Geomorphic Evidence for Late-Wisconsin and Holocene Tectonic Deformation, Death Valley, California

ABSTRACT

Eastward tilting of the Death Valley-Panamint Range structural block has resulted in segmentation of alluvial fans in south-central Death Valley. The youngest segment is generally near the fanhead on the east side and always near the toe on the west side. Six episodes of tilting have occurred, three of which postdate the last major high stand of Lake Manly, herein named the Blackwelder stand, which ended about 10,500 yrs ago. Estimates of the volume of sediment deposited after each episode of tilting suggest that distinct tectonic events occurred approximately 200, 1,000, 6,000, 17,000, 30,000, and 42,000 yrs ago. The average tilting rate appears to have increased exponentially with time.

On the Black Mountains, immediately east of the structural block, deposits of tufa and of carbonate-cemented lacustrine, alluvial, and colluvial gravel of diverse age are presently perched at elevations up to 100 m above present fans in positions where they could not have formed without support from older fans. On the west side of the valley, shorelines cut during the Blackwelder stand are about 30 m lower than these perched tufa and gravel deposits. Calculations based on these observations suggest that the average tilting rate doubled every 23,000 yrs during the late Wisconsin. The present rate is about 0.016 degrees/1,000 yrs.

INTRODUCTION

Evidence for the widely recognized (Maxson, 1950; Green in Hunt and Mabey, 1966, p. 112–114; Drewes, 1963; Denny, 1965) eastward tilting of the Death Valley-Panamint Range structural block (Fig. 1) is found in late Quaternary deposits of south-central Death Valley. In an attempt to interpret this record, six months were spent in the valley during the winters of 1967 through 1970. Pluvial-lake stratigraphy and shoreline features were studied, and thirteen alluvial fans were mapped in detail (Fig. 2). In mapping, gravels were placed in one of seven stratigraphic units (Table 1) distinguished on the basis of surface topography, topographic position, and weathering characteristics (Table 2). These units consist of unconsolidated to poorly consolidated, poorly sorted, stratified, pebble to boulder fanglomerates, probably of fluvial origin, with some unsorted massive beds presumed to be of debris-flow origin.

The units are not of uniform thickness because aggradation may be occurring on one part of a fan while another part, up- or down-fan from the first, is being eroded or is in a steady state. For instance, fans on the west side of Death Valley have been tilted eastward and incised at the head (Hunt and Mabey, 1966, p. A85). Recent deposition has been concentrated near the toe in a down-fan thickening wedge (Fig. 3A). On fans on the east side of the valley, recent deposition has been concentrated at the head in a down-fan thinning wedge (Fig. 3B), and older gravels are exposed near the toe.

In this paper attention is focused on the wedge-shaped parts of the stratigraphic units. The volume of gravel in these wedges is estimated, and these volumes are used to determine the relative length of time between episodes of tilting of the Death Valley-Panamint Range structural block. Relations between pluvial lake features and the stratigraphic units on the fans are used to establish a tentative absolute time scale for events in Death Valley during the late Wisconsin and Holocene.

DESCRIPTION AND INTERPRETATION OF MAP UNITS

The surfaces of the four youngest units, herein grouped as channel facies units (Table
DEATH VALLEY-PANAMINT RANGE
STRUCTURAL BLOCK

SEARLES VALLEY

WINGATE WASH

Qf
Quaternary fans

Qp
Quaternary playa

Pre-Quaternary bedrock

Faults bordering structural block

Subsidiary faults

Shoreline and tufa localities

Figure 1. Index map showing the Death Valley-Panamint Range structural block and vicinity.
TABLE 1. STRATIGRAPHIC UNITS

<table>
<thead>
<tr>
<th>Facies</th>
<th>Unit</th>
<th>Corresponding unit mapped by Denny (1965)</th>
<th>Corresponding unit mapped by Hunt and Mabey (1966)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Active Channel</td>
<td>Modern washes</td>
<td>No. 4 gravel</td>
</tr>
<tr>
<td></td>
<td>Overflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Inactive Channel</td>
<td>Abandoned washes</td>
<td>No. 3 gravel</td>
</tr>
<tr>
<td></td>
<td>Transitional</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>Younger Surface</td>
<td>Weathered gravel</td>
<td>No. 2 gravel</td>
</tr>
<tr>
<td></td>
<td>Intermediate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Older</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1), have the appearance of braided channels reflecting the character of the streams that deposited the material. The surface of the active channel unit occupies channels near the fanhead. The surface of the inactive channel unit forms terraces 0.5 to 1 m above active channel units, and the surface of the transitional channel unit forms terraces 0.5 to 2 m above inactive channel units.

It is assumed that gravels on successively higher terraces are older, and weathering characteristics support this assumption. Desert varnish is darker on rocks on successively higher terraces, and the lowest terraces are characterized by the bar and channel topography typical of braided streams, whereas a bar and pavement topography is found on higher terraces. The bar and pavement topography is believed to form over a period of years by creep-smoothing of the pebble gravel in former channels, Desert pavements thus formed are firm and are underlain by a thin vesicular A horizon, but are of only local extent. Farther down-fan the terraces are usually not as well defined, so weathering characteristics and surface topography must be used to identify the various channel facies units.

The surfaces of the three oldest units, herein grouped as surface facies units (Table 1), retain little if any evidence of their presumed initial bar and channel topography, but instead are extensive, well-developed desert pavements with darkly varnished stones. The relative ages of these units are again based primarily on their relative heights in terraces. For instance at the head of Hanaupah fan (Fig. 4B) the top of the younger surface unit is about 20 m above channel facies units in the main channel. The top of the intermediate surface unit is about 30 m and the top of the older surface unit about 60 m above these channel facies units. Successively higher terraces are steeper, so the terraces merge gradually down-fan (Fig. 3A). Gullies cut by rain falling on the terrace surfaces are deeper and wider on successively higher terraces (Fig. 4B), a quality which is particularly noticeable on air photographs (Denny, 1965), and areas of continuous pavement on interfluves are smaller. On the two higher terraces the A and B soil horizons have begun to creep into the gullies and, where caliche development was strong, a well-indurated K horizon is exposed at the surface.

Other characteristics of the exposed surfaces of these units are outlined in Table 2. Semi-quantitative weathering data are presented in Appendix A,\(^1\) together with additional maps and a brief discussion of some mapping problems (for detailed descriptions of some units see Denny, 1965, and Hunt and Mabey, 1966).

The relations among the four channel facies units are believed to be the result of random shifts in the positions of channels and random variations in storm area, duration, and intensity. Immediately after deposition, rocks on fans have a light-gray abrasion rind (Table 2, Note 2), and the deposits have bar and channel topography. However, rocks deposited by large floods may reside for many years in low braided terraces or floodplains slightly above active channels. The abrasion rind on rocks on such terraces has been darkened or removed by weathering; commonly a light-brown desert varnish has formed; and channel bottoms have been smoothed by soil creep, resulting in a bar and incipient pavement topography (Table 2, Note 4). Higher terraces are flooded less frequently, and thus have darker varnish and better developed bar and pavement topography.

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\(^1\) For Appendices A, B, C, D, E, and F, order NAPS document 01808 from ASIS National Auxiliary Publications Service, c/o CCM Information Corporation, 909 Third Avenue, New York, New York 10022; remitting $2 for microfiche or $5 for photocopies. Checks may be made payable to CCMIC-NAPS.
Explanation

1. Fan and drainage borders.
2. Segment boundaries, age number on younger side.
3. Borehole site and number.
4. Gravel
5. Sand
6. Brown silt and clay
7. Green = " "
8. Black = " "
9. Salt
10. Core not recovered.

1,100 Radiocarbon years B.P.
Warp structures due to right-lateral shear strain

Contour interval 240ft (73m)
Dotted contour on east side is -120ft (-36.5m)

North

BADWATER FAN
BADWATER FAH
WARREN TUFAL GIBLET
WESTILT COFFIN
COPPER FAN

12,980 B.P.
21,500 B.P.
66-34 BENNETTS WELL
68-66
A. WEST SIDE
(Looking South)

Terraces: Intermediate surface
Younger surface

Playa aggradation

Locus of active deposition.
Channel facies gravels interpreted as down-fan thickening wedge

Playa

Younger channel facies gravel

Local exposures of older channel facies gravels in stream banks and near toe.

B. EAST SIDE (except Goblet and Westilt)
(Looking North)

Channel facies gravels in incised channel interpreted as thin veneer over older, more steeply-dipping gravels.

NOT TO SCALE

Figure 3. Schematic geologic cross sections of fans. The relations in A reflect two episodes of tilting. Prior to the first episode the active surface was a-a'-a". Immediately before the second episode the active surface was b-b'-b" and the surface a-a' rose above the active surface as a terrace. Wedge a'-a''-b" was deposited between the two tilting episodes as was a thin veneer of gravel (not shown) on surface a'. The present active surface is c-c'-c" and gravels deposited since the second episode of tilting are shown by the circle pattern.

The channel facies units as a group comprise the active surface of a fan; that is, there is a finite, though perhaps small, probability that a flood large enough to rework these gravels will occur in any given year.

The relations among the surface facies units on west-side fans are interpreted in terms of episodic eastward tilting of the Death Valley-Panamint Range structural block. For instance, it is inferred that the top of the younger surface unit was once the active surface, and that tectonic steepening of the fans resulted in incision of this surface with a concomitant down-fan shift of the locus of active deposition (Fig. 3A). Weathering, creep-smoothing, and gullying then transformed this former active surface into a surface with the observed characteristics of the top of the younger surface unit. As the present active surface (c-c'-c" on Fig. 3A) aggrades, it gradually overlaps and buries the down-fan edge of the more steeply sloping younger surface unit at b'. The intermediate and older surface units were also once active surfaces and were incised, and their lower ends

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Figure 2. Index map showing locations of fans studied, borehole logs, and radiocarbon dates. Contours from U.S. Geol. Survey Bennetts Well and Furnace Creek 15-min quadrangles. Core logs and correlation lines for boreholes 100, 200, and 300 from Hunt and Mabey (1966). Hole 68-13 bored by Glen Miller with hollow stem auger, 1968. Holes 68-7 and 68-10 by bucket auger and 10-cm piston corer. Other holes by hand auger and piston corer. Detailed logs of all holes augered during this study are given in Hooke (1970).
buried as a result of earlier episodes of tilting. They were steepened further during the tilting event which caused incision of the younger surface unit.

**Map Units as Stratigraphic Units**

The map units are conventional stratigraphic units. The incision of a unit, producing terraces, results in a relatively abrupt cessation of deposition of the unit, so the terrace surface is an approximate time line. Thus a surface facies unit can be defined as consisting of all gravel deposited or extensively reworked between the initiation of one episode of incision and the initiation of the next. For instance, the younger surface unit consists of gravel reworked between the time that incision of the intermediate surface unit began and the time that incision of the younger surface unit began.

Where a unit is not overlain by younger gravels, its upper surface is part of the present fan surface and is thus readily identified. How-
Figure 4B. Map and representative topographic profile of Hanaupah fan. Denny (1965) has published an aerial photograph of Hanaupah fan on which the map units used here are readily distinguished. On profile wedge 2 consists of channel facies units which cannot be differentiated on a small-scale cross section. A thin layer of younger gravels covering the exposed parts of units 3 and 4 is not shown.
TABLE 2. QUALITATIVE CHARACTERISTICS OF STRATIGRAPHIC UNITS

<table>
<thead>
<tr>
<th>WEST-SIDE FANS</th>
<th>ROCK-SURFACE CHARACTER</th>
<th>TOPOGRAPHY</th>
<th>TOPOGRAPHIC POSITION</th>
<th>QUALITATIVE WEATHERING AND VEGETATIONAL CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CHANNEL FACIES</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active</td>
<td>Light-gray abrasion rind&quot; (N7/0–N8/0) to darker gray of fresh rock</td>
<td>Bar and channel</td>
<td>In channels radiating from fanhead and in broad braided surfaces on lower parts of fans</td>
<td>Not important</td>
</tr>
<tr>
<td>Overflow*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not mapped separately on west-side fans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inactive 1*</td>
<td>Light-brown desert varnish* (5YR6/4 to 5YR6/6)</td>
<td>Bar and channel to bar and incipient pavement*</td>
<td>In bars and terraces above* active channels. Also in channels diverging from active channel and higher than active channel at point of divergence</td>
<td>Not important</td>
</tr>
<tr>
<td>Inactive 2*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transitional</td>
<td>Moderate-brown desert varnish* (5YR3/4 aver)</td>
<td>Bar and channel to bar and pavement</td>
<td>In bars and wide terraces above active and inactive channels</td>
<td>Foliated rocks locally split. Carbonate rocks etched by solution</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SURFACE FACIES</th>
<th>ROCK-SURFACE CHARACTER</th>
<th>TOPOGRAPHY</th>
<th>TOPOGRAPHIC POSITION</th>
<th>QUALITATIVE WEATHERING AND VEGETATIONAL CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Younger</td>
<td>Shiny dusky-brown desert varnish* (5YR2/2)</td>
<td>Extensive continuous well-developed desert pavement</td>
<td>Broad surfaces above channel facies</td>
<td>With increasing age, splitting of foliated rocks becomes more common, etching of carbonate rocks is deeper, desert shrubs become less abundant, and grass more abundant</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Shiny dusky-brown desert varnish becomes less common with increasing age and is restricted to rocks in pavement patches.</td>
<td>Well-developed desert pavement but in discontinuous patches</td>
<td>Broad surfaces above channel facies. Up-fan* from younger surface unit and more deeply dissected than younger surface unit. Wide flat interfluves common.</td>
<td></td>
</tr>
<tr>
<td>Older</td>
<td>Patches of well-developed desert pavement are smaller than on intermediate surface unit</td>
<td></td>
<td>Deeply dissected surfaces. Up-fan from and above younger and intermediate surface units. Flat interfluves are narrow.</td>
<td></td>
</tr>
</tbody>
</table>

However, the contact at the base of a unit and buried parts of the unit's upper surface, though well-defined in principle, are difficult to locate in the field. Exposures of these contacts in vertical cross section are rare, partly because channel banks are generally mantled with colluvium, partly because banks of sufficient height to expose the contact are found only near the heads of fans on which the main channel is deeply incised, and partly because underlying gravels are commonly reworked during deposition of the younger unit, resulting in gradational contacts. The best exposure of such a contact is near the head of Johnson fan where a thick, well-indurated caliche horizon at the top of the older surface unit prevented erosion of this unit during deposition of intermediate surface gravels (Fig. 5). Similar exposures of the same contact were found on Hanaupah and Twin fans, and an exposure of the contact between the younger and intermediate surface units was found on Johnson fan.

The lines along which these buried contacts intersect the fan surface can be traced across the fans as well-defined breaks in slope which occur where the thin edge of the wedge-shaped part of the younger unit overlaps older gravels (see b' on Fig. 3A). The position of the buried contact beneath the wedge-shaped part of the younger unit can be estimated by projecting the exposed
top of the older unit beneath the younger gravels in the wedge, in the same way that strike and dip of bedding are used to project contacts to depth in any geologic cross section (Fig. 4).

**Locating Breaks in Slope**

Breaks in slope were located by drawing topographic profiles along fan radii (Fig. 4). Profiles of east-side fans were surveyed by plane-table methods. Most profiles were closed, and closure errors rarely exceeded 0.5 m. Profiles of west-side fans were plotted from U.S. Geological Survey 15-min quadrangles enlarged to a scale of 5.5 cm = 1 km. Where the fan surface along the profile line was dissected (Fig. 4B), the predissection surface was reconstructed by drawing new contours tangent to the outermost points of existing contours. Between 2 and 8 profiles were plotted for each fan depending on the size of the fan and complexity of the contact.

It is important to note that contacts between stratigraphic units do not always coincide with breaks in slope (Fig. 4). The break in slope coincides with the thin edge of the wedge-shaped part of the unit. Where this edge merges with a thin veneer of gravel of the same age (Fig. 3B), the contact between the wedge and the underlying older gravels is covered by the veneer.

<table>
<thead>
<tr>
<th>Rock-surface character</th>
<th>Topography</th>
<th>Topographic position</th>
<th>Qualitative weathering characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-gray abrasion rind (N7/0 to N8/0)</td>
<td>Bar and channel</td>
<td>In channels radiating from fanhead and in broad braided surfaces on lower parts of fans</td>
<td>Not important</td>
</tr>
<tr>
<td>Light-gray abrasion rind to darker gray or brown of fresh rock</td>
<td>Bar and channel</td>
<td>In channels diverging from active channel and 0.3 to 1 m higher than active channel at point of divergence</td>
<td>Not important</td>
</tr>
<tr>
<td>Gray or reddish brown of fresh rock</td>
<td>Bar and channel</td>
<td>In bars or terraces above younger channel units or in broad braided surfaces downfan from younger units. In latter case narrow active or overflow channels cross inactive channel unit</td>
<td>Fe-stain on soil visible between pebbles on surface</td>
</tr>
<tr>
<td>Light-brown desert varnish on some rocks near fanhead</td>
<td>Bar and channel to barren incipient pavement</td>
<td>Bar and pavement or weak pavement near fanhead. Flat areas of soft powdery soil near salt pan</td>
<td>Crumbling of some less-resistant rocks and more Fe-staining of soil</td>
</tr>
<tr>
<td>Moderate-brown desert varnish on rocks near fanhead</td>
<td>Bar and pavement or weak pavement near fanhead. Flat areas of soft powdery soil near salt pan</td>
<td>In terraces above younger units near fanhead. Visible beneath or in windows through younger units near salt pan</td>
<td>Reddish-brown or orange soil. Near salt pan soil is soft to walk on and lacks a vesicular A horizon. Rocks commonly have disintegrated to piles of angular pebbles, particularly near salt pan. Higher salt content than in younger units (Appendix A, Table A2, Sta. 236)</td>
</tr>
</tbody>
</table>

1. On laboratory fans (Hooke, 1967) it has been observed that active channels commonly aggrade rapidly during early stages of a flood when sediment concentration in the flow is high. The channel is deepened during later stages of the flood when the sediment concentration is lower. Similar aggradation may occur during early stages of floods on natural fans and may result in relatively frequent flow in overflow channels.

2. The abrasion rind on a rock is a surface layer, a few tenths of a millimeter thick, that has been fractured by collisions with other rocks during transport by water in channels. This layer is light gray and is similar to the light-gray or white percussion mark made by striking a rock with a hammer. The rind is lightest in color and best developed on edges and corners of rocks. During early stages of weathering it is altered or removed and the color of the rock surface approaches that of the fresh rock.

3. Varnish color is average color on rocks susceptible to varnishing. In an incipient desert pavement, stones at the surface are set in a mosaic but the underlying vesicular A horizon is thin or absent and steps indicating downslope creep (Denny, 1965) are not found. In bars or terraces above channel units near fanhead and in broad braided surfaces downfan from younger units. In latter case narrow active or overflow channels cross inactive channel unit. A horizon is light gray and is similar to the light-gray or white percussion mark made by striking a rock with a hammer. The rind is lightest in color and best developed on edges and corners of rocks. During early stages of weathering it is altered or removed and the color of the rock surface approaches that of the fresh rock.

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5. "Above" is used to imply vertical displacement only, as a terrace above a channel. "Up-fan" implies in addition a lateral displacement toward the fanhead. For example, the older surface unit occurs only near the fanhead and is thus up-fan from large areas underlain by the intermediate surface unit which occur downfan on the fan (Fig. 4B). It is also a terrace above those parts of the intermediate surface which occur near the fanhead.

6. Inactive; and Inactive not differentiated on west-side fans.

**TABLE 2 (continued)**

<table>
<thead>
<tr>
<th>EAST-SIDE FANS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moderate-brown to dusky-brown varnish</td>
</tr>
</tbody>
</table>

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SEGMENTATION

Introduction

That radial topographic profiles of alluvial fans generally consist of a series of segments with uniform slope was first recognized by Bull (1964). A typical segment consists of a surface of approximately uniform slope bounded up-fan and down-fan by breaks in slope which are roughly concentric with the fanhead, and bounded laterally by the edge of the fan or by older incised gravels (Fig. 2). Bull believed that each segment was formed during a period of tectonic stability during which it was the active surface. He attributed segmentation to episodic tectonic disturbance of the fan-source system.

The stratigraphic relations on segmented fans in Death Valley support Bull's explanation of episodes because the breaks in slope, or segment boundaries, coincide with the wedge-shaped edges of units which are approximately time stratigraphic. Contacts which intersect the fan surface at a break in slope (Fig. 5) demonstrate conclusively that the break in slope is not a primary depositional concavity in the profile.

That the active surface on an alluvial fan should have a uniform slope is at first thought unexpected. The main independent variables which collectively determine the equilibrium slope of a fan are the sizes of discharges reaching the fan, the debris size, and the concentration of sediment in the flows (Hooke, 1968). If discharges are small, sediment size is large, or sediment concentrations are high, the slope of the fan will be relatively steep so that the sediment load supplied can be transported by the available discharges. Conversely with larger discharges, smaller particle sizes, or lower sediment concentrations, the sediment load supplied can be transported on fans with gentler slopes. On the active surface the discharge per channel decreases down-fan because the flow is split up into smaller and smaller distributaries. If this splitting process alone were operative, one would expect fans to be convex because the smaller channels with lower discharges would have to carry the same caliber and concentration of sediment as larger channels nearer the fanhead; to transport this sediment the smaller discharges would require a steeper slope. However, as the flow proceeds down-fan, the coarser debris is deposited in bars, thus simultaneously decreasing the mean size of sediment that the water is carrying and decreasing the sediment concentration. Such bars commonly occur at places where a channel splits into two or more channels. Thus at precisely the point where an increase in slope would seem to be required to transport the sediment load supplied, the sediment load is decreased, and it is decreased in
just the right proportion to permit the water and its sediment load to continue in the smaller channels without a change in slope.\(^2\)

At the toe of a fan the situation is somewhat different because a well-defined, concave-upward transition zone, or gravel margin, separates the fan and the essentially horizontal playa. On the gravel margin the down-fan decrease in sediment caliber and concentration apparently more than offsets the decrease in discharge due to branching of channels. Thus at any point on the gravel margin, the sediment load remaining can be carried on a progressively gentler slope. Presumably these same conditions might obtain farther up-slope on some fans, thus resulting in a uniformly concave upward profile. However, I have not studied any such fans.

Hypothetically, a fan could be segmented by changing the sizes of discharges, the mean size of sediment, or the sediment concentration in the flows, or by physically tilting the fan. In the first three cases the equilibrium slope of deposition is changed. In the last case the slope of the existing fan is changed without necessarily changing the equilibrium slope at which flows deposit their sediment load.

Any explanation of segmentation which does not account for the origin of the break in slope is incomplete. For instance, segmentation should not be attributed to climatic change, without first demonstrating that the postulated change in climate could have changed one or more of the independent variables controlling fan slope in the direction necessary to produce the observed change in slope. At present it is impossible to demonstrate this because we do not know how changes in climate affect sediment size and sediment yield per unit discharge (= sediment concentration), nor do we know how the present frequency distribution of rainfall differs from that in the past. If, for example, the pluvial climate were characterized by more low-intensity storms and fewer high-intensity storms than at present, pluvial discharges could have been lower than present discharges, despite a generally higher mean annual rainfall during the pluvial period.

**Segmentation of Fans in South-Central Death Valley**

Segmentation of fans in south-central Death Valley is attributed to eastward tilting of the Death Valley–Panamint Range structural block. On the west side of the valley tilting has incised the fanhead and deposited at the toe (Fig. 4B; Hunt and Mabey, 1966, p. A85–A86), thus tending to regrade the fan to the equilibrium slope. Sediment concentrations in runoff may have increased due to steepening and down cutting of the main channel in the source area, but if so the resulting increase in the equilibrium slope has been small compared with the increase in slope of the fan surface due to tilting.

On east-side fans the youngest segment is generally at the head (Fig. 4A), and the steeper slope of this segment is attributed to an increase in sediment concentration in runoff reaching the fans. It is inferred that sediment concentrations increased when the lower reaches of trunk channels in the Black Mountains were steepened by down-faulting of the valley. Segmentation of these fans cannot be attributed solely to a decrease in fan slope due to tilting because the difference in slope between the upper and lower segments is much larger (\(=0.01 \text{ m/m}\)) than the amount of tilting that is inferred to have occurred since deposition in the upper segment began (\(=0.0002 \text{ m/m}\)).

**Segment Volumes**

With the use of plan area and topographic profiles, the volume of material that has been deposited since each segmentation event was estimated for each fan by projecting the slopes of older segments beneath the younger gravels. The concave upward gravel margin between the fan and playa was assumed to have had the same geometry through time. Thus volume calculations were made by projecting slopes of older segments to the toes of the fans as straight lines (Fig. 4B). Furthermore, because the playa has been aggrading, the contact between playa and fan material is assumed to dip gently westward beneath the fan gravels (Figs. 3A and 4B). In computing segment volumes it was assumed that the playa has aggraded \(7 \text{ m}\) since segmentation event 3 (Fig. 2, core 68-7). Segment volumes include only material which has

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\(^2\)Debris flows commonly deposit material near the heads of fans and thus tend to steepen the fan (Hooke, 1967). However much of the material in debris flows is subsequently reworked by running water. On most fans that I have studied, unreworked debris-flow material comprises less than 25 to 30 percent of the fan. Thus debris-flow deposition can be ignored in this preliminary attempt to explain uniform slopes of active surfaces on fans.
come directly from the main source area; gravels redeposited by flows originating on the fan, as on the north flank of Hanaupah fan (Fig. 4B), are excluded.

Estimates of the uncertainty in these volumes (Fig. 7A) are based on uncertainty in projecting slopes of older surfaces beneath younger gravels; uncertainty in locating segment boundaries (breaks in slope not in agreement with pertinent contacts mapped with the use of weathering differences); and uncertainty resulting from having few profiles crossing the pertinent unit (particularly the older surface unit).

AREA RELATIONSHIPS

Contacts between fan and playa were drawn at the lower limit of appreciable pebble-sized debris. Lateral contacts between fans were drawn so that the majority of the surface gravel at any location was associated with the fan draining the source area whence that material was derived. Contour lines, flow directions indicated by channels, topographic continuity of geomorphic surfaces, air-photo study, and lithology were used to determine the source of the gravel.

Areas of fans and their drainage basins (Fig. 7B) were measured from topographic maps. Westilt fan is at the mouth of two channels and runoff from them has diverged after reaching the fan, leaving an area of transitional channel material between the two main channels. Thus this fan provides two points on Figure 7B. On the west, smaller fans are often found between larger fans (Fig. 2). Because these small fans have definite boundaries and well-defined source areas, they are included in Figure 7B. As previously discussed, using less complete and less accurate data (Hooke, 1968), fans on the east side of the valley are smaller, reflecting eastward tilting of the valley and lower sediment yields from the drier watersheds in the Black Mountains.

Fan area is proportional to the 0.82 (east) or 0.89 (west) power of the drainage-basin area (Fig. 7B). This exponent implies that as watershed area increases, the volume of sediment supplied per unit area decreases, presumably because more sediment per unit area is stored in channels and on valley-side slopes in larger watersheds (Hooke, 1968). Thus in the following discussion it is assumed that the volume of sediment derived from an average watershed in a given length of time is proportional to the watershed area raised to the appropriate power.

Some fans on the same side of the valley appear to be substantially larger or smaller than one would expect from consideration of the sizes of their watersheds. These discrepancies are usually due to local differences in lithology or geologic history. For example, the upper 80 to 90 percent of the Coffin watershed drained to Copper fan at one or more times in the past. Only a low alluvial divide prevents drainage in this direction at present. Thus the long-term average sediment supply to Coffin fan has been lower than its present watershed area would imply and Coffin fan is correspondingly small. Conversely, Warren fan is larger than expected. Fifty-five percent of the Warren watershed is underlain by quartz monzonite that weathers to chips and blocks less than 5 cm long. Outcrops of this rock are cut by many closely spaced fractures (Drewes, 1963, p. 14 and Pl. 1). Tufa fan is also somewhat larger than expected and 40 percent of its watershed is underlain by quartz monzonite. In other east-side watersheds, quartz monzonite underlies less than 26 percent of the basin. The large sizes of Warren and Tufa fans can thus be attributed to a higher than average sediment yield from this highly fractured rock.

On the west side, Johnson fan is larger than average. Sixty-two percent of the Johnson watershed is underlain by the Johnnie Formation. This formation underlies less than 35 percent of the area of other west-side watersheds (Hunt and Mabey, 1966, Pl. 1). The argillite members of the Johnnie Formation break readily along bedding planes 2 to 4 cm apart and this rock is thus likely to be more erodible than other major lithologies in the Panamint Range.

INTERPRETATION OF SEGMENT-VOLUME DATA

Two simplifying assumptions were made in interpreting the estimates of segment volumes. First, it was assumed that all deviations of points from lines in Figure 7B are due to geologic factors affecting the rate of sediment supply, and segment volumes were normalized to remove the effects of these geologic controls. The normalized volume, $V^*$, is given by

$$ V^* = \frac{cA^s}{A_f} V = f \times V $$

where $c$ and $n$ are the coefficient and exponent in the equations in Figure 7B, $A_f$ and $A_d$ are...
the fan and drainage-basin areas, respectively, and \( V \) is the measured segment volume. The quantity \( cA_d^n \) is the area that the fan would have if the sediment yield from its source area equaled the average yield for this side of the valley. Thus \( f \) is the ratio of this area to the actual fan area, and \( V^* \) is the volume that the segment would have if the source area had an average sediment yield.

Second, it is assumed, except as discussed subsequently, that adjacent fans were segmented at the same times. Thus ideally values of \( V^* \) for a given event should be proportional to \( A_d^n \), \( V^* = vA_d^n \), where \( n \) equals 0.89 (west) or 0.82 (east), and \( v \) is the volume of sediment expected from a 1 km\(^2\) watershed with average sediment yield in the time since the segmentation event.

In accord with these assumptions, \( V^* \) has been plotted against \( A_d \) in Figure 7A. The ordinate value of each point on the figure represents the normalized volume deposited on a particular fan between the time of a given segmentation event and the present. Thus the point for segmentation event 4 on Hanaupah fan represents the sum of the volumes in the wedge-shaped parts of the stratigraphic units labeled 2, 3, and 4 on the profile in Figure 4B. Because most fans have been segmented more than once, there are several points on the ordinate for each source area on the abscissa. Points representing the same segmentation event on different fans are enclosed by pairs of dashed lines, and solid lines with the appropriate slope, \( n \), were drawn through the points for each event. Values of \( v \) (Fig. 7A) for these lines were determined by a least-squares procedure.

If it is assumed that sediment yield has been relatively constant over the time span represented by these tectonic events, the age of an event is approximately proportional to \( v \). The relative time scale in Figure 6 is based on this assumption. Radiocarbon dates from borehole 68-7 (Table 3) suggest that the change in sedimentation rate between the pluvial (pre-10,000 B.P.) and post-pluvial periods is less than 20 percent of the mean rate. Thus errors in Figure 6 due to this assumption are small compared with other sources of error.

The volume of material deposited since the youngest segmentation event on Death Valley fan is too large to correlate this event with the second segmentation event on other fans, but smaller than expected if it is related to the third event. Death Valley fan is the northernmost west-side fan that was mapped in the field. However, the volume of material deposited since the youngest segmentation event on Trail fan, immediately north of Death Valley fan (Fig. 2), was determined from topographic maps and air photographs. From this estimate it appears that the youngest event on Trail fan occurred at approximately the same time as the youngest event on Death Valley fan. Still farther north, a radiocarbon date from borehole 67-16 (Fig. 2) indicates a rate of sedimentation of about 0.21 m/1,000 yrs or about one-fifth of the average rate between Tule Spring and Badwater (Table 3). All of these observations are consistent with the hypothesis that
the rate of tilting, or rate of down-faulting of the valley, decreases northward from Badwater (Hunt and Mabey, 1966, p. A101-A102), and that some of the tectonic events recorded by fans south of Death Valley fan did not affect Death Valley fan or fans farther north.

In order to establish an absolute time scale for the segmentation events discussed above it is necessary to study the relations between the stratigraphic units on the fans and the deposits and strandlines left by Wisconsin pluvial lakes. Segment volume data for east-side fans are presented and discussed in Appendix C, and deposits of post-Wisconsin pluvial lakes are described in Appendix D.

**DEPOSITS OF LAKE MANLY**

Lake Manly features are discontinuous and obscure in comparison with features formed by other late pluvial lakes in the Great Basin. This led Blackwelder (1933, 1954) to conclude that Lake Manly formed in early Wisconsin (Tahoe) time and that a shallower lake formed in late Wisconsin (Tioga) time. As is discussed in the section on "Absolute Age," I believe that these features were formed during a high stand of Lake Manly in latest Wisconsin time, between 10,000 and 11,000 B.P. This high stand, herein named the Blackwelder stand, is defined as that stand which cut the youngest strandlines in Death Valley and left the freshest tufa at eleva-
Drainage basin area, Ad, km$^2$

Figure 7. (A) Relation between drainage-basin area and normalized volumes deposited since segmentation events. Lines by least-squares constrained to have exponent of 0.89. Segmentation-event numbers at left ends of lines. Segmentation event 1 recognized only on eastside fans (see Appendix C). (B) Relationship between drainage-basin area and fan area. Lines fitted by least-squares techniques.

tions of about 90 m on the Black Mountains. Sedimentation rates are high in Death Valley because the sediment yield from a large source area is crammed into a depositional basin which is small relative to the total size of the catchment basin. Furthermore, due to tilting and segmentation, post-pluvial deposition on west-side fans has been concentrated at elevations where Lake Manly strandlines formed. Thus many lake features formed during the Blackwelder stand have been subsequently eroded or buried.

Lake Sediments

A typical stratigraphic section in the lake sediments beneath the Death Valley salt pan consists of 3 to 15 m of light-brown silt and clay grading downward into black silt and clay (Fig. 2). The transition zone is generally a meter or two thick and is olive green in color. The black sediment contains organic carbon and the top part of it has yielded radiocarbon dates of 11,900 and 12,980 yrs B.P. (Fig. 2 and Table 3). Upon exposure to air the black sediment oxidizes and becomes light brown in color.

The black silt and clay is interpreted to be lake sediment which has never been exposed to air. The green transition zone and lower part of the light brown layer are also believed to be lake beds, but upon desiccation of the lake this material was partly or completely oxidized before being covered by light-brown playa sediment. There are 3 to 4 m of black and green mud above the 12,980 and 11,900 yr-old levels in cores 68-7 and 68-10, respectively. Thus a perennial lake probably existed in Death Valley from some time prior to 26,000 B.P. (core 67-16) up to about 10,000 B.P. The absence of oxidized zones between 21,500 and 12,980 B.P. in core 68-7 suggests that the lake did not desiccate during this time interval, but thick salt beds in cores 200 and 300 reflect periods of lower lake level.

The light-brown silt and clay overlying the lake deposits are typical playa sediments. Near the fans they contain higher concentrations of sand and gravel representing periodic contributions of coarser sediment from the fans. Sand beds in cores farther from the fans may have been deposited in channels similar to the distributary channels that flow northward across the salt pan at present or may consist of wind-blown sand. The combination of clastic and evaporite sedimentation from periodic lakes, floodplain sedimentation near channels, and sedimentation in channels, has resulted in a varied and distinctive stratigraphy including beds of salt, sand, silty sand, silt, and clay. Beds usually have gradational contacts and are 10 cm to a few meters thick, but locally they are laminated with laminae averaging 2 mm thick. Comparable beds have been observed on the
Explanation

- Colluvial gravels
- Water-sorted gravels
- Bedrock: symbol usually omitted
- Tufa

Figure 8. Stratigraphy of tufa deposits and associated carbonate-cemented gravels on Black Mountain scarp. The water-sorted gravels may be either lacustrine or alluvial. Several similar deposits at about the same elevation were not studied. Cross sections surveyed by tape and Brunton compass. Elevations on cross sections based on theodolite triangulation from bench marks on west side of valley. Angles turned at night using Coleman lanterns for survey points. Error shown is one half the difference between elevations determined from two separate bench marks. Two sections from Copper area are about 50 m apart across same cliff. Locations of sections are given in Appendix E and Figure 1.

Tufa and Near-Shore Gravel

Tufa deposits and associated gravels have been studied at several places along the Black Mountain scarp on the east side of the valley. Stratigraphic cross sections of five of these exposures are shown in Figure 8. The names of the localities in Figure 8 have been taken from names of the nearest fans, but the tufa deposits are all well above the present fan surfaces.

From a distance the tufa deposits appear as light yellowish-gray, relatively linear, horizontal streaks extending discontinuously along the mountain face for 100 to 300 m. They are commonly associated with carbonate-cemented, water-sorted, and colluvial gravel (Fig. 8). The water-sorted gravels are generally finer grained than the colluvial gravels, and are moderately well sorted, and locally well stratified. Where stratified they dip outward from the mountain front at angles of 10 to 20 degrees, and in most exposures the component of dip parallel to the Black Mountain scarp is negligible. Thus these exposures are not simply uplifted remnants of alluvial fans in which stratification dips radially from the fanhead. The water-sorted gravels are probably predominantly alluvial, but above and slightly south of the head of Goblet fan there are some angular to subrounded, well-sorted and well-stratified gravels with coarse cross beds dipping about 20 degrees south.

These are interpreted to be bar gravels deposited in Lake Manly. They are less well indurated and less weathered than the alluvial and colluvial gravels.

The tufa deposits appear to be of more than one age (Fig. 9). The youngest (Fig. 9A) are white (N9) on fresh surfaces and pinkish gray (5YR 8/1) on weathered surfaces. These deposits are tentatively correlated with the Blackwelder stand because they resemble tufas collected on the Anvil strandlines described below. The next oldest tufa deposits (Fig. 9B) are light brownish gray (5YR 5/1) on weathered surfaces and the oldest (Fig. 9C) are brownish gray (5YR 4/1). Successively older deposits are successively more deeply etched by solution. Detailed descriptions of the tufa deposits are given in Appendix D. The fresh deposits locally overlie weathered tufa deposits with sharp contacts. Thus the weathering contrast is almost certainly a result of a difference in age, not in exposure or susceptibility to weathering.

Strandlines

Strandlines were studied at seven localities (Table 4); locations are given in Figure 1 and Appendix E. The Mormon Point, Shoreline Butte, and Wingate areas were discussed briefly by Blackwelder (1933).

To aid in interpreting these strandlines, a wave generator was installed in the sand box used in previous alluvial-fan studies (Hooke,
Figure 9. (A) Blackwelder stand tufa from Goblet locality (Figs. 1 and 8). (B) Tufa probably of early
1967, 1968). An alluvial fan was built under subaerial conditions and the lower half of the
fan was then flooded and subjected to wave action. This study served to emphasize two
points. First, wave action on a steep slope produces two linear features, a step and a beach
cliff (Fig. 10, profile). The step is a depositional feature which occurs slightly below water level
and has an accumulation of coarser material on its lakeward slope (Strahler, 1966). The beach
cliff is an erosional feature above mean water level. On gentle slopes beach cliffs do not form,
but berms may develop. Beach "cliffs" are less common than steps in Death Valley, and their
slopes have been reduced by creep and other slope processes (Fig. 10).

Second, a beach on an alluvial fan is predominantly an erosional feature and is a zone of
transportation. Material moving along it will not form a thick deposit, and if of local
derivation it will not be appreciably rounded. This may explain why well-sorted and rounded
gravels are generally not found on strandlines in Death Valley. Rounded scoriaceous pebbles
and basalt cobbles were found on a few of the Shoreline Butte strandlines (Blackwelder,
1933) but nowhere else. On the other hand, subrounded well-sorted gravels in thick, sweep-
ing, lakeward-dipping cross beds are found in bars associated with the Wingate and Warm
Spring strandlines, and in a bar described by Blackwelder (1954) and Hunt and Mabey
(1966, p. 69) in north-central Death Valley. Such bars cross the mouths of valleys or broad
indentations in the topography which once held coves or bays of Lake Manly (Fig. 10).

The highest Gold Valley strandline (Fig. 1) consists of a step and a beach cliff, but the lower
two strandlines are marked by steps alone. The upper strandline is about twice as well de-
veloped as either of the lower ones.

On Mormon Point there are ten steps with a beach cliff above the highest step. As at the
Gold Valley locality, the top strandline is two to three times as well developed as any of the
others. Furthermore, the spacing of the top
three strandlines is nearly the same as the spacing of the Gold Valley strandlines (Table 4), strongly suggesting that the two sets are correlative and that the Gold Valley set has been displaced downward 12 m relative to the Mormon Point set.

On Shoreline Butte at the south end of the valley there are at least 26 strandlines, each consisting of a bench with a beach cliff on the upslope side. The convex break on the downslope side is probably predominantly erosional and hence not a true step. Beach cliffs are more common here than elsewhere, perhaps because the overall slope of the butte is steeper (Table 4). The best developed of these benches is the fifth from the top at an elevation of 87 m. From a distance, topography above this strandline appears rounded and mature, while that below appears planar, undissected, and young. It is easy to visualize a lake at this level with rounded hills rising above the water surface.

The four benches above this level are broader than the 87 m bench but they have been eroded and are thus less prominent and less-clearly horizontal. Rounded pebbles of scoriaceous cinder are often found on them, and in a closed basin behind a boulder bar associated with the next to highest bench (127 m) there is a deposit of fine sand and silt more than a meter thick and containing a 50 cm bed of silty halite (50 to 55 percent soluble in water).

On Shoreline Butte there are strandlines 18 and 27 m below the 87 m level which may be correlative with the second and third strandlines at Mormon Point and Gold Valley (Table 4). At lower elevations on Shoreline Butte there are so many benches that one can always be found within 2 or 3 m of the elevation of one of the Mormon Point steps. Thus correlation between the lower six steps on Mormon Point and benches on Shoreline Butte is not possible. This lack of correlation is understandable;
because the Mormon Point steps were formed on alluvial material, they could have developed relatively quickly, and were probably often destroyed by changes in lake level. Such steps would be preserved only if the lake level fell below the steps before they could have developed, and were probably often destroyed by changes in lake level. Such steps represent longer stands of the lake, and changes in lake level would be less likely to destroy them. More of the Shoreline Butte benches probably predate the last fall in lake level.

All tufa and strandline localities discussed so far, except Shoreline Butte, are east of the most recently active fault of the Black Mountains and Death Valley (Fig. 1). Because there does not appear to have been appreciable Quaternary displacement on the section of this fault northeast of Shoreline Butte (B. W. Trosset, 1971, written commun.), and because the tufa deposits and the highest uneroded strandlines are consistently about 90 m above sea level (Fig. 8 and Table 4), it is inferred that the Black Mountain structural block and Shoreline Butte have been relatively stable in post-Wisconsin time. The absolute sense of displacement is thus believed to have been down faulting of Death Valley. The total amount of post-Wisconsin displacement is estimated to have been about 63 m, and is thus substantially greater than the small differences in elevation between these various tufa and strandline localities.

The Artist's Drive strandline locality on the east side of the valley, and the Anvil, Warm Spring, and Hanaupah localities on the west, are all on the Death Valley-Panamint Range structural block and have been displaced downward relative to the Black Mountain localities. At each of the localities on the Death Valley block, the highest strandline is again the best developed, and the vertical spacing of the strandlines is similar to that at the Mormon Point and Gold Valley localities. These observations support correlating the strandline sequences in the several localities with each other and with the freshest tufa deposits on the Black Mountains.

The highest Artist's Drive strandline is about 36 m above sea level, or 54 m below the highest strandlines on the Black Mountain block. However, downward displacement of the Artist's Drive strandlines is likely to have been less than that of east-side fans south of Badwater because, as noted, deformation at the latitude of Trail Fan and Artist's Drive has been less rapid than deformation farther south. Hunt and Mabey (1966, p. 70 and Pl. 1) recognized strandlines and deposits of lacustrine gravel at sea level about 1 km northwest of the Artist's Drive locality.

The Anvil and Warm Spring localities on the west side of the valley were cut by northwest-trending graben and normal faults, and dissected by northeast-trending washes in pre-
Blackwelder stand time. During the Blackwelder stand, gravel moving southeastward along beaches was dropped into the washes and formed gravel bars across them (Fig. 10). These bars are probably storm berms formed a few meters above mean water level. In post-Wisconsin time the bars have been partly eroded. The crests of the highest bars are at an elevation of 66 to 67 m in both localities. In the Anvil area, at an elevation of about 66 m, there are scattered chunks of tufa comparable to the freshest tufa deposits on the Black Mountains. In both areas steps are present less than 100 m northwest of the bars and at an elevation of 55 to 56 m. In the Warm Spring area a well-developed beach cliff is present about 8 m above the step, and in the Anvil area a poorly developed possible beach cliff occurs 6 m above the step. At both localities there is a second step 8 to 10 m below the first, and in the Anvil area there are 6 additional steps at still lower elevations (Table 4). Several of the lower Anvil strands have associated tufa deposits or well-sorted, well-stratified, subangular, cross-bedded gravel deposits.

The most critical and least well preserved strandline locality is that on the south flank of Hanaupah fan (Fig. 4B). Two features interpreted to be beach cliffs are cut on the intermediate surface unit. They are roughly in line with the Hanaupah fault scarp (Hunt and Mabey, 1966), 3 km to the north, and could be part of it. However, they are neither as high nor as steep as the scarp and there are two strandlines, whereas the Hanaupah scarp consists of a single break over most of its length (Fig. 4B). No faults were seen in the stream banks truncating the beach cliffs but exposures were not adequate to eliminate a fault origin. Three lines of evidence suggest that these are shoreline features. First, carbonate-cemented gravels beneath active channel gravels east of the lower beach cliff are slightly better rounded and considerably better sorted than most fan gravels, and may be of lacustrine origin. Second, on the northeast side of the area of intermediate surface gravel below the lower beach cliff, there is some gravelly fine sand and silt containing nearly 4 percent soluble salt, and quite possibly of lacustrine origin. Finally, the upper beach cliff is at an elevation of 58 m, in agreement with the highest steps at the Anvil and Warm Spring localities, and the two benches are 19 m apart.

Discussion

The Hanaupah strandlines are cut on intermediate surface gravels. Weathering characteristics and the degree of dissection suggest that the gravels on which the Gold Valley, Mormon Point, Anvil, and Warm Spring strandlines are cut are also of intermediate surface age. The weathering characteristic most indicative of such an age is the presence of caliche float at the Gold Valley and Warm Spring localities and of a thick caliche bed on Mormon Point. Thus it is concluded that intermediate surface gravels predate the Blackwelder stand of Lake Manly. No strandlines have been found on the younger surface unit, so the youngest gravels in this unit are inferred to be post-Wisconsin in age. The absence of more extensive strandlines on west-side fans has confused earlier workers who, not recognizing the difference in age between younger and intermediate surfaces, were look-
ing for features on both surfaces, and were look-
ing for features at elevations up to 90 m rather
than 60 m (Blackwelder, 1933; Hunt and

**ABSOLUTE AGE**

To establish an absolute time scale for the
geologic events discussed in this paper, it is as-
sumed that lake levels in Death Valley have
fluctuated in phase with those in nearby Searles
Lake, where the late Wisconsin history is much
better preserved and better known (see Smith,
1968, for references). Smith (1968) believes
that Searles Lake overflowed briefly between
about 10,500 and 11,000 B.P., and again be-
tween about 22,000 and 24,000 B.P. It also
overflowed at least twice in early Wisconsin
time. Between 11,000 and 22,000 B.P., it was
between one-third and two-thirds full.

Support for the assumption that Lake Manly
and Searles Lake fluctuated in phase is found in
the playa stratigraphy in Death Valley. In core
68-10 (Fig. 2) sediment beneath a thin salt bed
is dated at 11,900 yrs, suggesting that the salt
bed formed about 11,000 B.P. (The date is an
average from 80 cm of core representing 600 to
700 yrs of sedimentation.) In cores 200 and 300
there are much thicker salt beds at somewhat
deeper levels. With the use of the 11,900-yr
date, the sedimentation rates in core 68-10
(Table 3), and the correlation lines shown in
Figure 2 (Hunt and Mabey, 1966, p. B42),
these salts are estimated to be about 15,300 yrs
old. The lowest levels of Searles Lake in late
Wisconsin time occurred about 11,000 B.P.,
and between 14,000 and 15,000 B.P. (Smith,
1968), in agreement with the estimated ages of
salt beds in Death Valley. In Searles Valley
these two low stages did not produce salt beds
(Smith, 1962), but it is reasonable to expect
that Death Valley was drier than Searles Valley
then, as it is now.

If the Wingate Delta is correctly correlated
with the Blackwelder stand, it follows that the
Blackwelder stand was nourished by overflow
from Searles Lake via Panamint Lake and
Wingate Wash. Thus the Blackwelder stand
must correlate with one of the overflow stages
of Searles Lake. Several observations suggest
that it should be correlated with the most
recent overflow stage (10,500 to 11,000 B.P.).
First, radiocarbon dates and playa stratigraphy
indicate that there was a lake in Death Valley
from sometime prior to 26,000 B.P. up to
about 10,500 B.P. If the Blackwelder stand oc-
curred early in this time period, we would
expect to see still more extensive or better pre-
served evidence of later high stands.

Second, weathering characteristics of the
youngest ufa deposits in Death Valley are
comparable to weathering characteristics of
tufa deposited in Searles Lake during its latest
Wisconsin stage (G. I. Smith, 1968, oral
commun.).

Third, I have argued previously that at
equilibrium the rate of deposition on a playa
equals the rate on adjacent alluvial fans averaged
over the entire fan surface (Hooke, 1968). Deposi-
tion in Death Valley is clearly not in equilib-
rium at present because recent sediment is con-
centrated at the toes of west-side fans and at
the heads of most east-side fans. However, the
departure from equilibrium is as yet small, and
equilibrium is re-established slowly (Hooke,
1968), so the rate of sedimentation on the
playa during the past 20,000 yrs should not
differ appreciably from the long-term average
rate required for equilibrium. From Table 3,
the average rate of sedimentation on the playa
in Manly time is estimated to be

\[ \frac{0.77 + 1.39}{2} = 1.08 \text{ m/1,000 yrs} \]

In post-Manly time the average is 0.86 m/1,000
yrs. Because lakes apparently occupied Death
Valley during most of the time interval repre-
sented by the deposits discussed herein, the
average sedimentation rate in Death Valley is
probably closer to the rate for Manly time than
to the post-Manly rate; therefore, a rate of
1 m/1,000 yrs is adopted. This rate is assumed
to be applicable on the fans as well as on the
playa.

The volume of material deposited in million
cubic meters per 1,000 yrs, \( V \), is

\[ V = T A_f \]

where \( T \) is the rate of deposition (1 m/1,000
yrs), and \( A_f \) is the fan area in km\(^2\) (Hooke,
1968). From the regression equation for west-
side fan areas (Fig. 7B) this becomes

\[ V = 0.95 T A_f^{0.89}. \]

The time \( t \) (in thousands of years), re-
quired to deposit a volume \( V^* \) is then

\[ t = \frac{V^*}{V} = \frac{\nu A_f^{0.89}}{0.95 T A_f^{0.89}} = \frac{\nu}{0.95} \]

where \( V^* \) is the normalized volume deposited
since a given segmentation event (p. 2084) and
the values of \( \nu \) are given in Figure 7A. The ages
of the segmentation events thus obtained,
starting with event 2, are 1,000, 6,000, 17,000, 30,000, and 42,000 yrs B.P. These ages are the basis for the time scale shown in Figure 6. Relative ages of the channel facies units and of segmentation event 1, which was recognized only on east-side fans, are discussed in Appendix F. According to this time scale the younger surface unit was deposited between about 17,000 and 6,000 B.P. and approximately 40 percent of the gravels in the younger surface unit were deposited in post-Manly time. Geomorphic evidence discussed in Appendix F suggests that between 30 and 50 percent of the younger surface gravels were deposited since the Hanapah strandlines were cut.

Two additional observations provide rough checks on this time scale. First, in Searles Valley, caliche horizons which are relatively well developed in comparison with those in younger soils, occur in gravels roughly 14,000 to 15,000 yrs old (Smith, 1968). In Death Valley relatively strong caliche horizons occur in soils developed on the intermediate surface unit, but generally not in soils on the younger surface unit. Deposition of intermediate surface gravels is inferred to have ceased 17,000 yrs ago (Fig. 6). In an absolute sense the best developed caliche horizons in Death Valley are six or seven times as thick as those in Searles Valley and are much better indurated. However, in correlating soils between two widely separated areas, the degree of development of a soil relative to other soils in the same area is a more important basis for correlation than is the absolute development of the soil (Richmond, 1962). In this case the degree of development of caliche horizons in both Searles and Death Valleys is markedly better on the 15,000 B.P. gravels than on any younger gravels. The absolute degree of caliche development varies widely in soils of the same age in the same valley (Appendix A), so differences between valleys do not invalidate this correlation. Certain other varnish and vegetational characteristics of intermediate surface gravels support the correlation (G. I. Smith, 1970, written commun.).

Second, the inactive channel, transitional channel, and younger surface gravels on Starvation fan contain an unusually high percentage of debris flow material derived from the Little Chief porphyry (quartz monzonite). Some of these flows were enormous; Hunt and Mabey (1966) estimate volumes of between 6 and 20 million cubic meters, and one flow of inactive channel age topped a bank of the main channel which is now about 15 m high. In vertical exposures of gravels deposited in late younger surface time, debris flows, averaging 1 m in thickness commonly comprise more than 75 percent of the gravels present. In contrast similar exposures of intermediate surface gravels on Starvation fan generally contain less than 50 percent debris-flow deposits with a tendency for debris flows to be more common near the tops of the banks. During pluvial periods the Panamint Range presumably had more vegetation and hence fewer debris flows. If this is the case, the greater frequency of debris flows in post-intermediate surface deposits is consistent with the time scale established above.

### RATES OF TILTING

The rate of tilting of south-central Death Valley can be estimated in several independent ways. First, we may assume that the difference in slope between two successive segments on west-side fans equals the amount of tilting that occurred between the two segmentation events. However, tilting rates obtained in this way (0.05 degrees/1,000 yrs between segmentation events 5 and 3, 0.16 degrees/1,000 yrs between events 3 and 2, and 0.76 degrees/1,000 yrs since event 2) are much higher than rates obtained in other ways below. It is therefore inferred that tilting has resulted in a decrease in the equilibrium slope of deposition on west-side fans, but the mechanism for this is not understood. However, the apparent increase in rate with time is consistent with Drewes (1963) interpretation of the change in tilting rate since middle Miocene time.

The second estimate of the tilting rate is based on six geologic observations, each of which can be represented by an equation, yielding six equations with six unknowns. We assume that the increase in the rate of tilting through time can be approximated by an exponential equation:

$$\bar{\theta}' = \theta_0 e^{-xt}$$  \hspace{1cm} (1)

where $\theta'$ is the tilting rate in radians/1,000 yrs at any time $t$, and $t$ is expressed in 1,000s of years B.P., $\theta_0$ is the present tilting rate in radians/1,000 yrs, and $x$ is a constant with dimensions (1,000 yrs)$^{-1}$. The mean tilting rate between the present and any time $t$ in the past will be approximated by

$$\bar{\theta}' = \frac{\theta' + \theta_0}{2} = \theta_0 (1 + e^{-xt})$$  \hspace{1cm} (1a)

The second equation is obtained from the observation that Blackwelder stand strandlines
Figure 11. Schematic cross section showing positions of critical localities with respect to the Black Mountain scarp. Heavy line is horizontal line in the Death Valley-Panamint Range structural block at some on the west are 30 m below the east-side strandlines with which they are correlated. As noted, it is assumed that the Black Mountains have been stable and that this difference in strandline elevations is entirely due to eastward tilting of the Death Valley-Panamint Range structural block. The resulting equation is

\[
\frac{30}{d - 13,000} = 10.5 \left( \frac{\theta_0}{2} (1 + e^{-10.5x}) \right) \tag{2}
\]

where the left side is the amount of tilting since the strandlines were formed, 10.5 thousand years ago (Fig. 11), and the quantity in brackets on the right is the average rate of tilting in the past 10.5 thousand years (equation 1a). The third equation is based on the observation that fault scarps at the heads of Badwater, Warren, and Copper fans average 28 m in height. Younger surface gravels occur above the scarps, and deposition of younger surface gravels is assumed to have ceased 6 thousand years ago during segmentation event 3 (Fig. 6). Because deposition has continued at the heads of the fans below the scarps, the total displacement is \((28 + 6r)\) meters where \(r\) is the average rate of sedimentation at the heads of the fans in m/1,000 yrs. It is expected to be greater than the 1 m/1,000 yrs assumed elsewhere in the valley because of the wedge-shaped geometry of these deposits (Fig. 3B). The resulting equation is analogous to equation (2), thus:

\[
\frac{28 + 6r}{d} = 6 \frac{\theta_0}{2} (1 + e^{-6x}) \tag{3}
\]

The fourth equation is based on the elevation of the Goblet bar gravels (p. 2088). These gravels are poorly indurated and appear fresh, so they are tentatively correlated with the Blackwelder stand. The base of the bar is estimated to be 45 m above the present fan surface. Therefore we time in the past. Due to eastward tilting, this line is rotated about the axis of tilting so that at some later time it coincides with the lighter inclined line. View south. To obtain the fifth equation we note that tilting of the Death Valley-Panamint Range structural block should result in uplift of shorelines on the Panamint scarp in Panamint Valley (Fig. 11). R.S.U. Smith (1970, written commun.) has identified a well-developed shoreline on the Panamint scarp 70 m above the present elevation of the Wingate Pass (Fig. 1) overflow level. Tufa deposits associated with this strandline are comparable in weathering character to tufa deposits in Death Valley which are tentatively correlated with the 22,000 to 24,000 B.P. overflow of Searles Lake. From these relations we obtain

\[
\frac{70}{40,000 - d} = 22 \frac{\theta_0}{2} (1 + e^{-22r}) \tag{5}
\]

The final equation is based on the observation that alluvial and colluvial gravels associated with tufa deposits on the Black Mountains could not have been deposited in their present position without support from valleyward gravels (Fig. 8). Present fan surfaces are an average of 110 m below the perched gravels. The resulting equation is

\[
\frac{110 + \pi r_f}{d} = t_f \frac{\theta_0}{2} (1 + e^{-t_f x}) \tag{6}
\]

where \(t_f\) is the time that faulting of these gravels began in thousands of years B.P. Because the youngest tufa deposits are found in cavities in the valley-facing scarps of these exposures, most of the gravels and part of the faulting must predate the Blackwelder stand. Equations (2) through (4) can be combined to obtain a single equation in \(x\), which can then
be solved by trial and error, yielding $x = 0.03$. The values then obtained for the other unknowns are $r = 1.7 \text{ m/1,000 yrs}$, $d = 25 \text{ km}$, $\theta_0 = 0.00028 \text{ radians/1,000 yrs} \approx 0.016^\circ/1,000 \text{ yrs}$, and $t_f = 40,000 \text{ B.P.}$ Equation (1) becomes

$$\theta = 0.016 e^{-0.016t}$$

(1')

where $\theta$ is now the tilting rate in degrees/1,000 yrs. These values are all geologically reasonable. In particular the value of $t_f$ is close to the estimated age of 42,000 yrs for the faulting and tilting which initiated the earliest recognized segmentation event (Fig. 6).

A possible conclusion, consistent with available geologic evidence, is that the oldest tufa deposits and most of the gravel on the Black Mountain scarp were deposited during a high stand of Lake Manly correlatives with the 52,000 to 67,000 B.P. overflow stand of Searles Lake (Smith, 1968), that a period of relative stability then prevailed until roughly 40,000 B.P., and that episodic tilting has been occurring with increasing frequency since that time. During the 22,000 to 24,000 B.P. high stand of Lake Manly younger tufa and gravel deposits, such as the upper units in the Badwater cross section (Fig. 8), were deposited on the sloping bench formed by the older gravels.

Four additional estimates of the tilting rate which are generally consistent with equation (1') are presented in Appendix F.

**STRIKE-SLIP MOVEMENT**

On the east side of Death Valley, the youngest segment boundary is high on the northwest flanks of Badwater, Warren, Tufa, Coffin, and Copper fans, and profiles suggest relatively little post-segmentation deposition on this flank (Fig. 4A). The most recent deposition has been concentrated on the southwest sides of these fans. This geometry is almost certainly due to right-lateral, strike-slip displacement during and since the youngest segmentation event. On Goblet and Westilt fans the oldest gravels are also on the northwest flanks. Northeast-trending grabens on the northwest flanks of Badwater, Tufa, and Goblet fans are consistent with the northwest-southeast tension required for right-lateral slip. The amount of movement is on the order of 20 to 40 m since segmentation event 2 on Goblet and Westilt fans, or 2 to 4 cm/yr.

If the present tilting rate is $0.016^\circ/1,000 \text{ yrs}$ and the tilting axis is 25 km west of the Black Mountain scarp, vertical movement on the Black Mountain fault is on the order of 0.7 cm/yr. The Black Mountain fault dips about 45 degrees westward (Drewes, 1963), so the vector sum of this vertical displacement and a $3 \pm 1 \text{ cm/yr}$ north-south strike-slip displacement is a tensional displacement of about $3 \pm 1 \text{ cm/yr}$ in a N. 17 + 6 W. direction. The east-west component of this displacement is comparable to Carter's (1971) estimate of 0.8 cm/yr for Pleistocene left-lateral displacement on the Garlock fault, and the direction of displacement is subparallel with the N. 40 W. trend of the San Andreas fault zone.

**CONCLUDING STATEMENT**

In view of the assumptions made in equations (2) through (6), a healthy skepticism should be maintained in using the solutions. The credibility of the solutions and their compatibility with other data suggest that the geologic observations are quantitatively as well as qualitatively internally consistent. Such consistency does not imply accuracy of either ages or rates of deformation. For instance, if the Blackwelder stand were correlated with the 22,000 to 24,000 B.P. overflow stand of Searles Lake, all ages of units in Death Valley would be multiplied by a factor of 2.2. The solution of equations (2) through (4) would then yield deformation rates 1/2.2 times those obtained above, and most geologic observations would still be internally consistent. This age for the Blackwelder stand is not favored because it requires that rates of deposition on the playa exceed those on the fans by more than a factor of two, and because there are no strandlines cut into the younger surface unit which would then be about 13,000 yrs old, or 2,000 yrs older than the youngest major lake in the valley as suggested by radiocarbon dates.

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