The Shape of Trail Canyon Alluvial Fan, Death Valley

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Abstract

A modified conic equation has been fit to high-resolution digital topographic data for Trail Canyon alluvial fan in Death Valley, California. Fits were accomplished for 3 individual fan units of different age. The fits and the values of the parameters of the fits show that older units are flatter at the cone apex and have less radial curvature, that the two younger units are entrenched into the fan head, and the youngest unit is depositing at the toe of the fan. These data can be used to make inferences about the processes that have formed and modified Trail Canyon fan. In particular, the similarity of the fan-unit shapes is probably a reflection of a consistent tectonic uplift rate since the deposition of the oldest unit.

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Introduction

Landforms in arid regions record the interplay between tectonic forces and climate. When a desert piedmont is dominated by erosional and transport processes; a pediment is formed. Conversely, when aggradational processes dominate, alluvial fans are formed. The relative rates of uplift vs. aggravation determine the slope of the fan and whether the fan is cut by a trench (Bull, 1991; Bull and McFadden, 1977). Changes in uplift rate or climatic conditions can lead to isolation of the currently forming fan surface through entrenchment and construction of another fan either further from the mountain front (decreased uplift or increased runoff) or closer to the mountain front (increased uplift or decreased runoff). Thus, many alluvial fans are made up of a mosaic of fan units of different age, some as old as early Pleistocene in age. For this reason, determination of the stages of fan evolution can lead to a history of uplift and runoff.

In an attempt to separate the effects of tectonic (uplift) and climatic (runoff) processes on the shapes of alluvial fan units, a modified conic equation developed by Troeh (1965) was fitted to digital topographic data for the Trail Canyon alluvial fan in Death Valley, California. This allows parameters for the apex position, slope, and radial curvature to be compared with unit age.

Troeh's (1965) equation is given as:

$$Z = P + S\sqrt{\left((X-X_0)^2+(Y-Y_0)^2\right\} + L\{(X-X_0)^2+(Y-Y_0)^2\}}$$

where Z is the height at position X, Y; X_0, Y_0, and P are the coordinates of the cone apex; S is the slope at the apex; and L is the radial curvature. Note that the term containing L adds a radial curvature to the simple right-circular cone described by the rest of the equation. The first derivative of Z with respect to R, the radial distance from the apex (X_0, Y_0), is the slope at a given R, defined as:

$$G=S+2LR$$

Using the above approach, Troeh (1965) found that the signs of L and G could be used to distinguish four categories of natural slopes:

1) G and L > 0 implies a bowl shape, concave radially and with concave contours. This is the shape of a basin or natural amphitheater.

2) G>0, L<0 represents less common landforms of first-order catchments or sinkholes where the radial profile is convex, but the contours "are, as before, concave.

3) Both G and L c O represents hilltops, convex in both directions, where creep dominates.

4) Finally, G<0, L>0 characterizes alluvial fans and pediments, concave radially but with convex contours. As Gilbert (1877) recognized long ago, the concave radial profile is characteristic of sheet-wash transport which is able to carry particles on more gentle slopes as distance from the mountain front increases.

Troeh (1965) accomplished his work with topographic contour maps. With the advent of modern digital computers and digital elevation models, his approach can now be taken further and used to compare the topographic attributes of many alluvial fans or individual fan units with their age, drainage basin size, relief, lithology, uplift rates, etc. Further, the original extent and volume may be estimated for fan units of which only remnants are exposed. The topographic signature of individual fan units will help in regional correlation of fan surfaces of similar age.

Procedure

In order to Troeh's (1965) equation to individual fan units on an alluvial fan, several preliminary steps must be undertaken. The first is to acquire digital topographic data of sufficient resolution and coverage so that fan units contain a large number of points over as large an area as possible. The data set used for this study was obtained by an advanced NASA airborne sensor that will be discussed later.

After data acquisition, a fan must be chosen and the x, y, z values for individual units on that fan must be extracted for input to the fitting routine. For this study, Trail Canyon fan in Death Valley (Fig. 1,2) was chosen as a well-defined fan with several readily identified units (Hunt and Mabey, 1966). Once the map is obtained, it is digitized and registered to the topographic data so that the unit boundaries can be used to guide the extraction of the x, y, z values for each fan unit (Fig. 3). Standard 2 and 3-dimensional graphical display software is used to examine the extracted points to minimize the number of outliers included in the file (Fig. 4, 5).

Once the x, y, z values have been extracted and placed in a file, that file is input to a nonlinear least-squares fitting routine. The routine used for this study was an implementation of the quasi-Newton algorithm provided in the SYSTAT (v. 5.1) package for Macintosh computers (Wilkinson, 1989). The same starting values for the fit parameters were used for all fits to speed execution time. For about 800 points, typical run times were 1-2 hours on a Macintosh IIfx.

After the fit is obtained, it is plotted with the original points overlain (Fig. 4, 5) to visually examine the quality of the fit. The fit is also evaluated quantitatively by calculating the residual z-values through subtraction of the fit from the original z-values at each x, y (Fig. 6). The residual image is then examined visually for patterns related to fault or shoreline disruption of the fan surface or to systematic errors in the data set, In addition, the rms of the residual is calculated to provide a single number representing the departure of the true fan surface from the smooth cone surface.

The five fit parameters (X_0, Y_0, P, S, L) are then tabulated (Table 1) and plotted (Fig. 7) for comparison with fan unit properties such as age, drainage basin size, relief, lithology, etc. X_0, Y_0, for each fan unit is also plotted on the map of the fan to show the migration of the cone apex through time (Fig. 3b).

Geologic and topographic data

A variety of techniques have been used over the years to map the relative ages of alluvial fan surfaces in arid regions. Since suitable material for numerical age determination is scarce in these environments, the actual depositional history of few fans has been determined. Exceptions include the fans on the west side of Silver Lake (Wells et al., 1987) and on the west side of the Owens Valley (Gillespie, 1982). These studies indicate that major pulses of fan aggravation are related to climatic changes that occur either during or at the close of major glaciation when rainfall and weathering processes are most conducive to the formation of debris flows and fluvial activity.

Geomorphic evidence for relative age of alluvial fan units include: dissection, surface morphology, preservation of surface morphology, desert pavement development, rock varnish development, and extent of soil development (Christenson and Purcell, 1985; Bull, 1991; Dohrenwend et al., 1991). These criteria were used by Hunt and Mabey (1966) to map three major units on the fans along the west side of Death Valley. Tentative age assignments for these units have been made by Dorn (1988) based on ^{14}C dating of rock varnish on the fan surfaces. These ages range from modern to approximately 800 k.a., and are reported in Table 1. (Note the wide range of ages for Hunt and Mabey's Unit 2.) For the Trail Canyon fan, recent and active fan segments are concentrated in distal areas. However, with the exception of the oldest segments which are apparently concentrated on the north side, older segments occur in all areas without any apparent spatial concentration. In other words, this fan system exhibits little evidence of 'telescoping'; its form probably approximates a simple conic section.

In order to characterize topographically the alluvial fan units mapped by Hunt and Mabey (1966), sufficient resolution is required to discriminate the individual units and sufficient coverage is required to provide enough points for a meaningful fit. Typical units, as mapped by Hunt and Mabey (1966) and by other students of alluvial fans (e.g. Hooke, 1972) are tens of m wide and cover in aggregate, at least in the case of the Trail Canyon fan, an area of several square km. Another requirement on the data to be used for 3-dimensional fitting, is that the vertical errors in the data are smaller than the signal on the alluvial fans. On the Trail Canyon fan, relief differences between fan units are generally less than 5 m, while dissection within units typically ranges between 1 and 2 m.

There are several sources of digital topographic data that could be used for measurements of desert piedmont shapes, The most widely available data that most closely satisfy the above requirements are the U.S. Geological Survey's 7.5' Digital Elevation Models (DEM). The horizontal resolution (pixel size) of these data is 30 m and the vertical accuracy ranges between 7 and 15 m (USGS, 1990). These DEMs, however, are not available for large areas, including Death Valley.

For this study, a new data type has been used, provided by an imaging radar interferometer. The NASA/Jet Propulsion Laboratory (JPL) airborne polarimetric radar (AIRSAR), which flies onboard the NASA DC-8 produces images at P-band (wavelength=68 cm), L-band (24 cm) and C-band (5.6 cm). This system has been augmented with a pair of C-band antennas, supplied by the Consorzio per la Ricerca e 10 Sviluppo di Telesensori Avanzati (CORISTA) in Italy, which are displaced vertically on the fuselage to form an interferometer, called TOPSAR (Zebker and Goldstein, 1986; Zebker et al., 1992; Evans et al., 1992). The spatial resolution of the TOPSAR data for' Trail Canyon is 20 m. Analysis of TOPSAR data in control areas indicates that statistical errors in height are in the 1 m range, while systematic effects due to aircraft motion are in the 1-2 m range. Performance is best in areas of low relief and degrades slightly in the far range, as the signal to noise ratio decreases. In addition, for the Trail Canyon data, a slight motion-compensation error is discernible in the data. This takes the form of vertical (nearly north-south) bands of slightly lower elevations (Fig. 5,.6).

Results

The results of conic fits to the Trail Canyon alluvial fan units are summarized in Figures 4b, 5d, and 7. Figures 4b and 5d show that the oldest unit, 2, is higher than the two younger units in the proximal part of the fan. Because the slope and curvature of unit 4 are greater than unit 3, it intersects unit 2 at a higher elevation than unit 3 does. The distal conic-fit profile residuals (Fig. 5d) show these intersection points and how unit 4 is being deposited at the toe of the fan. At the fan head, these profiles show unit 4 at a higher elevation than unit 3. Field observations and the data points of Fig. 5b and c show that unit 4 is entrenched into unit 3. Apparently, the inclusion of outliers in the data for unit 4 at the fan head caused the fit apex height and slope to be overestimated.

Figures 7a and b show more clearly that the older units have less curvature than the younger units. This characteristic may be a result of continuous weathering and transport acting to move material down-fan and onto the valley floor, thus lowering both proximal and distal areas, Other factors that affect fan surface slope and curvature are the nature of the material deposited on the surface and the processes of deposition. Debris flows create steeper slopes than do fluvial processes. The amount of fine-grained material and the rate and magnitude of rainfall help determine whether debris flows or fluvial processes dominate. The rate of uplift relative to the combined rates of degradational processes also affects fan slope and curvature, as well as apex height. If either uplift rate or climatic factors changed significantly subsequent to deposition of the major fan units, their original shapes would probably be affected. Other factors that may play a part include the effects of dissection, which should widen the distribution of points in the z dimension (Fig. 5), and systematic errors in the DEM, such as the motion-compensation error discussed above. In addition, tectonic tilting of the fan with time may be a factor; although the fan unit profiles (Fig. 5) do not seem to reflect any systematic tilt.

Because it is not clearly related to fan unit age, relative movement of the apex position (Fig. 3, 7c) is less easy to explain. At the time of deposition of unit 2, the fan apex apparently was further from the mountain front than during deposition of subsequent units. This may be a reflection, at least in part, of fan-head entrenchment after the formation of unit 2. The slight northward movement of the fan apex between deposition of units 2, 3, and 4 may indicate a tilt of the Panamint Mountains down to the north, but the amount of movement of the apex in this direction is only about 300 m, less than half the movement in the orthogonal direction. The apex height (Fig. 7d) also doesn't vary consistently with age. It might be expected that the height of the unit 2 cone apex would be greatest, since it has been subjected to the longest period of uplift, however its cone is the lowest. The range of heights is only about 50 m, perhaps limiting the significance of this result.

Discussion

It is clear from the conic fits to individual units on the Trail Canyon fan that the fan has changed shape over time. The causes of these changes may be climatic, tectonic, or a combination of the two. Judging from the general similarity of the shapes of the different units, the Trail Canyon fan probably has not undergone major changes in tectonic uplift rate nor have the climatic episodes responsible for the building of the fan been much different from each other. The most noticeable effects are seen as a flattening and straightening with age and a westward retreat of the fan apex, indicating fan-head entrenchment. In order to make more far-reaching conclusions, additional studies of other fans in Death Valley and in other desert basins need to be undertaken. Fan shapes need to be correlated to drainage-basin size, relief, lithology, etc. in order to separate the effects of climate and tectonic uplift. Comparing basins subjected to similar uplift rates, but with different basin geometries and lithologies will help isolate the climatic variable. Whereas, comparing basins with similar regional climate, and presumably paleoclimate, but with different uplift rates will help isolate the tectonic variable. In this way, comparative analysis of the three-dimensional shapes of alluvial fan units may be used in combination with field observations and aerial-photographic analyses, as well as the emerging techniques of remote sensing (Farr and Gillespie, 1984; Gillespie et al., 1984; Gillespie et al., 1986) for more precise mapping and regional correlation of alluvial fan units.

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Table 1. Conic fit parameters for the three Trail Canyon fan units.

Unit	Age* (k.a.)	P (m)	X_0 (m)	Y_0 (m)	S	L (x10^4)
4	0-2.5	442,50	2393	21032	-1.778	11.040
3	3-11	454.28	2195	21106	-1.716	8.450
2	13-800	400.50	2894	21320	-1.668	7.775

*** From Dorn (1988)**

Figure Captions

Figure 1. Index map, reproduced from the USGS 1:250,000 topographic sheet of Death Valley, showing location of Trail Canyon alluvial fan (center) within Death Valley, CA. Note convex contours of alluvial fans on eastern flank of Panamint Mountains.

Figure 2. Photograph from the French SPOT satellite showing Trail Canyon alluvial fan at the foot of the Panamint Mountains. Dark surfaces on fan are older surfaces darkened by rock varnish. Lighter tones are characteristic of active washes. Original data ©CNES.

Figure 3. Topographic and geologic data used for the conic fits. a) Shaded-relief depiction of digital elevation model of Trail Canyon fan produced from TOPSAR interferornetric radar data with contours overlaid. The original data were acquired from the west (left) so noise is evident in the far-range along the right edge. The data were smoothed with a 3x3 lowpass box filter and this shaded relief image, which simulates illumination from the east (right) at 10° elevation angle, was produced. Scale and orientation are the same as Fig. 3b. b) Geologic map of Trail Canyon fan simplified from Hunt and Mabey (1966). Points labeled "2, 3, and 4" are the apex locations (X_0, Y_0) of the cones fitted to each unit.

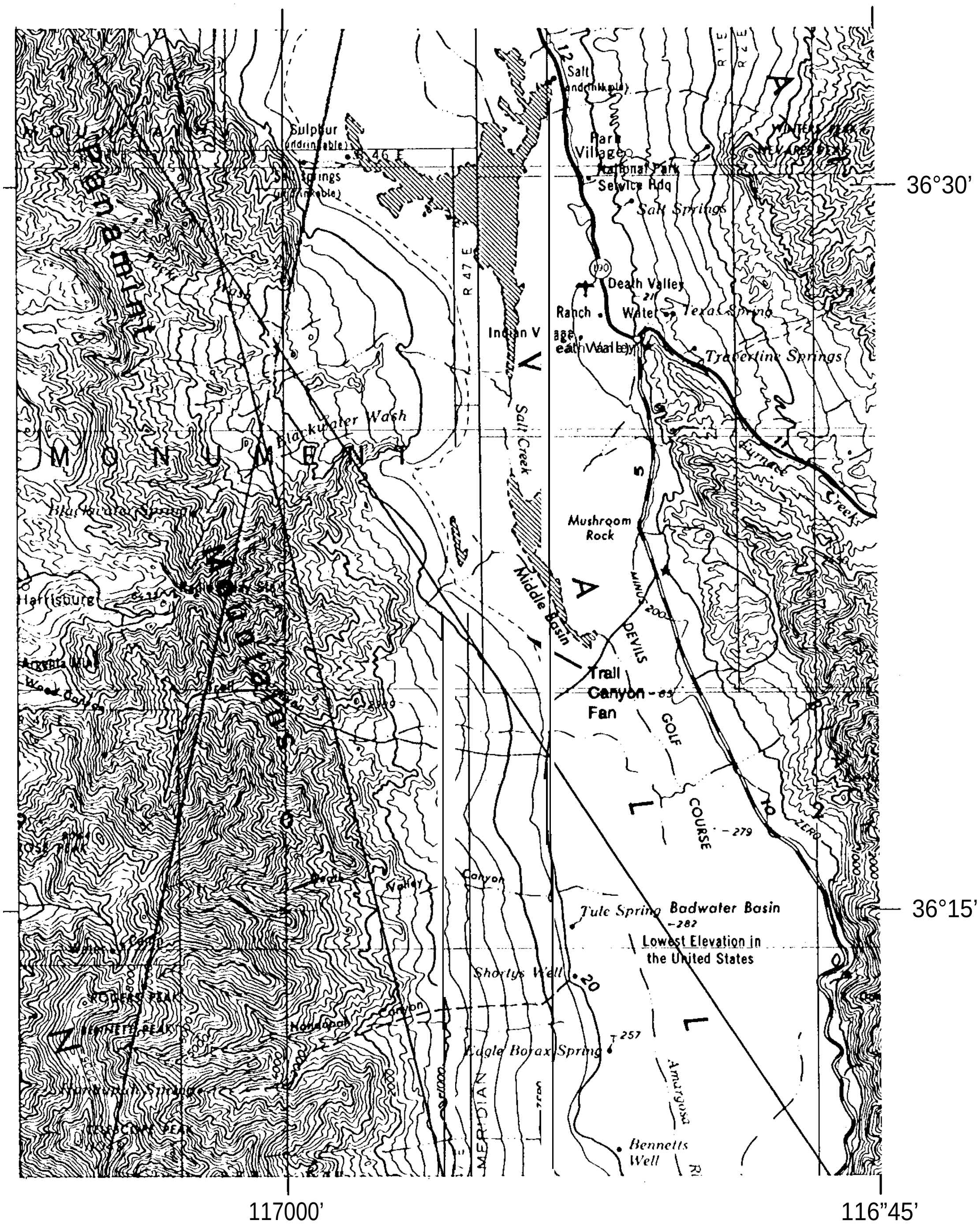
Figure 4. Projected profiles of the fan data and conic fits. a) The elevations of points used for the conic fits have been plotted as a function of radial distance from the fitted apex of Unit 3 (furthest west apex). Except for a few outliers, the points collapse very well onto a single curved line for each unit. The profiles have been offset vertically for clarity. b) The conic fits for the same surfaces, but only for the area within 2000 m of the fan apex, so that slight differences between the surfaces may be detected. These profiles have not been offset.

Figure 5. Residuals to a single linear fit to all three of the profiles. Because the profiles and fits shown in Figure 4 display small differences in relative elevation over large variations in absolute elevation, a straight line was fit to the profiles and the difference plotted here for each unit, The conic fits have also been plotted. Note the presence of outliers and the systematic errors (dips) probably

caused by antenna pattern mismatch. a) Unit 2. b) Unit 3). c) Unit 4. d) The conic fits shown in a, b, and c are plotted together to emphasize differences. Note that Unit 2 stands about 5 m higher that the other units and has the lowest slope (S) and smallest curvature (L) while Unit 4 has the highest values for these parameters.

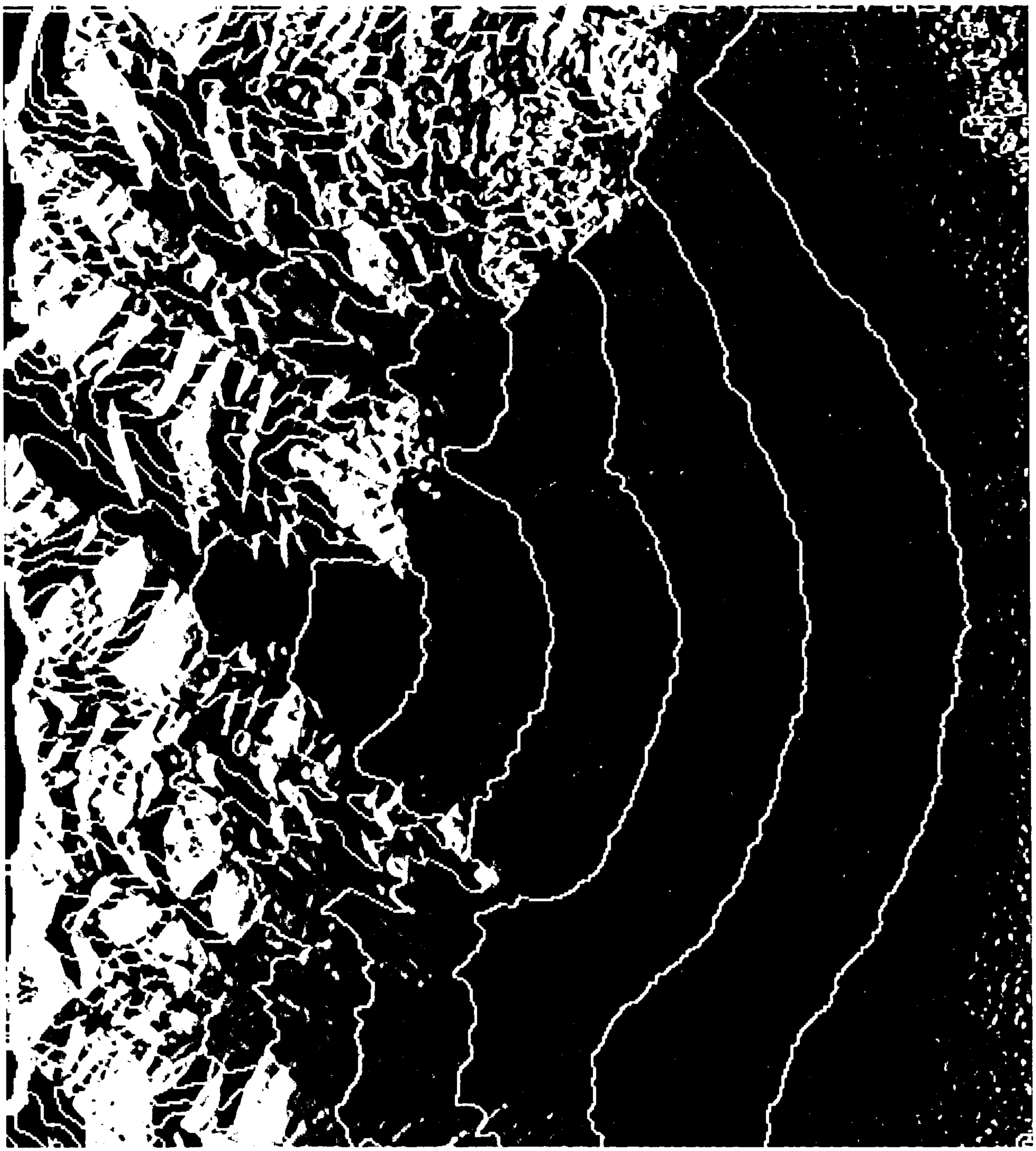
Figure 6. Images of the difference between the fitted cone and the true topography of each of the fan units. Brightness is proportional to the absolute value of the difference. Note the vertical dark bars caused by antenna pattern mismatch in the original DEM. Scale and orientation are the same as Fig. 3b. a) Unit 2. b) Unit 3. c) Unit 4.

Figure 7. Conic fit parameters as a function of fan unit relative age. a) Slope at R=O (S). Note that slope flattens with age. b) Slope curvature, or the change in slope with distance (L). Note that curvature decreases with age, c) Apex position: X_0, Y_o. Note that X. (nearly equal to the distance east) has not changed consistently, but Y. (nearly equal to the distance south) has tended to increase (i.e. move south) slightly with age. d) Apex elevation, P, has not changed consistently with age.

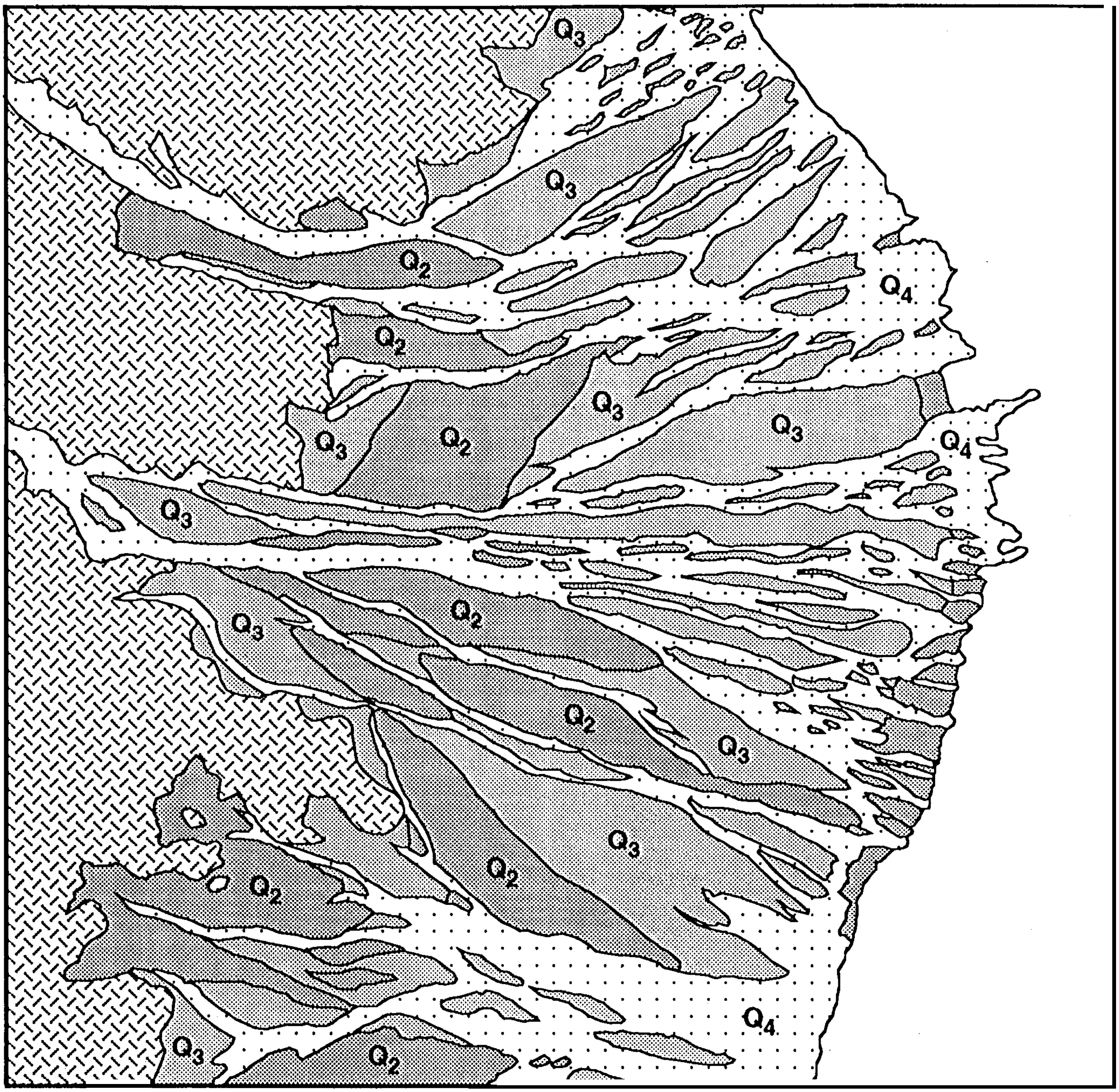


Farr and Dohrenwend, fig. 1

farr and dohrenwend, fig. 2



Farr and Dohrenwend, Fig. 3a



PRE-QUATERNARY BEDROCK UNITS

Q_2 OLDEST QUATERNARY FAN GRAVELS
HEAVILY DISSECTED AND VARNISHED
DESERT PAVEMENT SURFACES

Q_3 INTERMEDIATE QUATERNARY FAN GRAVELS
SOME DISSECTION AND VARNISH

Q_4 YOUNGEST QUATERNARY FAN GRAVELS
INCLUDES ACTIVE WASHES. NO DISSECTION OR VARNISH

EVAPORITE UNITS

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KILOMETERS

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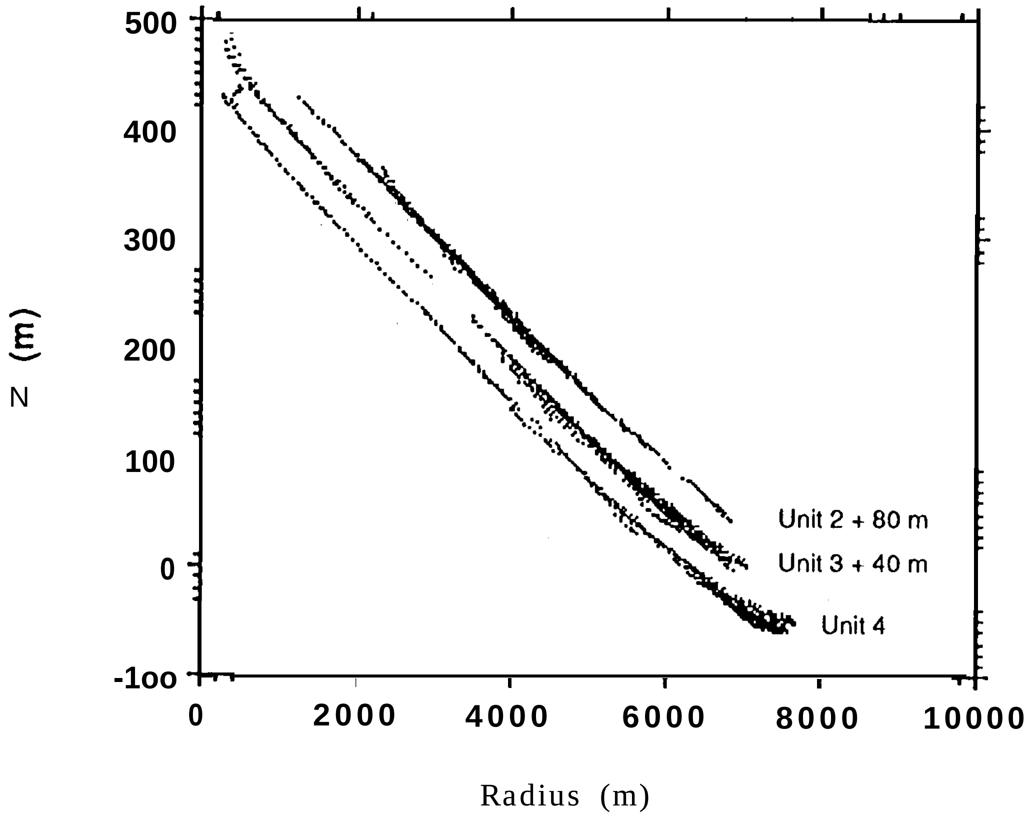

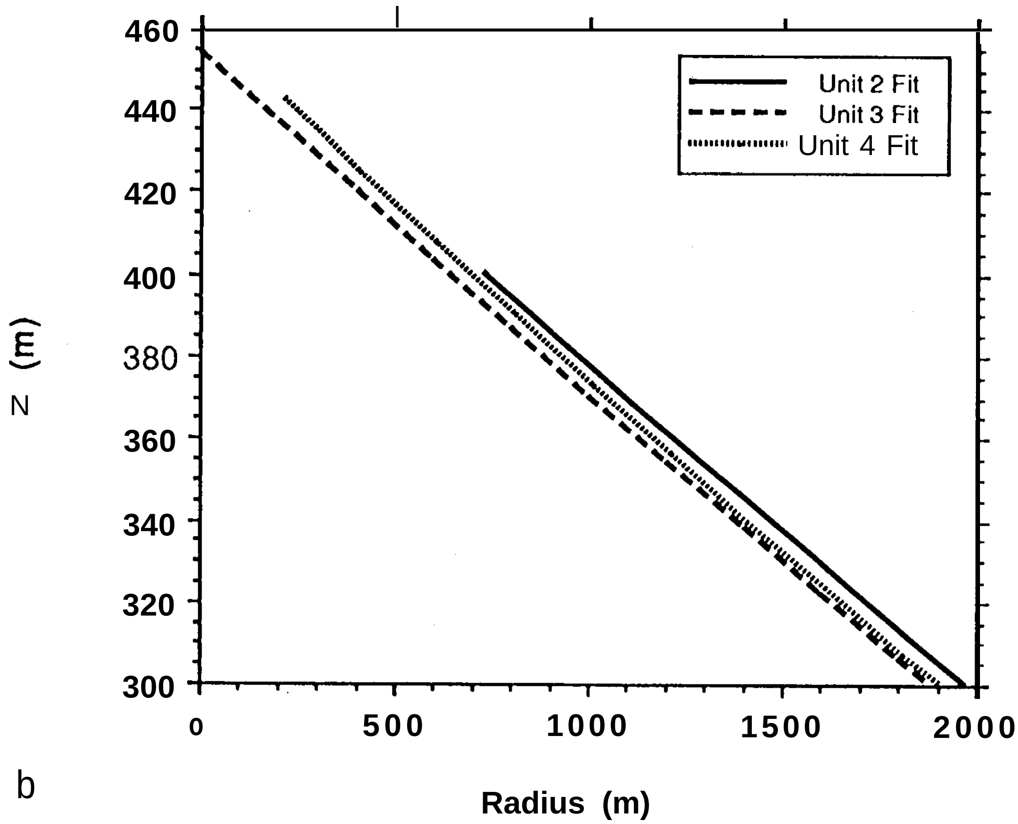

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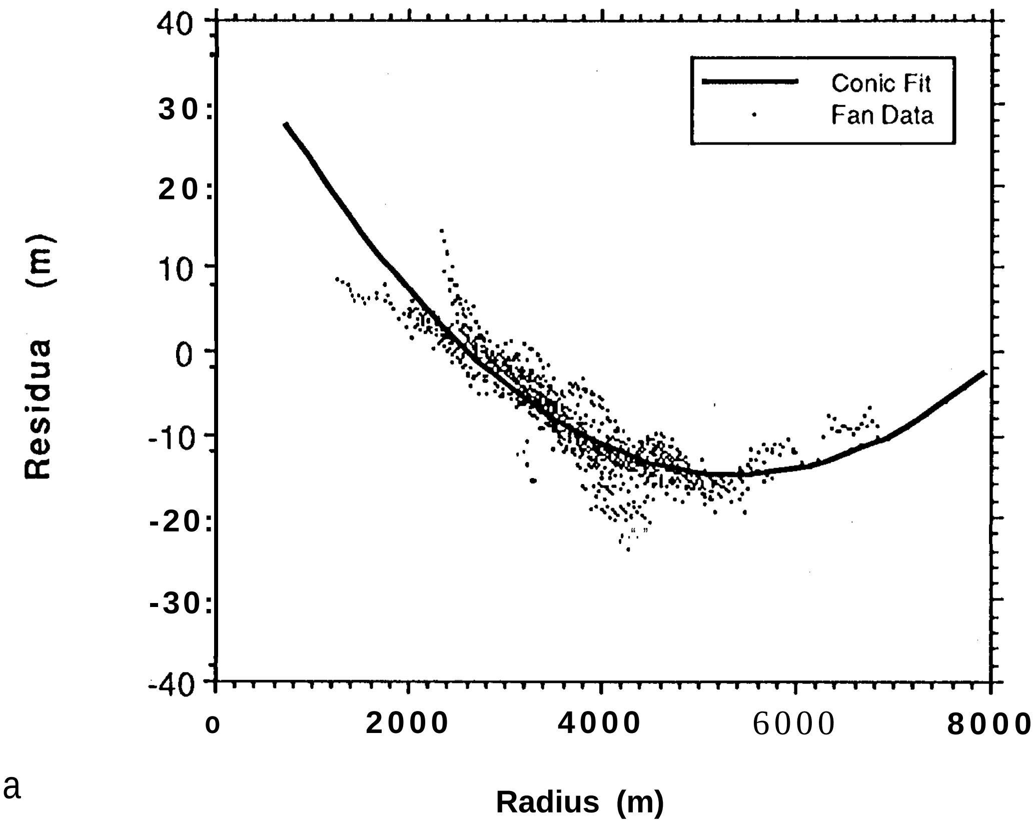
Farr and Dohrenwend, Fig. 4



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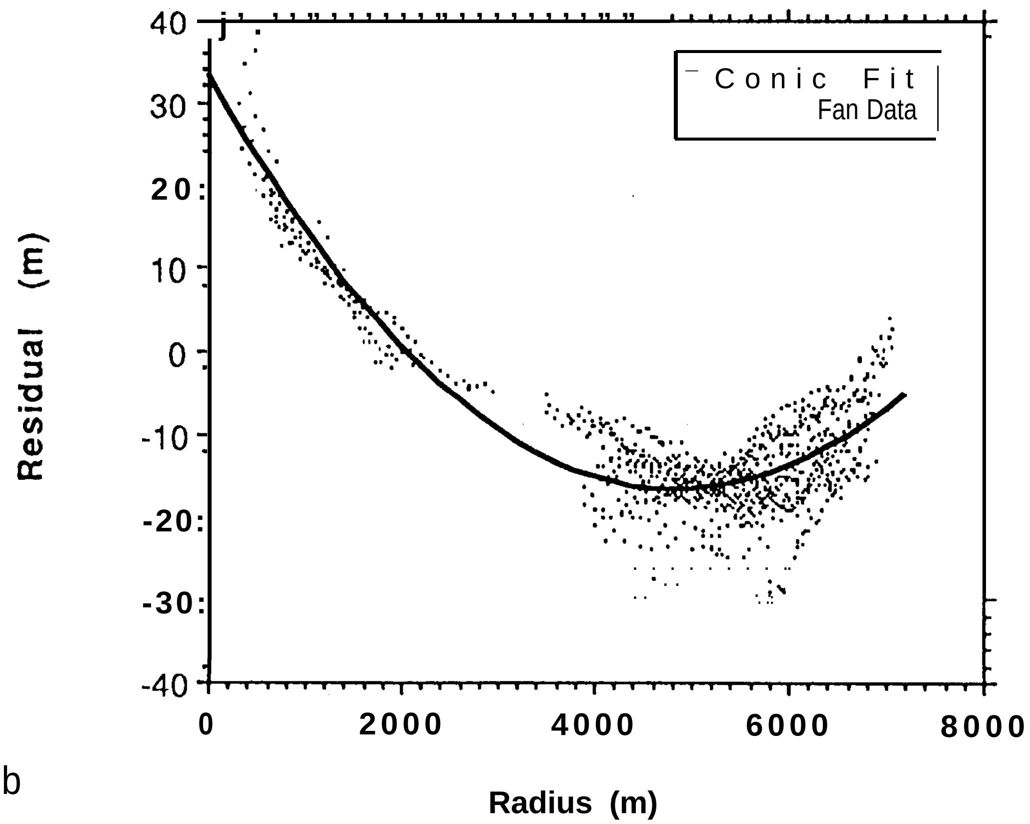

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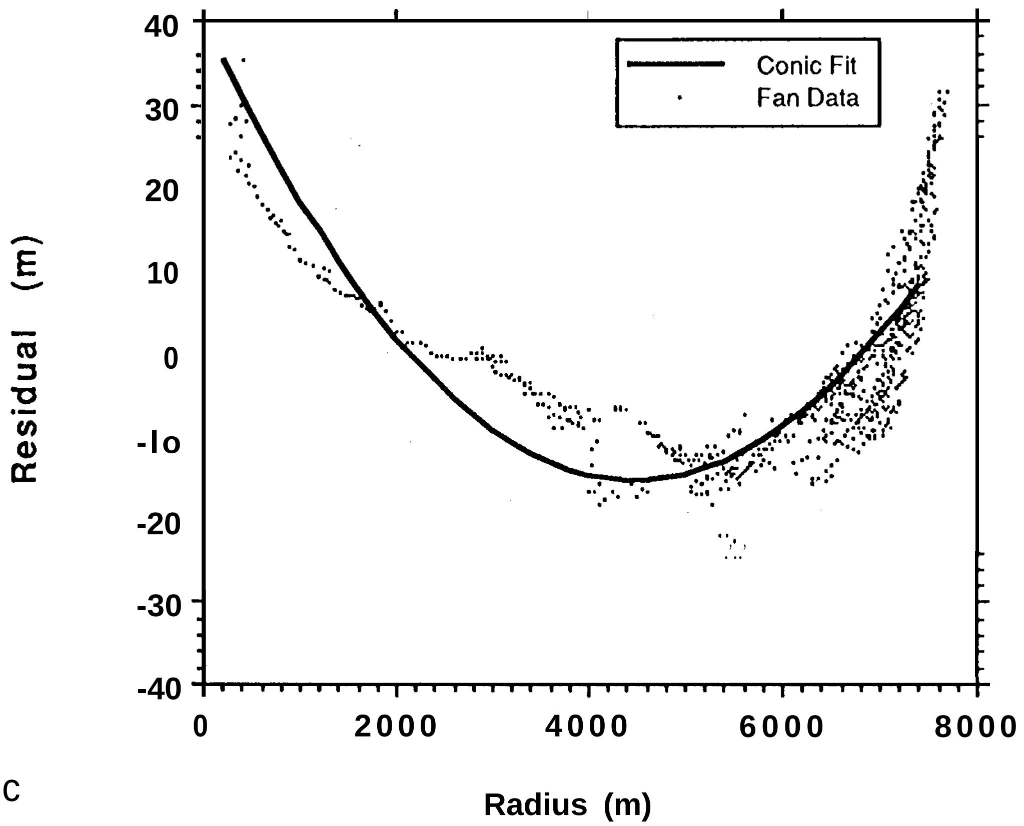

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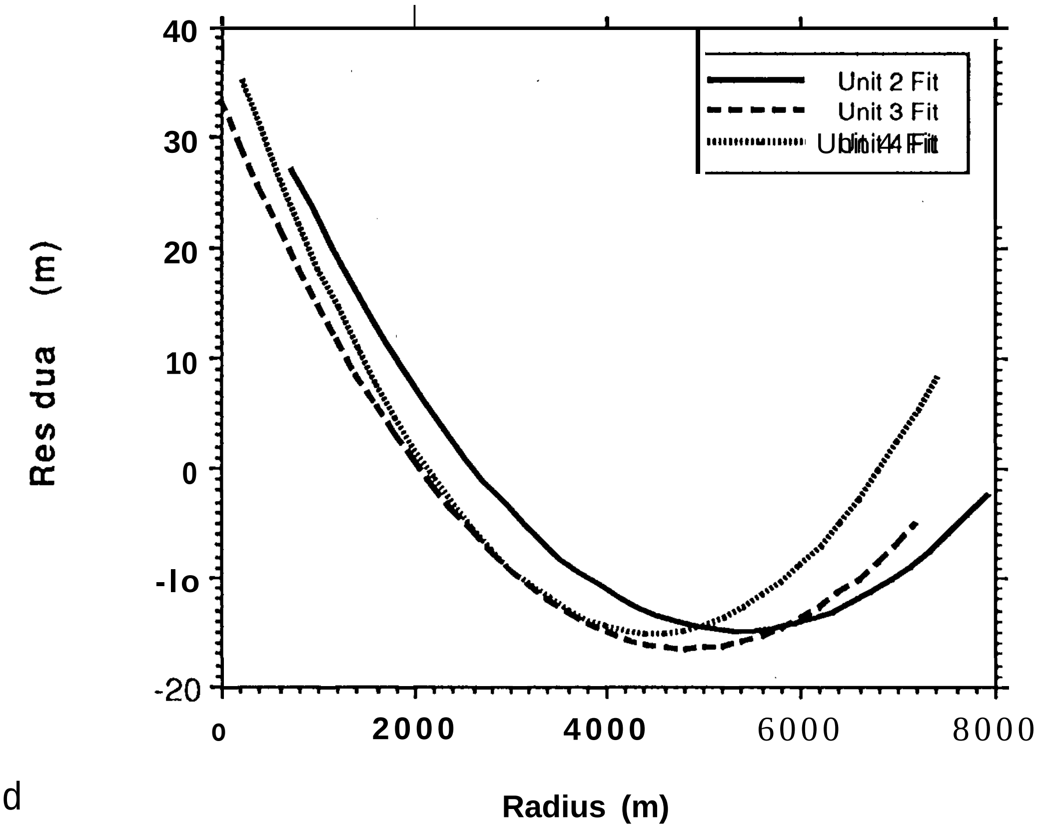

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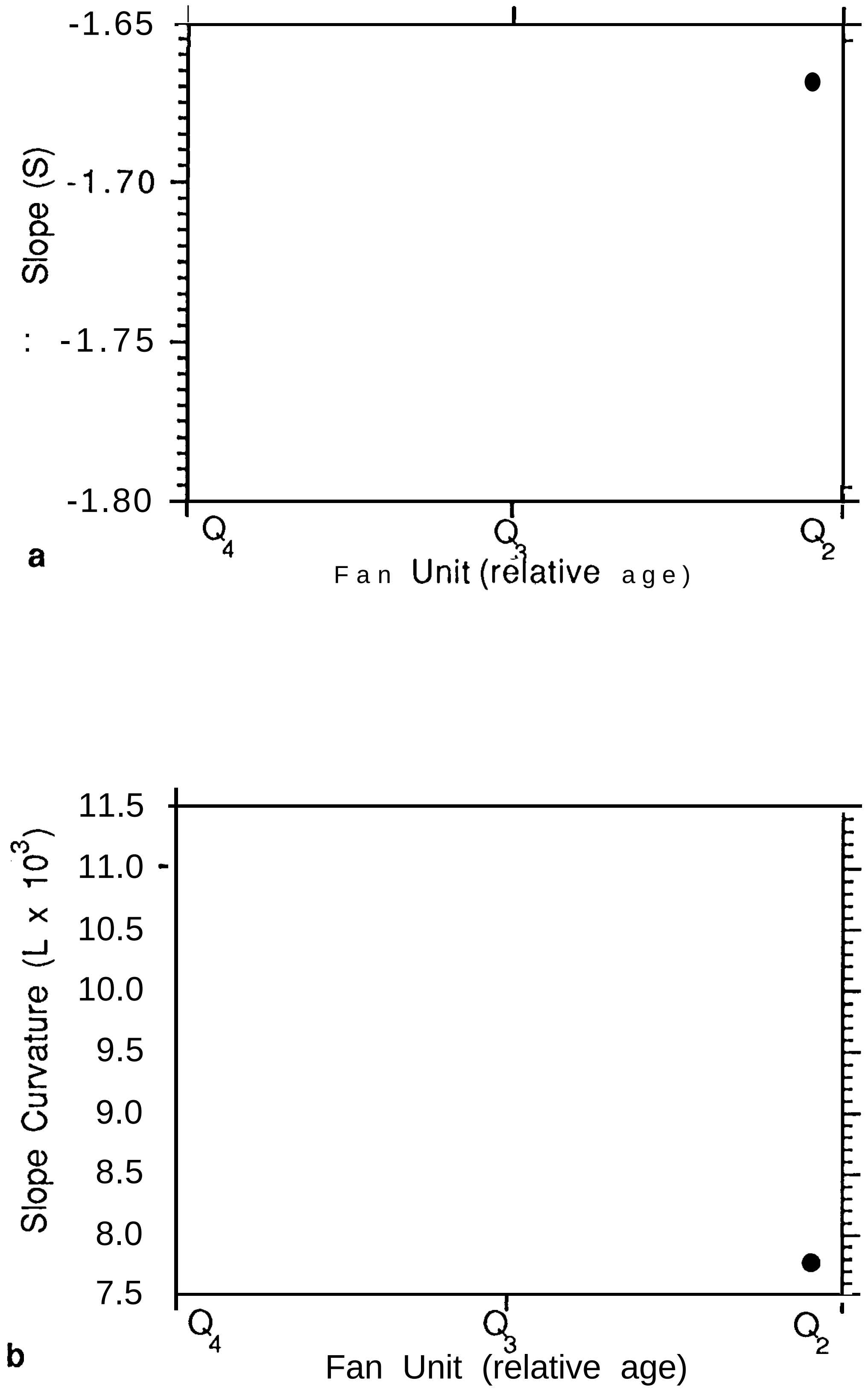
Farr and Dohrenwend Fig 6



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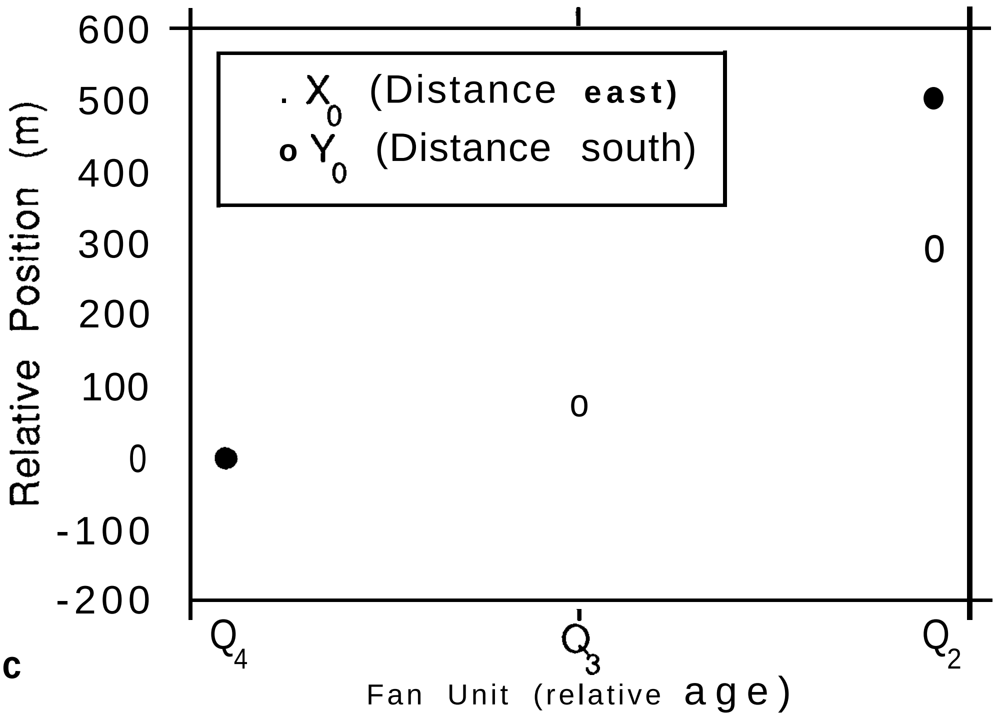

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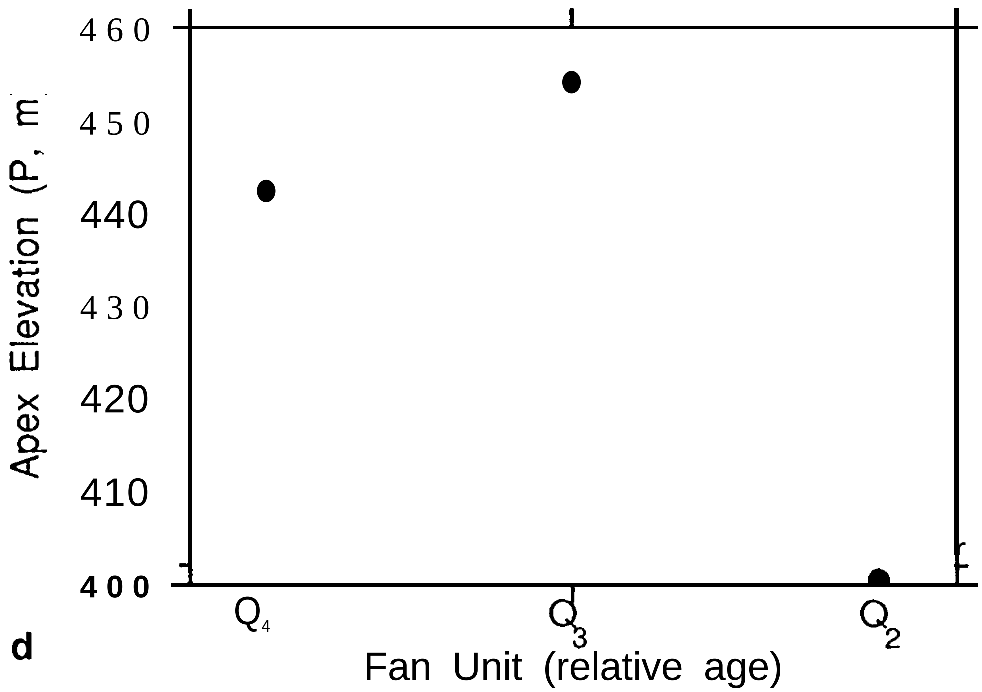

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Farr and Dohrenwend, Fig. 7