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Correlation and dating of Quaternary alluvial-fan surfaces using scarp diffusion

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Abstract

Great interest has recently been focused on dating and interpreting alluvial-fan surfaces. As a complement to the radiometric methods often used for surface-exposure dating, this paper illustrates a rapid method for correlating and dating fan surfaces using the cross-sectional shape of gullies incised into fan surfaces. The method applies a linear hillslope-diffusion model to invert for the diffusivity age, κt (m^2), using an elevation profile or gradient (slope) profile. Gullies near the distal end of fan surfaces are assumed to form quickly following fan entrenchment. Scarps adjacent to these gullies provide a measure of age. The method is illustrated on fan surfaces with ages of approximately 10 ka to 1.2 Ma in the arid southwestern United States. Two areas of focus are Death Valley, California, and the Ajo Mountains piedmont, Arizona. Gully-profile morphology is measured in two ways: by photometrically derived gradient (slope) profiles and by ground-surveyed elevation profiles. The κt values determined using ground-surveyed profiles are more consistent than those determined using photo-derived κt values. However, the mean κt values of both methods are comparable. The photometric method provides an efficient way to quantitatively and objectively correlate and relatively-date alluvial-fan surfaces. The κt values for each surface are determined to approximately 30–50% accuracy.

Keywords: Alluvial fans; Diffusion; Geochronology; Quaternary

1. Introduction

Alluvial fans are common in many arid and semiarid regions such as the southwestern United States. In these areas, alluvial-fan deposits provide an important record of Quaternary tectonics and climate change. On a single fan, these deposits are often expressed geomorphically as multiple surfaces that can be distinguished from one another by their relief above the active channel, soil and varnish development, dip of the surface, and degree of dissection and degradation (e.g. McFadden et al., 1989; Bull, 1991; Hooke and Dorn, 1992). Accurate ages for these fan surfaces are essential for developing a regional chronology of Quaternary deposits and for determining the relative roles of tectonism and climate in Quaternary fan evolution (Ritter et al., 1995). For example, since local tectonic events are not likely to be regionally synchronous, similar fan-surface ages over a broad region would support climatic triggering of episodes of alluvial-fan deposition. In semiarid areas around the world, many studies have argued for linkages

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between climate and fan evolution (e.g. Wells et al., 1987, 1997; Abrams and Chadwick, 1994; Smith, 1994; White et al., 1996; Owen et al., 1997; Harvey et al., 1999; Mack and Leeder, 1999; Ritter et al., 2000; Harvey and Wells, 2003). In particular, several studies have drawn preliminary regional alluvial chronologies for the southwestern United States (Christenson and Purcell, 1985; Wells et al., 1990; Bull, 1991, 1996; Gillespie et al., 1994; Swadley et al., 1995; Reheis et al., 1996; McDonald et al., 2003).

To tackle the difficult task of fan-surface dating, many methods have been used, including $^{230}Th/^{234}U$ analysis of pedogenic carbonate (Ku et al., 1979), qualitative rock-varnish development (Bull, 1991), desert-pavement development (Bull, 1991), ^{14}C of soil carbonate (Wang et al., 1996), soil-profile analysis (Simpson, 1991), cosmogenic nuclides (Liu et al., 1996), tephrachronology (Reheis et al., 1996), paleomagnetism (Pope, 2000), satellite imagery (Beratan and Anderson, 1998), infrared stimulated luminescence (Clarke, 1994), granulometric studies (Ibbeken et al., 1998), rock weathering (White et al., 1998), and multiparameter relative-age analysis (McFadden et al., 1989). Watchman and Twidale (2002) provide a thorough review of stratigraphic and surface-exposure dating methods and their limitations. Despite the great power of radiometric methods, they are costly and time intensive. Many questions in arid-land geomorphology would benefit from the development of a new method that was similarly objective and quantitative, but could be rapidly applied to many surfaces.

To fill this gap, we have extended the scarp-diffusion method well known in paleoseismic studies to the quantitative correlation and dating of alluvial-fan surfaces. We use both photometric and ground-based data collection. The photometric method has a great speed advantage because it uses aerial-photographic data only. However, this method is not as reliable as surveyed data, particularly for young surfaces and heavily vegetated terrain. The diffusion model has been applied to a variety of scarp-like landforms including faults, shorelines, and scarps bounding alluvial-fan terraces (e.g. Nash, 1984; Colman and Watson, 1983; Mayer, 1984; Andrews and Hanks, 1985; Pierce and Colman, 1986; Hanks, 2000). In this model, the flux of sediment down the scarp profile is proportional to the local gradient. Using the modern-day slope profile and an assumed initial profile, we can run the model forward until an optimal match is made with the observed profile. In this way, the method produces a diffusion age, κt, where κ is the diffusivity coefficient of the fan surface (m^2/ky), and t is age. The advantages of this method include (1) applicability across a wider range of detrital lithologies than many existing radiometric dating methods and (2) the ability to quickly analyze many surfaces over an extensive region. Using estimated κ values, we can derive absolute fan-surface ages for comparison with previously dated surfaces and establish new ages on undated surfaces. In addition, the method provides an objective means of correlating fan surfaces across a region, an application that does not require κ values to be known. In analogous work, Turko and Knuepfer (1991) used fault-scarp profiles as a means of objectively identifying fault segments.

As with fault-scarp dating, the quality of the absolute age is limited by incomplete knowledge of κ. As Hanks (2000) reviews, the uncertainties in scarp diffusion dating are due to (1) uncertainty in κt for the scarp of interest, (2) uncertainty in κ used, and (3) uncertainty in the applicability of κ due to temporal and spatial averages. These three factors combine to yield $\sim$70% uncertainty in the scarp of interest for the case of Bonneville and Lahontan shorelines (a type example for fault scarp dating), but uncertainty values of 25% have also been obtained at better-constrained locations such as the Lost River Fault in Idaho (Hanks, 2000). We can decrease uncertainties to some extent because κ generally varies by only a few factors in our study region.

Our goals are to develop a quantitative morphometric fan surface dating technique, increase the resolution of remotely sensed fan-surface mapping, and add fan-surface ages to existing datasets used to constrain the alluvial chronology of the southwestern US. To reach these goals, we use linear diffusion of cross-sectional gully profiles on arid and semiarid alluvial fans. We first review the diffusion model and its assumptions, then present and discuss the diffusion ages that we compiled from alluvial fans in the southwestern United States.

2. Methodology

The equation for linear diffusion is derived from the continuity equation and the dependence of down-slope transport on surface gradient. Under these two conditions, the change in elevation at any point on a hillslope profile is proportional to the local curvature. Since diffusion is a linear equation, 1-D profiles perpendicular to a straight gully evolve independently of the profile in the along-gully direction (i.e. the cross-sectional gully profile is independent of overall fan dip). We use the 1-D diffusion equation:

$$\frac{\partial h}{\partial t} = \kappa\left(\frac{\partial^2 h}{\partial x^2}\right) \quad (1)$$

where h is height (m), t is time (ky), x is the horizontal distance (m), and κ is the diffusivity coefficient (m^2/ky), which depends on factors such as rainfall, vegetative cover, soil-carbonate accumulation, and hillslope orientation. In the semiarid southwestern US, κ has been estimated at approximately 1 m^2/ky from shoreline scarps cut into young, weakly consolidated alluvial fans (Hanks, 2000 and references therein). The range of κ for nine data points in the western US is from 0.64 to 2.0±0.4 m^2/ky for paleo-shorelines in Utah and Nevada, fluvial-terrace risers in Montana, and fault scarps in Idaho, with one additional point at ~0.1 m^2/ky (Bare Mountain fault scarps, Nevada). Fig. 1 illustrates the linear diffusion of a vertical scarp through time, assuming the conditions of constant elevation at the gully bottom and a horizontal boundary at the fan surface.

The linear diffusion model has been applied to landforms with widely variable spatial and temporal scales. However, we have not found published literature that applies the scarp-diffusion method to the cross-sectional profiles of gullies incised into the interior of semiarid alluvial fan surfaces. Pierce and Colman (1986) used scarp diffusion dating on terrace risers. This application is problematic because the riser profile represents the latest date of the edge renewal by bank retreat, not necessarily the age of surface entrenchment. A description of the conditions and assumptions of our conception of fan surface development will illustrate why scarp diffusion of gully cross-sectional profiles is appropriate for fan surface dating (Fig. 2). This model is based on many previous field observations (e.g. Barsch and Royse, 1972) and experimental work (Pelletier, 2003), but is not applicable on every type of fan. For example, fan gravels that are underlain by fine-grained axial-channel deposits tend to maintain a steep gully profile through sapping processes. The diffusion model is not applicable in these cases.

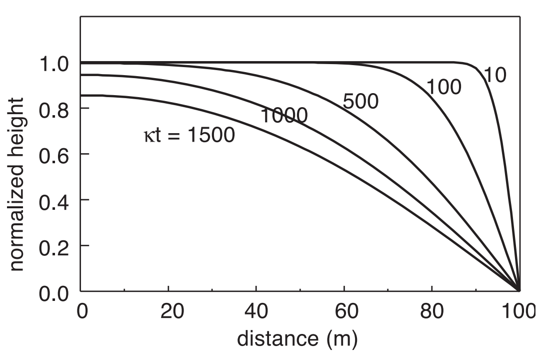

Fig. 1. Illustration of the evolution of an initially vertical scarp along a 100-m profile at κt values of 10, 100, 500, 1000, and 1500 m^2. The profile is representative of one-half of a cross-section across a fan gully, with gully bottom at normalized height of 0 and fan top initially at normalized height of 1.

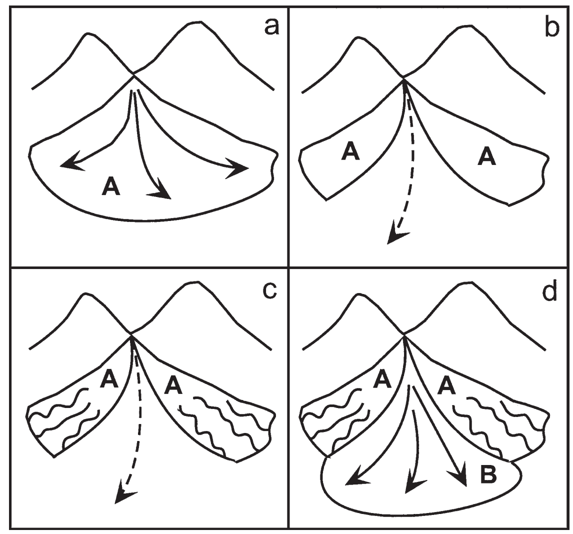

Fig. 2. Conceptual model of alluvial surface development showing how gully morphology is representative of surface age. (a) Aggradation across the mountain piedmont builds fan surface A. (b) A change in the system causes entrenchment and degradation, leaving only remnants of surface A (dotted line signifies erosion). (c) Immediately after entrenchment, the local base level lowering causes gullies to quickly work their way up the fan. The timescale of gully formation is much smaller than the timescale of fan deposition, regardless of position of initiation. (d) A change in conditions (e.g. increase in sediment load) causes another aggradational pulse, depositing surface B at a lower elevation than surface A. The cycle repeats itself from step (b).

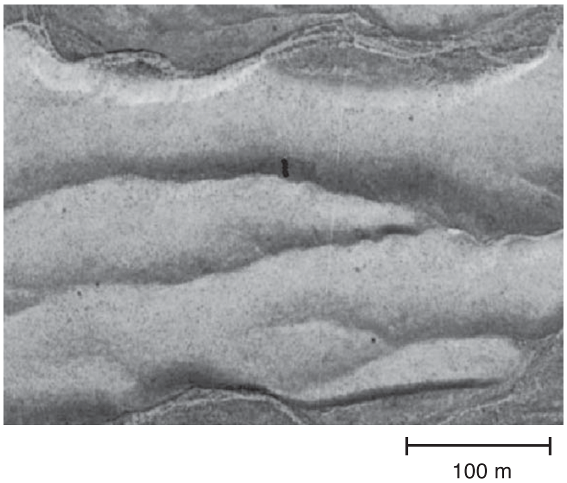

Fig. 3. An example of gullies cut into an alluvial fan on the Sandpass NW (Utah, US) USGS Digital Orthophotoquad. The image is oriented with the lighting from the top and fan dips to the right.

Our assumptions of fan evolution (Fig. 2) are as follows:

(a) Aggradation and frequent avulsion of the active channel across the piedmont create broad, low-relief surface A.
(b) A change in the system, such as decrease in sediment load, causes downcutting and narrowing, concentrating the erosive activity and rapidly enhancing the incision. Local base level is lowered and the upper surface A is abandoned.
(c) Gullies rapidly cut back into the fan on abandoned surface A, starting from the distal end and working their way to the proximal end. The timescale of gully formation is much smaller than the timescale of fan deposition, regardless of position of initiation.

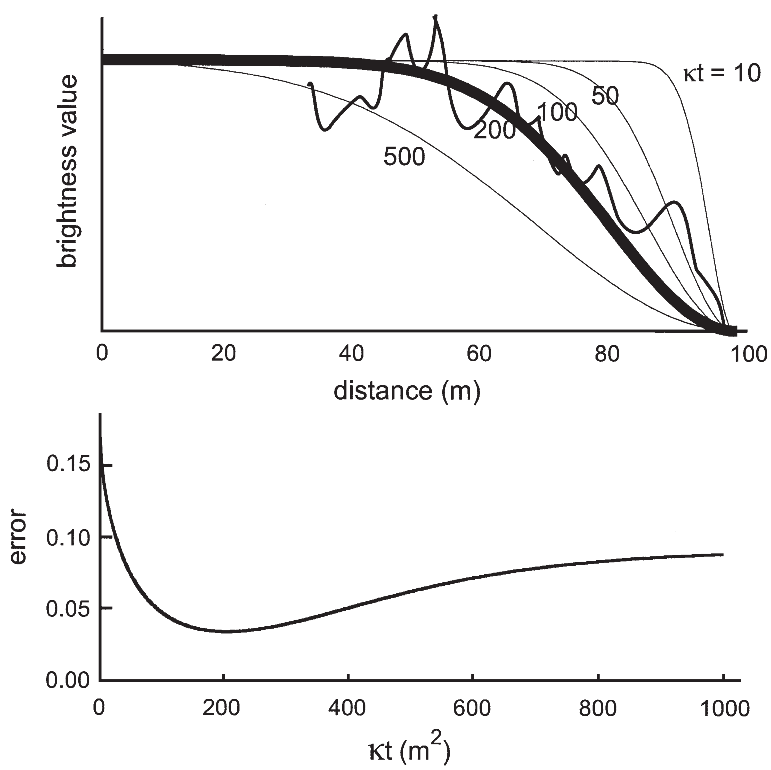

Fig. 4. Top panel shows an example of a brightness-value profile (noisy line) from a digital image. High brightness values at the fan surface decrease as the profile descends to the gully (here at 100 m). The brightness profile is proportional to the relative gradient of the gully cross-section, and therefore can be compared to relative gradient profiles of diffusive hillslope profiles (thin lines). In this example, the best fit to the model relative gradient profiles is at $\kappa t = 200$ m^2 (heavy line) as illustrated by the minimum mean square error at that diffusion age in the bottom panel.

Table 1
Locations of alluvial-fan surface diffusion analysis[a]

Quad name	Mountain range, state	Symbol	Data type[b]
Mount Ajo	Ajo Mts, AZ	AJ	S, P
Castle Cliff	Beaver Dam Mtns, UT	CC	P
Corona de Tucson	Santa Rita Mts, AZ	CO	P
Cowboy Pass	Confusion Range, UT	CP	P
Frisco Peak	San Francisco Mts, UT	FP	P
Galena Canyon CA	Panamint Mts, CA	GC	S, P
Hanaupah Canyon	Panamint Mts, CA	HC	S, P
Kielberg Canyon	Galiuro Mts, AZ	KC	P
Miller Cove	House Range, UT	MC	P
Parker NW	Whipple Mts, CA	PA	S
Sandpass NW	Fish Springs Range, UT	SP	P
West Mountain Peak	Beaver Dam Mtns, UT	WP	P
West of Furnace Creek	Panamint Mts, CA	WF	P

[a] Map of locations illustrated in Fig. 5.
[b] P: photometric method, S: ground survey.

(d) Another change in the system (e.g. increase in sediment load) causes broad aggradation to begin again. Sediment is deposited where the active channel has incised and laterally migrated since step (b), and also at the distal portions of the fan, forming surface B.

The cycle is repeated beginning from step (b), leaving remnant inset fan surfaces which decrease in age with decreasing elevation.

The model assumes that: (1) The initial fan surface is mostly planar. (2) Gullies begin to incise the fan immediately after the surface is abandoned and quickly work their way up-fan. The timescale of gully network formation, regardless of location of initiation, is much smaller than the timescale of surface deposition. (3) An initial gully profile has vertical faces. (4) Once the gully has formed, the elevation of the gully bottom is constant through time. (5) Material moves down the cross-sectional profile by the diffusive processes of creep, rainsplash, bioturbation, and overland flow, accumulating in the gully, but is periodically washed away by storm flows, inhibiting substantial aggradation on the gully bottom. This view of gully profile evolution is simplified but adequate for our purpose. These model assumptions are explored further in Discussion.

Photometric profiles across gullies were obtained from USGS 1-m resolution digital orthophotoquads (DOQs; Fig. 3). DOQs for Arizona, Utah, and California are available online. DOQs from other states are available from the US Geological Survey or online. For profiles of constant albedo and illumination, the pixel brightness values along a cross-sectional gully profile are directly proportional to the relative slope gradient. The brightness equation for the 1-D case is:

$$I(x) = aR[p(x)] \quad (2)$$

where I is the brightness, a is a constant that depends on the albedo, the imaging system, and other factors, R is the reflectance map, and $p = dz/dx$. For Lambertian surfaces (surfaces that reflect light equally in all directions), the brightness is proportional to the cosine of the angle between the vector normal to the surface and the vector in the direction of the light source. If the angle between the direction of the light source and the direction of the observer is greater than 30° and the surface is not too rough, the reflectance map can be approximated by a linear relationship (Pentland, 1988).

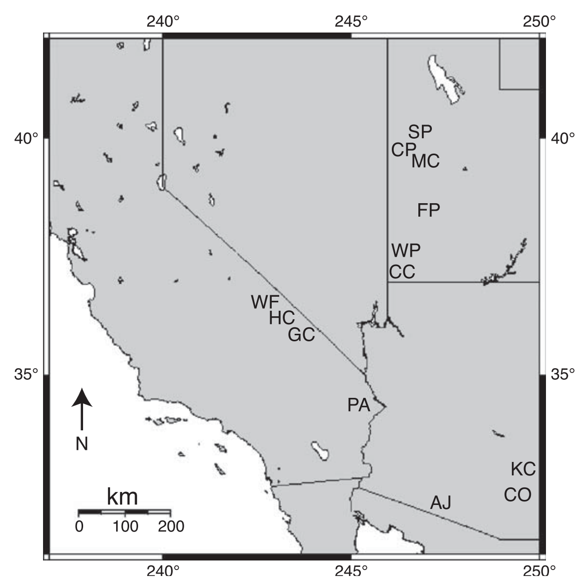

Fig. 5. Map of sites evaluated in this study. Abbreviations are defined in Table 1.

Table 2
Results from the photometric method[a]

Surface	Npts	Raw[b] mean κt (m^2)	S.D. (m^2)	Error[c] (%)	Integrated[b] mean κt (m^2)	S.D. (m^2)	Error[c] (%)
AJ1	9	1097.3	508.7	46.4	1328.2	460.0	34.6
AJ2	7	270.4	98.2	36.3	442.3	112.7	25.5
CC	8	127.1	61.7	48.5	228.2	74.1	32.5
WP	5	809.0	390.7	48.3	1062.7	282.9	26.6
CP	6	730.6	237.8	32.5	707.4	184.0	26.0
SP1	7	244.6	79.6	32.6	226.8	57.0	25.2
SP2	7	138.1	47.4	34.3	213.4	135.2	63.4
SP3	7	173.1	91.3	52.7	167.2	57.7	34.5
KC	10	362.6	113.0	31.2	490.0	105.7	21.6
MC1	12	355.5	193.2	54.4	427.6	115.8	27.1
MC2	4	297.0	374.0	125.9	174.9	121.6	69.5
GC1	13	526.6	213.6	40.6	569.3	187.7	33.0
GC2	12	454.8	181.8	40.0	488.0	159.6	32.7
HC1	11	811.9	294.9	36.3	762.4	158.6	20.8
HC2	5	220.3	108.1	49.1	278.8	119.5	42.8
WF	10	89.5	36.1	40.3	161.3	56.1	34.8
CO	12	391.8	127.5	32.5	521.6	141.4	27.1
FP1	5	39.3	14.1	35.8	62.4	12.3	19.7
FP2	8	75.8	50.2	66.2	88.7	50.4	56.8
FP3	4	107.0	47.6	44.5	84.1	15.5	18.4
FP4	5	146.2	54.9	37.5	139.9	30.3	21.7

[a] Grouped by mountain range.
[b] See Section 4.2.1 for distinction between the raw and integrated values.
[c] Standard deviation/mean×100.

Profiles for the photometric method were carefully chosen to avoid any inhomogeneity that would interfere with the brightness values representing the gradient, such as vegetation or human disturbances. We also avoided gully geometries with meander bends that might add a second dimension of diffusion or a non-uniform boundary condition along-strike. We matched the normalized profile of pixel brightness values to the best-fitting model relative-gradient profile to obtain a κt value (Fig. 4). We also integrated the

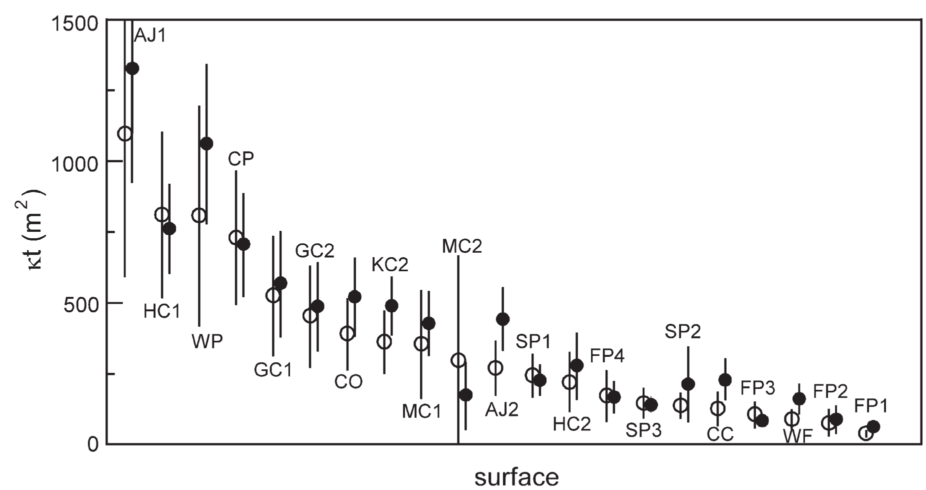

Fig. 6. Diffusivity age (κt) values for photo-derived gradient profiles. Gradient method shown with open circles, integrated elevation method shown with filled circles. Error bars represent one standard deviation.

Table 3
Results from the ground-survey method

Surface	Npts	Mean κt (m^2)	S.D. (m^2)	Error[a] (%)
HC1	2	726.7	79.8	10.98
HC2	6	249.1	16.5	6.62
HC3	6	68.8	25.3	36.77
GC1	3	2507.7	543.5	21.67
GC2	4	144.9	52.9	36.51
PA1	6	235.2	103.9	44.18
PA2	3	37.3	12.8	34.32
PA3	3	30.8	6.6	21.30
AJ1	1	295	n/a	n/a
AJ2	6	116.9	28.5	24.38

[a] Standard deviation/mean×100.

normalized pixel brightness profile to obtain a relative elevation curve, and matched this curve to the best-fitting model relative elevation profile to obtain a κt value. We compared both photometric age-determinations (non-integrated and integrated) from the same brightness profile for magnitude and consistency of results. Neither absolute slope nor measured elevation data were required for either analysis.

To ground-check our profiles obtained by the photometric method, we surveyed cross-sectional gully profiles in the field with a Sokkia SET4B Electronic Total Station (Table 1, Fig. 5). Field-surveyed profiles eliminate the photometric noise in the representation of slope gradient. Field surveying can also capture the morphology of younger gullies with shorter cross-sectional gully lengths than those acquired by the photometric method, which is limited to 1-m resolution (for USGS DOQs). We chose ground survey locations that were previously evaluated by the photometric technique or another fan surface dating technique so that each surface age could be compared with an independently obtained estimate.

3. Results

We calculated κt values from photometric analysis of 176 gully profiles on 21 distinct fan surfaces (Table 2, Fig. 6). Using the brightness profile matching technique (photometric relative gradient comparison), the mean κt values of the surfaces ranged from 39.3 m^2 in Frisco Peak Quadrangle (FP1) to 1097.3 m^2 in Mount Ajo Quadrangle (AJ1). Using the integrated brightness profile (photometric relative elevation comparison), the mean κt values of the surfaces ranged from 62.4 m^2 (FP1) to 1328.2 m^2 (AJ1). Each mean surface κt was calculated from an average of between 4 and 13 profiles. The standard deviations ranged from 18.9% to 125.9% (mean of 46.0%) of the mean κt value for the gradient comparison and 18.4% to 63.4% (mean of 33.1%) of the mean κt value for the elevation comparison.

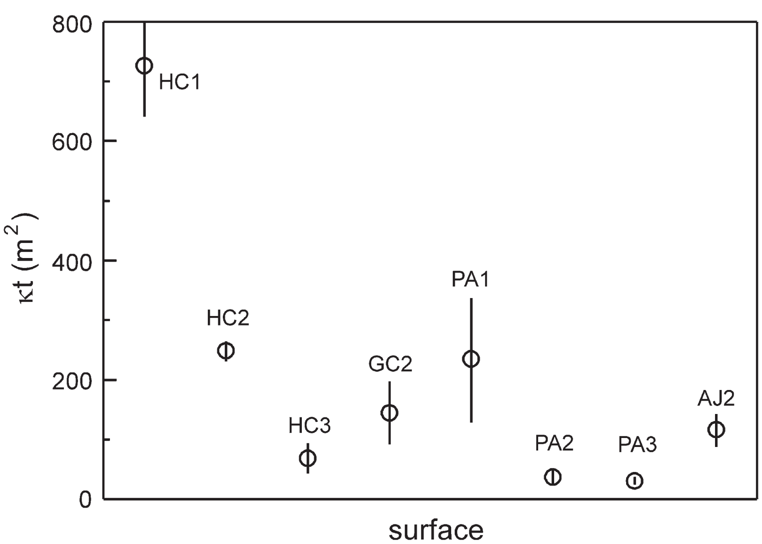

Fig. 7. Diffusivity age (κt) values for ground-surveyed elevation profiles. Error bars represent one standard deviation.

We determined κt values from elevation ground surveys of 40 profiles on nine fan surfaces (Table 3, Fig. 7). The mean κt values range from 30.8 to 2507.7 m^2 (PA2 and GC1, respectively). Standard deviations range from 6.6% to 44.2% of the mean diffusion age.

4. Discussion

The κt values of surfaces from different piedmonts cannot be compared directly because the diffusivity, κ, may vary significantly between piedmonts. However, on the same piedmont, where κ is assumed to be constant, the photometric and ground-based values of κt can be compared for consistency. This is a measure of how well the photometric method captures the actual profile shape.

On Hanaupah Fan Death Valley, the oldest surface (HC1) yielded κt values of 811.9 (294.9) m^2 (mean (standard deviation)) and 726.7 (79.8) m^2 for the photo and ground survey methods, respectively. A younger surface (HC2) yielded κt values of 220.3 (108.1) m^2 and 249.1 (16.5) m^2 for the photo and ground survey methods, respectively. The similarity of these ages (the photometric method is within 12% of the ground method) supports the efficacy of the photometric method for obtaining accurate gully-profile morphology. However, even in cases that are ideal for the photometric method, more consistent results are obtained by ground survey. The standard deviation is lower for the ground-survey method, which is expected because the noise associated with vegetation and 1-m grid pixel averaging for the photometric method are eliminated.

Comparing our morphologic ages with earlier work, Hooke and Dorn (1992) map the Hanaupah fan units as Q1 (500 to >800 ky) and Q2 (110–190 ky), based on conventional ^{14}C, AMS ^{14}C of varnish, cation-ratio of varnish, ^{14}C of carbonate rinds, and uranium series of calcrete. Ibbeken et al. (1998) collected quantitative granulometric data on the Hanaupah surfaces but did not find a correlation between age and grain size, sphericity, roundedness, or orientation.

More regionally, Bull (1991, 1996) created a framework of fan surface ages from sites in California, Nevada, Arizona. He identified nine surfaces based on field observations and radiometric dating, Q1 through Q4b from oldest to youngest. Q1 surfaces are early-middle Pleistocene, or older than 1200 ky. Q2a surfaces date between 400 and 730 ky. Q2b corresponds to 70 to 200 ky. Q2c corresponds to ages between 12 and 70 ky. Q3a surfaces and younger are of Holocene age and are beyond the resolution of the photometric method. Fig. 8 shows how the diffusion model ages compare with the frameworks of Bull (1991, 1996) and Hooke and Dorn (1992), assuming $\kappa = 1\ m^2/ky$. HC1 lines up with Bull's Q2a surface and

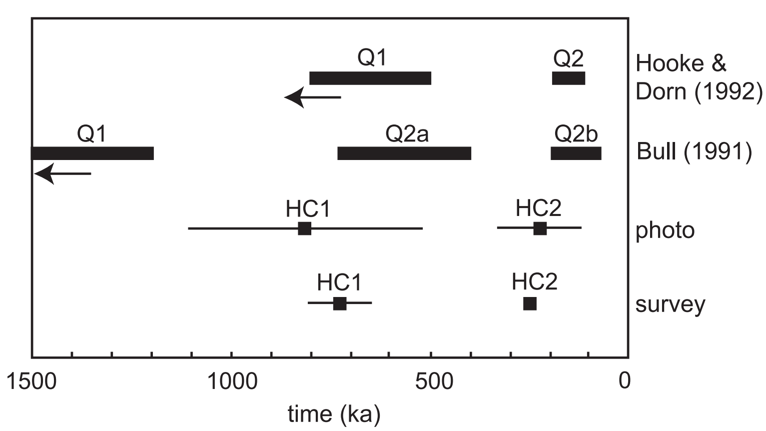

Fig. 8. A comparison of surface ages for two surfaces on the Hanaupah Canyon Fan, Death Valley, US, using κ=1 m^2/ky for the photo and survey dating methods. Squares denote mean value, lines denote one standard deviation from the mean, and bars denote an age range. Hooke and Dorn (1992) and Bull (1991) use a combination of radiogenic dates and field observations. Original nomenclature is preserved for each study.

Hooke and Dorn's Q1 surface. HC2 matches best with Bull's Q2b surface and Hooke and Dorn's Q2 surface.

Bull (1991) acknowledged that the depositional pulses that formed the older surfaces were large events that probably occurred during short intervals within the broad ranges, unresolvable by current data. Although limited by incomplete knowledge of the diffusivity value κ, the photometric method can work towards narrowing the surface age ranges by identifying clusters of κt values in areas of similar κ.

In other field areas, the photometric and ground-based methods did not yield similar κt values: The older surface on the Ajo Mountain piedmont (AJ1) was determined to be 1097.3 (508.7) m^2 and 295 m^2 (only one age determination) by photo and ground methods, respectively. The younger surface (AJ2) was determined to be 270.4 (98.2) m^2 and 116.9 (28.5) m^2 for photo and ground methods, respectively. We attribute the higher discrepancy on the Ajo Mountain, Arizona, piedmont to higher vegetation density, which adds significant noise to the brightness profile. In addition, the diffusion ages are quite sensitive to the location of the base of the slope in the profile. During photometric analysis, riparian vegetation can make it difficult to distinguish between the base of a slope and the gully channel, introducing error and yielding generally older ages.

The surfaces at Ajo have been previously evaluated by soil-profile analysis and cosmogenic dating. Simpson (1991) used soil-carbonate morphology to place AJ1 at early to middle Pleistocene (1.8 Ma to 900 ka) and AJ2 at latest Pleistocene to middle Holocene (300 to 50 ka). The cosmogenic ^{36}Cl study of Liu et al. (1996) concluded that AJ1 stabilized at 440 ka and was possibly reactivated between 230 and 330 ka. AJ2 was dated to between 100 and 180 ka. Assuming κ=1 m^2/ky, the photometric method values coincide with the soil-profile analysis values while the ground surveys are in better agreement with the cosmogenic study (Fig. 9).

Alternately, we can estimate a κ at the Ajo site using our κt values and the previous age determinations. Dividing our κt values by the t determined by the cosmogenic ages, possible κ range from 0.67 to 2.5 m^2/ky, in good agreement with values quoted earlier for the southwestern US.

Four main questions we further addressed are: (1) Do cross-sectional gully profiles on semi-arid alluvial fans degrade according to simple linear diffusion? (2) Is the model, its boundary conditions, and its assumptions an accurate representation of the evolution of fan gully profiles? (3) Do the photo-derived profiles accurately represent the actual ground slope gradient profiles? (4) What is the significance of the fan surface diffusion ages that we obtained?

4.1. Applicability of simple linear diffusion

Although simple linear diffusion has been used to describe the evolution of numerous types of land-

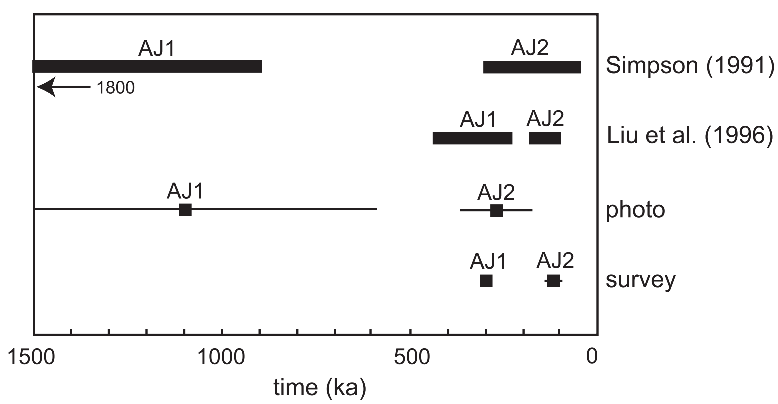

Fig. 9. A comparison of surface ages on the Ajo Mountain piedmont, AZ, US. Simpson (1991) used soil profile analysis and Liu et al. (1996) used ^{36}Cl dating. Squares denote mean value, lines denote one standard deviation from the mean, and bars denote an age range. Using $\kappa = 1$ m^2/ky, the photometric method agrees with the Simpson (1991) age estimates while the ground-survey method agrees with Liu et al. (1996). Vegetation is thought to be the main discrepancy between the photo and survey methods.

forms, in some cases this model is not appropriate. Certain factors may add a nonlinear component to the relationship between sediment flux and hillslope gradient, including landsliding on steep slopes or changes in the intensity of processes with distance from the divide (Martin and Church, 1997; Roering et al., 1999). We discuss the role of landsliding further in Section 4.2.2. We used our dataset to examine the relation between diffusion age, height, and hillslope orientation to systematically test the consistency of the linear-diffusion model.

Previous work indicated a relationship between diffusivity and scarp height. For example, Pierce and Colman (1986) observed a dependence of κ on scarp height on late-glacial terrace scarps in Idaho. Beaujon (1987) used a finite difference model to fit entire scarp profiles in Idaho and Wyoming for a best κt value and found significant correlation between κt and scarp height at sites with large variation in height. Nash (1998) suggested avoiding morphologic dating of scarps more than five meters high because the fit of the profile becomes increasingly poor and asymmetric with height, suggesting that debris flux on taller scarps cannot be assumed proportional to slope. However, this effect may be more appropriately related to scarp slope than scarp height.

The height of gully cross-sectional profiles on the alluvial fans that we measured varies from $\leq$2 m for young surfaces (Surface PA3, Parker NW Quadrangle) to >40 m for older surfaces (Surface GC1, Galena Canyon Quadrangle). We have a modest dataset for exploration of the height–κt value relationship, but we evaluated the linear relationship of these two parameters on surveyed surfaces where we have at least four measured profiles. On the five such surfaces, the average R^2 value was only 0.28, which does not support a significant correlation between height and κt in our profiles, but instead suggests height-independent diffusion.

Pierce and Colman (1986) observed a κ dependence on hillslope orientation (microclimate). This dependence was attributed in part to a difference in vegetation (and therefore vegetative anchoring of sediment) on north and south facing scarps. To minimize this effect, all of our photometric profiles were collected from the shaded side of the fan gullies. Most mountain ranges in the southwestern US trend north–south, so their associated fans and fan gullies trend dominantly east–west, producing north and south facing gully slopes. Since all of our sites are in the northern hemisphere, the shaded side of the gully is the north-facing slope. The consistency of measuring the north-facing slope should diminish the effect of orientation-dependent ages as found by Pierce and Colman (1986). Our ground-surveyed profile dataset, although not extensive, showed no κt dependence on orientation.

The fit of the measured profile to the best-fitting model profile is another test of the applicability of linear diffusion. For example, Fig. 10a shows a normalized photo-derived brightness profile from surface HC1 and its best-fit model κt profile (921 m^2). The R^2 fit (a measure of the amount of variance explained in the measured profile by the model profile, where a value of 1 is complete correlation) is quite good up until the dotted line at 50 m (R^2= 0.826). However, the fit degrades quickly beyond that point, and the overall R^2 fit for the entire 77 m is only 0.591. This observation suggests that we should be cautious in fitting the entire slope to the linear-diffusion model. Roering et al. (1999) observed divergence from linear-diffusion convexity towards the bottom of the slope. Such divergence is most likely only on high relief surfaces like HC1 because of steep basal slopes. The mean R^2 fit on a surface for the measured raw profile and the model profile varied between 0.370 and 0.912. Fig. 10b shows a profile from Surface FP2 with high correlation to its model fit, R^2=0.979.

4.2. Boundary conditions and assumptions

The robustness of the calculated κt value is dependent on the suitability of boundary conditions and other assumptions. Several assumptions in the model simulation, such as interpretation of the photometric profile, initial scarp angle, fixed gully bottom depth, and uniform diffusivity, are discussed further in this section.

4.2.1. Interpretation of the photometric gradient profile

Noise exists in photometric gradient profiles due to averaging of 1-m grid pixels and vegetation. We evaluated several ways to interpret the photometric profile, including using the raw brightness values, a

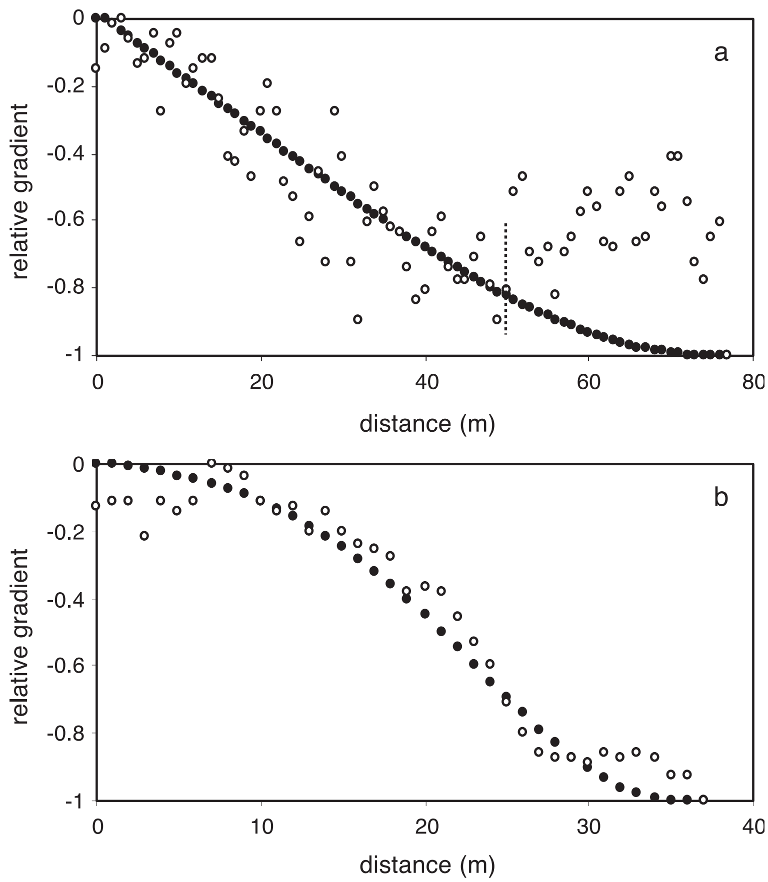

Fig. 10. (a) Correlation of photo-derived brightness profile from HC1 and model relative gradient profile. The match is good at the hilltop (left side) but degrades towards the gully (right side) after 50 m. (b) A photo-derived profile from surface FP2 and its model fit with an R^2 value of 0.979.

smoothed version of the profile, and an "envelope curve" that follows local maximum values along the curve (Fig. 11). The advantage in using the raw pixel-

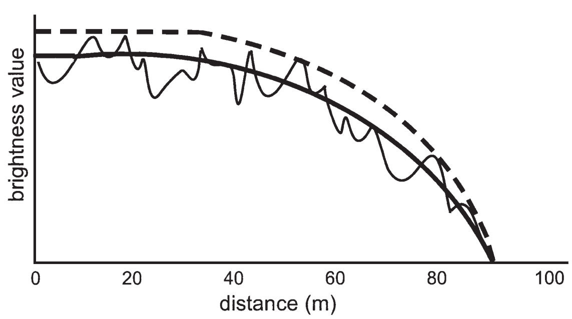

Fig. 11. Illustration of different gradient-profile model inputs. (a) Actual photo-derived brightness curve (noisy line), (b) smoothed curve (solid line), (c) envelope curve (dashed line).

resolution brightness value profile is that no subjective interpretation occurs and the diffusion age is unique for that profile. An automatically smoothed profile may unintentionally incorporate non-random noise that may be identified and removed from the raw curve. This includes noise from vegetation, which tends to darken the brightness values. An "envelope curve" follows the local maxima of the noise and may be best suited for regions with heavy vegetation, because vegetation introduces negative noise to the curve. The envelope curve will yield a younger age than the smoothed or actual profiles. For example, on the Ajo piedmont, the envelope curve profiles yielded κt values of 638.2 (AJ1) and 216.6 m^2 (AJ2), which are significantly younger than the raw profile values of 1097.3 and 270.4 m^2, and also closer to the cosmogenic analysis of 440 and 140 m^2 (Liu et al., 1996, assuming $\kappa \sim 1$ m^2/ky). We decided to use the actual raw profile for all surfaces to limit the subjectivity in determining the envelope curve. In highly vegetated areas, this profile may not be the best representation of surface gradient, as illustrated by the discrepancies in the Ajo area.

Another option for curve interpretation is to integrate the noisy raw brightness curve to obtain an elevation-profile approximation. This elevation profile is then compared to a model of evolving elevation κt profiles instead of gradient κt profiles. The integration acts as a low-pass filter, smoothing the curve. For our dataset, using the integrated curve yielded decreased standard deviations from the mean κt value on a given surface. But in addition, the integration-method κt values were an average of 28% older than the κt values derived from the raw brightness profiles (Table 2). The smaller variation in κt values suggests that the integrated curve may be a better alternative than the raw curve.

Another issue in curve interpretation is the hilltop shape. When gullies first incise the fans, the interfluvial areas are planar. As the sidewalls of neighboring gullies degrade towards each other, the planar portion of the surface decreases until it finally disappears completely and the interfluve becomes rounded on top. After this point in time, the interfluve lowers in amplitude, but the relative gradient values at stationary points stay roughly constant. This means that the method of matching relative gradient profiles will obtain only a minimum diffusion age for old surfaces in which no planar remnant is preserved. We draw our photometric profiles onto planar fan surfaces whenever possible to obtain a measure of the actual age instead of a minimum age.

4.2.2. Initial angle

The initial angle of the gully-wall scarp is an important consideration when dating young scarps. The two basic choices are a vertical scarp and a scarp at the angle of repose. Fig. 12 illustrates the differences in evolving slope profiles for initial angles of 90° (9a–9d) and 30° (9e–9h) on a 10-m-high profile. We chose 30° as a low-end case since the angle of repose for alluvium or soil is quoted as 30–35° (Carson and Kirkby, 1972; Pierce and Colman, 1986; Avouac, 1993). On a steep scarp, mass-wasting processes such as landsliding are more common than diffusive processes until the profile reaches an angle near the angle of repose (Wallace, 1977). Therefore, although we model the time between the vertical scarp and angle of repose scarp with diffusive processes, the actual time for the vertical scarp to degrade to the angle of repose may be shorter due to mass-movement processes. The discrepancy between these two times is a source of error in our κt determinations. Wallace (1977) reports that on fault scarps, the steep face is "geologically speaking, very short lived", with slope angles steeper than 37° disappearing within a few hundred or, at most, a few thousand years. Because we are generally modeling profiles over 50,000 years old, this error should be small in comparison to the overall age.

Fig. 12 also illustrates how there is a κt value at which the normalized profiles become indistinguishable from one another. For example, in Fig. 12g, no more than four profiles are distinguishable to the eye, although all eight profiles are plotted. That means that for an initial slope of 30° and slope profile length of 25 m (not uncommon on the fans we studied), after κt=200 m^2 the relative gradient profile does not evolve significantly. This is because the planar interfluve has degraded away. After this point, the diffusion model "matching" technique will yield only a minimum κt value of 200 m^2.

4.2.3. Gully formation and downcutting

We assume that the gully network forms on a timescale much shorter than that of the surface deposition. In addition, as a first-order approximation of gully cross-sectional profile evolution, we assume that gully bottom depth stays at constant elevation through time, rather than downcutting episodically or constantly. Episodic downcutting is recorded in the slope profile as a break in the slope convexity and can be avoided during ground surveying. Such composite slopes are present in western Death Valley as a result of multiple episodes of local base-level drop of the main fanhead trench associated with cutting and filling of inset fan units. Slow variations in downcutting may be important, and could be incorporated into the model, but Rainfall Experiment Facility experiments indicate that gullies on distal fans achieve grade very quickly relative to the hillslope relaxation time (Pelletier, 2003). Other studies on different lithologies suggest that most of the drainage network

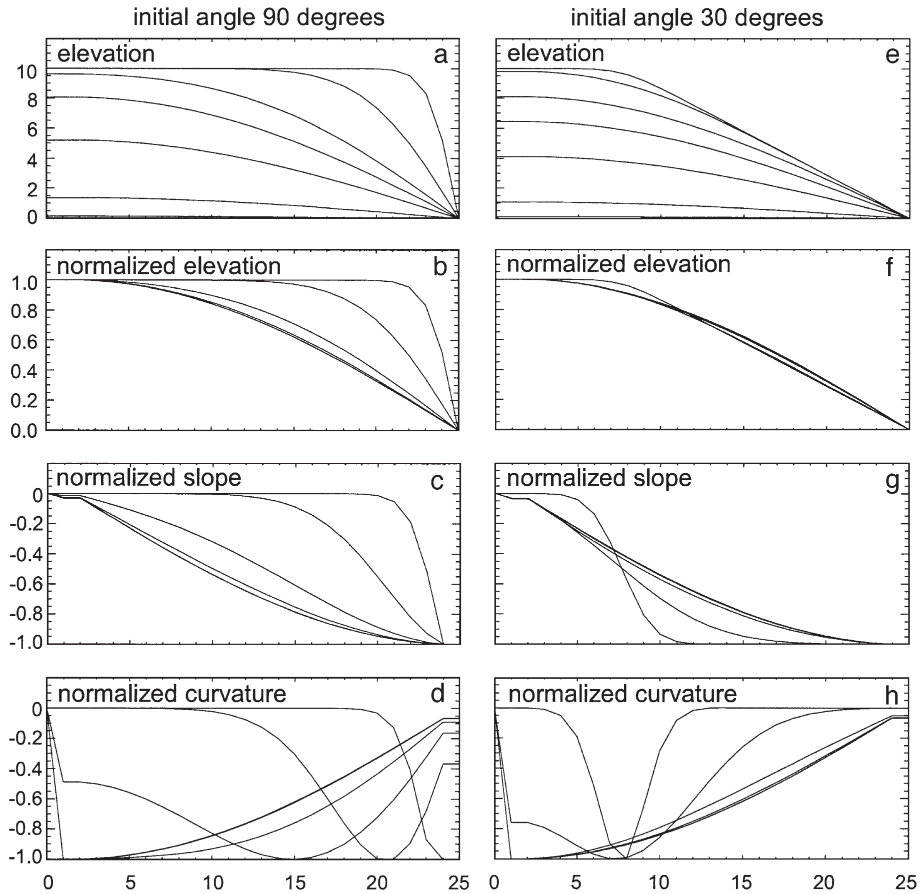

Fig. 12. Differences in hillslope morphology due to initial angle differences: (a–d) have an initial angle of 90°, (e–h) have an initial angle of 30° (angle of repose for alluvium). The contours are at κt=1, 10, 50, 100, 200, 500, 1000, and 1500 (m^2). Note that for the same κt, the profiles look markedly different for different initial angles, implying that the initial angle in the model is significant in determining κt of a measured profile.

formation occurs on the order of 20 ky (e.g. Dohrenwend et al., 1987). The assumption of constant gully bottom depth could be affirmed with future datasets by constant diffusion ages on a single gully at varying distances from distal to proximal ends. To exercise caution, we avoided taking profiles close to the channel head, which may be younger than those closer to the distal end of the fan.

4.2.4. Diffusivity coefficient variation over time

Variations in the diffusivity coefficient, κ, over the life of the alluvial fan is a concern because a varying coefficient will complicate the process of gully-profile evolution. Due to Quaternary climate change in the southwestern US, it is unlikely that κ has remained constant over the lifetime of these alluvial fans. In general, present-day diffusivities are thought to be applicable only over the Holocene (Hanks, 2000). The behavior of κ in the pre-Holocene climate is not easily determined even though we know the general trend of climate variation, because the understanding of how κ varies with different variables is still insufficient. The processes affected by changing κ include runoff and infiltration (Wells et al., 1987). As local climate records improve (e.g. Smith et al., 1997), associated temporally varying κ may be incorporated into the diffusion model to test the magnitude of dependence of κ on variations in precipitation and temperature. In addition, the evidence that north facing slopes with wetter microclimates degrade slower than south-facing slopes (Pierce and Colman, 1986) suggests that the shorter, wetter glacial intervals may have undergone lower erosion rates. This should lessen the effect of Quaternary climate changes on temporal variations in κ.

Some of the considerations discussed in this section, such as initial angle and gully downcutting, are parameters that can be incorporated into the model. Others, such as variability of κ through time, are harder to constrain. Fortunately, diffusion ages obtained by this technique provide a good opportunity for learning what variables control κ by comparing κt values for correlative terraces regionally. This will improve the accuracy of the method once better calibrations are obtained.

4.3. Accuracy of photo-derived profiles

Photoclinometry—the method of obtaining slope information from image brightness values—has been applied primarily to planetary bodies where direct slope measurement is impossible or prohibitively expensive. On Earth, ground surveying or high-resolution radarclinometry have been preferred because they generally yield more precise information. Jankowski and Squyres (1990, 1991) have outlined the major errors associated with photoclinometry, including noise, albedo variations, and atmospheric effects. It is important to note that the method utilizes a normalized profile of gradient, so it is relative, not absolute, gradient that we analyze. This process of normalization minimizes a number of errors.

Albedo variations can be indistinguishable from topography-induced brightness variations, but in our case the 25- to 200-m profile is drawn over a fan surface of presumably constant material and albedo. An exception to this assumption is the presence of desert varnish on some planar fan surfaces, which causes abnormally dark values. This varnished material is removed from the steeper slopes of the gully profiles by the slope diffusion. We avoid planar areas with varnish because two different albedo values are represented on brightness profiles from such areas. In contrast, evaluating fans of differing lithologies and reflective properties should not affect the method since we use *relative* brightness values along the profile. Where application of the photometric method is not optimal, we recommend using the ground-survey method for surface dating.

Atmospheric effects stem from the fact that radiation detected by the viewer is a sum of both the original source of illumination (the sun) and radiation scattered by atmospheric particles. However, on clear days the atmospheric contribution is likely a small constant additive term across the short profile. Since we normalize the slope profile, the effect of this contribution is minimized. The similarity of the Hanaupah Canyon fan surface κt values as discussed in Results suggests attainment of accurate surface morphology by the photometric method in this area.

4.4. Diffusion age (κt) significance

The main limitation of the photometric method is the resolution and quality of the data. This method produces mean κt values for surfaces with a standard deviation of 30–50% of the mean value. This resolution is generally good enough to differentiate surfaces defined by Bull's (1991) existing fan chronology, and to correlate two separated surfaces on a piedmont that were formed at the same time. However, DOQ aerial photos are rarely taken with the optimal sun angle. Using brightness values from large-scale aerial photographs is one option, though coverage is not as complete as with DOQs. Airborne laser altimetry is a technique that can bypass many of the problems of aerial photography while still achieving 1–2 m horizontal resolution. Laser altimetry is less dependent on weather and light conditions since it is an active remote sensing method that sends its own signal. The technique also has some ability to penetrate vegetation. The vertical resolution is close to 10 cm. Remotely derived profiles from airborne laser altimetry is likely to be a much closer representation of the actual surface morphology than the brightness profiles obtained from the DOQs. In the future, laser altimetry datasets may be used to obtain gully elevation profiles for this technique.

Although we cannot confidently compare the κt values between different piedmonts because of the uncertainty in κ, we can examine κt ratios between surfaces on single piedmonts. A similar set of surface–age ratios (i.e. old/intermediate/young) on different piedmonts suggests that the surfaces were deposited at the same time, but degraded differently according to different κ.

Given the limitations seen here, the most useful application of this morphometric method is to compare multiple surfaces from different mountain piedmonts and quantify the relative κt values within and between piedmonts. This exercise would supply a quantitative assessment of relative surface ages and be an improvement of existing fan-age correlations. The photometric method is useful for determining preliminary fan ages, and will improve with better topographic data and repeated use that establishes controls on spatial variations in κ.

5. Conclusions

A new application of linear hillslope diffusion to cross-sectional gully profiles determines diffusion ages (κt values) on Quaternary alluvial fan surfaces to 30–50% of a mean surface value. We applied this diffusion model to 25 alluvial fan surfaces in the southwestern US. A photometric method for deriving relative gradient profiles is consistent with ground-based methods of acquiring gully-wall scarp morphology, especially in poorly vegetated areas like Death Valley. In areas with denser vegetation, like the Ajo Mountain piedmont, the photometric method loses precision. The effects of vegetation on the photo-derived gradient profile may be minimized by taking the "envelope curve" of the raw brightness data. Variations in κt values can also be minimized by integrating the raw brightness curve to obtain a smoothed approximation of relative elevation. This remote technique is an efficient way to quickly analyze the relative ages of alluvial surfaces older than Holocene over a large area. Where the photometric method is non-optimal, ground surveying of the gully profiles can produce data for the diffusion model. The diffusion modeling of gully cross-sectional profiles is an additional tool for analyzing the difficult problem of determining fan-surface age.

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References

Abrams, M.J., Chadwick, O.H., 1994. Tectonic and climatic implications of alluvial-fan sequences along the Batinah Coast, Oman. Journal of the Geological Society 151, 51–58.

Andrews, D.J., Hanks, T.C., 1985. Scarp degraded by linear diffusion: inverse solution for age. J. Geophys. Res. 90, 10193–10208.

Avouac, J.-P., 1993. Analysis of scarp profiles: evaluation of errors in morphologic dating. J. Geophys. Res. 98, 6745–6754.

Barsch, D., Royse, C.F., 1972. A model for development of Quaternary terraces and pediment-terraces in the southwestern United States of America. Zeitschrift FuÉr Geomorphologie, N.F. 16, 54–75.

Beaujon, J.S., 1987. The relationship of height to geomorphic degradation rates of terrace scarps in Idaho and Wyoming. MS Thesis, University of Cincinnati.

Beratan, K.K., Anderson, R., 1998. The use of Landsat Thematic Mapper data for mapping and correlation of Quaternary geomorphic surfaces in the southern Whipple Mountains, California. International Journal of Remote Sensing 19, 2345–2359.

Bull, W.B., 1991. Geomorphic Responses to Climatic Change. Oxford Univ. Press, New York.

Bull, W.B., 1996. Global climate change and active tectonics: effective tools for teaching and research. Geomorphology 16, 217–232.

Carson, M.A., Kirkby, M.J., 1972. Hillsope Form and Process. Cambridge Univ. Press, Cambridge.

Christenson, G.E., Purcell, C., 1985. Correlation and age of Quaternary alluvial-fan sequences, Basin and Range Province, southwestern United States. In: Weide, D.L. (Ed.), Soils and Quaternary Geology of the Southwestern United States. Geol. Soc. Am. Special Paper, vol. 203. The Geological Society of America, Boulder, CO, pp. 115–122.

Clarke, M.L., 1994. Infrared stimulated luminescence ages from Aeolian sand and alluvial-fan deposits from the eastern Mojave Desert, California. Quaternary Science Reviews 13, 533–538.

Colman, S.M., Watson, K., 1983. Ages estimated from a diffusion equation model for scarp degradation. Science 221, 263–265.

Dohrenwend, J.C., Abrahams, A.D., Turrin, B.D., 1987. Drainage development on basaltic lava flows, Cima volcanic field, Southeast California, and Lunar Crater volcanic field, south-central Nevada. Geological Society of America Bulletin 99, 405–413.

Gillespie, A.R., Burke, R.M., Harden, J.W., 1994. Timing and regional paleoclimatic significance of alluvial fan deposition, western Great Basin. Abstracts with Programs-Geological Society of America 26, A150–A151.

Hanks, T.C., 2000. The age of scarplike landforms from diffusion-equation analysis. In: Noller, J.S., Sowers, J.M., Lettis, W.R. (Eds.), Quaternary Geochronology: Methods and Applications. American Geophysical Union, Washington, DC, pp. 313–338.

Harvey, A.M., Wells, S.G., 2003. Late Quaternary variations in alluvial fan sedimentologic and geomorphic processes, Soda Lake basin, eastern Mojave Desert, California. In: Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), Paleoenvironments and Paleohydrology of the Mojave and Southern Great Basin Deserts-Geol. Soc. Am. Special Paper, vol. 368. The Geological Society of America, Boulder, CO, pp. 207–230.

Harvey, A.M., Silva, P.G., Mather, A.E., Goy, J.L., Stokes, M., Zazo, C., 1999. The impact of Quaternary sea-level and climatic change on coastal alluvial fans in the Cabo de Gata ranges, southeast Spain. Geomorphology 28, 1–22.

Hooke, R.L., Dorn, R.I., 1992. Segmentation of alluvial fans in Death Valley, California: new insights from surface exposure dating and laboratory modeling. Earth Surface Processes and Landforms 17, 557–574.

Ibbeken, H., Warnke, D.A., Diepenbroek, M., 1998. Granulometric study of the Hanaupah Fan, Death Valley, California. Earth Surface Processes and Landforms 23, 481–492.

Jankowski, D.G., Squyres, S.W., 1990. What's wrong with photoclinometry? In: Solomon, S.C., Sharpton, V.L., Zimbelman, J.R. (Eds.), Scientific Results of the NASA-sponsored Study Project on Mars; Evolution of Volcanism, Tectonics, and Volatiles. LPI Technical Report 90–106. Lunar and Planetary Institute, Houston, TX, US, pp. 178–179.

Jankowski, D.G., Squyres, S.W., 1991. Sources of error in planetary photoclinometry. Journal of Geophysical Research, E. Planets 96, 20907–20922.

Ku, T.-L., Bull, W.B., Freeman, S.T., Knauss, K.G., 1979. Th^{230}–U^{234} dating of pedogenic carbonates in gravelly desert soils of Vidal Valley, southeastern California. Geological Society of America Bulletin 90, 1063–1073.

Liu, B., Phillips, R.M., Pohl, M.M., Sharma, P., 1996. An alluvial surface chronology based on cosmogenic ^{36}Cl dating, Ajo Mountains (Organ Pipe Cactus National Monument), Southern Arizona. Quaternary Research 45, 30–37.

Mack, G.H., Leeder, M.R., 1999. Climatic and tectonic controls on alluvial-fan and axial–fluvial sedimentation in the Plio-Pleistocene Palomas half-graben, southern Rio Grande rift. Journal of Sedimentary Research 69, 635–652.

Martin, Y., Church, M., 1997. Diffusion in landscape development models: on the nature of basic transport relations. Earth Surface Processes and Landforms 22, 273–279.

Mayer, L., 1984. Dating Quaternary fault scarps formed in alluvium using morphologic parameters. Quaternary Research 22, 300–313.

McDonald, E.V., McFadden, L.D., Wells, S.G., 2003. Regional response of alluvial fans to the Pleistocene–Holocene climatic transition, Mojave Desert, California. In: Enzel, Y., Wells, S.G., Lancaster, N. (Eds.), Paleoenvironments and paleohydrology of the Mojave and southern Great Basin Deserts. Geol. Soc. Am. Special Paper, vol. 368. The Geological Society of America, Boulder, CO, pp. 189–205.

McFadden, L.D., Ritter, J.B., Wells, S.G., 1989. Use of multiparameter relative-age methods for age estimation and correlation of alluvial fan surfaces on a desert piedmont Eastern Mojave Desert, California. Quaternary Research 32, 276–290.

Nash, D.B., 1984. Morphologic dating of fluvial terrace scarps and fault scarps near West Yellowstone, Montana. Geological Society of America Bulletin 95, 1413–1424.

Nash, D.B., 1998. Influence of scarp height on the accuracy of morphologic dating. Abstracts with Programs-Geological Society of America 30, 329.

Owen, L.A., Windley, B.F., Cunningham, W.D., Badamgarav, J., Dorjnamjaa, D., 1997. Quaternary alluvial fans in the Gobi of southern Mongolia: evidence for neotectonics and climate change. Journal of Quaternary Science 12, 239–252.

Pelletier, J.D., 2003. Drainage network evolution and denudation in a physical alluvial basin model: dependence on initial conditions. Geomorphology 53, 183–196.

Pentland, A., 1988. The transform method for shape-from-shading. MIT Media Lab Vision Sciences Tech. Report 106.

Pierce, K.L., Colman, S.M., 1986. Effect of height and orientation (microclimate) on geomorphic degradation rates and processes, late-glacial terrace scarps in central Idaho. Geological Society of America Bulletin 97, 869–885.

Pope, R.J.J., 2000. The application of mineral magnetic and extractable iron (Fe-d) analysis for differentiating and relatively dating fan surfaces in central Greece. Geomorphology 32, 57–67.

Reheis, M.C., Slate, J.L., Throckmorton, C.K., McGeehin, J.P., Sarna-Wojcicki, A.M., Dengler, L., 1996. Late Quaternary sedimentation on the Leidy Creek fan, Nevada–California: geomorphic responses to climate change. Basin Research 12, 297–299.

Ritter, J.B., Miller, J.R., Enzel, Y., Wells, S.G., 1995. Reconciling the roles of tectonism and climate in Quaternary alluvial fan evolution. Geology 23, 245–248.

Ritter, J.B., Miller, J.R., Husek-Wulforst, J., 2000. Environmental controls on the evolution of alluvial fans in the Buena Vista Valley, North Central Nevada, during late Quaternary time. Geomorphology 36, 63–87.

Roering, J.J., Kirchner, J.W., Dietrich, W.E., 1999. Evidence for nonlinear, diffusive sediment transport on hillslopes and implications for landscape morphology. Water Resources Research 35, 853–870.

Simpson, D.T., 1991. Soil and geomorphology of the Quaternary alluvial sequences on the western piedmont of the Ajo Mountains, Organ Pipe National Monument, Pima County, Arizona. Unpublished MS Thesis, University of New Mexico, Albuquerque.

Smith, G.A., 1994. Climatic influences on continental deposition during late-stage filling of an extensional basin, southeastern Arizona. Geological Society of America Bulletin 106, 1212–1228.

Smith, G.I., Bischoff, J.L., Bradbury, J.P., 1997. Synthesis of the paleoclimatic record from Owens Lake core OL-92. In: Smith, G.I., Bischoff, J.L. (Ed.), An 800,000-Year Paleoclimatic Record from Core OL-92, Owens Lake, Southeast California. Geol. Soc. Am. Special Paper, vol. 317. The Geological Society of America, Boulder, CO, pp. 143–160.

Swadley, W.C., Schmidt, D.L., Shroba, R.R., Williams, V.S., Hoover, D.L., 1995. Preliminary correlation of Quaternary and late Tertiary alluvial deposits in southeast Nevada. In: Scott, R.B., Swadley, W.C. (Eds.), Geologic Studies, in the Basin and Range-Colorado Plateau transition in southeastern Nevada, southwestern Utah, and northwestern Arizona, 1992, Barco Study Unit, U.S. Geological Survey, Washington: U.S.G.P.O.; Denver, Co, pp. 193–202.

Turko, J.M., Knuepfer, P.L.K., 1991. Late Quaternary fault segmentation from analysis of scarp morphology. Geology 19, 718–721.

Wallace, R.E., 1977. Profiles and ages of young fault scarps, north-central Nevada. Geological Society of America Bulletin 88, 1267–1281.

Wang, Y., McDonald, E., Amundson, R., McFadden, L., Chadwick, O., 1996. An isotopic study of soils in chronological sequences of alluvial deposits Providence Mountains, California. Geological Society of America Bulletin 108, 379–391.

Watchman, A.L., Twidale, C.R., 2002. Relative and "absolute" dating of land surfaces. Earth-Science Reviews 58, 1–49.

Wells, S.G., 1997. Influence of climatic regimes and their variations on the deposition of alluvial fans in Quaternary extensional basins. Abstracts with Programs-Geological Society of America 29, 240.

Wells, S.G., McFadden, L.D., Dohrenwend, J.C., 1987. Influence of late Quaternary climatic changes on geomorphic and pedogenic processes on a desert piedmont Eastern Mojave Desert, California. Quaternary Research 27, 130–146.

Wells, S.G., McFadden, L.D., Harden, J., 1990. Preliminary results of age estimations and regional correlations of Quaternary alluvial fans within the Mojave Desert of Southern California. In: Reynolds, J. (Ed.), At the End of the Mojave: Quaternary Studies in the Eastern Mojave Desert: San Bernardino County Museum Association and 1990 Mojave Desert Quaternary Research Center Symposium. San Bernadino County Museum Association, Redlands, CA, pp. 45–53.

White, K., Drake, N., Millington, A., Stokes, S., 1996. Constraining the timing of alluvial fan response to Late Quaternary climatic changes, southern Tunisia. Geomorphology 17, 295–304.

White, K., Bryant, R., Drake, N., 1998. Techniques for measuring rock weathering: application to a dated fan segment sequence in southern Tunisia. Earth Surface Processes and Landforms 23, 1031–1043.