Geomorphologic Flood-Hazard Assessment of Alluvial Fans and Piedmonts

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ABSTRACT

Geomorphologic studies are an excellent means of flood-hazard assessment on alluvial fans and piedmonts in the southwestern United States. Inactive, flood-free, alluvial fans display well developed soils, desert pavement, rock varnish, and tributary drainage networks. These areas are easily distinguished from flood-prone active alluvial fans on aerial photographs and in the field.

The distribution of flood-prone areas associated with alluvial fans is strongly controlled by fanhead trenches dissecting the surface. Where fanhead trenches are permanent features cut in response to long-term conditions such as tectonic quiescence, flood-prone surfaces are situated downslope from the mountain front and their positions are stable for thousands of years. Since the length and permanency of fanhead trenches can vary greatly between adjacent drainages, it is not appropriate to use regional generalizations to evaluate the distribution and stability of flood-hazard zones. Site-specific geomorphologic studies must be carried out if piedmont areas with a high risk of flooding are to be correctly identified and losses due to alluvial-fan flooding minimized.

To meet the growing demand for trained professionals to complete geomorphologic maps of desert piedmonts, undergraduate and graduate geomorphology courses should adopt an instructional unit on alluvial-fan flood hazards that includes: 1) a review of geomorphologic characteristics that vary with surface age; 2) a basic mapping exercise; and 3) a discussion of the causes of fanhead trenching.

Keywords: Education – graduate; education – undergraduate; engineering and environmental geology; geology – field trips and field study; hydrogeology and hydrology; surficial geology – geomorphology.

INTRODUCTION

Alluvial-fan flooding on piedmonts has resulted in millions of dollars of property damage and the loss of life in the United States (French, 1987). Losses due to alluvial-fan flooding are likely to increase in the near future with the continued population expansion of the southwestern United States, where over 30 percent of the land area is composed of alluvial fans (Antsey, 1966). The extent of flood-prone alluvial fans varies substantially between adjacent piedmonts (see definition below) and from region to region. Large portions of many piedmonts are composed of inactive alluvial fans that have been isolated from flooding for 10,000 years or more. Geomorphologic analysis and mapping can be used to delineate these inactive areas on a piedmont and thus identify those areas most susceptible to flooding (Rhoads, 1986; Pearthree and Pearthree, 1988; Kenny, 1990; Field and Pearthree, 1991a).

Despite calls for the wider use of geomorphologic mapping in flood-hazard studies of alluvial fans and piedmonts (Nelson, 1988), the value of mapping is still not widely appreciated or acknowledged by floodplain managers who are typically trained in engineering and hydrology but not in geomorphology. Geology and geomorphology courses that are commonly required for degrees in civil engineering and hydrology provide an ideal venue for demonstrating the usefulness of geomorphologic mapping as a method of flood-hazard assessment.

The purpose of this paper is to promote wider use of geomorphologic mapping in flood-hazard assessments of alluvial fans and piedmonts by: 1) outlining the numerous geomorphologic characteristics used to distinguish surfaces of different age; 2) illustrating the mapping process with an example from two Arizona piedmonts; and 3) reviewing the causes of fanhead trenching, an important process controlling the location of flood-prone surfaces.

PIEDMONTS AND ALLUVIAL FANS: DEFINING TERMS

In the basin and range province of the western United States, piedmonts (literally "the foot of the mountains") are the low relief, gently sloping plains between the mountain ranges and the streams or playas that occupy the lowest portions of the large basins (Figure 1). Piedmonts may be composed of active and inactive alluvial fans and bedrock pediments and knobs. Pediments, fairly planar, exposed or shallowly buried bedrock erosion surfaces form as a result of long-term erosion and retreat of the mountain front. Alluvial fans are generally cone-shaped depositional landforms with distributary drainage patterns that emanate from a discrete source and increase in width downslope. Older, or inactive, alluvial fans commonly are isolated from active depositional processes and dendritic drainage patterns are developed on them.

Piedmont areas composed of active alluvial fans are of particular concern from a floodplain-management perspective because they are subject to widespread inundation by floodwaters, local high-velocity flows, and drastic and rapid changes in channel positions. If development on piedmonts occurs without the location of active alluvial fans being identified, lives and

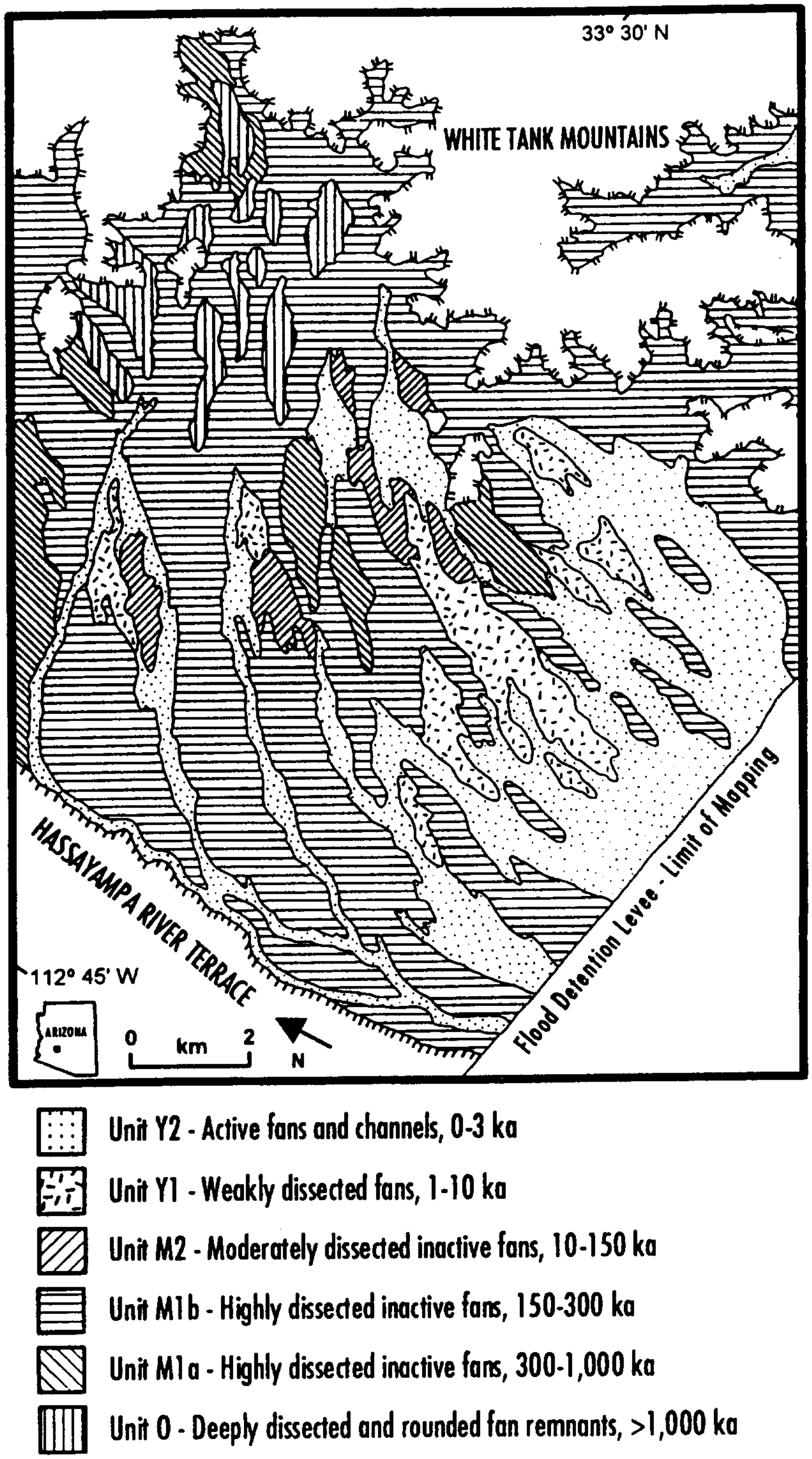

Figure 2. Geomorphologic map of alluvial surfaces on the southwestern piedmont of the White Tank Mountains, Arizona. Dotted and dashed regions are flood prone while units represented by solid lines are largely flood free. See Table 4 for detailed unit descriptions. Surface ages reflect the time since surface abandonment. Modified from Field and Pearthree (1991b).

older surfaces imply that floods have been conveyed through these areas in confined channels or fanhead trenches for long periods of time. In this section, we describe two piedmonts in Arizona where geomorphologic mapping was used to assess the extent of active alluvial-fan flooding.

White Tank Mountains

Geomorphologic mapping (Field and Pearthree, 1991b) of the western piedmont of the White Tank Mountains was completed for the Maricopa County Flood Control District in anticipation of urban expansion around the Phoenix metropolitan area. A simplified version of this mapping (Figure 2) and descriptions of surface characteristics (Table 4) illustrate how geomorphologic features can be used to delineate the location of flood-prone areas. The White Tank Mountains predominantly consist of felsic gneiss, granite, and dioritic dikes. Rock varnish is best developed on dioritic cobbles. The average annual rainfall around the White Tank Mountains piedmont is approximately 18 cm.

The relative ages of the surfaces are based on differences in drainage patterns, topographic relief, surface characteristics (for example, desert pavement), and soil development as determined from 1:24,000-scale natural-color aerial photographs, soil and topographic maps, and field checking (Figure 2; Table 4). The estimated age of each surface represents the length of time since the cessation of aggradation, or, in other words, the length of time since the surface has been flooded. The surface ages are inferred by correlation with similar surfaces and soils radiometrically dated elsewhere in the southwestern United States (Gile and others, 1981; Menges and McFadden, 1981; Bull, 1991). Desert pavement is progressively better developed as surface age increases (Figure 3; Table 4). Surfaces that are subject to flooding are undissected, display well preserved bar-and-swale topography, and lack desert pavement and varnish (Figure 4a). In contrast, surfaces that have not been flooded for hundreds of thousands of years are moderately to deeply dissected, have well developed desert pavements (Figure 4b) and abundant shattered cobbles on the surface (Figure 4c); their soils include substantial accumulations of clay and calcium carbonate (caliche).

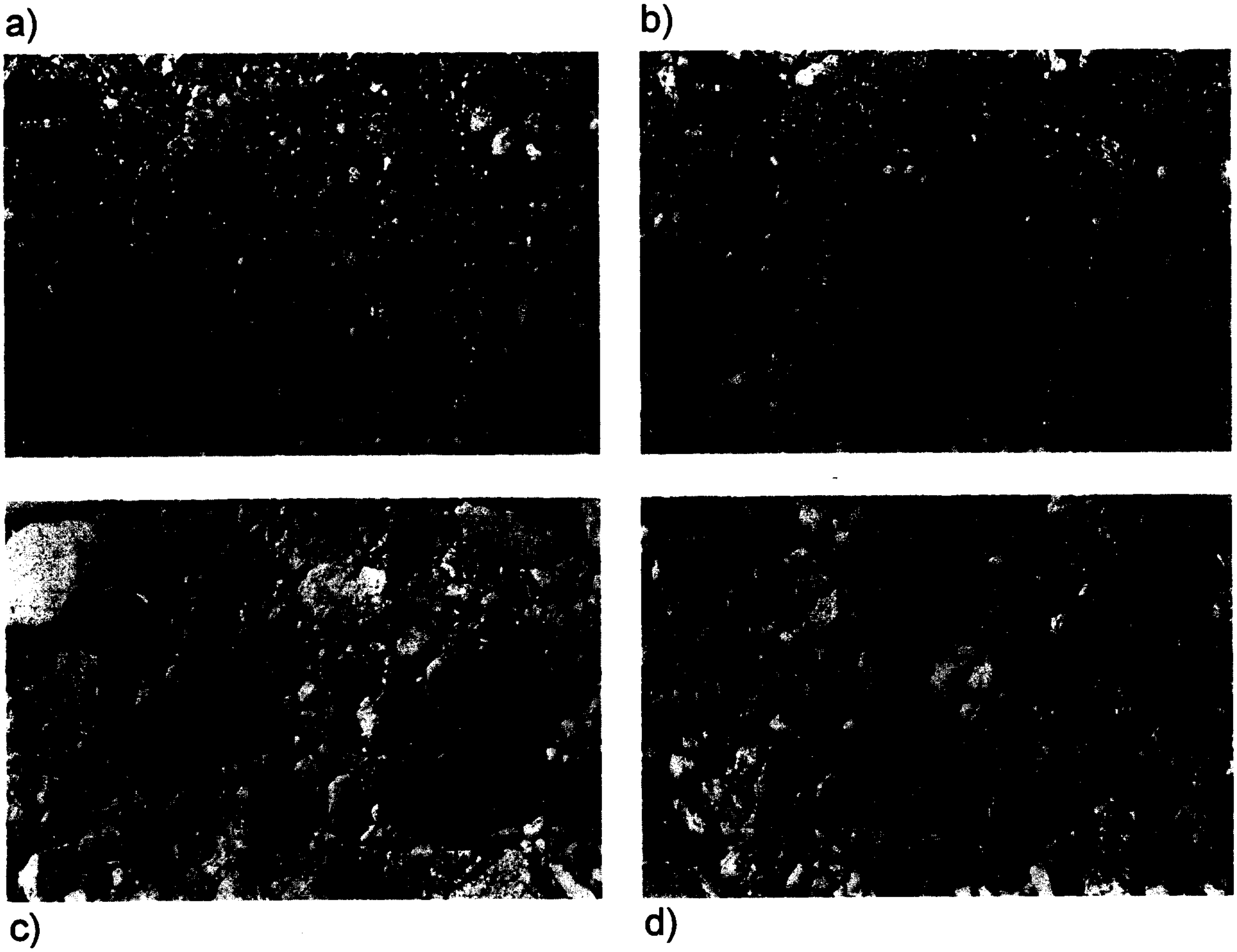

Figure 3. Progressive development of desert pavement on surfaces of different age on the White Tank Mountains piedmont: a) Unit Y1; b) Unit M2; c) Unit M1b; d) Unit M1a.

Term or Phrase Used	References
Fan-mesa	6,28,33
Abandoned surfaces	3,15,19
Fossil fans	32,36
Old(er) surfaces	11,27
Old-age fans	1
Inactive surfaces	15,18,19,24,25,30,31
High-fan surfaces	11
Ancient fan	4
Stabilized fan	1
Remnant fan	33
Fan segment	21,29
Depositional phase	35
Surface facies	10
Dismembered part of ancient bajada	34

Note: 1-26 as in Table 1-2; 27=Antsey, 1966; 28=Blissenbach, 1954; 29=Bull, 1964; 30=Funk and Dort, 1977; 31=Kesel and Lowe, 1987; 32=Mukerji, 1990; 33=Riccio, 1962; 34=Schick, 1971; 35=Silva and others, 1992; 36=Wasson, 1975.

Table 3 (left). Terms and phrases used to describe alluvial-fan surfaces isolated from flooding.

Tortolita Mountains

A geomorphologic map (Figure 5) and surface descriptions (Table 5) of the southwestern piedmont of the Tortolita Mountains (150 km southeast of the White Tank Mountains piedmont) are presented here to demonstrate how surficial features and the distribution of flood hazards can vary between piedmonts in the same region. A similar range of surface ages are estimated for the Tortolita and White Tank Mountains piedmonts. Surfaces with similar estimated ages have some characteristics in common (for example, surface relief and degree of dissection), but desert pavement and rock varnish are better developed on the White Tank Mountains piedmont (Figures 3d,5). Soil development for a surface of a given age is stronger on the Tortolita Mountains piedmont (Tables 4,5). Higher annual rainfall on the Tortolita Mountains piedmont (28 cm/yr vs. 18 cm/yr) promotes faster soil development while rock varnish and pavement development is probably inhibited by the denser vegetation cover and faster weathering of surface

Characteristic	Unit Y2	Unit Y1	Unit M2	Unit M1b	Unit M1a	Unit O
Drainage pattern	Distributary	Incipient dendritic	Dendritic	Dendritic	Dendritic	Dendritic
Relief above channels	O m	0 to 0.5 m	0.5 to 3 m	0.5 to 6 m	1 to 6 m	10 to 15m
Bar-and-swale topography	Well preserved	Well preserved	Moderately preserved	Poorly preserved	Not present	Not present
Desert pavement	Not present	Weakly developed	Moderately developed	Well developed	Well developed	Denuded surfaces
Rock-varnish color*	Not developed	Brownish black (10 YR 2/2)	Very dark brown (7.5YR 2/3)	Black (5 YR 1.7/1)	Black (5 YR 1.7/1)	Denuded surfaces
Soil Horizons**	Not developed	Cambic (Hue 7.5YR); Stage I-II calcic	Cambic (Hue 7.5YR); Stage I-II calcic	Argillic (Hue 5YR); Stage II calcic	Argillic (Hue 2.5YR); Stage IV calcic	Stage V-VI calcic
Others	–	–	–	–	Salt-split cobbles	Caliche rubble
Surface activity	Active	Slightly active	Inactive	Inactive	Inactive	Inactive
Estimated age	0 to 3 ka	1 to 10 ka	10 to 150 ka	150 to 300 ka	300 to 1,000 ka	>1,000 ka
Flood hazard	High	Slight	None	None***	None***	None

* Varnish colors and soil hues from Munsell's soil color chart
** Calcic horizon stages from Bachman and Machette (1977)
*** A slight chance of flooding is locally present on the middle piedmont in areas of low relief.

Table 4. Summary of characteristics found on each geomorphologic surface of the White Tank Mountains piedmont exemplifying the types of observations needed to assess flood hazards on piedmonts and alluvial fans.

Characteristic	Unit 2b	Unit 2a	Unit 1b	Unit 1a
Drainage pattern	Distributary	Incipient dendritic	Dendritic	Dendritic
Relief above channels	O m	1 to 2 m	1 to 3 m	2 to 10 m
Bar-and-swale topography	Well preserved	Moderately preserved	Poorly preserved	Not present
Desert pavement	Not present	Weakly developed	Poorly developed	Moderately developed
Rock varnish	Not developed	Not developed	Incipient development	Moderately developed
Soil Horizons*	Stage I calcic	Cambic (Hue 7.5YR);	Argillic (Hue 5YR);	Argillic (Hue 5YR);
		Stage I-II calcic	Stage II calcic	Stage IV-VI calcic
Surface activity	Active	Inactive	Inactive	Inactive
Estimated age	0 to 5 ka	5 to 20 ka	20 to 125 ka	> 125 ka
Flood hazard	High	None	None	None

*Soil hues from Munsell's soil color chart; Calcic horizon stages from Bachman and Machette (1977).
Note: Data from Pearthree and others (1991).

Table 5. Summary of characteristics found on each geomorphologic surface of the Tortolita Mountains piedmont.

trenches or have fanhead trenches that are overtopped during large floods. In areas where the faulting and uplift of mountain ranges has ceased, as in most of Arizona, climatic changes during the Quaternary (roughly the past 2 million years) likely have exerted a major control on the distribution of flood-prone surfaces. Climatic changes have resulted in variations in the sediment yields from mountain areas and changes in the hydrologic characteristics of stream systems, leading to alternating periods of aggradation and entrenchment on desert piedmonts (Dorn and others, 1987; Bull, 1991). On these piedmonts, stream channels tend to be permanently entrenched into older alluvial fans with the active alluvial fans located on the middle and lower piedmont. The aerial extent of active alluvial fans along any given drainage depends on sediment production rates (lithology, drainage size, and climate) and the stability of base level (base level fall could result in the entrenchment of the lower piedmont).

Recognizing whether a fan-head trench is a permanent or transient feature on an alluvial fan is critical for establishing whether the present position of flood hazards on a piedmont is stable or subject to rapid relocation. Several criteria can be used to distinguish between a permanent and temporary trench (Table 7). Fanhead trenches dissecting inactive surfaces with well developed soils, desert pavement, and

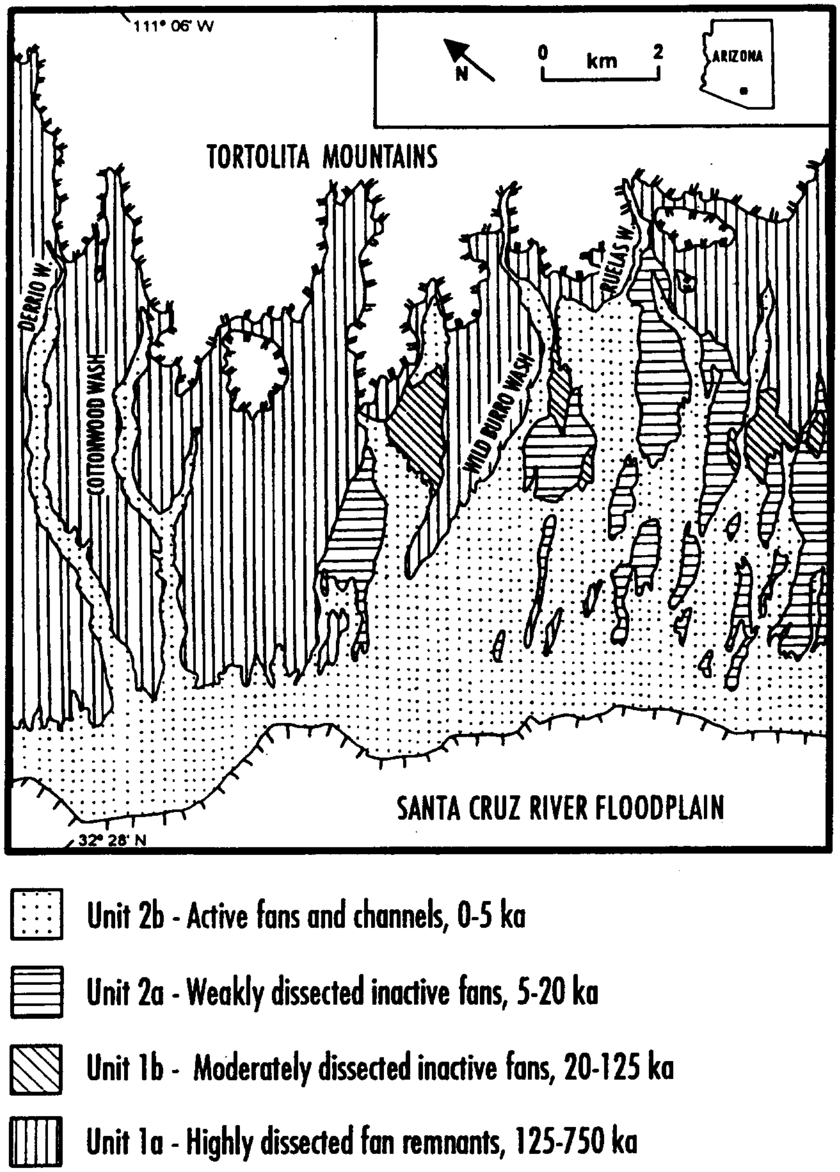

Figure 5. Geomorphologic map of alluvial surfaces on the southwestern piedmont of the Tortolita Mountains, Arizona. Dotted regions are flood prone while units represented by solid lines are free from flooding. See Table 5 for detailed unit descriptions. Redrawn from Pearthree et al. (1991) and unpublished data.

rock varnish are permanent features, since it is the incision of the trench itself that is largely responsible for the isolation of the adjacent old surfaces. A trench dissecting a young surface, on the other hand, is potentially only a transient feature. The depth of incision alone should not be used to determine whether a trench is permanent. Trenches as deep as 8 m can be filled and/or cut during a single debris flow event (Pack, 1923; Blackwelder, 1928; Morton and Cambell, 1974). In contrast, permanent fanhead trenches on the Tortolita and White Tank Mountains piedmonts, where there is no evidence of young debris flows, are typically less than 3 m deep. Regardless of the absolute depth of incision, a fanhead trench is not a permanent feature if floodwaters can overtop or backfill the channel under the prevailing hydrologic conditions.

LIMITATIONS OF GEOMORPHOLOGIC MAPPING

Geomorphologic mapping, although valuable in delineating potentially hazardous areas, provides little information on the severity and types of hazards present within these zones. More detailed studies, including sedimentological facies mapping and hydraulic analysis of flood discharges, can more precisely delimit flood-prone areas, identify flood-hazard types, and quantify the frequency and potential magnitude of each hazard (Field, 1994). Geomorphologic mapping is most useful as a first phase of more comprehensive multi-disciplinary assessment projects because it enables floodplain managers to 1) formulate land-use plans (Rhoads, 1986), 2) focus future studies and limited resources on the most hazardous areas (Field and Pearthree, 1991), and 3) avoid misapplications of hydraulic models on inactive surfaces (Pearthree and Pearthree, 1988).

RECOMMENDATIONS

Geomorphologic mapping of flood hazards is necessary for each piedmont or alluvial fan being considered for development. Extrapolating the results from one area to predict the distribution of flood hazards in another is unwise given the numerous regional and local

Figure 6 (bottom left). Desert pavement developed on Unit 1a on the middle piedmont of the Tortolita Mountains. Compare with Figure 3d showing desert pavement of approximately the same age on the White Tank Mountains piedmont.

Cause of Trenching	Resulting On-Fan Increase In	References
Short Term (Temporary)		
Single storm	W/S	39,47,51,53,57,58
Variation in depositional process	W/S	9,40
Variations in rainfall patterns/storm discharge	W/S	3,26,29,44,61
Intrinsic geomorphic thresholds	Slope	56,63
Short and Long Term		
Base level fall	Slope	43,55,62
Shift in channel course	Slope	3,9,54
Toe trimming/truncation	Slope	41,43,62
Tectonic uplift on fan	Slope	6,31,48,49,50
Long Term (Permanent)		
Tectonic uplift of mountains	Stream power	37
Tectonic tilting of fan	Slope	9,10,21
Tectonic cessation	Slope and W/S	6,32,35,41,45
Change to glacial climate	W/S	30
Deglaciation	W/S*	4,25,48,52,60
Change to more arid climate	W/S	13,18,26,35,38,42,50,59
Change to more humid climate	W/S	20,45,46,62

Note: W/S=Water:sediment ratio of flood discharges; 1-36 as in Tables 1-3; 37=Beaty, 1961; 38=Beaumont, 1972; 39=Blackwelder, 1928; 40=Bluck, 1964; 41=Carryer, 1966; 42=Dorn and others, 1987; 43=Drew, 1873; 44=Harris, 1964; 45=Harvey, 1987; 46=Hunt and Mabey, 1966; 47=Kesseli and Beaty, 1959; 48=Knopf, 1918; 49=Longwell, 1930; 50=Lustig, 1965; 51=Morton and Cambell, 1974; 52=Ono, 1990; 53=Pack, 1923; 54=Rich, 1935; 55=Ryder, 1971b; 56=Schumm, 1977; 57=Scott, 1971; 58=Sharp and Nobles, 1953; 59=Talbot and Williams, 1979; 60=Trowbridge, 1911; 61=Wasson, 1974; 62=Wasson, 1977; 63=Wells and Harvey, 1987

*Trenching usually follows a short period of rapid aggradation.

Table 6. Documented causes of fanhead trenching.

Criterion	Permanent Trench	Temporary Trench
Adjacent surfaces	Inactive (that is, well developed desert pavement and desert varnish)	Active (that is, well preserved depositional features)
Drainage pattern	Part of tributary network draining mountains and adjacent surfaces	Part of a distributary network of channels radiating from the fanhead
Material incised	Well developed indurated soils and bedrock	Unconsolidated sediments
Banks of trench	Possibly rounded and well vegetated	Steep-sided and immature vegetation
Hydraulic modelling	Probable maximum flood contained within banks	Design flood of interest not contained within banks
Historical/eyewitness accounts	Oldest available account shows evidence of trench*	Trench incision observed or not present on oldest maps or photos

*This evidence is consistent with trench permanency but not conclusive evidence of permanency.

Table 7. Criteria useful in distinguishing between permanent and temporary fanhead trenches.

factors controlling the development of fanhead trenches (Table 6) and location of flood-prone surfaces. The distribution of active surfaces can vary between piedmonts in the same region and even between adjacent drainages (Figures 2,5; Schumm, 1977).

Geomorphology educators who incorporate a one- to two-week unit on geomorphologic mapping of alluvial-fan flood hazards into graduate and undergraduate courses would serve three important purposes. They would 1) provide initial training to geology students who will be needed to complete geomorphologic studies throughout the southwestern United States; 2) make present and future floodplain managers aware of the value and reliability of geomorphologic mapping in delineating flood-prone areas on piedmonts; and 3) demonstrate an application of basic geomorphologic techniques that can potentially save lives and millions of dollars in property damage. The topics covered in such a unit should include (with suggested length of time): 1) a thorough examination of how and why the surface characteristics listed in Table 1 vary with surface age, climate, and lithology (1-2 lectures); 2) a basic geomorphologic mapping exercise of an alluvial fan from aerial photographs, soils and topographic maps, and, where possible, field reconnaissance (1-2 laboratories and optional field trip); and 3) a discussion of the processes responsible for forming fanhead trenches (Table 6) and methods for determining their permanency (Table 7) (1-2 lectures). Without the help of geomorphology educators, who have a unique opportunity to simultaneously train geologists, hydrologists, and engineers, utilization of geomorphologic mapping as a flood-hazard assessment technique on alluvial fans and piedmonts is likely to remain limited.

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