Processes of Channel Migration on Fluvially Dominated Alluvial Fans in Arizona

by John J. Field

Arizona Geological Survey
Open-File Report 94-13

June 1994

Research summarized in this report was partially funded by the Flood Control District of Maricopa County and the Arizona Department of Water Resources

This report is preliminary and has not been edited or reviewed for conformity with Arizona Geological Survey standards

OFR 94-13

Processes of Channel Migration on Fluvially Dominated Alluvial Fans in Arizona

by John J. Field

Arizona Geological Survey
Open-File Report 94-13

June 1994

Research summarized in this report was partially funded by the Flood Control District of Maricopa County and the Arizona Department of Water Resources

ABSTRACT

Historical aerial photographs, surficial features, and limited subsurface trenching on five fluvially dominated alluvial fans in Arizona demonstrate that channel abandonment occurs along bends and/or where bank heights are low. Channel migration occurs through a process of stream capture in which overbank flow from the main channel accelerates and directs headward erosion of a smaller channel heading on the fan. The action of small aggrading floods is critical in the migration process, because the greatest amount of overbank flow is generated where bank heights are lowest. Several large floods on the fans during the photographic record produced no significant channel changes and may have actually inhibited future diversions along certain reaches by eroding channel beds and increasing bank heights.

Although the processes of channel diversion are different on debris-flow fans, a literature review of documented avulsions demonstrates that flow on debris-flow fans is also commonly diverted into preexisting channels. These findings suggest that the location of future channels on alluvial fans may be more predictable than previously thought, although information on the frequency of diversions is still limited.

INTRODUCTION

The importance of channel shifting on alluvial-fan development has long been recognized (Drew, 1873). Over geological time, channels must migrate over the entire surface to ensure the establishment and maintenance of fan form. When considering the long-term aggradation of alluvial fans, the exact location of channels through time is indeterminate and channel migration can be modeled as a stochastic process (Price, 1974; Hooke and Rohrer, 1979). However, short-term processes of channel migration on alluvial fans are of greater interest to engineers and geologists studying flood hazards and the geomorphological effectiveness of floods. What role, if any, do small and large floods play in the process of channel migration? How frequent are individual diversion events? Are the locations of future channels unpredictable as assumed by Dawdy (1979)? Although short-term channel migration on debris-flow fans (Beaty, 1963) and fluvial fans (Kesel and Lowe, 1987; Wells and Dorr, 1987) has been examined, further studies are needed to adequately answer the above questions.

In this paper the influence of both large- and small-scale geomorphological events on the processes and frequency of channel migration is examined on five fluvially dominated alluvial fans in southern Arizona (Fig. 1). Historical aerial photographs and field reconnaissance were used to document the processes and events associated with recent channel diversions on the five fans. A literature review is conducted to determine if the findings from the Arizona fans are similar to previously documented channel diversions on debris-flow fans and other fluvial fans. Recurring observations made on fans of all types are potentially useful for predicting the location and timing of channel diversions and the positions of future channels.

STUDY SITES

Recent channel changes were studied on five alluvial fans located in the tectonically inactive Basin-and-Range province of southern Arizona: Ruelas Fan, Wild Burro Fan, Cottonwood Fan, White Tank Fan, and Tiger Wash Fan (Fig. 1). Drainage-basin characteristics for the five fans are shown in Table 1. All of the fans are active secondary fans forming at the downstream termini of fanhead trenches passing through abandoned Pleistocene surfaces (Fig. 1). Fan deposits are predominately fine grained (sand through clay fraction) and boulders are uncommon, because the fan apices are not situated at the mountain fronts and a large proportion of sediment is supplied from weathered Pleistocene soils (Fig. 1 and Table 1).

Rainfall at all five sites results from three types of weather systems: (1) areally extensive winter westerlies of relatively long duration but low intensity; (2) localized summer monsoonal thunderstorms of short duration but high intensity; and (3) occasional autumn tropical storms of long duration and high intensity. Stronger monsoonal precipitation accounts for the southeasterly increase in average precipitation between the study areas. The highest discharges on the fans result from the high-intensity storms in the summer and fall, but Tiger Wash Fan drains an exceptionally large area and may also respond to regional winter storms. Significant flows on the alluvial fans last for only a few hours after periods of heavy precipitation.

SURFICIAL PROCESSES

Detailed studies of surficial processes have been completed on Cottonwood Fan and White Tank Fan (Field, 1994), Wild Burro Fan (House et al., 1991 and 1992), and Tiger Wash Fan (Alluvial Fan, 1992). There is no evidence of debris-flow activity on the fans. Modern rates of weathering in southern Arizona are insufficient to produce an abundant supply of sediment for large debris flows (Melton, 1965). Secondary fans throughout southern Arizona are dominated by fluvial processes associated with discontinuous ephemeral streams, a distinctive stream pattern characterized by alternating erosional and depositional reaches (Fig. 2). Overland flow is generated along the margins of sheetflood zones and aggrading channels. Channel backfilling caused by the headward migration of aggradational reaches can transform a deep channel into an area of sheetflooding over periods of tens to hundreds of years (Packard, 1974; Waters and Field, 1986).

EVIDENCE OF CHANNEL MIGRATION

Historical aerial photographs were used to document recent channel changes on the five fans. Field reconnaissance identified surficial features associated with the changes and confirmed the presence of previously abandoned channels observed on the oldest photographs. Subsurface trench data from Cottonwood Fan, White Tank Fan, and Tiger Wash Fan further established the processes and frequency of channel migration. Of primary interest here are significant channel diversions responsible for major shifts in the locus of deposition, since these are the changes that produce the greatest surface modification and pose the greatest hazard. Minor diversions easily discerned on the photos are also discussed, but it is not practical or necessary to point out every change visible on the aerial photographs.

In the following survey of each fan, channel changes occurring during the photographic record are described first, followed by a discussion of older abandoned reaches and stratigraphic cross sections. Finally, a brief note is made concerning the likely location(s) of the next diversion. The range of dates mentioned in the text for channel diversions are sometimes closer approximations than reflected by the photographs presented here. In these cases, additional information has been garnered from aerial photographs of too low a quality to reproduce.

Ruelas Fan. A significant channel diversion occurred on Ruelas Fan between 1949 and 1956 (Fig. 3). In 1949 the main channel followed the course a-b-c. The majority of flow now runs down a channel (b-d) that was much narrower and barely visible on the 1936 photo. Boulders, showing signs of recent transport and found along the banks of the new channel (b-d), indicate that the diversion occurred during a large flood. No information is available on possible causative storms during this seven-year period. Although segment b-c has not been entirely abandoned, decreased discharge has led to vegetation growth (gray tone) in the channel and floodwaters now occupy only a small portion of the earlier channel (Fig. 3b). The main channel at the fan apex (a) shifted slightly southward during the same time period, probably a result of the same flood.

Two abandoned reaches are present on the 1936 photo (Fig. 3a). Flow to the sheetflood zone (e) at the toe of the fan was diverted into channel reach b-c. Cactus and small brush grow in the abandoned channel on the southern margin of the fan (a-f) and the decrease in discharge and sediment supply to this reach has caused minor incision of the old channel bed (Fig. 4).

The channel marked by the arrow in Figure 3b has a lower bed elevation than the main channel (a-b). During the next extreme discharge this channel could capture significant amounts of the flow and reactivate portions of channel a-f.

Wild Burro Fan. No major channel changes have occurred on Wild Burro Fan since 1936, despite an extreme flood in 1988 (Fig. 5). The recurrence interval of the 1988 flood was possibly much greater than 100 years, because it was the largest flood reconstructed during a paleoflood study of the drainage basin (House, 1991). Surface modifications resulting from the 1988 flood include: 1) deposition of fresh sand sheets (white tone) just beyond the banks of the main channel near points a,b, and c; 2) noticeable channel widening at points d,e, and g; 3) continued growth of the meander bend (f) that started forming after 1936. Flow crossing the sand sheets became reconfined downstream into narrow channels (Fig. 5), one of which was noticeably widened (d). The sand sheet near point c is slightly upstream of a similar sand sheet visible on the 1936 photo, and is evidence for the upstream migration of a sheetflood zone. The only other visible change on the aerial photographs is the appearance of channel segment f-g between 1949 and 1956 in the position of what was a much smaller channel.

At some point prior to 1936, floods followed two primary flow paths (a-c-h-i and a-c-f-j). Subsequent diversion of flow into channel segment h-g forced the abandonment of reaches h-i and f-j. While floodwaters still frequently enter reach h-i, segment f-j, with a bed elevation 70 cm higher than the active channel, receives very little flow and the channel has become increasingly less distinct on the aerial photographs (Fig. 5b).

The absence of large abandoned channels on Wild Burro Fan suggest that no recent shifts in the locus of deposition have occurred near the fan apex (a). The present medial position of the main channel (a-c) may be particularly stable, as high discharges are less likely to be deflected into alternate flow paths. Flow during the 1988 flood did enter three secondary reaches (a-k, b-l, and b-m) that might eventually become the next main channel.

Cottonwood Fan. Channel modifications on Cottonwood Fan since 1936, although numerous, have been restricted to the distal ends of the two main channels (a-b and a-c-d) (Fig. 6). Between 1936 and 1949, channel segment d-e started forming in a swale on the fan surface beyond the meander bend (d), capturing flow that previously entered channel reach d-f. The bed of the new channel (d-e) is presently 40 cm below the old channel bed (d-f).

Along the other main channel (a-b), widening of reach b-i between 1936 and 1949 accompanied the appearance of segment g-h in the position of what was a barely visible channel. In 1949, segment g-h appears to have been fed by overbank flow only, while the majority of discharge continued down reach b-i-j. The construction of a berm at point k between 1949 and 1956 diverted flow into reach g-h by forming a new extension of the channel (k-g)(see Fig. 6c). Although some flow returned to its original course (b-i-j) after the berm was breached between 1960 and 1972, the new channel (k-g-h) remained active. The Central Arizona Aqueduct built in the late 1980's has again diverted all of the flow into channel k-g-h (Fig. 6d).

A well defined distributary channel (i-o) at the terminus of the eastern channel (a-b) was probably still active in 1936 (Fig. 6a). The channel was abandoned when flow was diverted into a portion of the channel (p-j) flowing along the eastern margin of the fan (Fig. 6d).

The main channel along the western margin of the fan (a-c-d) was active until after 1960, but should now be considered abandoned because 1) trees along the banks of the lower channel (d-f) have disappeared, 2) vegetation (gray tone) is growing in the upper channel (a-c), 3) the bed of the upper channel (a-c) is being incised, and 4) the bed of the active channel (a-b) is presently 70 cm lower than segment a-c at the fan apex (a) (Fig. 6). A large flood in 1962, documented by Rostvedt and others (1968), was probably responsible for this abandonment and the breach in the berm (k). No major channel adjustments occurred along channel a-b in response to either this diversion or a moderate flood in 1990.

An old channel system (l-m), located on the medial line of the fan, was abandoned before 1936. The development of segment a-c may have caused the abandonment of this channel system by diverting flow into what was previously a channel draining the western margin of the fan (n-d).

Stratigraphic cross-sections of Cottonwood Fan expose several large channels associated with buried archaeological sites (Fig. 7; Field, 1985). The main channel was not in its present position 600 years ago as evidenced by the fire hearth (Fig. 7), so at least one major diversion has occurred since that time. The numerous buried channels and the abandoned channel system (l-m) on the surface suggest that the main channel has shifted more than once during the past 600 years.

The broad shallow swales (s) on the lower fan convey floodwaters during extreme events and are the potential sites of future channels.

White Tank Fan. Dramatic surface modifications occurred between 1942 and 1956 on White Tank Fan (Fig. 8). Flooding was reported on parts of the White Tank Mountains piedmont during a large tropical storm in 1951 (Kangieser, 1969). An extreme flood with an estimated recurrence interval greater than 100 years occurred during the past 100 years in the White Tank Fan drainage basin (Alluvial Fan, 1992), probably in 1951. On the 1942 photo, much of the fan surface appears inactive with the majority of flow following the fan's southern margin (a-b-c). During the 1951 flood the main channel (a-b) was breached at the bend (a), transforming the narrow reach a-d into the present main channel. Additional changes resulting from the flood include: 1) widening of numerous channel reaches and activation of large portions of the fan surface (Fig. 8b); 2) rerouting of flow towards the center of the fan (a-d-e/f); 3) incorporation of several minor dendritic drainages (g, h, and i) on the lower fan into the main flow path (Fig. 8a). Subsequent floods have produced no discernible modifications of the fan surface except for the transformation of a road into a narrow channel (k-l). Vegetation growth since 1951 has highlighted the northward shift in the main channel (a-d) and has obscured less active flow paths on the lower fan (j)(Fig. 8c).

Reference really is superceded - Published by Durrenberger (State climatologist) in 1978

Although no large abandoned channels are present on the surface, a stratigraphic cross section of White Tank Fan reveals that earlier channels have overtopped their banks after being partially backfilled (Fig. 9). Channel migration on White Tank Fan is further substantiated by the presence of former channels directly below present-day channel bars (Fig. 9).

The fan surface is slightly lower to the south, so future floods may reoccupy the earlier main channel (a-b-c).

Tiger Wash Fan. No significant channel changes occurred on Tiger Wash Fan during the photographic record extending from 1953 to 1988, despite a gauged flood with a recurrence interval greater than 10 years on August 20, 1970 (Alluvial Fan, 1992). Some channels abandoned before 1953 are, however, evident on the 1979 photo (Fig. 10). Faint traces of old channels are visible along the medial line of the fan (a-b). A younger abandoned channel (d-e) near the terminus of the present main channel (a-c-d) was active earlier this century, as historical tin cans are found scattered on the surface. Flow was diverted into channel reach d-f before 1953, creating a bend in the present channel at point d. Another bend (c) formed in the main channel when flow occupied a portion of a preexisting piedmont channel (g-c-d).

A headward advancing gully system along the eastern margin of the fan (h-i) receives overbank flow from the fan apex (a) during moderate floods, and will ultimately divert the majority of flow from the present main channel (a-c-d).
A topographic cross section of the fan reveals that this gully system is at a lower elevation than the main channel (a-c-d) and the abandoned channel system along the medial radial line of the fan (a-b)(Fig. 11).

FREQUENCY OF CHANNEL MIGRATION

Significant channel diversions occurred on Ruelas Fan, White Tank Fan, and Cottonwood Fan during the photographic record, with those on Ruelas Fan and White Tank Fan resulting in dramatic channel modifications. However, since no fan experienced two major diversions, the frequency of channel migration on the fans must be greater than 50 years. Stratigraphic and archaeological evidence from Cottonwood Fan indicate that major diversions occur at least once every 600 years (Fig. 7; Field, 1985). Several lines of evidence suggest that the actual frequency of channel migration is less than 600 years: 1) the original channel form of several abandoned reaches is well preserved; 2) vegetation in some abandoned reaches has probably not been growing for much longer than 100 years (Fig. 4a); 3) channel fill in the abandoned reaches still display well preserved sedimentary structures while lacking even incipient soil development. The abundance of abandoned reaches on Ruelas Fan may reflect a higher frequency of channel migration than on the other fans.

Tiger Wash Fan with the largest drainage basin has been the most stable. The fans with the smallest catchments, Ruelas Fan and White Tank Fan, have experienced the most dramatic changes. Some minor changes have occurred on all five fans this century, demonstrating that the fans are dynamic and prone to channel migration.

PROCESSES OF CHANNEL MIGRATION

Based on the examination of aerial photographs and field reconnaissance of new and abandoned channel reaches, a model is presented that depicts the processes preceding, accompanying, and following channel diversions on the five fans (Fig. 12). The following observations repeatedly made during the study must be incorporated into the model: 1) five distinctive channel morphologies are associated with varying stages of channel development (Fig. 13); 2) channel diversions occur along channel bends and/or where channel banks are low; 3) "new" channels follow preexisting channels and depressions; 4) the bed of the new channel is lower than the abandoned reach; and 5) large floods do not always precipitate diversions. The last observation is of particular interest since small to moderate floods on fluvial fans in other regions have caused significant channel diversions (Griffiths and McSaveney, 1986; Kesel and Lowe, 1987; Wells and Dorr, 1987). The model presented below demonstrates that certain stages of channel development are stable during extreme hydrological events while other stages of development are unstable even during small floods.

Numerous narrow, shallow, v-shaped channels drain inactive portions of the fan surfaces (Fig. 13a) and are sometimes part of an incipient dendritic drainage system, as exemplified at the toe of White Tank Fan (Fig. 8a). Portions of these erosional channels occasionally approach the much larger, aggrading, distributary channels connected to the entire drainage basin (Fig. 12a). As observed repeatedly on the aerial photographs, the erosional channels are occasionally incorporated into the main drainage net during the course of a flood (Figs. 8 and 12b). A channel incorporated into the distributary network undergoes a rapid transformation in response to the dramatic increase in discharge (Fig. 13b). The old and new segments of the main channel, joined at the point of diversion, have distinctive morphologies (Fig. 12b). Channel banks are low, rounded, and vegetated upstream of the diversion point, while downstream the banks are vertical (Fig. 14). Deepening and widening of the new channel reach continues as floods larger than the diversion event pass through the reach (Figs. 12c and 13c). At this stage of channel development a diversion is unlikely, because the channel is adjusted to convey large floods.

As the frequency of floods large enough to continue channel widening decreases, smaller floods will begin to modify the channel's morphology. In channels with high width:depth ratios (Figs. 12c and 13c), transmission losses are maximized, and only the largest floods can transport the imposed sediment load through the channel. Ephemeral streams characteristically aggrade during low flows because streamflows infiltrate into the channel before reaching the channel mouth (Bull, 1979). Decreases in flow velocities and increases in hydraulic roughness also accompany increases in the width:depth ratio of channels, further promoting channel aggradation. In the absence of large floods to flush accumulating sediments through the channel reach, a succession of small floods will reduce the height of the channel banks by raising the bed elevation (Fig. 13d).

As the bank heights decrease, floods begin to breach the channel banks, generating overbank flow (Figs. 9 and 12d). The carrying capacity of the channel is further reduced by the slumping, rounding, and vegetation of the stabilized channel banks (Figs. 13c and 14). With continued aggradation and bank stabilization, the magnitude of the smallest flood capable of producing overbank flow decreases.

Overbank flow is the most important agent responsible for channel migration on the alluvial fans. Since most of the sediment on alluvial fans is transported near the bed, overbank flows are relatively sediment free and thus capable of erosion (Hooke and Rohrer, 1979). Sediment that is carried by the overbank flows is deposited at the channel margins in response to the flow expansion, as illustrated by the sand sheets deposited during the 1988 flood on Wild Burro Fan (Fig. 5b). Previously abandoned channels are lower than the surrounding inactive surface, so overbank flow preferentially enters these reaches and erodes the old channel bed (Figs. 4, 12d, and 13e). Although initially expanding, overbank flow tends to recollect in preexisting channels like on Wild Burro Fan during the 1988 flood (Fig. 5b). Overbank flow deepens and enlarges small channels heading on the fan, and generates headward erosion directed towards the aggrading active channel (Figs. 12d and 15). When a channel is extended back to the aggrading reach, stream capture will occur, because the eroding channel is generally lower and/or steeper than the backfilled channel (Figs. 12e and 15). Stream capture caused by the headward erosion of a side bank, as opposed to the upstream lengthening of a channel, produces a new channel reach with two distinct segments joined at a sharp bend (Figs. 12d-e). The downstream segment occupies a portion of a preexisting channel headed on the fan or piedmont, as observed on Cottonwood Fan and Tiger Wash Fan (Figs. 6 and 10). Previously abandoned channels can also become reactivated through the incision of the old channel bed.

Although local runoff will cause some erosion, overbank flow accelerates and directs the erosion process. The sites of greatest overbank flow (i.e., low banks and outer bends) are the most common sites of stream capture. If headward erosion of the capturing channel was due exclusively to runoff generated by on-fan precipitation, an idea proposed by Denny (1967), then diversions should occur just as frequently on the insides of meander bends or where channel banks are high. The fact that this does not happen attests to the influence of overbank flow on channel migration. The capturing channel in this process of channel migration is in some respects a passive partner with the main channel dictating where and how rapidly headward erosion will occur.

The above model assumes that small channels are present on inactive portions of the fan surface, without addressing the question of how they initially appear. Alluvial-fan channels can form 1) from local runoff (Denny, 1967), 2) on oversteepened slopes (Hooke, 1967), 3) when geomorphological thresholds are crossed (Schumm, 1977), 4) in natural lows and depressions (Kesseli and Beaty, 1959), 5) along roads (Fig. 8), and 6) even along hippopotamus trails (McCarthy et al., 1992). In addition, overbank flow alone can erode broad swales that emanate from the main channel (Schumann, 1989). With the exception of the hippopotamus trails, all of these processes are probably operating on the Arizona fans.

FACTORS CONTROLLING THE RATE OF THE MIGRATION PROCESS

The rate at which the channel-migration process (Fig. 12) progresses depends on several factors, including: 1) the initial depth of the main channel; 2) the magnitude of the largest flood occurring during the active phase of the channel (Figs. 13b-d); 3) the sequencing of flood magnitudes; 4) the location of small on-fan channels; and 5) the composition of channel-bank sediments. The depth to which a new channel is eroded will determine in part the amount of aggradation required before overbank flooding is initiated. In some instances, the new channel is not cut below the original reach, and flow continues down both paths (e.g, Wild Burro Fan reaches h-g and h-i; Fig. 5). Elsewhere, a period of aggradation is necessary before significant overbank flow can occur. A truly catastrophic flood flowing down a deep main channel (Figs. 13b-c) could conceivably overwhelm the existing channel's capacity and produce enough overbank flow to precipitate a channel diversion. However, aggrading channel reaches (Fig. 13d) elsewhere on the fan would be the more likely sites of a channel diversion.

A series of large floods during the early stages of channel development can potentially prolong the diversion process by periodically flushing sediment out of a channel reach before overbank flow commences. In contrast, continuous aggradation resulting from an uninterrupted sequence of small sediment-charged flows will eventually lead to overbank flooding during even the smallest discharges. Within this context, diversions during small floods on humid-region alluvial fans (Griffiths and McSaveney, 1986; Kesel and Lowe, 1987; Wells and Dorr, 1987) should not be considered anomalous events. In arid and semi-arid climates, where record discharges can be hundreds of times larger than the mean annual discharge (Graf, 1988), an uninterrupted sequence of small floods is unlikely. Instead, aggradation resulting from a series of small floods increases the effectiveness of extreme events and hastens the diversion process.

Overbank flow will not produce channel diversions if there are no nearby channels receiving the flow. As parts of discontinuous ephemeral stream systems, aggrading reaches on the five alluvial fans migrate headward, and overbank flow is generated at different points along the channel through time. Eventually the aggrading portion of the main channel will approach an area where an on-fan channel can capture flow. For example, the incorporation of reach c-d into the main flow path on Wild Burro Fan was made possible by the upstream migration of sheetflooding (sand sheets) to point c between 1936 and 1988 (Fig. 5). Overbank flow emanating from the sand sheet in 1936 did not enter reach c-d and therefore could not precipitate the change.

Sandy channel banks accelerate the migration process. Channels with sandy banks tend to be shallow, so overbank flows begin after much less aggradation. Channel diversions are also possible on alluvial fans if the main channel is widened up to the head or banks of a small channel heading on the fan. Bank erosion is fastest along ephemeral streams with sandy banks (Slezak-Pearthree and Baker, 1987), and increases in channel width of over 1 km can occur during a single flood along large ephemeral streams (Graf, 1988). Overbank flow is essential in precipitating channel diversions along ephemeral streams with silt and clay-rich banks, because they are not prone to rapid widening (Schumann, 1989). Small aggrading flows become increasingly more important where channel banks are stable, because the chances of precipitating channel diversions through bank widening are low.

LITERATURE REVIEW OF CHANNEL MIGRATION ON ALLUVIAL FANS

Past channel diversions on alluvial fans worldwide have been documented numerous times through direct observations, surficial evidence, historical aerial photographs, and stratigraphic profiles (Table 2). Much of the evidence is fragmentary, sometimes recording diversion events that occurred thousands of years ago, but taken together a clearer picture emerges of the similarities and differences in channel migration on fans of different types. Channel avulsion is a term widely held synonymous with channel migration, but its usage here is limited to a process described by Beaty (1963) where the rapid blockage of a channel by debris dams forces the rerouting of flow into a new course. Channel avulsions are the most common process of channel migration on debris-flow dominated fans. Debris flows that massively overwhelm their channels are capable of activating large portions of the fan surface and completely altering the preexisting fan topography (Pack, 1923; Chawner, 1935; Kochel and Johnson, 1984). On fluvial fans, several years of channel aggradation typically precede diversions (Griffiths and McSaveney, 1986; Kesel and Lowe, 1987; Wells and Dorr, 1987), in a process referred to here as stream capture. Only one account exists of a channel avulsion due to stream flow alone (Eckis, 1928). The model of stream capture for the Arizona fans (Fig. 12) is similar to models constructed for other fluvial fans (Wells and Dorr, 1987; McCarthy et al., 1992) and ephemeral streams (Schumann, 1989), and is consistent with observations from other fluvial fans (Griffiths and McSaveney, 1986; Kesel and Lowe, 1987).

Although channel migration occurs by various processes, some aspects of channel migration recur, regardless of fan type or climate. Extreme discharges are usually responsible for precipitating diversions, especially on debris-flow fans, but they do not always result in significant channel shifting (Table 3). Low channel banks are not necessarily a preferred location for channel diversions on debris-flow fans, because thick deposits can backfill channels during a single flood (Chawner, 1935; Sharp and Nobles, 1953; Kesseli and Beaty, 1959; Scott, 1971; Morton and Cambell, 1974). However, channel bends promote debris damming (Beaty, 1963), and are common sites of channel diversions on debris-flow fans and fluvial fans alike. The position of channels following a diversion event commonly follow preexisting channels or depressions (Table 2). In a few instances an entirely new channel is reported to have formed (Table 2), but there is insufficient data presented in these works to substantiate these claims. After flow is diverted into a preexisting channel, dramatic changes in channel width (Figs. 3, 5, and 8) and depth (Kesseli and Beaty, 1959; Morton and Cambell, 1974) can take place that render the original channel unrecognizable. Only when an entire fan surface is modified by rare catastrophic floods (Kochel and Johnson, 1984; Blair, 1987; Wells and Harvey, 1987) is it possible to assume that entirely new channels have developed.

Very little information is available on the frequency of channel migration on alluvial fans. Occasionally, two or more diversions have occurred within the historical record of a fan (Gole and Chitale, 1966; Desloges and Gardner, 1981; Whitehouse and McSaveney, 1990), but the time span between two events does not necessarily represent an accurate long-term frequency. The frequency of debris flows is known in a few localities (Kochel and Johnson, 1984; Hubert and Filipov, 1989; Orme, 1989; Lips and Wieczorek, 1990) and represents a minimum frequency of channel migration, as not all debris flows are associated with diversions.

The frequency of channel migration is highly variable between alluvial fans, even within the same climatic setting (Table 2). The fans with the most frequent (Wells and Dorr, 1987; Whitehouse and McSaveney, 1990) and infrequent (Kochel and Johnson, 1984) rates of diversion are found in areas of high annual precipitation. This contrast may reflect the opposing influences of frequent discharges that speed the diversion process and heavily vegetated drainages that hinder sediment delivery and increase channel stability. In desert regions, the frequency of debris flows, and therefore diversions, is highest on fans with smaller typically steeper drainage basins (Kesseli and Beaty, 1959). The frequency of diversions on the fluvial fans in Arizona also appears to be higher on fans with smaller catchments.

DISCUSSION

Since the landmark paper by Wolman and Miller (1960), geomorphologists have debated the relative importance of small-and large-scale geomorphological events on landscape modification. Large infrequent floods are widely regarded as the effective geomorphological agents of change in arid climates (Wolman and Miller, 1960; Baker, 1977; Wolman and Gerson, 1978; Kochel, 1988). Although large infrequent floods result in most, if not all, channel diversions on arid-region alluvial fans, the action of small flows accelerate the migration process.

Without small aggrading flows on fluvial fans, significantly less overbank flow would be produced, and the effectiveness of the large floods would be diminished. The lack of surficial features (e.g., abandoned channels) on a fan surface formed by high-frequency storms does not necessarily mean that they are ineffective agents of change. Wolman and Miller (1960) recognized the importance of small floods on sediment transport. This paper demonstrates their role in modifying the surface of fluvially dominated alluvial fans.

Concern about alluvial-fan flooding is increasing with the rapid urbanization of the southwestern United States. In recognition of the potential hazards associated with channel migration, the Federal Emergency Management Agency has devised a stochastic hydraulic procedure for delineating flood-hazard zones on alluvial fans (Flood Insurance, 1985; Fan, 1990). The method is based on the assumption that channel position during each flood is random and, as such, every point on the fan is subject to flooding (Dawdy, 1979). While the potential for channel migration on alluvial fans during any 100-year planning period undeniably exists, this paper demonstrates that stochastic procedures are not valid for evaluating the possible locations of new channels. New channels on alluvial fans usually follow preexisting channels or depressions (Table 2), and large floods do not always result in diversions (Table 3). Stochastic procedures appear safely conservative, because they consider an entire fan subject to flooding. However, hazards along existing channels are severely underestimated when these techniques are used (O'Brien and Fullerton, 1990; House et al., 1992; O'Brien and Fuller, 1993).

Site-specific assessments are perhaps the most promising method of determining the likely locations of diversions. Although several channels may be present on a fan at any given time, the probable sites of a diversion can be constrained through hydraulic modeling of several reaches (Richards et al., 1987) and by identifying points along the main channel prone to abandonment (i.e., low channel banks and bends). The most likely paths of future channels have been identified on the five Arizona fans based on the positions of secondary channels in relation to meander bends and aggrading reaches along the main channels (see above). Follow up studies over a number of years will establish the accuracy of these predictions and the value of field studies for identifying future channel locations.

Flood hazard assessments should not concentrate solely on large floods. Headward migration of an aggrading reach due to a series of small floods will alter the likely location of a diversion event on fluvial fans. Such changes will be missed if hazard assessments are updated only after large floods. Constant monitoring of fans is necessary to avoid unanticipated changes brought about by the action of seemingly ineffective small floods.

SUMMARY AND CONCLUSIONS

A model has been presented which characterizes the processes of channel migration on fluvially dominated alluvial fans in southern Arizona (Fig. 12). After a period of bank widening along a new channel reach, aggradation begins due to small floods that are unable to transport the imposed sediment load through the stream system. The resulting decrease in bank height leads to the generation of overbank flow which accelerates and directs the headward erosion of secondary channels. Stream capture ultimately occurs.

The model is consistent with processes operating on fluvial fans in different climates and explains how small floods, under certain circumstances, can complete a diversion while large floods often do not precipitate changes. Small floods, in general, do not precipitate diversions, but they do accelerate the migration process culminated by large floods. The role of both small and large floods on channel migration suggests that the debate on geomorphological effectiveness should focus on how different scales of geomorphological events work in concert to modify landscapes rather than on which scale of events is the most important agent of change.

Although channel diversions may occur suddenly, channel migration on alluvial fans should no longer be regarded as an unpredictable phenomenon, since new channels almost invariably follow preexisting flow paths. A careful analysis of all existing flow paths in relationship to potentially unstable reaches along the active channel may help pinpoint the location of future channel positions. The frequency of channel diversions on alluvial fans is still poorly understood and should be the focus of future studies.

REFERENCES CITED

Alluvial fan data collection and monitoring study, 1992, Flood Control District of Maricopa County, Phoenix, Arizona.

Antsey, R.L., 1965, Physical characteristics of alluvial fans: U.S. Army Natick Laboratories, Technical Report ES-20, 109 p.

Baker, V.R., 1977, Stream-channel response to floods, with examples from central Texas: Geological Society of America Bulletin, v. 88, p. 1057-1071

Beaty, C.B., 1963, Origin of alluvial fans, White Mountains, California and Nevada: Annals of Association American Geographers, v. 53, p. 516-535.

Beaty, C.B., 1970, Age and estimated rate of accumulation of an alluvial fan, White Mountains, California: American Journal of Science, v. 268, p. 50-77.

Beaty, C.B., 1974, Debris flows, alluvial fans and a revitalized catastrophism: Zeitschrift Geomorphologie Supplementband, no. 21, p. 39-51.

Beaty, C.B., 1990, Anatomy of a White Mountains debris-flow --the making of an alluvial fan, in Rachocki, A.H., and Church, M., eds., Alluvial fans: a field approach: New York, John Wiley and Sons, p. 69-89.

Beaumont, P., and Oberlander, T.M., 1971, Observations on stream discharge and competence at Mosaic Canyon, Death Valley, California: Geological Society of America Bulletin, v. 82, p. 1695-1698.

Blair, T.C., 1987, Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park, Colorado: Journal of Sedimentary Petrology, v. 57, p. 1-18.

Blair, T.C., and McPherson, J.G., 1992, The Trollheim alluvial fan and facies model revisited: Geological Society of America Bulletin, v. 104, p. 762-769.

Bowman, D., 1978, Determination of intersection points within a telescopic alluvial fan complex: Earth Surface Processes, v. 3, p. 265-276.

Bryan, K., 1922, Erosion and sedimentation in the Papago country: U.S. Geological Survey Bulletin, 730-B, p. 19-90.

Bull, W.B., 1979, Threshold of critical power in streams: Geological Society of America Bulletin, v.90, p. 453-464.

Chawner, W.D., 1935, Alluvial fan flooding, the Montrose, California flood of 1934: Geographical Review, v. 25, p. 255-263.

Conway, W.M., 1893, Exploration in the Mustagh Mountains: Geography Journal, v. 2, p. 289-303.

Davis, W.M., 1898, Physical geography: Boston, Massachusetts, Ginn and Company Publishers, 428 p.

Dawdy, D.R., 1979, Flood frequency estimates on alluvial fans: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 105, p. 1407-1413.

Denny, C.S., 1965, Alluvial fans in the Death Valley region, California and Nevada: U.S. Geological Survey Professional Paper 466, 62 p.

Denny, C.S., 1967, Fans and pediments: American Journal of Science, v. 265, p. 81-105.

Desloges, J., and Gardner, J., 1981, Recent chronology of an alpine alluvial fan in southwestern Alberta: Albertan Geographer, v. 17, p. 1-18.

Drew, F., 1873, Alluvial and lacustrine deposits and glacial records of the Upper Indus basin: Quarterly Journal Geological Society of London, v. 29, p. 441-471.

Eckis, R., 1928, Alluvial fans in the Cucamonga district, southern California: Journal of Geology, v. 36, p. 224-247.

Fan: An alluvial fan flooding computer program, 1990: Washington, D.C., Federal Emergency Management Agency.

Field, J.J., 1985, Depositional facies and Hohokam settlement patterns on Holocene alluvial fans, N. Tucson Basin, AZ. [M.S. prepublication manuscript]: University of Arizona, Tucson, 68 p.

Field, J.J., 1994, Surficial processes, channel change, and geological methods of flood hazard assessment on fluvially dominated alluvial fans in Arizona [Ph.D. thesis]: Tucson, Arizona, University of Arizona, 258 p.

Flood insurance study: Guidelines and specifications for study contractors, 1985: Washington, D.C., Federal Emergency Management Agency, FEMA-37.

French, R.H., 1992, Preferred directions of flow on alluvial fans: Journal of Hydraulic Engineering, v. 118, p. 1002-1013.

Gole, C.V., and Chitale, S.V., 1966, Inland delta building activity of the Kosi River: American Society of Civil Engineers, Journal of the Hydraulics Division, v. 92, p. 111-126.

Graf, W.L., 1988, Fluvial processes in dryland rivers: New York, Springer-Verlag, 346 p.

Griffiths, G.A., and McSaveney, M.J., 1986, Sedimentation and river containment on Waitangitaona alluvial fan - South Westland, New Zealand: Zeitschrift fur Geomorphologie N.F., v. 30, p. 215-230.

Gundlach, D.L., 1978, Approaches to "plain" problems: Water Spectrum, v. 10, p. 33-37.

Hack, J.T., and Goodlett, J.C., 1960, Geomorphology and forest ecology of a mountain region in the Central Appalachians: U.S. Geological Survey Professional Paper 347, 66 p.

Harvey, A.M., 1984, Geomorphological response to an extreme flood: a case from southeast Spain: Earth Surface Processes and Landforms, v. 9, p. 267-279.

Hooke, R. LeB., 1967, Processes on arid-region alluvial fans: Journal of Geology, v. 75, p. 438-460.

Hooke, R. LeB., and Rohrer, W.L., 1979, Geometry of alluvial fans: effect of discharge and sediment size: Earth Surface Processes, v. 4, p. 147-166.

House, P.K., 1991, Paleoflood hydrology of the principal canyons of the Southern Tortolita Mountains, Southeastern Arizona [M.S. prepublication manuscript]: Tucson, Arizona, University of Arizona, 21 p.

House, P.K., Pearthree, P.A., and Vincent, K.R., 1991, Flow patterns, flow hydraulics, and flood-hazard implications of a recent extreme alluvial-fan flood in southern Arizona [abs.]: Geological Society of America Abstracts with Programs, v. 23.

House, P.K., Pearthree, P.A., and Vincent, K.R., 1992, Geological insights into deficiencies in federal procedures for flood hazard assessment on alluvial fans [abs.]: Geological Society of America Abstracts with Programs, v. 24.

Hubert, J.F., and Filipov, A.J., 1989, Debris-flow deposits in alluvial fans on the west flank of the White Mountains, Owens Valley, California, U.S.A.: Sedimentary Geology, v. 61, p. 177-205.

Hunt, C.B., Averitt, P., and Miller, R.L., 1953, Geology and geography of the Henry mountains region Utah: U.S. Geological Survey Professional Paper 228, 234 p.

Kangieser, P.C., 1969, Major rainstorms and snowstorms in Arizona 1897-1969 [unpublished report]: Tempe, Arizona, Arizona Weather Bureau, 25 p.

Kellerhals, R., and Church, M., 1990, Hazard management on fans, with examples from British Columbia, in Rachocki, A.H., and Church, M., eds., Alluvial fans: a field approach: New York, John Wiley and Sons, p. 335-354.

Kesel, R.H., 1985, Alluvial fan systems in a wet-tropical environment, Costa Rica: National Geographic Research, v. 1, p. 450-469.

Kesel, R.H., and Lowe, D.R., 1987, Geomorphology and sedimentology of the Toro Amarillo alluvial fan in a humid tropical environment, Costa Rica: Geografiska Annaler, v. 69A, p. 85-99.

Kesseli, J.E., and Beaty, C.B., 1959, Desert flood conditions in the White Mountains of California and Nevada: U.S. Army Environmental Research Division, Technical Report EP-108, 107 p.

Kochel, R.C., 1988, Geomorphological impact on large floods: review and new perspectives on magnitude and frequency. In Baker, V.R., Kochel, R.C., and Patton, P.C. (eds), Flood Geomorphology, Wiley and Sons: New York, p. 169-188.

Kochel, R.C., 1990, Humid fans of the Appalachian Mountains, in Rachocki, A.H., and Church, M., eds., Alluvial fans: a field approach: New York, John Wiley and Sons, p. 109-129.

Kochel, R.C., and R.A. Johnson, 1984, Geomorphology and sedimentology of humid-temperate alluvial fans, Central Virginia, in Koster, E.H. and Steel, R.J., eds., Sedimentology of Gravels and Conglomerates: Canadian Society of Petroleum Geologists Memoir 10, p. 109-122.

Kostaschuk, R.A., MacDonald, G.M., and Putnam, P.E., 1986, Depositional process and alluvial fan-drainage basin morphometric relationships near Banff, Alberta, Canada: Earth Surface Processes and Landforms, v. 11, p. 471-484.

Leggett, R.F., Brown, R.J.E., and Johnston, G.H., 1966, Alluvial fan formation near Aklavik, Northwest Territories, Canada: Geological Society of America Bulletin, v. 77, p. p. 15-30.

Lips, E.W., and Wieczorek, G.F., 1990, Recurrence of debris flows on an alluvial fan in central Utah, in French, R.H., ed., Hydraulics/Hydrology of Arid Lands: New York, American Society of Civil Engineers, p. 555-560.

McCarthy, T.S., Ellery, W.N., Rogers, K.H., Cairncross, B., and Ellery, K., 1986, The roles of sedimentation and plant growth in changing flow patterns in the Okavango Delta, Botswana: South African Journal of Science, v. 82, p. 579-584.

McCarthy, T.S., Ellery, W.N., Stanistreet, I.G., 1992, Avulsion mechanisms on the Okavango fan, Botswana: the control of a fluvial system by vegetation: Sedimentology, v. 39, p. 779-795.

McGee, W.J., 1897, Sheetflood erosion: Geological Society of America Bulletin, v. 8, p. 87-112.

Melton, M.A., 1965, The geomorphological and paleoclimatic significance of alluvial deposits in southern Arizona: Journal of Geology, v. 73, p. 1-38.

Morton, D.M., and Cambell, R.H., 1974, Spring mudflows at Wrightwood, southern California: Quarterly Journal of Engineering Geology, v. 7, p. 377-384.

O'Brien, J.S., and Fuller, J.E., 1993, Discussion on "Preferred directions of flow on alluvial fans": Journal of Hydraulic Engineering, v. 119, p. 1316-1318.

O'Brien, J.S., and Fullerton, W.T., 1990, Two dimensional modeling of alluvial fan flows, French, R.H., ed., Hydraulics/hydrology of arid lands: New York, American Society of Civil Engineers, p. 262-267.

Ono, Y., 1990, Alluvial fans in Japan and South Korea, in Rachocki, A.H., and Church, M., eds., Alluvial fans: A field approach: New York, John Wiley and Sons, p. 91-107.

Orme, A.R., 1989, The nature and rate of alluvial fan aggradation in a humid temperate environment, northwest Washington: Physical Geography, v. 10, p. 131-146.

Pack, F.J., 1923, Torrential potential of desert waters: Pan-American Geologists, v. 40, p. 349-356.

Packard, F.A., 1974, The hydraulic geometry of a discontinuous ephemeral stream on a bajada near Tucson, Arizona [Ph.D. thesis]: Tucson, Arizona, University of Arizona, 127 p.

Price, W.E., Jr., 1974, Simulation of alluvial fan deposition by a random walk model: Water Resources Research, v. 10, p. 263-274.

Rannie, W.F., 1990, The Portage la Prairie "Floodplain Fan", in Rachocki, A.H., and Church, M., eds., Alluvial fans: a field approach: New York, John Wiley and Sons, p. 179-193.

Rannie, W.F., Thorleieson, L.H., and Teller, J.T., 1989, Holocene evolution of the Assiniboine River paleochannels and Portage la Prairie alluvial fan: Canadian Journal of Earth Sciences, v. 26, p. 1834-1841.

Rapp, A., 1960, Recent development of mountain slopes in Karkevagge and surroundings, northern Scandinavia: Geografiska Annaler, v. 42, p. 65-200.

Ribble, G.E., 1988, Scodie Canyon flash floods of 1984, in Abt, S.R., and Gessler, J., eds., Hydraulic engineering: New York, American Society of Civil Engineers, p. 258-263.

Richards, K.S., Brunsden, D., Jones, D.K.C., and McCraig, M., 1987, Applied fluvial geomorphology: river engineering project appraisal in its geomorphological context, in Richards, K., ed., River channels: environment and process: Basil, Switzerland, Blackwell, p. 352-382.

Rostvedt, J.O., and others, 1968, Summary of floods in the United States during 1962: U.S. Geological Survey Water-Supply Paper 1820.

Ryder, J.M., 1971, The stratigraphy and morphology of paraglacial alluvial fans in south-central British Columbia: Canadian Journal of Earth Sciences, v. 8, p. 279-298.

Schumann, R.R., 1989, Morphology of Red Creek Wyoming, an arid-region anastomosing channel system: Earth Surface Processes and Landforms, V. 14, p. 277-288.

Schumm, S.A., 1977, The fluvial system: New York, John Wiley and Sons, 338 p.

Scott, K.M., 1971, Origin and sedimentology of 1969 debris flows near Glendora, California: U.S. Geological Survey Professional Paper 750-C, p. C242-C247.

Scott, K.M., 1973, Scour and fill in Tujunga Wash - a fanhead valley in urban California: U.S. Geological Survey Professional Paper 732-B, 29 p.

Sharp, R.P., and Nobles, L.H., 1953, Mudflow of 1941 at Wrightwood, southern California:

Geological Society of America Bulletin, v. 64, p. 547-560.

Slezak-Pearthree, M.S., and Baker, V.R., 1987, Channel change along the Rillito Creek system of southeastern Arizona, 1941 through 1983 -- implications for floodplain management: Arizona Bureau of Geology and Mineral Technology, Special Paper 6, 58 p.

Talbot, M.R., and Williams, M.A.J., 1979, Cyclic alluvial fan sedimentation on the flanks of fixed dunes, Janjari, central Niger: Catena, v. 6, p. 69-83.

Trowbridge, A.C., 1911, The terrestrial deposits of Owens Valley, California: Journal of Geology, v. 19, p. 706-747.

Wasson, R.J., 1974, Intersection point deposition on alluvial fans: An Australian example: Geografiska Annaler, v. 56, p. 83-92.

Waters, M.R., and Field, J.J., 1986, Geomorphological analysis of Hohokam settlement patterns on alluvial fans along the western flank of the Tortolita Mountains, Arizona: Geoarchaeology, v. 1, p. 329-345.

Wells, N.A., and Dorr, J.A., Jr., 1987, Shifting of the Kosi River, northern India: Geology, v. 15, p. 204-207.

Wells, S.G., and Harvey, A.M., 1987, Sedimentological and geomorphological variations in storm-generated alluvial fans, Howgill Fells, northwest England: Geological Society of America Bulletin, v. 98, p. 182-198.

Whipple, K.X., and Dunne, T., 1992, The influence of debris-flow rheology on fan morphology, Owens Valley, California: Geological Society of America Bulletin, v. 104, p. 887-900.

Whitehouse, I.E., and McSaveney, M.J., 1990, Geomorphological appraisals for development on two steep active alluvial fans, Mt Cook, New Zealand, in Rachocki, A.H., and Church, M., eds., Alluvial fans: a field approach: New York, John Wiley and Sons, p. 369-384.

Williams, G.P., and Guy, H.P., 1973, Erosional and depositional aspects of Hurricane Camille, in Virginia, 1969: U.S. Geological Survey Professional Paper 804, 80 p.

Winder, C.G., 1965, Alluvial cone construction by alpine mudflow in a humid temperate region: Canadian Journal of Earth Sciences, v. 2, p. 270-277.

Wolman, M.G., and Gerson, R., 1978, Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes, v. 3, p. 189-208.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphological processes. Journal of Geology, v. 68, p. 54-74.

Woolley, R.R., 1946, Cloudburst floods in Utah, 1850-1938: U.S. Geological Survey Water-Supply Paper 994, 128 p.

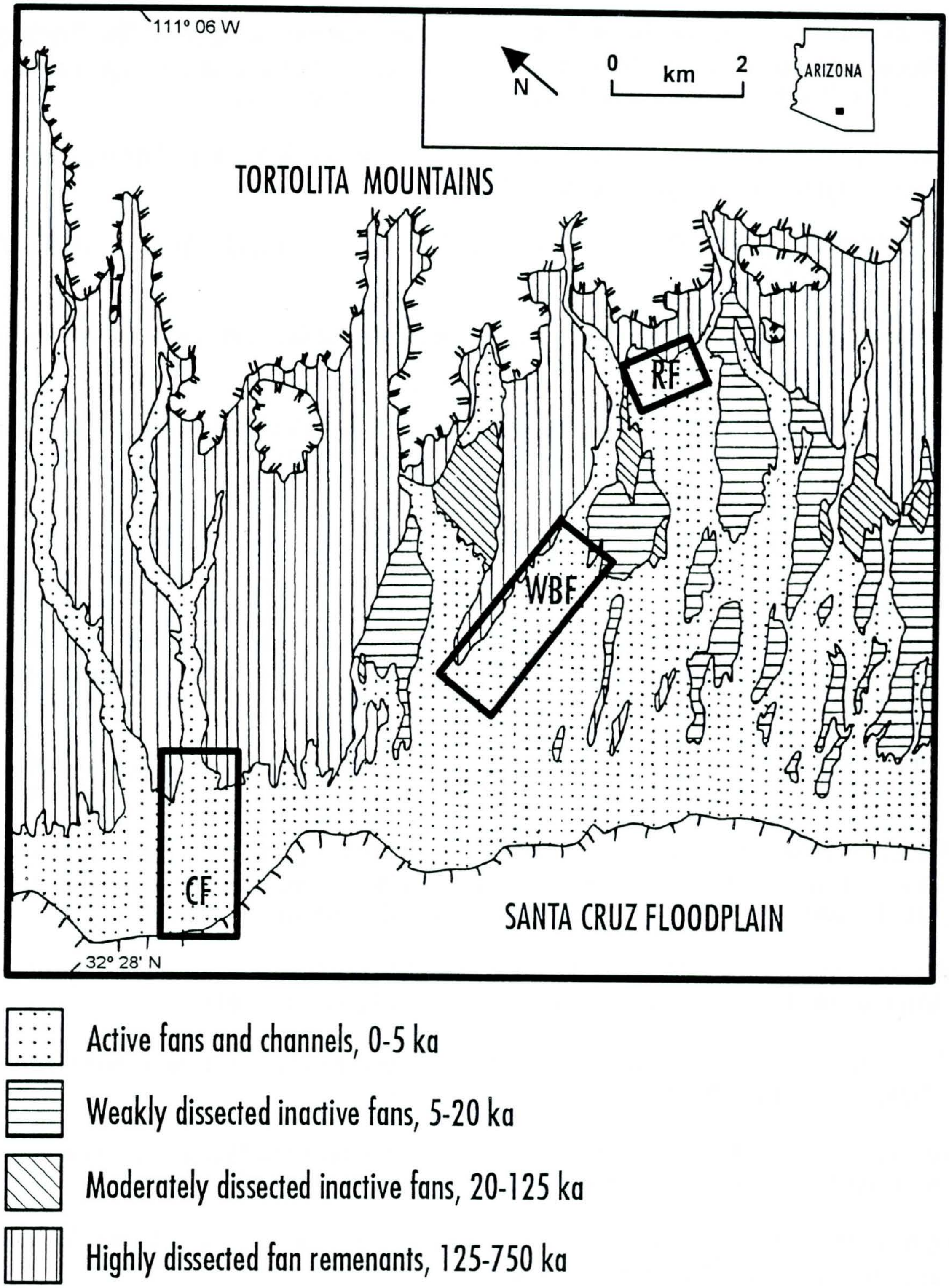


Figure 1a. Geomorphologic map of the Tortolita Mountains piedmont showing the location of Ruelas Fan (RF), Wild Burro Fan (WBF), and Cottonwood Fan (CF). Surface ages reflect the time since surface abandonment.

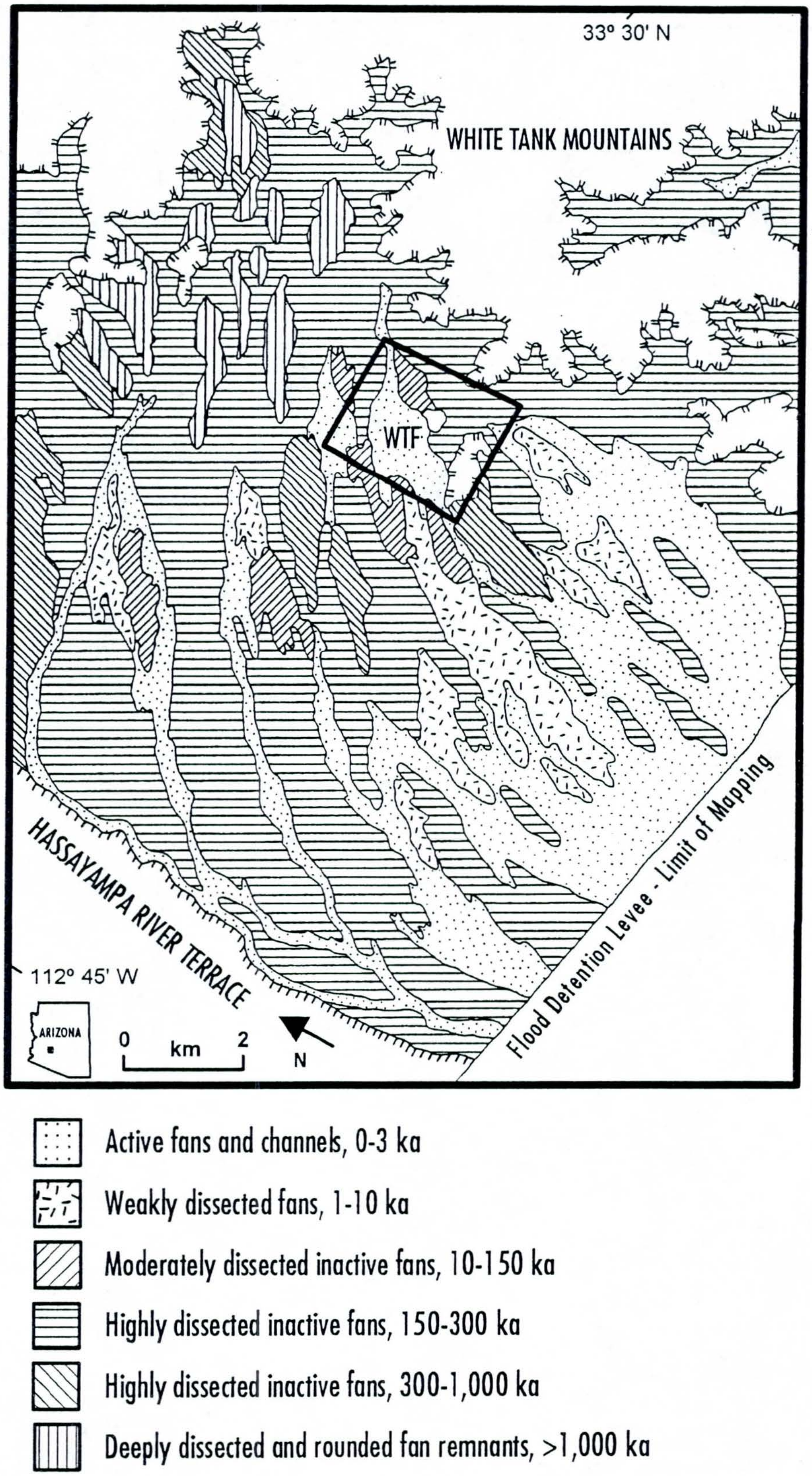


Figure 1b. Simplified geomorphologic map of the White Tank Mountains piedmont showing the location of White Tank Fan (WTF).

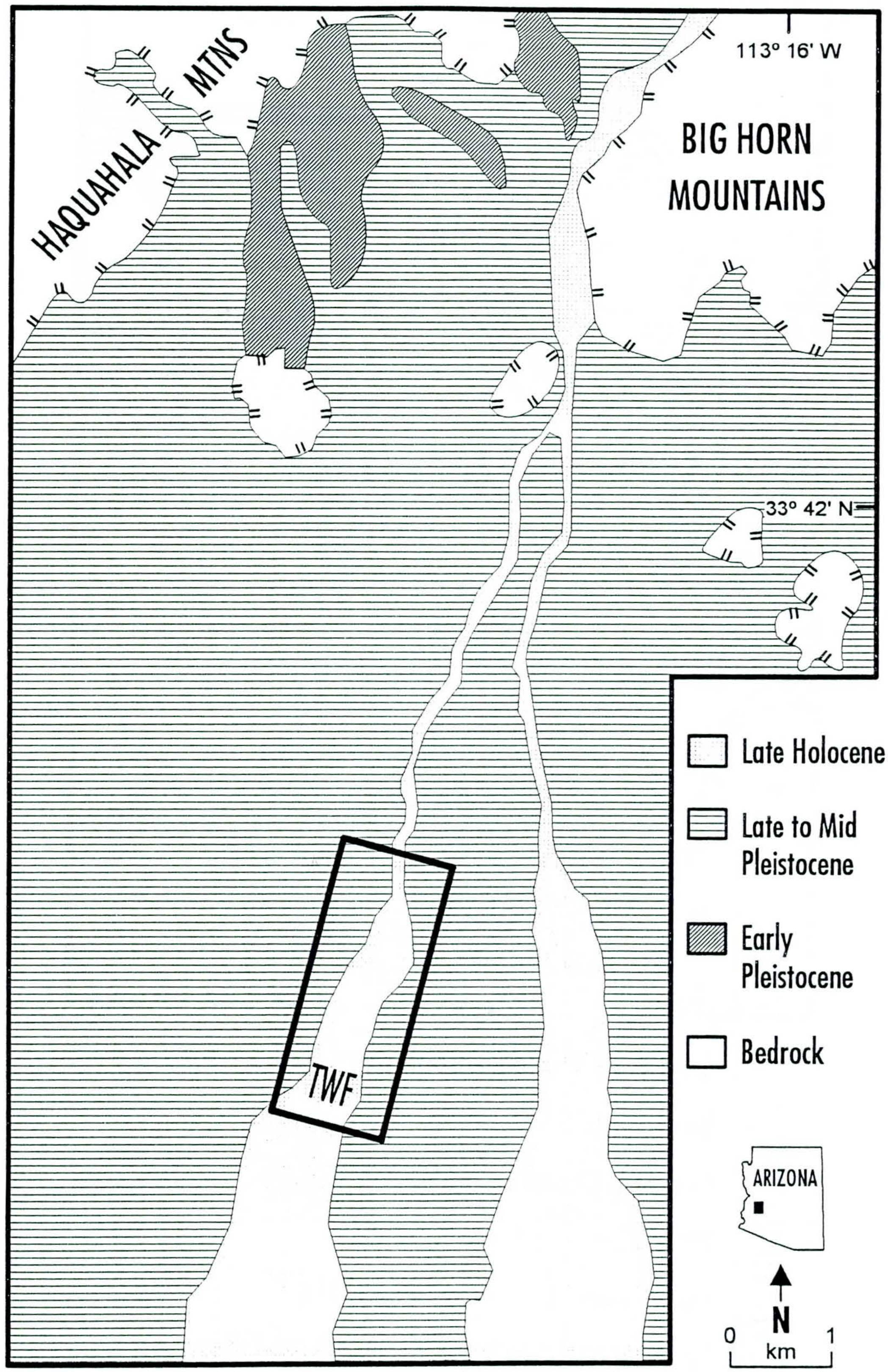


Figure 1c. Geomorphologic map of the upper Harquahala Valley showing the location of Tiger Wash Fan (TWF).

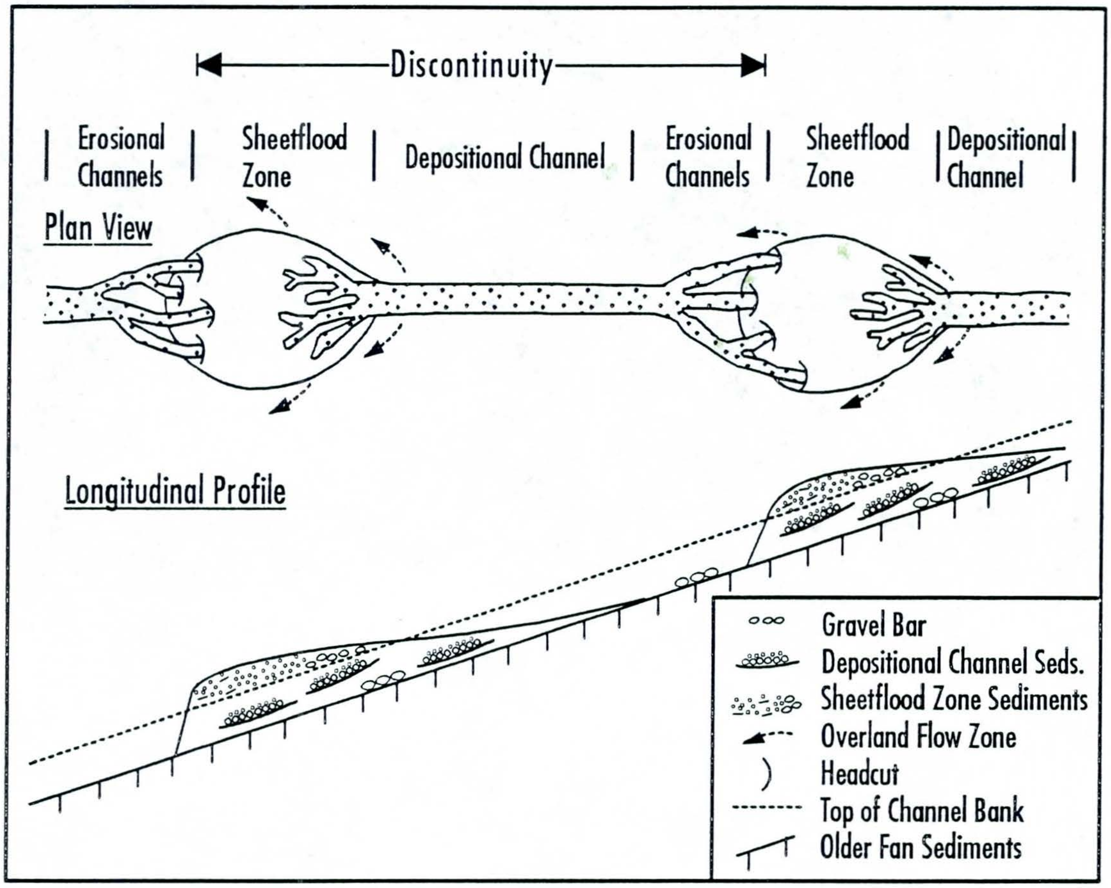
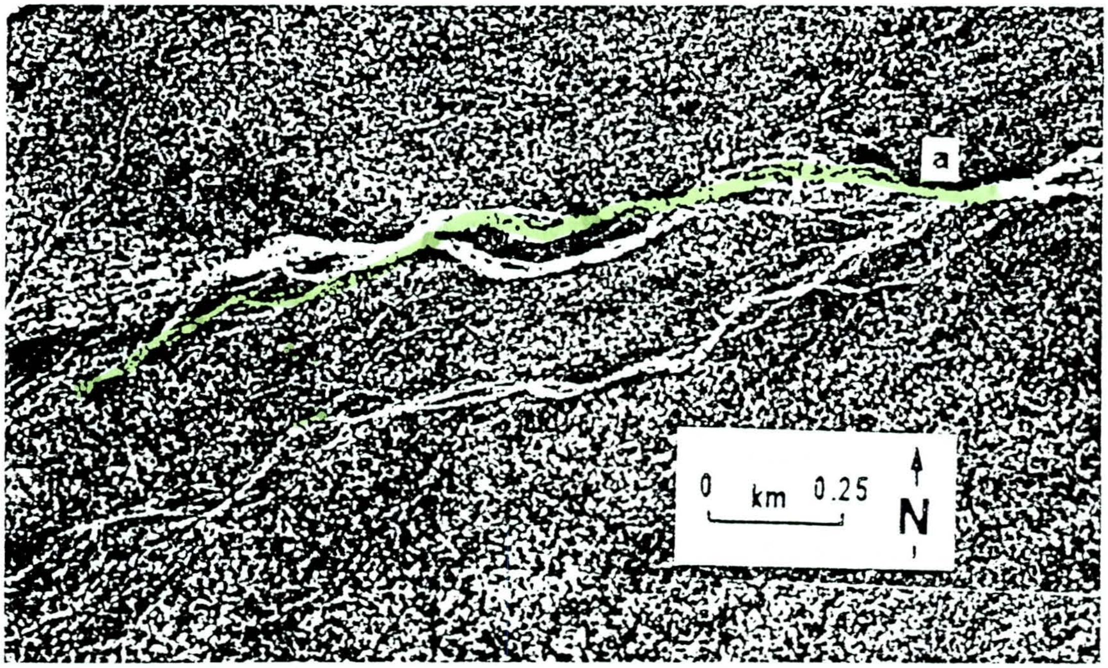
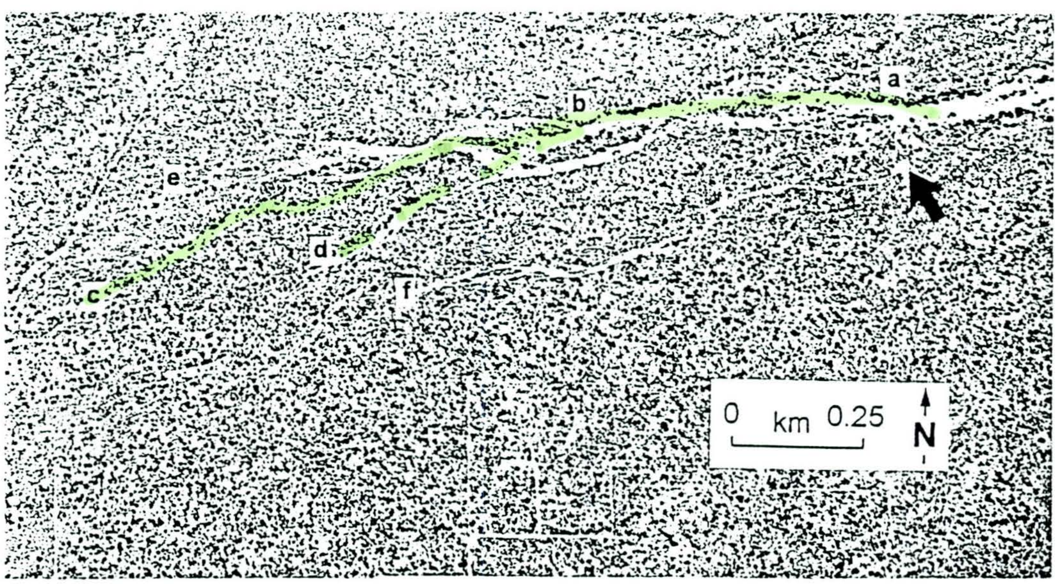


Figure 2. Schematic drawing of a discontinuous ephemeral-stream system. Not to scale.



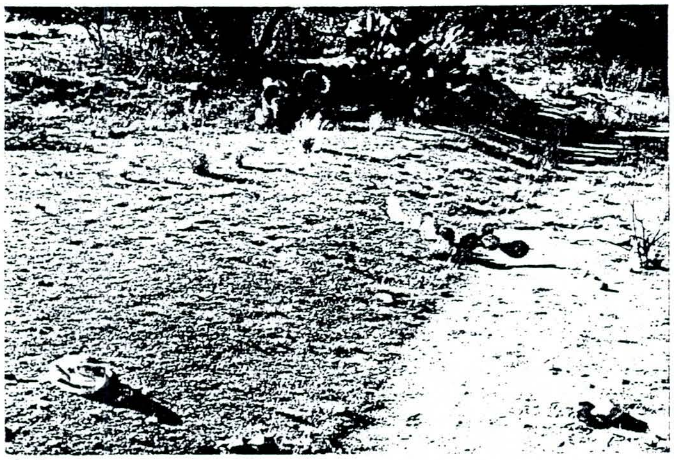
a. 1936



b. 1988

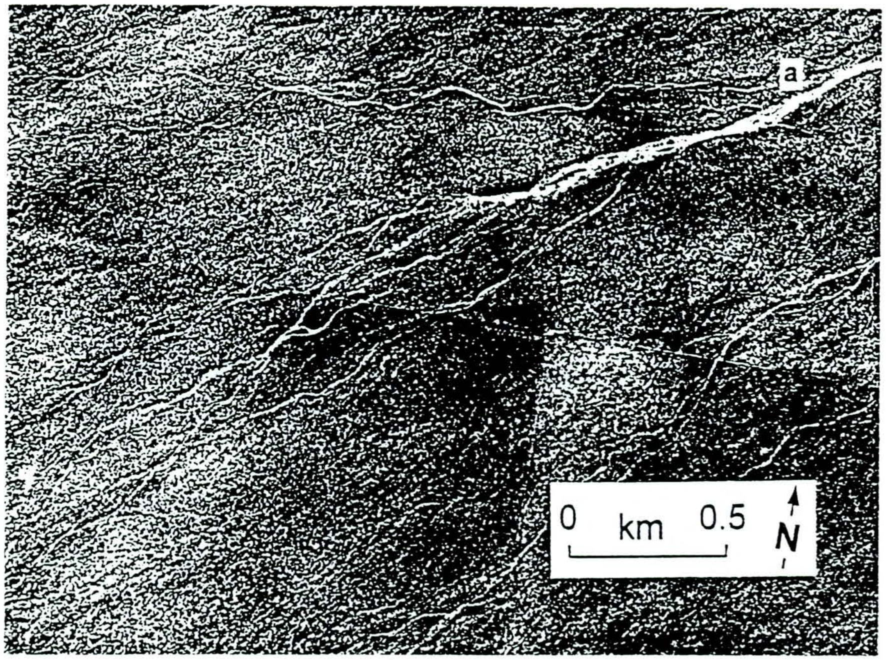
Figure 3. Aerial photographs of Ruelas Fan: a) 1936 and b) 1988.

a)

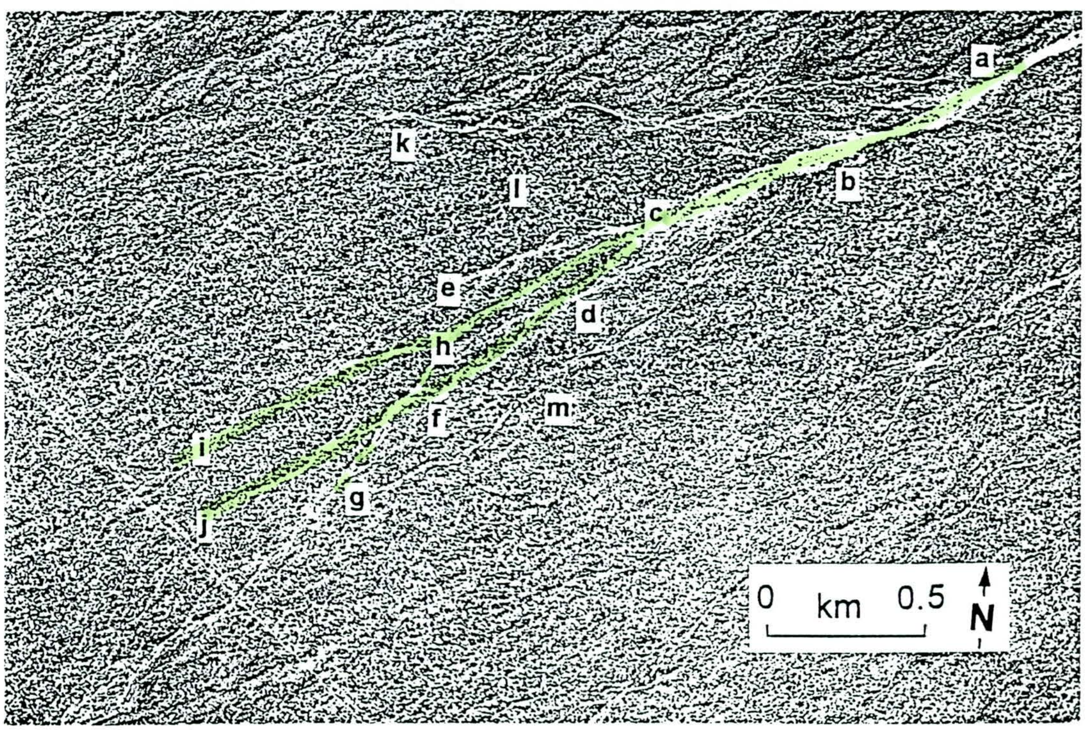


b)

Figure 4. Photograph of abandoned channel (a-f) on Ruelas Fan showing a) vegetation growth on old channel bed and b) incision of old channel bed.

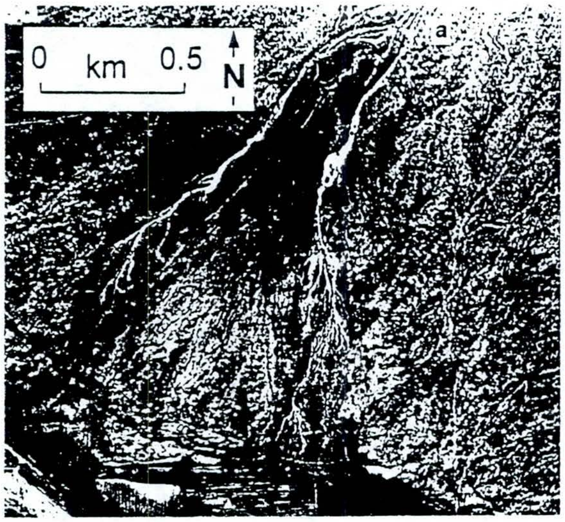


a. 1936



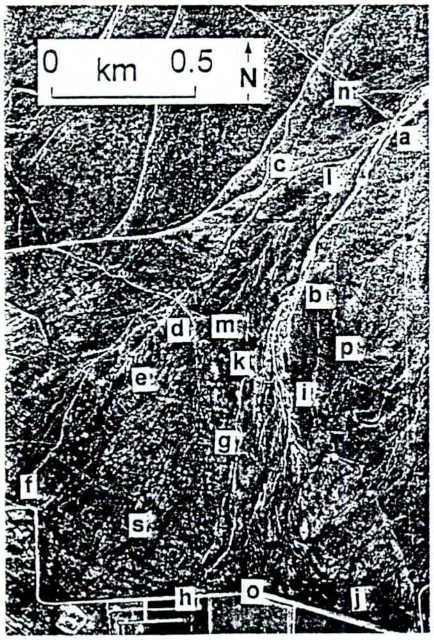
b. 1990

Figure 5. Aerial photographs of Wild Burro Fan: a) 1936 and b) 1990.

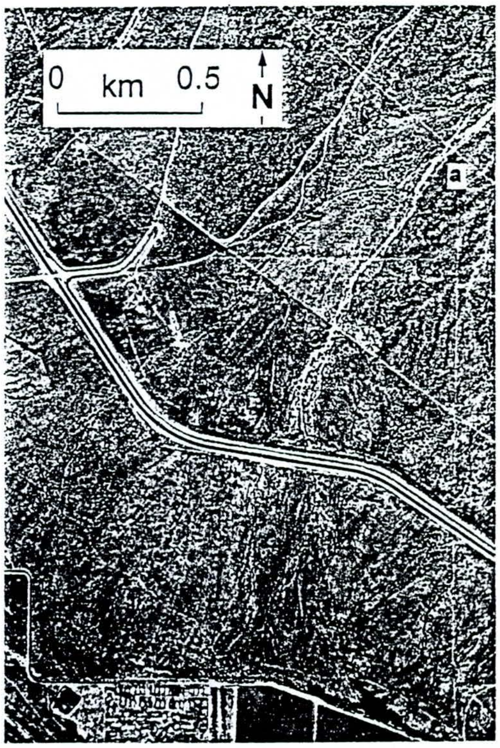


a. 1936

b. 1949



c. 1980



d. 1993

Figure 6. Aerial photographs of Cottonwood Fan: a) 1936, b) 1949, c) 1980, and d) 1993.

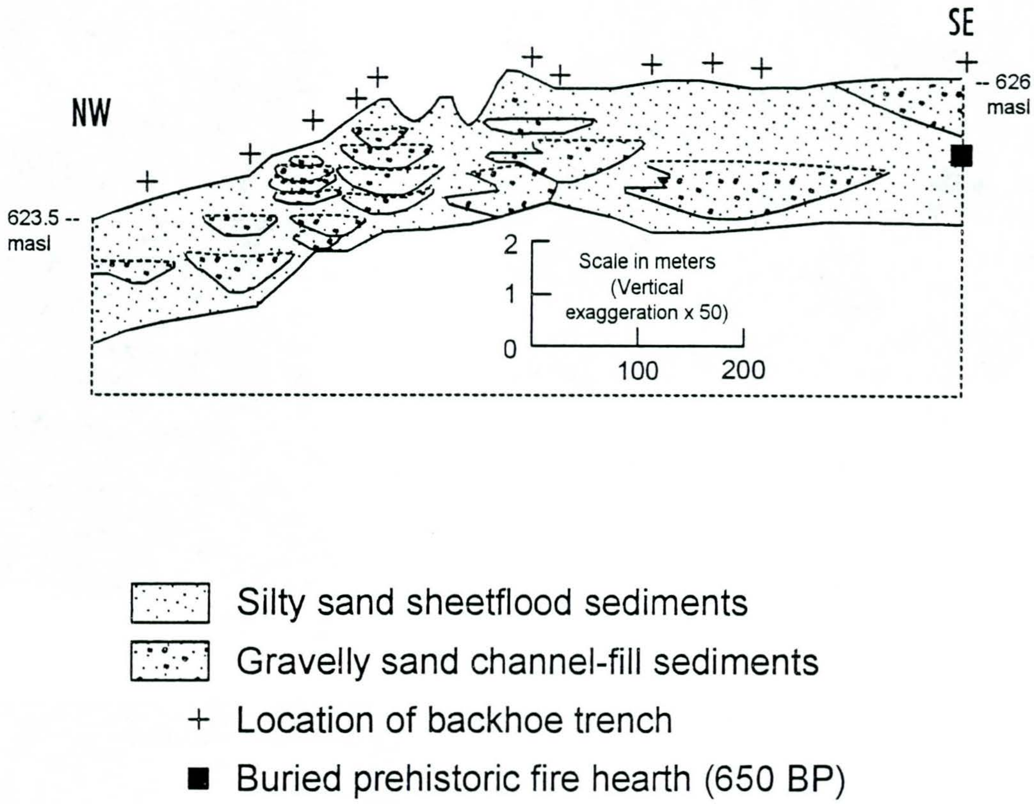
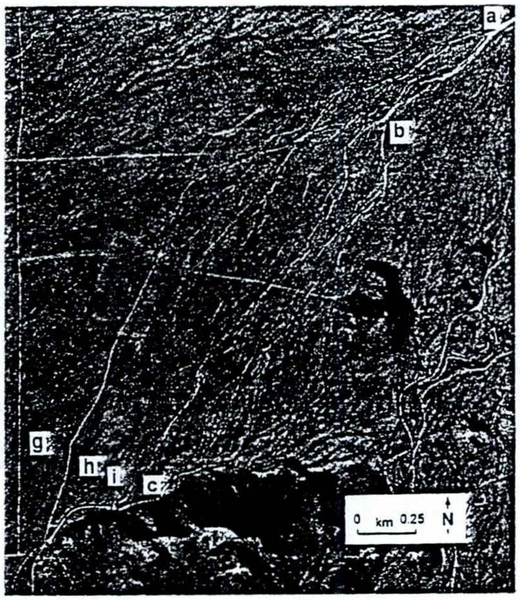
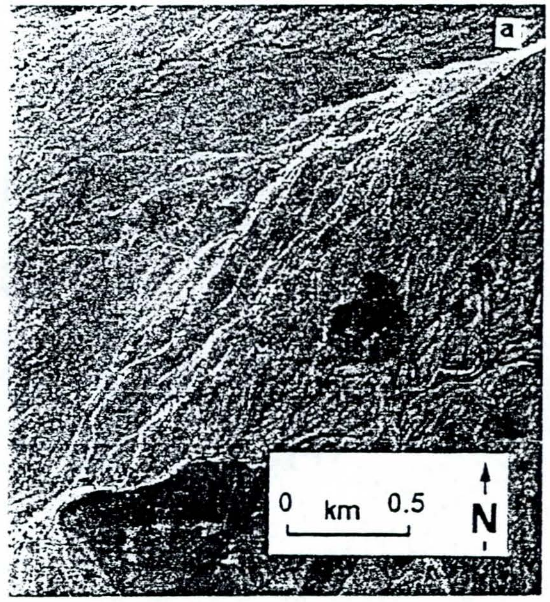


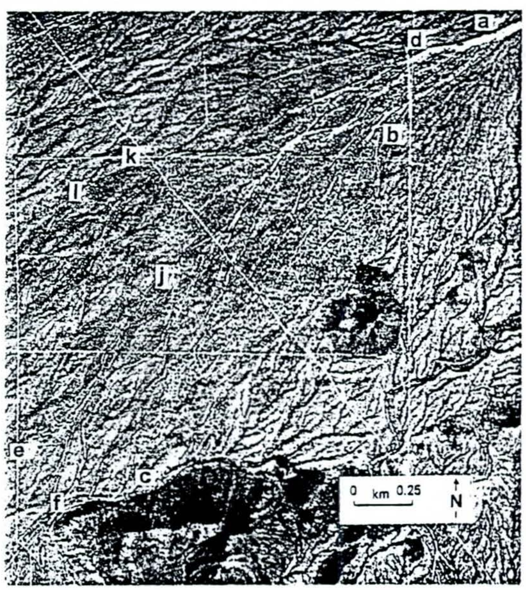
Figure 7. Stratigraphic cross section of Cottonwood Fan showing the former and present (SE corner) positions of the main channel. Cross section interpolated from trench data. Modified from Waters and Field (1986). Location of cross section runs along a line between points d and i (Fig. 6c).



a. 1942



b. 1953



c. 1992

Figure 8. Aerial photographs of White Tank Fan: a) 1942, b) 1956, and c) 1992.

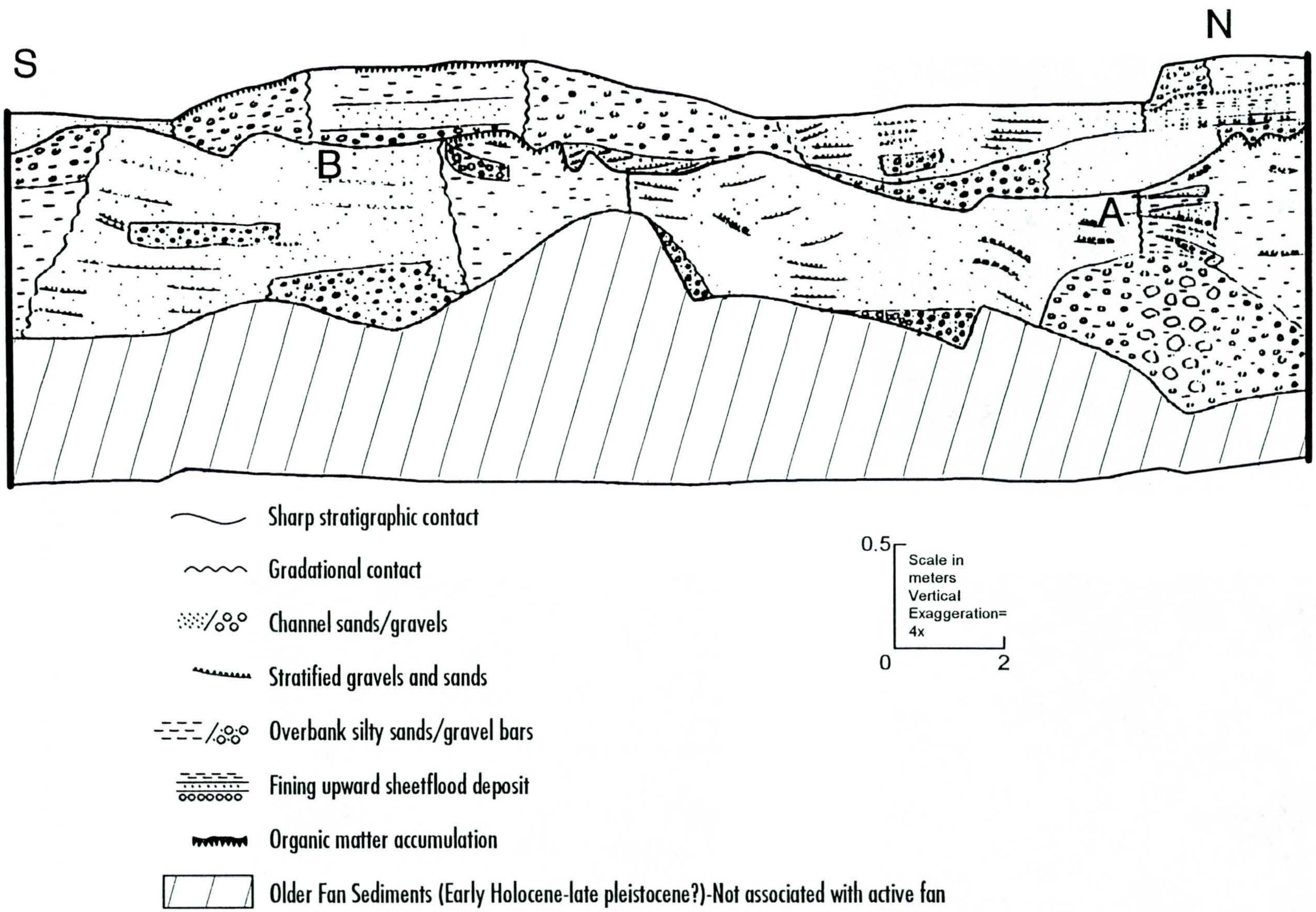


Figure 9. Stratigraphic cross section of White Tank Fan showing breach deposits at the edge of a former channel (point A) and a former channel directly beneath the position of a present-day bar (point B).

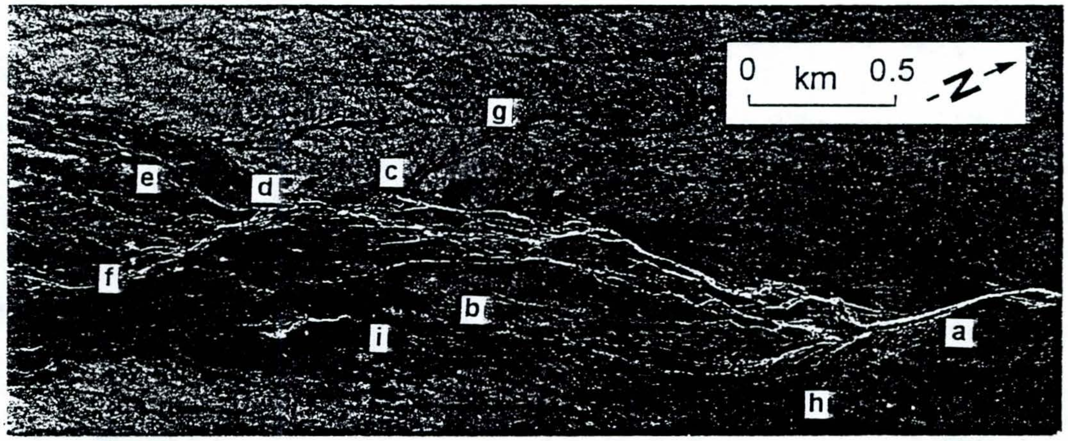


Figure 10. 1979 aerial photograph of Tiger Wash Fan.

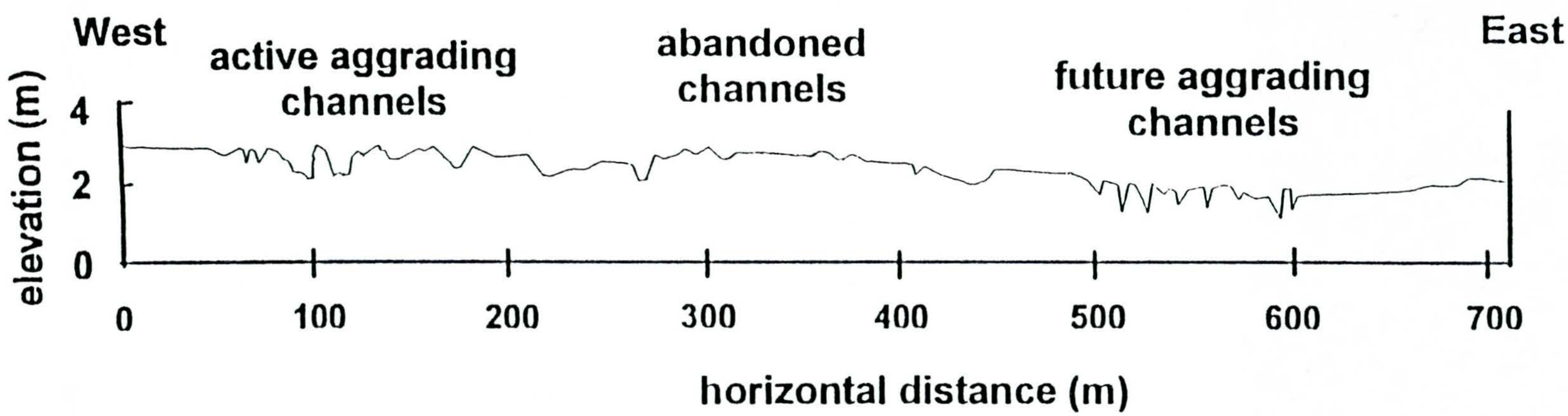


Figure 11. Topographic cross section of Tiger Wash Fan showing the former, present, and potential future positions of the main channel. Location of cross section runs through point b perpendicular to the flow direction. Cross sectional data from P.A. Pearthree (1994, written communication).

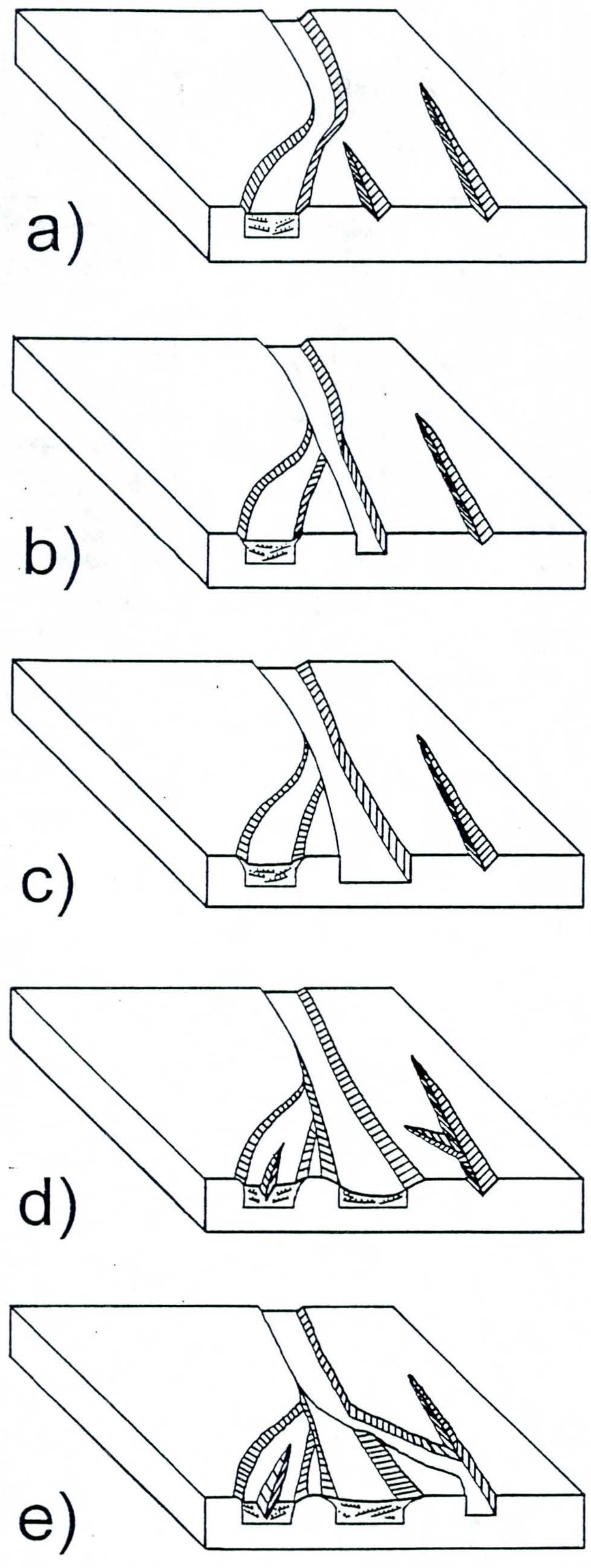


Figure 12. Model of channel migration developed from observations on the Arizona fluvial fans. See text for details.

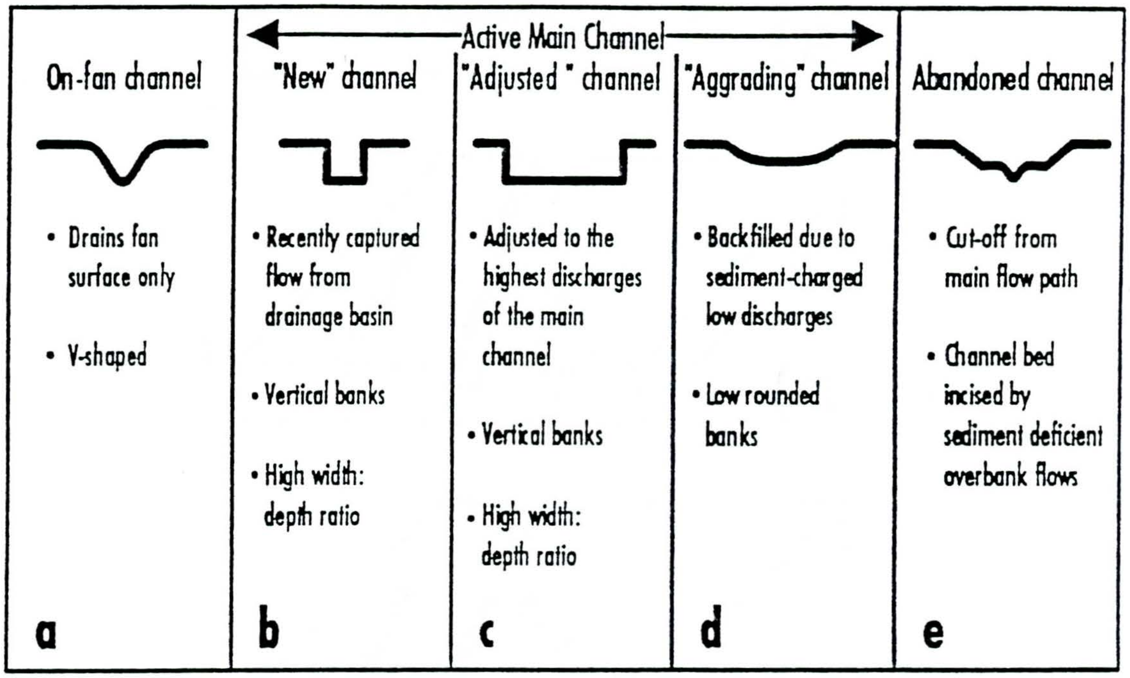
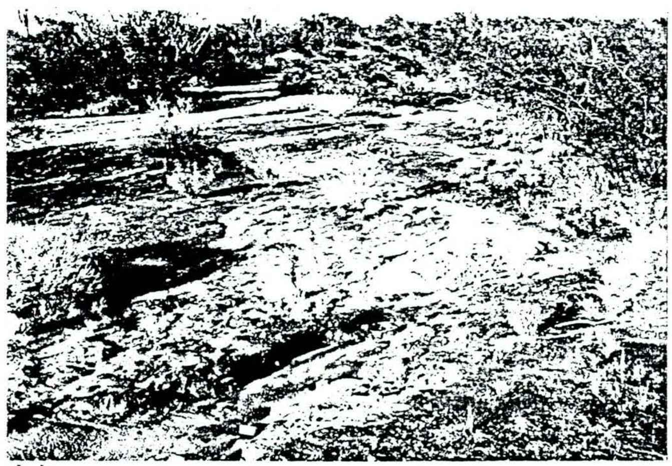


Figure 13. Five channel morphologies observed on the Arizona fluvial fans. Note that a single channel reach can go through each phase of channel development through time, and each stage of development may be observed at different places on the fan at the same time (see Figure 12).

Figure 14. Location (arrow) of major diversion on Ruelas Fan between 1949 and 1956. View looking downstream. Note rounded channel banks upstream of diversion and vertical banks downstream.

a)



b)

Figure 15. a) Small-scale analogue of the diversion process presented in Figure 12. Photograph taken on the lower White Tank Fan near point f (Fig. 8c). b) Close-up of a portion of the same area shown in fig. 15a.

Table 1. Selected drainage-basin characteristics for the five study fans

Alluvial Fan	Total Drainage Area (km)	Drainage Area on Piedmont (km)	Area on Piedmont (%)	Distance Fan Apex to Mtn Front (km)	Dominant Lithology	Average Annual Rainfall (cm)
Ruelas Fan	9.3	0.51	5	1.77	Granite Granodiorite	28
Wild Burro Fan	18.5	1.55	8	4.3	Granite Granodiorite	28
Cottonwood Fan	34.54	9.89	29	10.4	Granite Granodiorite	28
White Tank Fan	14.58	2.61	18	4	Gneiss Granite	20
Tiger Wash Fan	249.68	9.58	4	6.45	Mix	15

Table 2. Documented evidence of past channel diversions on alluvial fans

References*	Location	Type of Change**	Flow Type	Preexisting Channel***	Type of Evidence	Frequency (Yrs)****	Notes
Arid Climates							
1	California	Avulsion	Debris		Observed	>20	Mudflows followed multiple courses
2	California	Capture	Stream	Yes	Observed		Flow confined to 2 large channels
3	California	Overflow	Debris	New	Observed	~ 100	Forest fire preceded 100-year storm
4	California	Avulsion	Stream		Observed		Deposition dammed channel and split flow
5	California	Avulsion	Debris	Yes	Surficial	>320	Debris flow frequency of 320yrs
6	California	Aggrade	Debris?		Surficial	Geologic?	Radiating channel pattern
7	California	Avulsion	Debris	Yes?	Surficial	Geologic	Abandoned channels on Pleistocene surface
8	California	Capture	Stream?	Yes	Surficial	Geologic?	Abandoned channels >2ka present
9	California	Capture	Debris	Depression	Surficial		Evidence from geomorphic map of fan
10	California	Capture?	Stream	New	Observed		Pre-flood surface completely changed
11	California	Capture	Stream	Yes	Surficial	Eng.?	Abandoned channels active during floods
12	California		Debris		Surficial		Abandoned channels active during floods
13	Arizona		Stream		Surficial	Eng.?	Dead trees mark position of old channels
14	Arizona		Stream		Surficial	Eng.?	Older channels obliterated by flooding
15	Arizona	Capture	Stream	Yes	Historical	50-600	Frequency of change at fan toe <50yrs
16	Utah	Overflow	Debris	New	Observed		Diversion occurred at sharp bend
17	Utah		Debris		Surficial		Several debris flows per century
18	Utah	Capture	Stream?	Yes	Surficial	Geologic?	Deeply entrenched inactive fans
19	Australia	Capture	Stream	Yes	Surficial	>40	Observed 40-year flood caused no change
20	Niger		Stream		Surficial	>300	Sand-dune source area
21	Israel		Stream?		Surficial	~ 3000	Six channel positions in 17,000 yrs
22	Saudi Arabia	Capture	Stream	Yes	Surficial		Aeolian and human backfilling of channels
Humid-Temperate							
23	Virginia	Overflow	Debris	New	Observed	~ 3000	>30% of fan surfaces activated
24	Washington	Overflow	Debris	New	Observed		>50% of fan surface activated
25	Canada		Debris		Strat.	Geologic?	Overflow from mudflows smooth surface
26	Canada	Avulsion	Debris	Depression	Surficial	Eng.?	Evidence from aerial photographs
27	Canada		Stream		Surficial	Eng.?	Evidence from aerial photographs
28	Canada	Capture?	Stream		Surficial	Eng.?	Dendrochronology used to date diversion
29	Canada	Capture?	Stream		Surficial	~ 1,500	8 or 9 changes in Holocene

Table 2 - continued

	30	New Zealand	Capture	Stream	Yes?	Observed	100	Lateral migration of present channel threatens abandonment
	31	New Zealand	Avulsion	Debris	New	Historical	>3	2 changes from 1957 to 1965; No change for more than 37yrs preceding 1957
	32	Switzerland	Avulsion	Debris		Surficial		Roman artifacts buried 5 ft.
	33	England	Overflow	Debris	Depression	Observed		Large portions of small fans activated
	34	Japan	Overflow	Debris	Yes	Observed	<5	Steep debris fan with frequent flows
Other								
	35	Canada		Stream		Surficial	Eng.?	Permafrost inhibits gullying
	36	Costa Rica	Capture	Stream	Yes	Historic	100-500	Abandoned channels active during floods
	37	Colorado	Overflow	Debris	New	Observed		3 loci changes during dam break flood
	38	Himalayas		Debris?		Strat.	Geologic?	Back-filled channels observed in sediments
	39	Himalayas		Debris		Observed		Mudflows entirely changed the surface
	40	Kosi Fan	Capture	Stream	Yes	Historic	<30	70 mile lateral shift of river in 200 years
	41	Scandanavia		Debris	Yes	Observed	>57	Debris flow lobes on various parts of fan
	42	Botswana	Capture	Stream	Yes	Observed	50-100	Vegetation accelerates channel blockage

*1=Morton and Cambell, 1974; 2=Scott, 1973; 3=Chawner, 1935; 4=Eckis, 1928; 5=Kesseli and Beaty, 1959; Beaty, 1963; Beaty, 1970; Hubert and Filipov, 1989; 6=Trowbridge, 1911; 7=Whipple and Dunne, 1992; 8=Denny, 1967; 9=Hooke and Rohrer, 1979; 10=Antsey, 1965; 11=Denny, 1965; 12=Hooke, 1967; 13=Bryan, 1922; 14=McGee, 1896; 15=This paper; 16=Pack, 1923; 17=Wooley, 1946; 18=Hunt et al., 1953; 19=Wasson, 1974; 20=Talbot and Williams, 1979; 21=Bowman, 1978; 22=Richards et al., 1987; 23=Hack and Goodlett, 1960; Williams and Guy, 1973; Kochel and Johnson, 1984; Kochel, 1990; 24=Orme, 1989; 25=Ryder, 1971; 26=Kellerhals and Church, 1990; 27=Kostaschuk et al., 1986; 28=Desloges and Gardner, 1981; 29=Rannie et al., 1989; Rannie, 1990; 30=Griffiths and McSaveney, 1986; 31=Whitehouse and McSaveney, 1990; 32=Davis, 1898; 33=Wells and Harvey, 1987; 34=Ono, 1990; 35=Leggett et al, 1966; 36=Kesel, 1985; Kesel and Lowe, 1987; 37=Blair, 1987; 38=Drew, 1873; 39=Conway, 1893; 40=Gole and Chitale, 1966; Wells and Dorr, 1987; 41=Rapp, 1960; 42=McCarthy et al., 1986; McCarthy et al., 1992

**Avulsion=rapid abandonment of channel by debris blockage; Capture=slower process by which backfilling of main channel accelerates headward erosion and deepening of on-fan channels that ultimately capture flow; Overflow=floodwaters overwhelm channel and significantly alter fan surface; Aggrade=long-term deposition raises surface and forces shift to lower regions of fan

***Yes=flow diverted into preexisting channel; New=floodwaters formed an entirely new channel; Depression=flow diverted into a depression or topographic low

****Geologic=diversions occurred several thousand years ago; Eng.=available evidence suggests diversions occur on an engineering time scale (10's-100's of years)

Note: In many cases there is not enough information presented in the original paper to determine the type and frequency of diversions. Question marks used where information given here is not explicitly stated by original author.

Table 3. Floods on alluvial fans that caused no major channel diversions

Location	Year of Flood(s)	Recurrence Interval (Yrs)	Reference	Notes
California	1941,1943		Sharp and Nobles, 1953	Snow-melt flood debris flows
California	Several	300?	Kesseli and Beaty, 1959	Numerous large debris flows
California	1984	>200	Ribble, 1988	No changes in existing channel alignment
California	1970		Beaumont and Oberlander, 1971	Small flood confined to main channel
Arizona	1988	~100	House et al., 1991	Wild Burro Fan
Utah	Several	~5	Wooley, 1946	4 debris flows in 20 years followed path of large debris flow in 1923
Canada	1962		Winder, 1965	Mudflow followed existing channels
Canada			Kellerhalls and Church, 1990	Historic photos show debris flow following preexisting channel
Canada	1956,1967	<50	Desloges and Gardner, 1981	Decreasing sediment yield decreasing chances of diversion
Australia	197	>40	Wasson, 1974	No changes above intersection point
England	1982	>100	Wells and Harvey, 1987	Small storm-generated fans
Spain	1980	25-100	Harvey, 1984	Minor diversion on unconfined lower fan