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Recognition and significance of streamflow-dominated piedmont facies in extensional basins

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ABSTRACT

Alluvial slopes are piedmonts characterized by parallel steam channels rather than alluvial fans. They are common landforms in extensional basins of the south-western United States but have received little attention from geomorphologists or sedimentologists. Persistence of channellized flow across piedmonts, as opposed to sheetflooding due to loss of flow confinement on alluvial-fan surfaces, distinguishes alluvial-slope and alluvial-fan facies. Miocene strata of the Tesuque Formation (Española basin, New Mexico) and Pliocene strata of the St. David Formation (San Pedro Valley, Arizona) provide examples of extensional basin–piedmont successions constructed by discrete gravel and sand bedload channels and aggrading interfluve floodplains and aeolian sand sheets. Distinction of alluvial-fan and alluvial-slope piedmont deposits has several important implications. The contrasting facies geometries associated with the two landforms produce distinctly different aquifer and reservoir properties. It is hypothesized that alluvial slopes are more likely to form than alluvial fans where mountain fronts lack abrupt structural and topographic definition. This circumstance will most likely be met (a) along tectonically inactive and embayed mountain fronts and (b) on the hangingwall ramp side of half grabens.

INTRODUCTION

The geomorphology of arid extensional continental basins (e.g. the Basin and Range region of the western United States) is typically described in terms of a basin floor, where an axial river, lake or playa is situated, and flanking piedmonts classified as either pediments or alluvial fans (e.g. Denny, 1967; Abrahams & Parsons, 1994). Such descriptions overlook, however, the common piedmonts characterized by long, parallel channels and interfluve floodplains and aeolian sand sheets that are morphologically distinct from alluvial fans. Further ambiguity results from varied definitions of alluvial fans. Although all definitions recognize the distinctive half-cone morphology of a fan, consistent with the etymology of the phrase, not all workers emphasize the physical processes producing the landform. Blair & McPherson (1994a), following Bryan (1922) and Bull (1972), advocate a restrictive use of the term that emphasizes deposition near the downslope transition from confined to unconfined flow where channels cross sharp topographic and channel-form boundaries at a mountain front.

Other fan-shaped accumulations of alluvium have been included with alluvial fans (e.g. Stanistreet & McCarthy, 1993) although I join Blair & McPherson (1994a,b) in arguing that these other varieties should be considered both genetically and sedimentologically distinct from alluvial fans. Fully channellized streams and rivers can produce fan-shaped accumulations of sediment through the process of nodal avulsion (Leeder, 1978) whereby pendular channel migration occurs in an alluvial reach downstream of a bedrock-confined reach. A single channel is present at any one time, deposition occurs in discrete channel and floodplain environments, and depositional slopes remain low (commonly $<1°$), all of which distinguish these ‘fans’ (e.g. Kosi fan of Wells & Dorr, 1987; Rio Grande and Kern River fans illustrated by Galloway & Hobday, 1996) both morphologically and sedimentologically from alluvial fans, *sensu stricto*. Some so-called streamflow-dominated piedmont alluvial-fan successions have also been interpreted to result from such migration of a single channel (e.g. Viseras & Fernandez, 1994; Leeder *et al.*, 1996; Jo *et al.*, 1997) but are not alluvial-fan deposits as considered here. Single-thread streams may develop distributary patterns as a consequence of increasing within-channel deposition of bars where slope diminishes below a threshold for transport of dominant grain sizes (e.g. delta distributaries) or as a result of loss of discharge by infiltration (fluvial distributary systems and terminal fans of Friend, 1978; Kelly & Olsen, 1993). Fluvial fans described by Love & Seager (1996) and Mack *et al.* (1997) may owe their origin to both nodal avulsion and infiltration-induced development of distributary channels and are appropriately distinguished from alluvial fans. From a sedimentological perspective, only alluvial fans in the strict sense of Blair & McPherson (1994a) can be inferred from a stratigraphic record by the notable absence, or near absence, of facies indicative of confined streamflow. In this strict and arguably most useful sense there is no such thing as a streamflow-dominated alluvial fan. Most objectively, fluvial-channel facies provide few if any insights into landform morphology that could demonstrate the presence of a streamflow-dominated fan if channellized-stream systems are incorporated into a broader definition of alluvial fans.

The distinction of alluvial fans, produced by largely unconfined flow, and streamflow-dominated piedmonts reveals a greater variety of geomorphic and sedimentary processes in extensional basins. The distinct morphologies and resulting deposits, in turn, must be linked to watershed and piedmont processes reflecting tectonics and discharge characteristics of the streams. These characteristics, in turn, hold clues to tectonic and climatic changes impacting the streams. The contrasting sedimentary facies and facies architecture of fan and nonfan piedmonts should be important for understanding hydrocarbon reservoir and aquifer properties and geometries. The research necessary to understand what determines the formation of alluvial fans or persistent channellized streams on piedmonts remains to be completed. The purpose of this paper is to highlight the recognition of streamflow-dominated piedmont deposits, to hypothesize conditions favouring formation of such piedmonts instead of alluvial fans, and to stimulate further study of the geomorphology and sedimentology of extensional-basin piedmonts.

TERMINOLOGY FOR STREAMFLOW-DOMINATED PIEDMONTS

Before progressing further, it is desirable to select a term for describing piedmonts lacking the morphology of an alluvial fan and/or where channellized streamflow persists across the width of the piedmont even where a gently sloping fan shape is apparent near the channel. Some sources (e.g. Cooke & Warren, 1973; Bates & Jackson, 1987) propose the term *bajada* for this circumstance, but others (Summerfield, 1991; Harvey, 1997) define bajadas as coalesced alluvial fans. Bryan (1922) introduced the term *alluvial slope* for ‘a surface composed of alluvium which slopes down and away from the sides of mountains and which merges with the plain or broad valley floor upon which it rests’ (p. 86). Bryan’s further development of the definition and usage indicate that he intended alluvial slope in the sense of a piedmont plain (cf. Cook & Warren, 1973) to be inclusive of alluvial fans and piedmont streams lacking fan morphology. Hawley & Wilson (1965) restricted *alluvial slope* to a piedmont plain ‘that lacks the distinctive surface form of one or several coalesced alluvial fans’ (p. 8), a definition also utilized by Bull (1977) and Bates & Jackson (1987). The term alluvial slope, in the latter sense, is adopted here for describing streamflow-dominated piedmonts.

Examples of alluvial slopes

Casual examination of topographic maps and aerial photography from throughout the Basin and Range region of the western United States indicates that many piedmonts are characterized by parallel drainage patterns extending from mountain front to basin floor without development of alluvial-fan morphology or loss of significant flow confinement. Although some examples may overlie bedrock pediments, others are not found in association with bedrock outcrops or monadnocks that would indicate such. These features are analogous to the alluvial slopes distinguished by Hawley & Wilson (1965) in their studies near Winnemucca, Nevada. Care is taken also to distinguish between geomorphic forms indicative of persistent channellized flow as opposed to alluvial fans that have become entrenched along most or all of the length of a fan as a consequence of late Quaternary climate-change regulation of discharge characteristics (e.g. Bull, 1991).

Figures 1–3 illustrate characteristics of three contrasting alluvial-slope drainages in the Basin and Range. The east flank of the Toiyabe Range in central Nevada is skirted by a piedmont of parallel, gravel-bedload streams flowing toward a central playa. Most of the piedmont lacks evidence of fan morphology and even where contours define a fan shape (e.g. along Birch Creek, Fig. 1a) slopes are relatively low (mostly 0.2–0.8°) and confined flow is persistent in a nonentrenched channel. The Birch Creek fan probably formed by nodal avulsion of a stream channel with a large watershed. Wild Burro Wash in the Tortolita Mountains of southern Arizona (Fig. 2) is a sand-bedload, braided ephemeral stream, which persists across an 8-km-wide piedmont to the Santa Cruz River floodplain. Although the channel has expansion reaches where distributaries form, most of these multiple thalwegs rejoin downstream and sheetflow, typically by clearwater flow, only occurs during overbank flooding (Fields, 1994). Hadley Draw, adjacent to the Cooke’s Range of southern New Mexico (Fig. 3), is an important variant of alluvial-slope drainages commonly encountered in southern New Mexico and Arizona. The channel is strongly vegetated with grasses, in contrast to xeric shrubs in interfluve areas, probably because of the moisture retention of the fine-grained nature of the channel fill. Vegetation in the channel strongly baffles sediment from flows in the channel leading to deposition of fine sand and silt despite a high channel gradient (mostly 0.6–1.0°). Bioturbation by roots and fauna associated with the vegetated habitat obliterates most primary sedimentary structures. Fine-grained alluvium is common in the Quaternary stratigraphy of the south-western United States and other arid regions (e.g. Bull, 1997) and commonly reflects deposition in vegetated, aggrading channels, rather than on floodplains.

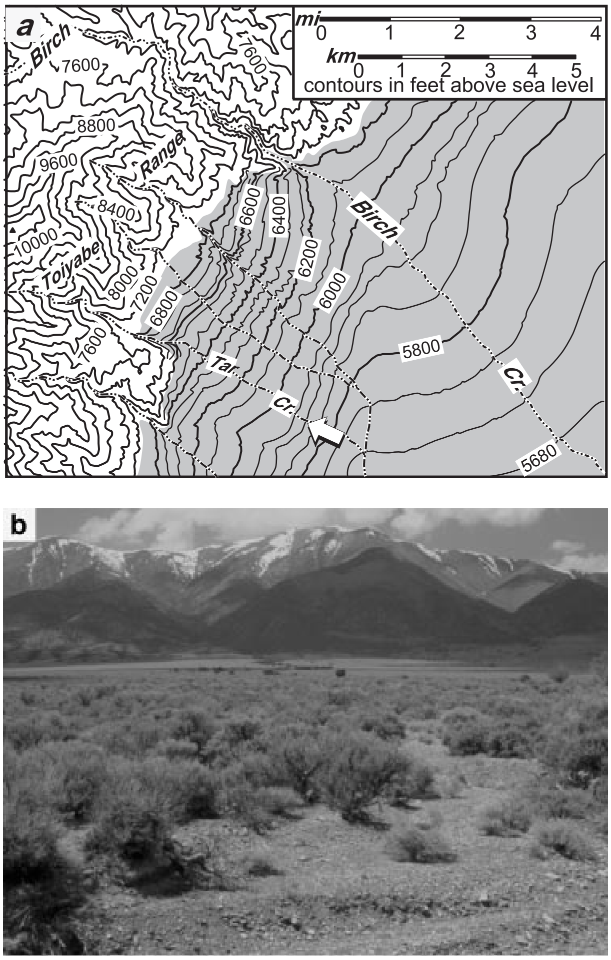

Fig. 1. (a) Topographic map of a part of the eastern piedmont of the Toiyabe Range in central Nevada. Shaded region approximates extent of alluvial piedmont; arrow shows location and direction of view shown in (b). Note the general absence of alluvial-fan morphology along the mountain front except near Birch Creek, where a low-gradient, fan-shaped area of the piedmont has been produced by nodal avulsion of the channel. (b) View upslope across the piedmont along Tar Creek. Note the absence of fan morphology and the single-thread channel outlined by riparian vegetation. The dry gravel-bedload channel is also visible in the foreground.

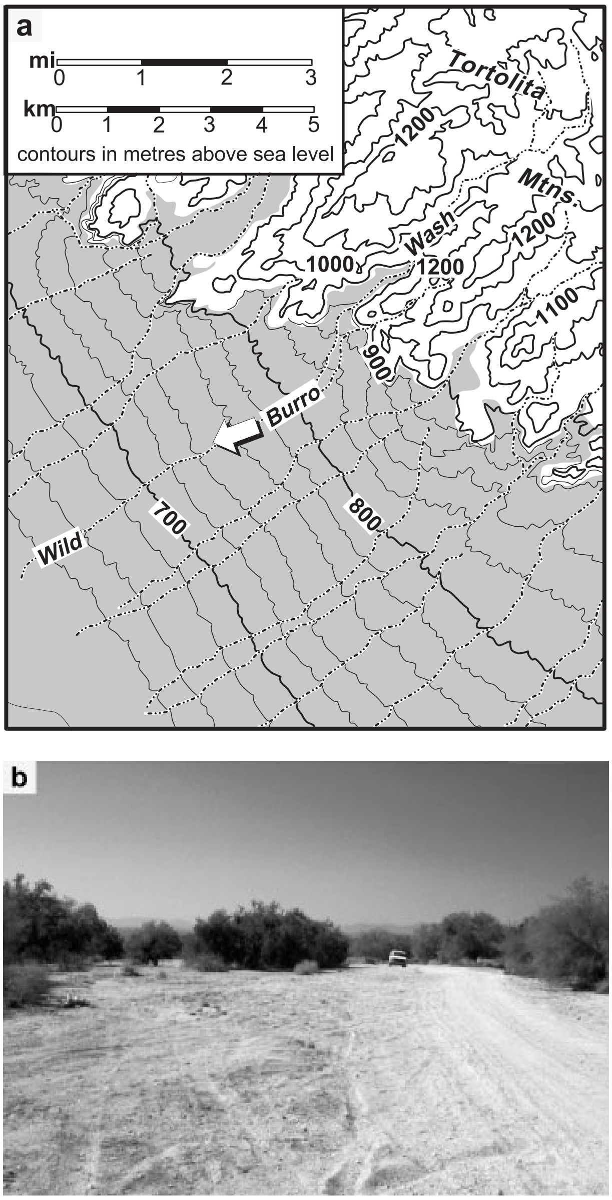

Fig. 2. (a) Topographic map of the western piedmont of the Tortolita Mountains in south-eastern Arizona. Shaded region approximates extent of alluvial piedmont; arrow shows location and direction of view shown in (b). Note the highly embayed mountain front and the absence of alluvial-fan morphology. (b) View downstream along the shallow braided channel of Wild Burro Wash. Vehicle is parked in the main channel with a slightly higher channel on the left.

RECOGNITION OF ALLUVIAL-SLOPE DEPOSITS

Expansion of flow at the intersection point of an alluvial fan leads to two important consequences for fan morphology and resulting deposits that are distinct from those of alluvial slopes. First, the loss of flow confinement causes water and sediment to be dispersed over broad areas in which channel margins are undefined, resulting in remarkably tabular beds that are typically thin (<1 m thick) and with rare or absent channel margins. Second, the flow expansion necessarily diminishes flow depth thereby drastically reducing shear stress and sediment-transport competency and capacity. Consequently, deposition takes place abruptly leading to the semiconical shape that is definitive of alluvial fans, commonly observed steep depositional gradients (Blair & McPherson, 1994a) and abrupt downslope decrease in grain size that characterizes many alluvial fans (Heward, 1978; Rust & Koster, 1984; Blair & McPherson, 1994a). Abrupt deposition over broad, unchannellized areas also means that bedload and suspended load are deposited more or less simultaneously and at the same sites (in contrast to distinct channels and floodplains of alluvial-slope environments) and results in remarkably poorly sorted facies.

The importance of lateral grain size variation to distinguish alluvial-slope and alluvial-fan deposits requires

Fig. 3. View north-west across the channel of Hadley Draw toward the Cooke's Range in south central New Mexico. Lines outline the approximately 15-m-wide channel, completely covered by grasses rooted in fine-grained alluvium. Gravel in foreground is associated with an older, higher geomorphic surface and is covered with xeric shrubs.

further examination. Blair & McPherson (1994a) appeal to the downslope diminishment of basal shear stress (because of diminishing hydraulic radius) for expanding flows on fan surfaces to account for the commonly observed, abrupt downslope decrease in maximum clast size in alluvial-fan deposits (e.g. Heward, 1978, fig. 1; Rust & Koster, 1984, fig. 4). A more rigorous analysis of the effects of flow confinement on the grain-size distribution of active bedload under conditions of steady, high discharge was undertaken using the sediment routing approach of van Niekerk *et al.* (1992) and Slingerland *et al.* (1994, chapter 4). That analysis does demonstrate the greater transport efficiency of coarse clasts by channellized flow, but notably most of the difference in grain size with distance occurs within the first kilometre of transport from the mountain front (Fig. 4). Beyond this distance, change in grain size with distance is similar for both confined and unconfined flow conditions. For some alluvial fans, grain size does not appear to undergo the expected dramatic, downslope decreases (Denny, 1965; Ritter *et al.*, 1993; Blair, 1999). It is likely that the persistent downstream transport of coarse clasts by shallow flows is related to the complexity of transport of sediment mixtures covering a wide range of grain size. Outsize clasts in a heterogeneous size mixture have a larger cross-section exposed to the flow and are placed in motion at lower shear stresses than for the same size clasts in a homogeneous clast population (e.g. Bridge & Bennett, 1992). Lift forces in shallow, rapid flow also permit entrainment of large clasts at otherwise unexpectedly low shear stresses (Baker & Ritter, 1975). Depending on the range of grain sizes being transported, it should not be unexpected to find that the largest sizes (which are the ones most readily noted and recorded in sedimentological studies) show a less dramatic downslope decrease than that expressed by the median grain size.

Because of possible ambiguity in the significance of grain-size trends, the most important sedimentological traits of alluvial slopes are deposits of aggrading channels and interfluve environments and the rarity or paucity of sheetflood deposits definitive of alluvial fans. Lateral migration of channels may, as in any fluvial environment, obliterate most or all evidence of channel margins. Tabular sheets of sand and gravel are not by themselves therefore indicative of sheetflood deposition. Excellent sedimentological descriptions of sheetflood deposits have been provided by Bull (1972), Tunbridge (1981) Blair (1987, 1999) and Blair & McPherson (1994a). Most typical of sheetflood facies are laterally extensive, tabular, planar-bedded couplets of relatively coarse- and fine-grained sediment, rarely interrupted by significant scour structures. Alluvial-slope channels are recognized not only by channel-form geometries, if preserved, but by other indications of transport by relatively deep, and hence likely confined flows. These features include decimetre-scale or metre-scale bedform-produced cross-stratification and/or scours and bar forms. Streamflow deposits should be a very minor component of strictly defined alluvial-fan successions (Bull, 1972; Blair & McPherson, 1994a).

Although distinctly fluvial in origin, alluvial-slope-channel facies are inadequately described in terms of most existing concepts of fluvial process and depositional record derived from study of large rivers (e.g. Miall, 1997). Gradients for selected Basin and Range alluvial-slope streams are relatively steep (Fig. 5), with slopes of 0.5–2.0 degrees being common. These slopes fill the alleged slope gap (0.4–1.0°) of Blair & McPherson (1994a), which they feel distinguishes alluvial fans and rivers and reflects the lack of piedmont stream channels in the small data set of rivers that they considered. Channel depths are also relatively shallow, being generally less than 1.5 m. Most such streams, in the arid south-west USA, are also ephemeral with flows of significance for sediment transport being rapid, shallow and markedly unsteady (Graf, 1988). Upper-flow-regime sedimentary structures, and abundant scour-and-fill structures should dominate the resulting deposits because of the steep slopes, shallow depths, and unsteady flow.

EXAMPLES OF NEOGENE ALLUVIAL-SLOPE DEPOSITS

St. David Formation, Pliocene, south-eastern Arizona

Pliocene strata of the middle member of the St. David Formation accumulated on a 20-km-wide piedmont on the east side of the San Pedro valley (Fig. 6; Smith, 1994). The basin formed during the Miocene and tectonic quiescence during Pliocene aggradation is revealed by depositional overlap of range-front faults so that the St. David Formation locally rests on bedrock pediments developed on footwall blocks. The approximately 80 m of middle member strata exposed east of the valley centre

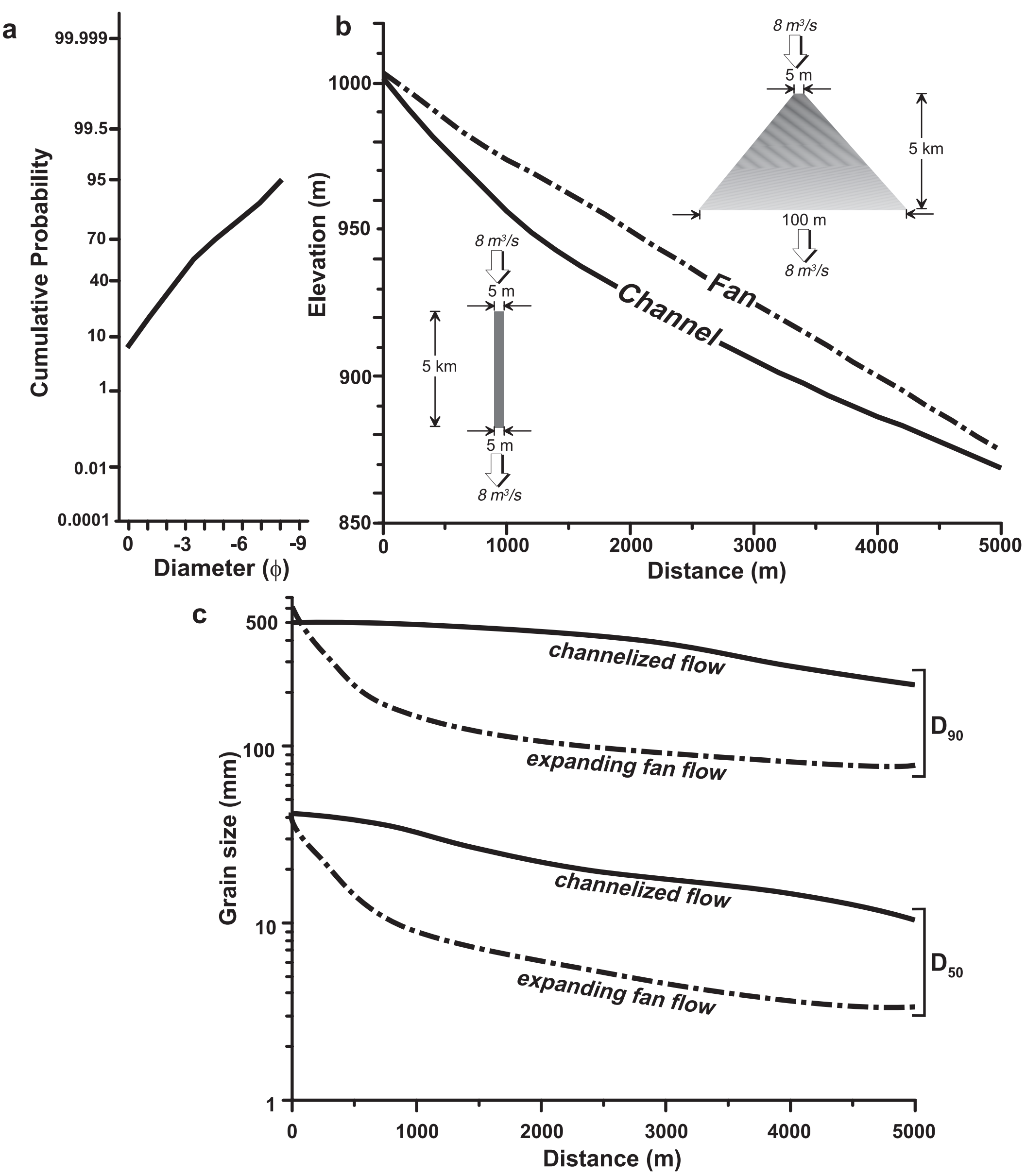

Fig. 4. Graphical summary of results from simple simulations of bedload transport with a steady, high discharge (8 m^3 s^{-1}) through a channel of fixed width (5 m) and across a fan surface where flow expands from 5 m to 100 m wide. Simulations were undertaken using the ROUTE1D of Slingerland *et al.* (1994). (a) Grain-size distribution of sediment mixture introduced at the head of the channel (at the mountain front). (b) Equilibrium profiles for channel and fan surface measured from the mountain front. (c) Median and 90th percentile grain size present in the bed at varying distance from mountain front for the channellized and expanding fan flow simulations.

accumulated between about 3.4 and 1.6 Ma (Smith, 1994; Fig. 7). Sediment provenance and palaeocurrent indicators (Smith, 1994) demonstrate that these deposits were produced by streams flowing westward from the Dragoon Mountains (Fig. 6). Exposures are restricted to the lower piedmont (Fig. 6) so documentation of proximal-to-distal variations in the style of sedimentation is not possible. Six stratigraphic sections, correlated directly by tracing of beds or by magnetostratigraphy, illustrate the channel and floodplain strata comprising the alluvial slope (Fig. 7).

St. David Formation piedmont deposits consist of lateral transitions between sections dominated by channel facies and those composed almost entirely of floodplain mud and spring-related marl. Facies maps (Smith, 1994) reveal three major channel tracts, ~3–5 km wide, that coincide with the largest modern piedmont drainage systems, each of which heads in a large watershed along the eastern basin margin or north-east of the valley (Fig. 6). The Pliocene channel tracts are recorded in the Sheep Wash, Dragoon Wash and Curtis Wash South sections (Fig. 7). Channel facies feature generally upward-fining stacked conglomerate and sandstone beds 1–8 m thick intercalated with thin, typically <1.5 m, sandy siltstones containing calcareous palaeosols (Smith, 1994; Slate *et al.*, 1996). Although trough and planar–tabular cross-bedding are locally present, the channel

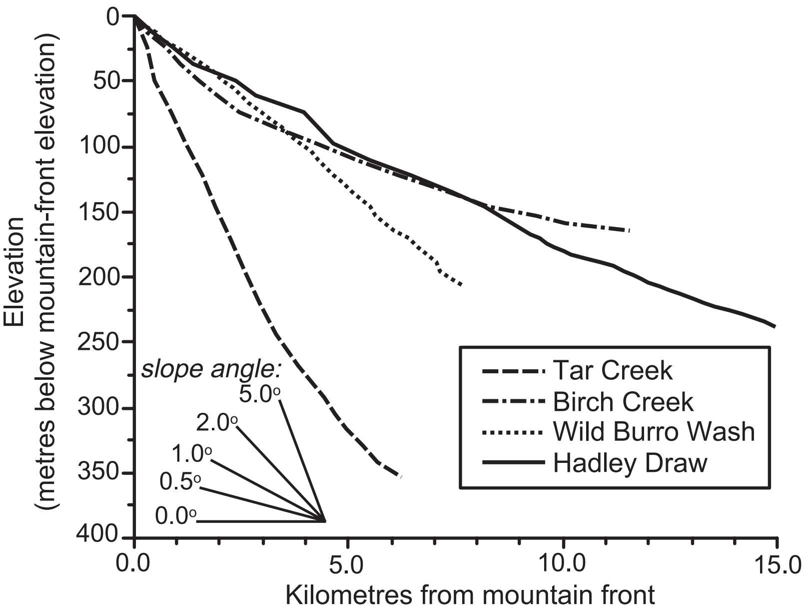

Fig. 5. Channel profiles for the principal alluvial-slope drainages illustrated in Figs 1–3.

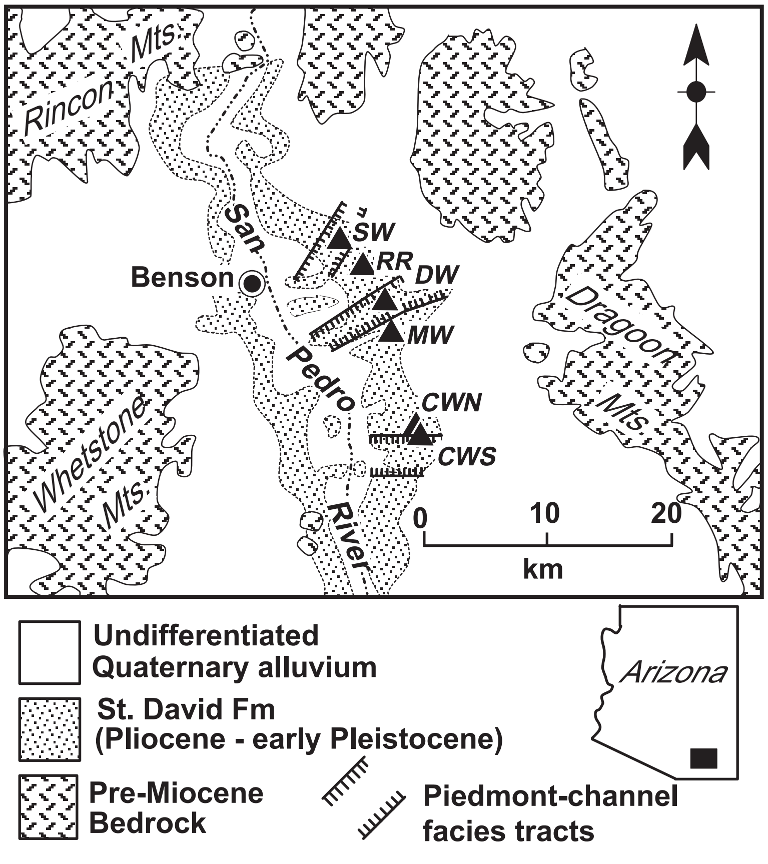

Fig. 6. Location of measured sections (Fig. 7) in the St. David Formation along the San Pedro Valley of south-eastern Arizona.

bodies consist mostly of plane-bedded and scour-and-fill bedded lithofacies (Figs 7 and 8). Locally well-exposed channel margins suggest depths of 1.0–1.8 m with most channel bodies consisting of laterally stacked channel deposits. Both ribbon (< 30 m wide) and sheet (> 30 m wide) channel bodies are present although channel migration within each type precludes easy interpretation of channel widths (Smith, 1994). The intervening floodplain tracts (e.g. McRae Wash and North Curtis Wash sections, Fig. 7) contain thick sequences of massive, reddened mudstone with well-developed calcic soils formed under both well-drained and hydromorphic conditions (Slate *et al*., 1996). Marls in the North Curtis Wash section include hydromorphic soils and pond deposits with local tufa and travertine marking springs. Rare, sharp-based, tabular, plane-parallel and ripple-laminated fine sandstone beds, less than 1 m thick, probably represent flood deposited sand sheets.

The presence of channel and floodplain deposits and lack of sheetflood facies indicate that Pliocene deposition

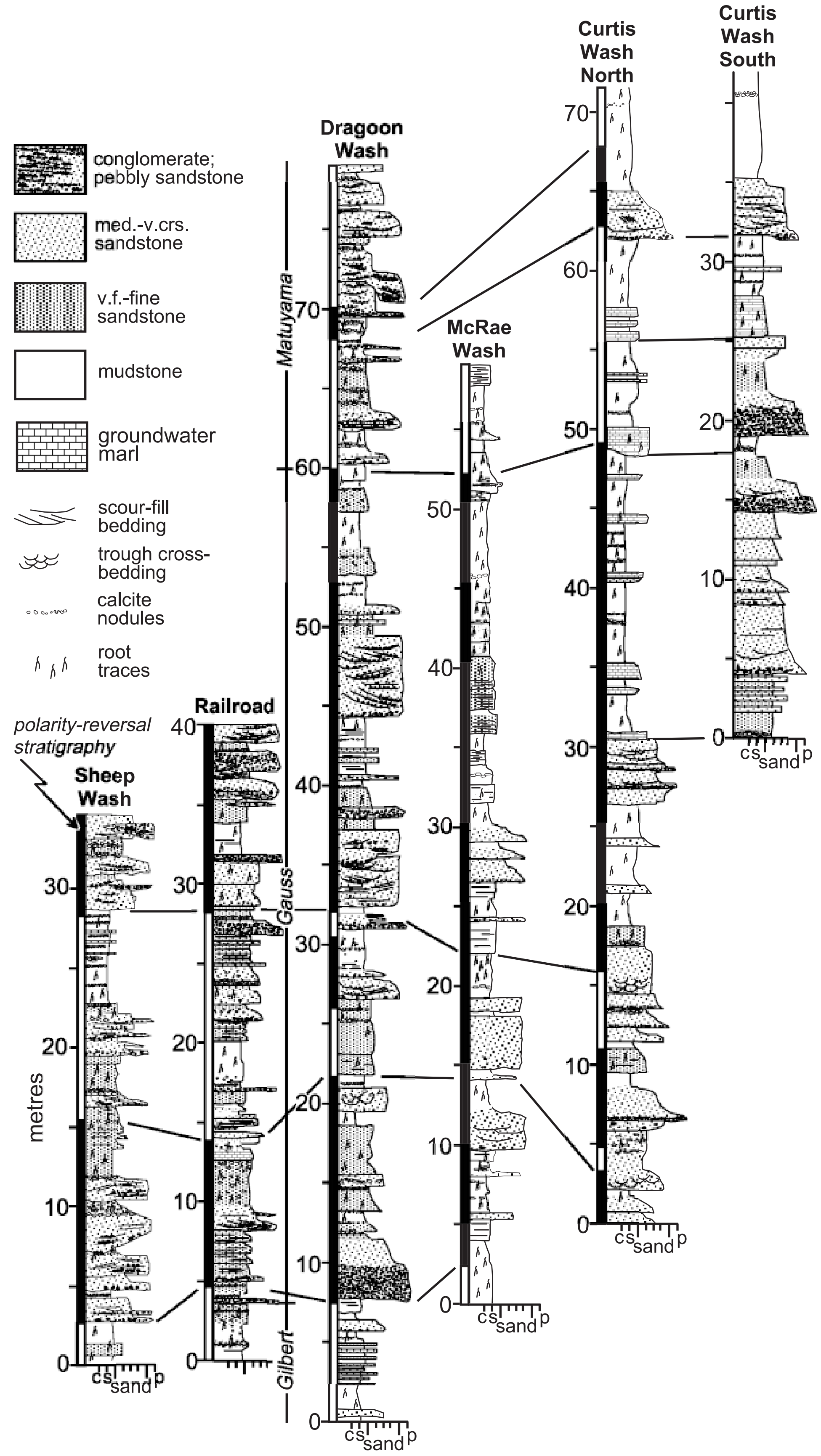

Fig. 7. Stratigraphic sections in the middle member of the St. David Formation representing lower piedmont deposition on the east side of the San Pedro Valley (see Fig. 6 for locations of sections). Polarity reversal stratigraphy from Smith (1994).

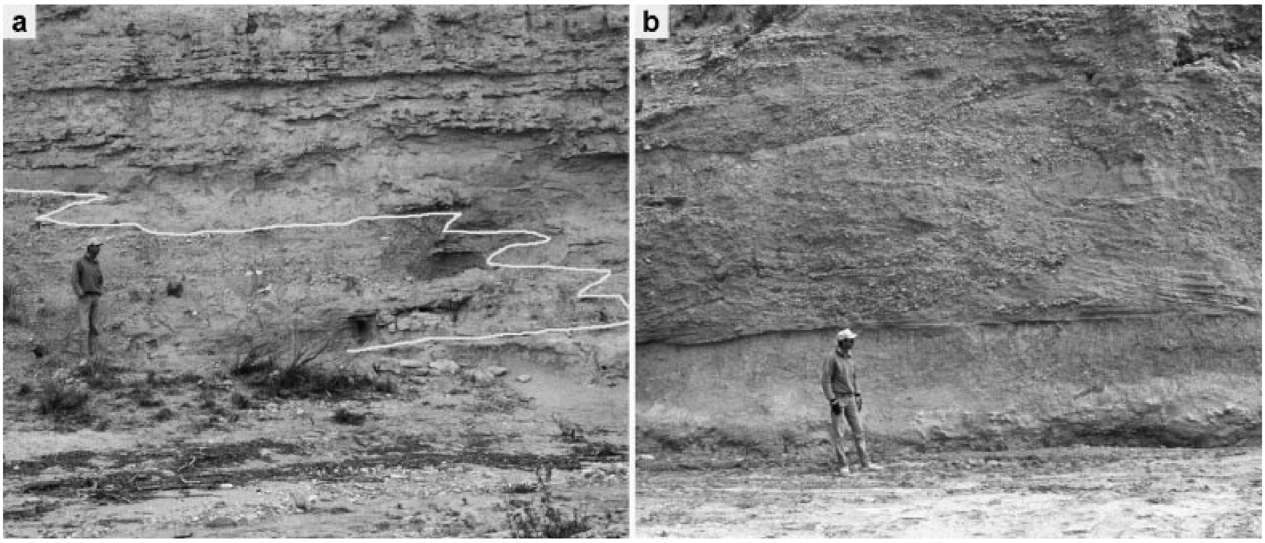

Fig. 8. Photographs of alluvial-slope channel facies in the St. David Formation at Dragoon Wash. (a) Lateral interfingering of channel gravel and bioturbated floodplain sandstone. (b) Base of a cross-bedded channel gravel resting on pedogenically modified floodplain mudstone.

on the eastern piedmont of the San Pedro Valley was associated with widely spaced streams and not alluvial fans. Aggrading floodplains separated three major channel tracts, spaced roughly 10 km apart, and areas of smaller channel systems (e.g. Railroad section). The laterally adjacent environments aggraded mostly vertically at rates of 2.5–7.5 cm kyr^{-1} (Smith, 1994) with channels migrating laterally over distances of less than 3 km.

Tesuque Formation, Miocene, Española basin, New Mexico

The middle Miocene Skull Ridge Member of the Tesuque Formation accumulated on the hangingwall ramp of the Española basin half graben within the Rio Grande rift (Fig. 9). Sandstone provenance and palaeocurrent data clearly demonstrate deposition on the west-sloping piedmont flanking the Sangre de Cristo Mountains (Cavazza, 1986). Superb badland exposures reveal deposition within channels of both ribbon and sheet geometry (Cavazza, 1989; Kuhle, 1997; Kuhle & Smith, in press) and by a complex interrelationship of overbank flooding and aeolian processes in interchannel areas (Kuhle & Smith, in press) but no sheetflood facies indicative of alluvial fans. Based on ages of interbedded tephra layers, accumulation rates were on the order of 50–100 cm kyr^{-1}. Strata are tilted westward toward the basin master fault and exposures are restricted along depositional strike and preclude examination of proximal to distal facies variation within the same stratigraphic level. The deposits illustrated in Figs 10 and 11 are located approximately 10 km from source areas to the east.

Most channel bodies in the middle of the Skull Ridge Member are single storey, 1–1.5 m thick, and composed mostly of coarse pebbly sand and less common conglomerate exhibiting scour-and-fill bedding and rare trough cross-bedding (Figs 10 and 11). Channel deposits are separated, both vertically and laterally, by massive, bioturbated sandy siltstones, interpreted as overbank facies, and laterally persistent, well-sorted fine sand interpreted as aeolian sand sheets between channels (Kuhle & Smith, in press). There are no sheetflood deposits and bedload was clearly conveyed across the piedmont in channels and not distributed across alluvial-fan surfaces.

The lowest 40 m of the Skull Ridge Member is dominated by massive, red, bioturbated calcareous sandy siltstone with rare ribbon channel bodies of sandstone and conglomerate. The upward transition from siltstone-dominated section to sandstone-dominated section has been traced almost continuously for 20 km along strike by taking advantage of an ash-bed marker near the facies transition (Rhoads & Smith, 1995) and represents an abrupt change in piedmont depositional processes. The siltstones seem far too voluminous to be overbank deposits related to the few, small, coarser channel bodies in this part of the section. Indeed, close examination shows that many of the sandy siltstone beds are lenticular and, in some cases, contain lateral accretion beds (Fig. 10). It seems likely therefore that most deposition in this interval was associated with broad vegetated swales, analogous to Hadley Draw (Fig. 3).

Kuhle & Smith (in press) suggest that the abrupt vertical grain-size and facies transition within the Skull Ridge Member was caused by climatic change, although in the absence of a climate proxy the influences of variable subsidence rates cannot be completely excluded. The exclusive presence of rare pond limestone in the lower part of the member and the restriction of aeolian facies to overlying strata are consistent with a transition to a relatively dryer climate and attendant changes in vegetation and discharge characteristics of the streams could account for the observed facies transition.

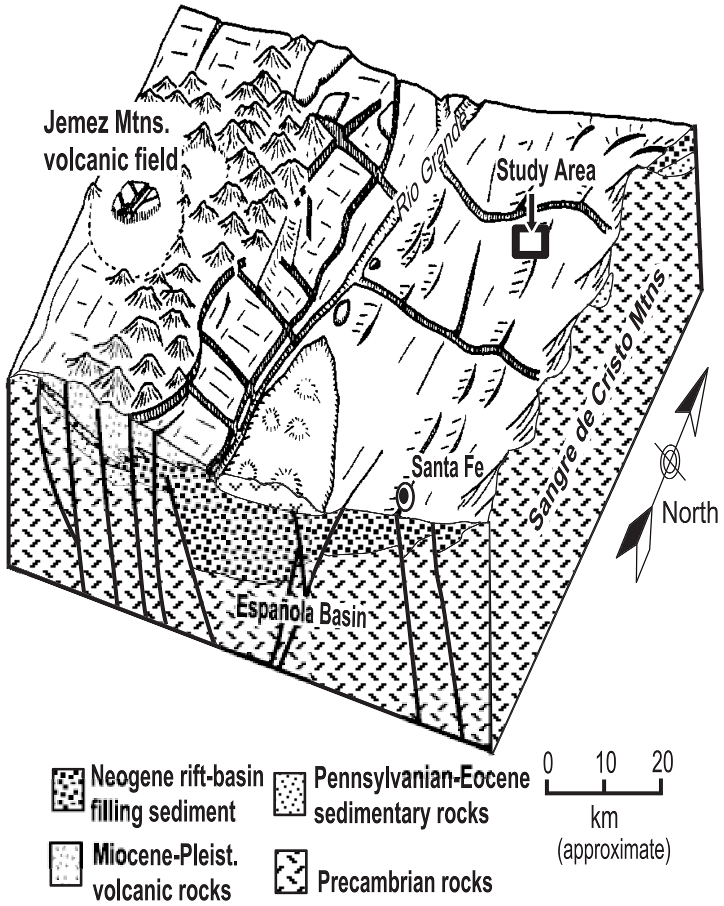

Fig. 9. Block diagram of the Española basin, Rio Grande rift, New Mexico (modified from Golombek *et al.*, 1983), showing location of Tesuque Formation study site within the half graben.

CIRCUMSTANCES FAVOURING DEVELOPMENT OF ALLUVIAL SLOPES

The conditions favouring formation of streamflow-dominated alluvial slopes, rather than unconfined flow on alluvial fans, remain to be determined and cannot be rigorously evaluated on the basis of the few existing relevant studies. The loss of flow confinement that defines alluvial fans likely requires persistent development of accommodation space at the mountain front. Otherwise, proximal depositional slopes would become too steep for the loose, underlying sediment to avoid being eroded by continued flow from the feeder channel. Thus, the fan head becomes entrenched (Denny, 1965, 1967; Hooke, 1967) and a segmented fan is produced, telescoping the active depositional lobes basinward until eventually channellized flow is established across the entire piedmont. It is for this reason that the ‘climatic fans’, as distinguished from ‘tectonic fans’, produce very thin deposits (Bull, 1997). Vegetation may also play an important role in determining the degree of flow confinement. Hyperaridity is favourable for alluvial fan development by restricting the density of vegetation that could serve to stabilize channel banks and also leading to rapid generation of runoff, overland flow and high rates of sediment supply. The modern alluvial slopes illustrated in Figs 1–3 are all moderately vegetated with local riparian communities along channel margins (Fig. 1b). Nonetheless, alluvial fans are also present in temperate climates so vegetation density alone is insufficient to determine the formation of alluvial fans vs. alluvial slopes.

A general survey of topographic maps for the Basin and Range region suggests that alluvial slopes are found in three circumstances. Most alluvial slopes form on piedmonts where there is no abrupt topographic margin at the mountain front and streams draining relatively large watersheds enter the basin through wide topographic embayments in the mountain front (e.g. Fig. 2). The alluvial slopes described by Hawley & Wilson (1965) are also of this type. The lack of a sharply defined mountain front can result from erosion along tectonically quiescent basin margins. That part of a hangingwall ramp that is distant from the master fault in a half graben or strongly asymmetric basin also lacks a fault-defined, topographically abrupt mountain front. Some alluvial slopes grade upslope into alluvial fans and appear to result from recombination of sheet flow off fan surfaces into a contributary drainage network on the lowermost piedmont. These alluvial slopes will form only on piedmonts that are wider than alluvial-fan radius (<10 km and commonly <5 km; Blair & McPherson, 1994b). This circumstance is most commonly encountered on the hangingwall ramp side of asymmetric basins because fans derived from the footwall uplift typically extend to the basin floor close to the locus of maximum subsidence rather than in the geometric centre of the valley.

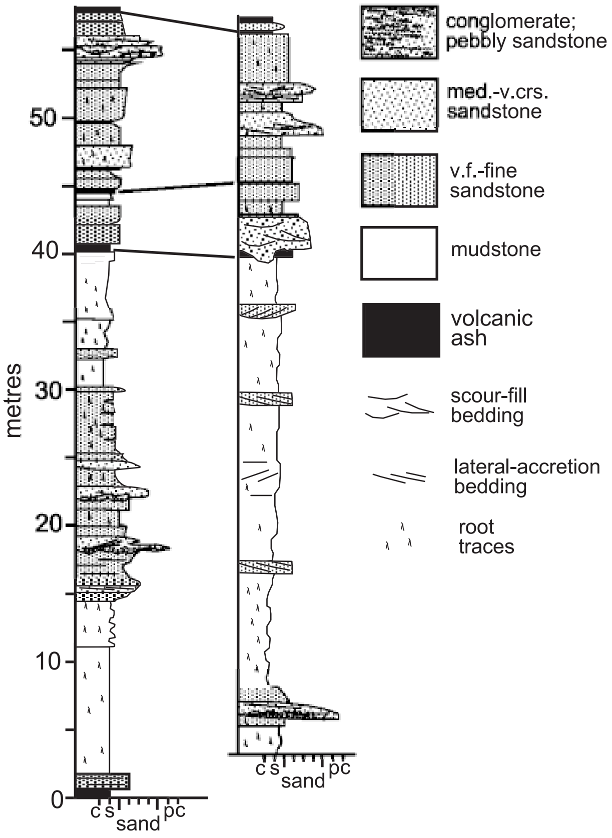

Fig. 10. Stratigraphic sections of the lower part of the Skull Ridge Member of the Tesuque Formation located approximately 4 km apart along depositional and structural strike. The sedimentological attributes of the section change abruptly near the level of an ash bed located 40 m from the base of the member. Strata below this level are markedly siltier although coarse-grained channel bodies are found both above and below the marker ash. Most of the very fine-grained sandstone found above 40 m is of aeolian origin; no aeolian facies are known below the ash marker.

Presumably, most sediment is deposited on the fan surface so that the amount of aggradation on these lower-piedmont alluvial slopes may be very small. The third type of alluvial slope is represented by dendritic drainages exiting extremely small, mountain-front–escarpment drainage basins located between large watersheds associated with mountain-front alluvial fans. These alluvial-slope deposits would be volumetrically minor compared to those derived from larger drainage basins feeding adjacent fans. Interfan alluvial-slope deposits may become buried under laterally prograding alluvial-fan deposits.

For sedimentologists interpreting the ancient stratigraphic record the thickest alluvial-slope deposits will likely be associated with the hangingwall-ramp side of asymmetric basins. The most prominent such deposits would be expected in half grabens where alluvial slopes may extend across a piedmont in the absence of an abrupt, fault-defined mountain front that would favour development of proximal alluvial fans. Geophysical data suggest that the piedmont deposits in the middle member of the St. David Formation accumulated on the hangingwall side of the basin and also suggest that deposition of the studied strata post-dated significant basin subsidence (Smith, 1994). Hence, both basin asymmetry and erosional maturity may have contributed to the development of an alluvial-slope piedmont. Tesuque Formation alluvial-slope facies clearly formed along a long hangingwall ramp in a half graben (Fig. 9).

If mountain-front morphology is the most significant determinant in the formation of alluvial slopes, vs. alluvial fans, then it is all the more important that sedimentologists endeavour to distinguish the deposits of these two piedmont landforms. Recognition of alluvial-slope deposits in an ancient record could, then, be inferred to represent deposition on the hangingwall ramp of a half

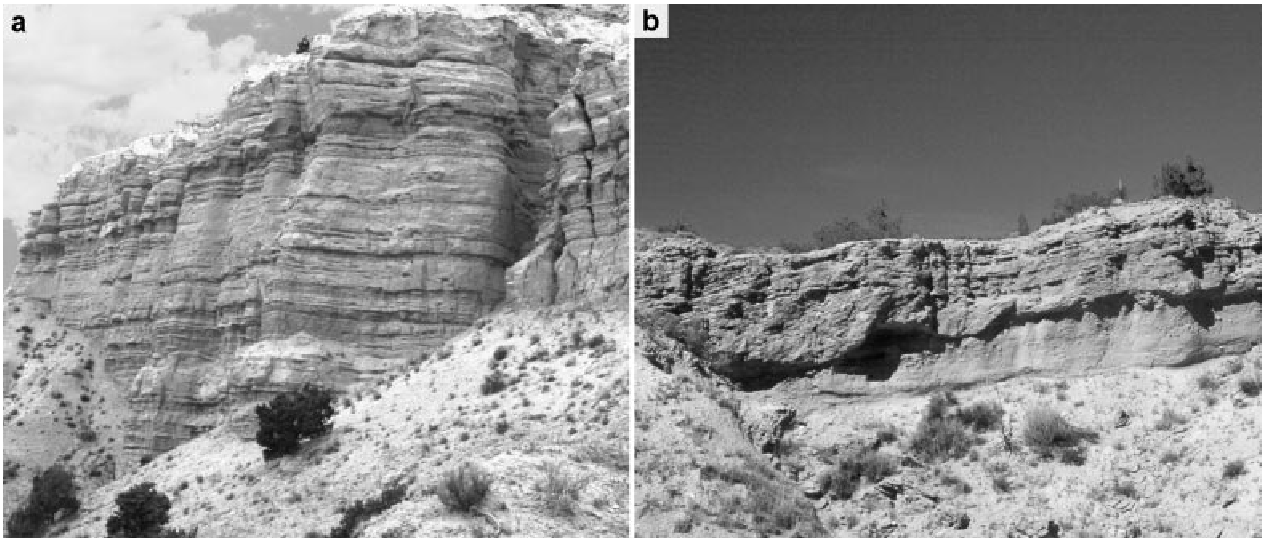

Fig. 11. (a) Approximately 30 m of lower Skull Ridge Member capped by white ash bed (present at 40 m in the section in Fig. 10). Mostly fine-grained alluvium contains channel forms and lateral-accretion surfaces suggesting not only overbank deposition but also sedimentation in vegetated channels (cf. Fig. 3). (b) Cross-bedded gravel channel fill resting erosively on pedogenically modified floodplain siltstone in the upper part of the Skull Ridge Member.

graben or to represent deposition adjacent to a footwall uplift during a period of relative tectonic quiescence in which the mountain front has become erosionally embayed, or where there is insufficient accommodation for a fan, or both. It must be emphasized, however, that at the present stage of understanding these suggestions stand only as testable hypotheses, not definitive guides for interpretation.

SIGNIFICANCE OF ALLUVIAL-SLOPE DEPOSITS TO RESOURCE STUDIES

Distinction of alluvial-slope and alluvial-fan deposits should be significant for evaluating the geometry of and heterogeneity within hydrocarbon reservoirs and aquifers hosted in extensional-basin successions. Coarse-grained sediment will be transported further into the basin by streams than by sheetfloods on fan surfaces (Fig. 4). Although flashy, unsteady flows in alluvial-slope channels may produce poorly sorted deposits, they will likely be better sorted than most alluvial-fan sheetflood deposits of comparable median grain size because (1) sediment in channels is more likely to be reworked and sorted by waning and subsequent flows, and (2) suspended load will be mostly deposited separately from bedload on interchannel floodplains rather than along with coarser sediment on sheetflood fan lobes. Lateral spreading of flow on alluvial fans should produce beds that are extensive along depositional strike and which undergo significant changes in facies type and, in many cases, grain size downslope. Alluvial slopes, like other fluvial environments, exhibit greatest contrast between laterally adjacent channels and floodplains and less significant changes in grain size and facies architecture along depositional dip. Because the hangingwall-derived piedmont deposits underlie the largest areal extent of asymmetric extensional basins, study of alluvial slopes and their resulting deposits may be critical to understanding rift-basin aquifers and reservoirs.

The St. David and Tesuque Formations offer strongly contrasting views of large-scale facies architecture resulting from alluvial-slope deposition. Widely spaced channel systems in the St. David Formation (Figs 5 and 6) produce broad swaths of more permeable facies parallel to depositional dip that likely persist over most of the piedmont width (~ 20 km). Channel spacing in the Española basin (Tesuque Formation) was apparently much closer than in the San Pedro Valley (St. David Formation) because such dramatic along-strike variations in proportions of channel and floodplain facies have not been recognized. Instead, vertical alternations in laterally persistent facies reflect wholesale changes in sediment transport and deposition on the piedmont (Fig. 10). The vertical alternation of relatively coarse- and fine-grained intervals is generally characteristic of much of the piedmont facies of the Tesuque Formation and is distinct from the typically considered grain-size cycles interpreted to result from shifting of alluvial-fan and basin-floor facies (e.g. Blair & Bilodeau, 1988). Finer grained strata produce local confining layers within the regionally important Tesuque aquifer (Hearne, 1985). Recharge and contaminant-transport pathways from a perched surficial alluvial aquifer are determined by where the surficial deposits overlie coarser, rather than finer, intervals within the tilted, underlying Tesuque Formation (Lazarus & Drakos, 1995).

CONCLUSION

Thorough study of modern alluvial-slope deposits has not yet been accomplished, and late Holocene to historic channel incision throughout most of the south-west United States may preclude easy study of aggrading examples in that region analogous to the stratigraphic record. Nonetheless, a number of critical features permit recognition of ancient alluvial-slope facies assemblages within outcrops where palaeocurrent or provenance data indicate piedmont deposition. These include: (1) recognition of distinct channel and floodplain deposits; (2) lack of widespread, tabular sheetflood and sediment-gravity-flow beds and (3) sedimentary structures indicative of deposition from unsteady, shallow, upper-flow-regime flows on piedmont slopes that are generally steeper than those associated with better studied deposits of larger rivers. The distinction of alluvial-slope and alluvial-fan successions should not be obscured by what some might view as a semantic debate over how broadly or narrowly to define alluvial fans. The depositional processes constructing alluvial slopes are distinct from those that construct strictly defined alluvial fans. It is hypothesized that the most important, of many potential, factors favouring formation of piedmont fans vs. alluvial slopes are related to mountain front morphology, which may in turn relate to the tectonic architecture and history of an extensional basin. If this is true, then greater attention to the complexities of piedmont facies may elucidate important tectonic interpretations as part of overall basin analysis. Regardless of how the origin of alluvial slopes becomes understood, predictable hydrocarbon-reservoir and groundwater-aquifer properties of alluvial slopes are distinct from those of alluvial fans.

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REFERENCES

Abrahams, A.D. & Parsons, A.J. (1994) *Geomorphology of Desert Environments*. Chapman & Hall, London.

Baker, V.R. & Ritter, D.F. (1975) Competence of rivers to transport coarse bedload material. *Geol. Soc. Am. Bull.*, **86**, 975–978.

Bates, R.L. & Jackson, J.A. (1987) *Glossary of Geology*, 3rd edn. American Geological Institute, Alexandria, Virginia.

Blair, T.C. (1987) Sedimentary processes, vertical stratification sequences, and geomorphology of the Roaring River alluvial fan, Rocky Mountain National Park. *J. Sedim. Res.*, **57**, 845–862.

Blair, T.C. (1999) Sedimentary processes and facies of the waterlaid Anvil Springs Canyon alluvial fan, Death Valley, California. *Sedimentology*, **46**, 913–940.

Blair, T.C. & Bilodeau, W.L. (1988) The development of tectonic cyclothems in rift, pull-apart, and foreland basins: sedimentary response to episodic tectonism. *Geology*, **16**, 517–520.

Blair, T.C. & McPherson, J.G. (1994a) Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *J. Sedim. Res.*, **A64**, 450–489.

Blair, T.C. & McPherson, J.G. (1994b) Alluvial fan processes and forms. In: *Geomorphology of Desert Environments* (Ed. by D. Abrahams & A.J. Parsons), pp. 354–402. Chapman & Hall, London.

Bridge, J.S. & Bennett, S.J. (1992) A model for the entrainment and transport of sediment grains of mixed sizes, shapes, and densities. *Water Res. Res.*, **28**, 337–363.

Bryan, K. (1922) Erosion and sedimentation in the Papago country, Arizona, with a sketch of the geology. *US Geol. Surv. Bull.*, **730**, 19–90.

Bull, W.B. (1972) Recognition of alluvial-fan deposits in the stratigraphic record. In: *Recognition of Ancient Sedimentary Environments* (Ed. by J.K. Rigby & W.K. Hamblin), *Soc. Econ. Paleont. Mineral. Spec Publ.*, **16**, 63–83.

Bull, W.B. (1977) The alluvial fan environment. *Prog. Phys. Geogr.*, **1**, 222–270.

Bull, W.B. (1991) *Geomorphic Responses to Climatic Change*. Oxford University Press, New York.

Bull, W.B. (1997) Discontinuous ephemeral streams. *Geomorphology*, **19**, 227–276.

Cavazza, W. (1986) Miocene sediment dispersal in the central Española Basin, Rio Grande rift, New Mexico, USA. *Sediment. Geol.*, **51**, 119–135.

Cavazza, W. (1989) Sedimentation pattern of a rift-filling unit: Tesuque Formation (Miocene), Española basin, Rio Grande rift, New Mexico. *J. Sedim. Petrol.*, **59**, 287–296.

Cooke, R.U. & Warren, A. (1973) *Geomorphology in Deserts*. Batsford Ltd, London.

Denny, C.S. (1965) Alluvial fans in the Death Valley region, California and Nevada. *US Geol. Surv. Prof. Pap.*, **466**.

Denny, C.S. (1967) Fans and pediments. *Am. J. Sci.*, **265**, 81–105.

Fields, J.J. (1994) Surficial processes, channel change, and geological methods of flood-hazard assessment on fluvially dominated alluvial fans in Arizona. PhD Dissertation, University of Arizona, Tucson.

Friend, P.F. (1978) Distinctive features of some ancient river systems. In: *Fluvial Sedimentology* (Ed. by A.D. Miall), *Can. Soc. Petrol. Geol. Mem.*, **5**, 531–542.

Galloway, W.E. & Hobday, D.K. (1996) *Terrigenous Clastic Depositional Systems*, 2nd edn. Springer-Verlag, Berlin.

Golombek, M.P., McGill, G.E. & Brown, L. (1983) Tectonic and geologic evolution of the Espanola basin, Rio Grande rift: structure, rate of extension, and relation to the state of stress in the western United States. *Tectonophysics*, **94**, 483–507.

Graf, W.L. (1988) *Fluvial Processes in Dryland Rivers*. Springer-Verlag, Berlin.

Harvey, A.M. (1997) The role of alluvial fans in arid zone fluvial systems. In: *Arid Zone Geomorphology: Process, Form and Change in Drylands*, 2nd edn (Ed. by D.S.G. Thomas), pp. 231–259. John Wiley and Sons, London.

Hawley, J.W. & Wilson, W.E. III (1965) Quaternary geology of the Winnemucca area, Nevada. *Desert Res. Inst. Techn Report*, **5**, 66+ pp.

Hearne, G.A. (1985) Simulation of an aquifer test on the Tesuque Pueblo Grant, New Mexico. *US Geol. Surv. Water-Sup. Pap.*, **2206**.

Heward, A.P. (1978) Alluvial fan sequence and megasequence models: with examples from Westphalian D – Stephanian B coalfields, northern Spain. In: *Fluvial Sedimentology* (Ed. by A.D. Miall), *Can. Soc. Petrol. Geol. Mem.*, **5**, 669–702.

Hooke, R.L. (1967) Processes on arid-region alluvial fans. *J. Geol.*, **75**, 438–460.

Jo, H.R., Rhee, C.W. & Chough, S.K. (1997) Distinctive characteristics of a streamflow-dominated alluvial fan deposit: Sanghori area, Kyongsang basin (Early Cretaceous), southeastern Korea. *Sediment. Geol.*, **110**, 51–79.

Kelly, S.B. & Olsen, H. (1993) Terminal fans – a review with reference to Devonian examples. *Sediment. Geol.*, **85**, 339–374.

Kuhle, A.J. (1997) Sedimentology of Miocene alluvial-slope deposits, Española Basin, Rio Grande rift: an outcrop analogue for subsurface heterogeneity. MSc Thesis, University of New Mexico.

Kuhle, A.J. & Smith, G.A. (in press) Alluvial-slope deposition of the Skull Ridge Member of the Tesuque Formation, Española basin, New Mexico. *New Mex. Geol.*, in press.

Lazarus, J. & Drakos, P. (1995) Geohydrologic characteristics and hydrocarbon contamination of the shallow alluvial/ Tesuque Formation aquifer, Santa Fe, New Mexico. In: *Geology of the Santa Fe Region* (Ed. by P.W. Bauer, B.S. Kues, N.W. Dunbar, K.E. Karlstrom & B. Harrison), *New Mex. Geol. Soc. Guid.*, **46**, 307–311.

Leeder, M.R. (1978) A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness. In: *Fluvial Sedimentology* (Ed. by A.D. Miall), *Can. Soc. Petrol. Geol. Mem.*, **5**, 587–596.

Leeder, M.R., Mack, G.H. & Salyards, S.L. (1996) Axial–transverse fluvial interactions in half graben: Plio-Pleistocene Palomas basin, southern Rio Grande rift, New Mexico, USA. *Basin Res.*, **12**, 225–241.

Love, D.W. & Seager, W.R. (1996) Fluvial fans and related basin deposits of the Mimbres drainage. *New Mex. Geol.*, **18**, 81–92.

Mack, G.H., Love, D.W. & Seager, W.R. (1997) Spillover models for axial rivers in regions of continental extension: the Rio Mimbres and Rio Grande in the southern Rio Grande rift, USA. *Sedimentology*, **33**, 637–652.

Miall, A.D. (1997) *The Geology of Fluvial Deposits*. Springer-Verlag, Berlin.

van Niekerk, A., Vogel, K.R., Slingerland, R.L. & Bridge, J.S. (1992) Routing of heterogeneous sediments over movable bed: model development. *ASCE J. Hydr. Eng.*, **116**, 246–262.

Rhoads, M. & Smith, G.A. (1995) Contrasting modes of tephra preservation in the Skull Ridge Member of the Tesuque Formation. In: *Geology of the Santa Fe Region* (Ed. by P.W. Bauer, B.S. Kues, N.W. Dunbar, K.E. Karlstrom & B. Harrison), *New Mex. Geol. Soc. Guid.*, **46**, 5.

Ritter, J.B., Miller, J.R., Enzel, Y., Howes, S.D., Nadon, G., Grubb, M.D., Hoover, K.A., Olsen, T., Reneau, S.L., Sack, D., Summa, C.L., Taylor, I., Touysinhthiphonexay, K.C.N., Yodis, E.G., Schneider, N.P., Ritter, D.F. & Wells, S.G. (1993) Quaternary evolution of Cedar Creek alluvial fan, Montana. *Geomorphology*, **8**, 287–304.

Rust, B.R. & Koster, E.H. (1984) Coarse alluvial deposition. In: *Facies Models,* 2nd edn (Ed. by. R.G. Walker), *Geosci. Can. Repr. Ser.*, **1**, 9–21.

Slate, J.L., Smith, G.A., Wang, Y. & Cerling, T.E. (1996) Carbonate-paleosol genesis in the Pliocene-Pleistocene St. David Formation, southeastern Arizona. *J. Sedim. Res.*, **66**, 85–94.

Slingerland, R., Harbaugh, J.W. & Furlong, K. (1994) *Simulating Clastic Sedimentary Basis. Physical Fundamentals and Computer Programs for Creating Dynamic Systems*. Prentice Hall, Englewood Cliffs.

Smith, G.A. (1994) Climatic influences on continental sedimentation during late-stage filling of an extensional basin, southeastern Arizona. *Geol. Soc. Am. Bull.*, **106**, 1212–1228.

Stanistreet, I.G. & McCarthy, T.S. (1993) The Okavango fan and the classification of subaerial fan systems. *Sediment. Geol.*, **85**, 115–133.

Summerfield, M.A. (1991) *Global Geomorphology*. J. Wiley and Sons, New York.

Tunbridge, I.P. (1981) Sandy high-energy flood sedimentation – some criteria for recognition, with an example from the Devonian of S.W. England. *Sediment. Geol.*, **28**, 79–95.

Viseras, C. & Fernandez, J. (1994) Channel migration patterns and related sequences in some alluvial fan systems. *Sediment. Geol.*, **88**, 201–217.

Wells, N.A. & Dorr, J.A. Jr (1987) A reconnaissance of sedimentation on the Kosi alluvial fan of India. In: *Recent Developments in Fluvial Sedimentology* (Ed. by F.G. Ethridge, R.M. Flores & M.D. Harvey), *Soc. Econ. Paleont. Mineral. Spec. Publ.*, **39**, 51–62.

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