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Steven G. Crews

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TECTONIC CONTROL OF SYNRIFT SEDIMENTATION PATTERNS, RESERVE GRABEN, SOUTHWESTERN NEW MEXICO

STEVEN G. CREWS

ARCO Exploration & Production Technology, 2300 West Plano Parkway, Plano, TX 75075

Abstract—The Reserve graben is part of a Miocene and younger extensional corridor that lies between the Mogollon Plateau volcanic center and the Colorado Plateau; it comprises a series of distinct half-graben sub-basins, each associated with one or more bounding normal faults, and each filled with alluvial deposits of the Gila Group. Topography and uplift/subsidence patterns created by extensional faulting directly influenced nearly every aspect of synrift sedimentation. Thickness, texture, sediment-transport direction and depositional environment of the synrift sediments were all directly affected by episodic movement on basin-bounding normal faults. The primary depositional environments represented in the deposits in these half grabens are hanging wall dip-slope alluvial fans, axial fluvial systems and footwall-derived alluvial fans. The footwall-derived fans are coarser grained, but areally smaller and less common than the dip-slope fans, which dominate the basin. Mass-flow deposits filling arroyos (which probably fed the hanging wall fans), and small colluvial wedges originating from fault scarps, have also been recognized. No lacustrine deposits have been identified. Two tectonic influences stand out. First, paleoflow was mostly either down structural dip or along strike—i.e., dip-slope fans and axial fluvial systems dominate the basin fill. This suggests that fault kinematics directly affected drainage patterns. Second, the finest-grained deposits in each half graben often occur adjacent to the fault scarps, in spite of the high topographic relief found there. Many individual processes probably contributed to this situation, but most can be traced back ultimately to the influence of fault kinematics on topography and on the distribution of uplift and subsidence within the basin. In general, footwall uplifts in the Reserve graben do not act as prolific line sources of sediment. Large influxes of footwall sediment occur only at a few special points, such as topographic gaps associated with transfer zones in the border fault system.

INTRODUCTION

Tectonics and sedimentation in continental rifts

The distinctly asymmetrical "half graben" morphology that characterizes most extensional basins can exert a strong influence on drainage, distribution of sedimentary environments and, ultimately, on stratigraphic architecture (Davis, 1925; Blair, 1987; Leeder and Gawthorpe, 1987; Frostick and Reid, 1987; Mack and Seager, 1990; Paton, 1992; Leeder and Jackson, 1993). Sedimentation patterns are also influenced by other related structural/tectonic features characteristic of extensional basins, including (1) the formation of low- or high-relief "accommodation zones" at transfer zones between alternating-polarity sub-basins; (2) transfer zones or other discontinuities in border fault systems; (3) the asymmetry of rift-shoulder or footwall uplifts; (4) the episodic nature of faulting; and (5) the geometry and kinematics of normal faults (Rosendahl, 1987; Hamblin and Rust, 1989; Morley, 1989; Crews and McGrew, 1990; Mack and Seager, 1990; Cohen, 1991; Lambiase, 1991; Schlische, 1991; Scholz and Rosendahl, 1991; Gawthorpe and Hurst, 1993).

A typical half graben is characterized by an abruptly faulted, high-relief margin on one side, contrasting with a hinged or more gradually faulted opposing margin with proportionately lower topographic relief. If the structural asymmetry of a half graben is mirrored in the surface topography during tectonically active periods, the basin floor will slope in the same direction as the structural dip (i.e., towards the fault-bounded margin of the basin). Leeder and Gawthorpe (1987) termed this concordance between land surface and structure "tectonic slope".

Depositional systems having deposits contributing to the fill of a continental half graben can be divided into four basic groups: (1) transverse alluvial systems with a source on the hanging wall dip slope and flowing down the tectonic slope; (2) transverse systems flowing into the basin from the footwall uplift (opposing tectonic slope, if they cross the basin axis); (3) longitudinal fluvial systems, flowing parallel to the axis of the basin (perpendicular to tectonic slope); and (4) low energy or slope-independent/autochthonous depositional systems such as lakes, swamps, playas and ergs that may occupy a topographic low coincident with the structural axis of the basin. Various depositional systems of these four classes will in essence compete to fill the basin, and to dominate the stratigraphic architecture of the preserved basin fill. The relative proportions of deposits from each group, and the characteristics of each group's component facies, depend on a variety of factors including rate, magnitude and episodicity of extension, fault spacing and kinematics, climate, watershed size and pre-existing geology.

Intuitively, one might expect the high relief typically found on the fault-bounded margins of a half graben to result in the construction of large alluvial fans or braidplains that prograde across the basin, dominating the stratigraphic architecture. However, this is clearly not the case in most rift basins. Davis (1925) noted "flat detrital plains, sloping gently *toward* the ranges" throughout the Great Basin. The competition between low-relief but large-area hanging wall catchments and high-relief small-area footwall catchments is usually won by the dip-slope systems—drainage area is apparently more critical than drainage basin relief in determining sediment yield. Death Valley provides an excellent modern example of this phenomenon (Fig. 1).

The contribution of footwall-uplift-source fans to the basin fill is usually limited for several reasons. The total sediment flux may be low because footwall uplifts are typically narrow, severely limiting the amount of sediment they can provide, and the asymmetry of footwall uplifts tends to create a dip slope that promotes transport *away* from the associated half graben, rather than into it (of course, in many extensional provinces, the footwall uplift of one half graben may form the dip slope of another half graben). From this it may be seen that the footwall uplift is not so much a contributor of sediment as a barrier to sediment from beyond the rift shoulder getting into the basin. Moreover, since rapid subsidence and uplift are juxtaposed at the faulted margin of a half graben, sediment that does enter the basin from the footwall-uplift will tend to be absorbed by the rapidly subsiding basin axis. Significant progradation cannot occur unless sediment flux is sufficient to overfill the axis and reverse the tectonic slope.

An important exception to the foregoing occurs when streams enter the basin from the footwall but their source is not in the footwall. Topographic gaps in footwall uplift (associated with transfer zones or other discontinuities in bounding fault system) may allow streams that access large drainage basins located beyond the rift shoulder into the half graben. Explanations of why footwall-uplift clastic wedges typically do not dominate half-graben basin fill are more fully developed by Blair (1987), Blair and Bilodeau (1988), Crews, (1993), Leeder and Gawthorpe (1987), and Leeder and Jackson (1993).

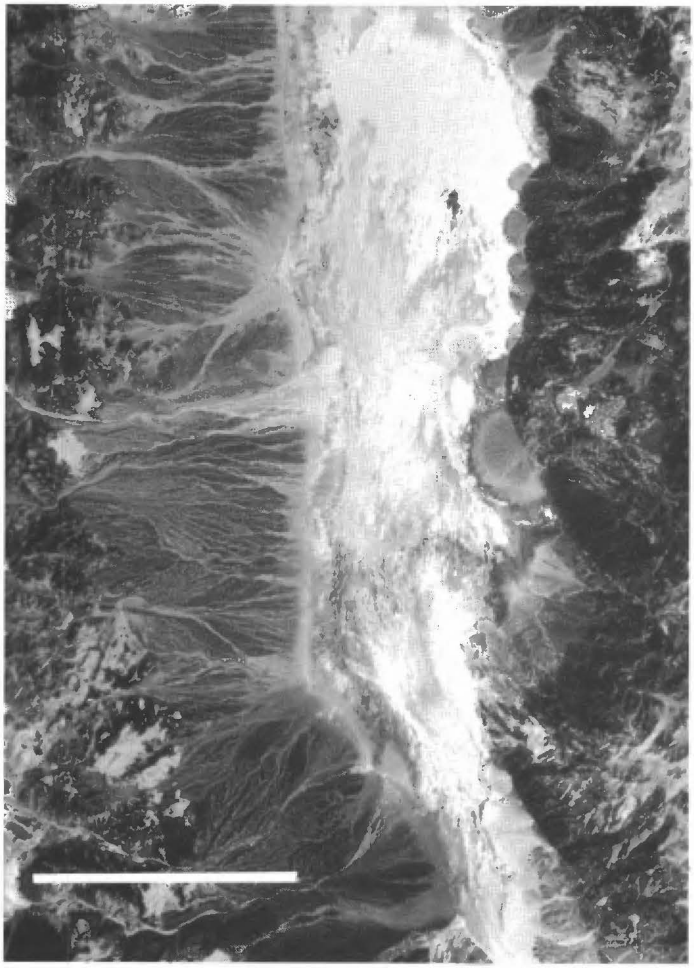

FIGURE 1. SPOT image of southern Death Valley, USA. The structure of Death Valley is that of a half graben, in which the main bounding fault zone is adjacent to the Black Mountains (right side of image), while the Panamint Range (left) forms the hinged margin. The dip-slope alluvial fans issuing from the Panamint Range cover a much larger area and coalesce more extensively than the footwall fans issuing from the Black Mountains. The relatively wide flat area adjacent to the footwall uplift is occupied by a playa lake during wet climatic periods; currently, it is a salt pan. If an axial river system existed, it would presumably flow down this corridor. Scale bar is approximately 10 km long (from cover of GSA Bulletin, v. 101, November, 1989).

Geologic setting

The Reserve graben lies between the southeastern edge of the Colorado Plateau and the northwestern rim of the Mogollon Plateau, in Catron County, New Mexico (Fig. 2). The graben forms one link in a chain of narrow mid-Miocene and younger extensional basins that encircles and helps defines the Mogollon Plateau, a topographic high that was a major center of caldera-derived mid-Tertiary ignimbrites within the larger Mogollon-Datil volcanic field (Elston et al., 1973; Ratté et al., 1984; Bornhorst, 1988).

The basins adjoining the Reserve graben are the San Agustin Basin, directly to the east-northeast, and the Mangas trench, or Glenwood graben, directly to the south-southeast (Figs. 2 and 3). The San Agustin Basin is notable because it is still a largely undissected, hydrologically closed basin, whereas most of the other basins in the region have been incised and partially exhumed by integrated Quaternary stream systems. The Reserve graben is itself drained and dissected by the San Francisco River—a principal tributary of the Gila River—and its own tributaries. The sedimentary rocks filling the Reserve graben comprise the mid-Miocene and younger Gila Group.

The main axis of the Rio Grande rift lies immediately across the Mogollon Plateau, a distance of about 100 km; it is linked to the Reserve graben by the San Agustin Basin (Fig. 2). As a result of its unique location at the intersection of the Basin and Range province, Rio Grande rift, Colorado Plateau and Mogollon-Datil volcanic field, the tectonic evolution of the Reserve graben is intertwined with that of each of these features.

Intermediate volcanism in the Mogollon-Datil volcanic field began about 40 Ma and continued until about 21 Ma, punctuated by episodes of silicic ignimbrite eruption (Elston et al., 1973; Elston, 1984; Ratté et al., 1984; Bornhorst, 1988; McIntosh et al., 1992). The Mogollon Plateau, now a topographically high region rimmed by Miocene extensional faults and defined geophysically by a distinct gravity anomaly (Krohn, 1976), was a particularly notable center of ignimbrite eruption, especially during a brief but intense burst of activity 27.4 to 29 Ma (McIntosh et al., 1992). Elston et al. (1976) suggested that the pattern of Basin and Range faulting surrounding the Mogollon Plateau may reflect an underlying batholith: "Basin and Range faults, younger than the Mogollon Plateau, tend to wrap around it ... [this] pattern may reflect adjustment to the buoyant and rigid mass of the inferred Mogollon Plateau composite pluton, modified by regional trends ..." The regional trends referred to include the Morenci-Reserve trend and San Agustin trend, or Morenci lineament, of Ratté (1989).

Mid-Tertiary andesitic volcanism ended in the region, and throughout much of the Basin and Range, by 21 Ma. Subsequent volcanism has largely consisted of a bimodal association dominated by true basalts and high-silica rhyolites, with less intermediate-composition material (Elston et al., 1973; Ratté et al., 1984; Hamilton, 1987). A correlation between this change in magma composition and the beginning of Basin-and-Range-style block faulting and sedimentation has been noted by many workers, especially—but not only—in southwestern New Mexico (Elston et al., 1976; Elston and Bornhorst, 1979; Ratté et al., 1984; Engebretson et al., 1984; Coney, 1987). However, Chapin (1988), emphasized slightly earlier basin sedimentation in the Rio Grande rift proper: "sedimentary basins were accumulating bolson-type sediments along the entire length of the Rio Grande rift by 25-27 Ma".

In the Reserve graben, Gila Group sediments that were clearly deposited in the context of the same fault blocks that define current topography overlie pre-faulting 23-27 Ma Bearwallow Mountain Andesite, and are interbedded with basalt flows having ages ranging from 1 to 21 Ma (Marvin et al., 1987; Ratté, 1989; Ratté and Bové, 1990). These relationships are consistent with a change in tectonic style during the 40-Ma history of the extensional orogen, and imply that this change occurred about 21 Ma in southwestern New Mexico.

The basic structure of the Reserve Basin is illustrated in Figures 3 and 4. The San Francisco Mountains, on the northwest, and the Tularosa Mountains, on the southeast, define the primary margins of the basin, while some smaller intrabasin ranges, notably Jon S Mountain, Higgins Mountain and the Saliz Mountains, split the basin into two or more separate half grabens. Principal faults strike north-northeast to northeast, and nearly all dip southeasterly (some down-to-the-northwest faults occur near the southeast margin of the basin). Transverse faults that strike roughly east-west are associated with mountainous zones at each end of the basin, separating the Reserve graben from its neighbors.

The San Francisco Mountains fault zone, which defines the northwest margin of the Reserve graben, appears to be the main bounding fault zone of the basin. The steep dips noted near the footwall cutoffs of the fault-bounded intra-basin uplifts suggests a domino-style, fault-rotation model for the structure of the basin (Fig. 4). However, apparent tilting of footwall rocks may not always be sufficiently diagnostic to allow discrimination between dominoes and closely spaced non-rotating listric faults (Stewart, 1971; McGrew and Crews, 1990).

The sedimentary unit that fills the basin, the Gila Group, was named by G.K. Gilbert (1875) for exposures "along the gorges of the Upper Gila and its tributaries"; it is quite possible, but not recorded, that Gilbert visited the Reserve graben itself. Gilbert (1875) defined the Gila as:

> "A system of valley beds, of which a conglomerate is the characteristic member... The bowlders of the conglomerate are of local origin, and their derivation from particular mountain flanks is often

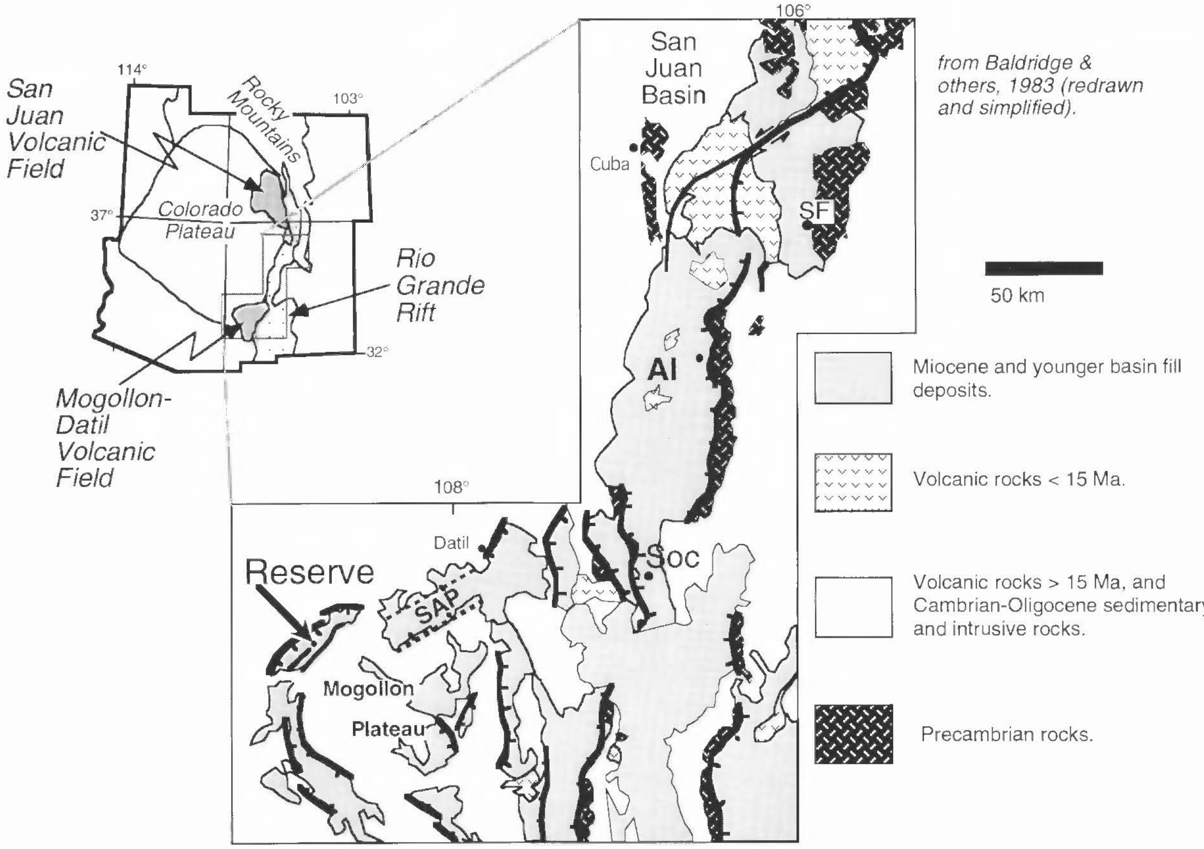

FIGURE 2. Regional location map, placing the Reserve graben in the context of the Basin and Range province, Colorado Plateau and Rio Grande rift. Abbreviations: SF = Santa Fe; Al = Albuquerque; Soc = Socorro; SAP = Plains of San Agustin.

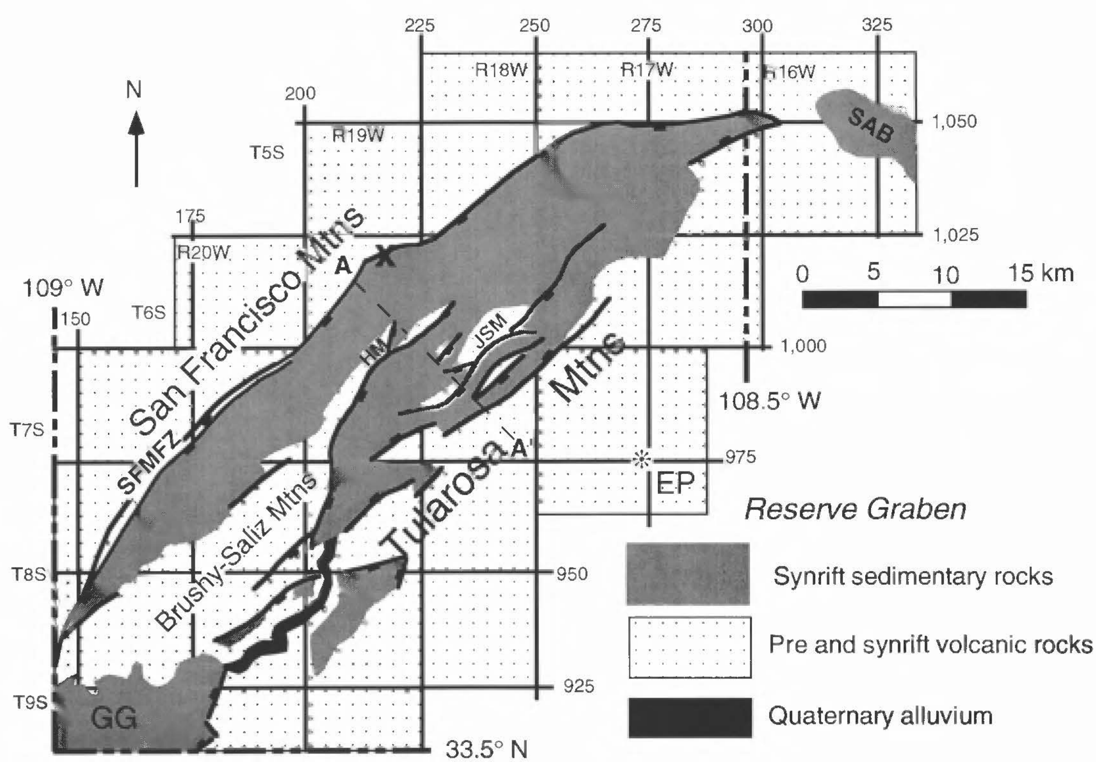

FIGURE 3. Simplified tectonic map of the Reserve graben. Abbreviations: SAB = San Agustin Basin; JSM = Jon S Mountain; EP = Eagle Peak; HM = Higgins Mountain; SFMZ = San Francisco Mountains fault zone; GG = Glenwood graben. "X" marks "the Box"—a box canyon located on a bend in the SFMZ where the modern San Francisco river enters the basin, and where a large Miocene alluvial fan complex was located (see text). Line A-A' marks the location of the cross section shown in Fig. 4. JSM, HM and Brushy-Saliz Mountains are intra-basin tilted fault blocks. Most bounding faults dip southeast; most strata dip northwest.

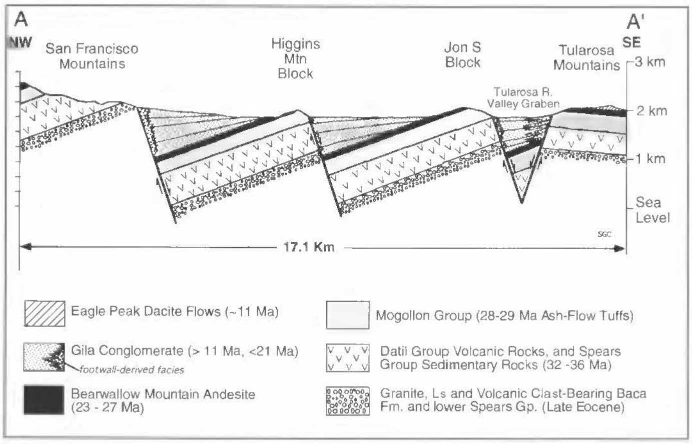

Figure 4. Diagrammatic cross section across the Reserve graben (line of section indicated on Fig. 3). Note the "domino"- like effect of a section across an area comprising several intra-basin fault blocks. Deep fault geometry is not known, nor is pre-Baca stratigraphy.

> indicated by the slopes of the beds ... Its cement is calcareous. Interbedded with it are layers of slightly coherent sand, and of trass, and sheets of basalt ... One thousand feet of the beds are frequently exposed, and the maximum exposure on the Prieto [River] is probably 1,500 feet."

Constraints on the age of the Gila Group in the Reserve graben were mentioned above—the base of the Gila overlies Bearwallow Mountain Andesite (23-27 Ma) or, where the Bearwallow Mountain Andesite has been erosionally removed, rests unconformably on tuffs derived from Mogollon plateau calderas (24-32 Ma). The Gila is interbedded with 21-1 Ma basalts (post-caldera "Group II" rocks of Futa and Ratté, 1989). Deposition of the Gila Group probably occurred episodically throughout this entire period, ending only when Quaternary stream incision began to exhume the basin. Most beds examined in this study are well-lithified conglomerates and sandstones believed to pre-date the 11 Ma Eagle Peak dacite flow (Ratté and Bové, 1989; Bové, 1990), which separates well-lithified lower Gila from poorly consolidated or caliche-cemented upper Gila.

The Reserve graben, especially its sedimentary facies, has not been extensively studied. Weber and Willard (1959) published a reconnaissance map of the thirty-minute quadrangle (on a non-topographic base) that contains the basin; more recently, detailed mapping and study of the volcanic rocks in and around the basin have been undertaken by J.C. Ratté and his colleagues at the US. Geological Survey (Ratté, 1980; Ratté et al., 1984; Ratté, 1989; Futa and Ratté, 1989; Ratté and Bové, 1990; Bové, 1990; Bové and Ratté, this volume).

FACIES ASSOCIATIONS AND DEPOSITIONAL ENVIRONMENTS

The syntectonic basin fill of the Reserve graben was divided into five distinctive facies associations in this study. Each of these sedimentary facies associations is described below, and interpreted in terms of sedimentary process, depositional environment, and relationship to tectonic features of the basin.

Facies association 1: coarse proximal deposits

This facies consists of massive beds of cobble and boulder conglomerate with little or no discernible sorting or fabric (Fig. 5). Maximum clast size is about 1.5 m; average clast size ranges from 10-50 cm, typically decreasing appreciably in the downstream direction over distances of a few 100s of m. A sandy matrix is ubiquitous and typically supports the clasts; matrix content varies from a matrix-rich end member in which clasts appear to "float" in matrix (Fig. 5B) to a matrix-poor end member in which clast-clast contact is more common than not (Fig. 5A). Deposits are usually ungraded but inverse and normal grading each occur in places. A-axis imbrication is sometimes present. Bedding is tabular, with sharp, slightly erosional bases. The upper surfaces of beds commonly show more relief than their bases—a result of clasts that project upward into overlying beds. Bed thickness ranges from <1 m to several m; bed thickness generally appears to correlate with maximum particle size, although quantitative methods such as the MPS/BTh plot described by Nemec and Steel (1984) have not yet been attempted.

Facies association 1 occurs in two modes: (1) as fill in well-defined erosional scours, 10s to 100s of m wide located high on the dip slopes of intra-basin imbricate fault blocks (Fig. 6), and (2) as larger and thicker accumulations located adjacent to the largest bounding faults, especially at a few locations along the San Francisco Mountain fault zone. The erosional scours filled by facies association 1 deposits typically cut through the Bearwallow Mountain Andesite (youngest of the pre-Gila, pre-block faulting units in the Reserve Basin) and into underlying tuff—creating erosional relief of up to 100 m (Fig. 6). Exposures of Facies 1 adjacent to major faults become interbedded with sheetflood and ephemeral stream deposits (see facies association 2 below) 10s to a few 100s of m away. In other words, grain size decreases laterally in all directions, suggesting a point source of coarse sediment along the fault scarp.

The primary sedimentary process reflected in the rocks of this facies is viscous or plastic mass flow, probably where flow was at least partially confined, either by bedrock canyons (on the dip slopes of imbricate fault blocks) or by fan-head channels (adjacent to fault-bounded basin margins). The variability of the facies suggests a range of mass-flow processes, from "fluidal flows" (Lowe, 1979) or hyperconcentrated streamflood (Smith, 1986), to true debris flows (Nemec and Steel, 1984). The environments in the Reserve Basin where this high energy mass flow took place include both small canyons or arroyos incised into the dip slopes of intra-basin tilt blocks, and incised channels and channel-mouth outflow lobes located near the heads of large, discrete, alluvial fans occurring in a few places along the fault-bounded margins

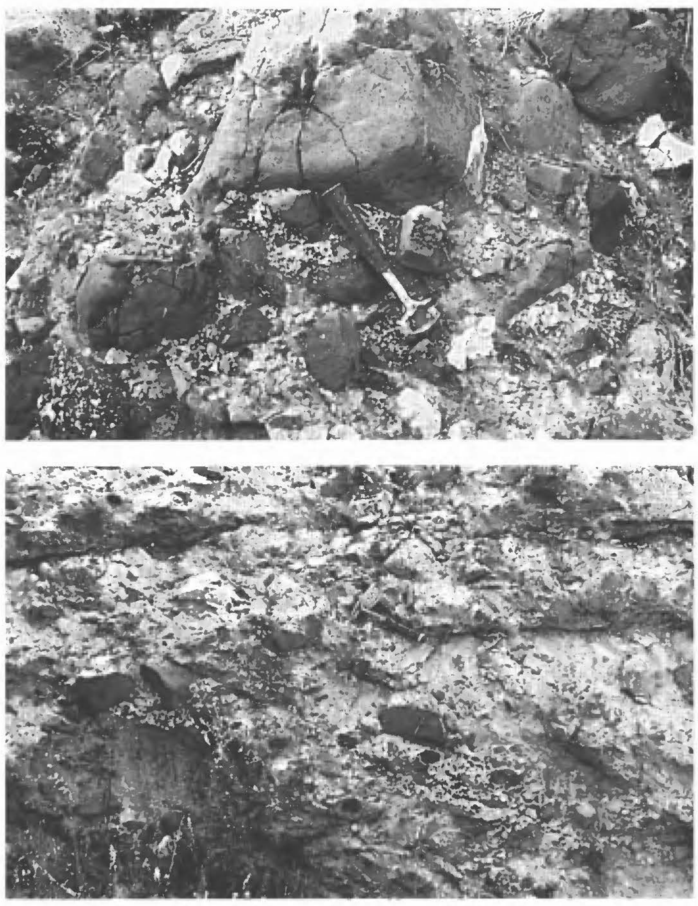

FIGURE 5. Facies association 1, coarse proximal deposits. A, Lower-matrix-content facies typical of proximal alluvial fan occurrence of facies association 1. B, Matrix-rich end member from dip-slope canyon fill occurrence. Both end members comprise mostly mass-flow deposits.

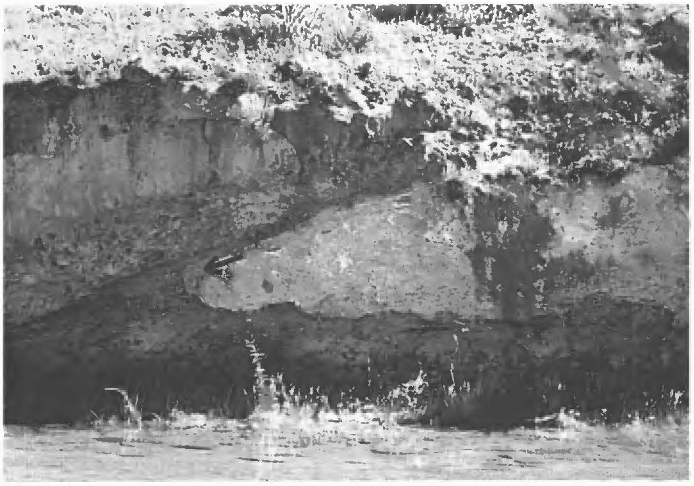

FIGURE 6. Example of dip-slope paleocanyon fill. Arrow is parallel to erosional base of canyon fill and points to a straw hat hanging just below the contact between the canyon fill and underlying Triangle C Ranch tuff.

of the basin. The paleocanyon occurrence of this facies tends to be more matrix rich than the fan-head channel occurrence.

The presence of significant erosional features on the hanging walls of an active half graben was predicted in the conceptual model of Leeder and Gawthorpe (1987), and modern analogs were described by Davis (1925) from the Oquirrh and Panamint ranges, both of which have fault-bounded western sides and dip to the east:

> "The V-gorges and the sharp clefts recently cut in the rock faces of the revealed fault surfaces on the west side of these two ranges in consequence of their upheaval may therefore be correlated with a moderate, down-grade furrowing of the detrital deposits on their eastern slopes in consequence of an increase in declivity there.... the furrows are several hundred yards wide and 100 or 200 feet deep ..."

Although the gradient of the hanging wall dip slope is gentle compared to the fault-bounded margin of a half graben, it is likely to be quite steep in stream-gradient terms. A relatively modest hanging wall dip of 1-5° will result in high-energy stream flow and is therefore likely to provoke canyon entrenchment over much of the hanging wall dip slope.

Dip-slope paleocanyon fills can be seen in many places around the Reserve graben, on both the Higgins Mountain and the Jon S Mountain intrabasin fault blocks. The best exposure is located along the San Francisco River in SE1/4 sec. 26, T6S, R19W (Fig. 6). A more accessible example of a canyon-fill deposit can be seen in a roadcut on Highway 12, near the center of sec. 29, T6S, R18W.

In many cases, as on the dip slope of the Higgins Mountain block, the paleocanyon fills occur immediately updip from mid-distal fan deposits, suggesting that the canyons fed the hanging wall fans. The deep erosion and coarse grain size associated with these dip-slope canyon fills certainly imply that the imbricate blocks existed as topographic features during the formation and fill of the basin—an indication that tectonism outstripped erosion and deposition enough to control topography and therefore drainage. Sediment produced by canyon incision and transported down the dip slope would be deposited on fans/braidplains at the canyon mouths. With time, sediment supply must have increased relative to tectonic movement, since the canyons eventually filled with sediment. Increased sediment flux relative to subsidence or tilting rate would cause the fan/sandflat environment to onlap the hanging wall as the dip-slope canyons backfilled.

Proximal alluvial-fan deposits are relatively rare in the Reserve graben, although there are some striking examples. The best and largest example is adjacent to the San Francisco Mountains fault zone (SFMFZ) in sec. 11, T6S, R19W, which is the same place where the modern San Francisco River enters the Reserve graben through a spectacular canyon known as the Box. The location of this fan also coincides with a 30° bend in the strike of the SFMFZ (Fig. 3). It seems quite likely that this bend results from segmentation of the fault zone—a displacement-transfer zone. As discussed above, this structural situation can result in a topographic gap in the footwall uplift through which an external drainage system may enter the basin, potentially delivering large volumes of sediment and water to the basin (Leeder and Gawthorpe, 1987; Jackson and White, 1989; Gawthorpe and Hurst, 1993).

Proximal fan deposits are also exposed adjacent to the SFMFZ in the bed of Pueblo Creek, in the southwestern corner of the study area (SE1/4 sec. 14, T8S, R21W; Fig. 3). It is important to note that Gila outcrops at many locations along the SFMFZ have been examined and found *not* to include proximal fan deposits. The San Francisco Mountains did not therefore constitute a major line source of sediment for the Reserve graben; rather, sediment entered the basin through discrete passages in the mountain front.

A third locus of proximal fan deposits is found on the southeast margin of the Reserve graben, adjacent to one of the down-to-the-northwest faults that border the Tularosa Mountains. These deposits can be seen in roadcuts along the Reserve-Beaverhead Road in sec. 3, T8S, R19W.

Facies association 2: mid-distal alluvial-fan deposits

This facies association is characterized by tabular-bedded poorly stratified sandstone and conglomerate, occurring in thin (10-100 cm), flat-based beds that often extend laterally for 100s of m in both strike and dip directions (Fig. 7). Grain size ranges from medium sand to large cobble but is dominated by very coarse sand through pebble-sized clasts (1-32 mm). Internal stratification, where present, consists either of horizontal or nearly horizontal sets (plane-bed stratification) or of low-angle trough cross-bed sets (Fig. 7B). Horizontal stratification is commonly defined by alternation of coarser (pebbly) and finer (sandy) laminae. Massive beds are also common. Facies association 2 is commonly interbedded with facies association 1; in such cases the ratio of facies association 2 to facies association 1 increases in the paleo-downstream direction.

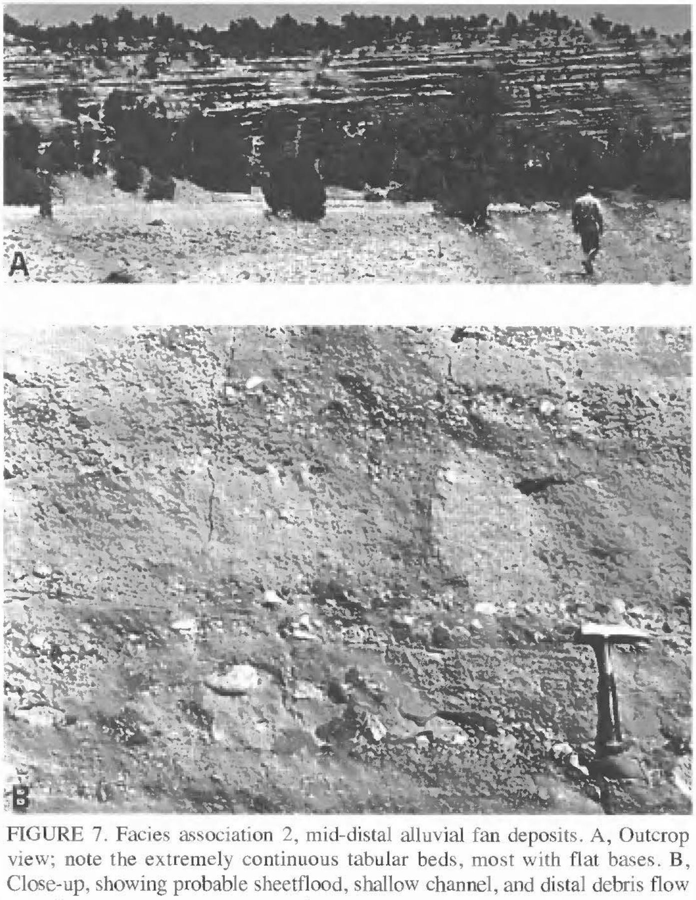

FIGURE 7. Facies association 2, mid-distal alluvial fan deposits. A, Outcrop view; note the extremely continuous tabular beds, most with flat bases. B, Close-up, showing probable sheetflood, shallow channel, and distal debris flow deposits typical of this facies association.

Several processes are reflected by this facies association, including non-channelized "sheetflood" deposition, deposition in small, ephemeral, relatively wide and shallow sandy streams (streams of the sort described by Bull (1972) from arid-region alluvial fans), and relatively fine-grained (compared to facies association 1) mass flows. This collection of processes probably reflects a mid-distal alluvial fan or sandflat depositional environment. This interpretation is strengthened by the common occurrence of facies association 2 as a downstream equivalent of the proximal fan and canyon fill deposits of facies association 1.

Facies association 2 is extremely common in the Reserve Basin, constituting roughly half the outcrop exposure of the basin fill. In several places within the basin, sections 50-100 m thick that are dominated by facies association 2 are overlain by sections of similar thickness that consist largely of through-going fluvial channel deposits (see facies association 3, below). This vertical transition may reflect a widespread change in depositional style, from fan-dominated to axial-stream dominated deposition and suggests a decrease in relative subsidence rate that allowed sedimentation to "catch up" with tectonism.

Paleocurrents are difficult to obtain from the poorly stratified deposits of this environment but sparse imbricated pebbles generally indicate southwesterly transport, suggesting that the deposits reflect drainage down structural dip—down the hanging wall dip slopes of tilted intra-basin fault blocks. As mentioned above, facies association 2 is the most common type of deposit in the basin. It is likely that during the most active period of tectonic subsidence, much of the basin was covered with broad, sheetlike fans from the canyons incised into the dip slopes of tilted intrabasin blocks. Rapid subsidence would tend to encourage rapid aggradation with little sorting or reworking of sediment. Logically enough, the deposits inferred to reflect rapid subsidence are thicker than those associated with slower subsidence. This scenario is consistent with the model described above (also see Leeder and Gawthorpe, 1987; Blair, 1987; Cavazza, 1989) and with observations in Death Valley, where sheetlike hanging wall fans grade into sandflats bordering playas (Hunt, 1975; Fig. 1).

Depending on the hydrology of the basin, transverse systems originating on the hanging wall dip slope may empty into either an axial fluvial system or into a lake occupying the basin axis—in fact, an axial system may originate as a transverse system that curves into the axial trough and continues along strike. If the climate is arid, and if there is a wide low gradient zone in the axis of the basin, these systems may simply die out downstream due to loss of water and energy, forming "terminal fans" (Friend, 1978; Parkash et al., 1983; Kelly and Olsen, 1993). In Death Valley, transverse drainage systems terminate in a salt pan, or playa, which is usually dry (Hunt, 1975). In the Reserve graben, however, no mudstones or evaporites indicative of playa lake deposition have been found, but axial fluvial deposits are common.

Facies association 3: axial fluvial channel deposits

The third facies association (Fig. 8) comprises cross-bedded, channeled conglomerate and sandstone; grain size ranges from medium sand to large cobble (250 mm). In contrast to both the proximal and distal fan deposits just described, facies association 3 is marked by good sorting, abundant sedimentary structures (especially trough cross-bed sets), strong b-axis imbrication fabric, and high-relief bounding surfaces that reflect erosional scour (Fig. 8). Commonly the entire exposure of this facies at a given outcrop occurs within a channel-form erosional bounding surface; in other cases such channel fills are stacked and multi-lateral. Sedimentation units on the order of 1 m thick generally fine upward, from an erosional, conglomeratic base to a sandy top that is often reddened and devoid of primary sedimentary structures (suggesting paleosol development).

This distinctive facies association consists of fluvial channel and interchannel deposits. Detailed paleohydraulic work was not attempted, but the dominance of trough cross-bed sets, lack of lateral accretion surfaces, and apparent coarse-grained, non-cohesive nature of the bed and bank material suggest a low sinuosity bedload-dominated stream. Flow depth, estimated from the thickness of channel fill packages, was 0.5-5 m. Paleocurrents are typically parallel to the basin axis, suggesting that these were longitudinal fluvial systems, possibly flowing southwestward the length of the basin and passing into the next basin downstream.

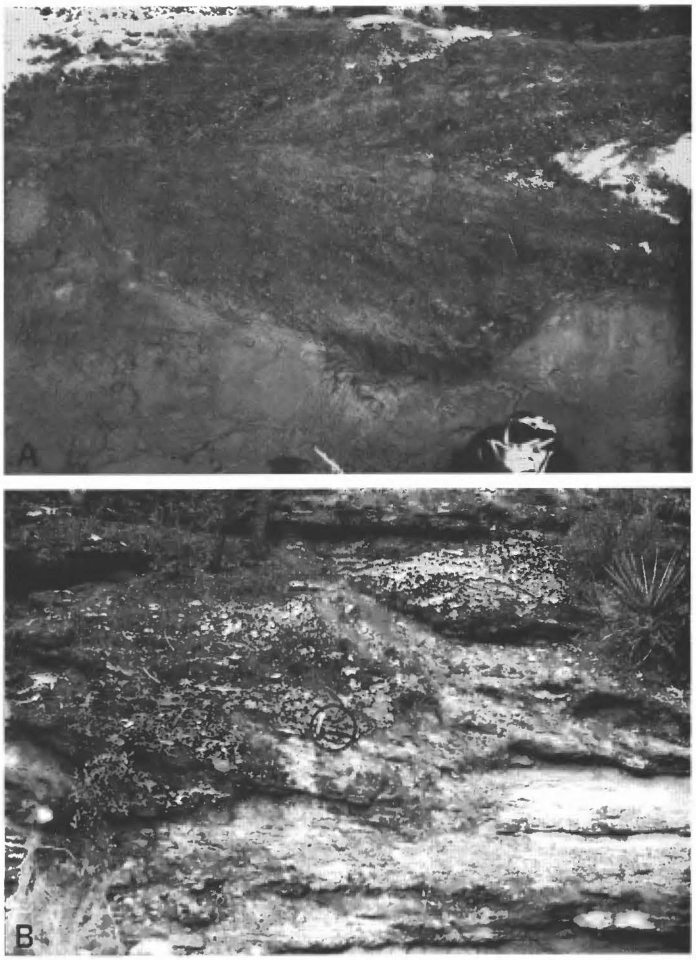

FIGURE 8. Facies association 3, axial fluvial channel deposits. A, Trough cross-bedded channel fill cut into fine-sand interchannel deposits. Object at base of photo is a knapsack. B, Larger-scale cross bedding from Wilson Canyon axial fluvial deposits, near the Tularosa River. Note hammer (circled) for scale.

Evidence of axial fluvial systems was found in all three of the sub-basins shown on the cross section in Figure 4. In the half graben between Higgins Mountain and Jon S Mountain, the axial system appears to be confined to the "deep" side, i.e., close to the Higgins Mountain fault (the eastern part of the half graben is dominated by dip-slope paleocanyon fill and distal fan deposits). Significantly, fine-grained floodplain deposits separating channel deposits are thickest and texturally finest immediately adjacent to the mountain front fault (Fig. 9). This suggests that rapid subsidence adjacent to the fault promoted rapid aggradation—i.e., vertical accretion was rapid compared to lateral migration of channels, so that preservation of interchannel deposits was enhanced (Bridge and Leeder, 1979; Leeder and Gawthorpe, 1987).

In the Tularosa River Valley graben (on the eastern edge of the Reserve Basin, Fig. 4), which is only a few kilometers wide, the axial system appears to have occupied most of the width of the sub-basin. This sub-basin is unusual in that it is bounded by faults on both sides, making it less asymmetrical than the other sub-basins—more like a full graben. The fluvial deposits in this sub-basin are unusually coarse, with little preservation of out-of-channel fines (Fig. 8B).

The axial deposits in the westernmost half graben in the Reserve Basin, between the San Francisco Mountains and Higgins Mountain, appear to be laterally (downstream) equivalent to the proximal fan deposits associated with the large fan that issued from the San Francisco Mountains near the Box. The transition occurs over a distance

FIGURE. 9. Contrasting modes of axial fluvial channel deposits. A, Stacked channel deposits with little preservation of interchannel fines; arrow points to 3-m-high tree at base of outcrop. B, Isolated channel bodies separated by interchannel fines found adjacent to the Higgins Mountain fault scarp, where rapid subsidence apparently allowed less reworking of the floodplain, leading to greater preservation of fine-grained interchannel deposits. Staff is 1.5 m long.

of approximately 5 km over which exposures are nearly continuous in the San Francisco river valley. This unique, large fan may have been elongated longitudinally, and may have brought sufficient volumes of sediment and water into the basin to create an axial system that passed from an alluvial fan environment distributary upstream to a fluvial channel environment downstream.

Where vertical control permits, the axial fluvial deposits in this most western sub-basin are often seen to overlie transverse fan deposits. In one case where exposure is especially good, permitting horizontal control of about 1 km and vertical control of about 100 m, the fluvial channel deposits appear to onlap hanging wall dip-slope transverse fan deposits. These observations suggest that an early phase of basin subsidence and fill was dominated by sedimentation on transverse fans flowing down the dip slope of the Higgins Mountain imbricate fault block, and that with time, the ratio of sediment supply to subsidence increased, enabling the axial fluvial channel system to occupy a progressively wider area of the half graben. Important questions are left unanswered by the work done so far; some may be resolved by further work, while others cannot be addressed because of the limitations of outcrop exposures. For example, it is not known whether the suspected increase in the ratio of sediment flux to subsidence resulted from a *decrease* in subsidence as tectonic activity decreased, or from an *increase* in the rate at which sediment was brought into the basin by the large longitudinal fan system. It is also possible that no axial fluvial system existed during the initial stages of basin evolution.

Facies association 4: massive, channeled sandstones

In a few places within the Reserve Basin, beds dominated by massive coarse sandstone occur. Bed thickness is variable and bed geometry includes clear cross-cutting channel forms (Fig. 10A). However, the beds lack internal stratification. Occasional pebble- or cobble-size clasts are seen "floating" within the sandstone (Fig. 10B).

The origin of this rare but prominent facies association is problematic. It is found only in proximal settings (mainly adjacent to fault scarps) and can be interbedded with the coarse mass- flow deposits of facies association 1. This association, together with the apparent lack of sedimentary structures, suggests a high energy mass-flow origin that contrasts strangely with the fine-grained texture of the facies. On the other hand, the facies usually occurs in *rapidly subsiding* proximal settings, where rapid deposition/aggradation is expected. High sediment concentrations associated with rapid deposition in sand-dominated environments may suppress bedform development, resulting in hyperconcentrated flood flow deposits that resemble this facies association (Smith, 1986).

FIGURE 10. Facies association 4, massive sandstones. A, Outcrop view; arrows highlight erosional bounding surface with massive sandstone fill. Note dip changes; the significant decrease in dip from base to top of the exposure reflects syntectonic deposition. Steeply dipping outcrops in lower right portion of photograph are axial fluvial deposits, not massive sandstones. B, Closer view of massive sand facies association. Note cobble-sized clasts "floating" in sandy matrix.

Another possibility is that the massive sandstone facies reflects a peculiar source-terrane lithology whose breakdown products did not include gravel, or, if gravel was produced, the clasts were too soft to survive transport. A likely source lithology is poorly welded ash flow tuff, which is extremely common in the mid-Tertiary "basement" underlying the Gila (e.g., Bloodgood Canyon Tuff, see Ratté et al., 1989).

The primary locality for observing this facies association is adjacent to a prominent fault scarp several tens of meters high associated with a collapsed segment of the Jon S Mountain tilted block, in SE1/4 sec. 33, T6S, R18W.

Facies association 5: colluvial wedge deposits

Large (boulder-size, some larger than 1 m) angular blocks of homogeneous lithology (usually basaltic andesite) are occasionally found cemented together in wedge-shaped deposits adjacent to intra-basin fault scarps (Fig. 11). The most prominent and accessible example of this facies is near a water gap in the Higgins Mountain fault block called Starkweather Canyon (SW1/4 sec. 2 and SE1/4 sec. 3, T7S, R19W). There the facies can be traced for approximately 500 m along strike but only about 10 m in the down dip direction. These deposits are devoid of sorting or fabric. Distal fan deposits of facies association 2 are found within 10 m of the deposit, with no discernible fault between the contrasting deposits.

This facies is probably of colluvial origin, specifically comprising colluvial wedges resulting from rock falls or slides on active fault scarps. They are rare, typically quite localized, and in the case of the Starkweather Canyon deposit constitute the only significant accumulation of coarse-grained material found adjacent to the fault. The significance of the example along the Higgins Mountain scarp is twofold. First, it is a further indication that the Higgins Mountain intrabasin fault block existed as a topographic feature during Gila deposition, and second, the fact that this single colluvial wedge apparently constitutes the only notable accumulation of coarse-grained material along the Higgins Mountain escarpment is an indication that relief does not guarantee a large sediment flux. In other words, it is significant that sediment accumulation adjacent to an active fault scarp is dominated by the deposits of transverse fans originating on the hanging wall and flowing toward the scarp, and by deposits of an axial fluvial channel system flowing parallel to the mountain front.

DISCUSSION AND CONCLUSIONS

Figure 12 depicts the syntectonic paleogeography of the Reserve graben, as inferred from paleocurrent measurements and the spatial distribution of the depositional environments discussed above. This diagram synthesizes many of the observations and interpretations of this study, and suggests a clear pattern of structural control over topography, drainage patterns and depositional systems similar to that predicted by the conceptual model outlined in the Introduction. Specific conclusions regarding the syntectonic deposits of the Reserve graben are: (1) surface topography conforms to the "tectonic slope" (i.e., the hanging wall slopes down to the structural axis of the half graben); (2) drainage of this hanging wall dip slope results in erosion of incised canyons on the upper part of the dip slope and deposition on large, relatively fine-grained alluvial fan complexes on the lower part of the dip slope; (3) longitudinal fluvial systems flow south-southwest along the coincident structural-topographic axis of the basin. These axial streams often flowed so close to bounding-fault escarpments that rockfall deposits are found among the alluvium, and rapid subsidence rates are reflected in increased floodplain:channel deposit ratios; (4) alluvial fans along the faulted, high relief, margins of half grabens are rare, isolated features, albeit coarser-grained than the dip-slope fans. Footwall uplifts in the Reserve graben did not act as major line sources of sediment because their catchment areas were small, and because progradation was inhibited by rapid subsidence of the basin axis; and, (5) footwall fans or axial fluvial systems fed by "gaps" in the footwall uplift were more important contributors of sediment than systems fed directly by erosion of the footwall uplift, as a result of their access to larger catchment areas.

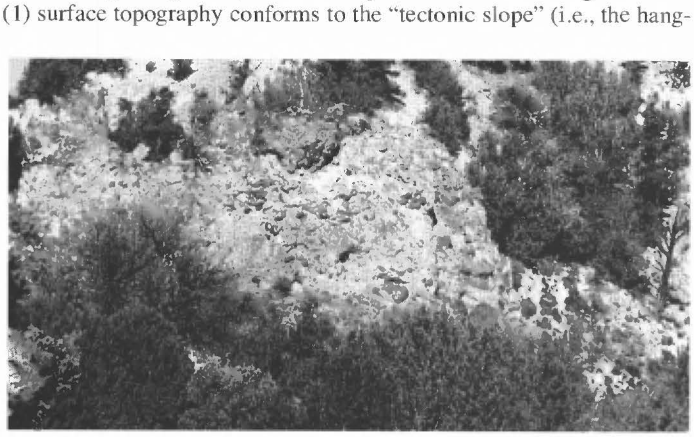

FIGURE 11. Colluvial wedge facies association. Exposure is about 8 m high. Deposit consists of chaotic accumulation of angular basalt clasts with no discernible bedding or fabric.

The presence of incised-canyon fills on the hanging wall dip slope, together with the widespread distal fan/sandflat deposits that reflect transverse drainage down the hanging wall dip slope, lead directly to the conclusion that the asymmetrical structure of the basin was mirrored in the surface topography. Similarly, the rare fans and colluvial deposits along basin-margin faults imply high relief across these faults. Finally, the concentration of longitudinal stream deposits near the structural axis of each sub-basin suggests that the structural axis of each half graben was overlain by a topographic low that naturally attracted longitudinal systems (Alexander and Leeder, 1987).

The scarcity of fans along the fault-bounded margins of each half graben, and their limited areal extent (i.e., the lack of transverse systems that reflect flow *up* the hanging wall dip slope), is still another indication that topographic and tectonic slopes dipped the same direction. It also supports two major concepts advanced above: high relief of marginal uplifts does not compensate for small drainage areas, in terms of ensuring high sediment supply. In other words, if a footwall uplift is narrow, it may not shed enough sediment to construct significant clastic wedges, even if it is a high uplift, undergoing rapid denudation. The fact that such uplifts are typically asymmetrical themselves effectively decreases their width even further, because much of the water and sediment drains down the dip slope, not into the basin. In addition, the juxtaposition of uplifts and rapidly subsiding basin axes on the active margins of asymmetrical basins further inhibits progradation, by increasing the volume of sediment required to construct a basinward slope.

The probable existence of a large longitudinal fan that issued from a topographic gap between two segments of the SFMFZ near the Box (Fig. 12) supports the assertion that drainages that originate beyond the rift-shoulder uplift, and cut across the uplift to reach the basin, constitute a more important source of basin-filling sediment than any drainages from within the footwall uplift itself. This of course is because these antecedent or superimposed systems have much larger potential watersheds than any system having a drainage basin limited to the footwall uplift. It is significant that these features can be seen, not only in Holocene settings such as the Great Basin, but in the stratigraphic record, since this justifies the extrapolation from two-dimensional models of topography and drainage pattern to three dimensional models of the basin fill.

The Gila Group was deposited in the context of the same Basin and Range fault-block topography that prevails today. To this conclusion two caveats must be added. First, the topography of today is largely erosional—fault blocks and escarpments have been exhumed as the San Francisco River and its tributaries dissected the basin, differentially eroding sedimentary and igneous rocks as they incised. As a result, although the topography of today may be broadly similar to the topography that influenced Gila deposition during the period 11-20 Ma, there may have been a subsequent period of more subdued topography that existed between the last episode of rapid uplift and subsidence and the downcutting of regional stream systems. Second, the

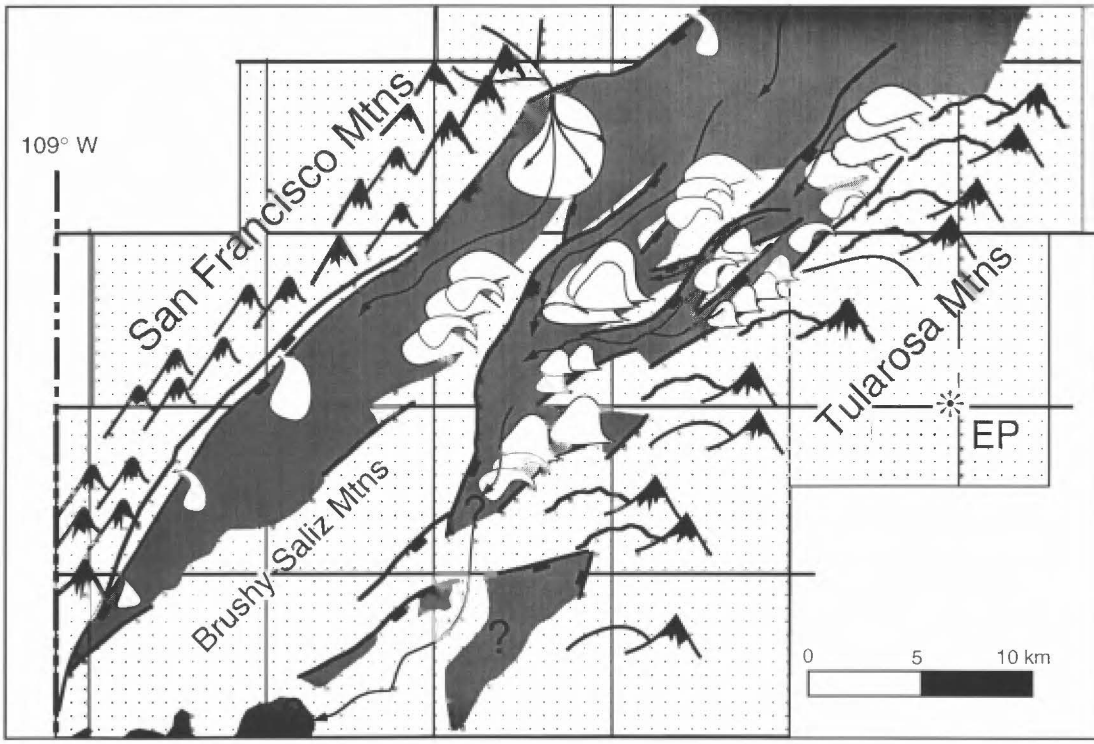

FIGURE 12. Miocene paleogeography of the Reserve graben, emphasizing drainage patterns and distribution of alluvial fans. The principal features are: (1) numerous dip-slope fans draining the uplifted intra-basin tilt blocks, and the Tularosa Mountains; (2) axial flow to the southwest (denoted by arrows), and (3) sparse fans issuing from the San Francisco Mountains, notably a large fan entering the basin at the bend/transfer zone in the main bounding fault. Note that this fan is depicted contributing to an axial-flow system.

Reserve graben is a highly faulted region, and not all faults within it share the same history—some are older than others, and many have undoubtedly experienced recurrent movement. To say that the structural framework reflected in today's topography is the same as that which affected the deposition of the Gila Group is not to say that every fault in the region was active before or during Gila deposition, nor is it meant to suggest that faults active during Gila deposition ceased moving once the section of the Gila studied here was deposited. On the contrary, the Gila is faulted in many places, and there is clear evidence of young faulting in the Milligan Mountain quadrangle, on the southeastern margin of the basin (Weber and Willard, 1959; Ratté, 1980; Ratté and Bové, 1990).

Finally, it should be noted that this investigation of sedimentation in the Reserve graben is not represented as a comprehensive study of the stratigraphy and sedimentology of the Gila Group—it is more a preliminary reconnaissance, specifically aimed at discerning the tectonic imprint on the basin fill. The principal accomplishments of this study are that it sheds some light on the manifestations of structural asymmetry in the stratigraphic record of continental extension, corroborates the essential aspects of the conceptual model sketched at the beginning of this paper, and provides a basis for future studies of the Gila Group in the Reserve graben.

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