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New Mexico Geology, v. 18, n. 4 pp. 81-92, Print ISSN: 0196-948X, Online ISSN: 2837-6420.
https://doi.org/10.58799/NMG-v18n4.81

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New Mexico GEOLOGY
• Science and Service
ISSN 0196-948X
Volume 18, No. 4, November 1996

Fluvial fans and related basin deposits of the Mimbres drainage

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Abstract

Geomorphically well-expressed fluvial fans cover more than 200 mi² in the Deming, Mimbres, and Columbus Basins of the Mimbres drainage in southern New Mexico. These broad fans and related broad valley floors exhibit several geomorphic and depositional features that provide new insights into interpreting extensional basin fill. The fluvial fans of the Mimbres River cross the basins at large angles (acute to orthogonal) to the extensional basin structures and radiate from spillover points from adjacent valleys, dominating aggradation within the basins. Only parts of the Mimbres and Deming Basins exhibit the familiar axial river facies on the hanging wall adjacent to the active footwall scarp.

On the surfaces of these large fans and valley floors are unusual anabranching distributary channel complexes that are raised in relief above the adjacent interchannel areas. The channels extend beyond all but a few historic floods of the Mimbres River that flowed beyond Deming, New Mexico, and consist of sand and gravel whereas the adjacent low areas are finer sand, silt, and clay. The positive relief of these channels may have several origins, including original constructional deposition, topographic reversal by eolian deflation of fine sediments, or eolian aggradation on top of inset channels. The weak calcic soils on these features are apparently late Pleistocene and Holocene in age. The channels are too extensive to have formed by a few large discharge events; rather, they probably formed over periods of time when the Mimbres River had flows of extended duration and magnitude.

Stratigraphy in shallow gravel pits suggests the fans have aggraded during both wet and dry climatic conditions. Extensive buried crossbedded sandy gravel layers suggest that the Mimbres River was much larger and more competent in the past (late Pleistocene?) and that the fan surfaces were actively aggrading or at least being reworked laterally. The overlying sand and loess and smaller positive-relief channels suggest that under drier conditions the fluvial channels are more localized and that eolian deflation and aggradation, as well as pedogenic processes, dominate the fans. The hypothetical resultant stratigraphy under semiarid conditions should have relatively thin but laterally extensive stacks of eolian and interdistributary fine facies with weak pedogenic horizons cut and/or buried by local channels. These units should alternate with more extensive crossbedded fluvial sands and gravels deposited during wet episodes.

Introduction

Rising high on the west flank of the Black Range and along the ridges of the Continental Divide, the Mimbres River snakes its way southward in a relatively narrow channel to a point just east of Deming, New Mexico (Fig. 1). A small perennial stream in its upper reaches where it is nearly enclosed by highlands, the river becomes increasingly influent downstream from Dwyer near City of Rocks State Park and more often dry as it begins its journey across desert plains to Deming. Those familiar with the river's seasonal runoff are not surprised by the occasional flood waters, confined to the channel, that cross the desert en route to Deming, but most unusual are the floods that make it all the way to the city or to the sump at the mouth of the river just north of the Florida Mountains. Still rarer are waters that reach the Mexican border, such as historic floods of the early twentieth century. Yet in the relatively recent geologic past (8,000 to 15,000 yrs or so) Mimbres streamflow and floodwaters have repeatedly and probably often extended to the Mexican border and beyond, having arrived there by way of the basins that lie both to the east and west of the Florida Mountains.

Testimony to these exceptional discharges and to the paths they took are broad expanses of river deposits in the form of meandering and anabranching stream sediments and huge fluvial fans that nearly fill the Mimbres Basin, the Deming Basin, and the Columbus Basin, as well as a large part of the Bolson de los Muertos in Mexico (Fig. 1). Not apparent from the ground, the fans and river channels are readily visible on both satellite and conventional photo images, as well as on 7½-min topographic maps. These, together with soil maps of Luna County (Neher and Buchanan, 1980), were used to delineate the impressive Mimbres River drainage system mapped by Seager (1995) and portrayed in Figs. 1 and 2.

The term *fluvial fan* is applied to the large geomorphic features in the basins and is derived from *fluvial*, of or pertaining to rivers, and *fan* derived from its surficial form (Bates and Jackson, 1987; J. Hawley, oral comm. 1981). Neither of the terms *alluvial fan* nor *fan delta* apply because their definitions imply mountain-front locations (Bates and Jackson, 1987). Clearly the Mimbres fluvial fans are within the basins and are deposited by rivers. Alluvial fans form alluvial aprons rimming the mountains adjacent to the basins; true delta fans are found near the former margins of pluvial Lake Palomas (Fig. 1; Reeves, 1969).

A distinctive feature of both the Deming and Columbus Basins is the delivery of Mimbres fluvial sediments oblique or orthogonal to the basin-bounding structures and across the basins rather than parallel to their axes. Cross-basin construction of fluvial fans contrasts markedly with previous models of extensional basin fill (e.g., Allen, 1978; Bridge and Leeder, 1979; Leeder and Gawthorpe, 1987; Mack and Seager, 1990; Cather et al., 1994; Smith, 1994) and may be applicable to many extensional basins that contain large fluvial systems (Mack et al., in press).

In this preliminary paper we describe the Mimbres fluvial system, its major into

Also in this issue

fluvial fans and some unusual raised channels preserved on fan surfaces. We estimate the ages of the fans and their channels, offer possible explanations for the channels, propose dominant processes for fan deposition, and discuss paleoclimatic implications. Finally, we summarize possible roles of fans as large cross-basin fluvial delivery systems in the filling of extensional basins, including their stratigraphic implications.

Mimbres River system

The Mimbres River basin is an internally drained area between the Continental Divide and the Rio Grande drainage to the east. Headwaters of the Mimbres River lie in the Mimbres Mountains, Black Range, Pinos Altos Mountains, and Cobre Mountains at elevations up to 10,000 ft. The drainage basin above Deming covers 1,370 mi^2 and 5,200 mi^2 north of the Mexican border. North of Deming only about 535 mi^2 of the drainage is above 6,000 ft in elevation, where most precipitation falls.

The Mimbres River is a small perennial stream in its upper reaches, but the river is used for irrigation and becomes influent downstream from Dwyer. Seasonal runoff produces occasional floods that reach Deming or the sump to the east at the present river mouth. Rare high-magnitude floods such as those of 1904 and 1906 described by Darton (1917) are documented to reach the Mexican border. Yet in the relatively recent geologic past floodwaters repeatedly spread to the Mexican border and beyond to contribute to pluvial Lake Palomas in the Bolson del los Muertos (Reeves, 1969).

The modern Mimbres River has an inset channel about 70–100 ft wide and 5–15 ft deep near San Lorenzo, changing to a braided channel 150 to 400 ft wide near City of Rocks and an incised channel about 75 ft wide at Deming. Terraces along the river indicate that this upper drainage has incised episodically throughout Pleistocene and Holocene time.

Stream gage records for the Mimbres River are incomplete, but provide insights

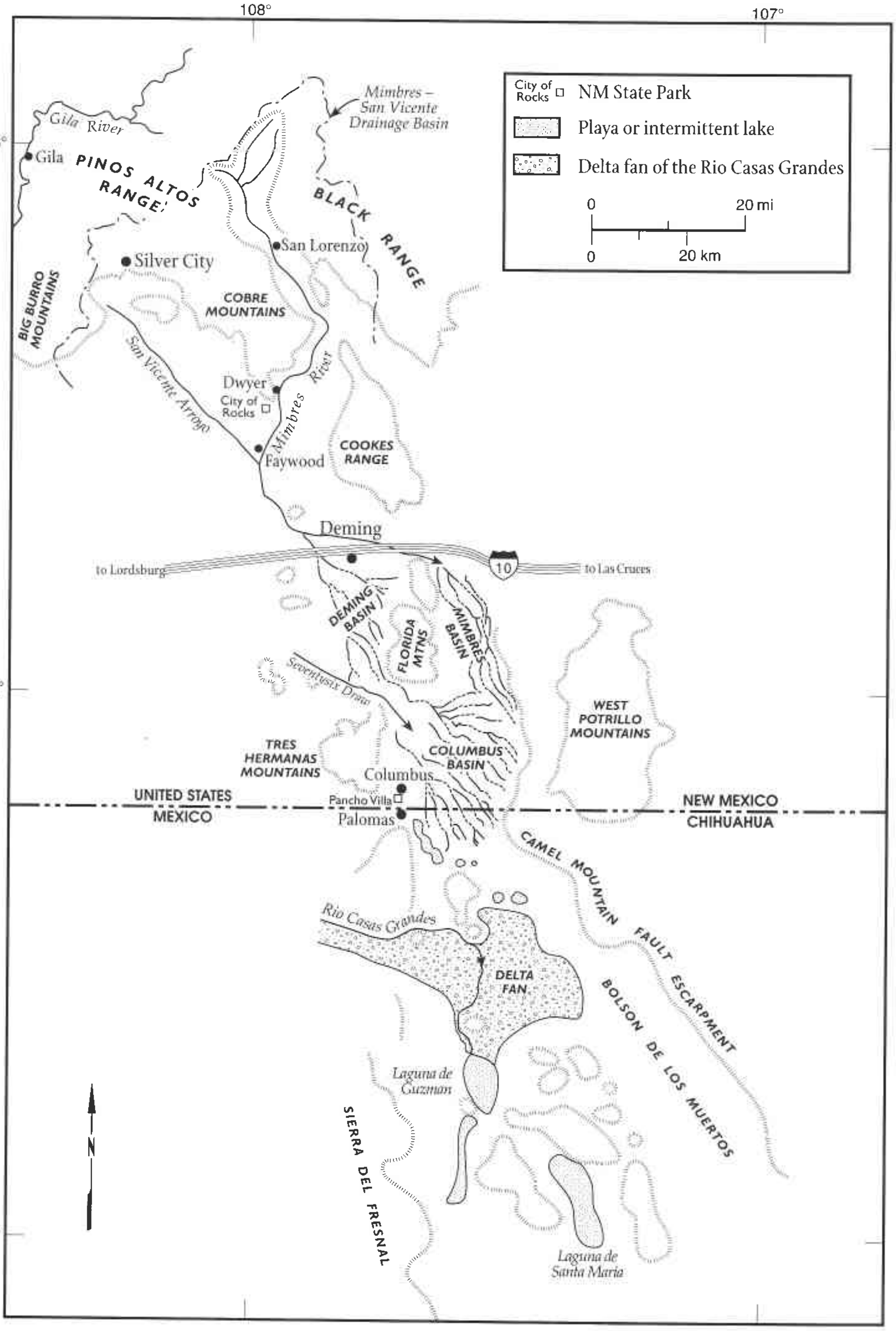


FIGURE 2—Fluvial fans deposited by the Mimbres River south and east of Deming, New Mexico.

New Mexico GEOLOGY
• Science and Service
ISSN 0196-948X
Volume 18, No. 4, November 1996

Editor: Carol A. Hjellming

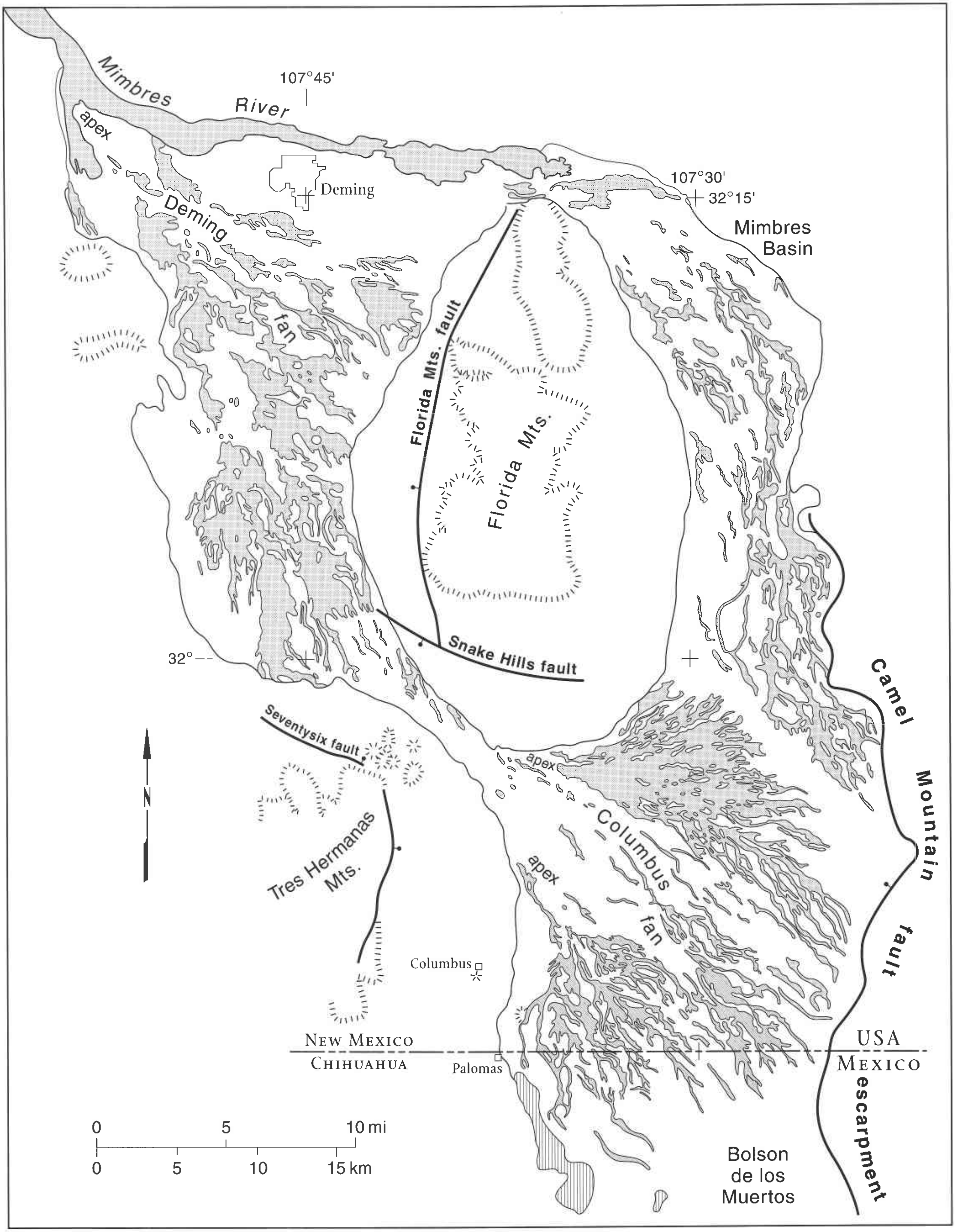
Published quarterly by
New Mexico Bureau of Mines and Mineral Resources
a division of New Mexico Institute of Mining and Technology

Subscriptions: Issued quarterly, February, May, August, November; subscription price $6.00/calendar year.

Editorial Matter: Articles submitted for publication should be in the editor's hands a minimum of five (5) months before date of publication (February, May, August, or November) and should be no longer than 20 typewritten, double-spaced pages. All scientific papers will be reviewed by at least two people in the appropriate field of study. Address inquiries to Carol A. Hjellming, Editor of *New Mexico Geology*, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801-4796.

Circulation: 1,000

Printer: University of New Mexico Printing Services


Mimbres River
107°45'
apex
Deming
Deming fan
107°30'
32°15'
Mimbres Basin
Florida Mts. fault
Florida Mts.
Snake Hills fault
32°
Seventysix fault
apex
Columbus fan
apex
Tres Hermanas Mts.
N
Camel Mountain fault
Columbus
New Mexico
Chihuahua
Palomas
USA
Mexico
escarpment
0 5 10 mi
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Bolson de los Muertos

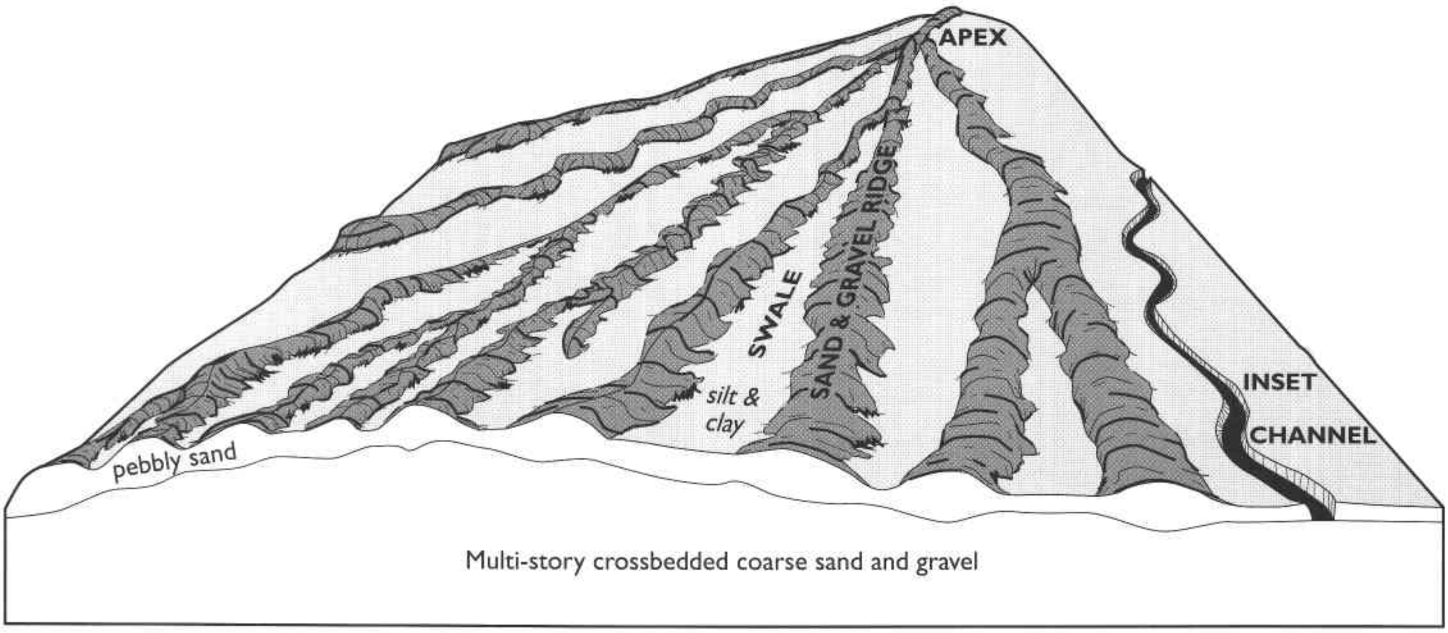

FIGURE 3—Block diagram of part of fluvial fan showing convex-upward shape, smaller channels and ridges dispersing from an apex upsteam, interdistributary areas of fine-grained sediment, modern inset channel, and underlying sheet of coarser, crossbedded gravelly sand. Subsurface relationships between ridges and swales remain undetermined.

into modern basin hydrology. Peak discharge at Deming recorded from the mid-1950s to mid-1960s did not exceed 800 cfs (Patterson, 1965). Recorded peak discharge near Dwyer is about 20,000 cfs (1939), and average annual discharge is 10,870 ac-ft/yr. San Vicente Arroyo, a major tributary to the Mimbres 15 mi downstream from Dwyer, has twentieth-century peak discharges of 4,680 and 6,800 cfs. A flood in 1895 probably exceeded 10,000 cfs (Waltemeyer, 1989).

The upper Gila River gage at Gila, New Mexico (Fig. 1), with similar drainage size (1,864 mi^2) and mountainous headwaters, has a peak discharge of about 25,400 cfs (Patterson and Somers, 1966). Floods on the Gila River can last a week or more (Burkham, 1970, 1972); historic flows on the Mimbres River, however, appear to be of much shorter duration or "flashy".

Sediment discharge records for the Mimbres River are nonexistent, and few exist for the Gila River. One of the few streams to have records of both suspended sediment and bedload discharge is the Rio Grande at San Marcial in central New Mexico. The Rio Grande records (data recorded one or two days per month) were used to estimate daily sediment discharge (*Qs*, tons per day) for large water discharge events (*Qw*, instantaneous cubic ft per second) by calculating a regression of *Qs* versus *Qw* (Love, unpublished data). A reasonable regression is $Qs = 9.097\ Qw$ (R^2 of 0.94 with a standard error of the estimate of 2829; Love, unpublished data). Because the Mimbres River probably has lesser sediment load than the Rio Grande, this regression will be used to make an order of magnitude estimate of sediment discharge (*Qs*) needed to fill the observed channels on the fans of the Mimbres River.

Fluvial fans and sinuous channels of the Mimbres River

Fig. 2 shows the general distribution of Mimbres fluvial sediments in the basins south and east of Deming. The southerly gradient of the fluvial surfaces is approximately 5–15 ft/mi. Relief on the Deming fan is about 350 ft over 19 mi. Relief on the Columbus fan from the narrow gap between the Florida and Tres Hermanas Mountains to the lowest part of the drainage near the Camel Mountain escarpment at the Mexican border is about 160 ft over a distance of 20 mi.

Two facies with distinct geomorphic expressions are distinguished on the map (Figs. 2, 3) based on interpretation of aerial photographs and soil maps, as well as in surface exposures, the latter in a few scattered gravel pits. The most widespread facies forms broad, rather barren, and locally alkaline plains although it also supports much of the irrigated croplands south of Deming. Not well exposed in cross section, this facies consists of tan fine sand, gray silt, and clay interpreted to be overbank and distal fan deposits and related loess deposits. In a few areas east of Columbus, apparent remnants of the fine-grained deposits are preserved in yardangs (cf. McCauley et al., 1977; Ward and Greeley, 1984).

The second facies form curvilinear low ridges best seen on topographic maps and aerial photographs (Fig. 4). The ridges consist of unconsolidated crossbedded fluvial gravel and sand, capped by structureless pebbly sand. They stand 1–5 ft above the surrounding silt and clay lowlands and are commonly mantled by clusters of coppice dunes, which in many places seem to have grown preferentially on the ridges. The gravel is a heterolithic mix of well-rounded volcanic and granitic clasts from nonlocal sources. Clast size in the ridges reflects distance of transport, becoming finer to the south and east. Clasts as large as 3–4 inches in diameter

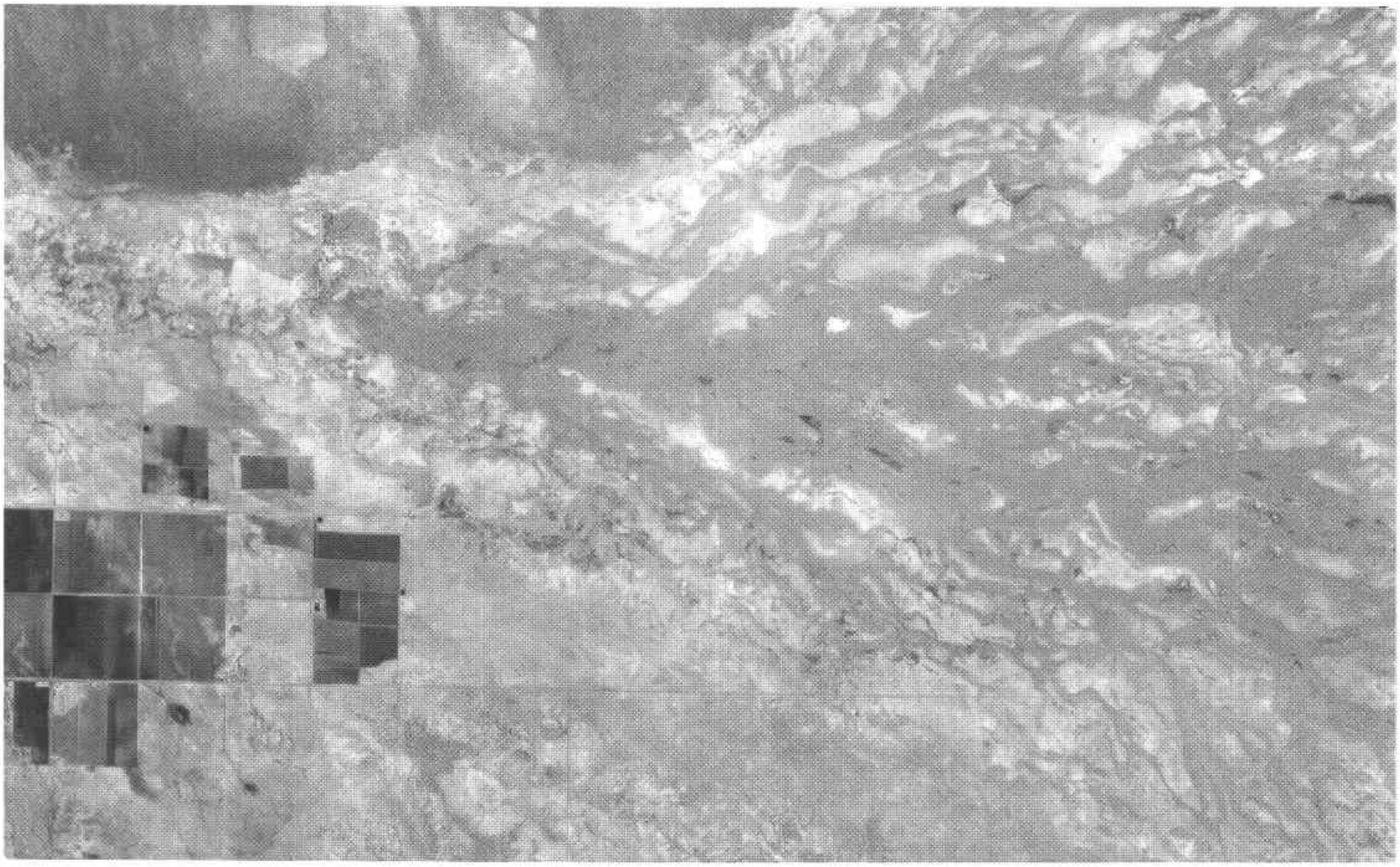

FIGURE 4—Aerial photograph showing elevated channels on the north part of the Columbus fan (HAP false color IR photograph, 1982). Dark area at top of photo is alluvial apron from the Florida Mountains to the north. One square mile comprises four of the irrigated squares on west side of photo.

are common in the Deming Basin, decreasing to less than 2 inches in diameter at the apex of the fan in the Columbus Basin, further diminishing to small pebble size in the distal portions of that fan.

The surficial sand and gravel ridges and channels are contained in a complex system of anabranching and meandering forms with the pattern of distributary systems on fans in both the northern Deming and Columbus Basins and as more axial channels in the Mimbres and southern Deming Basins. Far more intricate than the somewhat diagrammatic representation shown in Figs. 2 and 3, the true complexity of the distributary channels is obvious on aerial photos or satellite imagery (Fig. 4). Not all anabranching channels are coeval; rather, some channels appear to crosscut others. Perhaps because the channels are narrower and somewhat more widely separated, the distributary system in the Columbus Basin is especially striking. Channels crossing the Deming Basin fan appear wider, and more closely spaced, so that in Fig. 2 the distributary system there consists of broad channels of sand and gravel, the latter locally containing cobble-sized clasts. The difference in channel patterns between the two basins probably reflects original differences in parameters of hydraulic geometry (such as slope, depth, width), bedload, and discharge across the two fans.

The channel patterns on the fluvial fans diverge downstream from fan apexes, the distribution point from which sediments were furnished to the fans. The apex of the Deming Basin fan, adjacent to the modern Mimbres River channel 8 mi upstream from Deming, clearly shows the path by which floodwaters left the confined Mimbres River channel and spread across the basin southeast toward the base of the Florida Mountains. From the east edge of the basin, at times the Mimbres River turned northeastward and flowed around the north end of the mountains and diagonally across the Mimbres Valley to the south-southeast. At other times the stream flowed south through the Deming Basin around the western and southern distal alluvial aprons of the Florida Mountains into the Columbus Basin. In both the Mimbres and southern Deming Basins, evidence of multiple channels and perhaps anabranching, crosscutting channels dominate the basin floors over widths of 5–10 mi. Although there are large channels in the southern Deming Basin, and water from the southern Deming Basin should have been concentrated into channels in the narrow gap between the Florida and Tres Hermanas Mountains before spreading out again in the Columbus Basin, the only channels evident on aerial photographs are rather small, about the size of the modern Seventysix Draw. This narrow gap lacks surficial evidence of large discharge events.

Two elevated channel-fan complexes are recognized on the larger Columbus Basin fan. One complex spreads eastward toward the Camel Mountain escarpment from an apex 8 mi north-northeast of Columbus (Fig. 4). The most elongate channels of this fan spread from the apex southeast to the escarpment nearly 15 mi away and 85 ft lower. A second, perhaps younger elevated channel/fan complex spreads from an apex 4 mi northeast of Columbus and ends in playas with downwind lunettes in northernmost Chihuahua east of Palomas. Channel patterns show the movement of water and sediment from the toe of the Columbus Basin fan into the narrow, restricted Bolson de los Muertos in Mexico. Reeves (1969) and Hawley (1993) presented evidence for extensive late Pleistocene pluvial Lake Palomas in the Bolson de los Muertos into which late Pleistocene Mimbres River flows emptied.

The volume of sediment along one of the channel ridges was estimated to aid in determining possible modes of deposition. The channel selected in the northern Columbus Basin was traced on 1:24,000 quadrangles from the fan apex to the point where 5-ft contours no longer showed the alluvial ridge near the Mexican border, a distance of 14 mi. The ridge initially averaged 670 ft wide, narrowed to an average of 490 ft wide after 6 mi, and averaged only 370 ft wide near the snout. With a height of 5 ft, using the formula for the area of a segment and essentially cylindrical form, the calculated volume of this one ridge is over 130 million ft^3. At mid-fan, the northern Columbus Basin fan complex has at least a dozen similar channels.

In contrast to the pattern of large fluvial fans to the west and south, the pattern of fluvial features in the Mimbres Basin east of the Florida Mountains is tectonically controlled. Essentially a half graben, the Mimbres Basin is bordered on the east by the Camel Mountain fault scarp, downthrown to the west; the Florida Mountains are created by the upward-rotated part of the hanging-wall half-graben block. The Mimbres River heads diagonally southeastward toward the scarp from its entry to the Mimbres Basin north of the Florida Mountains. Southerly trending, anabranching river channels are concentrated along the east margin of the basin adjacent to the footwall scarp, a position clearly determined by asymmetric subsidence of the hanging wall (Allen, 1978; Bridge and Leeder, 1979; Leeder and Gawthorpe, 1987; Mack and Seager, 1990). Large hanging-wall fans derived from the Florida Mountains fill the western two-thirds of the basin. Downstream, the channel system in the Mimbres Basin merges with distal fan channels in the Columbus Basin and continues along the scarp.

In parts of the Mimbres fluvial system, particularly in the southern Deming and northern Mimbres valleys, indented (some incised) channels range in depths, widths, sinuosities, patterns of meander migration, and crosscutting relationships, indicating a long history and multiple episodes of channel evolution. Indented sinuous channels alternate downstream with having eolian-exaggerated levees on one or both sides of the channels to being "positive" ridges, wider than the precedent channel upstream, suggesting a large eolian buildup to form ridges over old channels (possible origins of channel ridges are addressed below).

Scattered shallow (10–15 ft) gravel pits in both the Deming and Columbus Basins reveal single- or multistory deposits of trough-crossbedded sand and sandy gravel in sets as much as 3 ft thick beneath 2–5 ft of finer-grained surficial deposits. Pebble imbrication shows north to south or southeast transport. Although many water wells penetrate the sand and gravel beds, which are excellent aquifers in both the Deming and Columbus Basins, examination of subsurface records was beyond the scope of this paper; consequently thicknesses and types of fluvial deposits at depth are not compiled here, but locally are known to exceed hundreds of feet.

Age of Mimbres surficial fluvial deposits

The age(s) of the fluvial ridges and large fans have not been determined by radiometric means, but their relative age may be estimated using geomorphology, soils, lake levels downstream, archaeological sites, and vegetational history.

From a geomorphic perspective the fluvial deposits of the Mimbres River appear to be very young. The simplest assumption is that the deposits forming the present surface are constructional tops and are nearly unmodified by erosion except for the growth of coppice dunes and deflation of some fine-grained deposits. Modern, active arroyos or alluvial fans draining nearby ranges are present around the margins of the fluvial deposits but have not encroached far across them, the only exception being Seventysix Draw which has built a small fan onto the back of the Columbus Basin fan (Seager, 1995).

If the fans were formed during catastrophic flood events, ages might be interpreted from regional floods radiometrically dated in surrounding drainage areas (such as Waters, 1989; Enzel et al., 1989; Ely et al., 1993, 1994; see below). However, if more gradual processes are involved, regional floods become less important as precise dating tools but remain significant in interpreting possible local history.

Soils developed on the fluvial deposits confirm their youth. Soil profiles at the top of fluvial fan deposits are exposed in gravel pits in both the Deming and Columbus Basins; they are uniformly weakly developed. The clay-enhanced B horizon extends from near the surface to depths of 1–2 ft and darkens but does not redden the parent material. Clay films occur as thin coatings around pebbles or in pore spaces. Below the clay-rich B horizon is a carbonate-rich horizon with stage I or stage II accumulation of Gile et al. (1981). The carbonate occurs as very thin continuous to discontinuous coatings on pebbles or cobbles. Fine carbonate filaments, small nodules, segregations and interpebble fillings are not obvious. These soil properties suggest thousands to tens of thousands of years of pedogenesis and relative landscape stability. The soils are most similar to the late Pleistocene and Holocene soils of the Desert Project (Gile et al., 1981). On the basis of correlation with soils in the Desert Project, we estimate that the uppermost Mimbres River fluvial deposits are no older than 15,000 yrs (latest Pleistocene) and may be, at least in part, Holocene. Similarly, Neher and Buchanan (1980) mapped these soils as late Pleistocene to late Holocene in age. Reeves (1969) described late Pleistocene lakes in the Bolson de los Muertos into which the ancestral Mimbres River discharged and coined the label "pluvial Lake Palomas". He noted three major shoreline elevations, the highest at 4,018 ft, the lowest and youngest at 3,854 ft. The highest lake level would have inundated the lower part of the Columbus Basin as well as approximately 3,000 mi^2 of Chihuahua. Although all shorelines are thought by Reeves to be Wisconsin in age, none are dated precisely enough to establish a temporal correlation with the latest Pleistocene to Holocene Mimbres River deposits described here. Perhaps the lowest, youngest shorelines mapped by Reeves (1969) and interpreted as younger than a lacustrine carbonate radiocarbon dated as 27,150 ± 1,060 yrs B.P. are coeval with Mimbres River deposits; if so, the toe of the Columbus Basin fan in the Bolson de los Muertos did, at least for a time, function as a delta fan. On the other hand, no shoreline features have been recognized at the toe of this fan on aerial photos or satellite imagery.

Archaeological sites on the Mimbres fluvial system may establish minimum ages for deposition. The archaeology of Luna County has not been evaluated in a systematic manner and much of the land is unsurveyed under private ownership, but surveys in the Columbus valley have reported a few archaeological sites on the Columbus fan. These sites are from the Mogollon culture (A.D. 600 to 1,000), except for one Archaic site near the toe of the fan (2,000 B.C. to A.D. 1; T. Hanley, written comm. 1995). The dates suggest little erosion or aggradation has taken place during the late Holocene at least in the areas where sites are found.

Ground-cover vegetation may reflect landscape age and/or patterns of surficial processes, both fluvial and eolian. Vegetative changes in ground cover, including the decrease in grassland and increase in desert scrub in historic time, is documented in southwest New Mexico by McCraw (1985). He interpreted the development of desert grassland across valleys of southwest New Mexico to have developed no later than about 8,000 yrs ago. A major climatic change to more arid conditions between 4,000 and 5,000 yrs ago brought the first creosote bush to the region; its spread as an indicator species of the northern Chihuahuan Desert reflects warm, semiarid climatic conditions since then. The Deming fan remains covered with grassland and mesquite whereas the Columbus fan probably has had desert scrub (mesquite and creosote bush) for at least the last 4,000 yrs (D. McCraw, oral comm. 1996). Coppice dunes are probably associated with historic depletion of grass cover and breakup of soil in both areas.

Discussion

Topics for discussion of the Mimbres fluvial fans progress from the origins of channels and fluvial ridges, to climatic conditions for channel development, to formation of the large fluvial fans, to broader implications for filling other extensional basins. The lack of detailed information in the Mimbres drainage regarding most of these topics reflects the preliminary nature of this paper and reinforces a cautionary approach to the discussion.

Origin of fluvial ridges

To determine the feasibility of various depositional mechanisms for the ridges, we first consider the volume of sediment delivered along one of the raised channels (calculated above at more than 160 million ft^3). If modern average annual discharge is roughly 10,870 ac-ft/yr, average instantaneous stream flow is only 15 ft^3/sec. With the sediment discharge formula of $Qs = 9.097\ Qw$ yielding sediment transport of 137 tons per day, and if sediment is deposited at 20 ft^3/ton, roughly 2,500 ft^3 is transported per year and is available for deposition downstream. The calculated volume of the 14-mi channel segment is 160 million ft^3 so it would take 52,000 yrs to transport and deposit one channel's worth of sediment at average modern rates. The geomorphology and soils indicate surface stability since the late Pleistocene, so development of the ridge must have preceded that time. Using average discharge, however, is probably not correct to explain the bulk of geomorphic work done in drainage basins. When the maximum historic water discharge of 20,000 cfs for the Mimbres River is used with the same formula for sediment discharge, 3.6 million ft^3 of sediment would be transported and available for deposition in a day, and it would take only 36 days to create the volume of the measured channel. This calculation of course raises concerns about rates of sediment production in the headwaters, let alone the duration and magnitude of storms necessary to generate such discharges. In historic time, only large floods have reached the Mimbres Basin, so it seems likely that large discharge events are responsible for delivering water and sediment to the fans in the past. It still seems unlikely that entire fan complexes from apex to tips of distributaries would have formed during a single flood. Rather, once a transport channel, fan apex, and distributary system was developed, it may have persisted over a period of time before the channel avulsed to form a new apex on a different part of the fan complex. If the raised channels' development also includes sediment redistribution by eolian processes as well as initial transport, the picture becomes much more complex. For example, if distributaries persisted and vegetation took advantage of the channel margins, eolian reworking of interdistributary areas could have helped build up the vegetated levees to raise the distributary channels prior to the next floods.

On the basis of their morphology, fluvial ridges in the Mimbres drainage system may have more than one origin. First, the distributary channels on fans may have been deposited as typical channels inset into the fan surface with levees and areas of fine-grained silts and clays between them. The ridges may have developed as "inverted topography", the result of wind deflation of interdistributary low areas, leaving the sandy and gravelly channels and levees standing in relief. Apparent remnants of finer-grained interchannel deposits preserved in yardangs adjacent to the ridges in a few areas east of Columbus support such a mechanism.

In other areas, as alluded to above, particularly in the southern Deming and northern Mimbres Valleys, inset meandering channels alternate downstream with having eolian-exaggerated levees on one or both sides of the channels to being "positive" ridges, suggesting a large eolian accumulation to form ridges over old channels. The channels also show various widths, sinuosities, evidence of meander migration, and crosscutting relationships, indicating a long history and multiple episodes of formation. Once the channels are covered with eolian sand, however, they develop similar ridge sizes and shapes and appear to be similar in age (essentially the age of the dunes at the surface).

The presence of several small channels and lack of obvious large channels passing through the gap between the Tres Hermanas and Florida Mountains suggests that the stream or streams feeding the raised fan apexes on the Columbus fan were small, but persistent as well. If the raised channels are created over a period of time with a combination of fluvial and eolian processes, large floods from the headwaters of the Mimbres system may not be required; rather, smaller local discharge events from the southern Deming Basin (like Seventysix Draw) could have fed the channels on the Columbus fan and eolian processes could have emphasized the former channels.

Another applicable mode of formation of alluvial ridges is documented on the Jornada del Muerto northeast of Las Cruces by Gile et al. (1981). The ridges are primary channel features extending from gully mouths downfan toward playas. Initially confined by constructional sandy levees and aggraded above the surrounding floodplain by deposition of bedload on the channel floor as flood waters subside, the current form is a steep-gradient sinuous ridge about 4 ft high. As shown in artificial trenches cut across the ridge, pebbly sand at the margins of the ridge interfingers downward and laterally with fine-grained sediments (Fig. 5A), indicating the sand and gravel deposits do not fill erosional channels bounded by scoured walls. J. Hawley (oral comm. 1995) envisions a multi-episodic buildup of levees and bedload to form the alluvial ridges (Fig. 5B), but it is conceivable that each ridge built during one large discharge event. A similar feature suggesting a single spectacular discharge event has been found buried in fill of the Albuquerque Basin (M. Davis and D. Love, unpublished data).

Climatic considerations of channel and fan development

No climate-related data have been synthesized from proxy records (tree-rings, middens, deposits, etc.) within the Mimbres drainage. If the above volumetric analysis of surficial channel ridges is correct, the channels did not form all at once, but over a period of time. These ribbon-like channels and distributaries carried water and sediment far beyond all but the biggest historic flows and deposited extensive gravelly sand and overbank facies, implying large-discharge events in the past. Beneath the surficial deposits are buried multistory gravelly sand sheets reflecting even more widespread fluvial transport and deposition from competent streams. Climatic conditions conducive for large-discharge events, if not longer-duration episodes in southwestern New Mexico, are summarized in Table 1.

Detailed analysis of channel deposits may reveal modes of deposition and their possible origins within the basin. For example, the surficial channels in the southern Deming Basin and Columbus fan may be related to local summer floods (similar to those discussed for Gila tributaries by Burkham, 1970) and not discharge from the headwaters. Conversely, the larger channels on the Deming fan and meandering channels on the valley floors may indicate long-duration discharge from the headwaters following one or a combination of precipitation events in the fall, winter, or spring.

Climatic conditions and timing of regional large discharge events may be applicable to the Mimbres Basin (Table 1). Many winter floods in Arizona and Utah occurred during El Niño episodes (Ely et al., 1994). Deposits along 19 streams in Arizona and Utah reveal extreme floods over the past 5,000 yrs (Ely et al., 1993). The floods cluster in three time intervals related to episodes of cool, moist climate and frequent El Niño events. The intervals include 4,800 to 3,600, 1,000, and after 500 yrs B.P. No floods were recorded between 3,600 and 2,200 yrs and 800 to 600 yrs B.P.

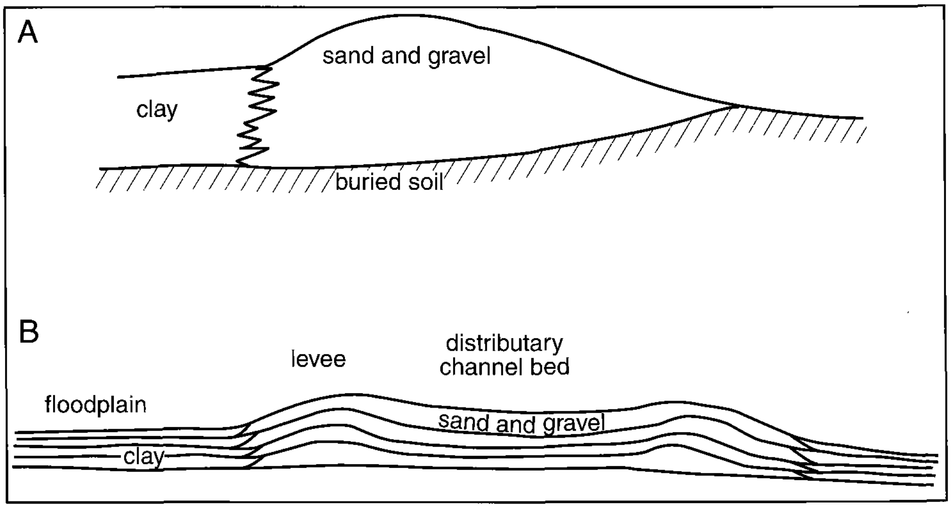

FIGURE 5—**A**, Cross section of sand and gravel ridge exposed in trench in Desert Project area northwest of Las Cruces. Drawing is adapted from Gile et al. (1981, p. 76). Note lateral and downward interfingering of sand and gravel lithofacies with clay lithofacies along margins of ridge. **B**, Diagrammatic illustration of how sand and gravel distributaries on fluvial fans may aggrade above the general level of the fan surface.

TABLE 1—Flood-producing conditions in southwestern New Mexico.

	Climatic condition	Times of year	Moisture sources	Extent of flooding	Examples and references
1.	Frontal storms	Fall & winter	Mid-latitude Pacific	Regional, from headwaters	Gila River (Burkham, 1970, 1972)
2.	Cutoff low pressure	Fall & winter	Mid-latitude Pacific	Regional, from headwaters	(Hirschboeck, 1991)
3.	Short-wave troughs	Fall & winter	Mid-latitude Pacific	Local/regional	(Hirschboeck, 1991)
4.	Mesoscale convective storms	Summer & early fall	Gulfs of Mexico or California	Regional, anywhere in drainage	(Hirschboeck, 1991)
5.	Local convective storms	Summer & early fall	Gulfs of Mexico or California	Local, anywhere in drainage	San Vicente Arroyo through Silver City (Waltemeyer, 1989)
6.	Tropical cyclones	Late summer & early fall	Gulfs of Mexico or California	Regional, throughout drainage	(Hirschboeck, 1991; Smith, 1986)
7.	El Niño years	Year-long cycle of moisture	Mid-latitude Pacific	Regional, headwaters in winter and spring	(1) Drainages to west (Ely et al, 1993, 1994) (2) New Mexico, (Kahya & Dracup,1994; D'Arrigo & Jacobi, 1991)
8.	Combinations of 1, 2, 3	Fall & winter	Mid-latitude Pacific	Regional, from headwaters	(Hirschboeck, 1991)
9.	Combinations of 5 and 6	Late summer/ fall	Combination, Gulfs	Local/regional, anywhere in drainage	1983 Willcox Playa flooded and evaporated (Smith, 1986; Waters, 1989)
10.	Combinations of 1, 2, 3, and 6	Early fall	Mid-latitude Pacific	Regional, throughout drainage	1970 S. Arizona (Hirschboeck, 1991; Hansen & Schwarz, 1981)

(Ely et. al., 1993).

The earliest interpreted floods apparently coincide with the latest relatively high stand of Lake Cochise in Willcox Playa, 102 mi west of Deming. According to Waters (1989) two high stands of the lake occurred prior to 14,000 yrs B.P. The most prominent shoreline, when the lake was 36 ft deep, dates between 13,750 and 13,400 yrs B.P. The playa filled nearly to the same level three times during the Holocene. The earliest fill episode was around 8,900 yrs B.P. The later two episodes were less well dated at about 5,400 and 3,000 to 4,000 yrs B.P. In contrast, the playa has undergone eolian deflation episodically in late Holocene time. Historic high-lake stands have been ephemeral and left no permanent record (Waters, 1989).

Other researchers' climatic models coupled with the Lake Cochise history suggest that during the late Pleistocene, winter storm tracks were displaced southward across the Southwest, resulting in cooler temperatures, reduced evaporation, and increased winter precipitation, perhaps doubling total annual amounts (Waters, 1989; Ely et al., 1994). Summer monsoonal precipitation was minimal (Waters, 1989). From 12,000 to prior to 8,900 yr B.P., winter precipitation was reduced, but summer precipitation increased to provide enough runoff to maintain a highstand of Lake Cochise. Then summer precipitation apparently declined between 7,000 and 5,000 yrs ago during the Altithermal. The two middle Holocene small lake stands apparently reflect more mesic conditions after the Altithermal (Waters, 1989).

If the ridges on the Mimbres fans are either eolian deflational topographic reversals of channels or eolian accumulations overlying channels, when might the strong action of wind have been prevalent? Desert scrub ground cover is more conducive to eolian erosion than are grasslands, so the vegetation history of the lowlands is important to determining how and when the ridges were formed. As reported above, McCraw (1985) suggested desert scrub dominated the Columbus fan for at least the past 4,000 yrs, but that grassland has persisted on the Deming fan to modern times. Based on soil stratigraphic, pollen, and stable carbon and oxygen isotopic relationships in the Hueco Bolson (southern New Mexico and west Texas), Buck (1996) reconstructed the late Quaternary vegetational and eolian history of the adjacent Chihuahuan Desert. According to Buck (1996) between about 18,000 and 8,000 yrs ago, grasses dominated the lowlands. At 8,000 yrs ago (±1,000 yrs), vegetation changed to desert scrubland, and a widespread and severe eolian deflational event eroded existing paleosols to form a surficial lag of pebbles and stage II carbonate nodules. Eolian and alluvial deposition following the erosional event contains evidence of persistent desert shrubs. Carbon isotopes indicate a slight increase in grasses between 2,000 and 5,000 yrs ago, followed by a slightly more- arid event at least locally. Oxygen isotopes show a slight increase in temperature before the major 8,000-yr erosional event and gradually increasing temperature, evaporation, and/or monsoonal moisture during the middle and late Holocene. Buck (1996) also noted the widespread historic eolian deflation of the last 150 yrs with grassland being replaced by desert scrub.

If Buck (1996) is right, the major eolian sediment transport event was between 7,000 and 9,000 yrs ago, and the ridges could all have similar soils on them after stabilizing after that active period. On the other hand, strong spring winds are normal in the northern Chihuahuan Desert and could have mobilized fine-grained sediment whenever it was exposed, leading to eolian reworked soils throughout the Holocene.

The multistory gravelly sand sheet below the surface in the Mimbres system may reflect the moist conditions prior to 8,900 yrs ago whereas the smaller surficial channels (both ridges and inset) and eolian reworked deposits probably reflect later Holocene conditions. Thus, the exposed units on the fans may show the stratigraphy formed during a pluvial/interpluvial climatic cycle. The coarse-grained gravelly sand sheets are interpreted to have been deposited during the pluvial hemicycle whereas the local channels and fine-grained interdistributary muds were preserved during the shift to the drier hemicycle, followed by eolian reworking and pedogenesis. With this model, during the pluvial hemicycle, most of the suspended sediment was only temporarily stored in floodplain and interdistributary areas. Channel shifts reworked the floodplains and produced the gravelly sand sheets. Most of the fine sediments were transported to pluvial Lake Palomas. With the onset of the drier hemicycle, suspended sediments commonly were left where they were deposited and less suspended sediment reached the bolson to the south. However, much of the sand and finer sediment underwent eolian reworking.

The climatic interpretation of shallow stratigraphy has several implications. First, fan stratigraphy should reflect pluvial/interpluvial cycles in the past if the wet hemicycles do not erode the previous dry-hemicycle deposits. This means coarse sand and gravel sheets should alternate with finer-grained deposits at depth. Second, dry-hemicycle deposits should be similar to present deposits where local channels crosscut and locally bury soils, interdistributary, and eolian units.

Local fan apices have become pronounced sediment accumulators whereas interdistributary areas have not had much net aggradation. Distal fan areas may not have accumulated much sediment either. Silts, clays, eolian sands, and soils dominate the areas between channels, and pedogenic/eolian modifications may grade upward from fluvial channels as the landscape aggrades. If current depositional conditions persist, vertical successions should include thin units showing flood surfaces, deflation surfaces (Langford and Chan, 1988), and sand-drift surfaces (Clemmensen and Tirsgaard, 1990) with weak pedogenic overprints along with channel, overbank, and eolian deposits. With episodic flooding and eolian accumulation, the dry-hemicycle deposits should show locally stacked, poorly developed soils.

Further implications of dry-hemicycle deposition for fan stratigraphy include the areal pattern and cross sections of localized channels as possibly important indicators of dry-hemicycle conditions. Local channels may range in pattern from sinuous to anabranching, but not be laterally extensive. In cross section either the channels may be incised as arroyos, or may be positive mounds above a scoured base (as in Figs. 3 and 5A). The channel fills may reflect lateral migration of meander loops or various styles of gully-fills (c.f. Love, 1983). Contrasting sedimentary characteristics may differentiate between channels with connections to the headwaters and channels developed from more local runoff events (compare modern Mimbres River near Deming with Seventysix Draw).

As discussed above, the wet-to-dry hemicycle may not be preserved during the next dry-to-wet reversal because during the wet part of the cycle the fluvial system may rework and obliterate the easily erodible surficial deposits. The broad fan shape of the fluvial fans and broad valleys with wide-spread fluvial features suggest that aggradation has dominated this part of the lower Mimbres system for much of Quaternary time so that the dry-hemicycle sediments and soils may be preserved. Future work with bore-hole descriptions may show whether sediments from past cycles are preserved.

Implications of Mimbres River deposits for other extensional basins with similar fluvial systems

The mode of deposition of sediments in extensional basins is a topic of current interest in geology. Widely recognized is the tectonic control exerted by grabens and half grabens on the location of axial fluvial or lacustrine systems and on the geometries of hanging wall and footwall fans (e.g., Allen, 1978; Bridge and Leeder, 1979; Leeder and Gawthorpe, 1987; Mack and Seager, 1990). In contrast, Smith (1994) illustrated basin aggradation influenced by Plio–Pleistocene climatic shifts during tectonic quiescence in the San Pedro Valley of southeast Arizona. Relatively rapid rates of sedimentation and coarser sheet-flood and channel deposits resulted from wetter, winter-dominant precipitation. Unlike tectonic interpretations, ratios of channel:floodplain facies varied directly with sedimentation rate. Systems-tract analysis of alluvial sequences may incorporate both tectonic and climatic interpretations of vertical and lateral changes in channel and overbank facies but it emphasizes the role of accommodation space in facies distribution and preservation. Alluvial depositional sequences having upward decreasing channel sizes and more interchannel muds, and soils have been interpreted as fluvial systems with limited accommodation space, that is, a limited volume where sediment may be deposited and not eroded later (Legarreta and Uliana, 1991; Shanley and McCabe, 1994).

The Mimbres River system offers an example of another mode of basin filling that may be of general importance: the filling of extensional basins by large, basin-wide fluvial systems that enter basins at an angle to their axes (Fig. 6; Mack et al., in press). The volume of sediment delivered to such basins is immense and may result in the flooding not only of single basins but also adjacent basins by fluvial sediment. This is illustrated by the deposition of Mimbres River sediments in the Deming, Columbus, and Mimbres Basins and in the Bolson de los Muertos. Large fluvial fans are the distinctive mode of deposition in these basins, although the asymmetry of the Mimbres Basin has also produced an axial fluvial system. Such fans in the Mimbres system spread transversely or obliquely across the basins, virtually filling them and forming a shifting drainage divide along the axis of the fan. One may envision several modes of fan aggradation within, but transverse to basins (Fig. 6) such that coarse-grained facies trend across the basins and finer-grained facies, perhaps including lacustrine facies, extend upvalley from the distal end of the fluvial fans. The downvalley end of the fans is transitional to the axial drainage.

What controls the avulsion of the fluvial system from one basin to the next? Mack et al. (in press) have documented both tectonic and autocyclic controls. Tilting of the Deming Basin to the east along the hanging wall of the Florida Mountains fault determined the orientation of the Deming fan and the subsequent courses of the ancestral Mimbres River along the east side of the Deming Basin and ultimately led to aggradation of the Deming Basin to two spillover points. The shifts of the Mimbres fluvial system alternately avulsing into the Mimbres and Columbus Basins is probably an example of autocyclic control. Examples of tectonic (mostly faulting) control of avulsion are documented by Mack et al. (in press) for the ancestral Rio Grande near Las Cruces. Tectonic controls may also have autocyclic aspects or at least lead to negative feedback. For example, when a fluvial system crosses a pass through the uplifted side of a rotated half graben and spills down the hanging wall into the adjacent basin (Fig. 6B), increased loading on the hanging-wall block by aggrading fluvial-fan deposits may produce further rotation of the half graben (Reiter, Barroll, and Cather, 1992). Further rotation may uplift the pass and divert the stream back into the adjacent basin, stopping further rapid loading. Half-graben rotations when fluvial systems enter basins from the footwall side or down the basin axis, however, do not have negative feedback consequences.

The contrast in stratigraphy in basins dominated by large fluvial fans and the more familiar ones dominated by hanging-wall and footwall fans and narrow axial-basin deposits is striking. Narrow but thick multistory deposits of axial fluvial or lacustrine sediment confined between narrow footwall and broad hanging-wall fans distinguish basin-fill deposits in half grabens. In comparison, large fluvial fans are dominated by radiating fluvial channels alternating with widespread fine-grained overbank deposits that are cut by broadly separated complexes of narrow fluvial sand and gravel channel tongues. Nearly continuous eolian deposits and soils are likely to be far better developed and preserved across the fluvial fan deposits as a result of periods of stability on the inactive parts of fluvial fans compared to the axial deposits in half grabens. As discussed above, long-term cycles of relatively wet and dry climatic conditions may enhance the thickness and preservation of these fluvial fan deposits. Axial fluvial deposition in broad full grabens probably is similar to deposition on fluvial fans, with the important difference that fluvial fans typically enter a basin transversely to its axis and spread both up and down the basin floor, often

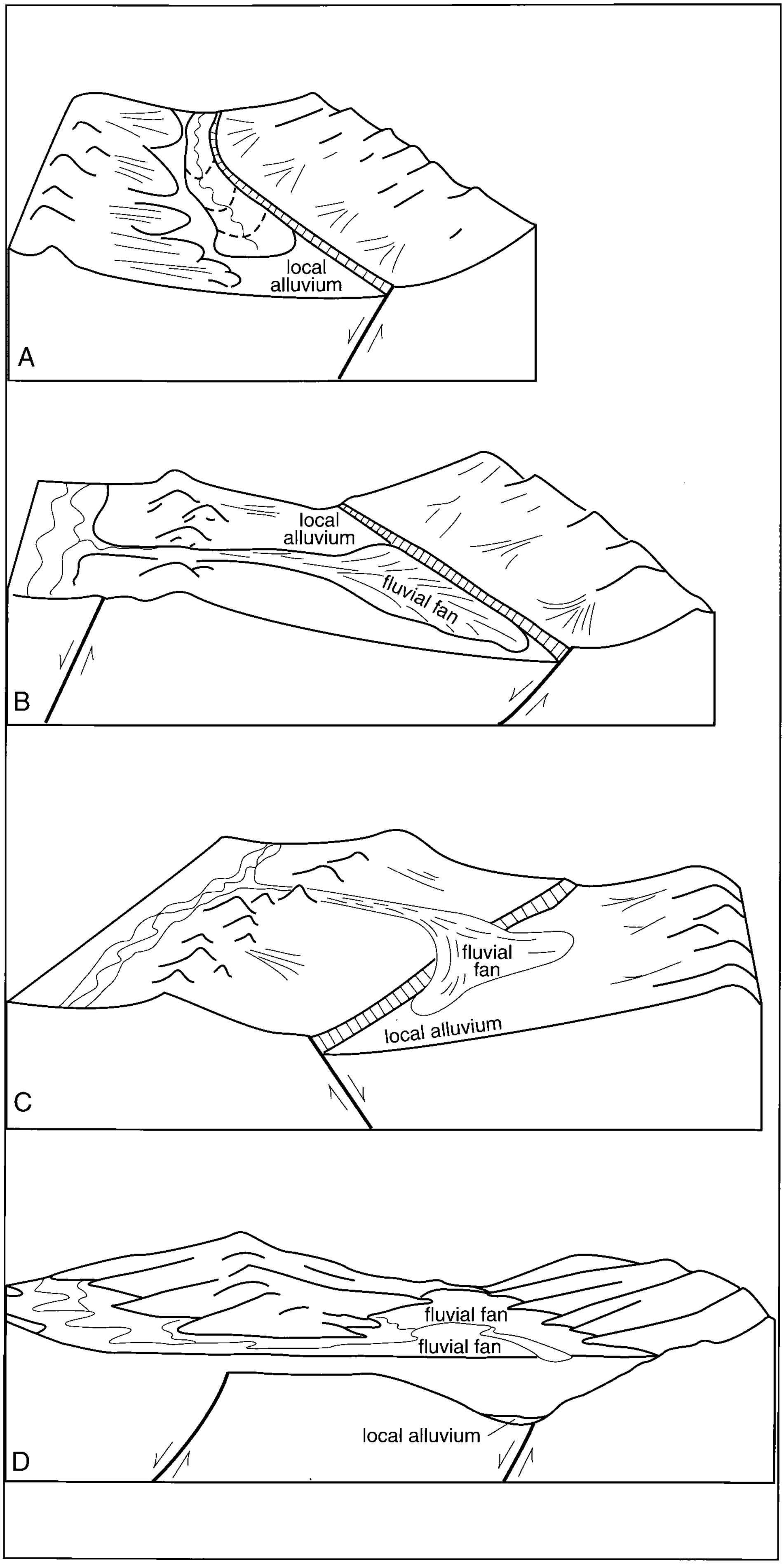

FIGURE 6—Schematic situations where extrabasinal sediment delivery overwhelms local basin deposition. **A**, Sediment delivery enters basin nearly parallel to scarp and axial valley (from either footwall or hanging-wall sides; former fluvial-fan positions dotted). **B**, Extrabasinal sediment descends hanging wall and builds fan blocking axial valley; further rotation of hanging wall resulting from tectonics or sediment loading may temporarily stop spillover from adjacent basin. **C**, Extrabasinal sediment crosses footwall and builds fan blocking axial valley. **D**, Extrabasinal sediment aggrades in former eroded tributary valley from downstream end. River flows from left to right.

but probably not always avulsing into adjacent basins.

Textural and facies changes in the upper few feet of the Mimbres fans are interpreted in terms of climatic shifts similar to Smith's (1994) interpretations of the San Pedro Valley. However, we interpret the lower, coarser, crossbedded pebbly sands as multistory, laterally reworked sheet-like deposits deposited during relatively wet episodes. In the Mimbres drainage, ribbon bodies (both as ridges and as inset channels) we associate with rarer large discharges during semiarid, interpluvial times. Extensive interchannel fine facies are deposited and perhaps preserved because the system is not capable of transporting the bulk of the sediment farther—either in the original floods or reworked in subsequent flows. Eolian and pedogenic processes dominate the periods of relative stability and nonflow.

Application of continental sequence-stratigraphic concepts to the Mimbres fans is problematic. Shanley and McCabe (1994) argued that sediments in continental basins are preserved below a somewhat theoretical base level of erosion and that where space exists to receive and preserve sediments, stratigraphic architecture is influenced by processes of sediment delivery. They discussed an alluvial depositional sequence in a continental basin in Argentina (after Legarreta and Uliana, 1991), beginning with multistory coarse, crossbedded sandstone and conglomerate overlain by crossbedded fine to medium sandstone with lateral accretion surfaces, in turn overlain by mudstone, siltstone, fine sandstone, and bioturbated paleosols. These descriptions are similar to the descriptions of the Mimbres fans' shallow stratigraphy. Shanley and McCabe (1994) interpreted the sequence as a coarse-grained lowstand-systems tract, a finer sandstone transgressive-systems tract, and a suspended-sediment-dominated highstand-systems tract. The increasing dominance of fine-grained sediment was interpreted as a result of limited accommodation space. It could be argued, however, that preservation of fines is enhanced by an increase in accommodation space and that preservation of only coarse, crossbedded sheet sandstones reflects lateral reworking during episodes of limited accommodation space.

The concept of accommodation space could be considered locally on the Mimbres fans or regionally in the tectonic context of the entire drainage. Deposition on the Mimbres fans continues to adjust to changing conditions of fluvial and eolian sediment delivery and storage. Down-fan gradients are about three times those of the modern Rio Grande in New Mexico, which are in turn an order of magnitude greater than the Mississippi gradients considered by Schumm (1993) in his discussion of sequence stratigraphy. These large gradients limit possible geomorphic responses of channels (Schumm, 1977). Because the Mimbres fans are prograding down hanging walls and the Columbus fan in particular has not yet buried the Camel Mountain fault escarpment, it would be hard to argue for limited available tectonic accommodation space. Just where the base-level control is with regard to erosion or equilibrium on the fan surfaces probably varies from flood to flood, depending on water and sediment discharge as well as other hydraulic factors. Eolian deposition continues across the fans even when the groundwater level is at depth. For deposits on the scale and complexity of the Mimbres fans, the concept of accommodation probably is better subsumed under larger geomorphic factors (cf. Schumm, 1985, 1991).

Summary

Large fluvial fans and related fluvial-valley fills dominate the Deming, Mimbres, and Columbus Basins of the Mimbres drainage. Whereas the valley floors typically parallel the extensional basins along the lowest part of the hanging wall near the footwall scarp, the broad fans cross the basins at angles to the structure from spillover points between ranges. The radiating fluvial channels interspersed with fine-grained interdistributary sediment and soils on the fans are in marked contrast with the typical axial-basin fluvial deposits confined between the footwall and alluvial fans of the hanging wall.

Anabranching and meandering channels are evident on the fans and valley floors even though only the largest historic stream flows have reached beyond Deming, New Mexico. Only two historic floods are documented to have reached the Mexican border. Therefore the channels seen beyond Deming must be related to large discharge events in the recent past. The channels are too extensive to have formed by just a few floods; rather channel-distributary complexes must have functioned repeatedly to form the networks seen across the fans and valley floors. Geomorphology, soils, archaeology, and vegetation all suggest that the surficial deposits and channels stabilized less than 15,000 yrs ago.

Some of the channels are topographically above the surrounding deposits. The channels consist of sand and gravel whereas the adjacent low areas are sand, silt, and clay. Some of these channels may have been deposited as positive constructional features; others may have undergone topographic reversal by eolian deflation; still others may have become positive features by eolian accumulation on top of channels and adjacent levees.

Shallow stratigraphy of the fans suggests that much of the fan construction was by a much more competent Mimbres River during Pleistocene time. During the most recent Late Pleistocene pluvial the river reworked and aggraded much of the fan surface. During Holocene time, the river channels became more localized; interdistributary areas and flood plains accumulated fine-grained fluvial and eolian sediments; eolian processes reworked sand across the landscape; and weak semiarid soils developed. The two types of deposits representing relatively wetter and drier parts of climatic cycles may be buried and preserved and should be sought in fluvial-fan deposits in other extensional basin settings.

ACKNOWLEDGMENTS—We are grateful for financial support for field work in the Deming area given by the New Mexico Bureau of Mines and Mineral Resources and for scientific support of our studies in southern New Mexico by Frank E. Kottlowski and Charles E. Chapin. We gratefully acknowledge discussions with John Hawley concerning the meaning of the word "fluvial" and his knowledge of geomorphic features in southern New Mexico. We thank Frank Pazzaglia, Bruce Harrison, and Steve Cather for making many suggestions to improve the manuscript and for suggesting more fieldwork to resolve issues this preliminary article has not addressed. We also thank Greg Mack, Gary Smith, and Barry Allred for their help. Figures were drafted by Kathy Glesner, David McCraw, and Becky Titus.

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