Alluvial-slope deposition of the Skull Ridge Member of the Tesuque Formation, Española Basin, New Mexico

Andrika J. Kuhle, Land and Water Consulting, P.O. Box 8027, Kalispell, MT 59904, and
Gary A. Smith, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131

Abstract

Miocene sediment eroded from the Sangre de Cristo Mountains is well exposed in the Española Basin and provides the opportunity to describe deposition on a non-fan, alluvial slope. The study site, located approximately 40 km (25 mi) north of Santa Fe, New Mexico, consists of a 150-m (492-ft) thick section of the Skull Ridge Member of the Tesuque Formation.

Eight depositional lithofacies were defined, and four vertically alternating and laterally continuous lithosomes were identified. The lithofacies are varied and range from massive, extensively bioturbated very fine sand and silt, to pebbly coarse bedded sand, to well-sorted fine sand. Internally massive lithofacies of fine sand and silt are most abundant, followed by fine sand channel deposits, then coarse pebbly sand channel deposits, and finally, well-sorted fine sand deposits. These lithofacies are interpreted to represent many small channels and adjacent floodplains on an alluvial slope. Persistence of channels across the piedmont is contrary to expectations for alluvial-fan deposition. The four lithosomes are tens of meters thick with abrupt vertical transitions. The first and third lithosomes consist predominantly of silt and very fine sand and are crudely bedded but internally massive due to extensive bioturbation. The second and fourth lithosomes consist of many channel-deposit lithofacies and well-sorted eolian sand in addition to internally massive beds of very fine sand and silt.

Variability in alluvial-slope deposits is observed at two scales. Depositional processes produce facies alternations at a bedding scale. External forcing mechanisms such as tectonics and/or climate produce lithosomes on a scale of tens of meters, which serve as confining units and heterogeneous permeable units. We favor climate as the allogenic control for the larger-scale variations.

Fundamental sedimentological differences exist between alluvial-fan and alluvial-slope deposits. These differences result in significant differences in bedding geometry and the lateral and vertical distribution of facies. The distinction between these alluvial-slope and alluvial-fan depositional environments must be made to properly characterize subsurface hydrological properties in terms of lateral and vertical variability.

Introduction

Sediment deposited on hanging-wall ramps constitutes the largest areal extent of fill in asymmetric extensional basins. These piedmont deposits, although voluminous, have rarely been addressed, and thus little is known of the associated sedimentation processes and facies patterns. A sedimentological framework may aid in basin analysis, delineation of rift-basin hydrocarbon reservoirs, and evaluating ground-water flow and contaminant transport in the western United States. To understand subsurface fluid flow in sedimentary basins, one must understand the sedimentary processes at the time of deposition, because fluid-flow properties are strongly influenced by patterns of sedimentation (e.g., Fogg, 1986; Tyler and Finley, 1991; Davis et al., 1993; Dreyer et al., 1993; North and Prosser, 1993).

Piedmonts of extensional basins are typically described as alluvial fans or pediments. Not all aggradational piedmonts can be strictly defined as fans (cf. Blair and McPherson, 1994a,b) and are best called alluvial slopes (Smith, 2000). There are significant differences of tectonic and economic importance between alluvial slopes and alluvial fans that must be recognized to adequately describe subsurface flow characteristics.

The objective of this paper is to describe middle Miocene deposits of the Tesuque Formation near Española, New Mexico, whose sedimentology is consistent with deposition on an alluvial slope. Additionally, the paper underscores the importance of distinguishing alluvial-fan deposits from alluvial-slope deposits to accurately characterize piedmont deposition, which is certain to determine first-order patterns of subsurface flow. We also address allogenic controls responsible for large-scale vertical changes in facies that reflect temporal variation in style of sedimentation.

Alluvial slopes

The term "alluvial fan" has been used in various restricted and general forms. The common vision of alluvial fans as features formed along steep mountain fronts fits most closely with the concepts elaborated by Blair and McPherson (1994a,b). Alluvial fans, in this strict sense, result from an abrupt downslope transition from confined to unconfined flow where bedrock channels cross sharp topographic and channel-form boundaries at or near the mountain front. The loss of flow confinement causes water and sediment to be dispersed over broad areas where channel margins are rare, undefined, or absent, resulting in remarkably sheet-like beds that are typically thin (<1 m thick [<3 ft]), or where channel margins are rare or absent. Consequently, deposition takes place abruptly, leading to the semi-conical shape that is definitive of resulting deposits (Bull, 1977; Rust and Koster, 1984; Blair and McPherson, 1994a,b). Abrupt deposition over broad, unchannelized areas also means that bedload and suspended load are deposited more or less simultaneously and at the same sites, which is in contrast to distinct channels and floodplains of fluvial environments. Abrupt deposition also results in poorly

NEW MEXICO GEOLOGY

A publication of
New Mexico Bureau of Mines and Mineral Resources
a division of New Mexico Institute of Mining and Technology

Science and Service

ISSN 0196-948X
Volume 23, No. 2, May 2001

Subscriptions: Issued quarterly, February, May, August, November; subscription price $10.00/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 Jane C. Love, 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

COVER—Middle Miocene strata of the Skull Ridge Member of the Tesuque Formation. These strata were deposited on an alluvial slope extending into the Española Basin from the Sangre de Cristo Mountains, visible in the background. Photo by Gary Smith, University of New Mexico.

sorted facies that, in the extreme, are the product of debris flows.

In contrast, the term "alluvial slope," first defined by Bryan (1922) and later modified by Hawley and Wilson (1965), designates the part of the piedmont that lacks the distinctive form of one or several coalesced alluvial fans. Hawley and Wilson (1965) recognize that gradations exist between a distinct cone-shaped alluvial fan and an alluvial slope, but they contend the latter term is necessary because not all deposition on the piedmont can be related to the distinct alluvial-fan morphology. Bull (1984) also uses the term alluvial slope generically to represent deposits that are usually found in conjunction with pediments where one is uncertain whether a depositional or erosional piedmont is present. The definition of alluvial slope used in this paper is consistent with that of Hawley and Wilson (1965) and advocated by Smith (2000).

Circumstances favoring development of alluvial slopes rather than alluvial fans are not well documented. Examination of topographic maps from the Basin and Range indicates that many nonentrenched piedmonts have relatively steep gradients, on the order of 0.01–0.04, but are characterized by parallel, commonly contributary, drainage patterns extending from mountain front to basin floor without development of alluvial-fan morphology. Hawley and Wilson (1965) observed that drainage basins for alluvial-slope streams are broad embayments that open directly onto the piedmont slope without a sharply defined mountain front. The lack of narrow canyons exiting mountain ranges across a distinct mountain front will most likely be associated with tectonically quiescent, erosionally embayed ranges or with drainages on the ramp side of half grabens where there is little or no active tectonic boundary at the mountain front.

Depositional processes on alluvial slopes, as distinct from alluvial fans, are also poorly documented. Alluvial-slope channels persist across wide piedmonts, resulting in distinct channel and interfluve environments and associated facies and with a lack of abrupt deposition that is definitive of alluvial fans. Nonetheless, these fluvial facies are unlike the deposits of large, perennial, low-gradient rivers whose description and interpretation dominate the fluvial-sedimentology literature (e.g., Miall, 1997). Alluvial-slope channels are steep, and ephemeral flows of significance for sediment transport are rapid, shallow, and markedly unsteady. Resulting deposits are expected to be dominated by upper-flow-regime sedimentary structures and abundant scour-and-fill structures.

A number of critical features should permit distinction of alluvial-slope facies assemblages where piedmont deposition can be inferred from paleocurrent and provenance data (Smith, 2000). These include: 1) recognition of distinct channel and floodplain deposits, 2) lack of widespread, sheetflood and sedimentary gravity-flow beds like those described by Blair and McPherson (1994a,b), 3) abundant sedimentary structures indicative of deposition from unsteady, upper-flow-regime flows, and 4) lack of abrupt downslope grain-size decrease of the sort typical of alluvial fans (Rust and Koster, 1984, fig. 4).

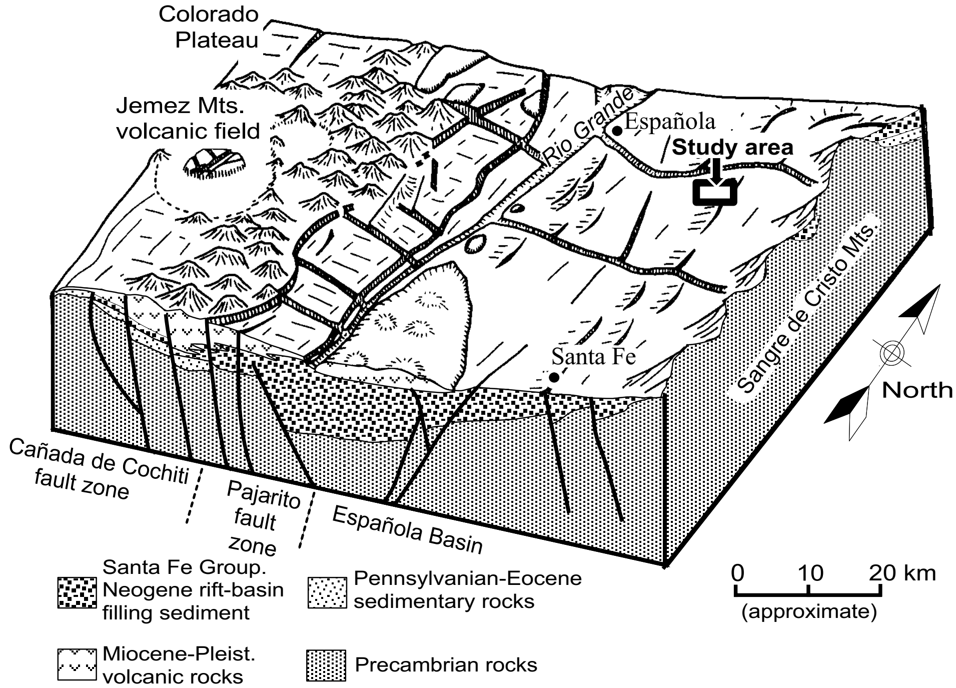

FIGURE 1—Schematic block diagram of the Española Basin showing the location of the study area, 40 km (25 mi) north of Santa Fe, New Mexico. The basin is a westward-tilted, asymmetric graben bounded to the west by the Jemez Mountains volcanic field, and the Sangre de Cristo Mountains to the east. The study area is within the west-dipping, hanging-wall-derived piedmont facies of the Tesuque Formation (Santa Fe Group). Modified from Golombek et al. (1983).

Geologic setting

The study site is located in middle Miocene sediment flanking the Sangre de Cristo Mountains on the east side of the Española Basin, approximately 40 km (25 mi) north of Santa Fe, New Mexico (Figs. 1, 2). The Española Basin is approximately 30 km (19 mi) wide and is a west-tilted half graben within the Rio Grande rift. The western slopes of the Sangre de Cristo Mountains are Precambrian igneous and metamorphic rocks locally overlain by Pennsylvanian limestone, sandstone, and shale. The paucity of Tesuque Formation detritus derived from Phanerozoic bedrock (Cavazza, 1986) implies that the Phanerozoic strata were removed during Laramide uplift of the Sangre de Cristo Mountains. The Española Basin is filled with Oligocene to Pleistocene sedimentary and volcanic rocks including the upper Oligocene–Pliocene Santa Fe Group. Santa Fe Group strata in the eastern part of the basin are assigned to the Nambé, Skull Ridge, and Pojoaque Members of the Tesuque Formation (Galusha and Blick, 1971) and have a total thickness of approximately 1,300 m (4,265 ft; Smith and Battuello, 1990).

The studied section is an ~150-m (~492-ft) thick interval within the Skull Ridge Member and consists of interbedded sandstone and mudstone, lenses of conglomerate, and many distinctive tephra layers.

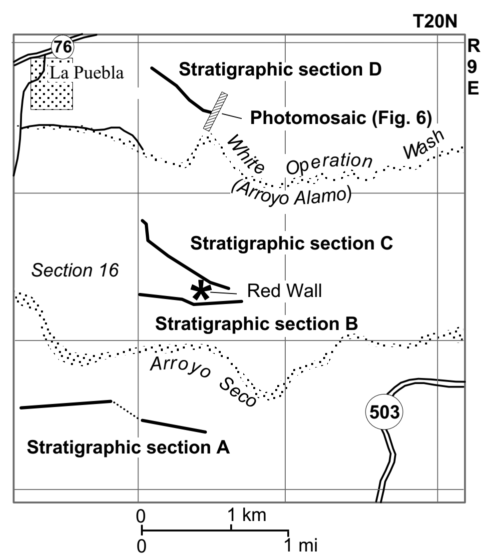

FIGURE 2—Map of the study area showing the locations of the four measured stratigraphic sections, the schematic diagram of oblique-aerial photomosaic (Fig. 6), and the two major east-west arroyos. The Red Wall of Galusha and Blick (1971) is the most prominent topographic feature visible in the study area.

FIGURE 3—View toward the west near section D (Fig. 2) illustrating good outcrop quality and continuity of White Ash #2 (arrows).

These strata are superbly exposed in badlands (Fig. 3). North-south-striking normal faults with up to tens of meters of displacement repeat the stratigraphic section, which dips uniformly approximately 10° to the west. The four most prominent and laterally continuous ash layers, White Ashes #1, #2, #3, and #4 (Galusha and Blick, 1971), are used as stratigraphic markers, and ashes #1 and #4 bound the studied stratigraphic interval.

The interval between White Ash #1 (WA #1) and White Ash #4 (WA #4) represents about 350,000–530,000 yrs of deposition. High-precision, single-crystal, sanidine laser-fusion $^{40}Ar/^{39}Ar$ ages for White Ashes #2 and #4 are 15.59 ± 0.07 Ma (W. C. McIntosh, pers. comm. 1997) and 15.42 ± 0.06 Ma (McIntosh and Quade, 1995), respectively. These $^{40}Ar/^{39}Ar$ ages for White Ashes #2 and #4 are consistent with ages obtained using magnetostratigraphy and biostratigraphy (Barghoorn, 1981; Tedford and Barghoorn, 1993). Glass composition of WA #1 supports correlation to a 15.86 ± 0.03 Ma ash erupted in Nevada (M. Perkins, pers. comm. 1996), although magnetostratigraphy of Barghoorn (1981) suggests an age older than 16.04 Ma (Kuhle, 1997).

Petrographic and paleocurrent analyses (Cavazza, 1986, 1989) indicate that the Tesuque Formation in the study area was derived almost entirely from the Precambrian-cored Santa Fe block of the Sangre de Cristo Mountains with paleocurrent directions predominantly to the west and southwest (Fig. 4). The basinwide distribution of paleocurrent data (Cavazza, 1989) suggests that the study site was positioned near the mid point of a west-sloping piedmont that was at least 15 km (9 mi) wide.

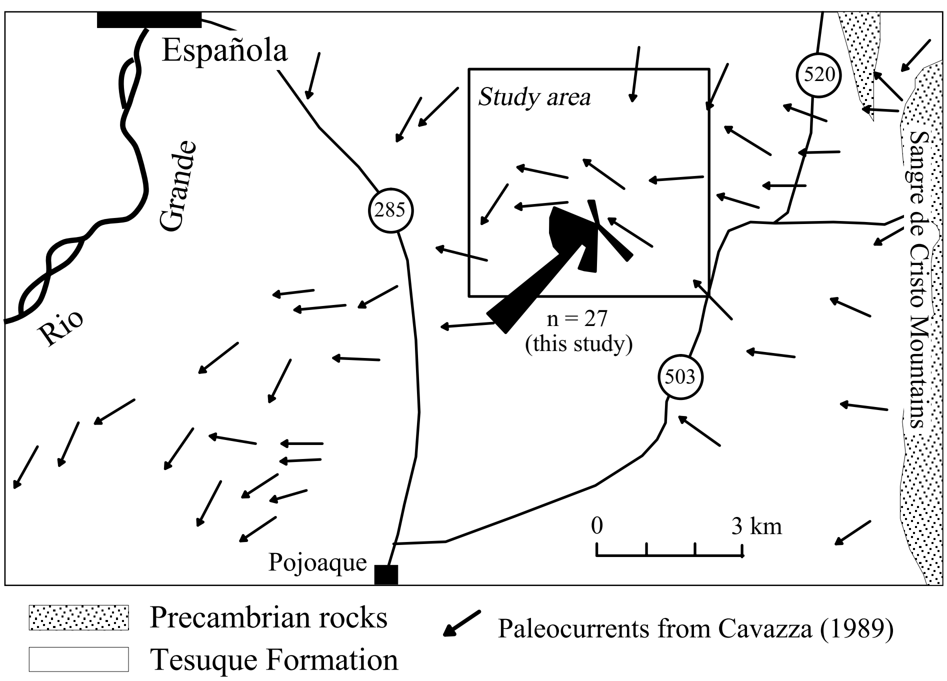

FIGURE 4—Petrographic and paleocurrent analyses (Cavazza, 1986, 1989) indicate that the Tesuque Formation in the study area was derived almost entirely from the Precambrian-cored Santa Fe block of the Sangre de Cristo Mountains. Paleocurrents from Cavazza (1989), represented by arrows, and paleocurrents from this study shown in rose diagram, indicate primarily southwest and west flow directions. Modified from Cavazza (1989).

Lithofacies and facies sequence

Four correlated stratigraphic sections were measured between WA #1 and WA #4 (Figs. 2, 5). The sections are spaced approximately 1 km (0.6 mi) apart, over a distance of 4 km (2.5 mi) along strike, and have an average thickness of approximately 150 m (492 ft). Outcrop mapping on oblique aerial photographs of the outcrops was used to depict lateral facies variability (Fig. 6; Kuhle, 1997). Eight lithofacies and four distinctive facies intervals were identified.

Lithofacies

Definition of lithofacies was based on sedimentary structures and grain size, so that each lithofacies represents a particular depositional process or a limited range of depositional processes. Lithofacies range from massive sand and mud indicative of floodplain deposition, to crossbedded sand and gravel indicative of channel processes, to well-sorted fine sand that may be indicative of eolian sand sheets. Physical descriptions and interpreted depositional environments for each lithofacies are summarized in Table 1.

The eight lithofacies generally reflect different depositional environments of two major kinds: interfluves and channels. Facies F_1 and F_{3a} are most obviously reflective of floodplain deposition. Facies F_2 may also represent floodplain deposits but could also record, in part, deposition in grassy channels and swales, as are common on many modern alluvial slopes in southern New Mexico and Arizona (Smith, 2000). The presence of abundant vegetation baffles flow, which enhances deposition of fine-grained sediment and, along with associated fauna, contributes to bioturbation of the sediment. Broadly lenticular beds of F_2, interstratified with F_1, are particularly abundant below WA #2 where the lenticular geometry suggests broadly channelized flow rather than unconfined deposition over a floodplain. Facies F_{3b}, F_4, F_5, and F_6 are found within channel-form bodies but form only about 10% of the section. Channel facies rarely contain bedform-produced crossbedding, and trough and planar-tabular crossbeds are less than one-third of the channel deposits, where

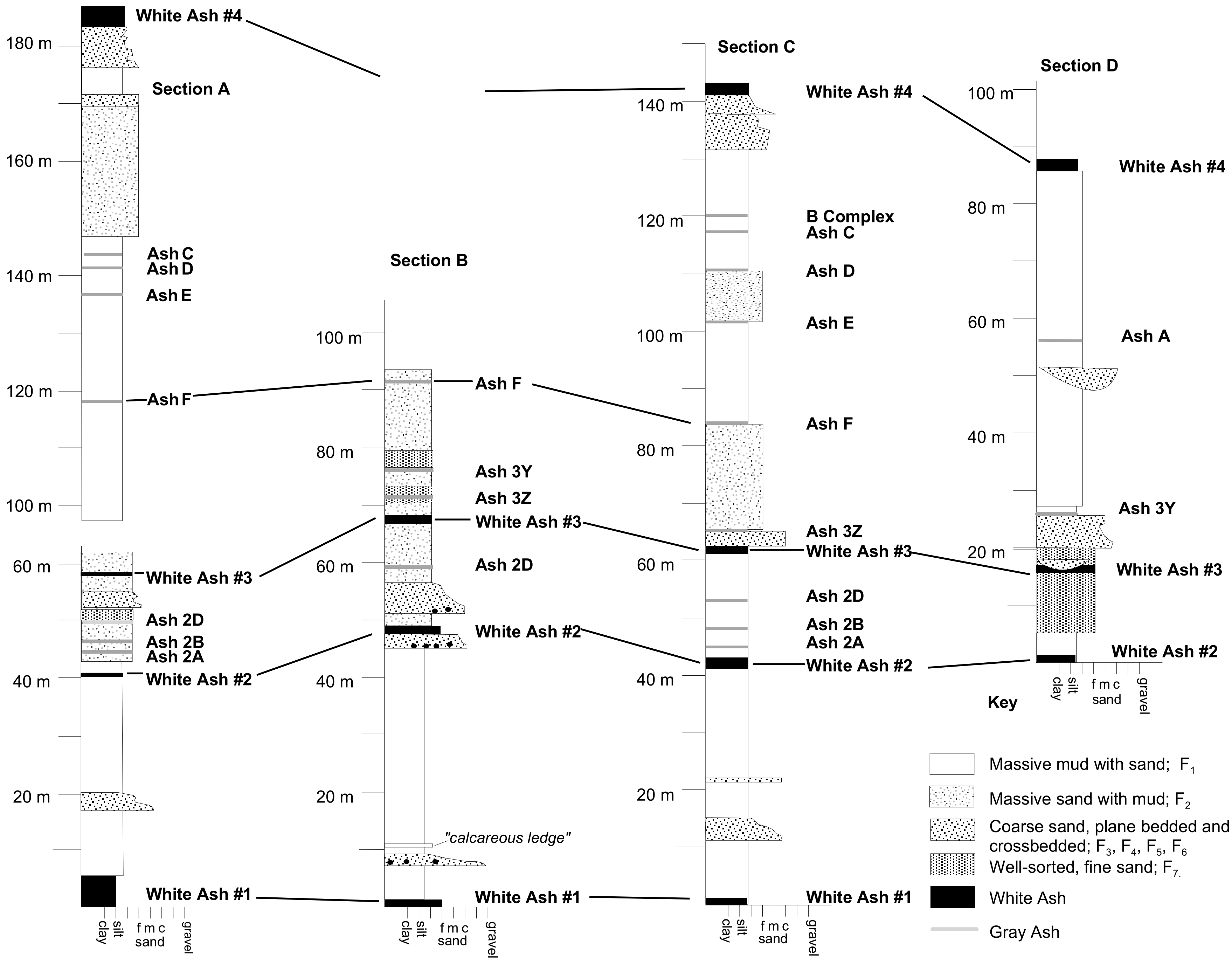

FIGURE 5—Generalized stratigraphic columns from the study area. Sections span the stratigraphic interval from White Ash #1 to the White Ash #4 and are spaced 4 km (2.5 mi) along strike from south to north. The average stratigraphic interval thickness is 150 m (492 ft). The stratigraphic section can be divided into four distinctive lithosomes that coincide closely with ash beds, which demonstrate the lateral persistence of the intervals. Black correlation lines have been drawn between the white ashes and one secondary ash.

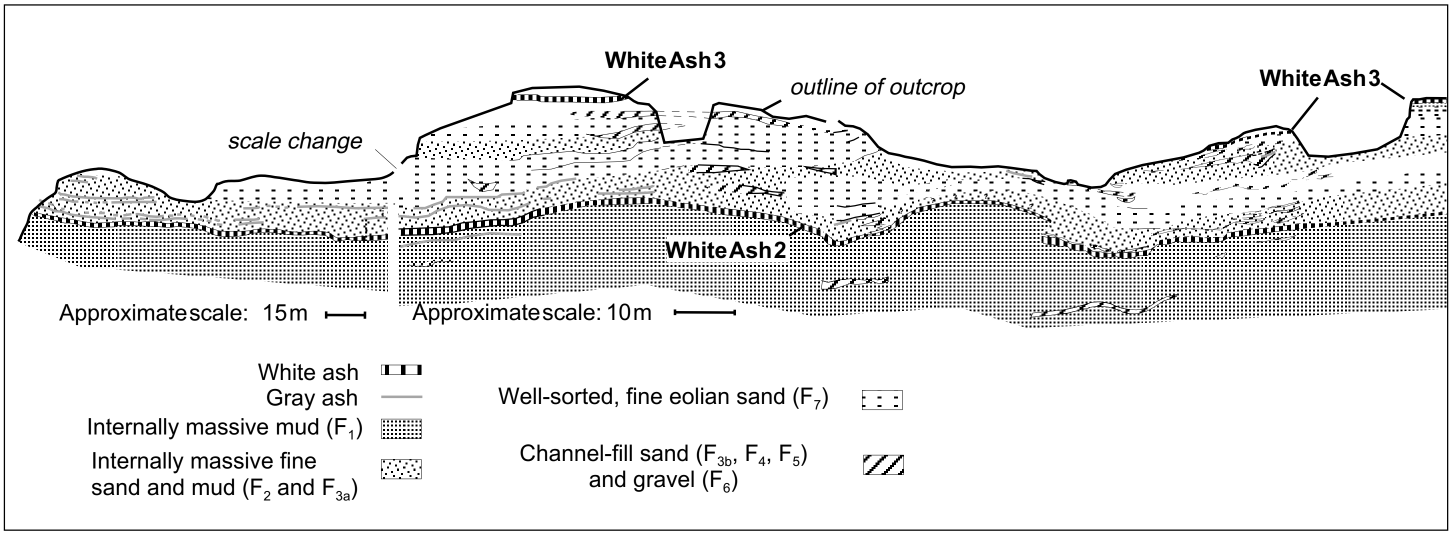

FIGURE 6—Schematic diagram of oblique-aerial photomosaic in the northern part of the study area (see Fig. 2 for location). This figure is a compilation of four different photos. Note the slight change in scale from left to right, which is from south to north. This photomosaic illustrates facies geometries and lateral variability for the stratigraphic interval above WA #2 and below WA #3 (WA #1 not shown). Note the abundance of channel deposits above WA #2.

present, suggesting generally upper-flow-regime conditions. These conditions reflect rapid, shallow, unsteady flows, all of which are compatible with ephemeral stream deposition.

The generally massive fine sand of facies F_7 lacks definitive features indicative of depositional process, but we suggest that it is an eolian facies. This facies typically forms sheet beds on the order of 1 m (3 ft) thick that are laterally continuous for at least 30 m (98 ft). Low (< 1-m-high [3-ft]) duneforms are rarely present and usually appear internally structureless, although translatent wind-ripple laminae (Hunter, 1977) have been observed in one case. Granulometric analyses (Kuhle, 1997) are consistent with an eolian origin because the facies is fine grained (median grain size of 3.5ø) and well sorted (50–65% between 4.5 and 3.0ø). We interpret this facies to represent variably bioturbated eolian sand sheets that formed in broad interfluves between sandy channels.

Facies intervals

The stratigraphic section can be vertically divided into four distinctive facies intervals that coincide closely with ash beds, which demonstrate the lateral persistence of the intervals (Fig. 5). The lowest interval is between WA #1 and WA #2, the second interval is between WA #2 and WA #3, the third interval is above WA #3 and below WA #4, and the fourth interval begins below WA #4. The ashes serve as stratigraphic markers and do not appear to have influenced deposition.

In the lowermost interval, F_1 is the dominant lithofacies, with minor amounts of the channel facies, F_6. Obvious channels in this stratigraphic interval are uncommon. The stratigraphic columns indicate that channel fills are spaced approximately 2 km (1 mi) apart. This pattern suggests that bedload channels are widely spaced and that mud represents the intervening floodplain or deposition in grassy swales. Pond deposits are also present in this stratigraphic interval. The abundance of red clay in facies of this interval imparts a distinct red color that, along with ash beds, aids in correlating the facies interval across fault blocks. The thin, tabular to broadly lenticular bedding that dominates this interval also imparts a distinct corrugated outcrop appearance.

The middle part of the section between WA #2 and WA #3 is markedly different (Fig. 5). Channel deposits are common, and the average grain size of the interval is coarser than the grain sizes of stratigraphic intervals below and above. Channel deposits have both ribbon and sheet geometry. Ribbon-shaped channel deposits are particularly numerous in the lower half of the interval, and sheet deposits become more abundant upward toward WA #3. Channel-fill deposits are typically ribbon shaped, much less than 10 m (33 ft) wide, and less than 3 m (10 ft) thick. Sheet beds have variable thickness, typically 2–7 m (6.6–23 ft), and extend laterally up to tens of meters. Eolian deposits, not observed in the lower interval, are most common in the middle stratigraphic interval and are from 1 to 5 m (3 to 16 ft) thick and persist for tens of meters. Massive sand and mud remain common but are not as abundant or as muddy as below WA #2. This facies of the middle interval also suggests deposition in channels and on floodplains. Channels, however, were more closely spaced and/or more mobile, and eolian deposition was common on interfluves.

The third stratigraphic interval is similar to the lowermost interval and consists predominantly of massive silty F_1. A single thin unit of eolian sand is found in this interval approximately 5 m above WA #3. Channel facies are present, but rare, and become more abundant upward toward WA #4. The pattern of deposition is similar to that of the lowest stratigraphic interval and is indicative of widely spaced channels and adjacent floodplains. The greater abundance of channel facies near the top of the sections indicates a fourth relatively coarse interval similar to the second lithosome.

Discussion

Depositional environment

Although these deposits are clearly the result of piedmont deposition, as indicated by the paleocurrent and provenance indicators, and although the mountain front may have been as near as 6 km (4 mi) to the east, these deposits are not those of alluvial fans associated with the Sangre de Cristo Mountains. The overall lateral pattern of deposition is of parallel, shallow channels separated by broad low interfluves subjected to overbank and, at times, eolian sedimentation. This pattern does not suggest abrupt deposition by expanding, unconfined flows on an alluvial-fan surface. Many of the sedimentary structures, however, are indicative of upper-flow-regime flow. The dominance of upper-flow-regime structures is the result of relatively shallow and probably less steady flows on generally steeper gradients than are characteristic for large aggrading rivers whose deposits dominate descriptions in the fluvial sedimentology literature.

Allogenic stratigraphic change

This transition from the lowest to the second facies interval, nearly coincident with WA #2, is abrupt and laterally continuous

TABLE 1—Summary of lithofacies.

Lithofacies		Texture, structures, and outcrop geometry	Depositional interpretation
F_1	Massive mudstone	Primarily silt and clay, with some very fine and fine sand. Extensively bioturbated with preferentially cemented bulbous burrows. Geometry is sheet-like. Crude bedding at meter scale is accentuated by weathering but is internally massive. Comprises 30% of stratigraphic section.	Unchannelized flow on a floodplain; associated with overbank flow from adjacent channels and suspension deposition.
F_2	Massive, muddy sandstone	Primarily fine- to medium-grained sand with minor mud. Mostly massive, with remnant laminae, discontinuous mud drapes, and crossbedding. Extensively bioturbated. Geometry is sheet-like to very broadly lenticular. Comprises 50% of stratigraphic section.	Deposition primarily by low-energy flows across floodplains or in broad channels or swales where vegetation influences deposition of fine sediment.
F_{3a}	Planar-laminated mud and muddy sandstone	Planar-laminated mud and muddy sand. Typically bioturbated and sheet-like in geometry. Comprises 2.5% of stratigraphic section.	Deposition from suspension on a floodplain.
F_{3b}	Parallel-laminated sandstone	Parallel-laminated fine to coarse sand. Moderately well sorted. Usually observed in sand bodies with channel-form geometry and scoured base. Comprises 1.8% of stratigraphic section.	Upper-flow-regime, plane-bed deposition in channels.
F_4	Low-angle crossbedded sandstone	Poorly sorted sand and silt with low-angle crossbeds. Deposits are 0.3–1.5 m (1–5 ft) thick with channel and sheet-like geometry and associated with scour-and-fill structures and scoured basal contacts. Comprises 2.6% of stratigraphic section.	Filling of scours by bedforms producing upper-flow-regime plane beds; migration of low-relief bars.
F_5	Crossbedded fine lithofacies	Scour-and-fill crossbedded and cross-laminated fine sand and mud with minor medium sand; includes mud rip-up clasts, mud drapes, and soft-sediment deformation. Present in ribbon-form channel bodies. Comprises 2.6% of stratigraphic section.	Filling of channels by strongly unsteady flows
F_6	Crossbedded coarse lithofacies	Scour-and-fill, trough and planar-tabular crossbedded coarse sand with gravel. Gravel clasts are 1–15 cm (4–6 inches), normally graded, and concentrated near scoured basal contacts. Present in wide, sheet channels. Comprises 2.9% of stratigraphic section.	Deposition in wide and/or laterally migrating channels, including deposition by migrating dunes and bars.
F_7	Well-sorted sandstone	Consists of massive, well-sorted very fine to medium sand. Sheet geometry with very rare dune forms. Comprises 7.4% of stratigraphic section.	Deposition in interchannel eolian sand sheets, possibly with some reworking by sheet flow.

over a 75 km^2 (129 mi^2) area where WA #2 is almost continuously exposed. Although the second interval is notable for more channel deposits and the lower interval for more fine-grained facies, both interfluve and channel facies are present in both intervals so that the transition cannot simply represent lateral migration of channels and floodplains. Furthermore, WA #2 has been traced nearly continuously for 20 km (12 mi) along strike (Smith and Battuello, 1990; Rhoads and Smith, 1995) and has not been observed crossing the transition; thus, the two facies are nowhere time equivalent along strike. Alternatively, the abrupt facies change might be interpreted as a progradation, perpendicular to strike, of proximal over more distal facies. We lack the ability to trace intervals sourceward, because exposures parallel strike, but the transition is abrupt and does not resemble a simple progradational sequence. These observations indicate that the different facies assemblages represent different sets of depositional processes that are the result of external forcing mechanisms, such as changing climate or subsidence rates, rather than intrinsic changes causing lateral migration of channels and floodplains.

The transition from coarser channel-fill and eolian dominated facies to muddier, massive sediment above WA #3 is not as vertically abrupt, nor has it been conclusively documented over as large an area as the lower change, but it is striking. Within 10 m (33 ft) above WA #3, sediment is predominantly massive, very fine sand and mud, with few obvious channel deposits. This change is observed in all four sections, with outcrops displaying the same corrugated appearance and reddened and bioturbated character as below WA #2. Approximately 15 m (49 ft) below WA #4, there is another less obvious upward transition back to more channel deposits, and average grain size again increases.

Cavazza (1986, 1989) suggests that faulting on the western side of the Española Basin could be responsible for the observed stratigraphic changes in the Tesuque Formation. Smith and Battuello (1990) question the interpretation of an exclusively tectonic control for the depositional sequences because Cavazza's conclusion is based solely on grain-size trends without consideration of facies trends that correspond to depositional changes. Alternations of coarse and fine-grained sediment are common in rift basins but are typically attributed to subsidence-controlled interbedding of footwall-derived-fan and basin-floor facies (e.g., Blair and Bilodeau, 1988; Mack and Leeder, 1999). Such explanations are not applicable to the textural variations in the Skull Ridge Member, which are expressed entirely within piedmont facies.

Tectonically induced cyclicity in hanging-wall-derived piedmont deposits has received less attention than cyclicity in deposits derived from footwall uplifts (e.g., Leeder and Gawthorpe, 1987). Increased subsidence would, hypothetically, steepen gradients on the hanging-wall piedmont slopes thus delivering coarser sediment, assuming it is available, to more distal sites and would result in the superposition of coarse facies on relatively finer ones. Deposition on the distal piedmont would lower gradients and ultimately return the piedmont-stream profiles to their initial state and dominantly finer grained deposition. Two observations suggest that such a scenario is unlikely for the Skull Ridge Member. First, although channels are less common in the lower interval, the deposits of these channels are as coarse as those found above WA #2. Therefore, shear stress does not appear to have changed as predicted by subsidence-induced steepening of the piedmont. Secondly, the transition from the first to second interval is abrupt rather than reflecting gradual facies progradation caused by subsidence.

Alternatively, climatic change could play a role in changing depositional styles by changing the density or type of vegetation, which would, in turn, vary the amount of overland flow or the rate and caliber of sediment delivered from hillslopes (e.g., Quade et al., 1995). In order to substantiate the possibility of a climatic control on the depositional sequences of the Tesuque Formation, a climate proxy is necessary to relate climate fluctuations to the observed stratigraphic variations.

Regrettably, there is a paucity of pedogenic carbonate and an absence of pollen that could be subjected to stable-isotope and paleofloral analyses that might serve as such a proxy. The presence of pond deposits in the lower stratigraphic interval and the restriction of apparent eolian deposits to the second stratigraphic interval does suggest that climate may have changed from relatively wet to more arid conditions.

Implications for subsurface flow

Sedimentary controls on subsurface heterogeneity are observed at two outcrop scales at the study site. Depositional processes, such as channel scour and fill or eolian transport, produce facies heterogeneity at bedding scale. External forcing mechanisms, such as tectonics and/or climate, produce lithosomes, the four facies intervals, on a scale of tens of meters, which serve as potential confining layers and permeable intervals.

The first and third intervals are fine-grained, laterally continuous, relatively low permeability strata that are tens of meters thick with few small non-interconnected channel bodies. An aquifer test approximately 17 km (11 mi) south of the study area suggests local confining layers coincident with fine-grained horizons within the aquifer characterized by repeated alternations of coarse and fine sediment (Hearne, 1985). We suggest that F_1-dominated intervals serve as confining units on a sub-basin scale and induce strong anisotropy to the aquifer. In the aquifer test, for example, horizontal hydraulic conductivity was found to exceed vertical conductivity by four orders of magnitude (Hearne, 1985). Lazarus and Drakos (1995) suggest that a shallow perched aquifer near Santa Fe is associated with surface flow over relatively impermeable dipping layers in the Tesuque Formation and is absent where flows infiltrated more permeable horizons. These observations suggest that the alternation of coarse and fine intervals can 1) lead to a complex distribution of heads in wells, 2) locally inhibit vertical connectivity in the aquifer, 3) influence patterns of recharge, and 4) facilitate communication between shallow alluvial aquifers, which are more prone to contamination, and the deeper Tesuque aquifer because the shallow aquifer rests unconformably on the dipping strata. The vertical alternation of contrasting facies probably relates, as in our study site, to large-scale allogenic changes observed within the watershed that resulted from tectonics or, as we prefer, climate change during deposition.

At the bedding scale, the arrangement of facies is not consistent with the typical view of laterally adjacent, permeable channel facies and impermeable floodplain deposits common to larger perennial streams (e.g., Fogg, 1986; Davis et al., 1993). In the middle stratigraphic interval, permeable channel facies are more abundant but remain subordinate in volume with respect to interchannel deposits. Nonetheless, the interchannel facies are composed of well-sorted eolian sand in addition to overbank mud, so empirical hydraulic conductivities, based on grain-size analyses, range over one and one-half orders of magnitude (Kuhle, 1997). The channel deposits are also heterogeneous and range from fine crossbedded and poorly sorted sand (F_4 and F_5) to coarse sand and gravel channel fill (F_6), with estimated hydraulic conductivities that vary over two orders of magnitude and overlap with those of the interfluve environment (Kuhle, 1997). Thus, a clear distinction cannot be made between interchannel and channel deposits in terms of hydraulic conductivity.

It should be noted that these observations are inconsistent with observations made for subsurface-flow patterns in alluvial-fan deposits. Alluvial-fan architecture and heterogeneity are complex, and there are few detailed descriptions (e.g., DeCelles et al., 1991; Neton et al., 1994). The most notable attributes are an abrupt downslope decrease in grain size (Rust and Koster, 1984; Blair and McPherson, 1994a) and a sheet-like geometry of beds formed by limited confinement of flow. Variations in grain size, and hence hydraulic properties, are most dramatic in the direction of transport. In alluvial-slope environments, and other settings where flow is better channelized, proximal-to-distal changes in sediment texture and hydraulic properties are less pronounced than those between laterally adjacent channel and interchannel facies (Smith, 2000).

Conclusions

The Skull Ridge Member of the Tesuque Formation was deposited on an alluvial slope, an under-appreciated depositional environment in extensional basins. A broad, hanging-wall piedmont slope was characterized by streams draining large watersheds in the Sangre de Cristo Mountains without crossing a sharp, fault-defined mountain front.

Eight lithofacies were defined, ranging from massive, very fine-grained sand and mud, which represent floodplain deposits, to well-sorted eolian lithofacies, which also represent interfluve areas, to channel-fill lithofacies ranging from fine sand to gravel. Deposition occurred in widely spaced, shallow stream channels that were separated by broad floodplains, which also sometimes experienced eolian deposition. Sedimentary structures are dominated by scour and fill structures, plane beds, and low-angle crossbeds, which indicate flows principally in the upper-flow-regime conditions. The steep gradient, along with shallow and probably unsteady flows, accounts for the dominance of upper-flow-regime structures.

The distinction between alluvial-slope and alluvial-fan deposits is important in order to properly characterize lateral and vertical variability of subsurface hydrological properties. Understanding vertical variability may explain variable hydraulic heads, distribution of confining layers, and patterns of recharge in the Tesuque aquifer. Lateral variability of channel and interchannel deposits may lead to extreme lateral flow variability in both saturated and unsaturated flow that would not be expected with the sheet-like geometry of alluvial-fan deposits.

Acknowledgments. This research was supported by Petroleum Research Fund (American Chemical Society) grant 29123-AC8 to Gary Smith. The manuscript was improved by helpful reviews from Greg Mack and Paul Drakos.

References

Barghoorn, S., 1981, Magnetic-polarity stratigraphy of the Miocene type Tesuque Formation, Santa Fe Group, in the Española Valley, New Mexico: Geological Society of America, Bulletin, v. 92, pp. 1027–1041.

Blair, T. C., and Bilodeau, W. L., 1988, Development of tectonic cyclothems in rift, pull-apart, and foreland basins—sedimentary response to episodic tectonism: Geology, v. 16, pp. 517–520.

Blair, T. C., and McPherson, J. G., 1994a, Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages: Journal of Sedimentary Research, v. A64, no. 3, pp. 450–489.

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

Bryan, K., 1922, Erosion and sedimentation in the Papago country, Arizona, with a sketch of the geology: U.S. Geological Survey, Bulletin 730, pp. 19–90.

Bull, W. B., 1977, The alluvial-fan environment: Progress in Physical Geography, v.1, pp. 222–270.

Bull, W. B., 1984, Alluvial fans and pediments of southern Arizona; *in* Smiley, T. L., Nations, J. D., Pèwè, T. L., and J. P. Schafer (eds.), Landscapes of Arizona—the geological story: University Press of America, Lanham, MD, pp. 229–252.

Cavazza, W., 1986, Miocene sediment dispersal in the central Española Basin, Rio Grande rift, New Mexico, USA: Sedimentary Geology, v. 51, pp. 119–135.

Cavazza, W., 1989, Sedimentation pattern of a rift-filling unit, Tesuque Formation (Miocene), Española Basin, Rio Grande rift, New Mexico: Journal of Sedimentary Petrology, v. 59, pp. 287–296.

Davis, M. J., Lohmann, R. C., Phillips, F. M., Wilson, J. L., and Love, D. W., 1993, Architecture of the Sierra Ladrones Formation, central New Mexico—depositional controls on the permeability correlation structure: Geological Society of America, Bulletin, v. 105, pp. 998–1007.

DeCelles, P. G., Gray, M. B., Ridgway, K. D., Cole, R. B., Pivnik, D. A., Pequera, N., and Srivastava, P., 1991, Controls on synorogenic alluvial-fan architecture, Beartooth Conglomerate (Paleocene), Wyoming and Montana: Sedimentology, v. 38, pp. 567–590.

Dreyer, T., Falt, L. M., Hoy, T., Knarud, R., Steel, R., and Cuevas, J. L., 1993, Sedimentary architecture of field analogues for reservoir information (SAFARI)—a case study of the fluvial Escanilla Formation, Spanish Pyrenees: International Association of Sedimentologists, Special Publication 15, pp. 57–80.

Fogg, G. E., 1986, Groundwater flow and sand body interconnectedness in a thick multiple-aquifer system: Water Resources Research, v. 22, pp. 679–694.

Galusha, T., and Blick, J. C., 1971, Stratigraphy of the Santa Fe Group, New Mexico: American Museum of Natural History, Bulletin, v. 144, no. 1, 127 pp.

Golombek, M. P., McGill, G. E., and Brown, L., 1983, Tectonic and geologic evolution of the Española Basin, Rio Grande rift—structure, rate of extension, and relation to the state of stress in the western United States: Tectonophysics, v. 94, pp. 483–507.

Hawley, J. W., and Wilson, W. E., 1965, Quaternary geology of the Winnemucca area, Nevada: University of Nevada, Desert Research Institute, Technical Report no. 5, 66 pp.

Hearne, G. A., 1985, Simulation of an aquifer test on the Tesuque Pueblo Grant, New Mexico: U.S. Geological Survey, Water-Supply Paper 2206, 23 pp.

Hunter, R. E., 1977, Basic types of stratification in small eolian dunes: Sedimentology, v. 24, pp. 362–387.

Kuhle, A. J., 1997, Sedimentology of Miocene alluvial-slope deposits, Española Basin, Rio Grande rift—an outcrop analogue for subsurface heterogeneity: Unpublished MS thesis, University of New Mexico, 205 pp.

Lazarus, J., and Drakos, P., 1995, Geohydrologic characteristics and hydrocarbon contamination of the shallow alluvial Tesuque Formation aquifer, Santa Fe, New Mexico; *in* Bauer, P. W., Kues, B. S., Dunbar, N. W., Karlstrom, K. E., and Harrison, B. (eds.), Geology of the Santa Fe Region: New Mexico Geological Society, Guidebook 46, pp. 307–311.

Leeder, M. R., and Gawthorpe, R. L., 1987, Sedimentary models for extensional tilt-block/half-graben basins; *in* Coward, M. P., Dewey, J. F., and Hancock, P. L. (eds.), Continental extensional tectonics: Geological Society of London, Special Publication, no. 28, pp. 139–152.

Mack, G. H., and Leeder, M. R., 1999, Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio–Pleistocene Palomas half graben, southern Rio Grande rift: Journal of Sedimentary Research, v. 69, no. 3, pp. 635–652.

McIntosh, W. C., and Quade, J., 1995, $^{40}Ar/^{39}Ar$ Geochronology of tephra layers in the Santa Fe Group, Española Basin, New Mexico; *in* Bauer, P. W., Kues, B. S., Dunbar, N. W., Karlstrom, K. E., and Harrison, B. (eds.), Geology of the Santa Fe Region: New Mexico Geological Society, Guidebook 46, pp. 279–287.

Miall, A. D., 1997, The geology of fluvial deposits: Springer-Verlag, Berlin, 582 pp.

Neton, M. J., Dorsch, J., Olson, C. D., and Young, S. C., 1994, Architecture and directional scales of heterogeneity in alluvial-fan aquifers: Journal of Sedimentary Research, v. 64b, no. 2, pp. 245–257.

North, D. P., and Prosser, D. J., 1993, Characterization of fluvial and aeolian reservoirs: Geological Society of London, Special Publication, no. 73, 450 pp.

Quade, J., Martin, M. D., Pratt, W. L., McCoy, W., and Burckle, L., 1995, Fossil spring deposits in the southern Great Basin and their implications for changes in the water-table levels near Yucca Mountain, Nevada, during Quaternary time: Geological Society of America, Bulletin, v. 107, no. 2, pp. 213–230.

Rhoads, M., and Smith, G. A., 1995, Contrasting modes of tephra preservation in the Skull Ridge Member of the Tesuque Formation; *in* Bauer, P. W., Kues, B. S., Dunbar, N. W., Karlstrom, K. E., and Harrison, B. (eds.), Geology of the Santa Fe Region: New Mexico Geological Society, Guidebook 46, p. 5.

Rust B. R., and Koster, E. H., 1984, Coarse alluvial deposition; *in* Walker, R. G. (ed.), Facies models: Geological Association of Canada, Toronto, Reprint Series 1, 2nd edition, pp. 9–21.

Smith, G. A., 2000, Recognition and significance of streamflow-dominated piedmont facies in extensional basins: Basin Research, v. 12, pp. 399–412.

Smith, G. A., and Battuello, P. A., 1990, Sedimentation pattern of a rift-filling unit, Tesuque Formation (Miocene), Española Basin, Rio Grande rift, New Mexico—discussion: Journal of Sedimentary Petrology, v. 60, pp. 175–177.

Tedford, R. H., and Barghoorn, S. F., 1993, Neogene stratigraphy and mammalian biochronology of the Española Basin, northern New Mexico—vertebrate paleontology in New Mexico: New Mexico Museum of Natural History and Science, Bulletin 2, pp. 159–168.

Tyler, N., and Finley, R. J., 1991, Architectural controls on the recovery of hydrocarbons from sandstone reservoirs; *in* Miall, A. D., and Tyler, N. (eds.), The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery: Society for Sedimentary Geology (SEPM), Concepts in Sedimentology and Paleontology, v. 3, pp. 1–5.

A Note to Our Readers

In the next issue of *New Mexico Geology*, you will notice that our name has been changed from

New Mexico Bureau of Mines and Mineral Resources
to
New Mexico Bureau of Geology and Mineral Resources.

As the geological survey for the State of New Mexico, we feel that the new name better reflects the broad scope of our efforts and activities. While proud of our seventy-four-year heritage and our long association with the mines and mining history of the state, we hope to avoid confusion with those state agencies with regulatory responsibilities related to the mining industry.

We continue to be a part of the New Mexico Institute of Mining and Technology, and our mission remains the same—to serve the people of New Mexico by conducting research, creating maps, and distributing information, both to the professional geologic community and the general public, on the geologic framework and resources of our state.