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

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Abstract
Moocene 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 sand beds, to well-sorted fine sand. Internally massive lithofacies of fine sand and silt are 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 bedded scale. External forcing mechanisms such as tectonics, climate, and sediment supply produce genetically controlled and heterogeneously bedded systems that are definitive of resulting sedimentary 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 between alluvial-fan and alluvial-slope deposits 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 is the 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 confine- ment 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...
Anumber of critical features should per-

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 nontrenched piedmonts have relatively steep gradients, on the order of 0.01–0.04, but are characterized by parallel, commonly contribu-
tory, 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 aqui-
escent, erosionally embayed ranges or likely be associated with tectonically qui-

dent from unsteady, upper-flow-regime sedimentary structures indicative of depo-
sition with pediments where one is certain 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 advanced by Smith (2000).

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-titled 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 Tusque 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 Oligo-
cene to Pleistocene sedimentary and vol-
canic rocks including the upper Oligo-
cene–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 approx-

imately 1,300 m (4,265 ft; Smith and Bat-

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

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 Tusque Formation (Santa Fe Group). Modified from Golombok et al. (1983).

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

**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 $F_3$ 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 $F_5$, $F_4$, $F_6$, and $F_7$ 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.
The stratigraphic columns indicate that this stratigraphic interval are uncommon. Sheets that formed in broad interfluves 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 (Kühle, 1997) are consistent with an eolian origin because the facies is fine grained (median grain size is 3.5ø) and well sorted (50–65% between 4.5 and 3.0ø). We interpret this facies to be dominantly of massive silty F1. A single spaced and/or more mobile, and eolian facies interval is between WA #2 and WA #3, the middle interval also suggests deposition. Massive sand and mud 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 deposits are abundant 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 F1. 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 subject 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. 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.
over a 75 km² (129 mi²) 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 mudier, 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 paleoflower 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 bedrock 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-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 bedrock 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 (F1 and F3) to coarse sand and gravel channel fill (F5), with estimated hydraulic conductivities that vary over two orders of magnitude and overlap with those of the interfluvic 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 interchannel facies 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.

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**References**


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.