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Sedimentology of the Tesuque Formation and tectonics of the Embudo fault system Near Dixon, New Mexico

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SEDIMENTOLOGY OF THE TESUQUE FORMATION AND TECTONICS OF THE EMBUDO FAULT SYSTEM NEAR DIXON, NEW MEXICO.

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ABSTRACT.—The northeastern part of the Velarde 7.5-minute quadrangle, in the Dixon area, is underlain by Tertiary strata of the Tesuque Formation and an isolated outcrop of Proterozoic metasedimentary rocks of the Hondo and/or Vadito Groups. Faults associated with the transfer zone between the San Luis and Española Basins of the Rio Grande rift traverse the map area from southwest to northeast. We use the term Embudo fault system to refer to this zone of deformation and have assigned informal names to individual faults and fault zones within this system. In this area, the Embudo fault system is a ~5-km-wide zone of normal, oblique-normal, and local reverse faults. The Chama-El Rito Member (~12.5-17.5 Ma), the informally defined (Steinpress, 1980) Dixon member (~11.8-13 Ma), the Ojo Caliente Sandstone Member (~11.5-13 Ma), and the Cejita Member (~7.5-10 Ma) of the Tesuque Formation are present. No radiometric ages have been obtained from within the map area and estimates listed above are a combination of estimates based on fossil evidence and regional stratigraphic relations. We provisionally designate mixed eolian, fluvially-reworked eolian and fluvial deposits lying above the Ojo Caliente Sandtone Member as the 'Cieneguilla member' of Leininger (1982). Pliocene basalt of the Servilleta Formation (~3.39(?) –2.81 Ma near Rinconada) caps La Mesita and mesas north of the Rio Grande. Quaternary landslides are ubiquitous north of the Rio Grande and on the flanks of La Mesita. Proterozoic-Pliocene units are offset along numerous faults within the Embudo fault system. Offset is mostly normal left-lateral and dominantly down–to-the-northwest although outcrop patterns suggest a complex history of deformation including tilting, extension, localized(?) compression, and shear. Compression in this area is most likely related to a restraining bend in the southeastern margin of the fault system. Tertiary unit contacts are laterally offset between ~1 and 2.75 km within and across a zone of intense deformation ~.5 km wide that makes up the southeastern margin of the fault system. Vertical-offset measurements within/across this zone cannot be made with confidence due to interfingering relations between Tertiary units and the complications arising from left-lateral offset. Pliocene basalt flows are offset 60-70 m vertically and possibly up to 460 m laterally across the La Mesita fault. Tertiary units generally dip toward the southwest. This tilting preceded or accompanied offset within the Embudo fault system and much of it probably occurred between deposition of the Dixon and Ojo Caliente members and deposition of the Cejita Member, although some post-Cejita tilting is also apparent. Paleocurrent measurements and clast counts largely confirm earlier interpretations that: 1) The Chama-El Rito Member was derived largely from the Latir volcanic field with input from Proterozoic and Paleozoic rocks near Taos and at least episodic input from the the Picuris Mountains. 2) The Dixon member and the younger Cejita Member were derived largely from Paleozoic rocks to the east and southeast with input from older Tertiary and Proterozoic units. 3) The Ojo Caliente Sandstone is an eolian unit transported from the southwest. 4) The Cieneguilla member represents primary eolian deposits interbedded with reworked Ojo Caliente sand and sediment derived from older Tertiary units, Proterozoic rocks of the Picuris Mountains and probably the southern Taos Range.

INTRODUCTION

Recent STATEMAP mapping of the Velarde 7.5-minute quadrangle adds insight into the Tertiary sedimentary history of the area, and helps to refine tectonic relations within the northeast-trending transfer zone (following usage of Faulds and Vargas, 1998) that relays extensional strain between the primarily down-to–the-west Española Basin to the southeast and the primarily down-to the-east San Luis Basin to the northwest. This transfer zone is defined by a zone of faulting which has been interpreted as an intracontinental transform fault (Muehlberger, 1979). We refer to this zone of faulting as the Embudo fault system and have assigned informal names to individual faults and one fault zone (Fig.1).

This paper focuses on the northeastern part of the Velarde quadrangle (Fig.1, Plate 11). The Rio Grande follows the Embudo fault system from northeast to southwest across this area and has incised to form a deep gorge. With the exception of a small (1-2 square kilometer) outcrop of Proterozoic metasedimentary rocks exposed between the towns of Dixon and Embudo, Tertiary sedimentary units of the Tesuque Formation (Galusha and Blick, 1971) underlie the entire area. These sedimentary units are partially covered by Pliocene basalt flows of the Servilleta Formation, (2.81-3.39(?) Ma near Rinconada; Appelt, 1998), and are disturbed by Quaternary landslides along the entire length of the Rio Grande and on the flanks of La Mesita. Quaternary deposits include those related to these landslides and terrace gravels that are largely restricted to the Embudo River valley.

Steinpress (1980, 1981) provided the first detailed stratigraphic and tectonic study of the area. This report builds on his study and attempts to refine tectonic interpretations and suggest possible controls on sedimentation.

TERTIARY SEDIMENTS OF THE TESUQUE FORMATION

Chama-El Rito Member of the Tesuque Formation

Volcaniclastic sediments north of the Embudo River and within the Embudo fault system have been mapped by Steinpress (1980) as the Chama-El Rito Member of the Tesuque Formation. This designation is retained here although lithologically similar beds have been assigned to the Picuris Formation to the northeast (Rehder, 1986), and the type section of the Chama-El Rito Member (Galusha and Blick, 1971) is dominated by quartz-rich silty sand with only subordinate volcaniclastic conglomerate. Galusha and Blick (1971) also show both Chama-El Rito Member and 'Picuris Tuff' on a poorly located cross section of the Dixon area (Galusha

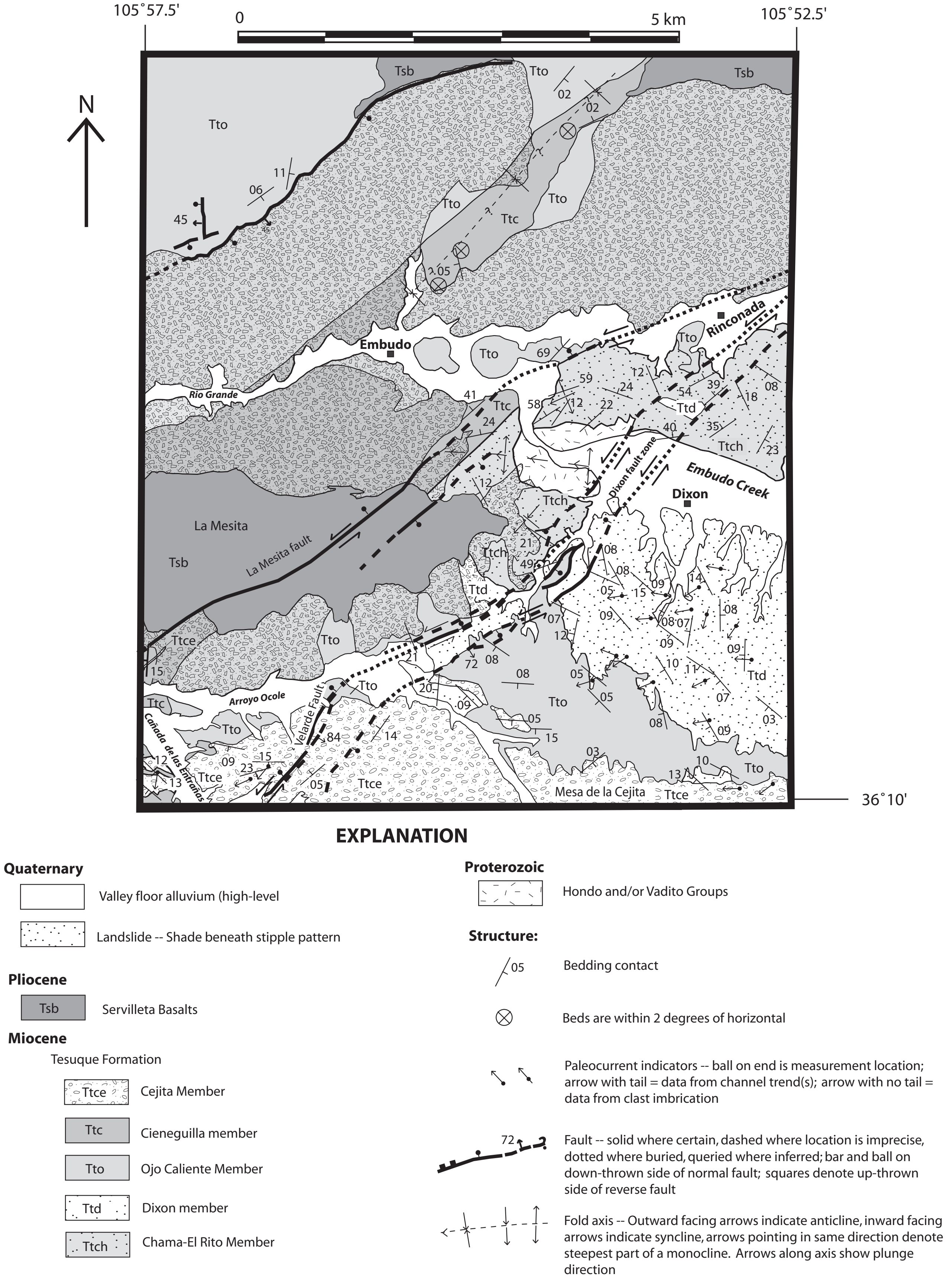

FIGURE 1. Simplified geologic map of the Dixon, New Mexio area.

and Blick, 1971, figure 28C), indicating that the originators of the term Chama-El Rito did not include all these beds in this member. Relations between volcaniclastic units in the area are treated in more detail in Aby et al. (2004, this volume).

In the central part of the map area conglomerates make up 42%, sandstones 50% and mudstones 8% of a 480 m section measured by Steinpress (1980). Conglomerates in the Chama-El Rito Member (Fig. 1) are poorly sorted silty, sandy pebble conglomerates containing (on average) 30% quartzite clasts, 9% Paleozoic sandstone clasts, 4% granite clasts and are characterized by Tertiary volcanic clasts (56%) including Amalia Tuff (Table 1). The presence of Amalia Tuff clasts indicates a source in the Latir volcanic field (including outflow ignimbrite deposited as far west as the Tusas mountains), and/or the adjacent volcaniclastic apron derived from this field (Lipman and Reed, 1989, Smith et al., 2002). Paleocurrent measurements indicating an average transport direction of 240 degrees (Table 2) corroborate this interpretation. Quartzite clasts indicate sediment contribution from a Proterozoic terrane. The absence of other Proterozoic clast types indicates a 'significant' (but unknown) transport distance and/or 'weathering out' of all other rock types in the source area. A small percentage of relatively friable granitic clasts (4%) and localized concentrations (up to 4%) of Pilar phyllite (a Proterozoic unit found only in the Picuris Mountains; Miller et al., 1963; Bauer and Helper, 1994), indicate some episodic contribution from the Picuris Mountains. The presence of Paleozoic sandstone clasts, indicate a contribution from Paleozoic sedimentary rocks. The absence of Paleozoic limestone (which is found in the overlying Dixon member) further indicates a source in the Taos area, as Paleozoic strata there are dominated by sandstone (P. Bauer, personal comm). Conglomerates are interbedded with generally purplish and/or reddish sand, silty sand and muddy silt beds up to a few meters thick. The lowest parts of this formation are dominated by Proterozoic clast types (Steinpress, 1980), but these beds are not exposed in the map area. The Chama-El Rito Member underlies the Dixon member in the study area although the contact is concealed beneath the Embudo River valley except in a small area southwest of Dixon (Fig.1). East of the map area, the Chama-El Rito Member overlies metasediments of the Hondo and Vadito Groups and Precambrian granitic rocks (Steinpress, 1980). Steinpress (1980) defined the contact between the Chama-El Rito Member and the overlying Dixon member as the top of the highest conglomerate in which Tertiary volcanic clasts 'predominate' over Paleozoic sedimentary clasts (Steinpress, 1980). Clast counts performed across the only exposure of this contact during this study indicate that the contact is gradational and interfingering over ~ 25 m (Table 1).

An ash found in several exposures northwest of the Dixon fault zone (Fig.1) is tentatively correlated (N. Dunbar, personal comm.) to the Skull Ridge White ash #1 (~16 Ma; Koning and Manley, 2003) or #4 (~15.5-15.35 Ma; Izett and Obradovich, 2001; Macintosh and Quade, 1995). This ash is located ~150-170m below the upper contact. Mammal fossils found near Rinconada (Tedford and Barghoorn, 1993 fig.2) suggest a late Barstovian North American Land Mammal Age (~14.5-11.8 Ma) for "the lower part of this unit" (Tedford and Barghoorn, 1993, page 162), and they indicate an age range for the entire member (including those parts in the Abiquiu embayment) of ~17.5-12.5 Ma. Because the overlying Dixon member (Steinpress, 1980) contains latest Barstovian (~11.8-12.5(?) Ma) fossils "…1 mile west of Dixon, 200 feet [~60 m] below Ojo sands…" (Benjamin John Burger, personal commun., 2004), the ash and fossil data together suggest a general age range of 17.5 to 12.5 Ma for the Chama-El Rito Member in the study area.

Dixon Member of the Tesuque Formation

The Dixon member was informally defined by Steinpress (1980). In a composite section measured by Steinpress this member consists of 30% conglomerate, 55% sandstone, and 15% mudstone (Steinpress, 1980). Conglomerates contain, on average, 29% quartzite, 5 % Tertiary volcanic, 64% Paleozoic sedimentary (sandstone 30%, limestone 29%, siltstone 5%), and 2% granitic clasts based on our clast counts (Table 1). Paleocurrent indicators measured during our mapping show derivation from the east and northeast (average 252 degrees;Table 2). Steinpress (1980) reported a mean paleocurrent direction of 290 degrees. Steinpress' map included areas to the east and his most easterly sites have a paleotransport direction of ~350 degrees (Steinpress, 1980, fig. 24). The Dixon member to the east may therefore have been transported in west to north-northwest flowing channels and then turned to the west and southwest in the map area.

The high proportion of Paleozoic sedimentary clasts (relative to Tertiary volcanics) was used to define this member, and combined with paleocurrent information indicates derivation from Paleozoic sediments to the east and southeast (Steinpress, 1980). East of the map area Paleozoic sedimentary rocks are found only east of the Picuris-Pecos fault (Miller et al., 1963).

Steinpress (1980) reported volcanic-clast dominated beds in the lower ~110 m of the Dixon member. We have also observed one volcanic-clast dominated lense within the upper, interfingering contact with the Ojo Caliente Sandstone Member. This lense (channel?) contains 14% quartzite, 47% Tertiary volcanic rocks, 24% Paleozoic sandstone, 1% Paleozoic siltstone, 5% granite, 5% vein quartz, and traces of Pilar phyllite. The absence of limestone in this lense is more characteristic of the Paleozoic clasts in the Chama-El Rito Member than in the Dixon (Table 1).

Dixon member sediments exposed within the Dixon fault zone north of the Embudo river (Fig. 1, Table 1 count #9) have a relatively high proportion of Tertiary volcanic clasts similar to those found near the gradational lower contact (Table 1), indicating that the contact may be located within this zone. Quaternary terrace gravels (not shown in Figure 1) overlying these outcrops along with pervasive deformation related to the Dixon fault zone make precise location of the contact here impossible.

The Dixon member generally underlies the Ojo Caliente Sandstone Member of the Tesuque Formation along an interfingering contact (Fig. 1). One small part of the Dixon member overlies and is inset into the Ojo Caliente Sandstone in the southeastern part of the map area (Fig. 1). Based on field examination of sand and gravel compositions in these outcrops, the lowest parts of this outlier are fluvially reworked Ojo Caliente Sandstone Member

TABLE 1. Clast count data for the map area. 100-150 clasts counted per site. Category notes: Quartzite =all types of Precambrian quartzite clasts including some rare schistose varieties, Volcanic= all Tertiary volcanic clast types including Amalia Tuff, Granite=all felsic plutonic rock types, Vein Quartz=mostly milky quart, Pilar phyllite= Proterozoic Pilar phyllite (Bauer and Helper). *'Contact average'= average of the 11 clast counts conducted across the Dixon/Chama El Rito contact (counts 14-24). ** Indicates clast count outside map area. Ttd=Dixon member, Ttch=Chama-El Rito Member (notation for counts 14-24).

Chama-El Rito Member clast counts

Count #	1	2	3	4	5	6	7	8	Average	Contact average*
Proterozoic quartzite	32	22	22	40	42	32	25	16	29	27
Volcanic rocks	53	47	70	52	58	51	58	68	57	56
Paleozoic sandstone	12	29	6	7	0	13	4	10	10	7
Paleozoic limestone	0	0	0	0	0	0	0	0	0	1
Granite	3	2	2	1	0	4	6	3	3	6
Pilar phyllite	0	0	0	0	0	0	4	0	0	0
Vein Quartz	0	0	0	0	0	0	3	3	1	5
UTM coordinates (Zone 13, NAD27)										
northing	4007525	4006975	4007125	4006450	4006200	4007625	4007990	4007985		
easting	421125	419950	418175	417875	417675	419425	421015	4211005		

Dixon member clast counts

Count #	9	10	11	12	13	Average	Contact average*
Proterozoic quartzite	18	36	26	35	31	29	9
Volcanic rocks	12	6	5	0	1	5	15
Paleozoic sandstone	25	45	45	16	17	30	23
Paleozoic limestone	35	12	15	40	42	29	46
Paleozoic siltstone	9	1	2	7	7	5	4
Granite	1	0	7	2	2	2	2
Vein Quartz	0	0	0	0	0	0	2
UTM coordinates (Zone 13, NAD27)							
northing	4007450	4002925	4004150	4004150	4005400		
easting	420375	420275	419800	420625	420350		

Clast counts across Chama-El Rito/Dixon contact northwest of Dixon fault zone and southeast of La Mesita

Count #	14	15	16	17	18	19	20	21	22	23	24
Proterozoic quartzite	9	7	11	9	20	7	27	39	29	41	6
Volcanic rocks	10	0	41	19	61	3	61	44	49	36	80
Paleozoic sandstone	23	27	17	17	8	33	3	8	6	7	7
Paleozoic limestone	51	56	28	42	1	50	0	0	0	1	3
Paleozoic siltstone	3	8	0	3	0	7	0	0	2	0	0
Granite	2	2	0	5	6	0	3	4	8	10	1
Vein Quartz	2	0	3	5	4	0	6	5	6	5	3
~Meters above #24	305	255	253	248	245	237	225	218	208	158	0
UTM coordinates (Zone 13, NAD27)											
northing	4005075	4005175	4005178	4005183	4005187	4005180	4005250	4005325	4005400	4005475	4005775
easting	417775	417850	417860	417870	417875	418025	418050	418050	418055	418150	418375
Tesuque Fm Member:	Ttd	Ttd	Ttd	Ttd	Ttch	Ttd	Ttch	Ttch	Ttch	Ttch	Ttch

Cieneguilla member clast counts

Count #	25	26	27	28	29	30**	31**	32**	Average
Proterozoic quartzite	18	28	23	25	28	12	18	6	20
Volcanic rocks	35	35	9	28	7	31	27	55	28
Paleozoic sandstone	23	14	33	33	28	27	26	14	25
Paleozoic limestone	0	0	0	0	4	0	0	0	0
Paleozoic siltstone	3	1	0	3	6	0	0	1	2
Granite	14	11	35	8	24	22	5	18	17
Pilar phyllite	7	11	0	0	3	1	1	3	3
Vein Quartz	0	0	0	3	2	7	23	3	5
UTM coordinates (Zone 13, NAD27)									
northing	4010075	4009075	4009000	4006860	4004550	4006550	4001950	4007695	
easting	421300	417550	417225	415170	412020	412110	403160	410755	

TABLE 1. - cont.

Cejita member clast counts					
Count #	33	34	35	36**	Average
Proterozoic quartzite	31	28	33	18	28
Volcanic rocks	6	7	10	2	6
Paleozoic sandstone	46	48	15	16	31
Paleozoic limestone	15	11	32	53	28
Paleozoic siltstone	1	3	0	0	1
Granite	1	3	3	4	3
Pilar Phyllite	0	0	0	0	trace
Vein Quartz	0	0	7	7	4
UTM coordinates (Zone 13, NAD27)					
northing	4003625	4002800	4003120	4002725	
easting	416250	421150	419110	413830	

mixed with 'typical' Dixon member conglomerate clasts. The Dixon and Cejita members of the Tesuque Formation are nearly identical in clast composition (Table 1), and the contact between them is not easily identifiable where the Ojo Caliente Sandstone Member is absent (G. Smith, personal comm., 2003). We believe this outlier to be part of the Dixon member (and not the Cejita Member) based on our interpretation of a local angular unconformity at the base of the Cejita Member (see below) in the map area and the general concordance of attitudes within this outlier and the underlying Tertiary units. It is possible that this inset deposit is a relatively fine-grained portion of the Cejita Member, in which case an angular unconformity within the Cejita Member would be indicated.

Steinpress (1980) estimated an age range of 12-14 Ma for the Dixon member based on regional relations. Tedford and Barghoorn (1993) report latest Barstovian (~13-11.8 Ma) fossils equivalent to fossils found in the upper parts of the Chama-El Rito in the Chama sub-basin (Abiquiu embayment). We favor the age estimate of Tedford and Barghoorn (1993), as this age estimate comes from fossils found within the Dixon member. South of the map area, granite-rich deposits correlative to lithosome A of Cavazza (1986) prograded to the east at ~13-14 Ma (Koning, 2002a, 2002b), roughly coincident with progradation of the Dixon member over the Chama-El Rito Member in the map area.

Ojo Caliente Sandstone Member of the Tesuque Formation

The eolian Ojo Caliente Sandstone Member was deposited by northeastward-migrating dunes (Galusha and Blick, 1971; May, 1980; Steinpress, 1980). In the map area, the unit is 62% quartz, 28% feldspar, and 10 % lithic grains (Steinpress, 1980). Lithic grains are dominantly volcanic (82%), although sedimentary (8%) and metamorphic grains (10%) indicate input from non-volcanic sources (Steinpress, 1980). The Ojo Caliente Sandstone Member is approximately 250 m thick in the southwestern map area, and pinches out to the east (Steinpress, 1980). Steinpress (1980) estimated an age of 12-13 Ma for this unit based on stratigraphic relations in the map area and age estimates for overlying and underlying units. Tedford and Barghoorn (1993) indicate an age range of ~11-13 Ma for the unit as a whole based on fossil evidence. The bulk of the Ojo Caliente Sandstone Member to the south has recently been interpreted as being between 11.5-13 Ma (Koning et al, 2004, this volume). To the southwest (Galusha and Blick, 1971; May, 1980) the Ojo Caliente Sandstone Member overlies and interfingers with the upper part of the Chama-El Rito Member.

Cieneguilla Member

In the map area the eolian Ojo Caliente Sandstone Member is overlain by a mixture of eolian, fluvially-reworked eolian, and fluvial facies. Fluvial facies are recognized by decimeter-scale trough-cross bedding in sandy portions and beds of coarse sand-to-pebble conglomerate composed of, on average, 20% quartzite, 3% Pilar phyllite, 17% granite, 27% Paleozoic sedimentary rocks (25% sandstone, 2% siltstone), and 28% Tertiary volcanic rocks (Table 1). Fluvially reworked eolian deposits are indicated by trough-cross stratified sand bodies that are, based solely on field criteria, composed of Ojo Caliente-type sand. The definition of this unit and its regional extent are discussed in more detail in Koning et al. (2004, this volume).

Cejita Member of the Tesuque Formation

The Cejita Member (Manley, 1977) beneath Mesa de la Cejita in the southern part of the map area (Fig.1) is composed of at least 80 meters of sandy, pebble-to boulder conglomerate with sparse lenses of coarse sand. This conglomerate is composed of (on average) 60% Paleozoic sediments (31% sandstone, 28 % limestone, 1% siltstone), 28 % quartzite, 3% granitic rocks, 6% Tertiary volcanic rocks, and traces of Pilar phyllite (Table

TABLE 2. Paleocurrent measurements made during this study. (Includes some measurements not shown in Figure 1). Location of all measurements plotted in Koning and Aby (2003). Approximately 66% of measurements are bearings of channel walls and the remainder are clast imbrication measurements. Average number of measurements per site=~3 for channel wall measurements and ~15 for clast imbrication measurements.

Average paleotransport direction		
Member	Azimuth	Number of sites*
Chama-El Rito	240	8
Dixon	252	18
Cejita	269	9

1). This clast assemblage is almost identical to conglomerates in the Dixon member (Table 1). This suite of clast types indicates mixing of sediment from Proterozoic basement and older Tertiary deposits(?) with a large contribution from east of the Picuris-Pecos fault (as outcrops of Paleozoic sedimentary rocks are not found to the west of this fault). The Cejita Member indicates a shift in the fluvial system of this area, as no older Tertiary deposits contain such thick deposits of coarse fluvial conglomerate. Manley (1979) estimated that aggradation of these conglomerates occurred over an area at least 5.6 km wide north-to-south.

The lower contact of the Cejita Member has previously been described as disconformable (Steinpress, 1980). Bedding orientations are not easy to obtain due to the conglomeratic nature of this unit and the absence of good exposures transverse to strike. Based on our mapping and bedding attitudes indicated by Manley (1977) just to the south, we believe the lower contact of the Cejita Member has ~3-6 degrees of angular unconformity with the underlying Dixon and Ojo Caliente members. This angular unconformity is not observed further south (Koning and Aby, 2003) or to the southeast (Smith et al., in press). Paleocurrent measurements indicate westward transport (Table 2).

No age control is available in the map area, but the age of the Cejita Member to the south has recently been estimated at 6.5-10 Ma (Koning and Aby, 2003). As the Cejita Member exposed in the map area is clearly not the youngest portion of this unit we estimate an age range of ~7.5-11 Ma for these strata.

EMBUDO FAULT SYSTEM

Introduction

The Embudo fault zone has long been recognized as both a transfer zone (as defined in Faulds and Vargas, 1998) between the Española and San Luis Basins of the Rio Grande rift, and as a tectonic expression of the Jemez lineament (e.g. Kelly, 1978; Aldrich, 1986). The fault zone (or simply the Embudo fault) has generally been shown passing along the southeastern slope of Black Mesa, passing through La Mesita (e.g. Kelley, 1978, Aldrich, 1986), and then striking northeast either through or north of the town of Rinconada. Kelson et al. (1997) provided a summary of kinematic studies of the zone indicating left-lateral oblique (down-to–the northwest) motion is dominant. Aldrich (1986) suggested left-lateral oblique motion on the northeast portion of the fault zone and right-lateral oblique motion on the southwest portion. Additionally, thrust/reverse motion has long been recognized in an area of excellent road-cut exposures at Hondo Canyon south of Taos (Muehberger, 1979). Faults exposed here have most recently been interpreted as a positive flower structure related to a restraining bend in the fault zone (Bauer et al., 1999).

Our mapping (Koning and Aby, 2003) reveals one fault zone, several major faults, and several discontinuous fault splays (as well as associated folds), within a zone extending from ~1.5-3 km northwest of the Rio Grande to just northwest of Dixon. Steinpress (1980) and Bauer and Helper (1994) have mapped additional faults just east of the map area. We use the term 'Embudo fault system' to indicate this entire area and have assigned informal names to individual faults and one fault zone within this system (Fig. 1). The major faults exposed in the map area, along with associated minor fault splays and folds, are discussed below. Additional faults within this system on Black Mesa are described in Koning et al. (2004, this volume).

La Mesita Fault

This fault is a normal left-lateral fault that offsets the basalt flows on La Mesita by 60-70 m down-to-the-northwest and possibly 460 m left-laterally. The apparent left-lateral offset of the western margin of the basalt flows (Fig.1) is expressed in an area of mass movement and therefore is somewhat ambiguous. Such offset would be consistent, however, with other evidence of left-lateral offset within the fault system discussed below. A fault splay located at the northeastern end of La Mesita and southeast of the La Mesita fault is down-to-the-southeast (Fig. 1). Proterozoic rocks exposed on the northern slopes of La Mesita show evidence of brittle deformation in brecciated quartzite layers and gouge zones sub-parallel to the La Mesita fault. Appelt (1998) reported a range of ages for the youngest Servilleta basalts of ~2.81-3.39(?) Ma near Rinconada, indicating post-middle Pliocene displacement on this fault.

The Dixon Fault Zone

The southeastern boundary of the Embudo fault system between Rinconada and Arroyo Ocole is a 0.4-0.6 km wide zone of deformation (Fig.1). We suggest the informal name Dixon fault zone for this zone of complex deformation. Immediately adjacent to the Proterozoic rocks west of Dixon, this zone consists of tight and overturned folds in Tertiary rocks, tectonic imbrication of Proterozoic and Tertiary strata, and (locally) older-over-younger fault contact between Proterozoic and Tertiary rocks. This style of deformation indicates an element of compression in this area. To the northeast and southwest of this zone of particularly intense deformation, the Dixon fault zone is expressed mainly by steep (>~30 degree) inclination of Tertiary strata and left-lateral offset of contacts. Apparently, the presence of the mechanically resistant block of Proterozoic metasedimentary rocks has intensified deformation adjacent to this block, and/or acted to localize compressive strain. Within Dixon member beds exposed in north-facing bluffs south of Rinconada, tight, overturned folds with northeast–trending axes indicate generally northwest-southeast directed shortening. Additional evidence of compression outside the Dixon fault zone includes folding of the Chama-El Rito Member both southwest and northwest of the Proterozoic rock outcrops (Fig. 1).

The Dixon fault zone has previously been described as having an element of left-lateral and normal offset (Steinpress, 1980). Such motion is supported by offset of contacts within and across fault-zone boundaries (Fig.1). The Dixon/Ojo Caliente contact is apparently offset ~2.0-2.5 km across the southeastern boundary of the fault zone. The Dixon/Chama-El Rito contact is offset ~1 km within the fault zone and offset ~2.25-2.75 km across the entire fault zone (Fig. 1). The range in offset estimates results from burial of the Dixon/Chama-El Rito contact beneath the Rio Embudo and burial of the Dixon/Ojo Caliente contact in Arroyo Ocole (Fig.1). Interfingering of these units and map-scale variations in unit thickness also hinder direct measurements of offset. These estimates of offset are therefore offered only as an indicator of the scale of translations. Steinpress (1980) estimated vertical offset on faults within this zone at between 50 and 480 m based on apparent stratigraphic displacement and pure (?) normal slip. He also indicated that slickenlines at the southwest end of this fault zone and on two fault splays north of the Rio Embudo and east of the map area rake 5-25 degrees to the southwest. Taking our estimates of left-lateral offset of Tertiary strata, this range of obliquity, and assuming normal left-lateral displacement on a vertical fault plane would give a range of vertical displacement between ~130-1160 m within or across this fault zone. This range is reported to illustrate that observed apparent vertical displacements can be easily accommodated by oblique slip and not as an estimate of actual throw in a specific location. Only detailed stratigraphic and kinematic analysis combined with large-scale mapping of the fault zone will allow for exact measurements of offset.

Localized extension within the Dixon fault zone is indicated by the northern outlier of the Dixon member that lies within the Dixon fault zone. Offset within this zone is *dominantly* left-lateral if slickenline orientations reported by Steinpress (1980) are indicative of long-term displacement, and undoubtedly has a component of left-lateral offset based on offset of member contacts (Fig.1). Left-lateral offset indicates that this northern outlier was originally deposited further north than its present position. These facts suggest that the northern outlier of Dixon member was down-dropped to its present structural level. Down-dropping probably occurred prior to left-lateral offset, as these strata would otherwise have been transported to the southwest with the rest of the Dixon member exposed within the fault zone.

Present evidence does not allow for an unambiguous interpretation of the sequence of deformation outlined above, but it appears that localized (?) extension within the Dixon fault zone preceded left-lateral offset. The compression that caused folding of Dixon member sediments may have occurred simultaneously with shear. If so, then compression also postdates extension. It seems likely that the deformation seen within the Dixon fault zone and tilting of adjacent Tertiary strata represent a continuum of deformation associated with evolution of the Embudo fault system.

Quaternary terrace gravels north of the Embudo River (not shown in Figure 1, see Koning and Aby, 2003) do not show obvious vertical offset, but could be offset laterally without developing a clear topographic scarp. Reconnaissance to the northeast of the map area indicates some offset of Quaternary hillslope(?) deposits on faults subparallel(?) to the Dixon fault zone.

The Dixon fault zone is interpreted to link with the Velarde fault of Manley (1976, 1977) in a poorly exposed area along Arroyo Ocole (Fig.1, Plate 11). Striations on the Velarde fault exposed 1.5-2 km north of Rio Truchas (~5 km southwest of the map area) indicate oblique slip on this fault at least this far south.

CONCLUSIONS

Deposition of the Chama El-Rito Member in this area indicates transport between the San Luis Basin (Latir volcanic field) and northern Española Basin until sometime during the late Barstovian ((14.5-11.5) Ma. The beginning of Dixon member deposition marks the end of deposition of sediment derived from the San Luis Basin in the map area. Since Chama-El Rito deposition continued into the latest Barstovian in the Abiquiu embayment while Dixon member sedimentation was occurring in the map area (Tedford and Barghoorn, 1993), this transition suggests deflection of Chama-El Rito deposition to the northwest by Dixon member streams. Eastward progradation and coarsening of granite-rich deposits correlative to lithosome A of Cavazza (1986) near Española at ~13-14 Ma (Koning, 2002a) and eastward progradation of the Dixon member into the study area were roughly coincident. Because this coarsening and progradation occur in conjunction with a progressive decrease in dip magnitudes, these trends have been attributed to increased rates of rift tectonic activity (Koning, 2002b; Koning, 2003). The coincidence of Dixon member progradation at about this time may also be due to this inferred increase in rift tectonic activity.

Deposition of the Ojo Caliente Sandstone Member commenced during deposition of the Dixon member. These two units initially interfingered and then the Ojo Caliente dune field prograded to the east. Dixon member deposition resumed for a short time in the southeastern part of the map area. During deposition of the Cieneguilla member, sediment from the ancestral Picuris Mountains and the Taos Range were again transported into the map area and interbedded with primary eolian and reworked Ojo Caliente-type sand.

Sometime after deposition of the Ojo Caliente Sandstone Member and before deposition of the Cejita Member, strata in the map area were tilted to the southwest. Deposition from the same source(s) as the Dixon member resumed during this tilting (or was deflected to the south for a time by this localized tilting). The resulting Cejita Member is generally coarser than the Dixon member, reflecting increased relief in the source area, or paleoclimatic influences (Koning, 2002). Following or during deposition of the Cejita Member, the Dixon fault zone (and the La Mesita fault?) was active in a complex manner that involved extension, compression, and shear of Tertiary sediments and underlying Proterozoic basement. Offset on the La Mesita fault continued until at least the middle Pliocene based on offset of basalt flows on La Mesita.

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