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The Picuris Formation: A late Eocene to Miocene sedimentary sequence in northern New Mexico

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THE PICURIS FORMATION: A LATE EOCENE TO MIOCENE SEDIMENTARY SEQUENCE IN NORTHERN NEW MEXICO

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ABSTRACT.—New geologic mapping and 12 new 40Ar/39Ar ages from the Picuris Formation have provided new information on this noteworthy Tertiary sedimentary unit in Taos County, New Mexico. Where exposed along the northern and southern flanks of the Picuris Mountains, the formation is composed of: 1) a lower, basement- and volcanic-derived, highly weathered, conglomerate, sandstone, and siltstone member; 2) a middle, tuffaceous/pumicious sandstone member; and 3) a volcaniclastic pebble-conglomerate to mudstone member. Although compositional and textural variability exists within the members and between exposures, and some interfingering of the upper two members occurs, for simplicity we informally refer to them as the lower conglomerate member, the middle tuffaceous member, and the upper volcaniclastic member. The lower conglomerate member is derived from local Proterozoic basement and, in the northeastern Picuris Mountains, from a mixed basement/volcanic source. The volcaniclastic components of the upper two members are derived from the Latir volcanic field with additions from Proterozoic sources. In some areas the upper volcaniclastic member also contains Paleozoic clasts. The lower conglomerate member contains and/or underlies ash layers dated at ca. 34.5 Ma. The middle tuffaceous member contains a 27.9 Ma ash in the north and overlies the 28.3 Ma Llano Quemado breccia. The middle tuffaceous member in the south contains 27.7-23.0 Ma pumice clasts. The upper volcaniclastic member contains volcanic clasts that range in age from 27.3-18.6 Ma. A basalt clast from near the base of the upper volcaniclastic member in the south, dated at 19.8 Ma, provides a maximum age for the southern part of the upper volcaniclastic member. Because the Picuris Formation spans a time range of greater than 34.5 Ma to less than 18.6 Ma, sedimentation may span the time between the end of Laramide shortening and onset of Rio Grande rift extension. The upper volcaniclastic member of the Picuris Formation may be equivalent to the Miocene Chama-El Rito Member of the Tesuque Formation of the Santa Fe Group.

INTRODUCTION

Writing about the Cenozoic rocks and deposits around the Picuris Mountains, Ingersoll et al. (1990) stated: "Cenozoic stratigraphic nomenclature of the study area is extraordinarily complex.....due to interfingering of distantly and locally derived nonmarine units of widely differing provenance and lithology. There are many examples of published geologic maps with different stratigraphic units mapped in the same places by different geologists. This confusion of nomenclature results from both the complex stratigraphy and poor exposure of some slightly consolidated lithologies."

One ingredient in this complexity is the Picuris Formation ("Picuris Tuff of Cabot, 1938"), a Tertiary clastic and volcaniclastic unit that is both complex and poorly exposed. The entire area of exposure of this formation has not previously been mapped or analyzed in detail. The Picuris Formation is only exposed around the Picuris Mountains. Elsewhere it is either covered by Santa Fe Group sediments and Quaternary deposits, is not preserved, or was not deposited. The importance of the Picuris Formation cannot be overstated, as it is one of the few, exposed sedimentary sequences that may span the temporal and structural transitions between Laramide crustal shortening and Rio Grande rift crustal extension. The clast composition of the various members of the Picuris Formation provides information on the emergence of the Picuris Mountains. The distribution and clast composition of the lower conglomerate and middle tuffaceous members may provide information on the paleogeography of a late Eocene/Oligocene, Laramide and/or very early rift basin.

Recent 1:24,000-scale geologic mapping around the flanks of the Picuris Mountains during STATEMAP quadrangle projects (Bauer and Kelson, 1997; Kelson and Bauer, 1998; Bauer et al., 1999; Bauer et al., 2003), and 12 new ⁴⁰Ar/³⁹Ar ages on volcanic constituents of the Picuris Formation, have provided us with additional information on the complex architecture and chronology of the deposit. This report presents our observations and preliminary interpretations of the Picuris Formation based on in-progress field mapping. Additional radiometric age estimates and sedimentologic analyses are currently underway, and are expected to add to the developing picture of this little-studied formation.

GEOLOGIC SETTING AND BACKGROUND

The Picuris Mountains of north-central New Mexico are a Proterozoic-cored uplift that extends westward from the Sangre de Cristo Mountains just south of Taos (Fig. 1). The range is flanked to the north, west, and south by Tertiary/Quaternary sedimentary and volcanic rocks, and to the east by fault-bound blocks of Mississippian, Pennsylvanian, and Tertiary strata within the Picuris-Pecos fault system. Paleoproterozoic metamorphosed supracrustal and plutonic rocks are exposed over an area of approximately 250 km² in the Picuris Mountains (Bauer, 1993). The north and west flanks of the range are separated from the San Luis Basin by the Embudo fault zone, a rift transfer zone that separates the easttilted San Luis Basin from the west-tilted Española Basin (Kelson et al., 2004, this volume). The eastern edge of the range is defined by the Picuris-Pecos fault system, a long-lived zone of complex, high-angle faults (Bauer and Kelson, 2004, this volume). On the south flanks of the range, Proterozoic rocks are apparently overlain by Tertiary sedimentary rocks of the Picuris Formation in the absence of any obvious range-front faults.

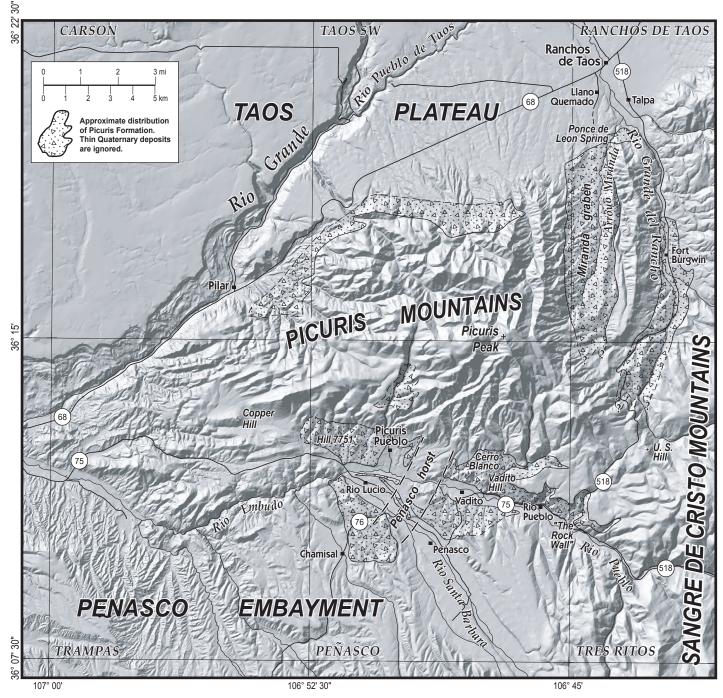


FIGURE 1. Index map of the Picuris Mountains showing generalized outcrop distribution of the Picuris Formation, principal geographic features, and locations discussed in text.

Investigations of the Cenozoic geology of the Picuris Mountains area have been conducted by Manley (1976), Muehlberger (1979), Steinpress (1980), Leininger (1982), Dungan et al. (1984), Aldrich and Dethier (1990), and Ingersoll et al. (1990). The oldest Cenozoic unit in the area is the Picuris Formation (Cabot, 1938; Montgomery, 1953; Miller et al., 1963; Rehder, 1986), a sequence of sedimentary rocks that represent pre-rift and syn-rift sedimentation. It has been proposed that the early shallow rift basins of northern New Mexico were initially filled by

a combination of volcanic eruptions and volcaniclastic alluvial aprons with sources in the San Juan volcanic field to the north (Baltz, 1978). The Picuris Formation was thought to represent such a deposit (Manley, 1984). However, new geologic mapping (Bauer and Kelson, 1997; Kelson and Bauer, 1998; Bauer et al., 1999; Bauer et al., 2003) and geochronology (Bauer and Kelson, 2004, this volume) indicate that the oldest parts of the Picuris Formation (>34.6 Ma) predate the traditional 27-25 Ma onset of rifting (e.g., Lipman and Mehnert, 1979; Miggins et al., 2002),

and that sedimentation continued well into the Miocene (Bauer and Kelson, 2004, this volume). Moore (2000) proposed extension during deposition of the lower Abiquiu Formation at >27 Ma. Brister and Gries (1994) suggested that the Blanco Basin Formation (which also underlies ca. 35 Ma volcanic rocks) in the San Luis Basin of Colorado may have been deposited in a late-Laramide, wrench fault-related basin. The geometry and kinematics of the basin into which the oldest Picuris Formation was deposited are not currently known, but the formation will undoubtedly prove useful in resolving the details of the transition from Laramide compression to Rio Grande Rift extension.

THE PICURIS FORMATION

Previous Work

Cabot (1938) was the first to describe tuffaceous and conglomeratic beds near Vadito and explicitly assigned both tuff and conglomerate to the Picuris Tuff. He suggested a correlation to other "pre-Santa Fe" units in the region. Montgomery's (1953) report on the Proterozoic geology of the Picuris Mountains, and Miller et al.'s (1963) report on the Sangre de Cristo Mountains make only brief mention of the Picuris Tuff.

The only previous study focused solely on the Picuris Formation divided it into three members: the lower member, the Llano Quemado breccia member, and the upper member (Rehder, 1986). These members were defined by examining and then correlating 11 scattered exposures along the eastern edge of the Picuris Mountains. This work was a major contribution to understanding the formation. Although the Llano Quemado breccia is an excellent local marker bed in the Talpa area, it crops out as small, scattered, fault-bound exposures and is therefore not useful for regional correlations. In light of new radiometric ages, previously unrecognized faults in the area, and additional clast-composition data, we offer a revised member-level subdivision of the Picuris Formation.

Member-level Subdivisions

We have chosen to informally divide the Picuris Formation into three mappable members that are lithologically distinct and apparently of regional extent. The lower conglomerate member is generally greenish and composed mainly of locally derived, generally highly weathered, Proterozoic clasts at its base and in the south with additions of volcanic clasts in the upper(?) parts in the north. The lower conglomerate member also contains sandstone and siltstone beds and generally fines upward and/or has fine-grained parts. The middle tuffaceous member consists of tuffaceous debris-flow deposits, mostly fine-grained fluvially reworked tuffaceous/pumicious material, and primary volcanic ash(?). The upper volcaniclastic member is composed of interbedded mudstone, siltstone, sandstone and pebble conglomerate. Pebble conglomerates are dominated by Tertiary volcanic clasts with significant amounts of Proterozoic quartzite and/or local Paleozoic sandstone.

The middle tuffaceous member is volcaniclastic by definition, but we use the term here to distinguish the distinctive, fine-grained, light-colored, tuff and pumice-bearing section from overlying, generally coarser, purplish to reddish, pebbly conglomerates and associated, generally red and orange sandstone, siltstone, and mudstone. We hope that this lithology-based division will prove flexible enough to accommodate the additional complexity that will undoubtedly be revealed by future studies, while providing a simple means for referring to various parts of the formation. For the sake of brevity, we sometimes refer to the various members with just one of the descriptive terms (e.g., "the lower member" or "the conglomerate member"). We are most certain of the validity of the upper, middle, and lower designations in the southern Picuris Mountains. If this stratigraphic interpretation proves invalid in other areas then the various units could simply be referred to as the conglomerate, tuffaceous, and volcaniclastic members, and their relations redefined.

We have divided the analysis of the Picuris Formation into a northern domain and a southern domain. The northern domain includes exposures along the northern flank of the Picuris Mountains between Pilar and Talpa. The southern domain includes the relatively well-exposed rocks along the southern flank of the range near Picuris Pueblo. We have also made reconnaissance observations of exposures along NM-518 between Vadito and Fort Burgwin (Fig. 1). These exposures link the northern and southern domains, but discussion of them is included in the "Southern exposures" section below. Table 1 is a generalized stratigraphic system for the southern and northern domains based on our subdivisions of upper, middle, and lower members. The radiometric dates shown on Table 1 are described in Table 2.

Methods

The Peñasco 7.5-minute quadrangle in the southern domain was mapped as a STATEMAP project in 2002 and 2003. No detailed petrographic study was undertaken and all observations can therefore be considered as field observations of hand samples, although some additional observations of individual samples were made using a 30x binocular microscope. Exposures of the Picuris Formation in the northern domain were mapped in 1997-2003 (Bauer and Kelson, 1997; Kelson and Bauer, 1998; Bauer et al., 2003) with additional observations by the senior author during 2003-4. Clast counts were conducted at 59 selected outcrops, mostly in the southern domain (Table 3). At each outcrop, from 100 to 185 clasts (sized from 2 mm and 9 cm) were identified. Paleocurrent measurements were recorded at 46 sites on the Peñasco quadrangle, with preference given to outcrops showing either well-defined channels and/or pervasive clast imbrication (Table 4). Between one and five channel wall orientations and/or an average of 15 cobble imbrications were measured at each of the 46 sites. Rough stratigraphic sections, which emphasized major, diagnostic stratigraphic breaks, were made at select outcrops along the southen range-front exposures. Thickness of individual members/beds at these stratigraphic sections were estimated in the field. Thickness estimates in Table 1 are a combination of

TABLE 1. Summary stratigraphic columns for the southern and northern domains of the Picuris Formation. See Table 2 for details of the radiometric ages.

			Overthern Danielle			
Northern Domain			Stratigraphic			Southern Domain
Description	Thickness	Ar/Ar Age (Ma)	Unit	Ar/Ar Age (Ma)	Thickness	Description
No field criteria have been identified that distinguish upper volcaniclastic member of Picuris Fm from strata mapped as Chama-El Rito Member of Tesuque Fm in Dixon area (Aby and Koning, 2004; Steinpress, 1980). See text for discussion. Ojo Caliente Ss of Tesuque Fm overlies volcaniclastic conglomerate near Pilar.	460 m near Dixon (Steinpress, 1980)	18-14 (Steinpress, 1980)	Dixon member of Tesuque Fm (south). Chama-El Rito member (north).	14-12 Ma (Steinpress, 1980)	75-100 m	Dixon member distinguished from Picuris Fm by predominance of sedimentary clasts over volcanic clasts.
Uncertain contact due to extensive faulting in Pilar	area.		gradational?	Conta	ct not exposed be	ut appears to be gradational and/or interfingering.
		18.6 (basalt clast)		19.8 (basalt clast)		Possible reworking of upper part of upper volcaniclastic member during Dixon member deposition.
Entire 207 m measured by Rehder (1986) dominated by Tertiary volcanic clast-rich sandy pebble-to-cobble conglomerate and sandstone in Arroyo Miranda.	>207 m in Arroyo Miranda (Rehder, 1986)	25.2 and 27.3 (Tv clasts)	Upper volcaniclastic member of Picuris Formation	25.9 (ignimbrite clast)	>125 m and possibly >350 m	Characterized by reddish/purplish, silty, sandy pebble conglomerates dominated by felsic-to-mafic Tertiary volcanic clasts and/or Proterozoic quartzite and 0-19% Paleozoic sandstone clasts, but commonly containing >50% red-to-orange, mudstone, siltstone and sandstone.
Conglomerates near base are composed almost exclusively of Tertiary volcanic clasts with up to 20% welded Amalia tuff clasts. Base of section near Pilar is mostly volcanic clasts plus quartizite clasts (7-56%) and local beds with up to 25% Paleozoic sandstone clasts.						Near base, commonly contains beds and/or lenses of locally derived, Proterozoic metasedimentary and igneous clasts including 10+ m of cobble conglomerate near Chamisal. Base of upper member is locally to pervasively silica-cemented.
At Pilar, upper mbr is over lower mbr on sharp, conc	ordant, low re	lief contact.	conformable and/or interfingering	Sharp ero	osional contact a	nd/or interfingering. Local soft-sediment deformation.
				23.0 (pumice) 23.7 (pumice)		Upper part of middle member contains rare to common, biotite-rich pumice lapilli and locally is pervasively silica-cemented. West of the Village of Rio Pueblo, contains rare to common beds of local Proterozoic metasedimentary clasts; such beds are more abundant up-section, particularly at Hill 7751. Near village of Rio Pueblo upper part may be interbedded(?) with pebble conglomerates of the upper member.
Middle member is poorly exposed in Arroyo Miranda and absent near Pilar. Near Arroyo Miranda, it consists mainly of tuffaceous sandstone and pumicious conglomerate with generally well-rounded lapilli and blocks up to 25 cm in diameter.	Poorly constrained in Arroyo Miranda, but probably <150 m.	27.9 (ash from Arroyo Miranda)	Middle tuffaceous member of Picuris Formation	27.7 (pumice)	>90 m exposed at Cerro Blanco, but estimated at >125 m	Middle member is mostly massive or medium-to-thickly bedded tabular beds and <1% primary(?) ash falls up to ~60 cm thick, locally bioturbated. Ash-fall beds effervescent in hydrochloric acid in contrast to carbonate-poor tabular and massive section.
Lower contact with Llano Quemado breccia and upper contact with upper member not seen in north. In Arroyo Miranda, Llano Quemado breccia is everywhere in fault contact with Picuris Formation.		28.4 (rhyolite clast from Llano Quemado breccia)				Lower part of middle member contains rare to common, white, biotite-poor pumice lapilli and rare blocks that commonly weather to pink and/or brown. Percentage of pumice lapilli generally increases upward (relative to tuffsize fraction). Lower part also contains rare lenses of volcanic pebbles.
At Pilar, upper mbr is over lower mbr on sharp, conc	ordant, low re	lief contact.	unconformity?	Cor	ntact not exposed	but dips appear concordant across boundary.
Near Arroyo Miranda, lower member is overlain by up to 45 m of Llano Quemado breccia (Rehder, 1986). Near Arroyo Miranda (and along NM-518) the upper parts of the lower member contain up to 56%Tertiary volcanic clasts but no Amalia tuff.	Estimated at 300-400 m near Pilar, but					May contain extremely rare, very highly weathered volcanic clasts in upper part. Lower member is weathered to yellowish and/or greenish
Lower member is fine–grained (silty sandstone to mudstone) and interbedded coarse conglomerate. Greenweathered, boulder-pebble size clasts are commonly fractured. Pilar section is dominated by Proterozoic quartzite and granitic clasts. All but +10 m of section near Pilar appears to underlie a ~34.5 Ma ash. Contains rare, well-sorted, primary ashes and/or reworked tuffaceous beds.	Unknown near Talpa	34.5 (ash near Pilar) 34.6 (ash near Talpa)	Lower conglomerate member of Picuris Formation	White ashes not datable.	Approximately 200 m at the Rock Wall	Lower member is weathered to yellowish and/or greenish with clasts commonly cracked and/or friable due to pervasive weathering and fine-grained parts highly weathered and locally mottled green and red. Near basal contact contains some Paleozoic clasts but generally consists entirely of locally-derived(?) Proterozoic metasedimentary and granitic clasts. Section at "Rock Wall" shows general fining up trend from boulder conglomerate to sandy pebble conglomerate and sandstone.
Possible unconformity on Precambrian	near Talpa.		unconformity	A	ngular unconforr	nity with Paleozoic sediments at 'Rock Wall'.

these estimates and estimates made from geologic map patterns and bedding attitude data (Bauer and Kelson, 1997; Kelson and Bauer, 1998; Bauer et al., 2003). At a few outcrops of the lower conglomerate member, degree of fracturing of cobble-sized clasts was determined by lightly striking 130-170 clasts and recording whether or not they fractured.

Southern Exposures of the Picuris Formation

Outcrop distribution

The middle tuffaceous and upper volcaniclastic parts of the Picuris Formation are exposed in a series of hills that parallel the

southern range front of the Picuris Mountains. The only exposures of the basal conglomerate in this area are located in road cuts at the "Rock Wall" (Fig. 1). South and west of the Rio Santa Barbara, exposures are very poor except in a small area between Peñasco and Chamisal just east of NM-76 (Fig. 1). The southern exposures of the Picuris Formation were analyzed more thoroughly than the northern exposures, and they are described in detail below.

Range-front exposures

Exposures parallel to the southern range front of the Picuris Mountains are mostly of the middle tuffaceous member that gave the formation its original designation of Picuris Tuff (Cabot, 1938). The exposures reveal medium- to thickly bedded, mostly

tabular, white to yellowish buff, siltstone to coarse sandy silt and silty sandstone with local concentrations and isolated individual lapilli- to block-sized, rounded pumice (Figs. 2, 4). The majority of tuffaceous beds are only weakly effervescent in hydrochloric acid. Some tabular beds of fairly well sorted silty and/or very fine sandy ash are in places strongly effervescent in hydrochloric acid and are locally bioturbated. The relatively well-cemented beds weather to ledges that are visible from a distance, such as on the lower slopes of Cerro Blanco. Microprobe analysis of two of these beds from Cerro Blanco and Hill 7751 (Figs. 1, 2) indicate that they are primary ash-fall deposits that are chemically similar, from different eruptions, and too altered to be dated (N. Dunbar, personal commun. 2003). The range-front exposures reveal broadly similar stratigraphic sections, but with significant sub-kilometer-scale lateral variability. Each of the exposures is

TABLE 2. Summary of ⁴⁰Ar/³⁹Ar geochronology of the Picuris Formation. All analyses were performed in the New Mexico Geochronology Research Laboratory (NMGRL) at the New Mexico Bureau of Geology and Mineral Resources. All analytical data are available in NMGRL Open-File Report AR-24 posted at http://geoinfo.nmt.edu/publications/openfile/argon/

	Member	Member Location Ag		Uncertainty	Rock type	Material Dated	UTM coo (1927		Confidence	Comments
				(+/- Ma)	5.	Dated	Northing	Easting	of Age	
	Upper	Arroyo Miranda	18.59	0.70	basalt cobble in conglomerate	groundmass	4016380	443800	moderate	Maximum age for upper Picuris Fm
	volcaniclastic member	volcaniclastic North flank of 25 16 0 10	25.16	0.10	volcanic cobble	15 sanidine	4018000	436250	high	San Juan or Latir volcanic
Study Area			in conglomerate	1 biotite	4018000	436250	high	Probably San Juan volcanic		
rn Study	Middle tuffaceous member?	Arroyo Miranda	27.93	0.08	white ash	15 sanidine	4019200	444900	high	Good eruptive age
Northern	Llano Quemado breccia	Arroyo Miranda	28.35	0.11	rhyolite clast	15 sanidine	4019200	444900	high	Good eruptive age. Local unit.
	Lower	Carson quad south of Pilar	34.5	1.2	fine-grained white ash	17 sanidine	4013600	431070	moderate	Sanidine altered
	conglomerate member	Talpa	34.64	0.16	coarse-grained white ash	15 sanidine	4020550	446350	high	Good eruptive age
	Upper volcaniclastic	Hill 7751	19.78	0.24	basalt clast	groundmass	4007375	434565	moderate	Maximum age for upper Picuris Fm
rea	member	Hill 7751	25.93	0.22	ignimbrite clast	26 small sanidine	4007375	434565	moderate	Amalia Tuff?
n Study Area		Cerro Blanco	23.010	0.090	pumice clast	8 sanidine	4005963	439400	high	Mixed population. Maximum age
Southern	Silicified upper volcaniclastic member	Picuris Pueblo	23.71	0.042	pumice clast	8 sanidine	4006609	437536	high	Single population. Maximum age
	member	Vadito hill	27.72	0.046	pumice clast	13 sanidine	4005644	439738	high	Single population. Good eruptive age.

TABLE 3. Clast count data for Picuris Formation and related units. 100-185 clasts counted per site. Category notes: Quartzite = all types of Proterozoic quartzite clasts including some rare schistose varieties; Volcanic = all Tertiary volcanic clast types including Amalia Tuff (Tertiary basalt and pumice sometimes listed separately when unique); Sandstone, limestone, and siltstone = Paleozoic rock types; Granitic = all felsic plutonic rock types; Vein Quartz = mostly milky quart; Pilar phyllite = Proterozoic Pilar Formation phyllite (Bauer and Helper, 1994) and probably includes some Piedra Lumbre Formation phyllite. UTM coordinates are zone 13S, NAD 1927.

	Dixon member of the Tesuque Formation														
Count #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Avg.
Quartzite	55	57	40	1	43	17	66	25	24	40	43	10	50	26	36
Volcanic	0	0	23	0	0	1	1	24	0	12	3	0	0	18	6
Sandstone	10	10	19	16	15	26	8	17	28	45	43	34	19	22	22
Limestone	32	28	18	19	41	48	21	28	38	2	10	46	26	33	28
Siltstone	2	2	0	1	0	8	4	6	4	0	0	8	5	1	3
Granitic	0	0	0	0	1	0	0	0	2	0	1	1	0	0	0
Vein Quartz	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0
Amphibolite	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Schist	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0
unknown				1		0	0	0	1	0	0	1	0	0	0
UTM Northing	3999095	3999095	4004119	3998577	3998119	4001167	4000714	4003667	4003333	4001552	4000476	4003040	3998119	4001119	
UTM Easting	433190	433190	435119	435417	435643	433905	436214	434333	434214	436062	434607	439429	435643	434143	

	Upper volcaniclastic member of the Picuris Formation on Penasco quad														
Count #	15	16	17	18	19	20	21	22	23	24	25	26	27	28	Avg.
Quartzite	24	11	25	1	39	14	17	6	44	18	24	41	10	55	24
Volcanic	48	89	67	99	52	65	81	94	53	82	70	31	89	38	68
Sandstone	16	0	7	0	7	1	1	0	1	0	4	19	0	4	4
Limestone	10	0	1	0	0	0	0	0	0	0	1	3	0	1	1
Siltstone	2	0	0	0	0	0	0	0	0	0	1	3	1	2	1
Vein Quartz	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
Pilar Phyllite	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Schist	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Basalt	0	0	0	0	2	20	0	0	0	0	0	0	0	0	2
UTM Northing	4004333	4003667	4003669	4007352	4002667	4006238	4004810	4005214	4004143	4003810	4004738	4003452	4003452	4004040	
UTM Easting	439762	438833	438833	434580	437286	437571	434792	436119	433881	436190	441857	438619	438619	439214	

Upper	volcanic	lastic me	ember of	Picuris F	ormatio	n on Car	son quad	i
Count #	29	30	31	32	33	34	35	36
Quartzite	20	27	7	14	56	8	50	39
Volcanic	75	44	92	85	43	92	50	38
Sandstone	0	25	0	0	0	0	0	12
Limestone	0	0	0	0	0	0	0	0
Siltstone	0	0	0	0	0	0	0	0
Granitic	0	4	1	0	1	0	0	9
Vein Quartz	2	0	0	0	0	0	0	0
Pilar Phyllite	3	0	0	0	0	0	0	1
Amphibolite	0	0	0	1	0	0	0	0
Schist	0	0	0	0	0	0	0	1
UTM Northing	4013537	4013805	4013536	4013927	4013586	4013603	4013683	4013708
UTM Easting	430024	430780	430439	431586	431195	431208	430976	430854

Uppe	Upper volcaniclastic mbr in Arroyo Miranda										
37			38								
0			0								
99	(20% Am	alia	100	(15% Am	alia						
0	Tuff)		0	Tuff)							
0			0								
0			0								
1			0								
0			0								
0			0								
0			0								
0			0								
4019390			4019537								
444009			444224								

Silicified (lower) parts of upper volcaniclastic member of Picuris Formation on Penasco quad										
Count #	39	40	41	42	43	44				
Quartzite	25	43	0	27	16	2				
Volcanic	0	23	93	31	63	0				
Sandstone	0	1	0	0	0	0				
Limestone	0	0	0	0	0	0				
Siltstone	0	0	0	0	0	0				
Granitic	47	0	0	17	3	85				
Vein Quartz	0	7	0	8	7	8				
Pilar Phyllite	1	18	0	17	9	0				
Amphibolite	26	5	0	0	2	5				
Schist	1	3	0	0	0	0				
Pumice	0	0	7	0	0	0				
UTM Northing	4004738	4005452	4004595	4003850	4004150	4004275				
UTM Easting	435976	433619	438690	435625	435700	435850				

Middle tuffaceous member of Picuris Fm on Penasco quad								
45	46	47	48					
0	0	25	22					
0	0	0	0					
0	0	0	0					
0	0	0	0					
0	0	0	0					
69	92	0	15					
5	0	0	1					
0	0	69	50					
26	8	3	4					
0	0	2	8					
0	0	1	0					
4004095	4004929	4007345	4004714					
436792	438619	434585	438643					

Lower conglomerate member in S. Picuris Mountains									
Count #	49	50	51	52					
Quartzite	57	57	58	97					
Volcanic	0	0	0	0					
Sandstone	0	0	0	0					
Limestone	0	0	0	0					
Siltstone	0	0	0	0					
Granitic	3	4	6	1					
Vein Quartz	3	0	0	0					
Pilar Phyllite	28	33	33	2					
Schist	9	6	3	0					
UTM Northing	4003525	4003530	4003550	4014341					
UTM Easting	444700	444475	444425	431902					

Lower conglomerate member on Carson quad									
53	54	55	56						
100	100	72	98						
0	0	0	0						
0	0	0	0						
0	0	0	0						
0	0	0	0						
0	0	19	0						
0	0	3	1						
0	0	0	0						
0	0	6	2						
4014439	4013976	4013586	4013586						
432098	431903	431195	431195						

Lower conglomerate member along NM-518								
57	58	59						
97	48	41						
	51	56						
1	1	2						
2								
		1						
4004488	4010490	4012320						
444464	446200	448000						

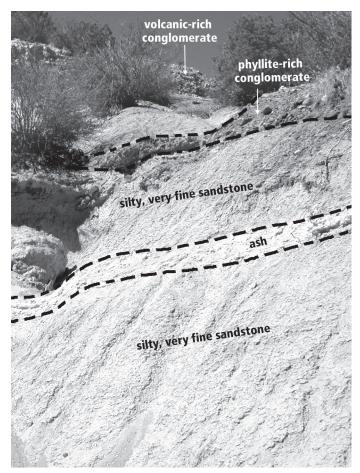


FIGURE 2. Photograph of the middle tuffaceous member of the Picuris Formation exposed on the southeastern slope of Hill 7751 in the southern domain. The meter-thick white ash is interpreted as a primary ash-fall deposit that is too altered to date, although it is geochemically similar to other middle member ash beds. Pumice clasts extracted from cemented middle tuffaceous member rocks that are above a similar ash layer on Cerro Blanco yielded a date of 23.0 Ma. The dark layer above the ash is a phyllite-rich conglomerate bed that was locally derived from the Picuris Mountains to the west and/or north. The conglomerate bed is overlain by more tuffaceous material and other interbedded beds/lenses of pumice-rich conglomerate of the middle member.

discussed below and labeled on Figure 1. The base of the middle tuffaceous member is not exposed.

The Hill 7751 exposures west of Picuris Pueblo (Figs. 1, 2, 3) consist of approximately 60 m of buff to yellowish, mostly massive, ashy, silty fine sand, containing sparse to common pumice lapilli and fine to coarse, sand-sized grains of Proterozoic quartzite and phyllite. Reworking is indicated by rounded to well-rounded quartz(?) grains and very fine to medium, sand-sized grains of Proterozoic rock types mixed with finer-grained ash. Some of the very well rounded, very fine sand may be eolian. Channels of sandy-silty pebble conglomerate composed of Pilar Formation phyllite, quartzite, rare schist and amphibolite, and very rare biotite-poor, pink pumice lapilli (Table 3, count # 47) are rare near the base of the section and become more common up-section. The channels are lenticular to tabular, generally from 20 cm to 1

TABLE 4. Summary of paleocurrent data for the Picuris Formation and Dixon member of the Tesuque Formation (Dixon member not discussed in text) on the Peñasco 7.5-minute quadrangle. Methods are discussed in the text

Formation	Member	Transport Direction (azimuth degrees)	Number of Sites
Tesuque	Dixon	349	17
Diameia	Upper volcaniclastic	196	17
Picuris	Middle tuffaceous	269	12

m thick, clast supported to matrix supported, weakly to moderately carbonate cemented, and very poorly imbricated to chaotic (Fig. 3). Measurements of channel-wall trend indicate eastward or westward transport (Table 4). The channels are weakly cemented and apparent channel orientation may therefore be biased to some extent by outcrop orientation. However, because outcrops of Pilar Formation phyllite are found only to the west and north, we interpret eastward transport of Proterozoic clasts.

The tuffaceous beds with interbedded Pilar Formation phyllite-rich channels are conformably overlain by approximately 7 m of locally silicified, silty sand and silt containing abundant biotite-bearing pumice lapilli. These beds are in turn overlain by approximately 15 m of locally silicified silty sand and silt with stringers of Proterozoic and Tertiary volcanic clasts including the first occurrence of welded Amalia Tuff. The Amalia Tuff



FIGURE 3. Photograph of a phyllite-rich channel of conglomerate in contact with typical yellowish, fine-grained siltstone of the middle tuffaceous member on Hill 7751. Field book in lower left corner for scale.



FIGURE 4. Photograph of the middle tuffaceous member of the Picuris Formation on the southern slope of Vadito hill. The ledge-forming beds are silicified, gray sandstone with pebbles of Tertiary volcanic rocks. The less-resistant interbeds (partly snow-covered) are sandstones and gravels that contain rounded clasts of Tertiary volcanic rocks.

(Lipman and Reed, 1989) is a welded tuff from the Questa caldera/Latir volcanic field (Plate 2) containing distinctive, blue, chatoyant sanidine crystals. The fine tuffaceous beds are overlain by approximately 20 m of red to purple, pebble conglomerate with abundant Tertiary volcanic clasts (Table 3, count # 18), and mostly orange silty sand. Dated Tertiary volcanic clasts from the sequence include a 19.8 Ma basalt and a 25.5 Ma purple, welded ignimbrite (Table 2).

Exposures on Cerro Blanco, Vadito hill, and adjacent areas are similar to those on Hill 7751, but with notable differences. To the west of Cerro Blanco is a basement high, probably a horst (herein called the Peñasco horst), that exposes a distinctive Proterozoic quartz monzonite porphyry that contains megacrysts of feldspar up to 5 cm long. The horst forms a topographic spur that projects southward from the Picuris Mountains for at least 5.5 km (Fig. 1). East of the horst, the middle tuffaceous member contains granite gruss mixed with sand and ash. Presumably, the weathered granite material was shed from the horst during deposition of the middle member.

Just west of the Peñasco horst and north of the Rio Pueblo is an isolated exposure of silicified, sandy pebble to cobble conglomerate. The conglomerate consists of beds and/or lenses containing a range of proportions of Proterozoic metasedimentary and Tertiary volcanic clasts. Some individual beds contain essentially 100%

Tertiary volcanic clasts or 100% Proterozoic metasedimentary clasts.

These silicified beds are overlain by beds of the upper volcaniclastic member with an unusually high proportion of basaltic clasts (Table 3, count #20). The basalt-rich beds dip toward the western horst-bounding fault at approximately 20°. Bedrock exposures to the west are poor, but fine-grained float containing pebbles of Pilar Formation phyllite indicate that middle tuffaceous member rocks similar to those exposed at Cerro Blanco and Hill 7751 underlie the silicified beds.

On the south side of Cerro Blanco, approximately 90 m of finegrained, massive- to tabular-bedded middle tuffaceous member are exposed. Two relatively laterally extensive phyllite-rich beds are exposed approximately 53 m and 86 m above the base of the southern slope. The phyllite-rich beds also contain biotite-poor pumice lapilli and rounded rip-up clasts of the underlying tuffaceous rock (Table 3). Sparse paleocurrent data indicate transport from the west (Table 4) and some channels in the sequence indicate transport from the north. The fine-grained middle tuffaceous member is overlain by 11 m of interbedded medium to coarse, grey, volcaniclastic sandstone, fine-grained, locally orange to pink, tabular, tuffaceous, silty fine sandstone, and pumice-rich sandy conglomerate. Pumice clasts in the conglomerates are biotite-rich. The grey sandstone contains chatoyant sanidine crystals that we interpret as weathered Amalia Tuff (Lipman and Reed, 1989).

Overlying the relatively fine-grained interval of the upper volcaniclastic member are approximately 13 m of strongly silica cemented, silty, sandy, pebble conglomerate. Pebble- to cobble-sized clasts in the lower 4 m of the silicified section are mostly Proterozoic metasedimentary clasts, whereas the upper part contains both Tertiary volcanic and Proterozoic metasedimentary clasts. A pumice clast from near the top of Cerro Blanco has been dated at approximately 23 Ma (Table 2).

In most exposures in the southern Picuris Mountains, the recognizable base of the upper volcaniclastic member coincides with the initial appearance of pebble- to cobble-sized clasts of welded Amalia Tuff overlying the middle tuffaceous member along a sharp contact. In the strongly silicified beds exposed on Cerro Blanco, pumice-rich, Proterozoic clast-rich and Tertiary volcanic clast-rich beds are interbedded. This interbedding makes exact location of the upper/lower member contact somewhat subjective in this area. We locate the contact at the base of the first laterally extensive pebble conglomerate bed composed predominantly of well-rounded Tertirary volcanic clasts (in this case located on Vadito hill). These field relations support the contention that the upper and middle members interfinger in some areas.

The Picuris Formation section exposed on Vadito hill is similar to the Cerro Blanco section. The lower, massive, tuffaceous rocks are poorly exposed on the western side of Vadito hill, but interbedded phyllite-rich horizons are inferred by the presence of phyllite-rich float. The massive part of the middle tuffaceous member is overlain by locally silicified, sandy, mostly pumice-rich conglomerate with local concentrations and/or beds containing clasts of metasedimentary and Tertiary volcanic rocks (Fig. 4). A pumice clast from a pebbly sandstone bed just above the

massive tuff is dated at 27.7 Ma (Table 2).

The disparate ages of pumice clasts between Cerro Blanco (27 Ma, Table 2) and Vadito hill (23 Ma, Table 2) suggest either mixing of pumice of different ages during middle member deposition, or the presence of a west-down fault in the valley between the hills. Such a fault would be consistent with faults of unknown magnitude mapped in bedrock exposures to the north (Bauer et al., 2003), although stratal dips and stratigraphic sequences are similar on the two hills.

South of Cerro Blanco and the Rio Pueblo (Fig. 1) are small outcrops of the middle tuffaceous and upper volcaniclastic members. These exposures show tabular, relatively sandy beds of the middle tuffaceous member containing channels of Pilar Formation phyllite and gruss-rich sediment and a single, 2- to 3-meter-deep, bouldery channel fill that consists entirely of quartz monzonite porphyry and amphibolite derived from the Peñasco horst to the west (Table 3, count #45). The channels containing Proterozoic clasts are oriented approximately east-west, indicating eastward transport. The upper volcaniclastic member overlies the middle tuffaceous member with a mild erosional unconformity, and soft-sediment deformation features are preserved at the contact.

Rehder (1986) measured a stratigraphic section north of NM-75 near the village of Rio Pueblo (Fig. 1). It consists of 43 m of a pumice-rich middle tuffaceous member with prominent silicification near the top of the tuffaceous member and the base of the upper volcaniclastic member. The contact between the middle and upper members interfingers(?) at this location, in contrast to the sharp contact exposed at Hill 7751. Indeed, Amalia Tuff-bearing volcaniclastic pebble conglomerate beds seem to underlie parts of the pumice-rich middle tuffaceous member in these exposures. Flame structures (soft-sediment deformation features) exist at the base of some volcaniclastic beds.

Chamisal Exposures

The cliffs between Chamisal and Peñasco, east of NM-76, provide the only known exposures of the middle tuffaceous member and the base of the upper volcaniclastic member south of the Rio Santa Barbara (Fig. 1). These outcrops also contain at least 13 m of cobble and boulder conglomerate composed of Proterozoic clasts at their base(Table 3, count #39) derived mostly from the Peñasco horst. The upper 10 m of exposed conglomerate are strongly silica cemented.

The conglomerate could be interpreted as equivalent to the basal conglomerate exposed near the intersection of NM-518 and NM-75 (see below). However, the Proterozoic clast-dominated beds overlying and within the middle tuffaceous member north of the Rio Pueblo indicate a period of basement-derived sedimentation during (and particularly near the end of) middle tuffaceous member sedimentation. Because basement-derived conglomerates north of the Rio Santa Barbara are associated with Tertiary volcanic-rich beds containing Amalia Tuff clasts, and the Amalia Tuff clasts are found above the middle tuffaceous member in most well-exposed areas, we favor the interpretation that these conglomerates are stratigraphically above the middle tuffaceous member. In support of this interpretation is the fact that clasts and

matrix are not weathered in the manner characteristic of the lower conglomerate member.

Complicating interpretation of the conglomerates is the presence of unique, thinly laminated to thinly bedded, silica-cemented beds of alternating pumice-rich and/or ash-rich and/or Tertiary volcanic clast-rich beds that overlie the conglomerate. In no other location in the southern Picuris Mountains are pumice-rich and Tertiary volcanic-rich beds interbedded on the small scale observed here, and we therefore interpret these beds as representing reworking of pumice-rich parts of the middle tuffaceous member during the onset of upper volcaniclastic member sedimentation at this relatively distal location (Fig. 1). The rocks are pervasively silica cemented, and the cementation has preserved spectacular soft-sediment (liquifaction?) structures. As noted above, soft-sediment deformation features exist in some locations at the base of the upper volcaniclastic member, and we view this as additional evidence that these rocks represent the middle(?) and upper members rather than an anomalous exposure of the lower conglomerate member.

This part of the stratigraphic section is exposed because of west-down faulting along the west side of the Peñasco horst. Many of the clasts are clearly derived from the granitic rocks of the horst block to the north. The exposures here therefore represent a transition from horst-derived deposition to horst-related relative uplift at this location. This would appear to require southward propagation of the Peñasco horst with time.

Silicification of the Picuris Formation in the southern study area is variable and locally favors the coarsest beds. The one consistent aspect of the cementation in well-exposed rocks is that it occurs just above or near the top of the fine-grained, massive- to tabular-bedded part of the middle tuffaceous member. The fine-grained zones of the middle tuffaceous member are generally not effervescent in hydrochloric acid, even though most other Tertiary sedimentary rocks in the region are, including the underlying and overlying parts of the Picuris Formation. The absence of carbonate in this zone is probably due to low permeability. We propose that the silicification above the fine-grained beds of the

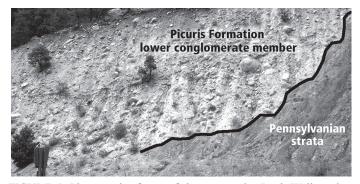


FIGURE 5. Photograph of part of the spectacular Rock Wall roadcut at the intersection of NM-518 and NM-75. The west-dipping Pennsylvanian sedimentary rocks are unconformably overlain by west-dipping conglomerate of the lower conglomerate member of the Picuris Formation. Boulders up to 2 m in diameter are primarily quartzite and granite. Clasts of Paleozoic sedimentary rocks are found only near the unconformity.

middle tuffaceous member is the result of perching of silica-rich ground water at some time in the past.

The "Rock Wall" Roadcuts at the Junction of NM-75 and NM-518 $\,$

A section of the lowermost Picuris Formation is well exposed in roadcuts near the intersection of NM-75 and NM-518, labeled the "Rock Wall" on the Tres Ritos 7.5-minute topographic map (Fig. 1). At the lower end of the roadcut, west-dipping Pennsylvanian strata are depositionally overlain by a boulder conglomerate along a west-dipping 20° angular unconformity (Fig. 5). Cabot (1938) specifically included all 200+ m of the conglomerate in the Picuris Tuff. In contrast, Rehder (1986) presented a measured stratigraphic section that contained only 16 m of the lower conglomerate member.

The lower conglomerate member consists of yellowish-green, mostly clast-supported, poorly sorted, sandy to silty, boulder to pebble conglomerate and minor sandstone. Pebbles in the conglomerate are composed mostly of Proterozoic quartzite and Pilar Formation phyllite (Table 3, counts #49-52). The conglomerate displays a general fining-upward trend with very large (up to 2 m) boulders at the base and poorly sorted, sandy, pebble to cobble conglomerate near the top. Many large boulders near the base of the section are granitic, in contrast to the predominance of quartzite clasts in pebble counts (Table 3, counts # 49-51). Clast counts demonstrate that the lower section of the conglomerate is lithologically similar to the upper 16 m assigned to the Picuris Formation by Rehder. We therefore follow Cabot (1938) and include the entire section in the lower conglomerate member. We also note that this is the only exposure of the base of the lower conglomerate member identified in the southern Picuris Mountains. Paleocurrent measurements have not been made in the lower member conglomerate due to a lack of channels or well defined imbrication, but clast composition (overall lack of Paleozoic clasts and the presence of Proterozoic rock types found in the Picuris Mountains) indicates derivation from the west.

Farther up the roadcut, the lower conglomerate member is overlain by approximately 40 m of the middle tuffaceous member (Rehder, 1986). The middle tuffaceous member contains sparse pebbly lenses composed entirely of Tertiary volcanic clasts, and isolated cobbles of Tertiary volcanic clasts (up to 11 cm long) within fine, tabular, tuffaceous beds. Pumice lapilli within this part of the middle tuffaceous member are biotite poor and commonly weather(?) to a distinctive pink color.

Exposures Between Vadito and Fort Burgwin Along NM-518

We have made reconnaissance observations of the exposures described by Rehder (1986) along NM-518 between Vadito and Fort Burgwin (Fig. 1). All exposures in the area are of the lower conglomerate member, except for the middle tuffaceous member exposed northwest of the Rock Wall. South of the U.S. Hill summit, the lower conglomerate member consists of sandy boulder to pebble conglomerate, green and red, locally mottled siltstone/mudstone, and greenish and yellowish sandstone.

As noted by Rehder (1986), Proterozoic clasts predominate in the southern exposures. We have observed minor Paleozoic cobbles and boulders in the lower 15 m of the Rock Wall exposures, and very rare, very highly weathered, possibly volcanic clasts in the uppermost parts of exposures north of the Rock Wall along NM-518. In general, however, pebbles in southern exposures of the lower conglomerate member are composed of Proterozoic rock types (Table 3, counts # 49-52). Phyllite is exposed to the north along the Picuris-Pecos fault, and we therefore presume some element of southward transport of these sediments, and infer a possible fault control of sedimentation based on the location of these outcrops along the trace of the Picuris-Pecos fault system (Bauer et al., 1999).

Clasts are very highly weathered, with 54% of clasts (including quartzite) in the upper part of the exposures fracturing with a light hammer blow. Fractures are mineral-stained, indicating that the clasts were fractured and weathered *in situ*. The fine fraction is likewise highly weathered and the percentage of primary matrix is difficult to determine in hand sample. This fact complicates determination of clast support versus matrix support, but most beds appear to have originally been clast supported.

Near U.S. Hill are exposures of sandstone and pebble to boulder conglomerate composed of both Proterozoic metasedimentary rocks (and sparse granitic clasts) and volcanic clasts of basalt, basaltic andesite, andesite, and dacite (Table 3, count #58). No silicic clasts (such as Amalia Tuff) were identified. Individual beds composed entirely(?) of Proterozoic clasts do exist. Weathering of volcanic clasts is highly selective, with completely weathered clasts located adjacent to relatively hard, unaltered clasts. Quartzite and rare schist clasts are also fractured and/or weathered with 43% of all clasts fracturing with a light hammer blow.

North of U.S. Hill, some exposures of the Picuris Formation consist of fine, greenish material and interbedded ash. Other exposures reveal poorly sorted, locally matrix-supported, boulder conglomerate with clasts up to 1.3 m. Some outcrops contain only assorted Proterozoic clasts, whereas others are a mixture of Proterozoic and Tertiary volcanic clasts. Just south of Fort Burgwin, carbonate-cemented, cobble to boulder conglomerate with Proterozoic and Tertiary volcanic clasts (Fig. 7;Table 3, count #59) is interbedded with sparse, sandy beds/lenses and massive(?), green, fine-grained material with interbedded ash. Carbonate cementation in the conglomerates is pervasive, with sand grains and pebbles/cobbles 'floating' in a matrix of carbonate.

Rehder (1986) interpreted the lack of volcanic clasts in the south as indicative of southward transport from a northern source. Smith (in press) has postulated a topographic barrier to southward transport of volcanic debris that was overtopped with time. We suggest that it is equally possible (based on individual beds and outcrops in northern exposures composed entirely of Proterozoic clasts) that the lower conglomerate member consists of a lower Proterozoic clast-dominated zone overlain by polymictic conglomerates. If so, then deposition of the lower conglomerate member may both predate and postdate the earliest Tertiary volcanism to the north (~35 Ma according to Lipman and Mehnert, 1975 and Miggins, et al., 2002). Proterozoic clast-dominated con-

glomerates near Talpa and Pilar, which underlie 34.5 Ma tephras (Table 2) support this contention if the conglomerates are coeval with the rocks along NM-518. Alternatively, volcanic clasts in the lower conglomerate member could represent the only record of some earlier period of volcanism, just as some later periods of volcanism in the Latir volcanic field are known only from dated clasts in the Chama-El Rito Member of the Tesuque Formation (Ekas et al., 1984; Smith, in press).

Northern Exposures of the Picuris Formation

Outcrop Distribution

Exposures of the Picuris Formation exist in the Carson (Kelson and Bauer, 1998), Taos SW (Bauer and Kelson, 1997), and Ranchos de Taos (Bauer et al., 1999) quadrangles, along the structurally complex northern flank of the Picuris Mountains. Outcrops are generally fair to poor, with extensive mantling by Quaternary deposits, although locally small sections of the unit are well exposed. The poor exposures, plus the pervasive faulting along the Embudo fault zone and the Picuris-Pecos fault system, prevent us from creating a detailed stratigraphic section. However, a general stratigraphic sequence appears to exist in the Talpa area, from the oldest rocks near the Rio Grande del Rancho to the youngest rocks west of Arroyo Miranda (Fig. 1). Along the mountain front west of Arroyo Miranda, exposures are rare until the Rito Cieneguilla drainage east of Pilar. All of the exposures along the northern piedmont appear to belong to the upper volcaniclastic member.

In the Talpa area, surface exposures of the Picuris Formation exist mainly west of the Rio Grande del Rancho. It is not known if the Picuris Formation exists in the subsurface of the basin east of the Rio Grande del Rancho, but the examination of numerous well records do not support its presence there (Bauer et al., 1999).

Lower Conglomerate Member

Within the northern study area, the lower conglomerate member of the Picuris Formation consists of a basal boulder to pebble conglomerate and conglomeratic sandstone interbedded with thinly bedded sandstone and siltstone. The boulder unit is distinctive, generally greenish, poorly sorted, mostly clast supported, highly weathered and composed of well-rounded, crudely bedded, Proterozoic quartzite clasts plus variably altered clasts of intermediate to mafic Tertiary volcanic rocks and rare Paleozoic sedimentary rocks (Fig. 6). Volcanic clasts seem to be more abundant in parts of the lower conglomerate member that lie near the contact with the overlying Llano Quemado breccia (i.e., in the youngest part of the conglomerate). Well data indicate that the basal boulder conglomerate has north-down vertical separation across a series of faults within the Embudo fault zone (Bauer et al., 1999). The boulder unit fines upward (or at least contains fine-grained upper parts) to less indurated pebble conglomerate and conglomeratic sandstone, and variegated green, red, and white siltstone and mudrock. Local layers of primary(?) white to



FIGURE 6. Photograph of an exposure of polymictic lower conglomerate member in the southern Ranchos de Taos quadrangle, east of NM-518. This unit is dominated by well-rounded, poorly sorted clasts of Proterozoic quartzite (probably mostly derived from the Hondo Group in the Picuris or Sangre de Cristo Mountains) and assorted Tertiary volcanic rocks (andesite, basaltic andesite, basalt, and dacite).

gray to yellow to brown ash-fall deposits are well sorted and contain sanidine and biotite crystals. A white ash that crops out near Talpa, and is interbedded with clastic sediments of the lower conglomerate member, yielded an ⁴⁰Ar/³⁹Ar age of 34.64±0.16 Ma that is interpreted as an eruptive age (Table 2). This date pushes back the age of the Picuris Formation to late Eocene and, if our stratigraphy is correct, it means that the oldest part of the Picuris Formation is older still.

In the northeastern part of the Picuris Mountains the lower conglomerate member was interpreted as a sequence of debris-flow and alluvial-fan deposits derived from the Sangre de Cristo Mountains and Latir volcanic field to the north and northeast (Rehder, 1986). However, the deposit (part of which is older than 34.5 Ma; Table 2) cannot be older than the source (28.5 Ma for the Latir field according to Smith, 2004), and therefore, the volcanic component of the unit may have been derived from older San Juan volcanoes to the north and northwest (Plate 2). Alternatively, the source could be a buried or eroded, unrecognized, older volcanic unit.

McDonald and Nielsen (2004, this volume) performed detailed mapping and analysis of Tertiary conglomerate in the Miranda graben of the northeastern Picuris Mountains. His description of a poorly sorted lower conglomerate dominated by large quartzite



FIGURE 7. Photograph of the "type-section" of the Bradley conglomerate of Leininger (1982). Lower in this section the lower conglomerate member contains quartzite clasts up to 3 m long. The 34.5 Ma age of a nearby ash indicates that these rocks are probably equivalent to the lower conglomerate member of the Picuris Formation exposed south of Talpa and in the Rock Wall exposures. At this location, the lower conglomerate member is overlain by the carbonate-cemented upper volcaniclastic member of the Picuris Formation (slightly darker rock in upper part of photo), and underlain by slope-forming, unconsolidated, partly fine-grained lower member sediments.

clasts appears consistent with our observations of the lower conglomerate member in nearby areas.

In the area near Pilar, the base of the lower conglomerate member consists of poorly exposed, interbedded, clast and matrix(?)-supported, quartzite-rich, mostly highly weathered, silty-sandy pebble to boulder conglomerates, fine to coarse sandstone, and reddish, greenish and yellowish sandy siltstone with interbedded(?) volcanic ash (Fig. 7). Clasts are up to 3 m long. These deposits are not as green-colored as exposures near Talpa, but the two deposits are probably chronologically equivalent based on their positions beneath similar 34.5 Ma and 34.6 Ma tephras (Table 2). Cobbles in conglomerate beds are commonly cracked (Leininger, 1982), and most parts of the unit are highly weathered. Leininger (1982) measured fracture orientations in these cobbles and interpreted them as consistent with left-lateral wrench faulting along the Embudo fault zone.

The Pilar-area conglomerates were informally named the Bradley conglomerate member of the Tesuque Formation and were interpreted as debris-flow deposits derived from the Picuris Mountains to the southeast by Leininger (1982). We believe that some apparent matrix support is due to weathering of fine-grained material, and therefore interpret much of the unit as fluvial. All but approximately 10 m of the conglomerate underlies a 34.5 Ma ash (Table 2), and is therefore assigned to the lower member of the Picuris Formation. Because the conglomerates do not contain Tertiary volcanic clasts (although weathering prevents identification of some clasts and some of the matrix may be ashy), they may represent either a part of the Picuris Formation that predates local volcanic activity or a part of a late-Laramide or early-rift depositional basin that was isolated from cobble-sized volcanic detritus.

Llano Quemado Breccia

Because of its limited geographic extent we do not feel the Llano Quemado breccia deserves member status, although it is a useful local marker bed in the northeastern Picuris Mountains. The Llano Quemado breccia is a monolithologic volcanic breccia of distinctive, extremely angular, poorly sorted, light gray, recrystallized rhyolite clasts in a generally reddish matrix (Fig. 8). Rhyolite clasts contain phenocrysts of biotite, sanidine, and quartz. The rock is highly indurated and crops out as a ridge-former. The breccia was interpreted as a series of flows from a now-buried, nearby rhyolite vent (Rehder, 1986). However, excellent exposures in Arroyo Miranda display layering and sedimentary structures such as crossbedding that indicate that at least parts of the unit are reworked volcaniclastic sediments. At least locally, the lower part of the Llano Quemado breccia displays soft-sediment deformation suggesting rapid accumulation. A rhy-



FIGURE 8. Photograph of typical Llano Quemado breccia containing angular, light-colored, rhyolite clasts in fine-grained matrix. This rock yielded a ⁴⁰Ar/³⁹Ar age of 28.35 Ma that probably dates the eruption of a now-buried, rhyolite volcano in the Talpa area.

olite clast from the Llano Quemado breccia south of the village of Llano Quemado yielded a plateau age of 28.35±0.11 Ma (Table 2). This probably represents the eruptive age of a rhyolite dome that was later eroded, buried, and/or down-dropped. The rhyolite dome was approximately coeval with the oldest unit of the Latir volcanic field (28.5 Ma according to Smith, 2004). A poorly indurated, white ash found near the breccia was dated at 27.93±0.08 Ma (Table 2), confirming that parts of the Picuris Formation are approximately time equivalent to the Llano Quemado breccia.

Middle Tuffaceous Member

The middle tuffaceous member of the Picuris Formation in the northeastern Picuris Mountains is a buff, gray and pinkish gray, immature, pumice-rich, ashy, conglomeratic sandstone. It consists mainly of sandstones with pebble- to cobble-sized clasts of pumice, minor Proterozoic quartzite and silicic- to intermediate-composition volcanic rocks. Conglomerates include clasts up to 25 cm in diameter. Most clasts are rounded to well rounded. Easily accessible exposures of the middle tuffaceous member are sparse in the northern Picuris Mountains. The middle tuffaceous member is not found in the Pilar area where upper volcaniclastic member pebble conglomerate directly overlies quartzite-rich cobble conglomerate (Fig. 8).

Upper Volcaniclastic Member

In the northern Arroyo Miranda area, the upper volcaniclastic member is composed of sandy pebble to cobble conglomerates and interbedded pebbly to silty sandstone dominated by Tertiary

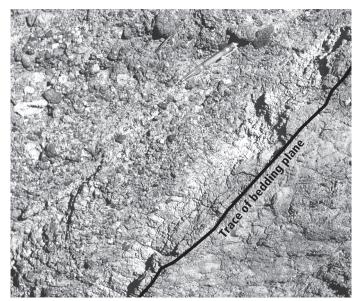


FIGURE 9. Photograph of typical volcaniclastic gravel beds of the upper volcaniclastic member of the Picuris Formation in the northern Miranda graben of the northern domain. Welded Amalia Tuff makes up a significant portion of the clasts.

volcanic clasts (Fig. 9). A high proportion (relative to more southern and western exposures) of volcanic clasts are positively identifiable as welded Amalia Tuff (Table 3, counts #37, 38). Carbonate cementation is locally pervasive, particularly in coarser beds. Paleoflow measurements indicate a source to the north (Rehder, 1986). These beds (along with middle tuffaceous member sediments he included in his upper member) have been interpreted as alluvial-fan deposits derived from the Latir volcanic field shortly after deposition of the 25 Ma Amalia Tuff (Rehder, 1986). We agree, in part, but would add that a basalt clast from the upper member in Arroyo Miranda dated at 18.59±0.70 Ma (McDonald and Neilsen, 2004, this volume) demonstrates that part of the section accumulated at least 6 million years later. This date is a minimum age due to some argon loss, but nonetheless indicates that Picuris Formation deposition continued into the Miocene. The lower part of the volcaniclastic member exposed on the west side of Arroyo Miranda does not contain Proterozoic quartzite or Paleozoic sandstone clasts but is composed almost entirely of volcanic clasts (Table 3, counts #37 and 38).

Field Relations Between the Upper Volcaniclastic Member of the Picuris Formation and the Chama-El Rito Member of the Tesuque Formation

Early workers in the Picuris Mountains included the volcaniclastic pebble conglomerates that overlie the tuffaceous beds exposed near Picuris Pueblo and Vadito in the Santa Fe Formation (Cabot, 1938; Montgomery, 1953; Miller et al., 1963), but none specifically studied these rocks. Rehder (1986) included volcanic clast-rich pebble conglomerates in the southeastern and northeastern Picuris Mountains in his upper member of the Picuris Formation. Steinpress (1980) and Leininger (1982) mapped volcanic clast-rich deposits near Dixon and Pilar, respectively, as the Chama-El Rito member of the Tesuque Formation. The originators of the term Chama-El Rito member show both Chama-El Rito member and Picuris Tuff on a schematic(?) cross section of the Dixon area (Galusha and Blick, 1971, figure 28C). Kelley (1978) noted that some fine-grained beds of the Picuris Tuff exposed in the "Picuris salient" are "..identical to such beds in the Tesuque Formation."

We believe that the volcanic clast-rich conglomerates exposed in the Picuris Mountains near Talpa, Picuris Pueblo/Peñasco, Pilar, and Dixon are lithologically and chronologically(?) equivalent. They are lithologically correlative based on gross lithology of the pebble fraction (e.g., Table 3; table 1 of Aby and Koning, 2004), a general correspondence of sedimentary properties (grain size, sedimentary structures, color, transport direction, etc.), similar stratigraphic position, and similar contact relations with the overlying Dixon member of the Tesuque Formation. They are possibly chronologically correlative based on an age estimate for the entire Chama-El Rito member based on fossil ages of 18.5-12 Ma (Tedford and Barghoorn, 1993) and the maximum age of 18.6 Ma for part of the upper volcaniclastic member of the Picuris Formation indicated by the age of a basalt clast (Table 2).

SUMMARY OF AGE RELATIONS OF THE THREE MEMBERS OF THE PICURIS FORMATION

Some of the lower conglomerate member in the northwest (Pilar area) and northeast (Talpa area) underlies 34.5 Ma ash layers, indicating that part of the Picuris Formation is Eocene or older. The existence of volcanic clasts in the upper part of the lower conglomerate member in the north (Table 3) suggests that deposition of the lower member may predate and postdate the onset of volcanic activity to the north (ca. 35 Ma according to Lipman and Mehnert, 1975 and Miggins et al., 2002). Alternatively, such clasts could be derived from older, unrecognized volcanoes. The lower conglomerate member underlies the 28.3 Ma Llano Quemado breccia in the north and is therefore entirely older than 28.3 Ma and at least partly older than 34.5 Ma.

The middle tuffaceous member contains a 27.9 Ma ash and overlies(?) the 28.3 Ma Llano Quemado breccia in the northern Picuris Mountains. Near Vadito, the upper part of the middle member contains pumice clasts that range in age from about 23.0 Ma to 27.7 Ma. Locally, the top of the middle tuffaceous member is interbedded with parts of the upper volcaniclastic member, which contains 25 Ma Amalia Tuff clasts. The middle tuffaceous member is therefore younger than 28.3 Ma in the north and partly younger than 23.0 Ma in the south.

Age control on the upper volcaniclastic member comes from the dates on five clasts, a 25.9 Ma ignimbrite clast (possibly Amalia Tuff) and a 19.8 Ma basalt clast from Hill 7751, an 18.6 Ma vesicular basalt clast from Arroyo Miranda and 25.2 and 27.3 Ma volcanic clasts from the northern range front (Table 2). The first two clasts were sampled just above the base of the upper volcaniclastic member. The stratigraphic position of the third sample is uncertain due to nearby faulting. The upper member can therefore be constrained as younger than about 23 Ma (the maximum age of the upper part of the middle member) and at least as young as 18.6 Ma. It is possible that the upper volcaniclastic member is considerably younger, as at least 120 m (and possibly >350 m) of this member overlie the 19.8 Ma basalt clast found near the base of this member in the south.

DEPOSITIONAL MODEL FOR THE PICURIS FORMATION

The Picuris Mountains area seems to have been a source of sediment during deposition of the lower conglomerate member, during the deposition of the middle(?) and upper parts of the middle tuffaceous member, and during deposition of the upper volcaniclastic member. This is true despite the fact that the regional transport direction was to the south across the Picuris Mountains area during deposition of the middle and upper members. Bauer and Kelson (2004a, this volume) demonstrated that the Picuris-Pecos fault system was active at least until about 5 Ma, well after deposition of the upper volcaniclastic member of the Picuris Formation. We propose that this long-lived fault system (Bauer and Ralser, 1995) exerted some control on the distribution of bedrock highs, drainage patterns, and deposition of the Picuris Formation. Our geologic mapping, sedimentologic analysis, and

new geochronology allow us to construct a working depositional model for the Picuris Formation, although our current data allow for multiple interpretations of the relation of the Picuris Formation to other Eocene-Miocene sedimentary units in the region. We therefore offer this model as a summary of current working hypotheses in the hope that it will lead to further discussion of the "Laramide to rift" transition in northern New Mexico.

Lower Conglomerate Member (>34.5 Ma to 28.3 Ma)

Deposition of the lower member began some time prior to 34.5 Ma with accumulation of very coarse (up to 3 m), poorly sorted, locally derived, Proterozoic basement-derived clasts mixed with substantial amounts of silt, sand, and ash(?). In the Pilar area, where most clasts are local varieties of quartzite and granite (Leininger, 1982; Table 3, counts # 53-56), the sediments were presumably shed northwestward from the Proterozoic-cored highlands of an ancestral Picuris Mountains (Leininger, 1982). The lower conglomerate member appears to overlie Proterozoic basement in the Pilar area, but outcrops are paltry. The absence of Pilar Formation phyllite clasts in the conglomerate near Pilar is puzzling, as vast areas of phyllite crop out in the central Picuris Mountains, and phyllite clasts do exist in the lower conglomerate member in the southeastern Picuris Mountains. One possibility is that the erosionally resistant, northern strike ridge of Ortega Formation quartzite in the Picuris Mountains (Bauer, 1993) prevented northward transport of eroded phyllite during mid-Tertiary time. Leininger (1982) interpreted the deposits near Pilar as debris-flow deposits derived from a source of previously fluvially rounded quartzite clasts. We believe that some apparent matrix support in these beds is an artifact of weathering of fine-grained material in situ, and that rounding of conglomerate clasts is due to fluvial transport. These deposits are therefore thought to be primarily fluvial in origin, but poor exposure allows for the interpretation of mixed fluvial and debris-flow (alluvial-fan?) deposits.

The base of the Picuris Formation is only well exposed in the southeastern Picuris Mountains, where sandy boulder conglomerate overlies west-tilted Paleozoic rocks (Fig. 5). Paleozoic clasts are rare near the base of this conglomerate and absent higher in the section, while quartzite and Pilar Formation phyllite are abundant in the pebble-size fraction throughout this section (Table 3, counts # 49-51). Because Paleozoic rocks predominate in the Sangre de Cristo Mountains to the north and east, we suggest that the lower member here was transported eastward from the ancestral Picuris Mountains. In support of this theory are the distinctive, kyanite- and sillimanite-bearing Hondo Formation orthoquartzite clasts found in the conglomerates along NM-518.

The lower member conglomerates were therefore transported to the west/northwest in the Pilar area and to the east in the south-eastern Picuris Mountains, indicating that the boundaries of the 'ancestral Picuris Mountains' were similar to the present physiographic boundaries. If true, this observation suggests long-lived structural control of the topographic boundaries of the Picuris Mountains. The Picuris-Pecos fault system has a documented history of movement reaching back to the Proterozoic (Bauer and Ralser, 1995). The Embudo fault system is believed to be a struc-

tural expression of the Jemez lineament (Aldrich, 1986) and is believed to also have a Proterozoic ancestry.

Volcanic clasts in the upper part of the lower conglomerate member in the northeastern Picuris Mountains and along NM-518 (Table 3, counts #58, 59) suggest southward transport from the volcanic fields to the north. These volcanic clasts were transported at least as far south as U.S. Hill either during or after deposition of basement-derived conglomerate exposed at the Rock Wall. These volcanic clasts include basalts that may predate the widespread basaltic volcanism of the Hinesdale series that began at 25-27 Ma (Lipman and Mehnert, 1975) and are commonly thought to indicate the beginning of lithospheric extension (Smith, 2004).

We are not yet able to report on the geometry and structural style of the basin in which lower Picuris Formation sediments were deposited. Deposition may have been controlled by the late Laramide basins (Rio Grande del Rancho and Miranda grabens) that were associated with the Picuris-Pecos fault system (Bauer and Kelson, 2004, this volume; McDonald and Neilsen, 2004, this volume). Brister and Gries (1994) proposed wrench fault-related basins for broadly correlative deposits to the north. Deposition of these sediments may be related to late Eocene/early Oligocene climate change as proposed by Smith (2004).

The lower conglomerate member in the southeastern Picuris Mountains displays an overall fining-upward trend, and the upper parts of the lower member in the north and northwest are at least partly fine grained, although the transition from coarse to fine appears to be more abrupt and/or interfingering there. This trend may represent a decrease in overall stream energy, perhaps reflecting either filling of the basin, a single sedimentary response to a discrete tectonic pulse, a decrease in relief through time, and/or some response to climate change.

Middle Tuffaceous Member (28.3 Ma to <23 Ma)

Deposition of the middle tuffaceous member took place after deposition of the Llano Quemado breccia (28.35 Ma; Table 2), which itself represents some of the oldest known silicic volcanic activity in the region. We presume that accumulation of the middle member began in the north and progressed southward. In the southern Picuris Mountains, deposition of primarily tuffaceous/pumicious material occurred until at least 23 Ma by a combination of fluvial and debris-flow processes. Some coarse volcaniclastic debris did reach the southeastern Picuris Mountains during deposition of the middle member, probably along the Laramide basins of the Picuris-Pecos fault system (Bauer and Kelson, 2004, this volume). Some of the coarse material was transported by channelized flows, whereas some was rafted in on tuffaceous debris flows.

Deposition of the middle tuffaceous member in the southern Picuris Mountains was characterized by the progressive influx of basement-derived debris through time. Phyllite and quartziterich debris was transported from the west at Hill 7751 (Table 3, counts #47, 48) and granite-rich material was transported from the west (and north?) away from the Peñasco horst in the southcentral Picuris Mountains (Table 3, counts 45 and 46; Table 4).

These observations indicate that the Picuris Mountains were locally emergent, but the presence of tuffaceous debris flows derived from the Latir volcanic field to the north indicate that uplift did not prevent southward transport of sediment. If uplift and sedimentation were indeed influenced by the Picuris-Pecos fault system, then sediment may have moved along north-trending grabens. This would explain the small-scale lateral variability of the middle member in the southern Picuris Mountains. There is no evidence of material derived from the Sangre de Cristo Mountains at this time, indicating that either the mountains were not yet emergent or that eroded Paleozoic sediments were being deposited elsewhere.

Upper Volcaniclastic Member (<23 Ma to <18.6 Ma)

Deposition of the upper volcaniclastic member of the Picuris Formation records an influx of relatively coarse debris derived largely from the Latir volcanic field with additions from Proterozoic basement and, locally, Paleozoic sedimentary rocks. The lowest parts of the upper member in the north are composed of nearly 100% volcanic clasts, whereas clasts in the southern domain include abundant quartzite. This observation supports the idea that quartzite clasts were derived from basement highs within the Picuris Mountains, as hypothesized by Rehder (1986). In addition, the presence of Paleozoic sandstone clasts demonstrate some sedimentary contribution from the southern Taos Range during at least parts of upper member deposition. Paleocurrent data are consistent with the interpretation of southward transport of upper member sediments.

Soft-sediment deformation features at the base of the upper member indicate that the middle member was unconsolidated and probably at least partly water-saturated at the time of deposition. This fact, along with local interbedding of the two members, suggests that they represent a continuous sequence of deposition. This may indicate progressive southward progradation of a single volcaniclastic apron derived from the Latir volcanic field. The tuffaceous middle member would then represent a more distal facies. If this interpretation is correct, then the middle and upper members may record an unroofing of the Latir volcanic field.

In the southern Picuris Mountains, a pulse of basementderived sedimentation at the end of middle member and beginning of upper member deposition was accompanied and followed by an influx of relatively coarse debris from the Latir volcanic field, including abundant clasts of welded Amalia Tuff and early Miocene volcanic rocks. The coincidence in timing of local basement-derived sedimentation and the influx of coarse, fluvially transported debris from the Latir field in the southern Picuris Mountains suggest a tectonic control on the timing of sedimentation. Although some welded Amalia Tuff did reach the southern Picuris Mountains area during the later stages of middle member deposition, for the most part, coarse volcaniclastic debris did not reach the area until 5 m.y. after eruption of the Amalia Tuff. Deposition of the middle tuffaceous and upper volcaniclastic members indicates a southward gradient across the Picuris Mountains from about 28 Ma to at least 20 Ma.

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