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VOLCANICLASTIC ROCKS OF THE KERES GROUP: INSIGHTS INTO MID-MIOCENE VOLCANISM AND SEDIMENTATION IN THE SOUTHEASTERN JEMEZ MOUNTAINS

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Abstract—Volcaniclastic rocks of the Keres Group (13-6 Ma; Gardner et al., 1986) in the southeastern Jemez Mountains consist of autoclastic flow breccias, pyroclastic-flow deposits, and debris-flow, hyperconcentrated-flow, and streamflow deposits that were deposited primarily between 11 and 9 Ma. Volcaniclastic sediments are interbedded with pyroclastic-flow and fall deposits and lava flows of the Paliza Canyon Formation, and are derived primarily from basalts, andesites and dacites of the Paliza Canyon Formation. Channel orientations and thickness of volcaniclastic sediments suggest that most of the sediments were derived from the northeast. Volcaniclastic sediments near Boundary Peak are interbedded with several pyroclastic-flow deposits and andesitic lava flows indicating proximity to eruptive centers. The much thicker volcaniclastic sediments in Sanchez Canyon, to the southwest, are dominated by shallow braided stream deposits, typical of volcaniclastic aprons, and are in part the distal equivalent of deposits near Boundary Peak. The greater accumulation of volcaniclastic sediments in Sanchez Canyon also may have been accommodated by faulting. Volcaniclastic sediments in Cochiti Canyon are channeled into cone-forming andesitic flow breccias, but were largely derived from andesitic and dacitic sources to the northeast. The lack of interbedded rhyolitic pyroclastic deposits, and sparsity of rhyolite clasts in sediments suggests that there was little or no explosive rhyolitic volcanism during this time or that rhyolites were deposited elsewhere.

INTRODUCTION

Volcaniclastic sediments are commonly found on and around composite volcanoes and record parts of the volcanic record that are not preserved elsewhere, especially the products of explosive volcanism. Volcaniclastic sediments are also important for reconstructing the volcanic record where primary rocks have been eroded or buried by subsequent eruptions (Erskine and Smith, 1993; Smith et al., 1987, 1988). This study examines volcaniclastic sediments contemporaneous with Keres Group (13-6 Ma) volcanism, with the objectives of documenting the volcaniclastic record; comparing this record to the volcanic record to help refine the evolution of Keres Group volcanism; and determining sedimentation patterns on and around Keres Group volcanoes and how these relate to volcanism and tectonism.

The Keres Group, as defined by Bailey et al. (1969) consists of the Paliza Canyon Formation basalts, andesites and dacites, the Canovas Canyon Rhyolite, and the Bearhead Rhyolite. Keres Group rocks are best exposed in the southeastern Jemez Mountains (Fig. 1), and have been mapped by Smith et al. (1970), Gardner (1985), Guilbeau (1982) and Goff et al. (1990). The study area (Fig. 2) is located within the area of the geologic map of Goff et al. (1990). Many of the Keres Group rocks have been eroded, buried by the products of subsequent eruptions, or buried by alluvium in the Rio Grande rift. Although temporal and stratigraphic relations of basaltic through rhyolitic rocks of the Keres Group are relatively clear (Guilbeau, 1982; Gardner, 1985; Gardner et al., 1986; Goff et al., 1990), the volcaniclastic sediments derived from these rocks remain largely unstudied. Volcaniclastic sediments interbedded with Keres Group volcanic rocks have been included in the Cochiti Formation, which was originally defined by Bailey et al.

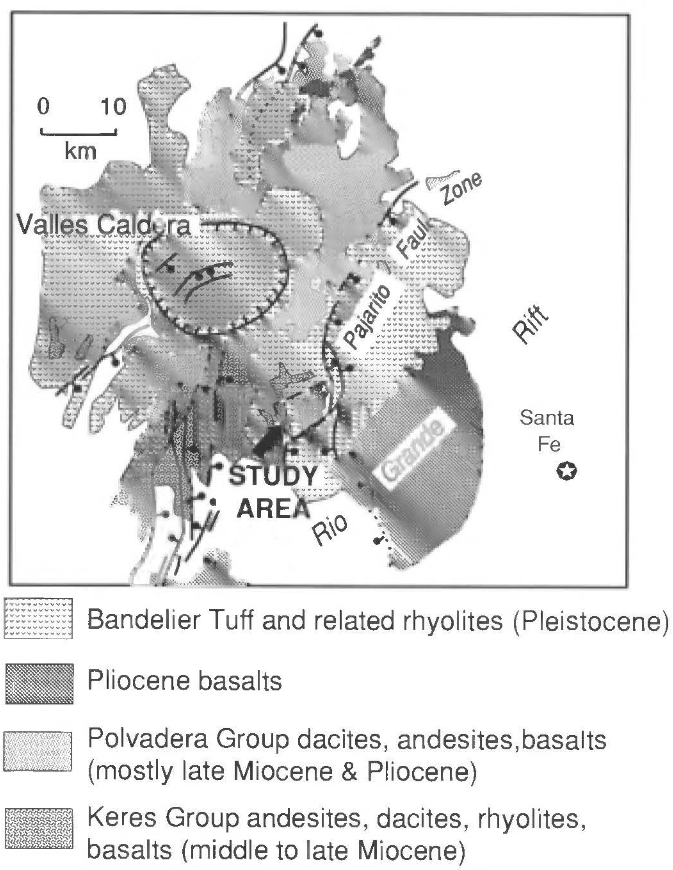

FIGURE 1. Geologic map of the Jemez Mountains (modified from Gardner et al., 1986).

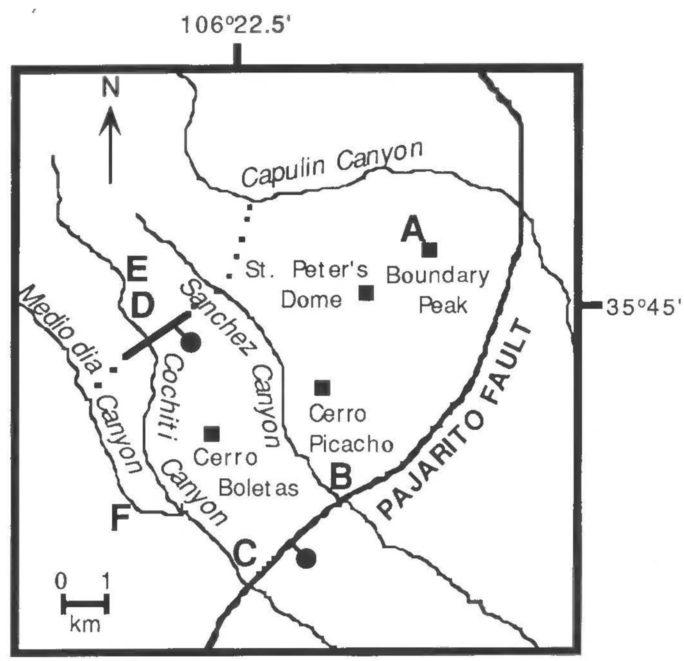

FIGURE 2. Map of study area showing locations of stratigraphic columns, lettered A–F, and major geographic features (modified from Goff et al., 1990).

(1969) as "a thick sequence of volcanic gravel and sand, consisting of basalt, andesite, dacite and rhyolite detritus derived from penecontemporaneous erosion of units of the Keres Group". The concept of the Cochiti Formation has become obscured over time because the formation has been mapped and described in several different ways (see Smith and Lavine, this volume), beginning with the map of Smith et al. (1970), in which the Cochiti Formation was mapped as younger sediments that post-date Keres Group volcanism. More recently, Gardner et al. (1986) described the Cochiti Formation as a unit consisting of lahars, vent breccias and gravels interbedded with Keres Group domes, flows and pyroclastic deposits. Using this definition, the Cochiti Formation was mapped by Gardner (1985) and Goff et al. (1990) to include large areas of andesitic and basaltic andesite flow breccias, as well as small-volume pyroclastic deposits interbedded with volcaniclastic sediments. Gardner et al. (1986) described the Cochiti Formation as thickening to the east, representing deposition of volcaniclastic sediments shed from the west into subsiding basins of the Rio Grande rift. Volcaniclastic sediments derived from penecontemporaneous erosion of Keres Group volcanoes and interbedded with Paliza Canyon Formation volcanic rocks were previously included in the Cochiti Formation (Bailey et al., 1969; Gardner, 1985; Gardner et al., 1986; Goff et al., 1990), but are referred to here as Paliza Canyon Formation volcaniclastic sediments.

This study examines the type, distribution, and thickness of volcaniclastic facies in areas mapped as Cochiti Formation by Goff et al. (1990), to refine the record of Keres Group volcanism, sedimentation and tectonism.

VOLCANICLASTIC FACIES

Volcaniclastic deposits of the Paliza Canyon Formation can be divided into five facies: autoclastic flow breccias, pyroclastic-flow deposits, debris-flow deposits, hyperconcentrated-flow deposits and channelized streamflow deposits (Figs. 3–6). Clasts, lavas and tephras were named according to the following hand-sample and thin-section phenocryst mineralogy: basalt (olivine, pyroxene, plagioclase and opaques); andesite (pyroxene, plagioclase and opaques ± hornblende); dacite (plagioclase, biotite, ± hornblende ± pyroxene and opaques); rhyolite (quartz, sanidine, plagioclase, ± biotite).

Autoclastic flow breccias

Autoclastic flow breccias of the Paliza Canyon Formation consist of andesitic flow breccias with intercalated dense lava, and minor amounts of associated andesitic scoria (Fig. 3). These autoclastic breccias represent the proximal cone-forming facies of an andesitic composite volcano (Hackett and Houghton, 1989). The deposits are found in upper Cochiti Canyon and consist of approximately 70% autoclastic breccias and 30% intercalated lava flows, which range in thickness from 30 cm to 10 m and dip 25–30° to the southwest (Fig. 4). Andesitic flow breccias are clast supported, consisting of subangular, vesicular, two-pyroxene andesite and scoria in a pulverized matrix of the same composition. Some of the more vesicular and scoriaceous fragments may have originated as fall deposits that were mixed into the surface of brecciated, moving flows. Intercalated dense andesite of the same composition have irregular contacts with overlying and underlying breccias. Some lavas are fairly extensive tabular flows, whereas many display lenticular or channel geometries.

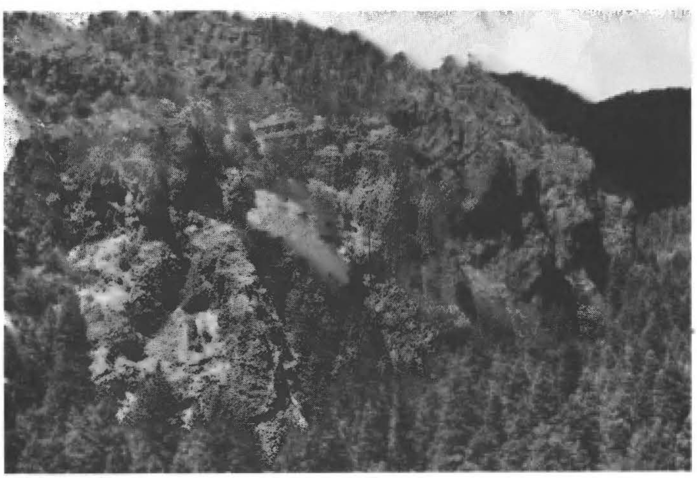

FIGURE 3. Andesitic autoclastic flow breccias with intercalated flows in upper Cochiti Canyon near sections D and E.

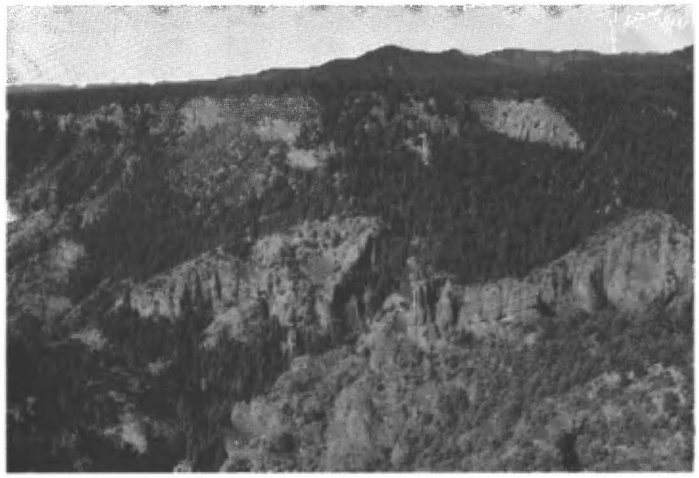

FIGURE 4. Southwest-dipping cone-forming andesitic flow breccias and flows in upper Cochiti Canyon.

Pyroclastic-flow deposits

Pyroclastic-flow deposits are interbedded with Paliza Canyon Formation volcaniclastic sediments and are derived from eruption column collapse and lava flow or lava dome collapse (Cas and Wright, 1984). Most of the pyroclastic flow deposits are lithic-rich (block-and-ash-flow deposits). These have an ashy matrix, with irregular thermal oxidation patterns, and contain abundant angular blocks of the same composition, some of which exhibit radial cooling joints. Radial joints in glassy andesite and dacite clasts indicate that the clasts were still hot when deposited and cooled in the deposit (Smith and Lowe, 1991). Most of these clasts were probably derived from collapse of andesitic and dacitic domes. Scoria-flow and pumice-flow deposits are also interbedded with volcaniclastic sediments and consist of scoria or pumice and accessory lithics in an ashy, thermally oxidized matrix.

Debris-flow deposits

Debris-flow deposits are massive, matrix-supported conglomerates and breccias. Most debris-flow deposits in the Paliza Canyon Formation have a matrix of sand- to pebble-sized volcanic and volcaniclastic fragments, including dacitic pumice, and contain clasts of dacite and andesite up to 4 m in diameter and rare clasts of basalt and rhyolite. Debris-flow deposits containing mostly subangular to angular clasts are considered to be the result of remobilization of loose material on the slopes of volcanoes, whereas deposits containing mostly rounded clasts are the result of bulking of alluvial clasts into moving debris-flows. Debris flows can be triggered by dilution of debris avalanches, by erupted material mixing with streams or snowmelt during eruptions, or by rainfall or snowmelt during times of no eruptive activity (Smith and Lowe, 1991). Debris-flow deposits consisting of >80% andesitic and/or dacitic ash and pumice indirectly represent explosive eruptions, and are shown as tephra in the stratigraphic columns (Fig. 7).

Hyperconcentrated-flow deposits

Hyperconcentrated-flow deposits are generated by flows intermediate in nature between dilute, turbulent streamflow and more viscous, non-turbulent debris flows (Smith, 1986; Smith and Lowe, 1991). Hyperconcentrated flows can be generated by the dilution of debris flows or bulking of dilute streamflows. Hyperconcentrated-flow deposits are recognized by normal grading and stratification in finer-grained parts of sandy deposits and by normally graded, gravelly de-

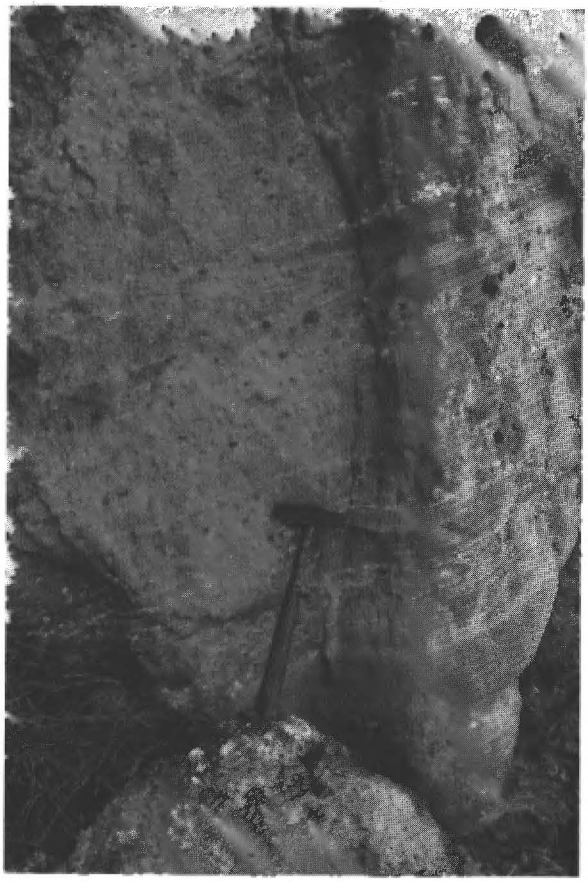

FIGURE 5. Andesitic tephra reworked by channelized streamflow on the west side of upper Cochiti Canyon across from section E. Deposit contains dacitic pumice (white) and andesitic lithics (black) in addition to predominant grey andesitic tephra.

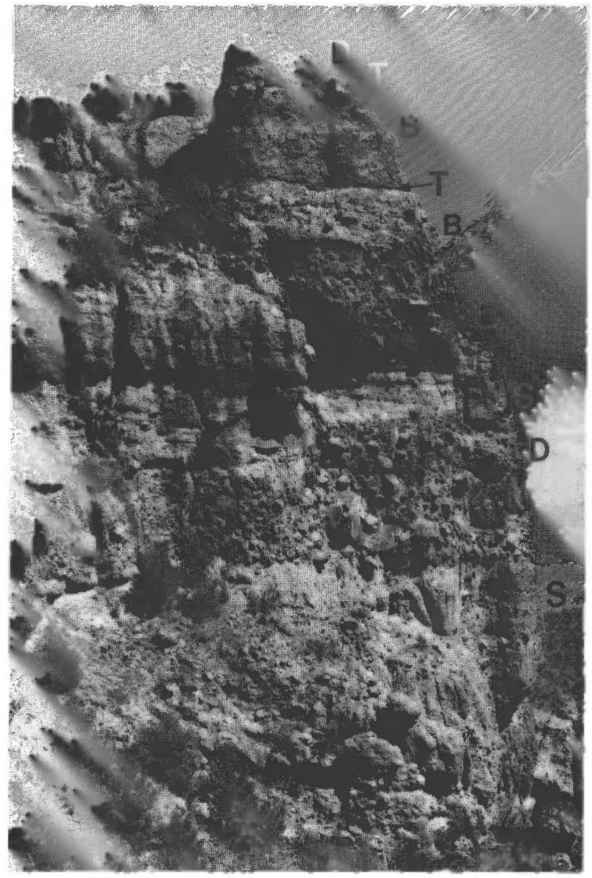

FIGURE 6. Volcaniclastic sediments in Sanchez Canyon within the upper 40 m of sediments in stratigraphic column B. Block-and-ash flow deposits (B), debris-flow deposits (D), streamflow deposits (S), and two thin reworked tephras (T) are illustrated.

posits (Smith and Lowe, 1991). Most hyperconcentrated-flow deposits are normally graded, laminated, reworked andesitic tephras.

Channelized streamflow deposits

Streamflow deposits of the Paliza Canyon Formation display some cross-bedding and stratification in sandy parts, but generally are poorly sorted, clast-supported, pebble- to cobble-sized breccias that display irregular channel geometries and scour-and-fill structures (Fig. 5). These breccias were deposited by shallow braided streams on volcaniclastic aprons. Streamflow deposits containing >80% andesitic and/or dacitic ash and pumice indirectly represent explosive eruptions, and are shown as tephra in the stratigraphic columns (Fig. 7).

STRATIGRAPHY

Stratigraphic sections (Fig. 7) were measured in six locations in the southeastern Jemez Mountains (Fig. 2) where the Cochiti Formation was mapped by Goff et al. (1990). Stratigraphic columns show the types of deposits; composition of the deposits is discussed for each stratigraphic column and is based largely on handsample and thin-section examination. Biotites from selected tephras were dated using $^{40}Ar/^{39}Ar$ (Table 1, Fig. 8; see McIntosh and Cather, 1994, for methods).

Section A

Section A is located near St. Peter's Dome (35°46'15" lat., 106°21'45" long.) and is the northeasternmost section measured. The base of section A overlies thick olivine andesite and pyroxene andesite flows, and a basalt flow with a K/Ar age of 11.3 $\pm$ 0.9 Ma (Goff et al., 1990). The section is overlain by an 8.69 $\pm$ 0.38 Ma Paliza Canyon andesite flow (Goff et al., 1990). Biotite from a reworked dacitic tephra near the middle of the section provided a $^{40}Ar/^{39}Ar$ date of 9.47 $\pm$ 0.06 Ma (Table 1). This section is composed of 30% andesite flows, 20% pyroclastic-flow deposits, 25% debris-flow deposits, and 25% streamflow deposits.

Andesite flows are interbedded with pyroclastic deposits and volcaniclastic sediments throughout the section. Andesite flows are mostly two-pyroxene andesites, with brecciated flow bases and carapaces. The relative abundance of andesite flows in this section indicates proximity to volcanic sources. Block-and-ash flow deposits near the base and top of the section contain radially jointed blocks of glassy, aphyric andesite, which have only been recognized in volcaniclastic sediments. One scoria-flow deposit near the top of the section contains numerous scoria bombs and andesitic lithics in an oxidized matrix. Debris-flow deposits contain subangular to subrounded, pebble- to boulder-sized andesite, dacite and basalt clasts. Pebble- to cobble-sized streamflow deposits are channelized, stratified and matrix supported. Sand- to pebble-sized streamflow deposits are channelized, laminated, and cross-bedded and consist primarily of andesitic tephra.

The base of the section is dominated by streamflow deposits, which become less dominant as more debris flows were deposited toward the middle of the section, and the top of the section is dominated by pyroclastic-flow deposits. This upward change in facies may indicate progradation of the volcaniclastic apron or a progressive change from distal to more proximal volcanic sources. Paleosols near the middle and top of the section are recognized by oxidation, root traces, and burrows near the top of beds, and suggest that deposition was not continuous.

Section B

Section B (Fig. 6) is located in Sanchez Canyon just north of the Pajarito Fault, on the east side of the creek (35°43'45" lat., 106°22'45" long.). This section overlies a 12.4 $\pm$ 2.0 Ma rhyolite flow of the Canovas

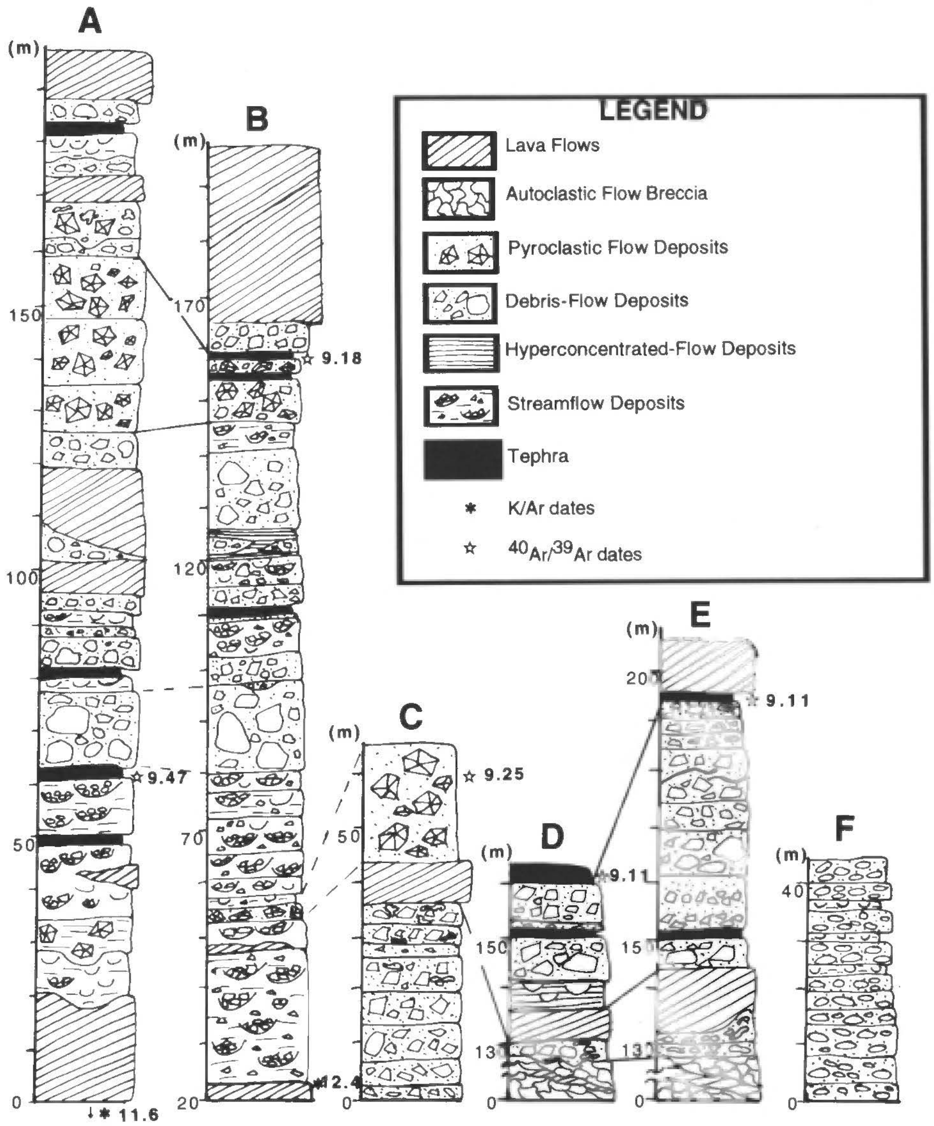

FIGURE 7. Stratigraphic columns (locations in Fig. 2) of Paliza Canyon Formation volcaniclastic sediments and interbedded lava flows and pyroclastic deposits. K/Ar dates from Goff et al. (1990).

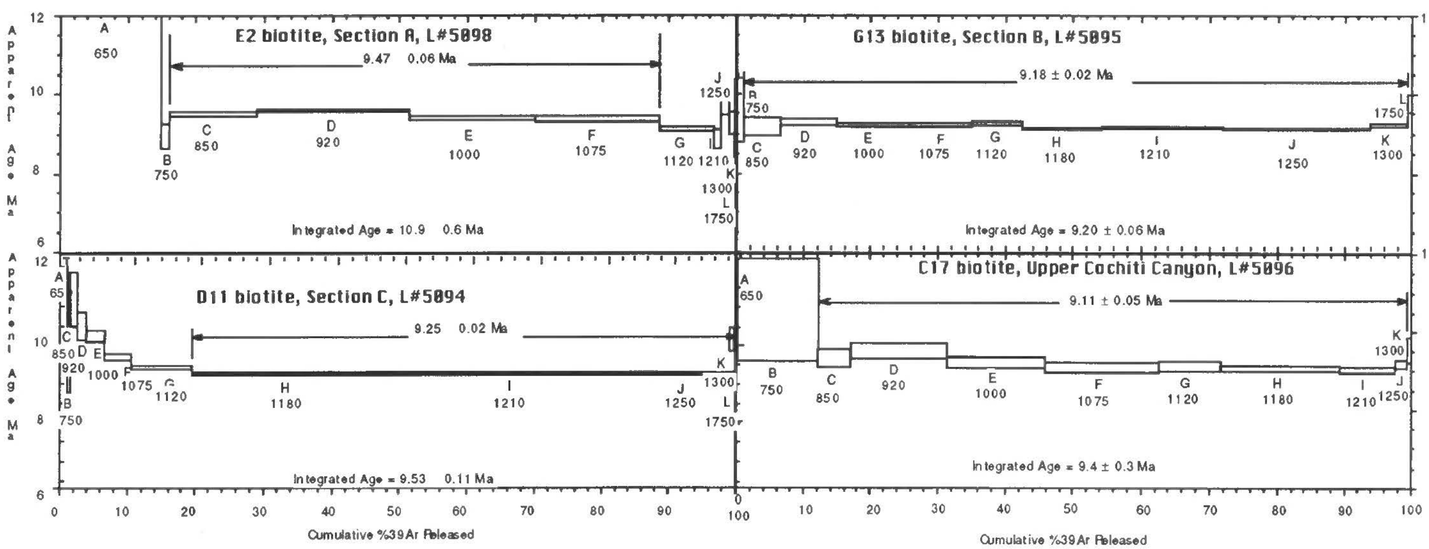

FIGURE 8. $^{40}Ar/^{39}Ar$ age spectra for biotite phenocrysts from dacitic tephras and block-and-ash-flow deposits.

TABLE 1. $^{40}Ar/^{39}Ar$ data for biotite crystals from dacitic tephras and block-and-ash-flow deposits.

Run ID#	Temp	40/39	37/39	36/39	39K moles	K/Ca	Cl/K	%40*	%39Ar	Age	± Err
Boundary Peak area, Section A											
E2,E16:33, 17.6 biotite, J=0.001448238±0.000002											
5098-01A	650	1.56E+02	2.03E-02	5.01E-01	4.2E-14	2.5E+01	1.1E-03	4.8	17.42	19.47	3.69
5098-01B	750	6.28E+00	1.56E-02	9.64E-03	2.6E-15	3.3E+01	1.2E-04	54.7	18.52	8.95	0.31
5098-01C	850	5.60E+00	1.21E-02	6.64E-03	3.0E-14	4.2E+01	1.8E-04	65.0	31.09	9.48	0.06
5098-01D	920	5.24E+00	9.88E-03	5.32E-03	5.2E-14	5.2E+01	2.1E-04	70.0	52.68	9.57	0.04
5098-01E	1000	5.71E+00	1.47E-02	7.13E-03	4.4E-14	3.5E+01	2.3E-04	63.1	70.99	9.39	0.05
5098-01F	1075	6.21E+00	2.48E-02	8.86E-03	4.3E-14	2.1E+01	2.1E-04	57.9	88.96	9.36	0.06
5098-01G	1120	5.30E+00	5.04E-02	6.09E-03	1.9E-14	1.0E+01	1.9E-04	66.1	96.97	9.14	0.06
5098-01H	1180	9.73E+02	1.43E-01	3.41E+00	-1.5E-17	3.6E+00	-8.7E-04	-3.5	96.96	-92.50	214.30
5098-01I	1210	5.30E+00	1.63E-01	6.48E-03	2.2E-15	3.1E+00	3.0E-04	64.1	97.88	8.86	0.23
5098-01J	1250	1.56E+00	1.83E-01	-7.19E-03	2.7E-15	2.8E+00	2.0E-04	237.0	99.00	9.65	0.18
5098-01K	1300	8.30E-01	1.50E-01	-9.18E-03	1.9E-15	3.4E+00	2.9E-04	428.0	99.78	9.26	0.26
5098-01L	1750	-2.50E+00	4.43E-01	-2.05E-02	5.2E-16	1.2E+00	-2.5E-04	%-144.2	100.00	9.39	0.98
totel gas age					2.4E-13			n=12		11.17	0.68
plateau age - steps C-F								n=4		9.47	0.06
Sanchez Canyon, Section B											
G17,E13:33, 16.6 biotite, J=0.001448238±0.000002											
5095-01B	750	4.63E+01	3.90E-02	1.44E-01	2.8E-15	1.3E+01	5.3E-04	8.0	0.97	9.63	0.80
5095-01C	850	1.65E+01	1.35E-02	4.40E-02	1.5E-14	3.8E+01	2.6E-04	21.3	6.42	9.18	0.23
5095-01D	920	6.80E+00	9.69E-03	1.10E-02	2.4E-14	5.3E+01	2.1E-04	52.4	14.89	9.29	0.07
5095-01E	1000	4.67E+00	1.10E-02	3.83E-03	3.1E-14	4.6E+01	2.3E-04	75.8	25.72	9.23	0.04
5095-01F	1075	4.25E+00	1.85E-02	2.40E-03	2.6E-14	2.8E+01	3.1E-04	83.4	34.99	9.23	0.04
5095-01G	1120	4.20E+00	6.44E-02	2.22E-03	2.1E-14	7.9E+00	2.9E-04	84.5	42.45	9.24	0.04
5095-01H	1180	4.12E+00	1.34E-01	2.14E-03	3.3E-14	3.8E+00	2.7E-04	84.9	54.06	9.13	0.03
5095-01I	1210	3.96E+00	9.85E-02	1.52E-03	5.0E-14	5.2E+00	2.6E-04	88.9	71.85	9.17	0.03
5095-01J	1250	3.82E+00	2.82E-02	1.07E-03	6.2E-14	1.8E+01	1.8E-04	91.8	93.85	9.14	0.02
5095-01K	1300	3.82E+00	4.72E-03	9.67E-04	1.6E-14	1.1E+02	1.9E-04	92.5	99.36	9.22	0.03
5095-01L	1750	6.61E+00	6.35E-03	9.67E-03	1.8E-15	8.0E+01	3.5E-04	56.8	100.00	9.77	0.24
totel gas age					2.8E-13			n=11		9.20	0.05
plateau age - steps C-K								n=9		9.18	0.02
Lower Cochiti Canyon, Section C											
d11,E12:33, 15.3 biotite, J=0.001448238±0.000002											
5094-01A	650	6.80E+02	1.90E-01	2.23E+00	1.1E-15	2.7E+00	2.1E-03	3.1	0.39	53.83	13.76
5094-01B	750	5.40E+01	1.30E-01	1.70E-01	1.3E-15	3.9E+00	5.0E-05	7.1	0.83	9.98	1.18
5094-01C	850	3.54E+01	8.57E-02	1.05E-01	2.7E-15	6.0E+00	2.0E-04	12.1	1.79	11.17	0.69
5094-01D	920	1.58E+01	4.98E-02	3.99E-02	3.8E-15	1.0E+01	4.0E-04	25.4	3.16	10.47	0.37
5094-01E	1000	8.31E+00	4.41E-02	1.49E-02	7.8E-15	1.2E+01	2.7E-04	47.2	5.93	10.22	0.14
5094-01F	1075	6.33E+00	5.75E-02	8.86E-03	1.1E-14	8.9E+00	3.0E-04	58.8	9.82	9.70	0.08
5094-01G	1120	5.73E+00	5.89E-02	7.19E-03	2.5E-14	8.7E+00	2.1E-04	63.0	18.77	9.42	0.06
5094-01H	1180	4.89E+00	7.81E-02	4.56E-03	8.3E-14	6.5E+00	2.4E-04	72.6	48.29	9.25	0.04
5094-01I	1210	4.15E+00	7.23E-02	2.06E-03	1.0E-13	7.1E+00	2.5E-04	85.5	84.92	9.24	0.03
5094-01J	1250	4.11E+00	9.87E-02	1.92E-03	4.1E-14	5.2E+00	2.4E-04	86.4	99.44	9.26	0.03
5094-01K	1300	5.43E+00	1.05E-01	5.25E-03	1.6E-15	4.8E+00	3.1E-04	71.6	100.00	10.13	0.31
5094-01L	1750	3.79E+01	1.88E-01	1.13E-01	1.5E-16	2.7E+00	1.8E-03	11.9	100.05	11.72	3.45
total gas age					2.8E-13			n=11		9.53	0.11
plateau age - steps H to K								n=4		9.25	0.02
Upper Cochiti Canyon, across canyon from sections D andE											
C17,E14:33, 15.2 biotite, J=0.001448238±0.000002											
5096-01A	650	1.16E+01	0.00E+00	2.17E-02	-7.0E-16		-7.5E-04	44.5	-0.31	13.38	0.55
5096-01B	750	9.41E+01	1.51E-02	3.04E-01	2.7E-14	3.4E+01	6.8E-04	4.5	11.66	10.93	1.52
5096-01C	850	1.62E+01	8.45E-03	4.26E-02	1.2E-14	6.0E+01	2.3E-04	22.1	17.09	9.29	0.24
5096-01D	920	1.46E+01	8.73E-03	3.69E-02	3.2E-14	5.8E+01	2.3E-04	25.1	31.48	9.53	0.18
5096-01E	1000	1.21E+01	1.29E-02	2.89E-02	3.2E-14	4.0E+01	3.2E-04	29.3	45.90	9.20	0.14
5096-01F	1075	9.94E+00	2.04E-02	2.18E-02	3.8E-14	2.5E+01	2.3E-04	35.1	62.66	9.09	0.11
5096-01G	1120	9.81E+00	6.69E-02	2.14E-02	2.0E-14	7.6E+00	3.1E-04	35.7	71.63	9.12	0.12
5096-01H	1180	6.73E+00	1.64E-01	1.10E-02	4.0E-14	3.1E+00	2.7E-04	51.8	89.48	9.08	0.07
5096-01I	1210	5.43E+00	2.18E-01	6.71E-03	1.8E-14	2.3E+00	3.1E-04	63.8	97.68	9.03	0.06
5096-01J	1250	5.22E+00	1.25E-01	5.78E-03	4.2E-15	4.1E+00	2.5E-04	67.5	99.54	9.18	0.10
5096-01K	1300	5.49E+00	4.73E-02	6.19E-03	1.0E-15	1.1E+01	-1.8E-04	66.7	100.00	9.54	0.34
5096-01L	1750	3.05E+01	7.96E-02	9.43E-02	1.8E-16	6.4E+00	-1.4E-04	8.8	100.08	6.97	2.93
total gas age					2.2E-13			n=11		9.39	0.29
plateau ago - stepa C-J								n=8		9.11	0.05

Analytical parameters: discrimination = 1.0059 ± 0.0018, 39ArCa/37ArCa=0.0007±0.00005, 36ArCa/37ArCa=0.00026±0.00005, 38ArK/39ArK=0.0002±0.0003, 40ArK/39ArK=0.0002±0.0003

Canyon Rhyolite (Goff et al., 1990), and is capped by a thick dacite flow of the Paliza Canyon Formation. A reworked biotite-hornblende tuff near the top of the section was dated by $^{40}Ar/^{39}Ar$ at 9.18 $\pm$ .02 Ma (Table 1). This section is composed of <1% andesite flows, 5% block-and-ash-flow deposits, 25% debris-flow deposits, and 70% channelized streamflow deposits. Two thin block-and-ash-flow deposits near the top of the section contain radially jointed clasts of glassy, aphyric andesite (described in section A), as well as other andesitic and dacitic clasts. One dacitic block-and-ash flow deposit near the base of the section is approximately 5 m thick and is composed of glassy hornblende-biotite dacite clasts in a matrix of the same composition. Reworked andesitic and dacitic ash and pumice were deposited by channelized streamflows and debris flows. Debris-flow deposits are dominated by pebble- to boulder-sized, subrounded andesite and dacite clasts, with minor amounts of rhyolite. Channelized streamflow deposits are matrix supported, pebble- to cobble-breccias, containing very angular to subangular clasts in irregular channels, with abundant scour-and-fill structures typical of shallow braided stream deposits on volcaniclastic aprons.

Two poorly-formed paleosols are present in section B, one near the middle of the section, and one near the top of the section, both in reworked dacitic tephras, indicating that deposition was not continuous. The paleosols are oxidized and contain burrows near the top of the beds.

Section C

Section C is located in Cochiti Canyon, just north of the Pajarito Fault on the east side of the canyon (35°42'30" lat., 106°23'45" long.). The base of volcaniclastic sediments is not exposed at this location. The section is overlain by an andesite flow and dome with a K/Ar age of 9.33 ± 0.19 Ma (Goff et al., 1990). This section consists of 65% debris-flow deposits, 15% andesite flows, and 20% block-and-ash-flow deposits. Debris-flow deposits contain subangular clasts of basalt, glassy andesite and dacite, scoria, andesitic tephra clasts, and fragments of andesitic flow breccia derived from a large breccia-dominated cone in upper Cochiti Canyon (see section D). The distinctive andesitic tephra clasts are up to 1 m in diameter and show soft-sediment deformation, indicating that they were wet when deposited. Volcaniclastic sediments are capped by a 5-m-thick andesite flow, with a brecciated base. A 20-m-thick dacitic block-and-ash-flow deposit overlies the andesite flow, contains glassy hornblende-biotite clasts in a matrix of the same composition, and is 9.25 ± .02 Ma (Table 1).

Section D

Section D is located in upper Cochiti Canyon on the east side of the canyon (35°46' lat., 106°24'45" long.) and overlies at least 130 m of andesitic flow breccias and intercalated flows that are part of an andesitic cone. The section is capped by a 5-m-thick biotite-hornblende tuff that is correlative, based on stratigraphic position, petrographic textures and mineralogy, and plagioclase mineralogy (Fig. 9), to a nearby tuff dated by $^{40}Ar/^{39}Ar$ at 9.11 ± .05 Ma (Table 1). The southern end of the volcaniclastic sequence in this section of Cochiti Canyon is intruded by a rhyolite dated at 9.32±1.6 Ma (Goff et al., 1990). The section above the flow breccias consists of 65% debris-flow deposits, 5% hyperconcentrated-flow deposits, 25% streamflow deposits, and 5% andesite flows. Reworked pyroclastic deposits are massive, white, pumiceous biotite-hornblende dacitic tuffs and lapillistones, and gray hyperconcentrated-flow deposits and streamflow deposits of andesitic ash and ash to lapilli sized lithics. Debris-flow deposits at the base of the section, below the 5-m-thick andesite flow contain numerous andesite clasts, derived from the underlying cone-forming andesitic flow breccia, as well as andesite and dacite clasts, derived from other sources, and andesitic tephra clasts (see section C). Debris-flow deposits above the andesite flow contain subangular pebble- to boulder-sized clasts of andesite and dacite, with rare rhyolite or tuff clasts.

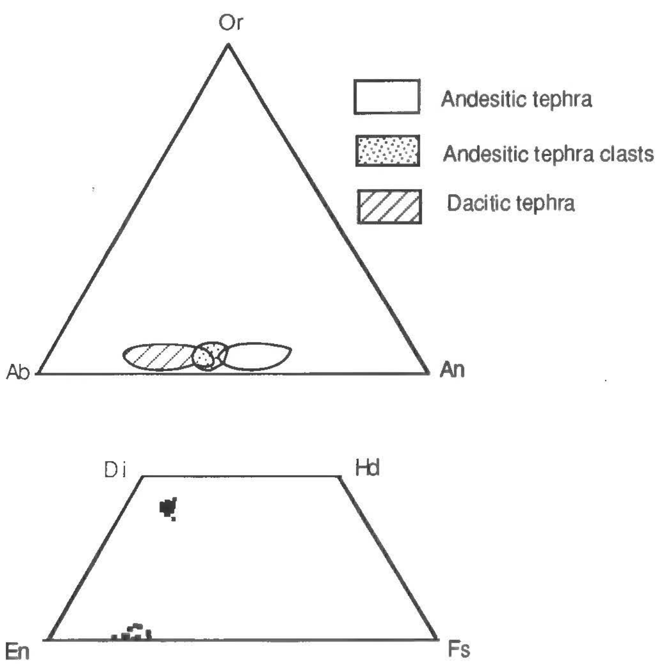

FIGURE 9. Plagioclase and pyroxene compositions from andesitic and dacitic tephras of the Paliza Canyon Formation.

Section E

Section E is located just north of section D on the east side of Cochiti Canyon (35°45'45" lat., 106°25' long.) and also overlies at least 130 m of andesitic flow breccias and intercalated flows. The section above the flow breccias consists of 20% flows, 75% debris-flow deposits, and <5% hyperconcentrated-flow deposits. A reworked pyroclastic deposit at the top of the section is correlative, based on stratigraphic position and similarities in thin section texture and mineralogy, to the 9.11 ± .05 Ma (Table 1) tephra. Andesite flows are interbedded with and overlie volcaniclastic sediments. Debris-flow and hyperconcentrated-flow deposits below the lower lava flow contain numerous andesite clasts and andesitic sand derived from the underlying andesitic flow breccias, and also contain andesitic tephra clasts described in section D. Debris-flow deposits contain clasts of andesite and dacite, with rare rhyolite and basalt, and dacitic biotite-hornblende pumice. Debris-flow deposits become thinner and display more internal layering near the top of the section. Reworked pyroclastic deposits are both gray, andesitic ashes that were deposited by hyperconcentrated flow, and white dacitic ashes deposited by debris flow.

Section F

Section F is located near the junction of Cochiti Canyon and Medio Dia Canyon on the west side of Medio Dia Canyon (35°43'15" lat., 106°25' long.). The base of the volcaniclastic deposits is not exposed, and the deposits are overlain by the Peralta Tuff Member of the Bearhead Rhyolite. This section consists of 85% heterolithologic debris-flow deposits with 15% interbedded sandy streamflow deposits. At least 70% of the debris-flow clasts in these deposits are rounded, indicating that the deposits were formed by bulking up of streams. Clasts are pebble- to boulder-sized, but are dominantly pebble- and cobble-sized, and consist of basalt, andesite, dacite and rhyolite. Rhyolite clasts are significantly more abundant in this section than in any of the others. Clasts of a glassy biotite-dacite flow that overlies volcaniclastic sediments to the north in Cochiti Canyon are also found in these deposits, indicating that the deposits are younger than other volcaniclastic sediments studied.

Stratigraphic correlations

Stratigraphic correlations are based on field relationships, hand samples and thin sections of clasts, lavas, and tephras, and electron-microprobe data of plagioclase and pyroxene from tephras. Because many of the sediments were deposited into channels or on irregular topography, there are large lateral variations in bed dimensions and bed geometry, making correlations based on stratigraphic position alone almost impossible in most cases. Correlations are substantiated by mineralogy and mineral chemistry. Pyroxene chemistry from tephras cannot be used for correlation because there is very little compositional variation among pyroxenes (Fig. 9). Plagioclase compositions from tephras cluster into three groups (Fig. 9), which do not require correlation of any units, but also do not contradict correlations suggested by stratigraphic position and handsample and thin-section similarities. Based on previously reported K-Ar dates (Gardner and Goff, 1984; Gardner et al., 1986; Goff et al., 1990) and $^{40}Ar/^{39}Ar$ dates obtained in this study (Table 1), most of the volcaniclastic rocks studied were deposited between approximately 10 and 9 Ma.

Sections A and B can be correlated by block-and-ash flow deposits near the top of both sections, that contain radially jointed clasts of glassy, aphyric andesite. These deposits are probably the result of dome collapse. The deposits are thinner in section B and contain fewer radially jointed clasts, suggesting that section B was farther from the source of these deposits. Sections A and B are also tentatively correlated based on similar petrographic characteristics of large boulders (up to 5 m in diameter) of glassy andesite found in debris-flow deposits in both sections.

Block-and-ash-flow deposits near the base of section B and at the top of section C are petrographically and physically very similar and are probably correlative. These deposits are much thicker and more extensive in Cochiti Canyon (section C) and were probably derived from a source to the west of both Cochiti and Sanchez Canyons.

The andesite flows in Cochiti Canyon near the top of section C and the bottom of sections D and E appear to correlate based on petrography and stratigraphy of the underlying debris-flow deposits, which contain distinctive andesitic tephra clasts and fragments of andesitic flow breccia. Tephra clasts from north of the fault (sections D and E) have very similar plagioclase compositions (Fig. 9) to tephra clasts from south of the fault (section C). This correlation is made across a fault mapped by Goff et al. (1990) that parallels and is north of the Pajarito Fault (Figs. 2, 10). Correlation of these andesite flows and the underlying deposits indicates approximately 200 m of down-to-the-south displacement along this fault. Sections D and E can also be correlated by a reworked biotite-hornblende pyroclastic deposit near the top of both sections.

Section F cannot be correlated with any of the other sections. Because debris-flow deposits in section F contain clasts of dacite flows that overlie volcaniclastic sediments of sections D and E (not shown in stratigraphic sections), section F was deposited later than other volcaniclastic sediments studied.

DISCUSSION AND CONCLUSIONS

Generalized volcanic evolution based on volcaniclastic rocks

Paliza Canyon volcaniclastic sediments and interbedded flows and pyroclastic deposits in the study area were deposited between 12.4 ± 2.0 Ma and 8.69±0.38 Ma. Large uncertainty for the older K-Ar date and stratigraphic relations suggest that most of the studied volcaniclastic rocks were deposited between approximately 11 and 9 Ma. The evolution of Keres Group volcanoes between 11 and 9 Ma is shown in Figure 10. Volcaniclastic sedimentation in the study area was preceded by basaltic, andesitic, dacitic and rhyolitic volcanism in the form of lava flows and autoclastic flow breccias. Andesite flows were erupted during as well as after volcaniclastic sedimentation. Volcaniclastic sediments are overlain by andesite and dacite flows and are intruded by rhyolite domes in Cochiti and Sanchez Canyons. Block-and-ash flow deposits indicate that growth and collapse of andesitic and dacitic domes to the northeast and the west of the measured sections began before 9.47 Ma and continued until 9.18 Ma. Explosive andesitic and dacitic eruptions occurred from at least 10 Ma until 9.11 Ma, depositing pyroclastic-flow and fall deposits, some of which were reworked.

Volcaniclastic sediments are largely coarse-grained debris-flow and channelized streamflow deposits containing andesite and dacite clasts, with minor amounts of basalt and very rare rhyolite clasts. The composition of volcaniclastic sediments in the measured sections does not show any major variation over time, except perhaps in Cochiti Canyon, where lower volcaniclastic sediments are derived from the underlying andesitic cone and upper volcaniclastic sediments are derived from other andesitic and dacitic sources. Also, at the junction of Cochiti and Medio Dia Canyons (section F), is a greater amount of rhyolitic and dacitic clasts in debris-flow deposits than in underlying deposits (sections D and E).

The absence of rhyolitic flows or interbedded pyroclastic deposits, and sparsity of rhyolite clasts in volcaniclastic sediments suggest that there was relatively little rhyolitic volcanism during deposition of the sediments, or that rhyolitic material was deposited elsewhere. Although rhyolite flows and domes with ages between 11 and 9 Ma are found in Sanchez, Cochiti, and Medio Dia Canyons (Gardner and Goff, 1984), the uncertainties of these dates (up to ± 2.0 Ma) and stratigraphic relationships suggest that rhyolitic eruptions occurred either prior to or postdating the volcaniclastic sedimentation described here. Many deposits mapped as Canovas Canyon Rhyolite tuff by Goff et al. (1990) are actually Paliza Canyon Formation dacitic tuffs.

Sedimentation and tectonism

Paliza Canyon Formation volcaniclastic sediments were shed onto volcaniclastic aprons around Keres Group volcanoes and into channels on the flanks of andesitic composite volcanoes (Fig. 10). Volcaniclastic sediments thicken to the southwest (sections A and B) and most channels are oriented northeast-southwest (Fig. 11), suggesting that most sediments were shed to the southwest off of volcanoes to the northeast,

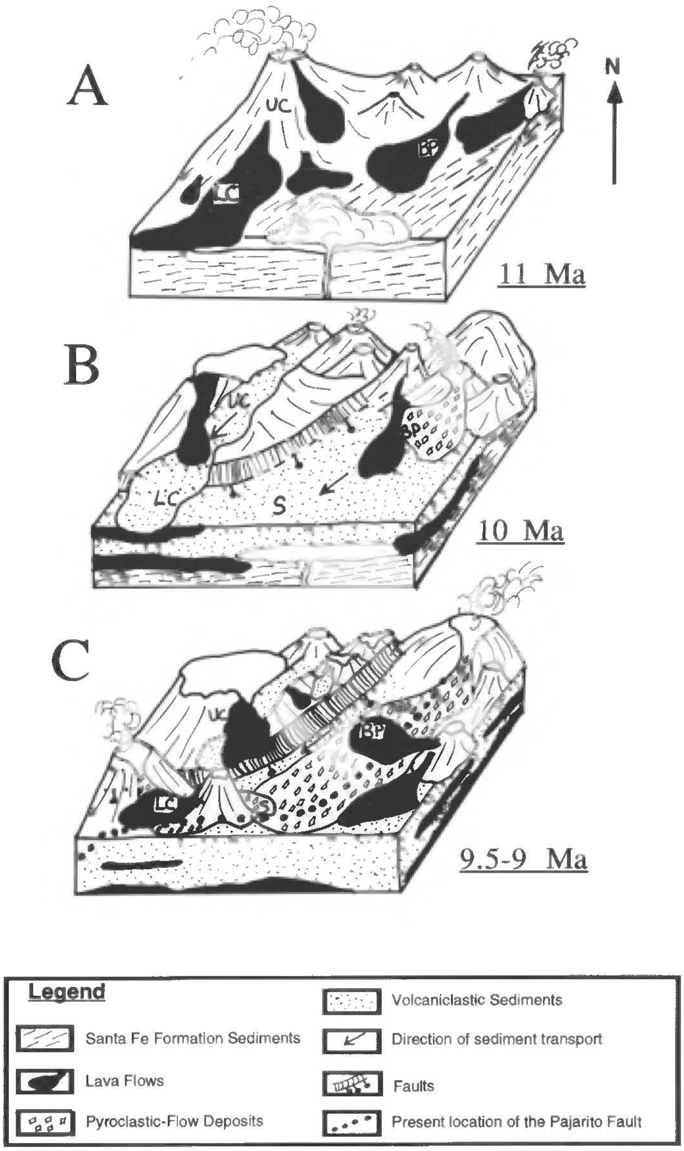

FIGURE 10. Schematic block diagrams showing the evolution of Keres Group composite volcanoes around the St. Peter's Dome area between 11 and 9 Ma. BP = Boundary Peak area, S = Sanchez Canyon, UC = Upper Cochiti Canyon, LC = Lower Cochiti Canyon. **Block A (11 Ma)** shows numerous andesitic and basaltic cones issuing lava flows near Boundary Peak, formation of a rhyolite dome and associated flow in Sanchez Canyon, and formation of a large, breccia-dominated andesitic cone in Cochiti Canyon. **Block B (10 Ma)** shows growth and collapse of andesitic domes, andesite flows, and formation of a volcaniclastic apron near Boundary Peak, possible inception of a normal fault to the northwest of lower Cochiti Canyon and Sanchez Canyon, and volcaniclastic sediments being shed to the southwest into the Sanchez Canyon area and into channels in Cochiti Canyon. **Block C (9.5-9.0 Ma)** shows continued faulting, accommodating thick accumulation of sediments at Sanchez Canyon, block-and-ash flows at the Boundary Peak area and near lower Cochiti Canyon, andesitic and dacitic lava flows, and continued sedimentation.

which are now buried in the Rio Grande rift. Volcaniclastic sediments in sections C to E were deposited into channels on an andesitic cone, creating significant variations in thickness over very short distances. However, dips up to 50° to the southwest in channeled streamflow deposits in section D, indicate that depositional slopes dipped toward the southwest, and that deposits in this area have experienced at least 20° of structural rotation. The greater thickness of sediments in Sanchez Canyon may have been accommodated by normal faulting parallel to the Pajarito fault between Sanchez and upper Cochiti Canyons (Figs. 2 and 10) before or during emplacement of volcaniclastic sediments.

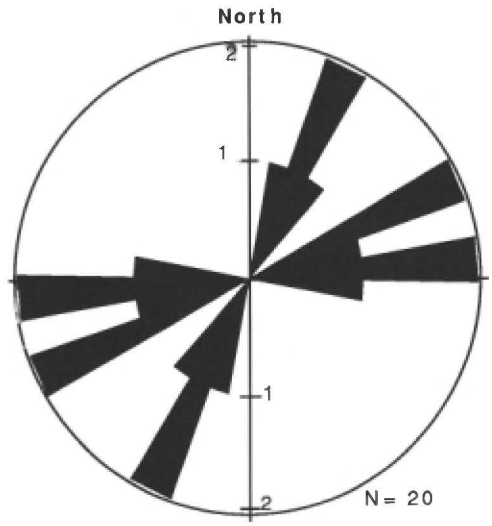

FIGURE 11. Rose diagram of channel orientations in volcaniclastic sediments.

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REFERENCES

Bailey, R. A., Smith, R. L. and Ross, C. S., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico: U.S. Geological Survey, Bulletin 1274-P, 19 p.

Cas, R. A. F. and Wright, J. V., 1987, Volcanic successions, modern and ancient, Allen and Unwin Publishers, London, p. 107–114.

Erskine, D. W. and Smith, G. A., 1993, Compositional characterization of volcanic products from a primarily sedimentary record: the Oligocene Espinaso Formation, north-central New Mexico: Geological Society of America Bulletin, v. 105, p. 1214–1222.

Gardner, J. N., 1985, Tectonic and petrologic evolution of the Keres Group: implications for the development of the Jemez volcanic field, New Mexico [Ph.D. dissertation]: Davis, University of California, 295 p.

Gardner, J. N. and Goff, F., 1984, Potassium-Argon dates from the Jemez volcanic field: implications for tectonic activity in the north-central Rio Grande Rift: New Mexico Geological Society, Guidebook 35, p. 75–81.

Gardner, J. N., Goff, F., Garcia, S. and Hagan, R. C., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico: Journal of Geophysical Research, v. 91, no. B2, p. 1763–1778.

Goff, F., Gardner, J. N. and Valentine, G., 1990, Geology of the St. Peter's Dome area, Jemez Mountains, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Geologic Map 69.

Guilbeau, K. P., 1982, Geology, geochemistry, and petrogenesis of the upper Keres Group, Ruiz Peak area, Jemez Mountains, New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 132 p.

Hackett, W. R. and Houghton, B. F., 1989, A facies model for a Quaternary andesitic composite volcano: Ruapehu, New Zealand: Bulletin of Volcanology, v. 51, p. 51–68.

McIntosh, W. C. and Cather, S. M., 1994, $^{40}Ar/^{39}Ar$ geochronology of basaltic rocks and constraints on late Cenozoic stratigraphy and landscape development in the Red Hill-Quemado area, New Mexico: New Mexico Geological Society, Guidebook 45, p. 209–215.

Smith, G. A., 1986, Coarse-grained non-marine volcaniclastic sediments: terminology and depositional processes: Geological Society of America Bulletin, v. 97, p. 1–10.

Smith, G. A., Campbell, N. P., Deacon, M. W. and Shafiqullah, M., 1988, Eruptive style and location of volcanic centers in the Miocene Washington Cascade Range: reconstruction from the sedimentary record: Geology, v. 16, p. 337–340.

Smith, G. A. and Lowe, D. R., 1991, Lahars: volcano-hydrologic events in the debris flow-hyperconcentrated flow continuum; *in* Sedimentation in Volcanic Settings, SEPM Special Publication no. 45, p. 60–70.

Smith, G. A., Snee, L. W. and Taylor, E. M., 1987, Stratigraphic, sedimentologic, and petrologic record of late Miocene subsidence of the central Oregon High Cascades: Geology, v. 15, p. 389–392.

Smith, R. L., Bailey, R. A. and Ross, C. S., 1970, Geologic map of the Jemez Mountains, New Mexico: U.S. Geological Survey, Miscellaneous Investigations Series Map I-571.

Turbeville, B. N., Waresback, D. N. and Self, S., 1989, Lava-dome growth and explosive volcanism in the Jemez Mountains, New Mexico: evidence from the Plio-Pleistocene Puye alluvial fan: Journal of Volcanology and Geothermal Research, v. 36, p. 267–291.