Preliminary Geologic Map of the Bland Quadrangle, Los Alamos and Sandoval Counties, New Mexico.

By

Fraser Goff[1], Steven L. Reneau[2], Scott Lynch[3], Cathy J. Goff[4], Jamie N. Gardner[2], Paul Drakos[5], and Danny Katzman[2]

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Open-file Digital Geologic Map OF-GM 112

Scale 1:24,000

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801 Leroy Place, Socorro, New Mexico, 87801-4796

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1:24,000

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Fraser Goff[1], Steven L. Reneau[2], Scott Lynch[3], Cathy J. Goff[4], Jamie N. Gardner[2], Paul Drakos[5], and Danny Katzman[2]

[1]Earth and Space Sciences Dept., University of New Mexico, Albuquerque, NM 87131
[2]EES-9, Los Alamos National Laboratory, Los Alamos, NM 87545
[3]New Mexico Bureau of Geology & Mineral Resources, Socorro, NM 87801
[4]Independent Consultant, 5515 Quemazon, Los Alamos, NM 87544
[5]Glorieta Geoscience, Inc., 1723 Second St., Santa Fe, NM 87505

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INTRODUCTION

The Bland 7.5 minute quadrangle is located in Los Alamos and Sandoval Counties and straddles the southeastern rim of the Valles caldera in the Jemez Mountains, New Mexico (Fig. 1). Topographically, the quadrangle is bounded by Valle Grande on the northwest, the Sierra de los Valles on the northeast, the Pajarito Plateau to the east and south, the St. Peter's dome area in the southeast corner, and Bearhead Ridge on the southwest. Geologically, the quadrangle consists of three domains: the southeast moat of Valles caldera represented by Valle Grande, precaldera volcanic rocks of the Jemez volcanic field represented by the mountains in the northeast and southwest, and an extensive plateau of Bandelier Tuff and scattered older volcanic rocks in the center and southeast. Each domain has unique geology as described below. The relatively new Valles Caldera National Preserve (VCNP) occupies the northeastern portion of the quadrangle. Before 2000, the Preserve belonged to the Baca Land and Cattle Company of Abilene, Texas. Access to the Preserve is presently is described at <www.vallescaldera.gov>. The rest of the quadrangle is primarily part of the Santa Fe National Forest and the Bandelier National Monument (BNM). Small but significant private lands occur in the area between Pines Canyon and Medio Dia Canyon in the northwest central part of the quadrangle. New Mexico Highway 4 crosses the north part of the quadrangle. Most other areas can be visited by dirt roads. The southwest corner of the quadrangle near the abandoned town of Bland is rather remote and is only accessed by trails. Please be aware that the entire southern part of the quadrangle was extensively burned during the Las Conchas Fire of June-July 2011 <http://en.wikipedia.org/wiki/Las_Conchas_Fire>.

The quadrangle was once home to pre-Columbian Indian cultures (Paleo-Indian, Archaic, and ancestral Puebloan), Spanish land grants, homesteads and scattered ranches. BNM in the eastern part of the quadrangle contains numerous archeological sites that were protected in 1916 to preserve prehistoric, scientific and scenic values. VCNP occupies the northwest part of the quadrangle (Martin, 2003) and was created by the Valles Caldera Preservation Act of 2000 to preserve and protect the historic Baca Ranch and the geologically famous Valles caldera of the Jemez Mountains volcanic field. The VCNP is managed for limited public recreation, and for elk hunting, cattle grazing, fishing, and scientific study. Gold and silver were successfully extracted from the Cochiti Mining District near Bland in the late 1800s to early 1900s (Hoard, 1996) and precious metal exploration has been conducted sporadically on National Forest lands to the present. Geothermal energy was explored but not developed on both VCNP and National Forest lands in the 1960s to 1980s (Laughlin, 1981; Goff and Gardner, 1988). Before the Las Conchas Fire, timber was harvested and pumice was mined on National Forest lands.

The objectives of the present study are to provide detailed geologic mapping for the VCNP and the BNM, and to contribute quadrangle maps for the New Mexico State Map Program. The geology of the southeast part of the quadrangle was mapped previously (Goff et al., 1990) but was field checked and updated for the present project. The rest of the quadrangle was mapped during parts of 2003, 2004 and 2005. Regional geology and

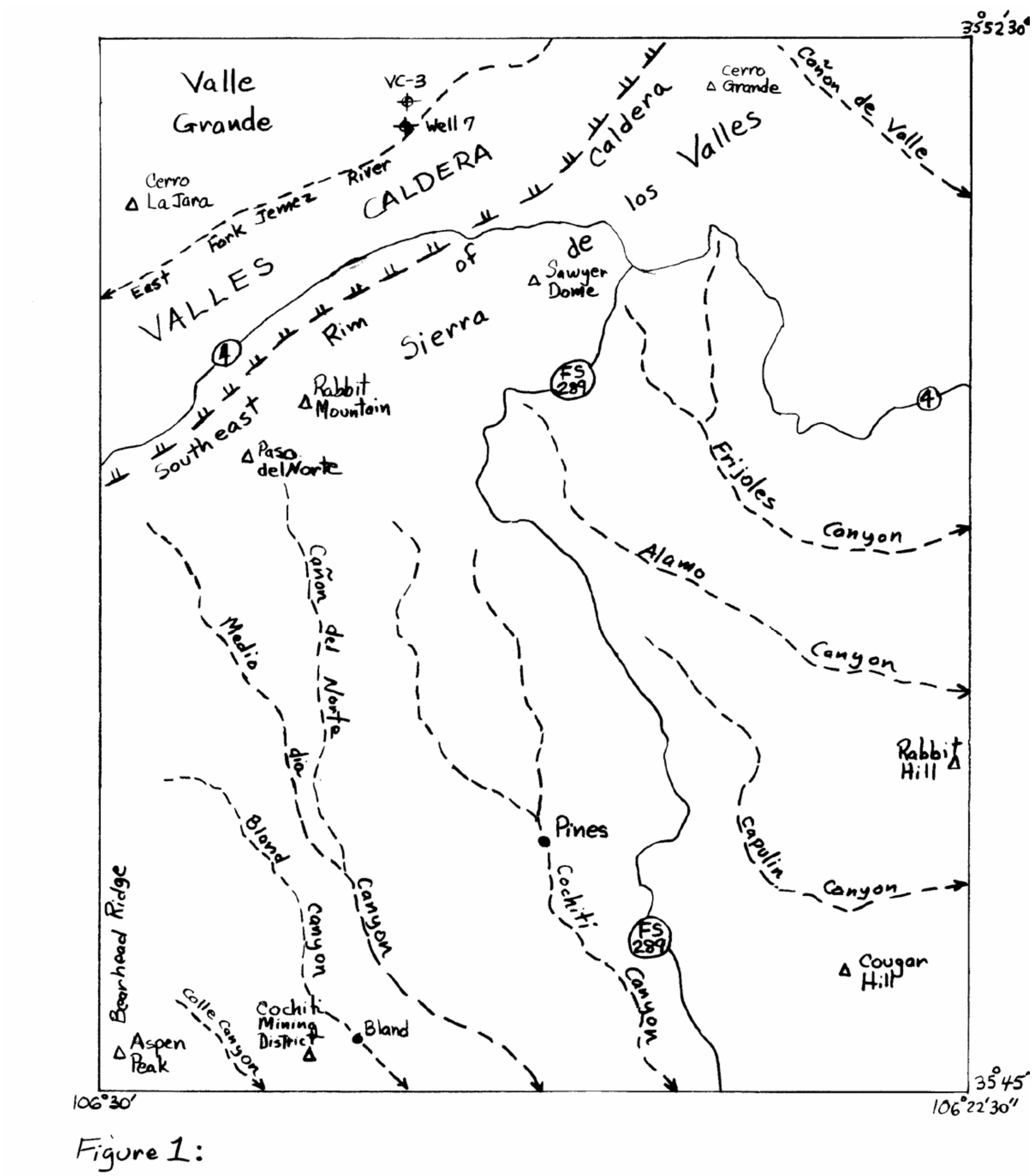

Figure 1: Map of Bland quadrangle showing locations of Valles caldera, the southeast rim of the caldera, the Cochiti Mining District and major physiographic features.

stratigraphy have been previously published by Griggs (1964), Bailey et al. (1969), Smith et al. (1970), Kelley (1978), Gardner (1985), Gardner and Goff (1984), Gardner et al. (1986), Goff and Gardner (2004), and Gardner et al. (2010). Adjacent and nearby NM State Map quadrangles have been published by Goff et al. (2002, 2005), Kempter and Kelley (2002), Osburn et al. (2002), Kelley et al. (2003) and Lynch et al. (2004). Broxton and Vaniman (2005) presented a geologic framework for aquifers beneath the southern

Pajarito Plateau. Several of these maps were recently compiled to produce a 1:50,000-scale color map of the Valles caldera (Goff et al., 2011).

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STRATIGRAPHY

The southwest corner of the Bland quadrangle contains an interesting assortment of intensely faulted, hydrothermally altered volcanic, intrusive and sedimentary rocks previously assigned as Eocene in age (the Bland Volcanics of Smith et al., 1970). A single date presented by Stein (1983) from a sample of monzonite in the Bland stock yielded a Miocene age of 11.3 ± 0.3 Ma for these rocks and suggested that the Bland Volcanics are actually part of the Keres Group of the Jemez Mountains volcanic field (Gardner et al., 1986). This last interpretation is confirmed by our geologic mapping of the Bland quadrangle reported herein. The intrusive rocks of the Bland stock display moderate to extreme hydrothermal alteration. We obtained two new $^{40}Ar/^{39}Ar$ dates on rocks from the stock but the resulting ages (7.8 ± 0.6 and 7.4 ± 1.0 Ma, respectively) suggest some resetting by later Bearhead Rhyolite intrusions. Our new dates also indicate that the age reported by Stein (1983) may be 1 to 3 Myr too old.

The oldest volcanic rock units in the Bland quadrangle (see Correlation Chart, geologic map) are exposed in Colle Canyon in the southwest corner of the map where a sequence (bottom to top) of basalt, andesite, and volcaniclastic rocks are intruded by various monzonitic rocks of the Bland stock. Many of these rocks display severe hydrothermal alteration to epidote-chlorite rank and cannot be dated. However, similar sequences of basalt and andesite intruded by monzonite dikes can be found in upper Bland Canyon and Medio Dia Canyon where the intensity of alteration diminishes northwards. In these areas, the basalt and andesite resemble those typical of the Paliza Canyon Formation.

Another sequence of potentially old rocks is exposed in Medio Dia Canyon just upstream of the Evans-Griffin Place. Here, a ledge of hydrothermally altered rhyodacite or rhyolite, probably correlative with the Canovas Canyon Rhyolite, is overlain by a sequence of altered olivine basalt lava flows. The basalt thickens dramatically to the east suggesting that an eroded vent once occurred on the ridge east of Medio Dia Canyon. The basalt is overlain by a thick package of altered two-pyroxene andesite flows.

Overlying these lowermost basalt and andesite flows is a highly discontinuous volcaniclastic unit of variable thickness (rock unit Tpv) best observed in Colle Canyon near the southern edge of the quad. Here the dark green beds dip 15° ± 5° to the east. Although the lower beds are altered to epidote-chlorite grade, they locally contain a significant fraction of gray to purple clasts of aphyric, flow banded rhyolite resembling Canovas Canyon Rhyolite (Bailey et al., 1969; Gardner et al., 1986). The few available dates on Canovas Canyon rhyolite from adjacent quadrangles indicate ages of roughly 10.5 to 9 Ma.

North of the Bland stock, the volcaniclastic unit is overlain by light-colored beds of fine to medium grained, well-indurated sandstone described by Bundy (1958) and Stein (1983). The contact between the two sedimentary units is sharp, occurring over an interval of a few meters. The sandstone overlies basaltic andesite and volcaniclastic rocks just south of the Bland quadrangle in Jenks and Union Draws (Lynch et al., 2004) but underlies andesite in Bland Canyon and adjacent ravines. Although difficult to find, rare bedding features indicate a dip to the east conformable with the underlying volcaniclastic unit. The sandstone is intruded by monzonitic rocks of the Bland stock and is locally converted to a hornfelsed quartzite. The sandstone is also cut by monzonite and andesite dikes in Bland Canyon.

A small, north-trending graben of sandstone is flanked by monzonite in the Washington Group mining claim on the high ridge WSW of Bland. In this area, the sandstone appears to be a faulted roof pendant on the stock and played host to extensive mineralization and hydrothermal alteration.

We have assigned the sandstone unit in the Bland district to the Santa Fe Group because of stratigraphic relations and general resemblance to other sandstone units in the Santa Fe. This sandstone is roughly similar in age to the Santa Fe Group rocks exposed to the west in the southern Redondo Peak quadrangle (roughly 10 Ma; Goff et al., 2005) but younger than the Santa Fe rocks exposed to the southeast, south of St. Peter's Dome (about 16 to 23 Ma; Goff et al., 1990; WoldeGabriel et al., in prep.). Apparently, the sandstone unit in the Bland area was deposited in a small, short-lived basin during early Keres Group time.

North of Bland and the Cochiti Mining District, lowermost Keres rocks are overlain and intruded by a complicated sequence of weakly altered to relatively fresh dacite, andesite, basalt and associated volcaniclastic rocks typical of Keres Group rocks described by Bailey et al. (1969) and Gardner et al. (1986). Dates on these units range from roughly 10.5 to 7.8 Ma (Goff et al., 1990; Justet, 2003; WoldeGabriel et al., in prep.). These rocks are locally intruded by monzonite plugs and dikes (undated) and by a multitude of Bearhead Rhyolite intrusive bodies roughly 7 to 6 Myr (Justet, 1996).

The northeast part of the Bland quadrangle is occupied by a series of dacitic domes and flows originating from three centers (Sawyer Dome, Cerro Grande and Pajarito Mountain) that form part of the northeast-trending Sierra de los Valles. They are assigned to the Tschicoma Formation of the Keres Group (formerly Polvadera Group – see Bailey et al., 1969, Gardner et al., 1986 and Goff et al., 2011). Relations with older Keres Group rocks are not exposed. Dates on the fresh porphyritic rocks from these Tschicoma domes range from about 3.4 to 2.9 Ma (Dalrymple et al., 1967; WoldeGabriel et al., 2003, this map).

The central and southeast parts of the Bland quadrangle are covered primarily by rocks of the Tewa Group (Bailey et al., 1969; Gardner et al., 1986; Gardner et al., 2010), originating from the Toledo and Valles calderas (Smith and Bailey, 1968; Smith et al., 1970; Self et al., 1986). The lower (Otowi Member) Bandelier Tuff (1.62 Ma; Spell et al., 1996), erupted during formation of the Toledo caldera, is widely exposed in the deeper canyons and consists of weakly indurated, porphyritic rhyolitic ignimbrite relatively rich in lithic clasts. The Otowi is separated from the overlying upper Bandelier Tuff by a large debris avalanche and debris flow deposit that cascaded off of Rabbit Mountain (described below) and, locally, by a few meters of gravel consisting of rounded cobbles and sand of primarily andesitic to dacitic rocks of the Keres Group. Because thick Otowi ash flow sequences can be mistaken for Tshirege ash flows, we obtained three new dates on Otowi samples from about 1 m below the upper surface of the ignimbrite to verify an Otowi assignment. These samples are from Pines Canyon (1.58 ± 0.04 Myr), upper Alamo Canyon (1.70 ± 0.02 Myr), and upper Frijoles Canyon (1.53 ± 0.05 Myr).

Toledo caldera has been obliterated by the younger Valles caldera but two post-Toledo rhyolite dome and flow complexes stand on a highland of precaldera volcanic rocks forming the southeastern Valles topographic rim: Paso del Norte rhyolite and Rabbit Mountain rhyolite. The former rhyolite was mistakenly mapped as Bearhead Rhyolite by Smith et al. (1970) but was dated at 1.47 ± 0.04 Ma by Justet (1996). Rabbit Mountain is slightly younger at 1.43 ± 0.03 Ma (Goff et al., 1990) and is significantly larger. Both domes are remnants of substantially larger domes defining the Toledo caldera ring-fracture that was subsequently modified by collapse of the younger Valles caldera (Goff et al., 2011). This is best expressed by the northwest arcuate shape of Rabbit Mountain, which suggests that much of the northeast part of the dome has foundered into the present Valles caldera.

Extensive debris avalanche deposits from Rabbit Mountain and Paso del Norte rhyolite domes occur between the two members of the Bandelier Tuff (Smith et al., 1970; Goff et al., 2011). The Rabbit Mountain unit near Obsidian Ridge is highly indurated and was previously described as a glowing avalanche deposit (block and ash flow) by Bailey et al. (1969). The Paso del Norte unit was not mapped by Smith et al. (1970) and was incorrectly mapped as Rabbit Mountain tuff by Goff et al. (1990). This mistake by Goff et al. (1990) also resulted in an incorrect contact shown between the upper and lower Bandelier units in the area around Medio Dia and Cochiti Canyons. A second pair of small debris avalanche deposits from Rabbit Mountain, previously unmapped, overlies the upper Bandelier Tuff just southeast of the dome.

The upper (Tshirege Member) Bandelier Tuff (1.25 ± 0.01 Ma; Phillips, 2004; Phillips et al., 2007) originated during creation of Valles caldera and forms extensive mesas within the Bland quadrangle. The Tshirege also fills two deep paleocanyons that were cut into the Otowi Member from about 1.6 to 1.25 Ma. The northern paleocanyon was excavated on the north side of present upper Frijoles Canyon and was as much as 300 m deep. Erosion was probably enhanced along the north-trending Upper Frijoles Canyon fault. The south wall of upper Frijoles Canyon is composed mostly of Otowi Member, but the Otowi is mostly missing from the present north wall. The southern paleocanyon occupied the area of Upper Horn Mesa and lower Medio Dia Canyon northeast of Bland and was as much as 250 m deep. Canyon cutting was facilitated by a series of north-trending faults, from west to east, the Lone Star, Bland, Horn Mesa, and Pines Canyon faults. The northeast side of this paleocanyon displays a partially hidden, but near-vertical contact between Otowi and Tshirege Members. The Tshirege Member becomes progressively thicker crossing the faults on the west side of the paleocanyon.

The youngest sequence of rocks (<1.25 Ma) occurs in and adjacent to Valle Grande in the southeastern Valles caldera. This sequence includes rhyolite lavas and a dome (Cerro La Jara), part of the Valles Rhyolite (Bailey et al, 1969; Gardner et al., 2010) that are overlain and presumably underlain by sedimentary rocks. The rhyolite lavas were erupted from Cerro del Medio north of the quadrangle (1.229 Ma; Phillips et al., 2007), South Mountain west of the quadrangle (0.52 Ma; Spell and Harrison, 1993), and Cerro La Jara (0.53 Ma; Spell and Harrison, 1993). Sediment from two lakes are exposed in Valle Grande, the older associated with a South Mountain rhyolite dam and the younger with an El Cajete pumice dam at ca. 50-60 ka (Reneau et al., 2004; El Cajete age from Toyoda et al., 1995, and Reneau et al., 1996). Stream terraces associated with the East Fork Jemez River and Jaramillo Creek unconformably overlie South Mountain lake deposits and are overlain by reworked El Cajete pumice from the younger lake. Younger, lower stream terraces occur along the modern streams. Extensive alluvial fans, both older and younger than the El Cajete pumice, occur on the margins of Valle Grande.

STRUCTURE AND TECTONICS

The Bland quadrangle straddles the southeastern boundary of the Valles caldera, separating the Cañada de Cochiti fault zone (CFZ) in the south from cross cutting, caldera-related structures in the north. The CFZ is “a broad swath of north-trending normal faults that cuts the Keres Group rocks in the southern Jemez Mountains” (Gardner, 1985). The CFZ represented the western boundary of the Española basin of the Rio Grande rift from about 11 to 4 Ma (Gardner et al., 1986). Most of the north-trending faults within the Bland quadrangle (faults in the southwestern part of the map area are named in Fig. 2) have down to the east displacement and many fault blocks are tilted noticeably to the west. A major exception is the down to the west fault along the axis of Aspen Ridge straddling the boundary between the Redondo Peak and Bland quadrangles. There is apparently more than 500 m of cumulative, down-to-the-east, vertical offset across the entire fault zone (Gardner, 1985; Gardner et al., 1986; this map).

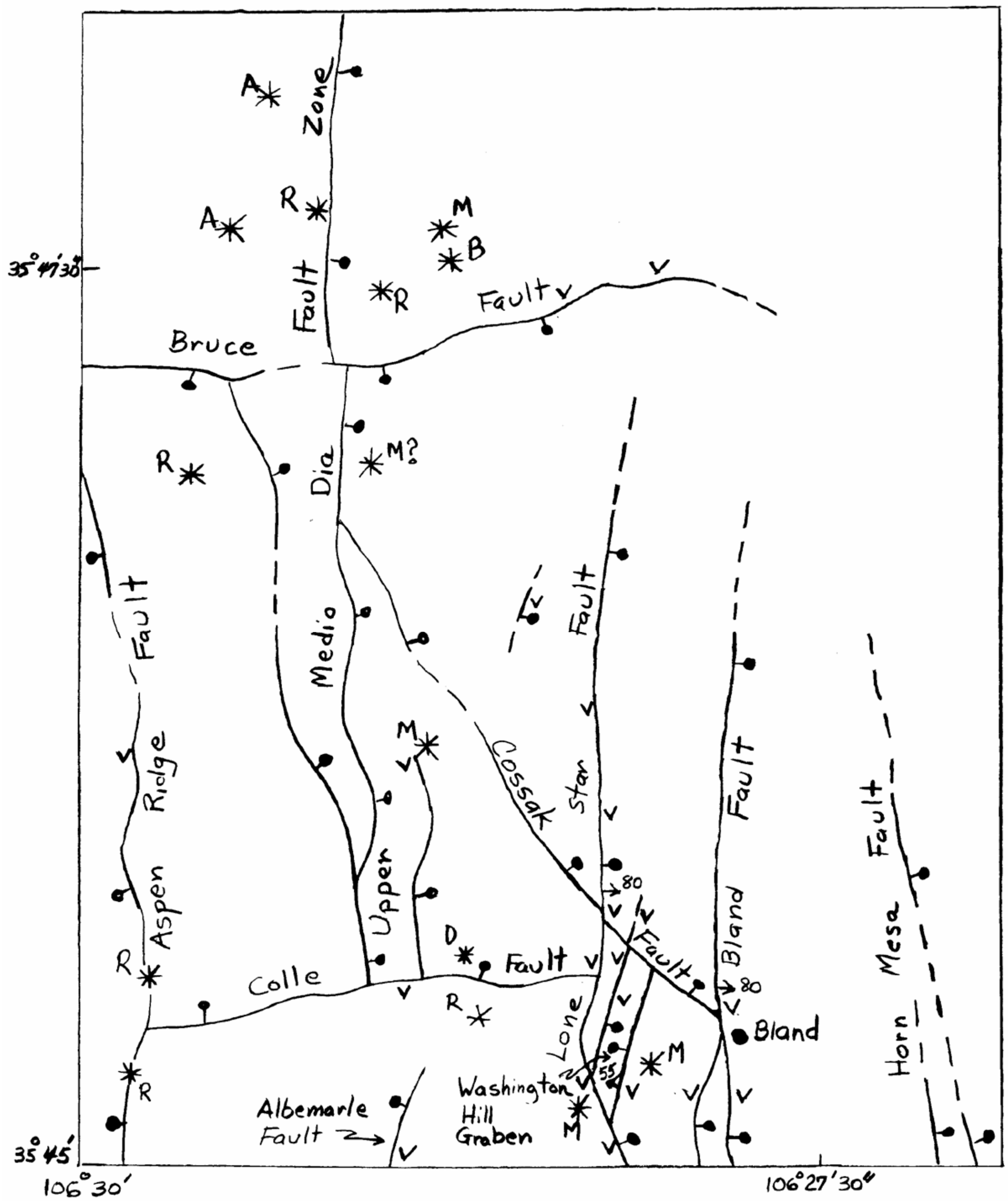

Figure 3: Map of southwestern Bland quadrangle showing named faults, locations of major quartz veins (denoted by "v"), and proximity to volcanic vents (shown by stars); B = basalt, A = andesite, D = dacite, R = rhyolite, M = monzonite; ball and bar on downthrown side of fault; arrow with number indicates dip of fault plane in degrees from vertical.

The CFZ was very active during Keres Group time because volcanic and volcaniclastic deposits generally thicken to the east across the zone (Gardner, 1985; Gardner and Goff, 1984). Although most faulting was completed prior to eruption of Bearhead Rhyolite (6 to 7 Ma), rhyolite intrusives clearly utilized the fault zone as conduits and rhyolite units are offset by more than 50 m along some of the faults. There is also a strong correlation between hydrothermal phenomena (alteration, brecciation, and veining) and many faults, particularly in the Cochiti Mining District and faults to the north. This hydrothermal activity lasted from roughly 8 to 5.6 Ma (WoldeGabriel and Goff, 1989). Additionally, there are several locations in the southwest portion of the quadrangle where displacements of ≥30 m are observable in the Bandelier Tuff. This is particularly noticeable along the north-trending Bland, Horn Mesa, and Pine Canyon faults and along the west-trending Bruce fault. Thus, although the CFZ was most active in Miocene time, significant faulting has occurred since 1.2 Ma.

Faulting caused by development of the Valles caldera and slightly earlier Toledo caldera is quite different from rift-related faulting along the CFZ. Collapse of these calderas during evacuation of roughly 800 km^3 of Bandelier magmas (Smith and Bailey, 1966; 1968; Goff, 2010) resulted in dramatic down-to-the north displacement along an arcuate fault zone of the southeast caldera wall. Faults within this zone are not exposed because they are buried beneath a thick section of post-caldera moat rhyolites and intra-caldera sediments. Maximum displacement on Precambrian basement is on the order of several kilometers based on gravity and drill hole data with displacement increasing toward the eastern sector of the caldera beneath Valle Grande (Goff et al., 1989). The position of this structural boundary of the caldera (the ring-fracture zone of Smith et al., 1961) is inferred by the arcuate locations of the South Mountain and Cerro La Jara domes, and the Cerro Del Medio vent. Presumably, a portion of the buried ring fracture zone of Toledo caldera is also buried beneath Valle Grande (see cross section A-A'). Slumping of the south caldera wall during and after caldera formation has extended the topographic rim well beyond the limit of the structural boundary (Smith and Bailey, 1968; Lipman, 2000). We could find no faults within the southeastern caldera moat, indicating that little if any displacement has occurred during the last 0.5 Ma.

STRATIGRAPHIC POSITION OF BLAND MONZONITE

Lindgren et al. (1910) published the first decent geologic study of the Cochiti Mining District and realized that mineralization was associated with intrusive bodies of monzonite and rhyolite. Bundy (1958) conducted a detailed wall-rock alteration study in the district. His stratigraphy concludes that the Bland Monzonite post-dates a "feldspathic sandstone," andesite flows, and volcanic breccias and tuffs, but is cut by andesite dikes, quartz veins and rhyolite intrusive bodies. Ross et al. (1961) stated that rocks in the district pre-dated widespread volcanism in the Jemez Volcanic Field and were probably correlative with Oligocene intrusive rocks in the Ortiz Mountains and Cerrillos Hills. Smith et al. (1970) continued this interpretation.

Stein (1983) produced a detailed 1:12,000 scale map of the district. Using field relations, whole rock chemistry and a single K/Ar date, Stein concluded that the Bland Monzonite post-dated early Keres Group volcanism. This conclusion was supported by Gardner et al. (1986) and by our recent detailed mapping in the Bland quadrangle. The confusion over age and stratigraphic position of the monzonite results from intense hydrothermal alteration, rugged topography, relative remoteness, and (until recently) restricted access to Bland. The singular occurrence of the feldspathic sandstone is also confusing.

Our mapping shows conclusively that the monzonite stock intrudes the feldspathic sandstone (Santa Fe Group) and volcanic units that can be walked out to the north into relatively unaltered Paliza Canyon basalt, andesite, and volcanic breccia. Other monzonite plugs and dikes in the area cut these Paliza Canyon rocks. Based solely on the dates of other equivalent Keres Group rocks, the monzonite is bracketed between about 9.5 to 7.5 Ma.

Although fresh samples are impossible to obtain, we dated two samples of monzonite from the Bland stock. One sample of medium-grained monzonite (F05-25) is from the high ridge south of the Washington Group of claims and just west of the Lone Star fault. It yielded an age of 7.8 ± 0.6 Ma. A second sample (F05-61) is from the west side of this body where fine-grained monzonite intrudes into andesite flow breccia and microgabbro. A broad Bearhead Rhyolite dike also intrudes the monzonite here. The indicated age of the monzonite is 7.4 ± 1.0 Ma. Certainly the later age and possibly the former age have been partially reset by intrusion of the rhyolite. Further north, a small hill of altered biotite dacite (Hill 8475) has been partially intruded by monzonite and Bearhead Rhyolite. East of this hill, a large block of this dacite is apparently engulfed by the intruding monzonite. The age of the dacite on the hill (sample F05-27) is 9.0 ± 2.0 Ma. Although the errors on these dates are large, they support the arguments on the age of the monzonite made above.

CHEMISTRY OF BLAND MONZONITE

Much has already been written about the geochemistry and petrogenesis of Keres Group rocks, in particular, the Canovas Canyon Rhyolite, the Paliza Canyon Formation, and the Bearhead Rhyolite (Stein, 1983; Gardner, 1995; Gardner et al., 1986; Justet, 1996, 2002; Wolff et al., 2005; Rowe et al., 2007). These sources provide a wealth of analyses to compare to those of the Bland Monzonite, of which there are very few. Table 1 lists 21 formerly unpublished analyses of Keres Group rocks in the Bland area and further north. Locations and field relations can be found in Appendix 1. Figure 3 is an alkali-silica diagram comparing all known analyses of the Bland Monzonite to Keres Group lavas (mostly) from the quadrangle. On this diagram the monzonite plots as trachyandesite and most rocks in the Paliza Canyon Formation are slightly alkalic. There are two analyses of quartz monzonite that are significantly more silica rich than other monzonitic samples and they plot as trachydacite-dacite. Alteration affects some of the analyses and probably all Bland monzonite and quartz monzonite samples to some degree. Silicification moves the compositions of fresh samples to the right of the diagram, while propylitic and potassic alteration moves the compositions of fresh samples up. Many, but not all of the lava and dike samples on Table 1 are distinctly altered in thin section showing chalcedony, quartz, calcite, clays, iron oxides, chlorite, epidote and pyrite replacing groundmass and phenocrysts. None-the-less, the data and the plot show that the Bland monzonite and quartz monzonite are chemically similar to the Paliza Canyon rocks that they intrude.

Table 1: Major element chemical analyses of Keres Group rocks from the western Bland quadrangle (analyses by E. Kluk, LANL; values in wt-%).

Name or description	Sample	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total	LOI
Uncorrected analyses					(Tot Fe)								
Altered andesite dike	F05-8	63.29	0.858	16.11	4.56	0.038	1.65	2.52	4.52	4.49	0.311	98.35	1.58
Altered andesite	F05-13	66.47	0.582	14.90	3.66	0.067	1.80	2.43	2.87	5.34	0.258	98.38	1.45
Diabase (microgabbro)	F05-19	49.19	1.859	16.03	9.72	0.132	6.48	9.03	3.75	1.44	0.527	98.15	2.27
Med-gnd monzonite	F05-25	60.31	1.041	16.46	5.81	0.097	2.48	4.29	4.18	3.43	0.347	98.44	1.41
Med-gnd monzonite	F05-28	55.51	1.083	15.23	6.43	0.088	4.15	4.91	3.15	4.69	0.477	95.73	4.44
Fine-gnd monzonite	F05-61	59.49	1.089	17.32	5.84	0.079	2.17	2.84	5.22	3.39	0.457	97.89	1.86
Hornblende dacite dike	F05-66	67.65	0.600	16.51	3.02	0.019	0.45	0.47	4.32	5.06	0.157	98.26	1.69
Qtz monzonite dike	F05-72	65.99	0.812	16.69	3.43	0.071	0.87	1.08	4.57	3.75	0.292	97.55	2.34
Biotite dacite	F05-78	68.55	0.498	15.38	3.06	0.026	1.10	2.20	4.31	3.37	0.141	98.63	1.71
Biotite hornblende dacite	F05-81	61.88	0.638	15.85	4.05	0.055	2.26	4.93	3.47	1.95	0.237	95.31	4.65
Hornblende andesite	F05-85	64.41	0.742	15.87	4.74	0.072	1.73	3.63	4.11	3.16	0.265	98.72	1.32
Volcanic sandstone	F05-87	61.83	0.619	15.95	4.02	0.056	2.30	4.93	3.46	1.92	0.235	95.32	4.65
Altered rhyodacite	F05-93	68.48	0.655	16.31	2.92	0.036	0.38	0.40	4.19	5.24	0.139	98.75	1.70
Olivine basalt	F05-96	47.64	1.946	17.79	11.41	0.134	4.63	8.64	3.80	1.28	0.788	98.06	2.07
Altered rhyolite	F05-100	66.06	0.673	15.98	3.17	0.071	1.35	1.43	4.34	4.48	0.160	97.71	2.54
Monzonite dike	F05-101	58.62	0.985	15.99	5.63	0.096	2.86	4.03	4.65	2.60	0.381	95.85	4.22
Olivine basalt	F05-106	46.44	1.748	17.30	11.3	0.166	7.14	9.53	3.11	0.77	0.444	97.93	1.68
Biotite dacite	F05-107	65.43	0.750	16.58	3.77	0.042	1.03	1.67	5.11	3.87	0.231	98.47	1.50
Altered basalt	F05-110	56.32	1.319	16.85	7.34	0.093	3.09	5.36	4.37	1.88	0.454	97.08	3.01
Olivine basalt	F05-113	47.11	2.020	16.93	11.27	0.113	3.89	8.57	3.60	1.00	0.707	95.20	4.16
Hornblende dacite	F05-118	65.19	0.655	15.92	4.69	0.075	1.82	4.02	4.08	2.73	0.255	99.44	0.74

HYDROTHERMAL ALTERATION AND ORE DEPOSITION

Pervasive hydrothermal alteration occurs within rocks of the Keres Group in the southwestern part of the quadrangle and is most evident near or along faults or around the margins of the Bland stock and the Bearhead pluton. Typically, the alteration is defined by green, red, white, and yellow colors overprinting the usual gray, pink, and black colors of basaltic to rhyolitic flows. Low-grade alteration consists primarily of silica (opal and chalcedony), calcite, Fe-rich smectite, kaolinite, jarosite, and Fe-oxides replacing the groundmass minerals and phenocrysts. As rank of alteration increases, zeolite, quartz, illite, chlorite, albite, hematite, pyrite, and epidote become more common and replacement of the volcanic host is more thorough. Bright green epidote is easily seen in rocks exposed along the bottoms and lower slopes of Colle, Bland, and Medio Dia Canyons. Vugs filled with epidote, chlorite, quartz and calcite are locally found within

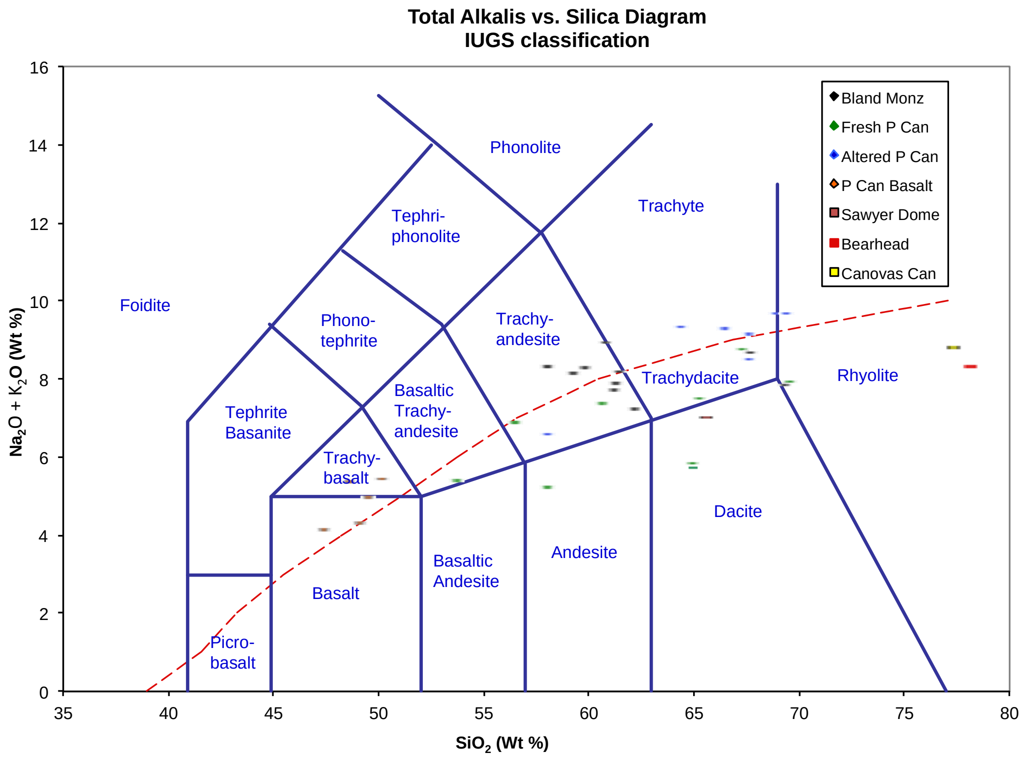

Figure 3: Alkali-silica diagram comparing compositions from the Bland Monzonite (stock and dikes) to those of Keres Group rocks within the Bland quadrangle (after La Bas et al., 1986 and IUGS). Bearhead and Canovas Canyon points are averages of four and two analyses, respectively (Rowe et al.., 2007). Red dashed line separates alkaline and calc-alkaline rocks. All analyses are normalized to 100% without LOI. Data sources are Table 1, Bundy (1958), Stein (1983), Wolfe et al. (2005) and Rowe et al. (2007).

the Bland stock. Several patches of hydrothermal breccia (mosaic breccia) were mapped along the ridge of biotite hornblende dacite south of Rabbit Mountain. These patches consist of highly altered dacitic rocks in a silicified, fine-grained matrix. Small quartz and calcite veins are found along and adjacent to most faults in the southwestern sector of the quadrangle.

Epithermal quartz veins and vein networks up to 50 m wide (marked with “v” along faults in Fig. 2) are pervasive along most faults in the Cochiti Mining District (Bundy, 1958) and are most dramatic near the Bland stock. These veins locally contain minor adularia plus pyrite, galena, sphalerite, chalcopyrite, bornite, and fine gold-silver electrum (Bundy, 1958; Wronkiewicz et al., 1984). From laboratory measurements and investigations of active geothermal systems, presence of epidote indicates paleo hydrothermal temperatures were at least 220°C in some areas of the district (Hochstein, 1982, p. 89). Wronkiewicz et al. (1984) obtained fluid inclusion temperatures of 195 to 375°C for the veins.

The timing of the gold mineralization is not entirely clear (see arguments in Bundy, 1958 and Stein, 1983) but is probably related to both the Bland stock and the Bearhead pluton. The distribution of productive claims is focused primarily around the top and margins of the Bland stock suggesting that metal-bearing hydrothermal fluids generated in the vicinity of crystallizing magmas fed fracture networks and pore spaces in surrounding Keres and Santa Fe Group rocks. However, the productive veins generally follow the north-trending faults of the CFZ (Fig. 2). These faults post-date the emplacement of the stock and are utilized by many of the later Bearhead Rhyolite intrusions. Dating of pervasive illite alteration in the Cochiti Mining District is 6.5 to 5.6 Ma (WoldeGabriel and Goff, 1989) indicating that the vein systems and the associated hydrothermal system that formed them circulated in late Bearhead time. Possibly, the metals originating from the stock were later concentrated by renewed hydrothermal activity in veins induced by the younger pluton.

Most of the gold and silver in the Cochiti Mining District was produced from 1897 to 1915 (Bundy, 1958; Hoard, 1996). Sporadic production continued until 1943. Land disputes, lack of water, rough and inaccessible terrain, poor roads, unhealthy mining and milling conditions, difficult winter weather, and the unpredictable distribution of ore within the veins hampered production. Bundy (1958) reports that \$695,000 in gold and \$345,000 in silver were produced by 1904 and that another \$83,000 in gold and \$46,000 in silver was mined in 1915. Finlay (1922 in Bundy, 1958) lists the entire output from the district at about \$1.2 million. These figures are not adjusted for inflation to 2005 values and do not include the production of later sporadic mining. Exploration in the district occurred in the early 1980s and 1990s but the price of gold has not justified the expense to reopen and resume mining. Until recently, the district contained an impressive collection of historic buildings in the Bland area, a large heap of rusting metal equipment in the Albemarle area, many scattered buildings in ruins, and a multitude of shafts, adits, pits and dumps distributed through the hills. However, the Las Conchas fire has destroyed all the old buildings of this historic area.

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APPENDIX 1

Appendix 1: Locations, map units and geologic relations for chemical samples listed in Table 1.

Name or description	Map Unit	Sample No.	Location	Notes
			(UTM NAD 27)	
Altered andesite dike	Tpa	F05-8	0367644 3957889	Dike cuts altered Santa Fe Group sandstone west of Bland Fault; epidote on fractures
Altered andesite	Tpa	F05-13	0366998 3958558	Stack of altered lavas, south of abandoned cabin, west side of Bland Canyon
Diabase (microgabbro)	Tpb	F05-19	0366523 3957037	In bottom of Colle Canyon, just north of quadrangle boundary
Med-gnd monzonite	Tm	F05-25	0367036 3957198	Fresh looking sample on ridge just west of Washington Fault
Med-gnd monzonite	Tm	F05-28	0366708 3957681	On flat east of Hill 8544
Fine-gnd monzonite	Tm	F05-61	0366703 3957169	At fault contact or chilled margin with volcanic breccia
Hornblende dacite dike	Tpd	F05-66	0365972 3957321	Dike-like body at end of ridge west of Colle Canyon
Monzonite dike	Tm	F05-72	0365562 3957984	On tiny hill cored with rhyolite, east of Aspen Peak
Biotite dacite	Tpbd	F05-78	0365157 3964979	From hill on ridge south caldera margin
Biotite hornblende dacite	Tpbhd	F05-81	0366961 3964662	Fresh outcrop south of fault, bottom west side Del Norte Canyon
Hornblende andesite	Tpha	F05-85	0364844 3964607	Small plug on ridge south caldera margin
Volcanic sandstone	Tpss	F05-87	0365038 3963654	Prominent sandstone layer between lava flows
Altered rhyodacite	Tpd	F05-93	0365227 3963341	Small patch of lava (or broad dike?) intruded by rhyolite
Olivine basalt	Tpb	F05-96	0366237 3962899	East side of Medio Dia Canyon

Altered rhyolite	Tcc	F05-100	0366344 3961958	Canovas Canyon Rhyolite on east side of Medio dia Canyon; underlies basalt
Monzonite dike	Tm	F05-101	0366778 3961958	In bottom of Medio Dia Canyon; intrudes basalt
Olivine basalt	Tpb	F05-106	0366196 3961844	Vent area south of hill of monzonite dikes
Biotite dacite	Tpbd	F05-107	0365942 3961903	Ridge west of sample 106
Altered basalt	Tpb	F05-110	0366721 3960923	In Bland Canyon south of Bruce Place; cut by monzonite dikes
Olivine basalt	Tpb	F05-113	0366587 3963118	On ridge east of Medio Dia Canyon
Hornblende dacite	Ttsd	F05-118	0370153 3967712	Summit of Sawyer Dome

DESCRIPTION OF UNITS

Note: Descriptions of map units are listed in approximate order of increasing age. Formal stratigraphic names are described in Griggs (1964) and Bailey et al. (1969) with usage revised in Gardner et al. (1986), Goff et al. (1990), Broxton and Reneau (1995), Goff and Gardner (2004), Gardner et al. (2010), and Goff et al. (2011). Field names of volcanic rocks are based on hand specimens and petrography, and may differ from names based on chemical classifications (Wolff et al., 2005; Rowe et al., 2007).

<u>Quaternary</u>

Qal **Alluvium—**Deposits of gravel, sand and silt in canyon bottoms; locally includes stream terraces and canyon wall colluvium; mostly Holocene in age; maximum thickness exceeds 15 m.

Qc **Colluvium—**Poorly sorted slope wash and mass wasting deposits from local sources; mapped only where extensive or where covering critical contacts or fault relations; mostly Holocene and Pleistocene in age; thickness can locally exceed 10 m.

Qt **Terrace gravel—**Slightly older alluvium that lies along the margins of present streams and basins; Holocene and Pleistocene in age; now undergoing erosion; maximum thickness as much as 15 m.

Qaf **Alluvial fans—**Fan-shaped deposits of coarse to fine gravel and sand at the mouths of valleys and in the Valle Grande; some fan deposits may be difficult to distinguish from older alluvial fans (described below); deposits in the Valle Grande are younger than the 50 to 60 kyr El Cajete pumice; maximum exposed thickness about 15 m.

Qls **Landslides—**Unsorted debris that has moved chaotically down steep slopes, or slumps or block slides partially to completely intact, that have moved down slope; slumps and block slides usually display some rotation relative to their failure plane; thickness varies considerably depending on the size and nature of the landslide.

Qlec, Qlb **El Cajete lake deposits—**Deposits of reworked El Cajete pumice and coarse sand in the Valle Grande; Qlec occurs below the upper level of a lake formed when deposits of the El Cajete pumice dammed the East Fork Jemez River (Reneau et al., 2004); may include some primary El Cajete fall deposits that were buried by the lake; Qlb designates constructional landforms along and near the margin of the lake, including beach ridges and spits; age about 50 to 60 ka; maximum exposed thickness about 4 m.

Qto **Older Terrace Gravel—**Older alluvial deposits of gravel, sand and silt that overlie deposits of the South Mountain lake within Valle Grande; gravels consist of volcanic fragments, particularly dacite, andesite, rhyolite, obsidian and welded ignimbrite from surrounding mountains;

underlies El Cajete pumice, younger alluvial fans and younger landslides; roughly contemporaneous with older alluvial fan deposits; maximum exposed thickness about 6 m.

Qafo **Older alluvial fans—**Fan deposits of coarse to fine gravel and sand in the Valle Grande and elsewhere that are older than the El Cajete pumice or contemporaneous lacustrine units; maximum exposed thickness is unknown.

Qlso **Older landslides—**Older slide deposits that are overlain by El Cajete pumice; maximum exposed thickness about 25 m.

Qlsm **South Mountain lake deposits—**Laminated to bedded, diatomaceous silty clay and mudstone; minor siltstone and sandstone; found in Valle Grande (Conover et al., 1963; Griggs, 1964; Reneau et al., 2004; Fawcett et al., 2004); lake formed when South Mountain rhyolite dammed drainage of the East Fork Jemez River (Reneau et al., 2004); possibly interbedded with older alluvial fan deposits (Qafo); overlies sedimentary deposits time equivalent to Qg1 (described below); age ≤552 ka (Fawcett et al., 2005); maximum drilled thickness in Valle Grande is about 95 m (Conover et al., 1963); drilled thickness in VC-3 core hole in eastern Valle Grande is 76 m.

Qg1 **Sedimentary deposits of southern caldera moat—**Various deposits of alluvium, colluvium, debris flows and minor lacustrine beds interbedded with lavas and pyroclastic rocks in the southern moat of Valles caldera (Goff et al., 2005); formed during at least three episodes of incision and blockage of the ancestral East Fork of the Jemez River and tributaries; generally poorly exposed; identified mostly by stratigraphic position; Qg1 underlies the South Mountain rhyolite (Qvsm) and Cerro La Jara rhyolite (Qvlj) and is composed primarily of gravels containing Bandelier Tuff, aphyric rhyolite, precaldera volcanics and rare Permian fragments where exposed west of map area; thickness beneath Valle Grande unknown.

Qalo **Older alluvium—**Older deposits of gravel, sand and silt that largely pre-date incision of canyons on the Pajarito Plateau; gravels consist of volcanic fragments, particularly porphyritic dacite, andesite, and welded ignimbrite from sources in Sierra de los Valles to the west; deposit along Highway 4 near SE margin of Valles caldera contains rare rhyolite, Tertiary sandstone and Precambrian fragments; underlies El Cajete pumice, younger alluvial fans and younger landslides; roughly contemporaneous with older alluvial fan deposits and landslides; overlies Tshirege Member, Bandelier Tuff and dacite of Cerro Grande; maximum exposed thickness about 6 m.

Qvs **Post-collapse lacustrine and fluvial deposits (cross section A-A' only)—**Intracaldera sediments post-dating formation of Valles caldera;

consists of white to buff, laminated to thinly bedded, diatomaceous mudstone and siltstone, and generally white to gray to tan cross bedded to normally graded sandstone and conglomerate; sandstone and conglomerate beds contain mostly fragments of rhyolite pumice, tuff and lava but also contain some grains of precaldera volcanics, Miocene to Permian sandstone, and Precambrian crystalline fragments; some beds contain ripple marks, flute casts and plane laminations and could be deltaic deposits near margins of initial caldera lakes (Goff et al., 2005); beds generally display zeolitic or less commonly acid sulfate alteration; underlies and/or interbedded with Qdf; overlies Qbt; thickness beneath Valle Grande is speculative.

Qdf **Post-collapse debris flow, landslide, and colluvium deposits (cross section A-A' only)—**Intracaldera sediments post-dating formation of Valles caldera; consists of dark gray to buff, matrix-supported beds containing fine silt to boulders of various early caldera rhyolites, Bandelier Tuff, precaldera volcanics, Miocene to Permian sandstone, Pennsylvanian limestone and Precambrian crystalline rocks; unit contains minor fluvial deposits; formed during rapid slumping and erosion of Valles caldera walls, erosion of exposed megabreccia blocks, and erosion of previously formed beds during uplift of the resurgent dome; finer-grained matrix is generally not exposed; weathering produces a lag of boulders and cobbles on landscape; presumably underlies most other units in the Valle Grande; thickness beneath Valle Grande is speculative.

Qgo **Older Gravels—**Sediments interbedded with the upper and lower Bandelier Tuff south and east of the caldera margin; consists primarily of dark gray to buff gravel, fluvial and minor debris flow deposits; clasts consist of precaldera volcanic rocks, aphyric obsidian attributed to Rabbit Mountain or Del Norte Pass domes, and welded to silicified Bandelier Tuff; exposures are often poor; without stratigraphic or spatial control, unit is difficult to distinguish from Tpy or Qdf if no Bandelier Tuff or obsidian clasts are present; maximum exposed thickness is 25 m.

Tewa Group (Quaternary)

Qvec **El Cajete pyroclastic beds (Valles Rhyolite)—**White to tan, moderately sorted, pyroclastic fall deposits of vesicular rhyolite; pumice clasts contain sparse phenocrysts of plagioclase, quartz, and biotite with rare microphenocrysts of hornblende and clinopyroxene; some clasts contain resorbed quartz with pale green, clinopyroxene reaction rims; originated from El Cajete crater (Bailey et al., 1969; Smith et al., 1970; Gardner et al., 1986; Self et al., 1988; Wolff et al., 1996; Gardner et al., 2010); maximum diameter of clasts is about 50 cm near vent but clast size diminishes away from source; contains relatively abundant lithic clasts of Bandelier Tuff and precaldera volcanic rocks but rare Paleozoic and

Precambrian rocks; overlies South Mountain rhyolite and various sedimentary deposits; unit dated at about 50 to 60 ka (Toyoda et al., 1995; Reneau et al., 1996); unit extensively reworked by erosion, collecting on south and east facing slopes; maximum exposed thickness about 20 m in valleys of the southeastern map area; thins on mesa tops and hills forming scant exposures too thin or small to map.

Qvsm1 **South Mountain rhyolite (Valles Rhyolite)—**Flow-banded, massive to slightly vesicular rhyolite lava containing phenocrysts of sanidine, plagioclase, quartz, biotite, hornblende, and clinopyroxene in a pale gray, perlitic to white, devitrified groundmass; rarely glassy; erupted from South Mountain west of map area; consists of four main flow units (oldest to youngest Qvsm1 to Qvsm4; Goff et al., 2005) but only Qvsm1 occurs in map area; fills valley in southwestern Valle Grande; underlies El Cajete pumice and various sedimentary deposits in Valle Grande; overlies Qg1 sedimentary deposits; $^{40}Ar/^{39}Ar$ age is 0.52 ± 0.01 Ma (Spell and Harrison, 1993); maximum exposed thickness about 30 m along East Fork, Jemez River.

Qvlj **Cerro La Jara rhyolite (Valles Rhyolite)**—Dome of flow-banded, massive to slightly vesicular rhyolite lava that closely resembles South Mountain rhyolite in mineralogy; probably originates from same magma batch as South Mountain; intrudes through early caldera fill debris flow deposits; flanked by El Cajete lake and beach deposits on east and by various alluvial fan deposits on other sides; $^{40}Ar/^{39}Ar$ age is 0.53 ± 0.01 Ma (Spell and Harrison, 1993); maximum exposed thickness about 75 m.

Qvdms **Cerro Del Medio rhyolite (Valles Rhyolite)—**Large dome and flow complex of aphyric obsidian to slightly porphyritic, flow-banded rhyolite; flow exposed in map area is one of the older southern flows erupted from the complex; contains sparse phenocrysts of quartz, sanidine, biotite ± hypersthene; flow is locally vesicular, spherulitic and devitrified; underlies alluvial deposits in Valle Grande; base of unit not exposed; most recent $^{40}Ar/^{39}Ar$ age on sample just north of map area is 1.229 ± 0.017 Ma (Phillips, 2004); maximum exposed thickness in map area is about 35 m.

Qrd2 **Rabbit Mountain debris flow deposits—**Two debris flow deposits overlying the upper Bandelier Tuff immediately south of Rabbit Mountain; general features resemble those of Qrd1 except the matrix is not as ash-rich and is not sintered; overlain by colluvium and El Cajete pumice; maximum exposed thickness is about 60 m.

Qbt **Upper Bandelier Tuff (Tshirege Member)—**White to orange to dark gray densely welded to non-welded rhyolitic, ash-flow tuff (ignimbrite); pumice and matrix contain abundant phenocrysts of sanidine and quartz, sparse microphenocrysts of black clinopyroxene and orthopyroxene and extremely rare microphenocrysts of fayalite (Warshaw and Smith, 1988; Warren et al., 1997); sanidine typically displays blue iridescence; consists of multiple flow units in a compound cooling unit (Smith and Bailey, 1966; Gardner et al., 1986; Broxton and Reneau, 1995; Warren et al., 1997). Upper flow units generally more welded than lower ones. Locally displays a thin (<2 m) laminated, pumice fall (Tsankawi Pumice) and surge deposit at base of unit that contains roughly 1% of hornblende dacite pumice (Bailey et al., 1969) but this deposit is very thin or absent within map area. Locally contains accidental lithic fragments of older country rock entrained during venting and pyroclastic flow. Qbt forms upper surface of western Pajarito Plateau in central and southeastern map area; originated from catastrophic eruptions that formed Valles caldera. Most recent $^{40}Ar/^{39}Ar$ age is 1.25 ± 0.01 Ma (Phillips, 2004); maximum observed thickness is over 260 m in upper Frijoles Canyon.

Qrd1 **Rabbit Mountain glowing avalanche deposits—**White to pale gray debris flows formed by multiple failures of the Rabbit Mountain dome; Qrd1 forms southeast-trending tongue of chaotic debris over 5 km long and 3 km wide that occurs between the Tshirege and Otowi Members of the Bandelier Tuff; exposures on Obsidian Ridge reveal at least three pulses in the avalanche deposit; sintered textured indicates failure of Rabbit Mountain while dome was still hot; surface of deposit is hummocky; deposit is matrix supported; matrix is extremely ashy; fragments consist of fine sand to large boulders; fragments consist primarily of devitrified massive to flow-banded rhyolite and subordinate obsidian; contains sparse fragments of welded Bandelier Tuff; also contains sparse fragments of biotite-hornblende dacite from dome and flow complex on the southwest shoulder of Rabbit Mountain; maximum exposed thickness is about 40 m.

Qcrm/Qcrmt **Rabbit Mountain rhyolite (Valle Toledo Member)—**Large dome with thick flows and flow breccias of black, aphyric to sparsely phyric obsidian to white, devitrified rhyolite; contains sparse visible phenocrysts of quartz, sanidine, and biotite; displays some spherulitic flow banding; displays zones of lithophysae and miarolitic cavities along summit ridges; dome has suffered several episodes of collapse to the north, south, and southeast; actual vent area is probably north of location shown on map having collapsed northward before or during formation of Valles caldera; small exposure of associated, bedded tuff (Qcrmt) occurs southwest of dome; K-Ar date of Qcrm is 1.43 ± 0.04 Ma (Goff et al., 1990); $Ar^{40/39}$ age is 1.428 ± 0.007 Ma (Peters and McIntosh, 2001, unpublished); maximum exposed thickness is about 410 m.

Qnd **Del Norte Pass debris avalanche deposit—**White to pale gray debris flows apparently formed by failure of Del Norte Pass rhyolite dome; forms irregular tongue of chaotic debris extending 4 km south-southeast from this dome, primarily south of a prominent ridge of biotite-hornblende dacite; consists of at least two pulses; surface of deposit is hummocky; deposit is matrix supported and matrix is extremely ashy; resembles avalanche deposits of Rabbit Mountain except that obsidian is much less abundant and large blocks of andesite and dacite are much more common; overlies Keres Group rocks near source; occurs between the Tshirege and Otowi Members of the Bandelier Tuff further from source; unit is locally so thick that overlying units of Qbt are absent; overlain by El Cajete pumice; maximum exposed thickness is about 60 m.

Qcnp/Qcnpt **Paso del Norte rhyolite (Valle Toledo Rhyolite)—**Small dome and flow of white to pale grey devitrified rhyolite with sparse phenocrysts of quartz, sanidine and biotite; displays some spherulitic flow banding; dome has suffered one major episode of collapse to the south during formation of Valles caldera, which apparently denuded the pumiceous and glassy carapace; layer of indurated, slightly altered, lithic-rich tuff (Qcnpt) underlies dome on east and southeast; originally mapped as Bearhead Rhyolite (Smith et al., 1970) but identified as part of the Cerro Toledo rhyolite by Justet (2003); Ar $^{40/39}$ age of sample from flow south of vent is 1.47 ± 0.04 Ma (Justet, 2003); maximum exposed thickness is about 110 m.

Qbo **Lower Bandelier Tuff (Otowi Member)—**White to pale pink to orange, generally poorly welded, vitric rhyolitic ash-flow tuff; pumice and matrix contains abundant phenocrysts of sanidine and quartz, and sparse mafic microphenocrysts; sanidine may display a blue iridescence; contains abundant accidental lithic fragments (Eichelberger and Koch, 1979); consists of multiple flow units in a compound cooling unit; contains a stratified pumice fall (Guaje Pumice; Griggs, 1964) and surge deposit at its base that is very thin or absent in most of the Bland quadrangle; may form tent rocks; Qbo discontinuously fills in rugged topography on a volcanic surface of pre-Toledo caldera age; has been extensively to completely removed by erosion in upper Frijoles Canyon, Pines Canyon and lower Medio Dia Canyon; very difficult to distinguish from non-welded, vitric portions of the upper Bandelier Tuff in hand samples and thin sections; best distinguished by poorer degree of welding, greater tendency to form slopes instead of cliffs, more abundant lithic fragments, less abundant iridescent sanidine, and stratigraphic position beneath the Tsankawi Pumice or beneath intervening deposits of older gravel (Qog); originated from catastrophic eruptions that formed Toledo caldera; ^{40}Ar/^{39}Ar ages 1.61 ± 0.01 to 1.62 ± 0.04 Ma (Izett and Obradovich, 1994; Spell et al., 1996); samples of uppermost Otowi just below contacts with Rabbit Mountain and Del Norte Pass debris flow deposits are 1.58 to 1.70 Ma; maximum exposed thickness about 60 m.

Tertiary (Pliocene – Oligocene?) Deposits
Keres Group (Pliocene-Miocene)
Tschicoma Formation (Pliocene)

Ttpm **Pajarito Mountain dacite—**Dome and flow complex of blue-gray to pale pink, massive to sheeted, porphyritic dacite containing phenocrysts of plagioclase, hypersthene, clinopyroxene, and opaque oxides in a devitrified groundmass; contains clots of complexly zoned plagioclase and occasional clots of two pyroxenes; thick flows contain intervals of flow breccia; unit forms a volcanic center probably consisting of several eruptive events; source is Pajarito Mountain northeast of map area; small intrusive body of similar dacite southwest of Cerro Grande may be satellite vent to the main eruption; overlies and intrudes hornblende dacite of Cerro Grande (Ttcg); locally underlies Tshirege Member of the Bandelier Tuff (Qbt); $^{40}Ar/^{39}Ar$ ages on widely separated samples range from 3.1 to 2.9 Ma (WoldeGabriel, 2001, unpub.); maximum exposed thickness is about 365 m.

Ttcg **Cerro Grande dacite—**Extensive dome and flow complex of light to dark gray to pale pink, massive to sheeted porphyritic dacite containing phenocrysts of plagioclase, hypersthene, and (usually) conspicuous hornblende; the latter two phases commonly show oxidized rims and may be difficult to see in hand sample; contains microphenocrysts of plagioclase, hypersthene and clinopyroxene, and clots of hornblende, hypersthene, plagioclase, and opaque minerals; thick flows contain intervals of flow breccia; source is Cerro Grande in northeast map area; unit forms a volcanic center apparently consisting of several eruptive events; underlies Ttpm and Tshirege Member of the Bandelier Tuff (Qbt); dates on widely separated samples range from 3.8 to 3.1 Ma (Dalrymple et al., 1967; WoldeGabriel, 2001, unpub. data); maximum exposed thickness is about 750 m.

Ttsd **Sawyer Dome dacite—**Dome and flow complex of gray to pale pink, generally massive, porphyritic dacite containing phenocrysts of plagioclase, hypersthene, opaque oxides and conspicuous hornblende up to 4 mm long; contains occasional mafic clots of plagioclase-hornblende up to 10 cm in diameter; underlies dacite of Cerro Grande; underlies Rabbit Mountain Rhyolite and Bandelier Tuff; $^{40}Ar/^{39}Ar$ age is 3.61 ± 0.21 Ma (WoldeGabriel, 2001, unpub. data); maximum exposed thickness is 245 m.

Ttu **Dacite and andesite, undivided (cross section A-A' only)—**Gray to pale pink porphyritic dacite and andesite with phenocrysts of plagioclase, orthopyroxene, clinopyroxene ± hornblende; underlies lower Bandelier Tuff (Qbo) and dacite of Sawyer Dome (Ttsd); overlies Paliza Canyon andesite (Tka); ages of major domes north of map area roughly 2 to 5 Ma

(Goff et al., 2002; Kempter and Kelley, 2002); thickness in cross section is speculative.

Bearhead Rhyolite (Pliocene-Miocene)

Thb/Tqv **Hydrothermal breccia and quartz veins—**Relatively small areas of hydrothermal rocks along northwest-trending ridge of dacite south of Rabbit Mountain and along or near fault zones in the Bland area; probably associated with volcanism of the Bearhead Rhyolite but may be related to Keres Group volcanism (Bundy, 1958; Stein, 1983; Goff et al., 2005); Thb consists of relatively circular, vertical pipes of mosaic breccia ≤100 m in diameter containing fragments of altered dacite in a fine-grained, silicified matrix; Tqv consists of quartz veins and vein networks up to 50 m wide cutting altered Bearhead Rhyolite and Keres Group volcanic rocks; veins exposed primarily along fault zones in southwest map area (Fig. 2); both units have been modified by post-emplacement faulting; veins contain minor adularia, Cu-Pb-Zn sulfides and gold-silver electrum; sulfides extensively altered to oxides, alunite and clay; units are probably between 5.6 and 8.5 Ma (WoldeGabriel and Goff, 1989); vertical thickness of breccia pipes is unknown; vertical extent of veins exceeds 250 m (Bundy, 1958).

Tbh/Tbp **Rhyolite intrusive rocks (Bearhead Rhyolite)—**White to gray dikes, plugs, sills, domes, and flows of slightly porphyritic to aphyric devitrified rhyolite containing sparse phenocrysts of quartz, potassium feldspar, and fresh to altered biotite ± plagioclase; margins of flows may be slightly pumiceous; contains minor flow breccia; margins of intrusions may display chilled contacts with black to gray to pink obsidian, perlite, and banded spherulitic rock; interiors of units are generally flow-banded; width of individual dikes shown on map are commonly exaggerated and may consist of many smaller sub-parallel dikes; associated lithic-rich tuffs (Tbp) occur only in southwest part of map in Aspen Peak area; pervasive, hydrothermally altered plugs and dikes occur throughout west and southwest map area probably emanating from shallow underlying pluton; intrudes or overlies other Paliza Canyon Formation rocks; dates on various Bearhead units range from about 6.0 to 7.2 Ma (Gardner et al., 1986; Goff et al., 1990; Justet, 1996); $^{40}Ar/^{39}Ar$ date on intrusion north of Aspen Peak is 6.76 ± 0.10 Ma; date on Cougar Hill plug is 6.80 ± 0.05; date on Rabbit Hill dome is 6.65 ± 0.03 (Justet, 1996); maximum observed thickness about 170 m.

Paliza Canyon Formation (Miocene)

Tpv **Volcaniclastic deposits—**Black to gray to pale pink to purple-red, highly diverse volcaniclastic unit consisting predominately of sandstones, gravels, lahars, block-and-ash flows, and other debris flows; mostly formed contemporaneously with Paliza Canyon Formation; locally contains hyper concentrated flow and fluvial deposits, cinder and scoria deposits, and pyroclastic fall deposits; contains andesite and dacite flow and flow-breccias too small or thin to map; older deposits display considerable hydrothermal alteration up to presence of epidote; unit has accumulated in small basins, topographic lows, and canyons cut into Paliza Canyon Formation volcanoes; unit generally thickens to south and east toward evolving Rio Grande rift; most of unit mapped according to the definition of Cochiti Formation described by Bailey et al., (1969) and Gardner et al. (1986) with stratigraphic interpretation extended into the Pliocene (Smith and Lavine, 1996); as defined here, includes both Volcanic Breccia 1 (volcanic sandstone and conglomerate) and Volcanic Breccia 2 (predominately scoria-derived deposits) of Stein (1983) in areas around and north of Bland; largest exposure of Tpy occurs in Cochiti Canyon where predominately lahars and block-and-ash flows are interbedded with small andesite and dacite flows, and with dacite tuffs; scoria-rich deposits occur in Bland Canyon, north of Bruce Place, and in areas of upper Medio Dia Canyon; bedded deposits with consistent 15 to 20° dip to east occur in Colle Canyon; exposure of dacite-rich boulder conglomerate occurs beneath upper Bandelier Tuff at southeast tip of Upper Horn Mesa; interbedded and intruded by all types of Keres Group lavas and dikes; intruded by monzonite in Colle Canyon and upper Bland Canyon; underlies Santa Fe Group sandstone in unnamed canyon north of Bland stock; age of Tpv in map area is bracketed between roughly 8 and 13 Ma; maximum exposed thickness is about 215 m.

Tpvs **Volcanic sandstone—**Brick red to tan moderately- to well-sorted sandstone containing mostly volcanic fragments, feldspar, mafic minerals, and minor quartz; mapped only where laterally extensive and at least 3 m thick; occurs between lava flow contacts in isolated locations throughout Paliza Canyon Formation.

Tphd **Porphyritic hornblende dacite—**Two eroded dome and flow complexes of gray to pale pink porphyritic dacite in southeast map area; contains phenocrysts of complexly zoned plagioclase and smaller phenocrysts of plagioclase, hornblende, clinopyroxene, opaque minerals ± biotite ± hypersthene ± apatite ± potassium feldspar; may contain clots of plagioclase and mafic minerals; may contain plagioclase-pyroxene-hornblende clots up to 20 cm in diameter; groundmass is glassy to devitrified and commonly trachytic; flows massive to sheeted; $^{40}Ar/^{39}Ar$ age of dome at head of Sanchez Canyon is 7.86 ± 0.14 Ma (Justet, 2003); maximum exposed thickness is 75 m.

Tpbd **Porphyritic biotite dacite—**Eroded domes, flows, dikes and plugs of gray to pale pink dacite having phenocrysts of plagioclase, biotite, clinopyroxene, orthopyroxene ± hornblende in a trachytic groundmass of plagioclase, pyroxene, and opaque oxides; contains complexly zoned and fritted plagioclase phenocrysts up to 15 mm in diameter; contains minor clots of plagioclase and pyroxene; many flows are extensively altered to silica, chlorite, clay, Fe-oxides ± calcite; interbedded with and intrudes andesite in most locations; interbedded with Tpy in southeast map area; dike intrudes monzonite west of Bland; intruded by Bearhead Rhyolite; ages of various units in map area unknown; $^{40}Ar/^{39}Ar$ age of flow on ridge top in west-central part of quad is 7.56 ± 0.08 Ma; K-Ar age of dome in upper Bland Canyon just south of map is 9.11 ± 0.19 Ma (Goff et al., 1990); maximum exposed thickness is 140 m.

Tpha **Hornblende andesite—**Gray to black flows, dome, and plug of glassy to devitrified andesite having small phenocrysts of plagioclase, clinopyroxene, oxidized to fresh hornblende ± hypersthene ± rare biotite in a trachytic to nearly intersertal groundmass of plagioclase, clinopyroxene, opaque minerals ± hypersthene ± hornblende; plagioclase may be complexly zoned; may contain plagioclase-pyroxene or plagioclase-hornblende clots; may display flow banding or contain flow breccia; ages of various exposures unknown; maximum exposed thickness about 45 m.

Tppa **Porphyritic andesite—**Gray to black domes and flows of coarsely porphyritic andesite having large phenocrysts of plagioclase and abundant phenocrysts of clinopyroxene and hypersthene in a glassy almost intersertal groundmass of plagioclase, clinopyroxene, hypersthene, and opaque minerals; plagioclase may be complexly zoned; may contain plagioclase-pyroxene clots up to 10 cm in diameter; flows generally sheeted with minor flow breccia; separated from other andesites only in southeast part of map where relations are not obscured by faulting and hydrothermal alteration; flows in map area not dated; K-Ar date of flow at summit of St. Peter's Dome just east of map area is 8.69 ± 0.38 Ma (Goff et al., 1990); maximum observed thickness is about 150 m.

Tpca **Clot-rich andesite—**Extensive dome and flow complex beneath the summit of St. Peter's Dome occurring in extreme southeast corner of map; consists of gray to black porphyritic andesite with abundant distinctive plagioclase-pyroxene clots 2 mm in diameter and phenocrysts of plagioclase, clinopyroxene, and hypersthene in a glassy almost intersertal groundmass; microphenocrysts consist of plagioclase, clinopyroxene, hypersthene, and opaque minerals; flows massive, rarely brecciated or sheeted; unit not dated; maximum observed thickness is about 50 m.

Tpd **Dacite—**Tan to gray to black, flow banded to massive, slightly porphyritic to aphyric dacite lavas, dikes and plug; groundmass is commonly trachytic with phenocrysts of plagioclase and sparse microphenocrysts of plagioclase, clinopyroxene, hypersthene, opaque oxides ± biotite ± hornblende; pervasively altered to chlorite, silica, and clay; intrudes monzonite and andesite in Colle Canyon; ages of various units unknown; maximum exposed thickness about 30 m.

Tpbhd **Porphyritic biotite, hornblende dacite—**Dome and flow complexes and highly faulted flows containing 10 to 15% phenocrysts of plagioclase, biotite (≤3 mm), oxyhornblende (≤5 mm), orthopyroxene, and clinopyroxene, in a trachytic groundmass filled with plagioclase and pyroxene microlites; groundmass also contains apatite microphenocrysts up to 0.5 mm long; plagioclase phenocrysts (≤20 mm) are fritted and complexly zoned; contains gray, vesiculated enclaves of plagioclase, pyroxene ± hornblende ± biotite up to 30 cm in diameter; partially obscured vent occurs beneath southwest flank of Rabbit Mountain; vent for flows east of Bearhead Ridge may occur north of Reid Canyon; fresh outcrops unusual; hydrothermal alteration consists of clay, silica, calcite, Fe-oxides, chlorite ± epidote; interbedded with andesite flows; intruded by Bearhead Rhyolite; $^{40}Ar/^{39}Ar$ age of dome and flow complex south of Rabbit Mountains is 8.66 ± 0.22 Ma; $^{40}Ar/^{39}Ar$ age of similar unit west of map area is 9.42 ± 0.22 Ma (Justet, 2003; Goff et al., 2005); age of pervasive hydrothermal alteration of this unit in upper Del Norte Canyon area is about 6.5 to 6.0 Ma (WoldeGabriel and Goff, 1989); maximum exposed thickness is at least 275 m.

Tpoa **Olivine andesite—**Black to gray dome and flow complex with minor red cinder deposits occurring in southeast map area; consists of slightly porphyritic andesite with phenocrysts of plagioclase, clinopyroxene, and olivine ± hypersthene in a glassy to almost intersertal groundmass; olivine may show both high- and low-temperature iddingsite; may contain sparse plagioclase-pyroxene clots; may contain apatite microphenocrysts; flows massive to sheeted, commonly with vesicular flow tops; apparently intruded by Tppa on east and overlain by Tpha on west; age of unit unknown; maximum observed thickness about 70 m.

Tpdt **Dacite tuff—**White pyroclastic fall deposits containing pumice, ash, crystals, and lithic fragments commonly found in volcaniclastic deposits of Tpv; mapped only where >3 m thick and over a hundred meters in length; phenocrysts in pumice clasts generally contain plagioclase, clinopyroxene, and hypersthene, ± hornblende, ± biotite; beds often slightly silicified; beds are not laterally extensive and pinch out due to erosion; may show reverse or graded bedding; $^{40}Ar/^{39}Ar$ dates of four tuff beds in canyons east of map area range from 9.1 to 9.5 Ma (Lavine et al., 1996); maximum thickness about 10 m but most beds ≤1 m thick and generally too thin or discontinuous to map.

Tpa **Two-pyroxene andesite, undivided—**Domes, flows, flow breccia, spatter deposits, and scoria of andesite from multiple sources; vents are widely scattered; individual units are slightly porphyritic to very porphyritic; flows dense to highly vesicular; tends to be relatively fresh and sometimes glassy in the east to hydrothermally altered in west and southwest; typically contains 20% phenocrysts of plagioclase, orthopyroxene, and clinopyroxene in an intersertal or slightly trachytic groundmass; groundmass usually contains abundant opaque oxides; plagioclase phenocrysts are commonly fritted and complexly zoned; most specimens contain plagioclase-pyroxene clots ≥ 1 mm in diameter; some units contain enclaves of plagioclase-pyroxene a few centimeters in diameter; some flows contain minor hornblende; visible alteration varies from slight to extremely intense; alteration generally consists of silica, calcite, Fe-oxides, clay ± chlorite ± zeolite ± pyrite ± epidote; interbedded with and intrudes most other Paliza Canyon units; overlies basalt in upper Bland Canyon and lower Colle Canyon; intruded by monzonite in lower Colle Canyon and at Bland; units in map area not dated; fresh andesite flows in upper part of unit west of map area range from 8.8 to 9.4 Ma (Goff et al., 2005); maximum exposed thickness about 150 m in upper Medio Dia Canyon.

Tpb **Olivine basalt and basaltic andesite, undivided—**Flows, flow breccia, spatter deposits, and scoria of basalt and subordinate basaltic andesite from multiple sources; one vent (shown within unit Tpy) occurs at east end of prominent ridge north of Bruce Place; most units are slightly porphyritic; flows dense to highly vesicular; typical basalt contains 5 % phenocrysts of olivine and plagioclase (≤2 mm) in intersertal groundmass of olivine, clinopyroxene, plagioclase, opaque oxides, and glass; olivine occurs rarely in clots ≤3 mm in diameter; most olivine has high-temperature iddingsite; some flows have diktytaxitic texture; some flows have clinopyroxene phenocrysts; most flows display variable amounts of hydrothermal alteration consisting of silica, calcite, Fe-oxides, clay ± zeolite ± chlorite ± epidote ± pyrite; interbedded with and underlies Tpa; intruded by monzonite in lower Colle Canyon, upper Bland Canyon and central Medio Dia Canyon; units in map area never dated; maximum exposed thickness about 150 m.

Bland Intrusive Rocks (Miocene)

Tm **Monzonite intrusive bodies—**Dikes, sills, pods, plugs and stocks of crystalline rocks collectively called monzonite (after Bundy, 1958); textures range from coarse-grained, hypidiomorphic granular and seriate to fine-grained, trachytic and porphyritic. Stein (1983) describes the full range of textures, mineralogy and chemical compositions in these intrusives, which range from monzonite to quartz monzonite; apparently a compound stock in the Bland area; primary minerals consist of plagioclase, clinopyroxene, orthopyroxene, potassium feldspar and quartz ± biotite ± hornblende. Alteration is moderate to intense, argillic to propylitic; replacement minerals consist mainly of clays, Fe, Mn-oxides, silica, calcite, illite, chlorite, epidote and pyrite; rank of alteration generally increases toward bottoms of canyons; locally contains cavities of quartz-chlorite-epidote-calcite; larger stock west of Washington Hill contains plexus of unmapped dikes with pronounced north-northwest trend; other stocks and plugs display central core of monzonite from which radiate monzonite dikes; width of single dikes shown on map are usually exaggerated and may consist of up to 20 thin, semi-parallel dikes; vent areas shown on map represent crystallized roots of andesitic to dacitic volcanoes of the Paliza Canyon Formation; monzonite intrudes basalt, andesite, volcaniclastic sediments (Tpv) and Santa Fe Group; overlain and intruded by andesite, dacite and Bearhead Rhyolite; K-Ar date on relatively unaltered sample from unspecified location is 11.3 ± 0.3 Ma (Stein, 1983); altered monzonite from main stock has $^{40}Ar/^{39}Ar$ ages of 7.8 to 7.4 Ma; maximum exposed thickness east of Colle Canyon is about 275 m.

Canovas Canyon Rhyolite (Miocene)

Tcc **Rhyolite—**Poorly exposed flow of pale greenish-gray, hydrothermally altered rhyolite in bottom of Medio Dia Canyon at Evans-Griffin Place; unit is silicified, containing quartz, feldspar, biotite and possibly hornblende altered to silica, clay, Fe-oxide, illite and chlorite; some specimens contain calcite; underlies basalt; bottom of unit not exposed; maximum exposed thickness about 10 m.

Tcct **Rhyolite tuff (cross section B-B' only)—**White to pink pyroclastic fall and pyroclastic flow deposits of the Canovas Canyon Rhyolite (Bailey et al., 1969; Gardner et al., 1986); lowermost unit exposed on east flank of St. Peter's Dome consists of pink, lithic-rich tuff containing abundant fragments of flow-banded rhyolite (informally named the "pink tuff"); underlies andesite, dacite and volcaniclastic rocks, and overlies the Santa Fe Group on the east side of St. Peter's Dome; age of similar pink tuff in Bear Springs quadrangle is about 9.4 Ma (S. Kelley, unpub. data); maximum observed thickness is about 20 m.

Santa Fe Group (Miocene)

Ts **Sandstone—**White to tan to very pale green feldspathic sandstone; generally medium-grained, well-sorted and well-indurated; grains are mostly subangular to subrounded and consist of roughly 65 to 90% quartz, 5 to 20% feldspar and a variety of other minerals and volcanic rock fragments; much of the quartz is polycrystalline; dark mineral laminations, which may represent bedding are found in scattered locations and have a consistent dip of 15 ± 5° east; feldspar grains are altered to illite and kaolinite (Bundy, 1958); cement consists of variable amounts of chalcedony, calcite, illite, chlorite, limonite, and hematite; near monzonite bodies the quartz grains are partially recrystallized; overlies altered volcaniclastic sediments (Tpv) north of Washington Hill; overlies basaltic andesite lava and altered volcanic breccia just south of map area; underlies andesite on northeast wall of lower Bland Canyon; intruded by monzonite stock and dikes in Bland area; underlies and is interbedded with basalt and andesite west of map area (Goff et al., 2005); underlies andesite, dacite, and rhyolite tuff, and overlies Gallisteo Formation in St. Peter's Dome area east of map (Goff et al., 2002); maximum observed thickness roughly 200 m. Age range of unit is roughly 9 to 18 Ma.

Eocene

Tgs **Galisteo Formation (cross sections only)—**Orange to tan to brick red beds of well-indurated sandstone, siltstone, arkose, and conglomerate; conglomerate beds may preferentially contain limestone, chert, and granitoid fragments from pebble to boulder size from eroded Paleozoic and Precambrian sources; unit exposed on rotated fault blocks with beds dipping steeply to the west along east flank of St. Peter's Dome (Goff et al., 2002); unconformably underlies the Santa Fe Group; bottom of unit is not exposed; maximum observed thickness is about 200 m; thickness in cross sections is speculative.

Permian

Pu **Permian rocks, undivided (cross section A-A' only)—**White to reddish white, well-sorted, generally plane to cross-bedded quartz arenite with some mica (Glorieta Sandstone); orange red, well-sorted, medium-grained quartzofeldspathic sandstone and minor siltstone (Yeso Formation); brick red to brownish red quartzofeldspathic sandstone, siltstone and mudstone; contains some obvious mica; contains minor conglomerate and limestone (Abo Formation); Yeso and Abo are usually indurated beneath the caldera as documented in geothermal wells west of map area (Goff et al., 2005) where they display considerable greenish hydrothermal alteration and minor calcite and quartz veining; contact of Pu with underlying Madera Formation is sharp to gradational depending on location; thickness is 501 m in Baca-12 west of map area (Nielson and Hulen, 1984).

Mississippian-Pennsylvanian

MIPu **Mississippian-Pennsylvanian rocks, undivided (cross section A-A' only)—**Light to dark gray, fossiliferous limestone and micrite with subordinate gray to buff arkose, sandstone, shale and mudstone (Madera Formation); may contain hydrothermally altered shale, sandstone, conglomerate, and limestone of the Sandia Formation; displays considerable hydrothermal alteration, veining, faulting, fracturing and brecciation in geothermal wells (Goff and Gardner, 1994 and references therein); thickness is ≤390 m in geothermal wells west of map area (Goff et al., 2005).

Precambrian

pCu **Precambrian rocks, undivided (cross section A-A' only)—**Highly variable unit of crystalline rocks throughout Jemez Mountains region (Goff et al., 1989, Table 2); displays minor to severe hydrothermal alteration (Goff et al., 2005); age is 1.62 to 1.44 Ga (Brookins and Laughlin, 1983).