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GEOLOGY OF THE NORTHERN JEMEZ MOUNTAINS, NORTH-CENTRAL NEW MEXICO

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Abstract — Recent geologic mapping of eight 7.5-minute quadrangles in the northern Jemez Mountains has yielded numerous insights into the late Oligocene to Pleistocene sedimentary and volcanic history of the region. Important observations include: (1) identification of variations in the lateral and vertical distribution of the Pedernal Chert Member of the Abiquiu Formation across the region; (2) documentation of westward migration of volcanism between 9 and 8 Ma, followed by eastward migration between 7 and 5 Ma across the northern Jemez volcanic field; (3) mapping of several sedimentary deposits that preceded, interceded, and postdated the Toledo and Valles caldera eruptions; and (4) recognition of significant variations in thickness and degree of welding for the Otowi Member of the Bandelier Tuff. Several new Ar^{40}/Ar^{39} ages for northern Jemez volcanic units are presented, together with a compilation of previous dates collected over the past four decades. These ages suggest that Lobato volcanic activity in the northeastern Jemez occurred primarily between 10.5 to 9 Ma, and was particularly intense between 10 to 9.5 Ma. The next major phase of volcanic activity occurred between ~8.5 to 7 Ma along the La Grulla Plateau, where andesitic and dacitic lavas cap a more mafic sequence of basaltic andesites to andesites. A relatively small volume of rhyolite was emplaced just northeast of the Valles caldera rim at ~7.1 Ma that we correlate to the Bearhead Rhyolite of the southern Jemez Mountains. This was followed by major Tschicoma Formation volcanism in the northeastern Jemez Mountains that was mostly emplaced between ~5.3 to 3 Ma. Along the western margin of Mesa El Alto, the El Alto basalt eruption occurred at ~2.9 Ma, followed by three El Rechuelos Rhyolite domes emplaced west of Polvadera Peak at ~2.1 Ma. Lastly, the Toledo and Valles caldera eruptions at ~1.61 Ma and ~1.25 Ma, respectively, deposited the Bandelier Tuff along two lowland corridors in the northern and northwestern Jemez Mountains.

INTRODUCTION

The northern Jemez Mountains include several geologic and geographic provinces, including the Colorado Plateau, the Rio Grande rift, and the Jemez volcanic field. Rock units related to each of these provinces overlap tectonic boundaries, creating zones of transition that are somewhat blurred and hard to define. For example, the boundary of the Colorado Plateau and Rio Grande rift is not defined by a single fault, and tectonic activity along this boundary migrated over space and time (Koning et al., 2007). The bulk of the northern Jemez Mountains is composed of Miocene to Early Quaternary volcanic rocks that fill in much of the western Rio Grande rift but also spill westward onto the Colorado Plateau to the northwest. The huge mass of volcanic rocks that constitute the Jemez volcanic field is often attributed to the intersection of the Rio Grande rift and the SW-NE-trending Jemez lineament (Goff and Grigsby, 1982).

Eight 7.5-minute quadrangles in the northern Jemez Mountains have been mapped at a scale of 1:24,000 since 2003, improving our understanding of the geologic and volcanic history of the region. These interpretations are enhanced by several new Ar^{40}/Ar^{39} dates to complement the recent mapping efforts. Stratigraphic nomenclature used here follows that presented by Gardner et al. (1986), with the exception of "Lobato basalts". We prefer Lobato Formation, as suggested by Baldridge and Vaniman in Goff et al. (1989). A variety of lavas, including andesites and dacites, were emplaced during the widespread pulse of "basaltic" volcanism referred to as "Lobato". We anticipate changes in stratigraphic nomenclature in the near future (see Kelley et al. 2007) to accommodate the diverse chemical and geographical range of lavas erupted in the northern Jemez Mountains prior to 7 Ma.

The highlands of the northern Jemez Mountains are built primarily of diverse lavas ranging in composition from basalt to rhyolite and emplaced mostly between the Late Miocene through the Pliocene. These highlands include the La Grulla Plateau, Tschicoma and Polvadera peaks, and Lobato Mesa (Fig. 1). In two low topographic corridors on either side of the La Grulla Plateau, the volcanic lava foundation is overlain by the Early Quaternary Bandelier Tuff, including both the lower (Otowi) and upper (Tshirege) Members, erupted at ~1.61 and ~1.25 Ma, respectively (Phillips et al., in press). To the northwest, pyroclastic flows of the Bandelier Tuff skirted the western margin of the La Grulla Plateau, forming Mesa Pinabetosa and extending to the modern village of Coyote. A second corridor existed between the La Grulla Plateau and the Tschicoma highlands, allowing both pyroclastic flow members to fill paleocanyons between the modern Cañones Creek and Polvadera Creek.

GEOLOGIC TRAVERSE ACROSS THE NORTHERN JEMEZ MOUNTAINS

The following overview provides a west to east geologic traverse across the northern Jemez Mountains (Figs. 1, 2), and six separate discussions of the distinct geologic, topographic and volcanic landforms. These include 1) the Colorado Plateau and the northwestern Bandelier Tuff corridor; 2) the La Grulla Plateau; 3) the northern Bandelier Tuff corridor; 4) the Tschicoma highlands; 5) Mesa El Alto; and 6) Lobato Mesa . The four main quadrangles of interest are Jarosa, Cerro del Grant, Polvadera Peak, and Vallecitos (Fig. 1). Our geologic investigations complement adjoining geologic studies and interpretations of the northern Valles caldera and Toledo embayment by Gardner and Goff (1996), Goff et al. (2006), and Gardner et al. (2006).

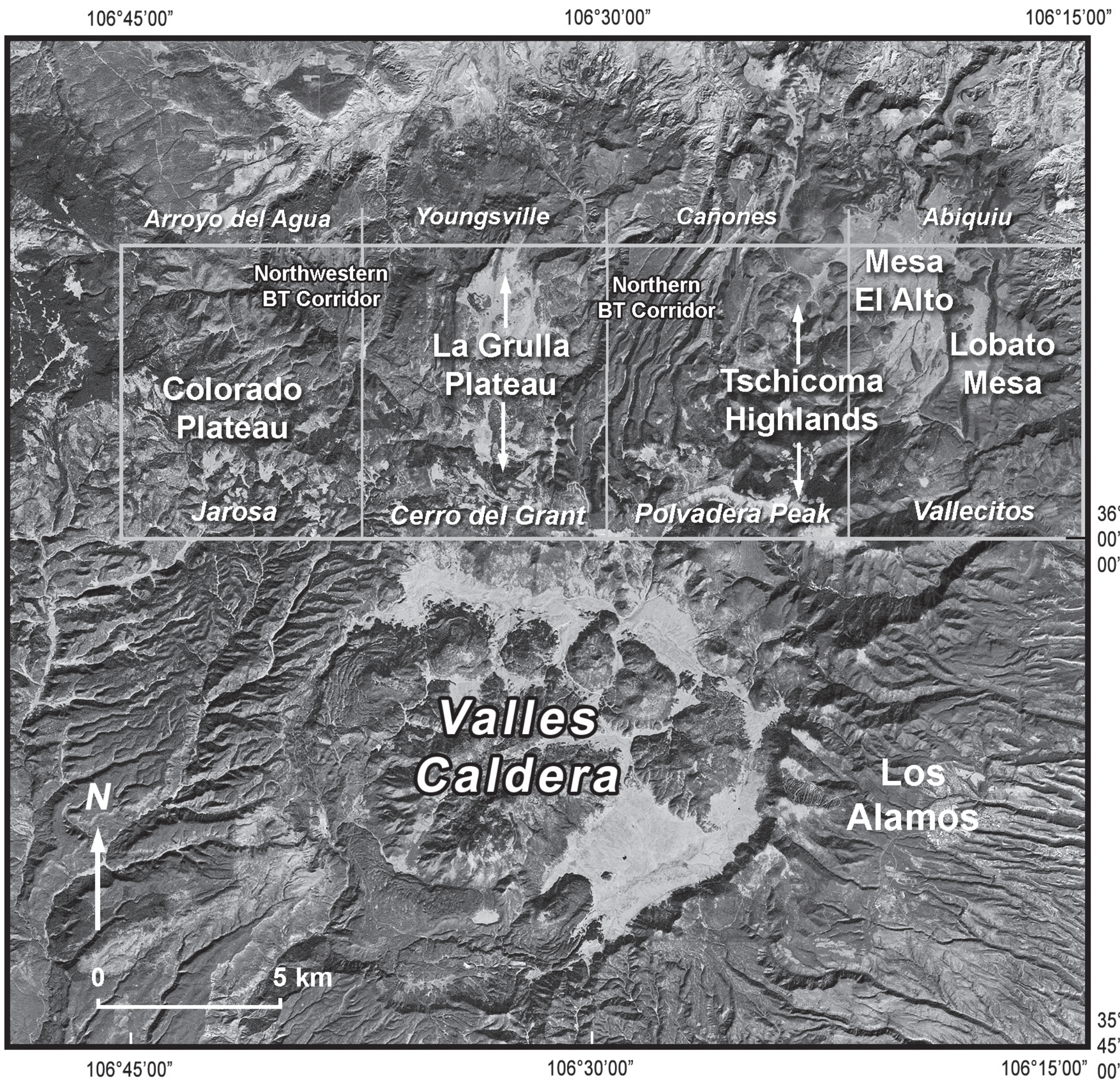

FIGURE 1. Satellite image of the Valles caldera and the northern Jemez Mountains showing geographic and geologic features discussed in this paper (Colorado Plateau, northwestern Bandelier Tuff corridor, La Grulla Plateau, northern Bandelier Tuff corridor, Tschicoma highlands, Mesa El Alto, and Lobato Mesa). 7.5-minute quadrangles are outlined and named in italics.

Age data for volcanic units in the northern Jemez Mountains, together with sample names, UTM coordinate positions, and reference information are provided where known (Table 1). These data are grouped by stratigraphic unit, with distinctions made between "Lobato" and "Tschicoma" Formations of the La Grulla Plateau versus those to the east (Tschicoma highlands and Lobato Mesa).

The Colorado Plateau and the northwestern Bandelier Tuff corridor

Proterozoic basement and late Paleozoic sediments

The northwesternmost Jemez Mountains includes the southeastern edge of the Colorado Plateau, represented by a thick sequence of late Paleozoic and Upper Triassic sediments that overlie Proterozoic basement rocks (Fig. 2). On the Jarosa 7.5-minute quadrangle (Timmer et al., 2006), rare windows into this underlying Proterozoic basement occur in the headwaters of Rio Puerco canyon, revealing mildly foliated muscovite-biotite granite with an mildly undulating, beveled surface overlain by a Late Paleozoic marine sequence. This unconformity, representing > 1.3 Ga of missing rock record (Woodward, 1996), is also observed in the southern Jemez Mountains and elsewhere in northern New Mexico where uplifted crustal blocks have re-exposed this impressive late Paleozoic beveled surface and nonconformity.

In the Jarosa quadrangle, the Late Pennsylvanian Guadalupe Box Formation (of Krainer et al., 2005), an upper arkosic limestone sequence, nonconformably overlies the Proterozoic basement, representing shallow marine limestone lithofacies and nonmarine fluvial clastics deposited directly upon the Proterozoic basement that was eroded during the ancestral Rocky Mountain orogeny (Woodward, 1996).

TABLE 1. Compilation of age data for volcanic rocks in the northern Jemez Mountains. UTM coordinates provided if available. 7.5-minute quadrangles abbreviations: ABQ = Abiquiu, CAN = Cañones, CDG = Cerro del Grant, CH = Chili, PP = Polvadera Peak, VA = Vallecitos.

Sample	Rock Unit	Quadrangle	Location	Description	Method	Age (Ma)	Reference
ER-8	Tshirege Member, Bandelier Tuff (?)	PP	0367144, 3987403	Rhyolite	Ar40/Ar39	1.21±0.20	Justet, 2003
V-15	Guaje Tephra, Otowi Member, Bandelier Tuff	VA	0386666, 3993046	Crystal-rich pumice	Ar40/Ar39	1.72±0.04	this study
V-13	Otowi Member, Bandelier Tuff	VA	0377691, 3997125	Crystal-rich ignimbrite	Ar40/Ar39	1.68±0.04	this study
P-70	El Rechuelos Rhyolite	PP	0628077, 3993982	Fine grained rhyolite	K-Ar	2.01±0.06	Loeffler, 1988
F01-54	El Rechuelos Rhyolite	PP	36° 2.913' / 106° 25.301'	Fine grained rhyolite	Ar40/Ar39	2.09±0.02	Goff, unpub data
	El Rechuelos Rhyolite	PP	Middle Dome	Fine grained rhyolite	K-Ar	2.07±0.06	Dalrymple, 1967
ER-4	El Rechuelos Rhyolite	PP	0371274, 3994152	Rhyolite	Ar40/Ar39	2.21±0.01	Justet, 2003
B04-10-89	El Alto Basalt?	CAN	03713692, 4000757	Basaltic andesite	Ar40/Ar39	2.87±0.24	this study
A13	El Alto Basalt	ABQ	383081.419, 4007234.779	Basalt	Ar40/Ar39	2.86±0.05	Maldonado and Miggens, 2007
V-14	El Alto Basalt	VA	0377551, 3995973	Hawaiite mafic lava	Ar40/Ar39	2.87±0.02	this study
	El Alto Basalt	VA	Mesas El Alto and Abiquiu	Hawaiite lavas	K-Ar	3.2-2.8	Baldridge et al., 1980
V-1	Puye Formation	VA	0379300, 3990700	Ignimbrite	Ar40/Ar39	4.01±0.56	this study
PolvP2	Bearhead Rhyolite	PP	0365927, 3986390	Rhyolite	Ar40/Ar39	7.11±0.13	this study
ER-7	Bearhead Rhyolite	PP	0366283, 3988402	Rhyolite	Ar40/Ar39	7.1±0.5	Justet, 2003
P-8	Bearhead Rhyolite	PP	0633591, 3988776	Rhyolite	K-Ar	7.54±0.28	Loeffler et al., 1988
P-80	Bearhead Rhyolite	PP	0632961, 3986732	Fine grained rhyolite	K-Ar	5.80±0.20	Loeffler et al.,1988
B04-10-25	Tschicoma Formation - NE Jemez	CAN	3733692, 40000757	Dacite	Ar40/Ar39	3.67±0.03	this study
B04-10-22	Tschicoma Formation - NE Jemez	CAN	0373223, 4000806	Dacite	Ar40/Ar39	3.67±0.05	this study
TD-13	Tschicoma Formation - NE Jemez	ABQ	0376642, 4004029	Dacite	Ar40/Ar39	3.79±0.21	Justet, 2003
PolvP1	Tschicoma Formation - NE Jemez	PP	0364950, 3987303	Dacite	Ar40/Ar39	3.36±0.06	this study
ER-6	Tschicoma Formation - NE Jemez	PP	0373642, 3995319	Pumice	Ar40/Ar39	2.90±0.70	Justet, 2003
ER1-2	Tschicoma Formation - NE Jemez	PP	0626559, 3995162	Pumice	K-Ar	5.21±0.25	Loeffler, 1988
TD-10	Tschicoma Formation - NE Jemez	PP	0374931, 3994500	Dacite	Ar40/Ar39	2.97±0.22	Justet, 2003
P-39	Tschicoma Formation - NE Jemez	PP	0368204, 3998108	Dacite lava w bio+hbl	Ar40/Ar39	3.34±0.10	this study
P-13	Tschicoma Formation - NE Jemez	PP	0366500, 3993000	Dacite lava w bio±hbl	Ar40/Ar39	3.23±0.4	this study
P-18	Tschicoma Formation - NE Jemez	PP	0365125, 3995421	Dacite lava w bio	Ar40/Ar39	2.62±0.64	this study
P3-11	Tschicoma Formation - NE Jemez	PP	0367952, 3988020	Basaltic andesite enclave	Ar40/Ar39	3.37±0.04	this study
	Tschicoma Formation - NE Jemez	PP	FR-27	Dacite lava with mafic clots	Ar40/Ar39	4.2 Ma	Goff et al, 1989
F01-55	Tschicoma Formation - NE Jemez	PP	36° 3.264' / 106° 24.626'	Rhyodacite lava	Ar40/Ar39	3.21±0.35	Goff, unpub data
F01-56	Tschicoma Formation - NE Jemez	PP	36° 2.169' / 106° 24.224'	Dacite lava	Ar40/Ar39	5.34±0.36	Goff, unpub data
F01-57	Tschicoma Formation - NE Jemez	PP	36° 1.302' / 106° 22.675'	Dacite lava	Ar40/Ar39	4.46±0.58	Goff, unpub data
P-99	Tschicoma Formation - NE Jemez	PP	Cerrito Chato	Dacite lava w bio+hbl	K-Ar	3.81±0.19	Goff et al, 1989
	Tschicoma Formation - NE Jemez	PP	Polvadera Peak	Dacite lava	K-Ar	3.13±0.07	Goff et al, 1989
	Tschicoma Formation - NE Jemez	PP	Cerro Pelon	Dacite lava w bio+hbl	K-Ar	2.96±0.27	Goff et al, 1989
	Tschicoma Formation - NE Jemez	VA	0379700, 3989700	Dacite lava	Ar40/Ar39	3.7±0.05	this study
V-39	Tschicoma Formation (Gallina flow)	VA	0379211, 3989228	Dacite lava w bio+hbl	Ar40/Ar39	4.29±0.49	this study
P-68	Tschicoma Formation (Gallina flow)	VA	Gallina Mesa	Dacite lava w bio+hbl	K-Ar	3.9±0.15	Goff et al, 1989
	Paliza Canyon (?) - La Grulla Plateau	CDG	SE corner of CDG quad	Andesite	K-Ar	8	Gardner, et al. 1986
04CDG04	Tschicoma Formation - La Grulla Plateau	CDG	0361717, 3991504	Dacite	Ar40/Ar39	6.58±0.35	this study
05CDG05	Tschicoma Formation - La Grulla Plateau	CDG	0362715, 3985676	Dacite	Ar40/Ar39	7.81±0.09	this study
	Tschicoma Formation - La Grulla Plateau	CDG	0362500, 3993260	Fine grained dacite	K-Ar	7.35±0.21	Singer, 1985
Hill 33	Tschicoma Formation - La Grulla Plateau	CDG	0363457, 3985656	Dacite	Ar40/Ar39	7.27±0.08	Lawrence et al., 2004
03-CDG-03	Tschicoma Formation - La Grulla Plateau	CDG	0361309, 3987656	Dacite	Ar40/Ar39	7.63±0.05	Lawrence et al., 2004
9-17-3-2	Tschicoma Formation - La Grulla Plateau	CDG	0364883, 3996197	Andesite	Ar40/Ar39	7.19±0.13	Lawrence et al., 2004
TD-20	Tschicoma Formation - La Grulla Plateau	CDG	0363682, 3985360	Andesite	Ar40/Ar39	7.17±0.12	Justet, 2003
TD-24	Tschicoma Formation - La Grulla Plateau	CDG	0355723, 3987182	Trachyandesite	Ar40/Ar39	7.43±0.14	Justet, 2003
LB-13		CAN	0371448, 4007679	Andesite	Ar40/Ar39	4.90±0.70	Justet, 2003
04Y10	Lobato Formation - La Grulla Plateau	CAN	0360499, 3999669	Basalt	Ar40/Ar39	8.07 ± 0.17	this study
B04-10-29	Lobato Formation - La Grulla Plateau	CAN	0371916, 3999491	Basalt	Ar40/Ar39	7.20±1.2	this study
04CM23	Lobato Formation - La Grulla Plateau	CAN	0371485, 4008642	Basalt	Ar40/Ar39	8.42±0.11	this study
LB-14	Lobato Formation - La Grulla Plateau	CAN	0371600, 4001020	Basalt	Ar40/Ar39	7.71±0.18	Justet, 2003
	Lobato Formation - La Grulla Plateau	CDG	Encino Point	Andesite	K-Ar	7.85±0.22	Singer, 1985
	Lobato Formation - La Grulla Plateau	CDG	0364882, 3996197	Basaltic andesite	Ar40/Ar39	8.67±0.06	Lawrence et al., 2004
9-19-3-1	Lobato Formation - La Grulla Plateau	CDG	0364781, 3993376	Basaltic andesite	Ar40/Ar39	8.01±0.14	this study
P-25	Lobato Formation - La Grulla Plateau	PP	0365275, 3996984	Fine grained basalt	Ar40/Ar39	8.01±0.08	this study
P-553	Lobato Formation - NE Jemez	CH	Clara Peak	Olivine basalt	K-Ar	9.99±0.27	Goff et al, 1989
LB-17	Lobato Formation - NE Jemez	CH	0388042, 3988898	Basalt	Ar40/Ar39	9.82±0.28	Justet, 2003
A50	Lobato Formation - NE Jemez	CH	397480.284, 3995329.796	Basalt dike	Ar40/Ar39	10.11±0.07	Maldonado and Miggins, 2007
A48	Lobato Formation - NE Jemez	ABQ	0380260, 3999773	Basalt lava	Ar40/Ar39	9.51±0.21	Maldonado and Miggins, 2007
V-3	Lobato Formation - NE Jemez	VA	0384321, 3988938	Fine grained basalt	Ar40/Ar39	9.57±0.07	this study
V-17	Lobato Formation - NE Jemez	VA	0387000, 3992750	Basalt dike / sill	Ar40/Ar39	9.74±0.21	this study
P-487	Lobato Formation - NE Jemez	VA	Lobato Mesa	Hawaiite lava	K-Ar	9.2±0.2	Goff et al, 1989
P-430	Lobato Formation - NE Jemez	VA	Lobato Mesa	Olivine basalt	K-Ar	10.8±0.3	Goff et al, 1989
P-465	Lobato Formation - NE Jemez	VA	Lobato Mesa	Olivine basalt	K-Ar	10.1±0.3	Goff et al, 1989
13 samples	Lobato Formation - NE Jemez	VA	Lobato Mesa	variety of basalt lavas	K-Ar	ABQ	Gardner, et al. 1986
V-9	Lobato Formation - NE Jemez	VA	0384700, 3988100	Fine grained dacite	Ar40/Ar39	9.65±0.05	this study
TD-25	Lobato Formation - NE Jemez	VA	0384474, 3987866	Dacite	Ar40/Ar39	9.23±0.26	Justet, 2003
LB-9	Lobato Formation - NE Jemez	VA	0383043, 3996914	Basalt	Ar40/Ar39	8.77±0.19	Justet, 2003
LB-10	Lobato Formation - NE Jemez	VA	0383097, 3997191	Basaltic andesite	Ar40/Ar39	10.53±0.10	Justet, 2003
LB-11	Lobato Formation - NE Jemez	VA	0383097, 3997191	Basalt	Ar40/Ar39	9.39±0.24	Justet, 2003
LB-16	Lobato Formation - NE Jemez	VA	0383929, 3986394	Basalt	Ar40/Ar39	9.8±0.8	Justet, 2003
04Y09	Mafic intrusion in Santa Fe Group	CAN	0361523, 3999607	Basalt intrusion	Ar40/Ar39	18.42 ± 0.37	this study
P-20	Chamita Formation, Hernandez Member (?)	PP	0365900, 3997600	Fluvial andesite clast	Ar40/Ar39	29.08±0.13	this study

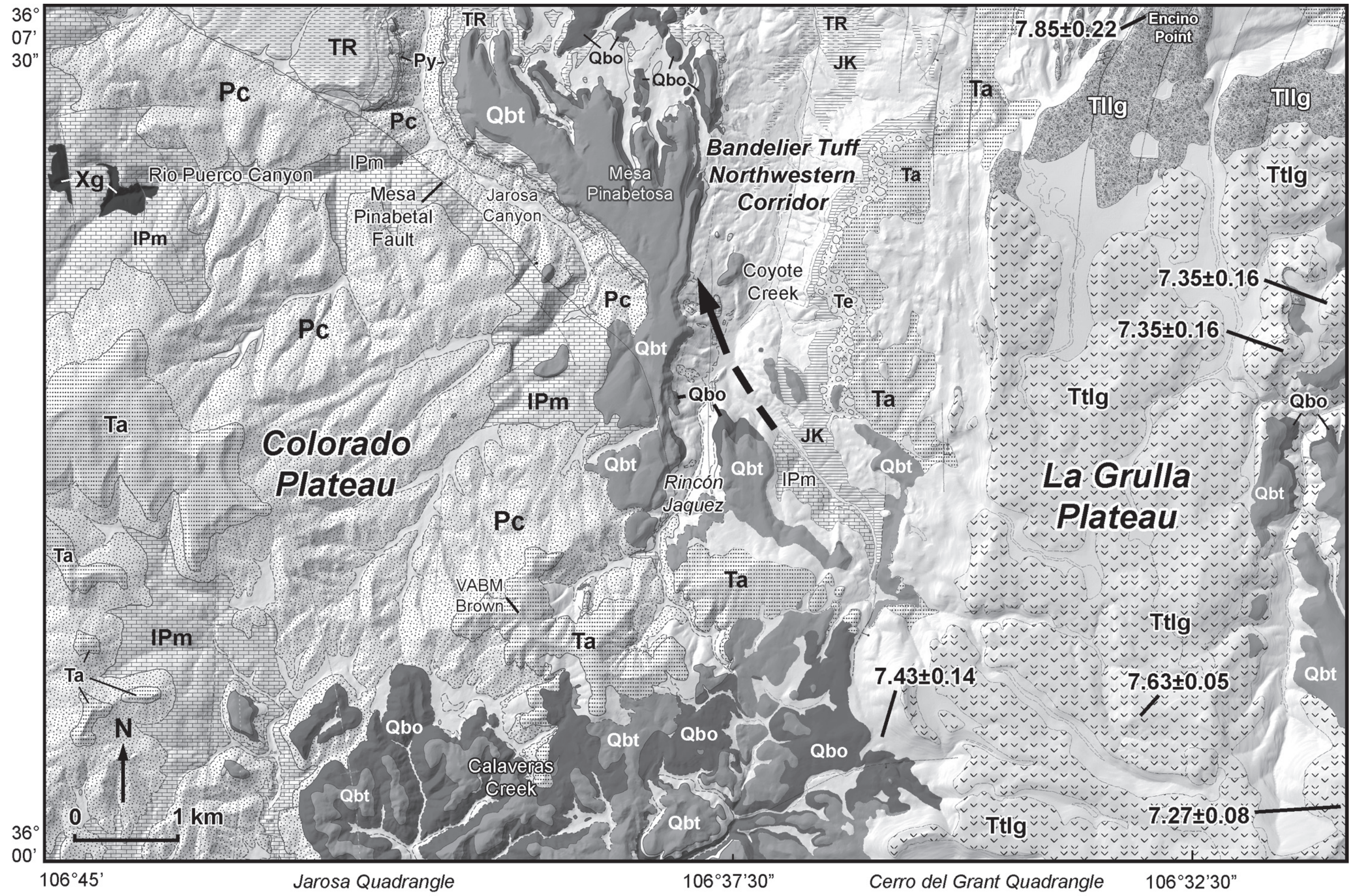

FIGURE 2. Simplified geologic map showing the distribution of major rock units in the northwestern Jemez Mountains, including the eastern margin of the Colorado Plateau and volcanic rocks of the La Grulla Plateau. Several types of Proterozoic granites (**Xg**) are overlain by Late Pennsylvanian Guadalupe Box Formation (**IPm**). Widespread Cutler Group deposits (**Pc**) are overlain by Permian Yeso Group eolian sandstones (**Py**). Upper Triassic Chinle Group (**TR**) disconformably overlies Permian rocks. Tertiary El Rito Formation (**Te**) caps Jurassic and Cretaceous sediments (**JK**) and are overlain by Abiquiu Formation (**Ta**). On the La Grulla Plateau an older sequence of basaltic andesite to andesite lavas (**Tllg**, ~7.5 to 8.7 Ma) is capped to the south by more silicic (andesite to dacite) lavas (**Ttlg**, ~7.0 to 7.8 Ma). Bandelier Tuff pyroclastic flows, including both the Otowi (**Qbo**) and Tshirege (**Qbt**) Members, ponded in the Calaveras Creek area to the west and found a northwestern corridor that skirted the eastern margin of La Grulla Plateau, forming Mesa Pinabetosa.

Where exposed in the northwestern Jemez Mountains, a gradational contact exists between the Guadalupe Box Formation and the overlying Late Pennsylvanian to Permian El Cobre Canyon Formation of the Cutler Group (Lucas and Krainer, 2005). For mapping purposes, the contact was placed at the highest laterally continuous limestone bed of the Guadalupe Box Formation. At the transition zone, micaceous red siltstones and arkosic sandstones of the overlying deposits represent a deltaic river floodplain environment and an oscillating shoreline until the sea retreated southward at ~300 Ma (Kues and Giles, 2004). In the Jarosa quadrangle, the El Cobre Canyon Formation is generally exposed south of the Mesa Pinabetal fault (Fig. 2) while the overlying Arroyo del Agua Formation is exposed north of the fault.

The Permian De Chelly Sandstone of the Yeso Group was also mapped in Jarosa Canyon (Fig. 2), gradationally overlying the Arroyo del Agua Formation. This eolian sandstone deposit, representing an erg that developed in arid conditions at approximately 275 Ma, extends northward into the Arroyo del Agua and Youngsville quadrangles where Yeso pinches out on Mesa Ojitos and Poleo Mesa (Kelley et al., 2005, 2006). A widespread paleoweathering horizon is typically observed at the top of this unit where the Upper Triassic Chinle Group disconformably overlies the Yeso Group.

Late Triassic sediments

Mapping of the Jarosa quadrangle (Timmer et al., 2006) has also documented a fairly complete section of the Upper Triassic Chinle Group that disconformably overlies the late Paleozoic rocks. These sediments were mainly deposited by westerly and northwesterly flowing rivers that meandered across a broad, flat landscape. At the base of the Chinle Group is the Shinarump Formation, a white to beige fluvial sandstone and conglomerate that locally reaches 15 m in thickness and often exhibits an impressive scoured disconformity (typically on Permian Cutler or Yeso Formation). Excellent exposures of the contact between the Yeso and the Shinarump occur in Jarosa Canyon, including spectacular outcrops in a small erosional amphitheater (UTM 0349476, 3996564). The Shinarump Formation was previously called the Agua Zarca Sandstone by Wood and Northrop (1946). Above the Shinarump is the Salitral Formation, forming poorly exposed slopes of brown to red shale. In turn, this unit is overlain by the Poleo Formation, forming resistant brown to beige sandstone cliffs that are typically well exposed in canyons, reaching a maximum thickness of ~100 m in Jarosa Canyon. Petrified wood and plant fragments are common in some horizons of the sandstone, indicative of a lush, tropical environment. In general, the thickness of the Poleo Formation increases northwards into the Chama Basin. Youngest of the upper Chinle Group sediments exposed in the region are discontinuous exposures of the Petrified Forest Formation, including thin remnants of the Painted Desert and Mesa Montosa Members.

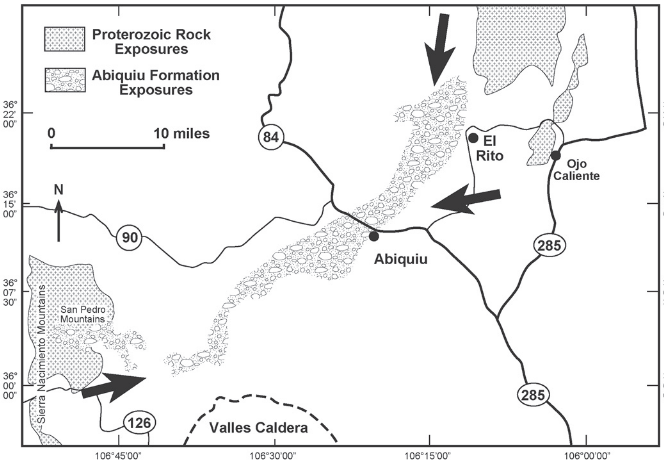

FIGURE 3. General outcrop distribution of Proterozoic rocks and deposits of the Tertiary Abiquiu Formation. The arrows depict the provenance of clasts in the lower member.

Jurassic to Cretaceous sediments

Along the boundary of the Jarosa and Cerro del Grant quadrangles (Figs. 1, 2), down-to-the-east, rift-related faulting has helped to preserve some of the upper Mesozoic strata that were stripped by erosion in the Jarosa quadrangle. Several Jurassic and Cretaceous units are exposed in the western Cerro del Grant quadrangle, including the Jurassic Entrada Sandstone, and Todilto, Summerville, and Morrison Formations, and the Cretaceous Burro Canyon and Dakota Formations and Mancos Shale (see Lawrence et al., 2004, for more detail).

Cenozoic sediments

In the northwestern corner of Cerro del Grant quadrangle (Figs. 1, 2), poorly exposed El Rito Formation siltstones, sandstones and basal quartzite conglomerate unconformably overlie the Cretaceous Dakota Sandstone and Mancos Shale. The age of these sediments is regarded as Eocene (Smith et al., 1961; Logsdon, 1981) and the unit is thought to have been deposited in a synorogenic basin between Laramide highlands in the Sierra Nacimiento to the west and the Tusas Mountains to the northeast. Exposures of the El Rito are rare and its thickness is estimated to be no more than 65 m.

One of the most interesting sedimentary units present in the northwestern Jemez Mountains is the Abiquiu Formation, capping the older sedimentary sequence and topping mesas approaching 3000 m in elevation. This unit, considered one of the first rift-fill sediments (Smith et al., 2002), crosses the margin of the Colorado Plateau and extends westward to the Sierra Nacimiento region (Figs. 2, 3). The Abiquiu Formation thickens progressively to the northeast toward El Rito, and age data imply a range from ~28 to 19 Ma (Smith et al., 2002; Koning et al., 2007; Maldonado and Miggins, 2007). Although incipient rift tectonics in the region may have already commenced, the extension of a broad Abiquiu Formation alluvial plain onto the Colorado Plateau indicates only an insignificant topographic distinction between the plateau and the rift during this time. Furthermore, the eastward structural tilt of the Abiquiu Formation on the eastern flank of the Sierra Nacimiento implies that a portion of the uplift and erosion of the Sierra Nacimiento occurred after early Miocene time.

The Abiquiu Formation was first recognized by Smith (1938), who described three units that together he called the Abiquiu Tuff. Subsequent studies by Church and Hack (1939), Vazzana and Ingersoll (1981), Moore (2000), and Smith et al., (2002) defined the sequence as the Abiquiu Formation, and investigated the sedimentology and origin of its members. Exposures of the Abiquiu Formation occur in a SW-trending discontinuous band of outcrops, extending from near El Rito in the northeast to the San Pedro Mountains to the southwest (Figs. 2, 3). Members of the Abiquiu Formation differentiated during mapping include the lower member, consisting of pink to gray arkosic sandstones and conglomerates, and the upper member, including white, tuffaceous, tabular-bedded, volcaniclastic sandstone. The upper member is a poorly exposed calcareous mudstone, limestone, and fine-grained sandstone toward the southwest on the Jarosa quadrangle (Timmer et al., 2006). Amalia Tuff clasts are absent southwest of Encino Point.

A third member, the Pedernal Chert, was consistently mapped at the contact between the upper and lower members on Cerro Pedernal, Mesa Escoba, and Encino Point on the Youngsville and Cerro del Grant quadrangles. The chert is usually 1 to 2 m thick, but is absent east of the Cañones fault zone (Moore, 2000; Smith et al., 2002). Toward the southwest, on the Jarosa quadrangle, the Pedernal Chert does not occur at a unique stratigraphic horizon within the Abiquiu Formation. A fairly persistent limy chert horizon occurs at the boundary of the upper and lower members, and another significant chert horizon often caps the upper member in the Jarosa quadrangle. Where broad and continuous, both chert layers can form flat-lying topographic benches, highly resistant to erosion. Discontinuous lenses of chert can occur in both the upper and lower members in the southwestern exposures. Vazzana and Ingersoll (1981) presented strong arguments that the chert formed by diagenetic silicification of carbonate paleosol horizons.

The lower member of the Abiquiu Formation is characteristic of a widespread piedmont alluvial fan that may have been derived from distinct Proterozoic source regions. Maldonado and Miggins (2007) refer to this unit as the conglomerate of Arroyo del Cobre. The poorly bedded nature of the deposit suggests a depositional environment of braided streams and debris flows. Paleocurrent data (Vazanna and Ingersoll, 1981) clearly indicate a southwesterly transport of clasts for much of the deposit, although variable paleocurrent data were documented by Timmer (1976) in the Jarosa quadrangle. The provenance of the lower member of the Abiquiu Formation requires further investigation. Recent mapping of the Jarosa (Timmer et al., 2006) and SE Canjilon quadrangles (Kempter et al., in progress) indicate three distinct source regions feeding the lower Abiquiu piedmont environment: a Proterozoic source north of El Rito that provided distinctive metagranite clasts with round, bluish-gray quartz; a second Proterozoic source that extended from northeast of El Rito to the southeast, providing a wide array of granitic and metamorphic clasts; and a third source from the Sierra Nacimiento, contributing a variety of Proterozoic clasts in addition to distinctive Pennsylvanian limestone and shale clasts (Fig. 3).

The upper member of the Abiquiu Formation reaches approximately 450 m in thickness and has been correlated with silicic volcanism in the Latir volcanic field (Smith et al., 2002). The distinctive presence of 25.1 Ma Amalia Tuff clasts and other Ar^{40}/Ar^{39} age data indicate that the bulk of upper Abiquiu sedimentation occurred as pumiceous debris flow deposits coincident with major ignimbrite eruptions in the Latir field between 24 and 25.2 Ma (Smith et al., 2002).

Quaternary volcanics

The La Grulla Plateau formed a topographic high during eruptions of both the Toledo and Valles calderas, directing pyroclastic flows of Bandelier Tuff into low topographic corridors on either side of the plateau. To the northwest, more than 150 m of Otowi pyroclastic flows filled paleocanyons, blanketing erosional topography on the late Paleozoic and upper Triassic section and covering the southern extension of the Mesa Pinabetal fault (Timmer et al., 2006). Pyroclastic flows directed more westerly from the caldera rim were blocked to the north by a broad mesa capped by upper Abiquiu Formation and Pedernal Chert (VABM Brown Peak on Fig. 2). These flows filled lowlands that currently occupy the headwater region of Calaveras Creek.

The subsequent eruption of the Tshirege Member followed many of the same paths as the Otowi, filling a post-Otowi paleocanyon at Rincón Jaquez and capping Otowi Member tuff throughout the Calaveras Canyon headwater region. Tshirege pyroclastic flows, however, extended farther to the northwest than Otowi flows, filling in paleotopography in the modern Jarosa Canyon vicinity (on both late Paleozoic and Upper Triassic deposits), and forming the fan-shaped Mesa Pinabetosa (Fig. 2). Rare exposures of Tsankawi tephra as much as 2 m thick occur at the base of the Tshirege Member on the northeastern wall of Jarosa Canyon (UTM 0350860, 399568).

La Grulla Plateau

The La Grulla Plateau is an elevated NS-trending volcanic plateau that extends northwards from the Valles caldera rim, capping several strata and structures at the boundary of the Rio Grande rift and the Colorado Plateau. Age data (Table 1; Fig. 2) for lavas exposed along the plateau indicate clearly that the bulk of volcanic activity occurred between ~7 to 8.5 Ma, with a thick andesite to dacite sequence overlying a more mafic (basaltic andesite to andesite) sequence exposed to the north. The younger, more silicic lavas have previously been mapped as Tschicoma Formation, whereas the older mafic deposits are included in the Lobato Formation (Lawrence, 2007). The older mafic lavas extend northward to Cerro Pedernal, Mesa Escoba, and Polvadera Mesa, where rift faulting has produced at least 670 m of offset (Koning et al., 2007).

Structural mapping across the La Grulla Plateau has recognized two distinct episodes of tectonic movement: north-trending high-angle faults that displace pre-Tertiary strata, likely associated with Laramide uplift in the Nacimiento Mountains, and a second set of high-angle, curvilinear faults associated with the western margin of the Española Basin. Most of the 7.4 to 7.8 Ma eruptive centers on the La Grulla Plateau are aligned along these younger faults. Landslide and fault reactivation along the western margin of the plateau has formed the modern escarpment, including the partial removal of a volcanic center and endogenous dome at Encino Point (Fig. 2; see Lawrence, 2007).

Northern Bandelier Tuff corridor

Tertiary rift-fill sediments

This relatively low-lying region in the northern Jemez Mountains not only provided passage for northward directed pyroclastic flows of the Bandelier Tuff, but also reveals key stratigraphic and structural relationships between older volcanic and sedimentary units. The oldest exposed sedimentary units beneath the volcanic pile (south of the village of Cañones) include the Chama-El Rito Member of the Tesuque Formation and the upper Abiquiu Formation. Farther south, up Cañones Canyon, the Ojo Caliente Sandstone Member of the Tesuque Formation is well exposed along the eastern wall of canyon (Fig. 4), exhibiting characteristic large eolian crossbeds. Rift boundary faults in the canyon have tilted the sandstone toward the east by 7-10 degrees and facilitated silica and carbonate cementation of the primary deposits (Kempter et al., 2004).

Underlying Lobato mafic lavas and capping the Ojo Caliente Sandstone is a thin (< 5 m thick) fluvial sandstone and gravel that includes rounded volcanic clasts of unknown origin. This deposit may correlate with the Hernandez Member of the Chamita Formation as described by Koning and Aby (2005). One of the volcanic clasts dated for this study yielded an age of ~29 Ma, indicating a volcanic source much older than the Jemez Mountains. Possible sources include the San Juan volcanic field (a remobilized clast from the Esquibel Member?), or the Latir volcanic field (pre-Amalia Tuff).

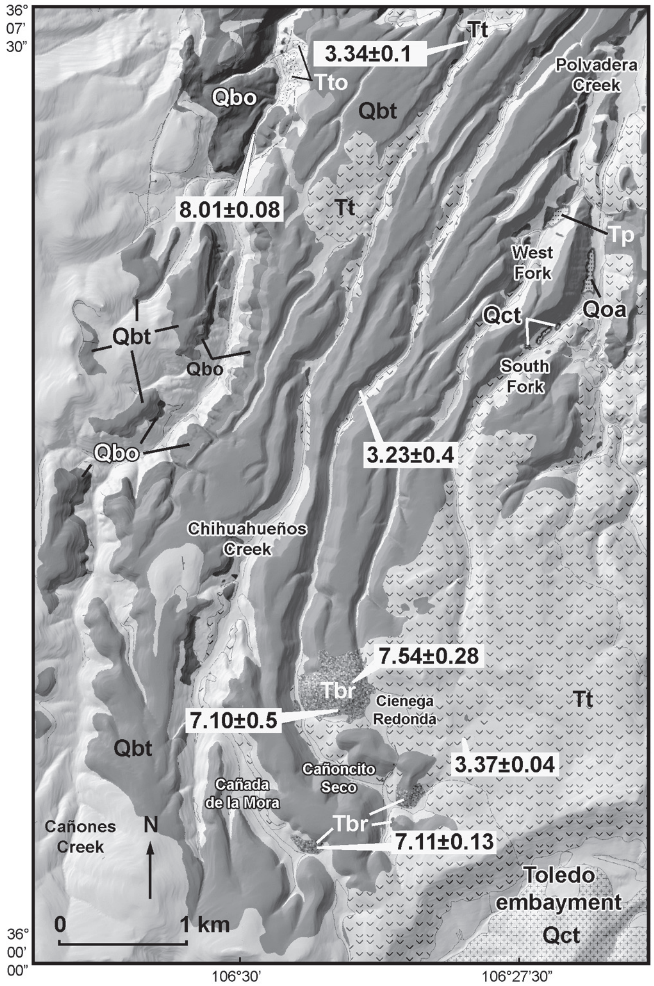

FIGURE 4. Simplified geologic map of the northern corridor of the Bandelier Tuff, including the northwest portion of the Toledo embayment. Lavas west of Cañones Creek belong to the La Grulla plateau (**Ttlg** and **Tllg** in Fig. 2). Thick Otowi pyroclastic flows (**Qbo**) are capped by thin Tshirege Member (**Qbt**). Tschicoma dacite lavas (**Tt**), at 3.23 to 3.37 Ma, possibly represent a single flow. Outcrops of Bearhead Rhyolite **(Tbr)** have ages of 5.8 to 7.5 Ma. Ojo Caliente Sandstone Member of Tesuque Formation (**Ttc**), Puye Formation (**Tp**), Cerro Toledo (**Qct**), and post-Bandelier Tuff alluvium (**Qoa**) are also exposed.

Late Miocene-Pliocene volcanics

Figure 4 shows the distribution of primary volcanic units along the northern Bandelier Tuff corridor, including sample locations for several ages discussed below. Basaltic andesite lavas, dated at ~7 to 8 Ma, cap the Tertiary sediments along the eastern rim of Cañones Canyon in the northwest corner of the Polvadera Peak quadrangle. The lavas are dark gray and fine grained with phenocrysts of plagioclase, clinopyroxene, orthopyroxene and olivine. The lavas thin and thicken dramatically over short distances, clearly filling in paleotopography at the time of the eruption. These lavas likely correlate with mafic lavas on the La Grulla Plateau, ~1 km to the west. As with the mafic lavas on La Grulla Plateau, they have been mapped as Lobato Formation for this study, but a revised nomenclature is expected in the future.

The next phase of volcanic activity in this area occurred north of the rim of the Toledo embayment, in upper Cañoncito Seco and Cañada de la Mora (Fig. 4). Outcrops of fine-grained rhyolite, previously mapped as El Rechuelos Rhyolite (Smith et al., 1970; Loeffler et al., 1988; Kempter et al., 2004), occur in several locations, including one large dome at the southern end of La Mesa del Pedregosa and adjacent to Cienega Redonda. Recent Ar^{40}/Ar^{39} dates (Table 1) suggest these rhyolites were emplaced at ~ 7.1 Ma, similar in timing to widespread Bearhead Rhyolite volcanism that affected the southern Jemez Mountains between 6-7 Ma (Justet and Spell, 2001; Justet, 2003). More rhyolite outcrops have recently been mapped along the northern rim of the Valles caldera, just south of the exposures in Cañada de la Mora Canyon (Gardner et al., 2006), and are likely comparable in age. These rhyolites are chemically and temporally distinct from the three El Rechuelos rhyolite domes located along the eastern flanks of Polvadera Peak, which are all aphyric and uniform in geochemistry (Loeffler, 1984) and yield ages of ~2.1 Ma. Although more study of these rhyolites is recommended, we suggest that these older rhyolites be considered part of the Bearhead Rhyolite phase of volcanic activity in the Jemez Mountains, and not the El Rechuelos Rhyolite.

Tschicoma Formation dacites extend northwards from the northwestern rim of the Toledo embayment and appear to have originated from vents within the embayment prior to its collapse and formation of the Toledo caldera (Gardner and Goff, 1996). Ar^{40}/Ar^{39} data from this study (Fig. 4) yielded nearly identical ages (3.23 to 3.27 Ma) for three porphyritic dacite lavas that border or underlie much of the northern Bandelier Tuff corridor, raising the possibility that one major dacite flow extends almost 7 km from the rim of the Toledo embayment to the distal edge of Mesa del Medio.

Quaternary volcanics

Both the Otowi and Tshirege Members of the Bandelier Tuff found passage northwards through this low topographic corridor between the La Grulla Plateau and the Tschicoma highlands. The modern canyons that have incised this region include (from west to east) Cañones, Chihuahueños, Cañoncito Seco, Polvadera (West and South Fork), and Cañada del Ojitos (Fig. 4). In several places these canyons have eroded deeply to cut through the Bandelier Tuff sequence and expose the underlying bedrock lava (typically 3-3.5 Ma Tschicoma Formation). Thick Otowi Member tuff in Cañones Canyon (exceeding 100 m), and steeply dipping contacts between the Otowi and the underlying Ojo Caliente Sandstone, reveal a paleo-Cañones Canyon prior to the Toledo caldera eruption. Exposures of the base of the Otowi Member on older lavas near the modern canyon floor indicate this paleocanyon was as deep as the modern canyon.

As observed in the northwestern Bandelier Tuff corridor, the Otowi Member is often more densely welded than the overlying Tshirege Member, forming massive brownish orange cliffs in canyon walls (Fig. 5). This welding pattern contrasts greatly with the Pajarito Plateau region (eastern Jemez Mountains), where the Otowi is typically poorly welded, forming vegetated

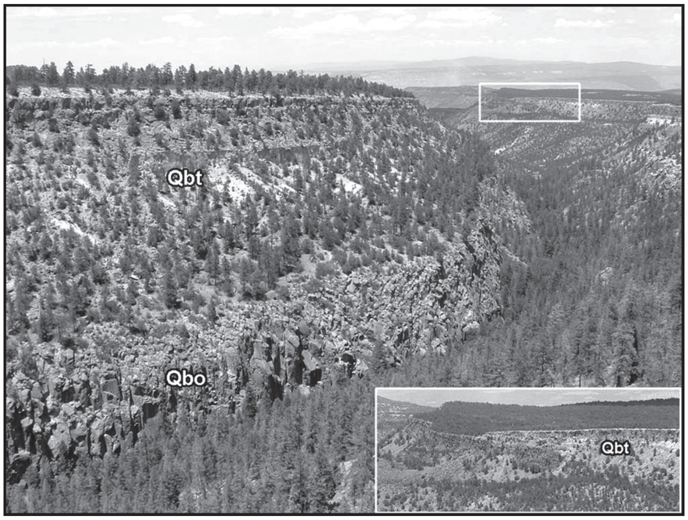

FIGURE 5. View to the northeast down Cañoncito Seco showing layered Tshirege Member tuff (**Qbt**) above massive, moderately to densely welded Otowi Member tuff (**Qbo**). Note onlap of Tshirege Member tuffs on basalts of Polvadera Mesa (**Tllg** in Fig. 4) down canyon.

slopes beneath the Tshirege. Other unusual features of the Otowi Member in the northern Jemez Mountains include general lack of tent structures, occasional presence of a vapor phase notch, and few lithic fragments in one of its most densely welded horizons. The boundary between the two tuffs commonly is marked by an erosional bench on the top of the Otowi Member where the softer Tshirege tuff has receded. Basal tephra deposits are rarely exposed.

In Polvadera Canyon are some unique exposures of sedimentary units that preceded, interceded, and postdated Bandelier Tuff eruptions. These deposits are exposed in the West Fork and the South Fork of Polvadera Creek (Fig. 4) south of the abandoned Polvadera Sawmill Camp (Kempter et al., 2004). A rare exposure of Puye Formation gravels underlies the Otowi Member in the West Fork, containing rounded to subangular clasts of Tschicoma Formation dacite lavas. In both the West Fork and the South Fork gravels occur between the Otowi and Tshirege tuffs that we have mapped as Cerro Toledo interval deposits (Broxton and Reneau, 1995). Another sedimentary deposit in the South Fork canyon of Polvadera Creek appears to have filled a post-Tshirege Member paleocanyon (Qoa in Fig. 4). Aggradation of this paleocanyon may have occurred when the river downcut into a mound of Tschicoma dacite (exposed at the confluence of Polvadera Creek and the West Fork Polvadera Creek), impeding erosion and backfilling the canyon with sediment. The modern canyon then incised slightly to the east of this paleodrainage, preserving the older alluvial deposits along the canyon's western margin.

Tschicoma highlands

Late Miocene through Pliocene volcanics

The eastern portion of the Polvadera Peak 7.5-minute quadrangle is dominated by dacitic lavas of the Tschicoma Formation, forming some of the highest peaks in the Jemez Mountains, including Polvadera (3423 m) and Tschicoma (3524 m) Peaks. These lavas erupted as high-aspect ratio, viscous, voluminous flows with steep-sided flow lobes. The main vents, including Tschicoma Peak (commonly spelled Chicoma), Polvadera Peak, and Cerro Pelón, show a conspicuous NS-trending alignment (Fig. 6). Age data from this and previous studies (Table 1) indicate that these massive lava domes and flows were mostly emplaced between 5 and 3 Ma, extending southward from Cerro Pelón to Sierra de los Valles, forming the eastern and southeastern rim of the Valles caldera. Much of the core of the Tschicoma volcanic center foundered into the Toledo embayment during the Toledo caldera eruption (Gardner and Goff, 1996).

Figure 6 shows the distribution of volcanic units and provides age data locations for several of the volcanic units discussed below. The oldest center along the main Tschicoma axis is a dome approximately 1 km south of Polvadera Peak (5.3 Ma). Lavas related to the Tschicoma Peak center yield ages between 3.5–4.5

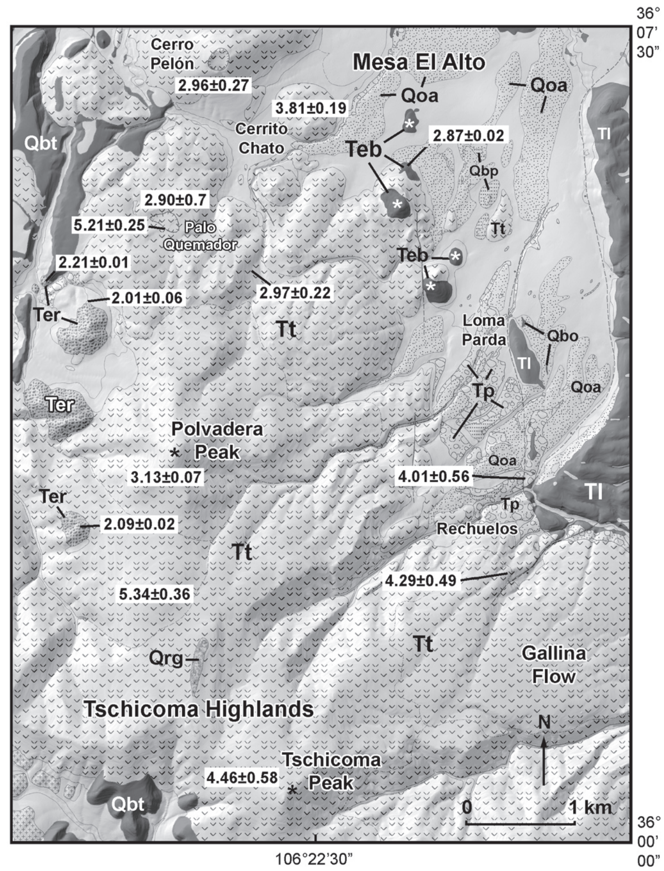

FIGURE 6. Simplified geologic map of the Tschicoma highlands and Mesa El Alto showing the distribution of primary volcanic and sedimentary units. Faulted Lobato mafic lavas (**Tl**) define the eastern margin of Mesa El Alto. Sedimentary units include Puye Formation (**Tp**), old alluvium with obsidian clasts (**Qoa** – but might be Cerro Toledo interval), and reworked Bandelier pumice deposits (**Qbp**). El Alto basalt (**Teb**), Tschicoma Formation dacites (**Tt**), El Rechuelos Rhyolite domes (**Ter**), and Otowi **(Qbo)** and Tshirege **(Qbt)** Members of the Bandelier Tuff are also exposed. **Qrg** is a possible rock glacier deposit (see Fig. 7).

Ma, including the massive Gallina Flow (3.9 to 4.2 Ma), which preserves an impressive flow lobe morphology that spilled over Puye deposits more than 3 km from its source vent high on the eastern flank of Tschicoma Peak. The Gallina flow, which covers an area of approximately 10 km^2, is typically flow banded and very porphyritic, including phenocrysts of plagioclase, biotite, and hornblende (Kempter et al., 2004).

The youngest lavas and domes formed Polvadera Peak (~3.1 Ma) and Cerro Pelón (2.96 Ma), both porphyritic dacites with plagioclase the dominant phenocyrst. Cerro Pelón also contains clinopyroxene and orthopyroxene, minor biotite and hornblende. In general, craters and other collapse features are rare in Tschicoma landforms, although a summit crater, breached to the south, is still preserved on Cerro Pelón. Another eruptive crater (El Lagunito Paleo Quemador) is located approximately 1.5 km southwest of Cerro Pelón (Fig. 6). Abundant pumice is pervasive within the crater, which has previously been mapped as part of the El Rechuelos Rhyolite (Smith et al., 1970; Kempter et al., 2004). This pumice has been dated with poor agreement at 5.21±0.25 Ma (Loeffler, 1988) and 2.90±0.70 Ma (Justet, 2003). Nonetheless, these ages, together with geochemical data presented by Loeffler (1984), suggest that pumices from this vent are more closely related to the Tschicoma Formation than the El Rechuelos Rhyolite.

Just west of Polvadera Peak are three rhyolitic domes of El Rechuelos Rhyolite, emplaced at ~2.1 Ma (Table 1). These domes erupted along a NS-trending fracture system west of Polvadera Peak, superimposed on the underlying Tschicoma surface. The rhyolite is generally aphyric, contains obsidian horizons, and is often brecciated along its margins. The northernmost dome, approximately 1.5 km northwest of Polvadera Peak, exhibits landslide scarps along its northwestern flank, and two satellite outcrops of rhyolite in Cañada de Ojitos Creek may represent detached remnants from the original dome (Fig. 6). High boulder terraces mapped as Quaternary-Tertiary gravel (Kempter et al., 2004) around this dome may actually correspond with the Puye Formation. The middle dome is the most voluminous and even spawned a short lava flow. The southernmost dome lies approximately 1.5 km southwest of Polvadera Peak (Fig. 6), where the ground surface is littered with obsidian and devitrified lava fragments.

Quaternary volcanics and sediments

The northern sector of the Toledo embayment is located in the southern portion of the Polvadera Peak quadrangle. The rim of the embayment is composed of massive Tschicoma lavas with broad talus slopes that extend into the Rito de Los Indios and Santa Clara Canyon. The embayment filled with voluminous Cerro Toledo rhyolite lavas following collapse of the Toledo caldera. These lavas are typically beige to pink, flow banded and crystal poor, with sparse phenocrysts of quartz and sanidine. The subsequent Valles caldera eruption contributed a thick pile of Tshirege pyroclastic flows that ponded in the northeast corner of the embayment, now part of the headwaters of Santa Clara Creek.

One unusual Quaternary deposit is located along a ridge halfway between Tschicoma and Polvadera Peaks (Qrg in Fig. 6). A large, elongate field of tabular Tschicoma lava blocks occupies the flat ridge top, extending in a north-south direction for 0.6 km (Fig. 7). Individual slabs may be over a meter in length, but the entire rock field appears chaotic with no matrix support. Some of the tabular blocks are imbricated, indicating flow to the north. We interpret this deposit to represent a rock glacier, mobilized very slowly by either interstitial ice that once formed a matrix between the rocks, or thawing alpine permafrost, providing a buoyant suspension zone beneath the rock slabs and facilitating movement over nearly flat topography.

Mesa El Alto

Plio-Pleistocene volcanics and sediments

Mesa El Alto is a high, perched valley located between the Tschicoma highlands and Lobato Mesa (Fig. 6). Its unique geography provided a rare depositional setting, preserving several Plio-Pleistocene sediments of distinct age and composition that were generally not preserved elsewhere in the northern Jemez Mountains. Steep-sided, distal flow lobes of the Tschicoma Formation define the western and southern margins of Mesa El Alto, whereas an uplifted footwall block of Lobato Formation basalt flows defines the eastern margin.

Puye Formation sediments are preserved in many parts of Mesa El Alto, especially adjacent to the steep flow margins of the Tschicoma lavas. Much of their aggradation was post-Gallina flow, as this is a common component in many of the sediments. Adjacent to Lobato highlands, however, clasts of Tschicoma dacites decrease significantly, replaced by clasts of mafic lavas. In the southern Mesa El Alto at least 30-40 m of Puye Formation is preserved. Along the southwestern flank of Lobato Mesa,

FIGURE 7. Unusual debris field of tabular Tschicoma dacite blocks, possibly a Quaternary rock glacier (**Qrg** in Fig. 6) along a flat ridge between Polvadera Peak and Tschicoma Peak.

remnants of Puye or younger gravels can be found at elevations up to 2470 m, suggesting either sediment fill in the valley was once much greater than at present, or Plio-Pleistocene faulting along the western margin of Lobato mesa has elevated remnant Puye Formation gravels on foot-wall blocks. Near the abandoned village of Rechuelos, a major fault juxtaposes Puye Formation sediments with Lobato mafic lavas, showing an estimated 20 m of post-Puye displacement. Nearby, a thin dacitic ignimbrite intercalated with Puye sediments just north of Rechuelos yielded an Ar^{40}/Ar^{39} age of 4.01 Ma (Table 1; Fig. 6).

The coarsest Puye deposits in the quadrangle, including massive boulder conglomerates (individual boulders exceed 5 m across), occur near the top of the present Puye surface where Rio del Oso exits the Tschicoma highlands and just west of Loma Parda (Fig. 6). The depositional mode of emplacement of these massive boulder conglomerates is difficult to interpret. Possibly they represent large-scale debris flows off the adjacent Tschicoma highlands, although there is very little matrix material within the deposit.

A spurt of mafic volcanism occurred along the western margin of Mesa El Alto at approximately 2.9 Ma, when at least four eruptive centers became active along a NS-trending fissure system flanking Rincón de Mora and Los Cerritos. These deposits include scoria and proximal lava flows. In the field, the basalt clearly overlies dacitic lava from Cerro Pelón (2.96 Ma). The basalt flowed northwards, filling the ancestral Abiquiu Creek valley and capping a broad terrace surface on the Ojo Caliente Sandstone as it flowed into the Chama Valley (now preserved as Mesa de Abiquiu).

In general, the Tschicoma highlands blocked Bandelier Tuff from entering Mesa El Alto. However, thin (less than 1 m thick), isolated exposures of Otowi Member tuff are present (Fig. 6), containing abundant quartz and sanidine phenocrysts and a moderate amount of lithic fragments. Locally, several meters of Guaje tephra underlie this condensed section of Otowi Member. Most likely, very distal clouds of Otowi pyroclastic flows settled in this valley, forming thin layers of tuff in locally conducive environments. No evidence of Tshirege Member pyroclastic flows is present in the valley. However, deposits of Guaje tephra (~1.61 Ma Otowi Member) and Tsankawi tephra (~1.25 Ma Tshirege Member) provided unconsolidated pumice material that was remobilized and incorporated into Quaternary alluvial deposits mapped in the valley. The widespread occurrence of obsidian fragments in these deposits also suggests a Cerro Toledo or El Rechuelos Rhyolite source.

Besides remnant Otowi Member tuff exposures, numerous mounds and poorly exposed outcrops of stratified pumice occur in the valley. Several occur in the vicinity of the tuff outcrops, suggesting a connection between the two (most likely Guaje tephra). In many places old Quaternary alluvium (Qoa in Fig. 6) caps Puye deposits. These deposits are at least of post-Otowi age, containing abundant crystals of Bandelier Tuff and well-rounded, greenish black obsidian pebbles that are likely related to Cerro Toledo obsidian domes prior to the Valles caldera eruption. Without Tshirege Member tuff preserved in the valley, however, the age of these alluvial deposits is unclear. If they are older than Tshirege then they could be classified as Cerro Toledo interval deposits.

Lobato Mesa

Miocene sediments

Lobato Mesa includes three NS-trending ridges of mafic lavas flanked by down-to-the-west normal faults. These faults are in general alignment with similar down-to-the-west faults to the south on the Pajarito Plateau (Guaje Mountain and Rendija faults) and might be related to subsidence along the Tschicoma Formation volcanic axis due to the large volume of dacite lavas emplaced between ~5.3 to 3 Ma (Kempter et al., 2005). Underlying the mafic lavas are sediments that belong to the rift-fill Chama-El Rito and Ojo Caliente Members of the Tesuque Formation. The Chama-El Rito Member consists of siltstones, sandstones and other fluvial gravels indicative of a relatively low energy floodplain depositional environment. The age of the Chama-El Rito spans from 18 to 13.4 Ma (Koning et al., 2007). The overlying Ojo Caliente Member consists primarily of massive medium-grained sand of eolian origin, representing a vast erg that covered much of the northern Jemez Mountains area between 13.4 to 12.5 Ma (Koning et al., 2007). Similar to exposures under Lobato basalt in Cañones Canyon discussed earlier, thin lenses of fluvial gravel cap the Ojo Caliente sandstone, dominated by volcanic clasts of uncertain provenance (possibly the San Juan or Latir volcanic fields), and lesser amounts of quartzite and granite that are most likely derived from areas to the north, including the Tusas Mountains.

Miocene volcanics and associated sediments

Mafic lavas of Lobato Mesa were primarily emplaced between 10.5 and 9.0 Ma, with the bulk of the eruptions occurring between 10 and 9.5 Ma, including those related to the Clara Peak center south of Rio del Oso Canyon (Table 1; Fig. 8). In general, these lavas are black to gray, sparsely to moderately porphyritic, containing phenocrysts of plagioclase, olivine, ± clinopyroxene in a variety of groundmass types. In general, these and other mafic lavas in the northern Jemez Mountains are referred to as basalts, although geochemical classifications (e.g., LeBas et al., 1986) indicate that many flows are not true basalts. Interlayered with the basalts are thin sediments of fluvial origin that may represent continued Santa Fe Group deposition in the area during Lobato volcanism. Most of the Lobato vents and dikes in the area are aligned roughly north-south, parallel to structural trends. Major vent sources include Clara Peak, La Bentolera, La Sotella, and the vicinity of Cerrito del Chibato (Kempter et al., 2005).

Fine- to medium-grained dikes and crystalline gabbroic sills or plugs intrude the mafic complexes and sedimentary rocks. One such gabbro related to the Clara Peak center is well exposed along Forest Road 144 as it first enters the Vallecitos quadrangle from the east (Stop 4 on the Day 1 road log). In Cañada del Almagre near the Chili and Vallecitos quadrangle boundary (Fig. 1), a spectacular combination dike/sill intrudes the Chama-

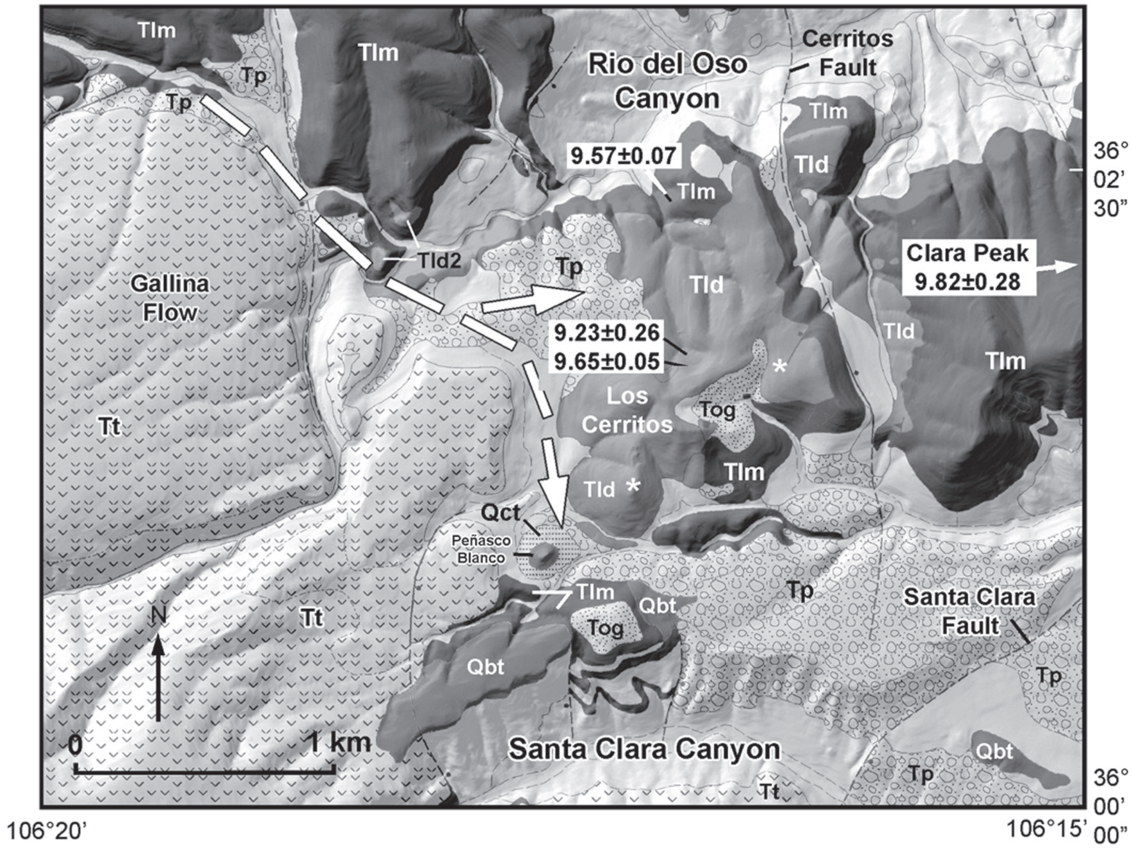

FIGURE 8. Simplified geologic map of the Los Cerritos area at the south end of Lobato Mesa. Distal flows of Tschicoma Formation dacite (**Tt**) overlap Lobato Formation mafic lavas (**Tlm**). Older Tschicoma-like dacites (**Tld2**) are interbedded with the Lobato mafic lavas. The Los Cerritos dacite center (**Tld**) caps the mafic lava sequence. Old Miocene (?) gravels (**Tog**) are significantly higher than later Puye Formation sediments (**Tp**). White path with arrow is an old Puye channel. Young deposits of Cerro Toledo interval sediments (**Qct**) and Tshirege Member tuff (**Qbt**) are preserved just north of the Santa Clara Canyon rim.

El Rito Member, the sill forming a resistant floor in part of the valley bottom. This intrusion, dated at 9.74±0.21 Ma, is offset by the Cañada del Almagre fault (see Koning and Kempter, 2007). Another prominent dike flanked by cinder deposits is located immediately south of Cerrito del Chibato. The youngest lavas on Lobato Mesa erupted from a vent near a ridge named La Bentolera. These distinctive lavas have a crystalline matrix and are nearly aphyric, containing 0-2% phenocrysts (and xenocrysts) of pyroxene, pyroxene-olivine aggregates, quartz, and potassium feldspar. Rare granitic xenoliths also occur in this unit.

Dacitic volcanic activity, though less voluminous, affected the area during the later stages of mafic volcanism. At least one large dacitic flow is interbedded with mafic lavas (exposed in Rio del Oso Canyon; Bailey et al., 1969), although its source vent is unknown. This flow is strikingly similar in appearance to later Tschicoma Formation lavas, including similar porphyritic textures with large phenocrysts of plagioclase and lesser amounts of biotite ± hornblende.

A large dacite center (Los Cerritos) west of Clara Peak and south of Rio del Oso Canyon (Fig. 8) caps the mafic lava package on the south side of Rio del Oso Canyon, and vented a fluid, low aspect-ratio lava that flowed to the northeast, lapping onto the western margin of the Clara Peak center (at Los Cerros). This dacite, dated at 9.23±0.26 and 9.65±0.05 Ma (Table 1), is light colored and fine grained, with few phenocrysts (plagioclase and hornblende). Brecciated horizons are common in several outcrops, possibly representing dacitic "aa", or a widespread block and ash flow event during the eruptive process. Just east of the Los Cerritos center, the Cerritos fault, a major NNW-SSE down-to-the-east fault offsets the lava by 50 to 65 m. Underlying basalts appear to be of similar thickness on either side of the fault, suggesting that this fault was mostly active after 9.5 Ma, the approximate age of the dacite lava.

A gravel-filled crater is believed to occur in the middle of the Los Cerritos center. These coarse gravels (Tog in Fig. 8) are perched at a much higher elevation than the younger Puye Formation, and are composed of angular to subrounded Lobato mafic and dacitic lavas. Another high gravel surface occurs ~1 km to the southwest of the crater (just southeast of Peñasco Blanco), and is similarly interpreted to represent late Miocene gravels older than the Puye Formation.

Plio-Pleistocene volcanics and sediments

Puye Formation gravels that spilled into Mesa El Alto also cap much of the Lobato sequence on the south side of Rio del Oso. The

~4.0 Ma Gallina flow extended to the southern margin of Lobato Mesa, constricting drainage between Mesa El Alto and areas to the east. We propose that this constriction facilitated Puye backfilling along the Gallina flow margin and Lobato basalts, especially in low points between Lobato fault blocks. Once backfilling was complete, however, an old Puye channel brought sediments from the southern Mesa El Alto southeastward into the Santa Clara Canyon area, bypassing the Rio del Oso drainage to the northeast (Fig. 8). Later (Pleistocene?) headward erosion of Rio del Oso Creek likely captured this southeastern drainage. This interpretation may explain the lack of Puye Formation deposits in the Chili badlands east of Lobato Mesa.

Old gravels of uncertain age occur in several places on Lobato Mesa, particularly in lowlands between fault blocks. A few dacitic pumice deposits, presumably of Puye age, also occur in valleys on the south side of Lobato Mesa.

Both the Otowi and Tshirege pyroclastic flows followed an ancestral Santa Clara Canyon drainage to be deposited in the northernmost Pajarito Plateau area. Several remnant outcrops of the Tshirege Member occur just north of Santa Clara Canyon after it exits the massive Tschicoma section to the east, including a knob named Peñasco Blanco just southwest of the Cerritos dacite center (Fig. 8). Farther east of the Santa Clara fault, Otowi pyroclastic flows filled in low channels on the upper Puye Formation surface, locally capping and preserving thick sections of Guaje tephra that is presently being mined for pumice on Santa Clara Pueblo Tribal lands.

SUMMARY

The geologic traverse presented here conveys the diverse and complex geologic settings that comprise the northern Jemez Mountains, from Colorado Plateau Paleozoic and Mesozoic stratigraphy on the west to dynamic Rio Grande rift faulting, sedimentation and volcanism toward the east. In the northwestern Jemez Mountains, the Pedernal Chert Member of the Abiquiu Formation occurs not only at the boundary of the lower and upper members, but also typically caps the upper member, forming high mesas that impeded pyroclastic flows of the Otowi and Tshirege Members of the Bandelier Tuff. These flows were directed along a northwestern corridor that skirted the western margin of the La Grulla Plateau, forming Mesa Pinabetosa and covering an eroded topography along the faulted margin of the eastern Colorado Plateau. A second corridor for the Bandelier Tuff existed between La Grulla Plateau and the Tschicoma highlands, where unusually thick and densely welded Otowi Member tuff filled a paleo-Cañones Canyon. A complex history of erosion and sedimentation is preserved along this northern corridor, including rare sedimentary deposits that preceded, interceded, and postdated Bandelier Tuff eruptions.

Available age data indicate that widespread mafic volcanism affected the northeastern Jemez Mountains between 10.5 and 9 Ma, and was especially intense between 10 and 9.5 Ma. A significant dacite center, Los Cerritos, caps the mafic sequence south of Rio del Oso and vented a low aspect ratio lava that lapped onto the western flank of the Clara Peak center at ~ 9.5 Ma. This dacite was subsequently offset by 50 to 65 m by the Cerritos fault, a northward splay of the Santa Clara fault. Volcanic activity then migrated eastward to the La Grulla Plateau, where eruptions between 8.5 and ~ 7 Ma emplaced a lower mafic sequence of basaltic andesite to andesite lavas (extending north to Mesa Escoba and Cerro Pedernal) capped by more silicic andesite to dacite lavas. Although geologic mapping to date has included these lavas into either "Lobato" or "Tschicoma" Formations, we anticipate changes in stratigraphic nomenclature in the near future (see Kelley et al. minipaper, 2007) to accommodate the distinct timing and geochemical range of lavas erupted on the La Grulla Plateau compared to those of the northeastern Jemez Mountains.

Volcanism shifted back to the east between ~5.3 to 3 Ma as massive high-aspect ratio dacitic lavas of the Tschicoma Formation erupted along NS-trending fracture systems. Lavas associated with Tschicoma Peak erupted between 4.5 to 3.5 Ma, including the massive Gallina flow at ~ 4.0 Ma. Porphyritic dacite lavas that extend from the rim of the Toledo embayment to the edge of Mesa del Medio (approximately 7 km to the north) yield nearly identical ages of ~3.3 Ma, possibly representing a single massive flow. Tschicoma volcanism spawned Puye Formation sedimentation in Mesa El Alto, and for a brief time after the emplacement of the Gallina flow the Puye drainage system exited to the southeast towards Santa Clara Canyon.

The El Alto basalt erupted at ~ 2.9 Ma from several vents along a fissure system on the west margin of Mesa El Alto, followed at ~ 2.1 Ma by three aphyric rhyolite domes (El Rechuelos Rhyolite) emplaced along a curvilinear fissure system west of Polvadera Peak. These were the last eruptions in the northern Jemez Mountains until the Toledo and Valles caldera and associated eruptions occurred at ~1.61 and ~1.25 Ma, respectively. In general, the Tschicoma highlands blocked the massive Bandelier Tuff pyroclastic flows from the Mesa El Alto and Lobato Mesa region, although thin and sparse outcrops of Otowi Member tuff are preserved.

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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.

Baldridge, W.S., Damon, P.E., Shafiqullah, M., and Bridwell, R.J., 1980, Evolution of the central Rio Grande rift, New Mexico: new Potassium-Argon ages: Earth and Planetary Science Letters, v. 51, p. 309-321.

Broxton, D.E., and Reneau, S.L., 1995, Stratigraphic nomenclature of the Bandelier Tuff for the Environmental Restoration project at Los Alamos National Laboratory: Los Alamos National Laboratory, Report: LA-13010-MS, 21 p.

Church, F.S., and Hack, J.T., 1939, An exhumed erosion surface in the Jemez Mountains, New Mexico: Journal of Geology, v. 47, p. 613-629.

Dalrymple, G.B., Cox, A., Doell, R.R., and Gromme, C.S., 1967, Pliocene geomagnetic polarity epochs: Earth and Planetary Science Letters, v. 2, p. 163-173.

Gardner, J.N. and Goff, F., 1996, Geology of the northern Valles caldera and Toledo embayment: New Mexico Geological Society, 47th Field Conference, Guidebook, p. 225-230.

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, p. 1763-1778.

Gardner, J.N., Goff, F., Reneau, S.L., Sandoval, M., Drakos, P., Katzman, D., and Goff, C.J., 2006, Preliminary geologic map of the Valle Toledo quadrangle, Sandoval County, New Mexico: N.M. Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM-133, scale 1:24,000.

Goff, F., and Grigsby, C. O., 1982, Valles caldera geothermal systems, New Mexico, USA: Journal of Hydrology, v. 56, p. 119-136.

Goff, F., Gardner, J., Baldridge, W.S., Hulen, J., Neilson, D., Vaniman, D., Heiken, G., Dungan, M., and Broxton, D., 1989, Excursion 17B: volcanic and hydrothermal evolution of Valles caldera and Jemez volcanic field: New Mexico Bureau of Mines and Mineral Resources, Memoir 46, p. 381-434.

Goff, F., Reneau, S.L., Goff, C.J., Gardner, J.N., Drakos, P. and Katzman, D., 2006, Preliminary geologic map of the Valle San Antonio quadrangle, Sandoval and Rio Arriba Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 132, scale 1:24,000.

Justet, L., 2003, Effects of basalt intrusion on the multi-phase evolution of the Jemez volcanic field [Ph.D. dissertation]: Las Vegas, University of Nevada, 248 p.

Justet, L., and Spell, T.L., 2001, Effusive eruptions from a large silicic magma chamber: the Bearhead Rhyolite, Jemez volcanic field, N.M.: Journal of Volcanology and Geothermal Research, v.107, p. 241-264.

Kelley, S.A., Lawrence, J.R., and Osburn, G.R., 2005, Geology of the Youngsville 7.5 minute quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 106, scale 1:24,000.

Kelley, S.A., Lawrence, J.R., Zeigler, K.E., Osburn, G.R., and Lucas, S.G. 2006. Preliminary geologic map of the Arroyo del Agua quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 124, scale 1:24,000.

Kelley, S.A., Kempter, K.A., and Lawrence, J.R., 2007, Stratigraphic nomenclature and trends in volcanism in the northern Jemez Mountains: New Mexico Geological Society, 58th Field Conference, Guidebook, p. 48-49.

Kempter, K.A., Kelley, S., Goff, F., and Rampey, M., 2004, Preliminary geologic map of the Polvadera Peak 7.5-minute quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 96, scale 1:24,000.

Kempter, K.A., Kelley, S., Koning, D., Ferguson, C., Osburn, B., and Fluk, L., 2005, Preliminary geologic map of the Vallecitos 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 108, scale 1:24,000.

Koning, D.J., and Aby, S.B., 2005, Proposed members of the Chamita Formation, north-central New Mexico: New Mexico Geological Society, 56th Field Conference, Guidebook, p. 258-278.

Koning, D.J., and Kempter, K.A., 2007, Inferences regarding middle to late Miocene vertical motion on the Cañada del Almagre and Cerritos faults near Clara Peak, northeastern Jemez Mountains: New Mexico Geological Society, 58th Field Conference, Guideboook, p. 49-51.

Koning, D.J., Kelley, S.A., and Kempter, K.A., 2007, Geologic structures near the boundary of the Abiquiu embayment and Colorado Plateau – a long history of faulting: New Mexico Geological Society, 58th Field Conference, Guidebook, p.43-45.

Krainer, K., Vachard, D., and Lucas, S.G., 2005, Lithostratigraphy and biostratigraphy of the Pennsylvanian-Permian transition in the Jemez Mountains, north-central New Mexico: New Mexico Museum of Natural History and Science, Bulletin 31, p. 74-89.

Kues, B.S., and Giles, K.A., 2004, The Late Paleozoic Ancestral Rocky Mountains system in New Mexico: *in* Mack, G.H., and Giles, K.A., eds., Geology of New Mexico, a geologic history: New Mexico Geological Society, Special Publication 11, p. 95-136.

Lawrence, J.R., Kelley, S.A., and Rampey, M., 2004, Preliminary geologic map of the Cerro del Grant 7.5-minute quadrangle, Rio Arriba and Sandoval Counties, New Mexico: New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 87, scale 1:24,000

Lawrence, J.R., 2007, Stratigraphy and geochronology of mafic to intermediate volcanic rocks of La Grulla Plateau, northwestern Jemez Mountains: New Mexico Geological Society, 58th Field Conference, Guidebook, p. 46-47.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Loeffler, B.M., 1984, Major- and trace-element and strontium- and oxygen-isotope geochemistry of the Polvadera Group, Jemez volcanic field, New Mexico: implications for the petrogenesis of the Polvadera Group [Ph.D. dissertation]: Boulder, University of Colorado, 259 p.

Loeffler, B.M., Vaniman, D.T., Baldridge, W.S., and Shafiqullah, M., 1988, Neogene rhyolites of the northern Jemez volcanic field, New Mexico, Journal of Geophysical Research, v. 93 (B6); p. 6157-6168.

Logsdon, M.J., 1981, A preliminary basin analysis of the El Rito Formation (Eocene), north-central New Mexico: Geological Society of America Bulletin, v. 92, p.

Lucas, S.G., and Krainer, K., 2005, Stratigraphy and correlation of the Permo-Carboniferous Cutler Group, Chama Basin, New Mexico: New Mexico Geological Society, 56th Field Conference, Guidebook, p. 145-159.

Maldonado, F., and Miggins, D.P., 2007, Geologic summary of the Abiquiu Quadrangle, north-central New Mexico: New Mexico Geological Society, 58th Field Conference, Guidebook, p.182-187.

Moore, J.D., 2000, Tectonics and volcanism during deposition of the Oligocene-lower Miocene Abiquiu Formation in northern New Mexico [M.S. thesis]: Albuquerque, University of New Mexico, 147 p.

Phillips, E.H., Goff, F., Kyle, P.R., McIntosh, W.C., Dunbar, N.W., and Gardner, J.N., in press, $^{40}Ar/^{39}Ar$ age constraints on the duration of resurgence at the Valles caldera, New Mexico: Journal of Geophysical Research.

Singer, B.S., 1985, Petrology and geochemistry of Polvadera Group rocks of La Grulla Plateau, northwestern Jemez volcanic field, New Mexico: evidence favoring evolution by assimilation-fractional crystallization (AFC): [M.S. thesis]: Albuquerque, University of New Mexico,148 p.

Smith, H.T.U., 1938, Tertiary geology of the Abiquiu quadrangle, New Mexico: Journal of Geology, v. 46, p. 933-965.

Smith, C. T., Budding, A. J., and Pitrat, C. W., 1961, Geology of the southeastern part of the Chama basin: New Mexico Bureau of Mines and Mineral Resources, Bulletin 75, 57 p.

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 Map I-571, scale 1:125,000.

Smith, G.A., Moore, J.D., and McIntosh, W.C., 2002, Assessing roles of volcanism and basin subsidence in causing Oligocene-lower Miocene sedimentation in the northern Rio Grande rift, New Mexico, U.S.A.: Journal of Sedimentary Research, v. 72, p. 836-848.

Timmer, R.S., 1976, Geology and sedimentary copper deposits in the western part of the Jarosa and Seven Springs quadrangles, Rio Arriba and Sandoval Counties, New Mexico [M.S. Thesis]: Albuquerque, University of New Mexico, 150 p.

Timmer, R., Woodward, L., Kempter, K., Kelley, S., Osburn,R., Osburn, M., Buffler,R. ,and Lawrence, J.R. 2006, Preliminary geologic map of the Jarosa quadrangle, Rio Arriba County, New Mexico, New Mexico Bureau of Geology and Mineral Resources, Open-file Geologic Map OF-GM 128, scale 1:24,000.

Vazzana, M.E., and Ingersoll, R.V., 1981, Stratigraphy, petrology, and basin evolution of the Abiquiu Formation (Oligo-Miocene), north-central New Mexico: Geological Society of America Bulletin, Part II, v. 92, p. 2401-2483.

Wood, G.H., and Northrop, S.A., 1946, Geology of the Nacimiento Mountains, San Pedro Mountain, and adjacent plateaus in parts of Sandoval and Rio Arriba Counties, New Mexico: U.S. Geological Survey, Oil and Gas Investigations Map OM-57.

Woodward, L.A., 1996, Paleotectonics of the late Paleozoic Peñasco uplift, Nacimiento region, northern New Mexico: New Mexico Geological Society, 48th Field Conference, Guidebook, p. 107-113.