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

By

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Open-file Digital Geologic Map OF-GM 42

Scale 1:24,000

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Geologic Map and Structure of the Frijoles Quadrangle, Los Alamos and Sandoval Counties, New Mexico

1:24,000

by

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INTRODUCTION

The Frijoles 7.5 minute quadrangle covers an area within Los Alamos and Sandoval counties and includes parts of the southern Pajarito Plateau and southeastern Jemez Mountains, New Mexico (Figure 1). Topographically, the Frijoles quadrangle is bounded by Los Alamos Canyon on the north, the Sierra de los Valles on the west, the San Miguel Mountains on the southwest, and White Rock Canyon of the Rio Grande on the extreme southeast. Much of the area of the quadrangle is covered by the Pajarito Plateau, formed by thick pyroclastic deposits of Bandelier Tuff emplaced at 1.2 to 1.6 Ma. The plateau of pyroclastic deposits has been deeply incised by streams, yielding a distinctive and rugged finger-mesa and canyon topography. The quadrangle includes portions of the Pajarito fault system, which forms the locally active, western boundary of the Rio Grande rift. Generally speaking, this fault zone separates the Jemez Mountains volcanic field on the west from the Pajarito Plateau and the modern Española Basin of the Rio Grande rift on the east. Sedimentary deposits beneath the Pajarito Plateau contain deep aquifers with potable waters that supply the needs of Los Alamos and White Rock, and several U.S. government installations.

Los Alamos National Laboratory now occupies the northern half of the quadrangle and Bandelier National Monument lies on the southern half. The western

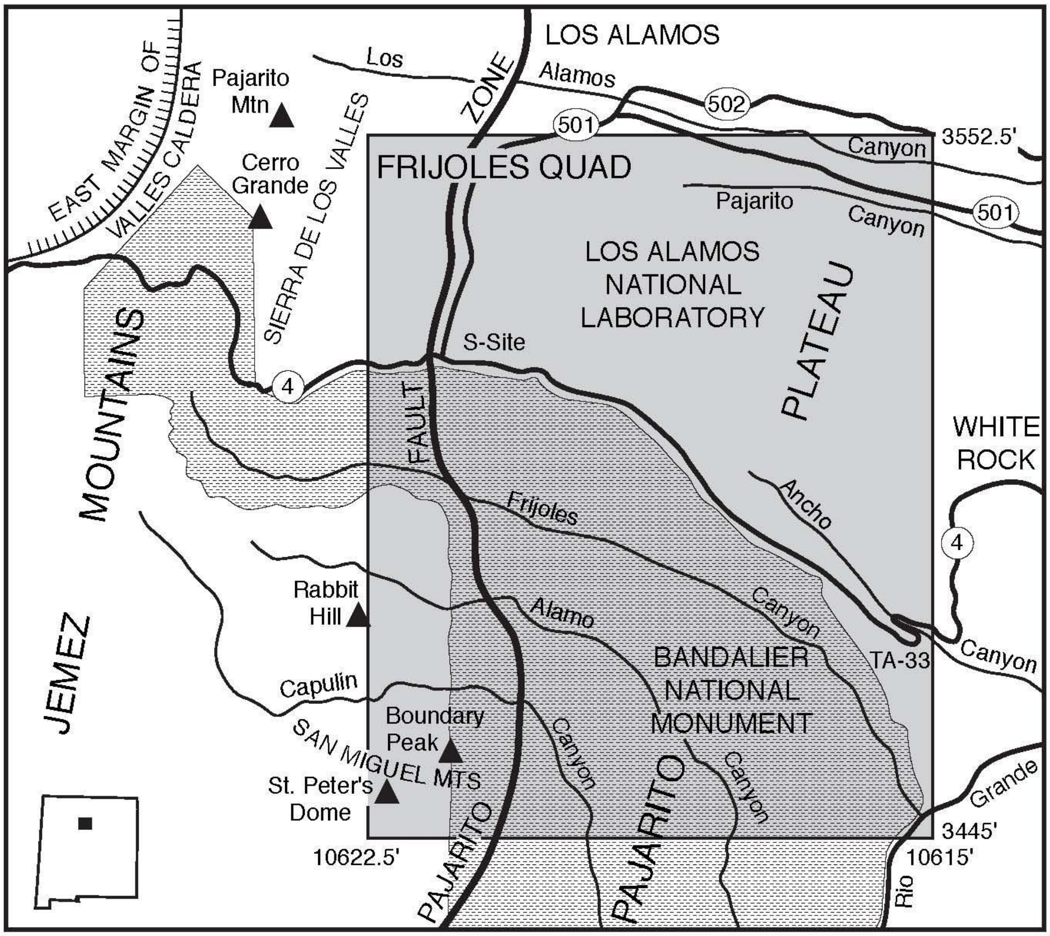

FIGURE 1. Location map of Frijoles Quadrangle, New Mexico showing major physiographic features.

margin of the quadrangle is part of the Santa Fe National Forest. The northern half of the Frijoles quadrangle is traversed by several paved roads. A paved road also accesses Eastern Frijoles Canyon in Bandelier National Monument. Access within most lands of Los Alamos National Laboratory (LANL) is highly restricted. Access to National Forest lands is by dirt road or trail. The southern part of the quadrangle, in the Dome Wilderness Area of Santa Fe National Forest and Bandelier National Monument (BNM), can only be accessed by trail.

This region was once home to pre-Columbian Indian cultures (ancestral Puebloan, or Anasazi) and later contained Spanish land grants, homesteads, scattered ranches, logging operations, and parts of the World War II Manhattan Project. Consequently, the map area has unique historic importance and contains hundreds, if not thousands, of ancestral Puebloan ruins that range from still-active shrines to single room field houses to large pueblo-style complexes. Paleoseismic excavations on Pajarito Mesa have revealed a pre-Anasazi hearth dated at about 10 ka (Reneau et al., 1995a).

The objectives of the Frijoles quadrangle map are to provide structural and stratigraphic boundary conditions for environmental and hydrologic programs of Los Alamos National Laboratory, to contribute to the geologic quadrangle mapping program of the New Mexico Bureau of Mines and Mineral Resources and U.S. Geological Survey, and to furnish archeological and volcanic information for the Bandelier National Monument and the Valles Caldera National Preserve. The geology of the quadrangle was mapped primarily during the spring and summer months of 2001, supplemented by published and unpublished mapping of the authors. Regional geology and stratigraphy have been previously published by Griggs (1964), Bailey et al. (1969), Smith et al. (1970), Kelley (1978), Gardner et al., (1986, 2010), Goff and Gardner (2004), and Goff et al. (2011). Detailed mapping of the St. Peter's Dome area was compiled from the geology of Goff et al. (1990). Gardner and Goff (1996) published a geologic map of the northern half of the Valle Toledo 7.5 minute quadrangle northwest of the Frijoles quadrangle. Detailed mapping of western Los Alamos National Laboratory was compiled from Gardner et al. (1999, 2001) and Reneau (unpub.). Detailed mapping of DP Mesa in the extreme northeast corner of the quadrangle was compiled from Goff (1995) and detailed mapping of the Chaquehui and Ancho canyon areas in the southeastern part of the quadrangle was compiled from Reneau et al. (1995a, and unpub.). Dethier (1997) published the geology of the White Rock Canyon 7.5 minute quadrangle, immediately east of Frijoles quadrangle. Additionally, it should be noted that most of the area of Los Alamos National Laboratory was previously mapped by Rogers (1995).

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STRATIGRAPHY

The oldest rock units in the Frijoles quadrangle occur east of St. Peter's Dome in the southwest part of the quadrangle and are composed of orange to brick-red, west-tilted sandstones and conglomerates of the Eocene Galisteo Formation (Stearns, 1943; Cather, 1992). This sequence consists of two lithologically similar exposures bounded on their east margins by parallel segments of the Pajarito fault zone. These Galisteo exposures are unconformably overlain by buff to white, nonindurated to weakly indurated sandstones and siltstones of the Miocene Santa Fe Group. Galisteo rocks dip west from 35 to 45° but Santa Fe Group rocks typically dip southwest from 7 to 15°. A thin flow and pillow-palagonite zone of alkali basalt occurs in the Santa Fe Group east of St. Peter's Dome. A K-Ar date of 16.5 Ma and recent $^{40}Ar/^{39}Ar$ dates of 18.6 to 25.3 Ma were obtained on similar basalt flows just south of the map area (Gardner et al., 1986; Goff et al., 1990; WoldeGabriel et al., 2006). Thus, the Santa Fe sequence in the southwest map area is roughly contemporaneous with sedimentary deposits of the Tesuque Formation, Santa Fe

Group (15.5 Ma, McIntosh and Quade, 1995) located east of the Rio Grande and northeast of the Frijoles quadrangle.

A poorly exposed unit of nonindurated Santa Fe Group occurs east of the Rio Grande across from Frijoles Canyon in the southeast corner of the map area. The unit correlates with Santa Fe Group rocks exposed discontinuously upstream along the Rio Grande in the White Rock quadrangle (Dethier, 1997). Where exposed, these Santa Fe rocks unconformably underlie the Puye Formation, including an ancestral Rio Grande facies (the Totavi Lentil), and Cerros del Rio hydromagmatic (maar) deposits and lavas. The age of these Santa Fe Group rocks is unknown. Dethier (1997) indicates they correlate in part with sedimentary deposits of the Tesuque Formation and suggests that they may correlate with deposits of the Ancha Formation, a Pliocene fanglomerate unit originating from sources east of the Rio Grande and east of the Frijoles quadrangle (Spiegel and Baldwin, 1963; Manley, 1979).

Unconformably overlying the Santa Fe Group is the Keres Group, the earliest sequence of Jemez volcanic rocks in the quadrangle. The lowest unit of the Keres Group having widespread exposure is a distinctive pink, lithic-rich, pyroclastic fall and flow deposit of Canovas Canyon Rhyolite on the east flank of St. Peter's Dome. Just south of the quadrangle, a thick rhyolite flow overlying the "pink tuff" has a composite K-Ar age of 12.4 Ma (Goff et al., 1990) and a recent $^{40}Ar/^{39}Ar$ age of 9.6 Ma (WoldeGabriel et al., 2006). Locally, the "pink tuff" is missing from the section, and younger Keres Group rocks rest directly on the Santa Fe Group. Other older Keres Group rocks in the quadrangle include a basalt flow in the bottom of Capulin Canyon north of St. Peter's Dome that has a K-Ar date of 11.3 Ma (Goff et al., 1990). Above the older units is a complicated sequence of Keres Group domes, flows and tuffs ranging compositionally from basalt through rhyolite that are interbedded with coeval volcaniclastic deposits. There is no compositional progression in this sequence of rocks, which is dominated by andesitic to dacitic units of the Paliza Canyon Formation. The youngest Paliza Canyon unit in the map area is a porphyritic andesite flow, dated at 8.7 Ma, capping St. Peter's Dome (Dalrymple et al., 1967; Gardner and Goff, 1984). Paliza Canyon rocks are intruded and overlain by the Bearhead Rhyolite.

Interbedded with Keres Group rocks is a thick sequence of volcaniclastic deposits included within the Cochiti Formation as defined by Bailey et al. (1969). We use a more inclusive definition of Cochiti Formation than offered by Smith and Lavine (1996). In the map area, these rocks consist of lahars, block and ash flows, dome collapse breccias, and other debris flows, with minor cinder cone and fluvial deposits (Goff et al., 1990). These deposits also include thin andesitic flows and andesitic to dacitic tuffs that are commonly too thin to be mapped individually. Several stratigraphic sections of these deposits were described in detail by Lavine et al. (1996) who dated four of the dacitic tuffs at about 9.1 to 9.5 Ma. Overall, this volcaniclastic sequence is bracketed between about 11 and 8.7 Ma. The volcaniclastic deposits, which were shed into topographic low areas between Paliza Canyon volcanic centers, generally thicken to the south and east toward the Rio Grande rift. They overlie the "pink tuff" east of St. Peter's dome. In the east wall of Capulin Canyon north of the Guard Station, a thin exposure (≤5 m) of the volcaniclastic deposits overlies the Santa Fe Group and underlies the Otowi Member of the Bandelier Tuff. This exposure is too thin to show on the map. Volcaniclastic deposits of the Cochiti Formation are intruded and overlain by Bearhead Rhyolite within the St. Peter's Dome region (Goff et al., 1990).

Based on exposures of Keres Group rocks on the northeast wall of Valles caldera (Smith et al., 1970; Gardner and Goff, 1996), fanglomerates of Cochiti Formation underlie the Puye Formation and domes of the Tschicoma Formation east of the Pajarito fault (cross section A-A'). Fanglomerates of the Cochiti Formation also underlie the Puye Formation, mafic flows and hydromagmatic deposits of the Cerros del Rio volcanic field in the southwestern Pajarito Plateau (cross section B-B'). Although these relations are not exposed, they can be inferred from exposures at either end of the cross section.

Domes, flows, and associated tuffs of Bearhead Rhyolite intrude and overlie all other units of the Paliza Canyon Formation. Within the Frijoles quadrangle, Bearhead Rhyolite consists only of the east edge of Rabbit Hill dome (6.6 Ma; Justet, 1996) and the unnamed rhyolite dome and flow complex on the mesa east of Rabbit Hill. The latter intrudes hornblende dacite of the Paliza Canyon Formation along a contact partly hidden by the El Cajete pumice, and overlies volcaniclastic deposits of the Cochiti Formation along the south wall of upper Alamo Canyon.

The next episode of volcanism in the Frijoles quadrangle is represented by the Cerro Grande and Pajarito Mountain dome and flow complexes in the Sierra de los Valles, west of Los Alamos. These large eruptive centers were constructed from about 3.8 to 2.9 Ma (Dalyrymple et al., 1967; G. WoldeGabriel et al., 2006) and are part of the Tschicoma Formation (Griggs, 1964; Bailey et al., 1969; Smith et al., 1970; Gardner et al., 1986; Goff and Gardner, 2004; Goff et al., 2011). Relations between these Tschicoma Formation flows and rocks of the Paliza Canyon Formation are not exposed in the Frijoles quadrangle although the two groups are discontinuously exposed in upper Frijoles Canyon. However, Tschicoma flows overlie Paliza Canyon rocks in the north wall of Valles caldera 10 km northwest of the map area (Smith et al., 1970; Gardner and Goff, 1996) and overlie a poorly exposed andesite of Paliza Canyon affinity in upper Los Alamos Canyon, just north of the map area (D. Broxton, unpub. data). Tschicoma dacite plugs intrude Paliza Canyon rocks in the southern Jemez Mountains (Gardner et al., 1986). The Tschicoma is overlain in part by ignimbrite of the Tshirege Member, Bandelier Tuff.

The Puye Formation is dominantly an extensive volcaniclastic alluvial fan complex shed eastward from volcanic domes and flows of the Tschicoma Formation. The fan facies of the formation is not exposed in the Frijoles Quadrangle but extensive thicknesses are penetrated by wells and thus appear in the cross sections. The Puye Formation was mapped by Griggs (1964) and by Smith et al. (1970). The unit is well exposed north of the Pajarito Plateau and is intersected by all deep, water wells in the Pajarito Plateau area (Dransfield and Gardner, 1985; Purtymun, 1995). Waresback (1986) studied the evolution of the Puye Formation on a sedimentological basis while Turbeville et al. (1989) investigated volcanological origins of the unit. The Puye Formation is distributed over an area of 200 km^2 and contains >15 km^3 of volcaniclastic material. Most of the Puye conglomerates contain cobbles of dacitic to andesitic composition in a volcanic sand matrix. At least 25 ash beds of dacitic to rhyolitic composition are interbedded within the fanglomerates. Basaltic ash beds, pillow-palagonite complexes and lacustrine deposits are found on the east side of the deposit, associated with the Cerros del Rio volcanic field. By original definition, (Bailey et al. 1969; Gardner et al., 1986), Puye deposits should be at least as old as 7 Ma and as young as 1.6 Ma. At this time, we are tentatively correlating sediments of the upper Santa Fe Group of Griggs (1964) and the Chaquehui Formation of Purtymun (1995) with older fanglomerates of the Puye Formation based on the abundance of volcanic fragments of Jemez volcanic field affinity in the sediments. As a result, lower Puye as defined here may be at least 9 Ma based on older olivine basalt dates in well OT-4 (section D-D', see below). However, because of recent revelations from drilling, dating and geochemistry, the nomenclature of sedimentary units beneath the Bandelier Tuff on the Pajarito Plateau has undergone serious revisions (Broxton and Vaniman, 2005).

As defined by Purtymun (1995), the Chaquehui Formation "is composed of a mixture of volcanic debris from the Sierra de los Valles and arkosic and granitic debris from the highlands to the north and east." Unfortunately, the Chaquehui Formation is named for a sequence of Pliocene maar deposits in lower Chaquehui Canyon just east of Frijoles quadrangle. Thus, the type locality does not match the definition of the formation in time, space or lithology and the authors do not recognize it as a viable formational name.

The Puye fanglomerates display considerable lateral variation and are complex, intertonguing mixtures of stream flow, sheet flow, debris flow, block and ash flow, pumice fall, and ignimbrite deposits. Maximum exposed thickness is about 120 m in Pueblo Canyon north of Frijoles Quadrangle (Griggs, 1964) but reaches an apparent thickness of nearly 660 m in hole OT-4. Interbedded Polvadera Group dacite and andesite flows, and Cerros del Rio basalt flows are common. The former relations are best observed in water wells on the western side of the plateau (CdV-R-15-3 and DT-5A) whereas the latter relations are well exposed in White Rock Canyon (Dethier, 1997).

The Puye Formation includes a coarse, poorly consolidated conglomerate that contains pebbles, cobbles and boulders of primarily quartzite, granite, pegmatite, and altered volcanics. Because it is sedimentologically similar to modern Rio Grande fluvial deposits, it is believed to represent deposits of an ancestral Rio Grande. It was originally named the Totavi Lentil by Griggs (1964), who defined it as the basal unit of the Puye Formation based on conformable bed relations with overlying fanglomerate layers. Because it is probably a time transgressive unit that occurs at various stratigraphic levels, more recent workers have abandoned the name Totavi Lentil and instead refer to these deposits as an axial facies of the Puye Formation (e.g., Dethier, 1997). However, the lithologies of the cobbles and the arkosic sandy matrix argue that the Totavi is more akin to axial deposits of the Santa Fe Group.

The axial facies of the Puye Formation is extremely distinctive due to the presence of well-rounded clasts of Precambrian lithologies (e.g. quartzite, granite, and pegmatite). It is exposed at several key locations around the margins of the Pajarito Plateau but within the Frijoles quadrangle is exposed only in lower Frijoles Canyon. South of Lower Falls, two layers of quartzite-bearing pebble conglomerate about 5 m thick are interbedded in maar deposits of the Cerros del Rio volcanic field. The maar deposits lie beneath the undated basalt forming the Lower Falls. An overlying alkalic lava (benmoreite) is dated at 2.75 Ma (WoldeGabriel et al., 1996). A poorly exposed section of axial gravels, perhaps 10 m thick, is interbedded with maar deposits just east of the mouth of Frijoles Canyon. Thus, it is clear that the unit is not a precise time-stratigraphic marker and that it does not always occur at the same horizons as in the type section.

The axial gravels are a key marker bed in lithologic logs used to determine stratigraphy beneath the Pajarito Plateau. Based on well logs shown in the cross sections, the axial gravels apparently thicken toward the southeast. Reneau and Dethier (1996) argue that the axial gravels likely occur as a series of discontinuous terrace deposits; however, in the absence of better control, we have shown it as a fairly continuous unit in the cross sections. Axial deposits are now bracketed between about 2.7 Ma, as mentioned above, and 5.3 Ma (WoldeGabriel et al., 2001).

The Cerros del Rio volcanic field consists of flows, domes, plugs, scoria, and hydromagmatic deposits of basalt with subordinate amounts of evolved compositions (hawaiite, mugearite, benmoreite, and dacite; Dunker et al., 1991; WoldeGabriel et al., 1996; Dethier, 1997). The lower part of the Cerros del Rio contains abundant hydromagmatic (maar) deposits formed by the interaction of mafic magma with shallow surface water or groundwater (Fisher and Schminke, 1984; Heiken et al., 1996). These deposits include cobbles, boulders, fragments, intact blocks, and depositional lenses of sediments resembling those in the Santa Fe Group and the axial facies of the Puye Formation (see above).

The last episodes of volcanism in the Frijoles quadrangle are represented by rocks of the Tewa Group and consist of the two members of Bandelier Tuff, the Pueblo Canyon Member of the Cerro Toledo Formation, and post-Bandelier pyroclastic fall deposits, including the El Cajete pyroclastic beds and earlier deposits inferred to have originated from the Cerro del Medio dome complex inside Valles caldera (Bailey et al., 1969; Smith et al., 1970; Broxton and Reneau, 1995; Gardner et al., 2010; Goff et al., 2011). The Otowi Member of the Bandelier Tuff formed during explosion of the Toledo caldera at about 1.6 Ma (Izett and Obradovich, 1994). On the Pajarito Plateau, the Otowi Member is generally non-welded and varies greatly in thickness associated with burial of the pre-existing topography and subsequent erosion (Broxton and Reneau, 1996). The basal unit of the Otowi Member, the Guaje Pumice Bed, is not exposed in the Frijoles quadrangle but has been penetrated in many bore holes.

Deposits of the Pueblo Canyon Member of the Cerro Toledo Formation (formerly called the Cerro Toledo interval of Broxton and Reneau, 1995) form zones of variable thickness and stratigraphy on top of the Otowi Member. Those exposed in Alamo Canyon are strictly fluvial with a conspicuous component of obsidian from Rabbit Mountain dome (west of the map area; Goff et al., 1990; Gardner et al., 2010) whereas those beneath the central Pajarito Plateau are often of mixed fluvial and pyroclastic origin. The primary pyroclastic deposits of the Pueblo Canyon Formation are dominantly fallout deposits of the Valle Toledo Member rhyolites (Gardner et al., 2010; Goff et al., 2011). Some exposures of Pueblo Canyon Member on the central plateau represent early Pleistocene stream terraces overlain by multiple pumice layers and buried soils, whereas other exposures are purely fluvial or purely pyroclastic. Locally, the Pueblo Canyon Member is absent or occurs as thin colluvial deposits on eroded Otowi ignimbrites.

Overlying the Pueblo Canyon Member is the Tshirege Member of the Bandelier Tuff formed during creation of the Valles caldera about 1.25 Ma (Izett and Obradovich, 1994; Phillips et al., 2007). Tshirege ignimbrites form the orange to pink cliffs characteristic of the Pajarito Plateau, and include multiple flow units and cooling units of variable thickness and welding. The Tshirege Member locally includes pyroclastic surge beds (e.g., Broxton and Reneau, 1995; Goff, 1995; Reneau et al., 1995a; Gardner et al., 1999, 2001). The base of the Tshirege Member is composed of the Tsankawi Pumice

Bed, which is typically about 0.3 m thick where exposed in the Frijoles quadrangle. Like the Otowi Member, the Tshirege Member is of variable thickness associated with burial of the pre-existing topography and subsequent erosion (Broxton and Reneau, 1996). In the southeast part of the Frijoles quadrangle, from Chaquehui Canyon to Lummis Canyon, the Tshirege Member completely buries an early Pleistocene canyon of the Rio Grande through the Cerros del Rio volcanic field. A spectacular exposure of this paleocanyon is observable along the Frijoles Canyon trail just upstream of the Upper Falls. Axial Rio Grande deposits are exposed beneath the Tshirege Member in the adjoining White Rock and Cochiti Dam quadrangles (Reneau and Dethier, 1996).

Discontinuous exposures of dacite-bearing older alluvium occur on mesa tops in Frijoles quadrangle, particularly near the Pajarito fault zone and the northern part of the quadrangle, although discontinuous remnants also occur on the eastern plateau. These deposits record the initial drainage system that formed following eruption of the Tshirege Member and before incision of the present canyons (Reneau, 1995; Reneau et al., 1995b; Reneau and McDonald, 1996; Gardner et al., 1999, 2001). Some exposures of the older alluvium include pumice beds that are geochemically similar to rhyolitic lavas from the Cerro del Medio dome complex in the Valles caldera, which have been dated at 1.18 to 1.23 Ma (Spell and Harrison, 1993; Izett and Obradovich, 1994; Phillips et al., 2007), and indicate an early Pleistocene age for these deposits.

The El Cajete pyroclastic beds (Gardner et al., 2010), the youngest volcanic unit erupted onto the Frijoles landscape, blankets most of the large mesa tops in the south central Pajarito Plateau. It also occurs locally on canyon walls and on the Pajarito fault escarpment (Goff et al., 1990), and has been penetrated in drill holes beneath some canyon bottoms (Reneau et al., 1996b). Pyroclastic materials in these beds were vented from El Cajete crater in southern Valles caldera at about 50-60 ka (Toyoda et al., 1995; Reneau et al., 1996a; Wolff et al., 1996, 2011) and formed pyroclastic fall ("Plinian") deposits similar to those that buried the Roman city of Pompeii. Roughly 10 km^3 of pumice was vented during the eruption (Wolff et al., 2011). Because the pumice deposits are nonindurated, they erode easily and collect on protected slopes and benches formed on the Tshirege Member of the Bandelier Tuff. An extremely strong correlation exists between the distribution of pumice and locations of ancestral Pueblo Indian ruins on the southern Pajarito Plateau. Evidently, the pumice beds were favored for agriculture because of water retention and easy tilling.

Alluvium occurs in the bottoms of canyons on the Pajarito Plateau and in the Jemez Mountains, and also in alluvial fans east of the Pajarito fault escarpment. Holocene alluvium is widespread, and exceeds 10 m in thickness in parts of some canyons on the plateau, including Frijoles and Mortandad canyons (Reneau and McDonald, 1996; Reneau et al., 1996b; Reneau, 2000). Some canyons have unincised alluvial fills, recording progressive aggradation through the Holocene, whereas others have stream terraces that record episodic incision. Pleistocene alluvium also occurs below stream terraces and below the bottoms of some canyons, and the presence of El Cajete pumice in the subsurface indicates that parts of some alluvial fills exceed 50-60 ka in age. Colluvium interfingers with alluvium in the canyon bottoms, and commonly overlies alluvium adjacent to canyon walls. Alluvial fans on the western plateau also contain deposits of both Holocene and Pleistocene age (Gardner et al., 2001).

STRUCTURE AND TECTONICS

The Frijoles 7.5 minute quadrangle straddles the western boundary of the modern Española Basin of the Rio Grande rift. The rift is a major tectonic feature of the North American continent, and it exhibits a long history of faulting, volcanism, and seismicity (for example, Riecker, 1979; Baldridge et al., 1984, and Keller, 1986). Abundant data indicate that the rift continues to be tectonically and magmatically active (for example, Sanford et al., 1991; Baldridge et al., 1995; Wolff and Gardner, 1995; Machette et al., 1998; Steck et al., 1998). The rift boundary in the Frijoles quadrangle is defined by the Pajarito fault system, which comprises, in the quadrangle, the Pajarito and Rendija Canyon fault zones (see for example, Gardner et al., 1999 and 2001). Both of these fault zones have been shown to be potentially seismogenic with likely Holocene ruptures, and paleoseismic studies indicate that each has generated multiple prehistoric earthquakes of approximate magnitude 7 (Kelson et al., 1996; McCalpin, 1998).

The structure of the Frijoles quadrangle is dominated by the Pajarito fault zone on the west, the Rendija Canyon fault zone at the north-central edge of the quadrangle, and the gentle 1 to 3 degree eastern dips of the Bandelier Tuff that forms the Pajarito Plateau.

The Pajarito fault zone is a broad swath of generally north-trending normal faults along the west margin of the quadrangle. We have found no kinematic indicators of earlier or contemporaneous strike-slip motion. The zone of deformation is 1.5 to 3 km wide and includes principle strands, forming >100 m scarps, monoclines masking deeper seated normal faulting, and numerous subsidiary strands and splays. Commonly, narrow grabens 250 m to <1 km wide, occur at the base of the main escarpment which may imply local listric geometry of some faults within the zone. In two areas stratigraphic separation on the Tshirege Member has been shown to be comparable to individual scarp heights with separations of about 125 m near Water Canyon and about 80 m near Pajarito Canyon (Gardner et al., 2001). Total down to the east displacement on the tuff across the whole zone of deformation at Water Canyon is about 140 m, but in the southern part of the map area where the fault zone is expressed as two major scarp-forming traces, total down to the east displacement on the Tshirege Member may exceed 200 m.

The southern end of the Rendija Canyon fault zone (see Gardner et al., 1999) is exposed along the north-central edge of the Frijoles quadrangle as its strike bends from north-south, north of the map area, to southwest. In the map area the Rendija Canyon fault zone is about 1.5 to 2 km wide comprising a series of northeast-trending faults and monoclines with only about 10 to 20 m of cumulative down-to-the-west displacement of the Tshirege Member. Individual structures typically display less than a few meters of down-to-the-west displacement of the tuff (note that only structures with greater than 1 m of offset on the tuff or younger units are shown on the map for clarity). North of the Frijoles quadrangle the Rendija Canyon fault zone becomes narrower and less complex, merging into two to three major north-trending normal fault strands with about 40 m of down-to-the-west displacement on the Tshirege Member.

Seismicity in the area of the Frijoles quadrangle is on-going but diffuse. Notably, a cluster of small seismic events has been recorded northwest of St. Peters Dome, but most recorded microseismic events cannot be directly attributed to mapped structures (House and Hartse, 1995). Since 1991, however, there have been three small earthquakes on elements of the Pajarito fault system, just north of the map area, that precipitated hundreds of felt reports and ground motions as high as Modified Mercalli Intensity VI (Gardner and House, 1994; Gardner and House, 1999).

As mentioned previously, the Pajarito fault system defines the local, active western boundary of the rift, and most workers maintain that the north-trending elements of the fault system became active at about 4 to 5 Ma (Golombek, 1981; Gardner and Goff, 1984; Aldrich and Dethier, 1990). Near the St. Peters Dome fault block and immediately south of the map area, angular unconformities occur between the Galisteo Formation, the Santa Fe Group, and the Keres Group. These relations, together with dates on a basalt within the Santa Fe Group, indicate that faulting on the northeast-trending segment of the Pajarito fault zone, just south of the map area, has been on-going since at least 16.5 Ma (Gardner and Goff, 1984). Gardner and Goff (1984) and Gardner et al. (1998) presented evidence that faulting forming the local western boundary of the rift has stepped about 10 km to the east probably twice in the last 17 million years, with the most recent shift to the Pajarito fault system happening at about 4-5 Ma. Some active rift structures, such as the older northeast-trending part of the Pajarito fault zone just south of the map area, appear to have pirated structures inherited from earlier tectonic episodes.

CROSS SECTIONS

Cross section A-A' runs west to east from the Sierra de los Valles across the Pajarito fault zone toward the eastern side of the Pajarito Plateau. Beneath the plateau, the section reflects stratigraphic intercepts from a variety of wells drilled east of the Pajarito fault zone. Interpretation of fault architecture along the Pajarito fault zone is based on the work of Gardner et al. (2001). Subsurface stratigraphy west of the Pajarito fault zone is interpreted from Smith et al. (1970), Goff et al. (1990) and the present geologic map. Subsurface information was obtained from the following sources: SHB-3 core hole (Gardner et al., 1993), R-25 characterization hole (Broxton et al., in press), CdV-R-15-3 characterization hole (Vaniman, personal commun., 2001), R-19 characterization hole (Broxton, personal commun., 2001), PM-2 water supply hole (Purtymun, 1995), and R-22 characterization hole (Ball et al., 2002). Based on contacts exposed in the wall of Pajarito Canyon, the log for PM-2 incorrectly shows the stratigraphy of the Bandelier Tuff and related rocks and is modified according to nearby core hole SHB-4 (Gardner et al., 1993). R-22 was drilled roughly 2 km east of the east boundary of Frijoles quadrangle but was examined to provide continuity to section A-A' east of hole PM-2.

The Pajarito fault zone generally consists of a 1.5 km wide zone of normal faulting with a total down-to-the-east stratigraphic separation on the Tshirege Member of the Bandelier Tuff of about 140 m near Water Canyon. The main topographic escarpment of the fault zone is formed by a large monocline, caused by deeper seated normal faulting (Gardner et al., 1999; Gardner et al., 2001), that exhibits about 125 m of separation on the Tshirege Member. Because portions of the Pajarito fault zone have been intermittently active since at least 16 Ma (Goff et al., 1990), displacement in older rocks is significantly greater. Fanglomerate deposits from the Cochiti and Puye formations thicken dramatically east of the fault zone (Smith et al., 1970). Thickness of Tschicoma and Paliza Canyon units west of the fault are unknown as is the depth to Santa Fe Group. Between the main topographic escarpment of the fault zone and core hole SHB-3 is a narrow graben filled with alluvium and older alluvial fan deposits (Gardner et al., 2001). For clarity, only structures with displacements >20 m are depicted in the cross section.

Well logs show that the two Bandelier Tuff ignimbrite sheets thin from west to east across the Pajarito Plateau away from their sources in the Valles/Toledo caldera complex. The ignimbrites also show local variations in thickness due to topography and erosion. Erosion has modified the upper surface of the Otowi Member onto which has been deposited an apparently persistent and thick sequence of the Cerro Toledo interval. The Cerro Toledo pinches out near hole PM-2 against an apparent high of Otowi Member and is not found in hole R-22 just east of the quadrangle. The Otowi in turn pinches out to the east against a thick sequence of Cerros del Rio volcanic rocks. In contrast the Cerros del Rio rocks pinch out to the west and are interbedded with the Puye Formation.

Hole CdV-R-15-3 penetrates a sequence of dacite and basalt lava flows from 294 to 309 m depth (Vaniman, personal commun., 2001). The dacite interval is only 5.2 m thick, has an $^{40}Ar/^{39}Ar$ age of 2.5 Ma (G. WoldeGabriel and D. Vaniman, unpub.), and chemically resembles evolved dacite lavas of the Tschicoma Formation (Gardner et al., 1986). This fact suggests that a vent or vents for Tschicoma type magmas lie on or east of the Pajarito fault. Perhaps these vents lie on buried faults that do not rupture the Bandelier Tuff such as those inferred by Dransfield and Gardner (1985). The 2.5 Ma date on the hornblende dacite suggests that the basalt beneath the dacite is part of the Cerros del Rio volcanic field (see discussion of section C-C' below).

Section B-B' runs northeast from the summit of St Peter's Dome across the southwestern Pajarito Plateau through characterization hole R-31 in the Ancho Canyon area (Vaniman, personal commun., 2001). St. Peter's Dome is an uplifted fault block tilted gently to the west that exposes some of the oldest volcanic rocks in the Jemez Mountains (Goff et al., 1990). Santa Fe Group rocks and the Eocene Galisteo Formation are exposed along the Pajarito fault zone but the dips of these units are not apparent on the cross section because the strikes of the beds are nearly parallel to the trend of the section line. Between Alamo and Ancho Canyons is a relatively thick section of the Otowi Member. The Otowi Member, Bandelier Tuff is exposed in Capulin, Alamo, Frijoles and Ancho canyons, along or very near the plane of the section. Cerro Toledo interval rocks are not continuous along this section, although the scarcity of exposures and drill holes hinder interpretation of this stratigraphic interval in this area. Cerros del Rio volcanic rocks probably form a nearly continuous layer beneath this sector of the Pajarito Plateau because they are encountered in hole R-31 and are exposed in several canyons between R-31 and the Pajarito fault zone. Significantly, Puye fanglomerates are not exposed in these canyons but probably overlap fanglomerates of the Cochiti Formation somewhere beneath Alamo and Frijoles canyons.

R-31 penetrated over 100 m of ancestral Rio Grande gravels, the thickest section of such gravels penetrated by any well on the Pajarito Plateau (Vaniman, personal commun., 2001).

Section C-C' runs south across the central Pajarito Plateau through core hole SHB-1 (Gardner et al., 1993), characterization well CdV-15-R-3 (Vaniman, personal commun., 2001) and observation well DT-5A (Weir and Purtymun, 1962; Purtymun, 1995). Using cuttings, stratigraphic boundaries among the Bandelier Tuff and related units in well DT-5A were incorrectly identified and are thus modified according to data from nearby core hole TA-49-2-700 (Stimac et al., 1994). The Bandelier Tuff thickens in a southerly direction across this sector of the Pajarito Plateau while the Cerro Toledo interval thins dramatically south of characterization hole CdV-R-15-3.

A sequence of lavas underlies the Bandelier Tuff, dips noticeably to the south and is interbedded in the Puye Formation. Geochemical work on the lava in the bottom of hole SHB-1 shows that it is a relatively glassy aphyric dacite of the Tschicoma Formation (Laughlin et al., 1993) with a date of 3.1 ± 0.2 Ma (WoldeGabriel, 1994; average of two $^{40}Ar/^{39}Ar$ isochron ages). SHB-1 dacite is equivalent to the aphyric lava flow encountered in hole EGH-LA-1 located west of section C-C' (see Goff, 1995, Figure 2). The SHB-1 dacite is more mafic than the dacite to the south intersected by hole CdV-R-15-3 but, as mentioned above, the latter dacite also has a late Tschicoma age and chemistry. The original lithologic log for well DT-5A indicates that two intervals of lava flows are composed of "latite and quartz latite," names often used interchangeably with dacite (Weir and Purtymun, 1962). Purtymun (1995), for reasons unknown, later renamed these flows basalts of the Cerros del Rio volcanic field. A thick sequence of porphyritic dacite has also been encountered at roughly 365 to 488 m in well CdV-R-37-2 located about 1 km west of section C-C' and east of S site (D. Hickmott, 2001, oral communication). Based on these data, it is our opinion that the west-central Pajarito Plateau is underlain in part with Tschicoma Formation domes and flows that erupted from vents on or east of the Pajarito fault zone. These Tschicoma eruptions are interbedded with fanglomerates of the Puye Formation and locally overlie intervals of axial gravels. Consequently, basaltic lavas beneath the dacite in CdV-R-15-3 and other nearby holes probably represent either Cerros del Rio basalt erupted ≥2.5 Ma or older basalts such as those in well OT-4 discussed below.

Section D-D' runs south along the east side of the Frijoles quadrangle through water supply well OT-4 (Purtymun, 1995), characterization hole R-15 (Longmire et al., 2001), water supply well PM-2 (Purtymun, 1995), and characterization hole R-31 (Vaniman, personal commun., 2001). Along this section the Bandelier Tuff ignimbrites display relatively uniform thickness but the Cerro Toledo interval pinches out to the south. Mafic lavas of the Cerros del Rio volcanic field are interbedded with the top of the Puye Formation but thicken dramatically to the south. Axial gravels of the Puye Formation consistently appear in all holes beneath Cerros del Rio units and also thicken dramatically to the south. Beneath the axial gravels is a thick sequence of fanglomerate now thought to be the lower sequence of the Puye Formation. The Santa Fe Group contact is encountered at roughly 700 m depth in the north part of the section and probably rises to the south and east toward hole R-31 and Santa Fe exposures along White Rock Canyon.

OT-4 encountered two intervals of older basaltic lavas below 352 m depth. Three $^{40}Ar/^{39}Ar$ isochron dates for these lavas average about 8.8 Ma (WoldeGabriel et al., 2001). These dates indicate that the lower fanglomerates of the Puye Formation are considerably older than previously recognized.

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), an Goff and Gardner (2004). Minor yet significant changes in regional stratigraphy and nomenclature have occurred here since this map was first compiled and are described in Gardner et al. (2010) and in the ***Geologic Map of the Valles caldera, Jemez Mountains, New Mexico*** (Goff et al., 2011).

Quaternary Deposits

Qdi **Disturbed Mesa Top—**Highly disturbed mesa top deposits of man-made origin; usually consists of a mixture of older alluvium, Bandelier Tuff rubble, mesa top soil, and imported fill; latter contains conspicuous clasts of Precambrian lithologies; unit mapped only where extensive at larger technical areas of Los Alamos National Laboratory (LANL); not shown in correlation chart; maximum thickness more than 2 m but usually less than 1 m.

Qal **Alluvium—**Deposits of gravel, sand and silt in canyon bottoms; locally includes stream terraces and canyon wall colluvium; alluvium in canyons originating on the Pajarito Plateau is dominated by weathering products from the Bandelier Tuff, including abundant quartz phenocrysts, whereas alluvium in canyons originating in the Jemez Mountains also includes abundant dacite clasts; mostly Holocene in age based on ^{14}C dates; some alluvium interbedded with El Cajete pumice encountered by LANL drill holes indicates an age >50-60 ka (e.g., Reneau and McDonald, 1996; Reneau et al., 1996a; Reneau, 2000; Gardner et al., 2001); maximum thickness exceeds 15 m.

Qc **Colluvium—**Poorly sorted slope wash and talus deposits from local sources; mapped only where extensive or where covering critical contacts or fault relations; 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; now undergoing erosion; mapped in only a few locations but relatively extensive along major streams such as Frijoles and Water Canyon creeks (Reneau, 2000); Holocene and Pleistocene in age based on ^{14}C dates (Reneau, 2000); 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, or older, coalesced fan deposits along the Pajarito fault zone; latter deposits partially Holocene in age as determined from ^{14}C dates (e.g., Gardner et al., 2001); other deposits partially overlain by pumice of El Cajete pyroclastic beds; may be difficult to distinguish from older alluvium (described below); 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; older slides may be overlain by El Cajete pyroclastic beds or by older alluvium (described below); thickness varies considerably depending on the size and nature of the landslide.

Qlst **Tereva block slide—**Extremely large, coherent block slide northeast of St. Peter's Dome; characterized by highly rotated contacts of volcanic units dipping to the west.

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; underlies El Cajete pumice, younger alluvial fans and younger landslides; roughly contemporaneous with older alluvial fan deposits and landslides; overlies Tshirege Member, Bandelier Tuff; may contain interbedded lapilli and ash deposits ≤1 m thick from Cerro del Medio rhyolite dome complex in Valles caldera (Reneau et al., 1995a; Reneau and McDonald, 1996; Gardner et al., 2001), indicating a maximum age of at least 1.1 Ma (Spell and Harrison, 1993; Izett and Obradovich, 1994); maximum exposed thickness about 6 m.

Tewa Group

Qvec **El Cajete pyroclastic beds (Valles Rhyolite)—**White to tan, moderately sorted, pyroclastic fall deposits of vesicular rhyolite; pumice clasts contain sparse phenocrysts of quartz, biotite, and plagioclase with rare microphenocrysts of hornblende and clinopyroxene; some clasts contain resorbed quartz with pale green, clinopyroxene reaction rims; maximum diameter of clasts is about 15 cm but clast size diminishes from west to east away from source; unit forms extensive mesa top cover in Bandelier National Monument (BNM) and southern LANL; unit extensively reworked by erosion, collecting on east facing slopes and on benches cut into the upper flow unit and/or cooling unit boundaries of Tshirege Member, Bandelier Tuff; Qvec originated west of map area from El Cajete crater in southern moat of Valles caldera (Bailey et al., 1969; Smith et al., 1970; Gardner et al., 1986; Self et al., 1988; Wolff et al., 1996; Gardner et al,. 2010); unit dated at about 50 to 60 ka (Toyoda et al., 1995; Reneau et al., 1996a); maximum exposed thickness about 10 m in southwest map area; thins to northeast on mesa tops forming scant exposures too thin or small to map.

Qbt **Bandelier Tuff, Tshirege Member**—White to orange to pink welded to non-welded rhyolitic ash-flow tuff (ignimbrite) containing abundant phenocrysts of sanidine and quartz, rare microphenocrysts of black clinopyroxene and trace microphenocrysts of hypersthene and fayalite; sanidine typically displays a blue iridescence; consists of multiple flow units in a compound cooling unit (Smith and Bailey, 1966; Broxton and Reneau, 1995; Gardner et al., 2001); upper flow units are generally more welded than lower ones, less voluminous, and are generally confined to western map area; contains localized pyroclastic surge beds ≤1 m thick that generally become more abundant toward top of unit; locally contains a thin (≤1m) laminated, pumice fall and surge deposit at its base (Tsankawi Pumice) that contains roughly 1% of hornblende dacite pumice (Bailey et al., 1969); locally contains lithic fragments of country rock entrained during venting and pyroclastic flow; Qbt forms conspicuous orange to pink cliffs throughout the Pajarito Plateau; forms thick intracanyon deposit in gorge of ancestral Rio Grande upstream of Upper Falls, Frijoles Canyon (Reneau and Dethier, 1996; Reneau, 2000); originated from catastrophic eruptions that formed Valles caldera; $^{40}Ar/^{39}Ar$ age is 1.22±0.01 Ma (Izett and Obradovich, 1994; Spell et al., 1996); maximum observed thickness in upper Frijoles Canyon greater than 260 m.

Qcpc **Pueblo Canyon Member (Cerro Toledo Formation)—**Discontinuous interval of epiclastic sediments and tephras of mixed provenance that lie between the two members of the Bandelier Tuff (Broxton and Reneau, 1995); tuffaceous layers are part of the Valle Toledo Member (Gardner et al., 2010) originating from sources in the Toledo caldera and Toledo Embayment (Smith et al. 1970; Heiken et al., 1986); tuffaceous layers consist of rhyolitic pyroclastic fall deposits usually less than 2 m thick (Heiken et al., 1986; Stix et al., 1988); pumice clasts generally aphyric but contain rare phenocrysts of quartz, sanidine, and biotite; in northern map area, the sedimentary deposits consist of poorly sorted sand, gravel, and coarse-grained detritus of porphyritic dacite, andesite, and rare ignimbrite from sources to west, commonly intermixed with reworked rhyolitic pumice (Goff, 1995); in southern map area, the sedimentary deposits additionally include conspicuous aphyric obsidian fragments from debris avalanche off Rabbit Mountain dome west of the map area (Goff et al., 1990); radiometric ages of tuffaceous units and source domes range from 1.21 to 1.64 Ma (Izett et al., 1981; Stix et al., 1988; Spell et al., 1996); maximum exposed thickness about 20 m but exceeds 30 m in several wells drilled on Pajarito Plateau.

Qbo **Bandelier Tuff, Otowi Member—**White to pale pink, generally poorly welded rhyolitic ash-flow tuff containing abundant phenocrysts of sanidine and quartz, and sparse mafic phenocrysts; sanidine may display a blue iridescence; contains abundant accidental lithic fragments; consists of multiple flow units in a compound cooling unit; contains a stratified pumice fall and surge deposit at its base (Guaje Pumice); may form tent rocks; Qbo discontinuously fills in rugged topography on a pre-Toledo caldera age volcanic surface; upper surface undulatory due to erosion; very difficult to distinguish from upper Bandelier Tuff in hand samples; 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 and/or Pueblo Canyon Member; 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); maximum exposed thickness about 75 m.

Tertiary Deposits (Earliest Pleistocene (?) - Eocene)

QTp **Puye Formation fanglomerate—**Pebble to boulder gravel, boulder-rich debris flows, massive to planer sands, thin beds of white to gray tephra and pumiceous alluvium, and beds of fine sand and silt rich in intermediate to silicic volcanic detritus (Griggs, 1964; Gardner et al., 1986; Turbeville et al., 1989; Dethier, 1997); drilled intervals beneath the Pajarito Plateau are rich in dacite and rhyodacite clasts derived from the Tschicoma Formation; locally contains interbedded lenses and layers of course boulder conglomerate of ancestral Rio Grande (Totavi Lentil, Tpt); recent holes penetrating the Pajarito Plateau suggest that the underlying Puye Formation is considerably thicker and more extensive than previously recognized (i.e., Broxton et al., 2001; Longmire et al., 2001); upper Santa Fe Group of Griggs (1964) and Chaquehui Formation of Purtymun (1995) are tentatively interpreted to be the lower Puye Formation and locally contain significant andesite and possibly rhyolite components (D. Broxton, D. Vaniman, and R. Warren, 2001, oral communication); overlies and interfingers with Santa Fe Group beneath eastern Pajarito Plateau; presumably overlies and interfingers with Cochiti Formation beneath the southwestern Pajarito Plateau although relations are not exposed; age range of exposed Puye is about 2.4 to 5.3 Ma (Turbeville et al., 1989; WoldeGabriel et al., 1996; 2001); lower Puye beneath Pajarito

Plateau in hole OT-4 is at least 9 Ma based on dated lavas described below (Tob); maximum exposed thickness north of map area is more than 200 m; maximum thickness indicated by drill hole intercepts is about 660 m.

Tpt **Puye Formation, ancestral Rio Grande facies (Totavi Lentil)—**Pebble to cobble gravel rich in clasts of quartzite, intrusive igneous rocks and various Precambrian lithologies, and in highly altered volcanic lithologies from sources north and east of the Pajarito Plateau (Griggs, 1964; Dethier, 1997); may contain thin beds of sand and silty sand; includes minor lacustrine deposits north of the map area; interbedded with mafic hydromagmatic deposits (Tcbm) in lower Frijoles Canyon; these exposures are bracketed by dates between 2.75 and 2.78 Ma (WoldeGabriel et al., 1996); maximum exposed thickness is about 20 m; maximum thickness intercepted in drill holes is at least 98 m.

Tob **Olivine basalt in lower Puye Formation—**Flows and scoriaceous zones of olivine basalt shown only in cross section D-D' on this map; interbedded with sedimentary deposits rich in volcanic detritus in well OT-4; originally thought to be part of the Santa Fe Group (Griggs, 1964); more recently thought to interbedded in the Chaquehui Formation of Purtymun (1995); however, two of the flows have $^{40}Ar/^{39}Ar$ ages of about 9 Ma and are roughly equivalent in age to basalt flows north of the map area in Bayo Canyon and near Lobato Mesa (Smith et al., 1970; WoldeGabriel et al., 2001); maximum drilled thickness is about 60 m.

Cerros del Rio Volcanic Field (Pliocene)

Tcb **Mafic lava flows**—Undivided flows, dikes and associated cinder deposits of basalt, hawaiite, and mugearite from Cerros del Rio volcanic field, best exposed east of the Rio Grande (Dunker et al., 1991); units generally contain phenocrysts of olivine, plagioclase ± clinopyroxene in a variety of groundmass types, depending on chemistry of magma and eruption style; may contain abundant xenocrysts of quartz, microcline, and Precambrian rock fragments (Iddings, 1890) from sedimentary rocks beneath the Pajarito Plateau; flows massive to sheeted, generally showing broad columnar joints; $^{40}Ar/^{39}Ar$ ages of most Cerros del Rio volcanic rocks range from 2.3 to 2.8 Ma (WoldeGabriel et al., 1996; 2001); $^{40}Ar/^{39}Ar$ date of hawaiite cone and flow at LANL Tech Area 33 (TA-33) 2.39±0.08 Ma; maximum exposed thickness about 40 m.

Tcba **Benmorite**—Thick lava flow exposed in upper walls of lower Frijoles Canyon and adjacent White Rock Canyon; contains phenocrysts of olivine, clinopyroxene, hypersthene and plagioclase in a trachytic groundmass; contains rare xenocrysts of quartz with clinopyroxene reaction rims; contains rare plagioclase-pyroxene clots; locally contorted and flow-banded within upper two thirds of flow; erodes into relatively thin plates; lower part of flow generally massive and cut by widely spaced columnar joints; overlain by Tshirege Member, Bandelier Tuff; overlies mafic lava flows and hydromagmatic deposits (Tcb and Tcbm); $^{40}Ar/^{39}Ar$ age 2.75±0.08 Ma (WoldeGabriel et al., 1996); maximum exposed thickness about 70 m.

Tcbc **Cinder deposit—**Basalt scoria, bombs, and associated thin lavas from partially exposed cone in east wall of Frijoles Canyon just upstream of Upper Falls; contains phenocrysts of olivine and plagioclase in glassy, vesicular groundmass; overlain by thin (0.5 m) sequence of hydromagmatic deposits and surrounded by intracanyon deposit of the Tshirege Member, Bandelier Tuff; relations with other Cerros del Rio volcanic rocks uncertain; maximum exposed thickness is about 25 m.

Tcbm **Mafic hydromagmatic deposits—**Layered hydromagmatic (maar) deposits consisting of cinders, ash, and decomposed glass with pebble- to boulder-sized fragments of quartz, microcline, volcanic rocks, quartzite, intrusive igneous rocks and other lithologies from sedimentary sources beneath the Pajarito Plateau; magmatic component is primarily basalt; contains numerous interbedded, mafic lava flows (Tcb) too thin or discontinuous to map; contains beds and lenses of ancestral Rio Grande gravels (Tpt); Tcbm most common near the axis of the ancestral and present Rio Grande (Heiken et al., 1996); formed by interaction of mafic magmas with shallow groundwaters or surface water (Fisher and Schminke, 1984); deposits show combinations of planer beds, cross beds, and surge beds; some beds contain accretionary lapilli; glass commonly alters to yellow-brown clay (palagonite); incorrectly correlated with the Chaquehui Formation by Purtymun (1995); overlies and is interbedded with Puye Formation; overlies Santa Fe Group (Ts, described below) in exposures along the Rio Grande upstream of Frijoles Canyon; $^{40}Ar/^{39}Ar$ age of basalt lava near base of maar sequence in mouth of Chaquehui Canyon just east of map area is 2.78±0.04 Ma (WoldeGabriel et al., 1996); maximum exposed thickness about 150 m.

Keres Group (Pliocene–Miocene)
Tschicoma Formation (Pliocene)

Ttpm **Pajarito Mountain dacite** (**Tschicoma Formation)—**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 consisting of several eruptive events; source is Pajarito Mountain west of map area; overlies hornblende dacite of Cerro Grande (Tphd); locally underlies Tshirege Member of the Bandelier Tuff (Qbt); $^{40}Ar/^{39}Ar$ ages on widely separated samples range from 2.93 to 3.09 Ma (WoldeGabriel, 2001; Goff et al., 2011); maximum exposed thickness is about 220 m.

Ttcg **Cerro Grande dacite (Tschicoma Formation)—**Dome and flow complex of light to dark gray to pale pink, massive to sheeted porphyritic dacite containing phenocrysts of plagioclase, hypersthene, and conspicuous hornblende; the latter two phases commonly show oxidized rims; 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 west of 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 3.35 to 2.88 Ma (Dalrymple et al., 1967; WoldeGabriel, 2001; Goff et al., 2011); maximum exposed thickness about 200 m. A 5.2-m-thick hornblende dacite lava with late Tschicoma chemistry was penetrated in well CdV-R-15-3 at 294 m depth. This lava has an $^{40}Ar/^{39}Ar$ age of 2.5 Ma (D. Vaniman and G. WoldeGabriel, unpub.) but the source is unknown.

Bearhead Rhyolite (Miocene)

Tbh **Bearhead intrusive rocks and flows—**White to gray intrusions, domes, and flows of slightly porphyritic to aphyric devitrified rhyolite containing rare 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; intrudes or overlies 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 Rabbit Hill dome on west edge of map 6.65±0.03 Ma (Justet, 1996); maximum observed thickness about 60 m.

Paliza Canyon Formation (Miocene)

Tpv **Volcaniclastic deposits**—Black to gray to pale pink volcaniclastic unit consisting predominately of lahars, block and ash flows, and other debris flows formed contemporaneous with Paliza Canyon Formation volcanism; locally contains hyperconcentrated flow and fluvial deposits, cinder deposits, and pyroclastic fall deposits; contains andesite to dacite flow-breccias and andesite lava flows too small or thin to map; unit has accumulated in small basins and topographic lows within Keres Group volcanoes; unit generally thickens to south, east, and north into the Rio Grande rift; age of Tpv is bracketed between 8.7 and about 11 Ma within the St. Peter's Dome area; intruded and overlain by the Bearhead Rhyolite;

overlies Canovas Canyon Rhyolite tuff and Santa Fe Group; relations with Polvadera Group rocks, particularly the Puye Formation, are not exposed but presumably Tpv underlies and interfingers with these units beneath the southwestern Pajarito Plateau; maximum exposed thickness about 450 m; unit mapped according to the definition of Cochiti Formation discussed by Bailey et al., (1969) and Gardner et al. (1986). However, Cochiti Formation rocks form an eroded apron of alluvial fan deposits east of the Pajarito fault zone, which overlie the Peralta Tuff member of the Bearhead Rhyolite south of the map area (Smith et al., 1970; Smith and Lavine, 1996).

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; K-Ar date of flow at summit of St. Peter's Dome 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; 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; maximum observed thickness is about 50 m.

Tpbd **Biotite dacite—**Extensive dome and flow complex beneath the summit of St. Peter's Dome; consists of gray to pale pink porphyritic dacite with phenocrysts of complexly zoned plagioclase and smaller phenocrysts of plagioclase, biotite, clinopyroxene, and opaque minerals in devitrified groundmass; flows are massive to sheeted; flows contain flow breccia; maximum observed thickness about 150 m.

Tpa **Andesite, undivided—**Gray to pink to black flows, domes, and minor intrusives of porphyritic andesite containing phenocrysts of plagioclase, clinopyroxene, and hypersthene in a glassy to almost intersertal groundmass; microphenocrysts consist of plagioclase, clinopyroxene, hypersthene, and opaque minerals; flows massive to sheeted; may contain flow-breccia; ages of various flows unknown; maximum observed thickness is about 50 m.

Tpoa **Olivine andesite—**Black to gray domes, flows, and minor red cinder deposits of slightly porphyritic andesite containing 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; ages of various flows 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 the Cochiti Formation; 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 within local area range from 9.1 to 9.5 Ma (Lavine et al., 1996); $^{40}Ar/^{39}Ar$ date of 2.5 m thick bed northeast of St. Peter's Dome 9.47±0.06 Ma; most beds ≤1 m thick and generally too thin or discontinuous to map.

Tphd **Hornblende dacite—**Domes, flows and intrusives of gray to pink porphyritic dacite containing 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 10 cm in diameter; groundmass glassy to devitrified and commonly trachytic; flows massive to sheeted; may contain flow-breccia; dome eruptions of Tphd may be the source for many dacite tuffs described above; K-Ar date of dome and flow complex beneath east flank of St. Peter's Dome 9.48±0.44 Ma (Goff et al., 1990); maximum observed thickness about 60 m.

Tpb **Olivine basalt (Paliza Canyon Formation)—**Black flows and black to red cinder deposits of sparsely porphyritic basalt containing phenocrysts of plagioclase and olivine ± clinopyroxene in an intersertal groundmass of plagioclase, clinopyroxene, olivine, opaque minerals, and glass; olivine generally displays iddingsite alteration; plagioclase may be complexly zoned; may contain sparse plagioclase-pyroxene and olivine-pyroxene clots; flows and cinder deposits have a variety of ages; K-Ar date of lava in bottom of Capulin Canyon north of St. Peter's Dome 11.3±0.9 Ma (Goff et al., 1990); maximum observed thickness about 20 m.

Canovas Canyon Formation (Miocene)

Tcct **Canovas Canyon rhyolite tuff—**White to pink pyroclastic fall and pyroclastic flow deposits of the Canovas Canyon Rhyolite (Bailey et al., 1969; Gardner et al., 1986); consists of several distinct deposits; 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'"); at other localities unit may contain white fine- to course-grained fall deposits; pumice and rhyolite clasts contain sparse phenocrysts of quartz, potassium feldspar, and biotite; unit is interbedded with older volcaniclastic deposits of the Cochiti Formation; "pink tuff" underlies all other Keres Group rocks and overlies the Santa Fe Group on the east side of St. Peter's Dome; estimated age range for various tuff deposits is about ≤10 Ma (Goff and Gardner, 2004; Goff et al., 2011); maximum observed thickness is about 20 m.

Santa Fe Group (Late to Middle Miocene)

Ts **Sedimentary deposits, undivided (shown mostly in cross sections)—** White to tan to pale green, massive to well-bedded sandstone and siltstone; contains minor gravel beds; local areas nonindurated; sand grains consist primarily of quartz and feldspar; beds generally dip to northwest and west; locally contains flows, pillows, and palagonite tuffs of alkali basalt (*Tstb*); unconformably overlain by mafic hydromagmatic deposits of the Cerros del Rio volcanic field near the mouth of Frijoles Canyon; unconformably overlain by the Keres Group east of St. Peter's Dome; unconformably overlies the Galisteo Formation; maximum observed thickness is about 100 m.

Tscv **Chamita Formation, lower Vallito Member—**Buff to yellow-orange, strongly to weakly cemented, fine- to coarse-grained sandstone; locally cross-bedded to planar laminated; otherwise massive. Contains two light-gray to white chert beds in the lower 100 m. Interbedded with tephras of the Canovas Canyon Formation in the upper 20 m. Estimated thickness is about 250 m.

Tstc **Chama El Rito Member—**Orange to pinkish, quartz-rich sandstone with a few thin lenses of volcanic pebbles derived from volcanic fields to the north (e.g., Latir volcanic field); thickness at least 200 m.

Tstb **Basalt flows—**Exposures of flow and pillow-palagonite tuff of black alkali basalt and basanite containing small phenocrysts of iddingsitized olivine, clinopyroxene, and plagioclase in intersertal groundmass of plagioclase, opaque minerals, and glass; glass devitrified and altered to clay; most vesicles are partially filled with calcite; interbedded with Santa Fe Group; $^{40}Ar/^{39}Ar$ ages of interbedded basalt lava south of St. Peter's Dome are 15.44 ± 0.30 to 18.79 ± 0.64 Ma (Justet, 2003; WoldeGabriel et al., 2001); ages of two other basalt flows south of map area are 20.83 ± 0.63 and 25.48 ± 0.84 Ma (WoldeGabriel, 2006); typical thickness of flows about 3 m.

Tstv **Conglomeritic sandstone—**Tan to pink beds with sparse, pebble-sized, angular volcanic clasts; thickness unknown.

Galisteo Formation (Eocene)

Tgs **Sedimentary deposits—**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; unconformably underlies the Santa Fe Group; bottom of unit is not exposed; maximum observed thickness is about 200 m.

REFERENCES

Aldrich, M. J., and Dethier, D. P., 1990, Stratigraphic and tectonic evolution of the northern Española Basin, Rio Grande rift, New Mexico; Geological Society of America Bulletin 102, 1695-1705.

Bailey, R., Smith, R., and Ross, C., 1969, Stratigraphic nomenclature of volcanic rocks in the Jemez Mountains, New Mexico. U.S. Geol. Survey Bull. 1274-P, 19 pp.

Baldridge, W. S., Dickerson, P. W., Riecker, R. E., and Zidek, J., (eds.), 1984, Rio Grande rift: Northern New Mexico; New Mexico Geological Society Guidebook 35, 379 pp.

Baldridge, W. S., Keller, G. R., Haak, V., Wendlandt, E., Jiracek, G. R., and Olsen, K. H., 1995, The Rio Grande rift; in Continental Rifts: Evolution, structure, tectonics; K. H. Olsen (ed.), Elsevier, Amsterdam, Holland, 233-275.

Ball, T., Everett, M., Longmire, P., Vaniman, D., Stone, W., Larssen, D., Greene, K., Clayton, N., and Mclin, S., 2002, Characterization well R-22 completion report; Los Alamos National Laboratory Report LA-13893-MS, 42 pp. w/Appendices.

Broxton, D., and Reneau, S., 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 pp.

Broxton, D.E., and Vaniman, D.T., 2005, Geologic framework of a groundwater system on the margin of a rift basin, Pajarito Plateau, north-central New Mexico: Vadose Zone Journal, v. 4, p. 522-550.

Broxton, D. E., and Reneau, S. L., 1996, Buried early Pleistocene landscapes beneath the Pajarito Plateau, northern New Mexico, *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N., eds., The Jemez Mountains region: New Mexico Geological Society Forty-Seventh Annual Field Conference Guidebook, p. 325-334.

Broxton, D., Vaniman, D., Stone, W., McLin, S., Marin, J., Koch, R., Warren, R., Longmire, P., Rogers, D., and Tapia, N., 2001, Characterization well R-19 completion report. Los Alamos National Laboratory Report LA-13823-MS, 58 pp w/ appendices.

Cather, S.M., 1992, Suggested revisions to the Tertiary tectonic history of north-central New Mexico. New Mexico Geological Society, Guidebook 43, p.109- 122.

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

Dethier, D., 1997, Geology of the White Rock quadrangle, Los Alamos and Santa Fe Counties New Mexico. N.M. Bur. Mines and Min. Res. Map 73, 1 sheet, 1:24,000 scale color.

Dransfield, B., and Gardner, J., 1985, Subsurface geology of the Pajarito Plateau, Española Basin, New Mexico. Los Alamos National Laboratory Report LA-10455-MS, 15 pp.

Dunker, K. Wolff, J., Harmon, R., Leat, P., Dicken, A., and Thompson, R., 1991, Diverse mantle and crustal components in lavas of the NW Cerros del Rio volcanic field, Rio Grande Rift, New Mexico. Contrib. Mineral. Petrol., v. 108, p. 331-345.

Fisher, R.V., and Schminke, H.-U., 1984, Pyroclastic Rocks. Springer-Verlag, Berlin, 472 pp.

Gardner, J., and Goff, F., 1984, Potassium-argon dates from the Jemez volcanic field: Implications of tectonic activity in the north-central Rio Grande Rift, in (Baldridge, W., Dickerson, P., Riecker, R., and Zidek, J., eds.) Rio Grande Rift: Northern New Mexico. N.M. Geol. Soc. 35th Annual Field Conf., Oct. 11-13, p. 75-81.

Gardner, J., and Goff, F., 1996, Geology of the northern Valles caldera and Toledo embayment, New Mexico, in (Goff, F., Kues, B., Rogers, M., McFadden, L., and Gardner, G., eds.) The Jemez Mountains Region. N.M. Geol. Soc. 47th Annual Field Conf., p. 225-230.

Gardner, J. N., and House, L. S, 1994, Surprisingly high intensities from two small earthquakes, northern Rio Grande rift, New Mexico; EOS, Transactions American Geophysical Union, 75, 240.

Gardner. J. N., and House, L. S., 1999, High Modified Mercalli Intensities from small shallow earthquakes, northern Rio Grande rift, New Mexico USA; *EOS, Trans. American Geophysical Union,* v. 80, n. 46, p. F710.

Gardner, J., Goff, F., Garcia, S., and Hagan, R., 1986, Stratigraphic relations and lithologic variations in the Jemez volcanic field, New Mexico. J. Geophys. Res., v. 91, p. 1763-1778.

Gardner, J.N., Goff, F., Kelley, S.A., and Jacobs, E., 2010. Rhyolites and associated deposits of the Valles-Toledo caldera complex. New Mexico Geology, v. 32, p. 3-18.

Gardner, J., Kolbe, T., and Chang, S., 1993, Geology, drilling and some hydrologic aspects of seismic hazards program core holes, Los Alamos National Laboratory. Los Alamos National Laboratory Report LA-12460-MS, 19 pp.

Gardner, J. N., Lavine, A., WoldeGabriel, G., Krier, D. J., Vaniman, D., McCalpin, J., 1998, Evolution of the western boundary of the Rio Grande rift, northern New Mexico*: EOS, Trans. American Geophysical Union*, v. 79, n. 45, p. F614.

Gardner, J. N., Lavine, A., WoldeGabriel, G., Krier, D., Vaniman, D., Caporuscio, F., Lewis, C., Reneau, P., Kluk, E., and Snow, M., 1999, Structural geology of the northwestern portion of Los Alamos National Laboratory, Rio Grande rift, New Mexico: Implications for seismic surface rupture potential from TA-3 to TA-55; Los Alamos National Laboratory report LA-13589-MS, 112 pp.

Gardner, J. N., Reneau, S. L., Lewis, C. J., Lavine, A., Krier, D. J., WoldeGabriel, G., and Guthrie, G. D., 2001, Geology of the Pajarito fault zone in the vicinity of S-Site (TA-16), Los Alamos National Laboratory, Rio Grande rift, New Mexico: Los Alamos National Laboratory Report LA-13831-MS, Los Alamos, New Mexico, 84 p.

Goff, F., 1995, Geologic map of Technical Area 21, in (Broxton, D., and Eller, P., eds.) Earth science investigations for environmental restoration - Los Alamos National Laboratory Technical Area 21. Los Alamos National Laboratory Report LA-12934-MS, p. 7-18 and Plate 1 (by F. Goff and S.L. Reneau).

Goff, F. and Gardner, J.N., 2004, Late Cenozoic geochronology of volcanism and mineralization in the Jemez Mountains and Valles caldera, north central New Mexico, in (G. Mack and K. Giles, eds.), *The Geology of New Mexico —A Geologic History*. New Mexico Geological Society, Special Publication 11, Socorro, p. 295-312.

Goff, F., Gardner, J., and Valentine, G., 1990, Geologic map of the St. Peter's Dome area, Jemez Mountains, New Mexico. N.M. Bur. Mines and Min. Res. Map 69, 2 sheets, 1:24,000 scale color.

Goff, F., Gardner, J.N., Reneau, S.L., Kelley, S.A., Kempter, K.A., and Lawrence, J.R., 2011, Geologic map of the Valles caldera, Jemez Mountains, New Mexico. New Mexico Bureau of Geology and Mineral Resources, Geologic map 79, 1:50,000 scale, color w/ 30 p. booklet.

Golombek, M. P., 1981, Structural analysis of the Pajarito fault zone in the Española Basin of the Rio Grande rift, New Mexico; Ph.D. dissertation, University of Massachusetts, 129 pp.

Griggs, R., 1964, Geology and groundwater resources of the Los Alamos area, New Mexico. U.S. Geol. Survey, Water Supply Paper 1753, 107 pp. (w/1:24,000 scale color map).

Heiken, G., Goff, F., Stix, J., Tamanyu, S., Shafiqullah, M., Garcia, S., and Hagan, R., 1986, Intracaldera volcanic activity, Toledo caldera and embayment, Jemez Mountains, New Mexico. J. Geophys. Res., v. 91, p. 1799-1815.

Heiken, G., Wohletz, K., Fisher, R., and Dethier, D., 1996, Part II: Field guide to the maar volcanoes of White Rock Canyon, in (Self, S., Heiken, G., Sykes, M., Wohletz, K., Fisher, R., and Dethier, D., eds.) Field excursions to the Jemez Mountains, New Mexico. N.M. Bur. Mines and Min. Res., Bull. 134, p. 56-72.

House, L., and Hartse, H., 1995, Seismicity and faults in northern New Mexico; New Mexico Geological Society Guidebook, 46, 135-137.

Iddings, J.P., 1890, On a group of rocks from the Tewan Mountains, New Mexico, and on the occurrence of primary quartz in certain basalts; U.S. Geological Survey, Bulletin 66, 34 p.

Izett, G.A., and Obradovich, J.D., 1994, $^{40}Ar/^{39}Ar$ age constraints for the Jaramillo Normal Subchron and the Matuyama-Brunhes geomagnetic boundary. J. Geophysical Research, v. 99, p. 2925-2934.

Izett, G., Obradovich, J., Naeser, C., and Cebula, C., 1981, Potassium-argon and fission-track zircon ages of Cerro Toledo rhyolite tephra in the Jemez Mountains, New Mexico: U.S. Geological Survey, Professional Paper 1199-D, p. 37-43.

Justet, L., 1996, The geochronology and geochemistry of the Bearhead Rhyolite, Jemez volcanic field, New Mexico: M.S. thesis, University of Nevada, Las Vegas, 152 p.

Keller, G. R., (ed.), 1986, Special section on the Rio Grande rift; Journal of Geophysical Research 91, 6142-6345.

Kelley, V., 1978, Geology of the Española Basin, New Mexico. N.M. Bur. Mines and Miner. Res. Map 48, 1 sheet, 1:125,000 scale color.

Kelson, K. I., Hemphill-Haley, M. A., Olig, S. S., Simpson, G. D., Gardner, J. N., Reneau, S. L., Kolbe, T. R., Forman, S. L., and Wong, I. G., 1996, Late-Pleistocene and possibly Holocene displacement along the Rendija Canyon fault, Los Alamos County, New Mexico, in (Goff, F., Kues, B., Rogers, M., McFadden, L., and Gardner, J., eds.) The Jemez Mountains Region: New Mexico Geological Society Guidebook 47, 153-160.

Laughlin, A.W., WoldeGabriel, G., and Dethier, D., 1993, Volcanic stratigraphy of the Pajarito Plateau. Unpublished preliminary report, Los Alamos National Laboratory, 30 pp.

Lavine, A., Smith, G.A., Goff, F., and Gardner, J., 1996, Volcaniclastic rocks of the Keres Group: Insights into mid-Miocene volcanism and sedimentation in the southeastern Jemez Mountains, in (Goff, F., Kues, B., Rogers, M., McFadden, L., and Gardner, J., eds.) The Jemez Mountains Region: New Mexico Geological Society, Guidebook 47, p. 211-218.

Longmire, P., Broxton, D., Stone, W., Newman, B, Gilkeson, R., Marin, J., Vaniman, D., Counce, D., Rogers, D., Hull, R., McLin, S., and Warren, R., 2001, Characterization well R-15 completion report. Los Alamos National Laboratory Report LA-12749-MS, 85 pp w/appendices.

Machette, M. N., Personious, S. F., Kelson, K. I., Haller, K. M., and Dart, R. L., 1998, Map and data for Quaternary faults and folds in New Mexico; U. S. Geological Survey Open-file report 98-521, 443 pp.

Manley, K., 1979, Stratigraphy and structure of the Española Basin, Rio Grande Rift, New Mexico, in (R. Riecker, ed.) Rio Grande Rift: Tectonics and Magmatism. Amer. Geophys. Union, Wash. D.C., pp. 71-86.

McCalpin, J. P., 1998, Late Quaternary faulting on the Pajarito fault, west of Los Alamos National Laboratory, north-central New Mexico; unpublished consulting report by GEO-HAZ Consulting, Inc., Estes Park, Colorado.

McIntosh, W., and Quade, J., 1995, $^{40}Ar/^{39}Ar$ geochronology of tephra layers in the Santa Fe Group, Española Basin, New Mexico in (Bauer, P. Kues, B., Dunbar, N., Karlstrom K., and Harrison, B., eds.) Geology of the Santa Fe Region. N.M. Geol. Soc. 46th Annual Field Conf., p. 279-287.

Phillips, E. H., Goff, F., Kyle, P. R., McIntosh, W. C., Dunbar, N. W., and Gardner, J. N., 2007, The$^{40}Ar/^{39}Ar$ age constraints on the duration of resurgence at the Valles caldera, New Mexico: Journal of Geophysical Research, 112, B08201, doi:10.1029/2006JB004511.

Purtymun, W., 1995, Geologic and hydrologic records of observation wells, test holes, test wells, supply wells, springs, and surface water stations in the Los Alamos area. Los Alamos National Laboratory Report LA-12883-MS, 339 pp.

Reneau, S. L., 1995, Geomorphic studies at DP Mesa and vicinity, *in* Broxton, D. E., and Eller, P. G., eds., Earth science investigations for environmental restoration--Los Alamos National Laboratory Technical Area 21: Los Alamos National Laboratory Report LA-12934-MS, Los Alamos, New Mexico, p. 65-92.

Reneau, S. L., 2000, Stream incision and terrace development in Frijoles Canyon, Bandelier National Monument, New Mexico, and the influence of lithology and climate: Geomorphology, v. 32, p. 171-193.

Reneau, S. L., and Dethier, D. P., 1996, Pliocene and Quaternary history of the Rio Grande, White Rock Canyon and vicinity, New Mexico, *in* (Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N., eds.), The Jemez Mountains region: New Mexico Geological Society Forty-Seventh Annual Field Conference Guidebook, p. 317-324.

Reneau, S. L., and McDonald, E. V., 1996, Landscape history and processes on the Pajarito Plateau, northern New Mexico: Rocky Mountain Cell, Friends of the Pleistocene, Field Trip Guidebook, Los Alamos National Laboratory report LA-UR-96-3035, Los Alamos, New Mexico, 195 p.

Reneau, S. L., Dethier, D. P., and Carney, J. S., 1995a, Landslides and other mass movements near Technical Area 33, Los Alamos National Laboratory: Los Alamos National Laboratory Report LA-12955-MS, Los Alamos, New Mexico, 48 p.

Reneau, S., Gardner, J., and Forman, S., 1996a, New evidence for the age of the youngest eruptions in the Valles caldera. Geology, v. 24, p. 7-10.

Reneau, S. L., Kolbe, T., Simpson, D., Carney, J. S., Gardner, J. N., Olig, S. S., and Vaniman, D. T., 1995b, Surficial materials and structure at Pajarito Mesa, *in* Reneau, S. L., and Raymond, R., Jr., editors, Geological site characterization for the proposed Mixed Waste Disposal Facility, Los Alamos National Laboratory: Los Alamos National Laboratory Report LA-13089-MS, Los Alamos, New Mexico, p. 31-69.

Reneau, S. L., McDonald, E. V., Gardner, J. N., Kolbe, T. R., Carney, J. S., Watt, P. M., and Longmire, P. A., 1996b, Erosion and deposition on the Pajarito Plateau, New Mexico, and implications for geomorphic responses to late Quaternary climatic changes, *in* Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N., eds., The Jemez Mountains region: New Mexico Geological Society Forty-Seventh Annual Field Conference Guidebook, p. 391-397.

Riecker, R. E., (ed.), 1979, Rio Grande rift: Tectonics and magmatism; American Geophysical Union, Washington, D. C., 438 pp.

Rogers, M., 1995, Geologic map of Los Alamos National Laboratory Reservation. N.M. Environment Dept., Santa Fe, 25 sheets, 1:4800 scale, color.

Sanford, A. R., Jaksha, L. H., and Cash, D. J., 1991, Seismicity in the Rio Grande rift; in Neotectonics of North America, Decade Map Volume 1, D. B. Slemmons, E. R. Engdahl, M. D. Zoback, and D. D. Blackwell, (eds.); Geological Society of America, 229-244.

Self, S., Goff, F., Gardner, J., Wright, J., and Kite, W., 1986, Explosive rhyolitic volcanism in the Jemez Mountains: vent locations, caldera development, and relation to regional structure. J. Geophys. Res., v. 91, 1779-1798.

Self, S., Kircher, D.E., and Wolff, J.A., 1988, The El Cajete Series, Valles caldera, New Mexico. J. Geophysical Research, v. 93, p. 6113-6127.

Smith, G.A., and Lavine, A., 1996, What is the Cochiti Formation? *in* (Goff, F., Kues, B. S., Rogers, M. A., McFadden, L. D., and Gardner, J. N., eds.), The Jemez Mountains region: New Mexico Geological Society Forty-Seventh Annual Field Conference Guidebook, p.219-224.

Smith, R. Bailey, R., and Ross, C., 1970. Geologic map of the Jemez Mountains, New Mexico. U.S. Geol. Survey, Misc. Geol. Invest. Map I-571, 1 sheet, 1:125,000 scale color.

Spell, T.L., and Harrison, T.M., 1993, $^{40}Ar/^{39}Ar$ geochronology of post-Valles caldera rhyolites, Jemez volcanic field, New Mexico. J. Geophysical Research, v. 98, p. 8031-8051.

Spell, T., McDougall, I., and Doulgeris, A., 1996, Cerro Toledo Rhyolite, Jemez volcanic field, New Mexico: $^{40}Ar/^{39}Ar$ geochronology of eruptions between two caldera-forming events: Geological Society of America Bulletin, v. 108, p. 1549-1566.

Spiegel, Z., and Baldwin, B., 1963, Geology and water resources of the Santa Fe area, New Mexico. U.S. Geological Survey Water-supply Paper 1525, 258 pp.

Stearns, C.E., 1943, The Galisteo Formation of north-central New Mexico. J. Geology, v. 51, p. 301-319.

Steck, L. K., Thurber, C. H., Fehler, M. C., Lutter, W. J., Roberts, P. M., Baldridge, W. S., Stafford, D. G., and Sessions, R., 1998, Crust and upper mantle P wave velocity structure beneath Valles caldera, New Mexico; Journal of Geophysical Research 103, 24301-24320.

Stimac, J.A., Broxton, D., Kluk, E., and Chipera, S., 1994, Preliminary stratigraphy of tuffs from borehole 49-2-700-1 at Technical Area 49. Los Alamos National Laboratory, unpublished report.

Stix, J., Goff, F., Gorton, M., Heiken, G., and Garcia, S., 1988, Restoration of compositional gradients in the Bandelier silicic magma chamber between two caldera-forming eruptions. J. Geophys. Res., v. 93, p. 6129-6147.

Toyoda, S., Goff, F., Ikeda, S., and Ikeya, M., 1995, ESR dating of quartz phenocrysts in the El Cajete and Battleship Rock Members of Valles Rhyolite, Valles caldera, New Mexico. J. Volcanology and Geothermal Research, v. 67, p. 29-40.

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

Waresback, D., 1986, The Puye Formation, New Mexico: Analysis of a continental rift-filling volcaniclastic alluvial fan sequence. M.S. thesis, Univ. Texas, Arlington, 225 pp.

Weir, J.E., and Purtymun, W.D., 1962, Geology and hydrology of Technical Area 49, Frijoles Mesa, Los Alamos County, New Mexico. Administrative report prepared for the U.S. Atomic Energy Commission by the U.S. Geological Survey, 225 pp.

WoldeGabriel, G., 1994, Letter report: Bulk and single crystal $^{40}Ar/^{39}Ar$ dating of basaltic and silicic rocks from the Pajarito Plateau. Unpublished memo to D. Broxton, Los Alamos National Laboratory, 5 pp.

WoldeGabriel, G., Laughlin, A., Dethier, D., and Heizler, M., 1996, Temporal and geochemical trends of lavas in White Rock Canyon and the Pajarito Plateau, Jemez volcanic field, New Mexico, USA, in (Goff, F., Kues, B., Rogers, M., McFadden, L., and Gardner, G., eds.), The Jemez Mountains Region. N.M. Geol. Soc. 47th Annual Field Conf., p. 251-261.

WoldeGabriel, G., Warren, R., Broxton, D., Vaniman, D., Heizler, M., Kluk, E., and Peters, L., 2001, Episodic volcanism, petrology, and lithostratigraphy of the Pajarito Plateau and adjacent areas of the Española Basin and the Jemez Mountains, *in* (L.S. Crumpler and S.G. Lucas, eds.) Volcanology in New Mexico. New Mexico Museum of Natural History and Science, Bulletin 18, p 97-129.

WoldeGabriel, G. Warren, R.G., Cole, G., Goff, F., Broxton, D. Vaniman, D., Peters, L, Naranjo, A., and Kluk, E., 2006, Volcanism, tectonics, and chronostratigraphic records in the Pajarito Plateau of the Española Basin, Rio Grande rift, north-central New Mexico, USA: Los Alamos national Laboratory Report LA-UR-06-6089, 122 pp.

Wolff, J. A., and Gardner, J. N., 1995, Is the Valles caldera entering a new cycle of activity?; Geology 23, 411-414.

Wolff, J., Gardner, J.N., and Reneau, S., 1996, Field characteristics of the El Cajete pumice deposit and associated southwestern moat rhyolites of the Valles caldera, in (Goff, F., Kues, B., Rogers, M., McFadden, L., and Gardner, G., eds.) The Jemez Mountains Region: New Mexico Geological Society, Guidebook 47, p. 311-316.

Wolff, J.A., Brunstad, K.A., and Gardner, J.N., 2011, Reconstruction of the most recent volcanic eruptions from the Valles caldera, New Mexico. Journal of Volcanology and Geothermal Research, v. 199, pp. 53-68.