Geologic Map of the Valle San Antonio Quadrangle, Sandoval and Rio Arriba Counties, New Mexico.

By

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Open-file Digital Geologic Map OF-GM 132

Scale 1:24,000

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GEOLOGY OF THE VALLE SAN ANTONIO 7.5 MINUTE QUADRANGLE, SANDOVAL AND RIO ARRIBA COUNTIES, NEW MEXICO

1:24,000

By

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INTRODUCTION

The Valle San Antonio 7.5 minute quadrangle is located in Sandoval and Rio Arriba Counties and straddles the northwestern rim of the Valles caldera in the Jemez Mountains, New Mexico (Fig. 1). Topographically, the quadrangle is bounded by the caldera wall on the north, San Antonio Creek and San Antonio Mountain on the west, and the Valles caldera resurgent dome (Redondo Peak and Redondo Border) on the east and south. Tectonically, the quadrangle overlies a portion of the boundary between the Rio Grande rift and the Colorado Plateau. The quadrangle consists of four domains: precaldera volcanic rocks exposed along the north wall of Valles caldera, rhyolite ignimbrites forming mesas and canyons northwest of the caldera, rhyolite lava domes and associated sediments filling the north and east moat zones of the caldera, and a resurgent dome of uplifted caldera floor rocks standing in the approximate center of the caldera. Each domain has unique geology as described below. The Valles Caldera National Preserve (VCNP), established in 2000, occupies the entire quadrangle except for a thin strip of land belonging mostly to the Santa Fe National Forest along the western edge of the quadrangle. Before 2000, the Preserve belonged to the Baca Land and Cattle Company of Abilene, Texas. Access to the Preserve is presently restricted and all roads are gated. Small blocks of private lands occur along Sulphur Creek in the southwest corner of the quadrangle. The quadrangle contains no paved roads at this time. All access is by dirt roads and by abandoned logging roads or trails, mostly within the VCNP.

The area of the quadrangle was once home to pre-Columbian Indian cultures (Paleo-Indian, Archaic, and ancestral Puebloan), Spanish land grants, homesteads and scattered ranches. Two 19 acre patented claims at Sulphur Springs near the southwest edge of the quadrangle were mined for sulfur during World War I. A spa and resort was constructed on this property in the 1920s but burned down in the early 1960s. VCNP owns most of the land in the quadrangle (Martin, 2003) and was created by the Valles Caldera Preservation Act of 2000 to preserve and protect the historic Baca Ranch and the geologically famous Valles caldera of the Jemez Mountains volcanic field. Currently, the VCNP is managed for limited public recreation, and for elk hunting, cattle grazing, fishing, and scientific study. Geothermal energy was explored but not developed on both VCNP and National Forest lands in the 1960s to 1980s (Laughlin, 1981; Goff and Gardner, 1988). Presently, timber is harvested and pumice is mined on selected National Forest lands surrounding the Preserve.

The objectives of the present study are to provide detailed geologic mapping for the VCNP and to contribute quadrangle maps for the New Mexico State Map Program. Field mapping was conducted during parts of 2002 to 2006. A detailed geologic map of the Sulphur Springs area was published by Goff and Gardner (1980). Regional geology and stratigraphy have been previously published by Griggs (1964), Bailey et al. (1969), Smith et al. (1970), Kelley (1978), Gardner (1985), Gardner and Goff (1984), Gardner et al. (1986), Goff and Gardner (2004), Gardner et al. (2010), and Goff et al. (2007, 2011). Adjacent and nearby NM State Map quadrangles have been published by Gardner et al., (2006), Goff et al. (2002, 2005a, 2005b), Kempter and Kelley (2002), Lawrence et al. (2004), Osburn et al. (2002), Kelley et al. (2003; 2004) and Lynch et al. (2004).

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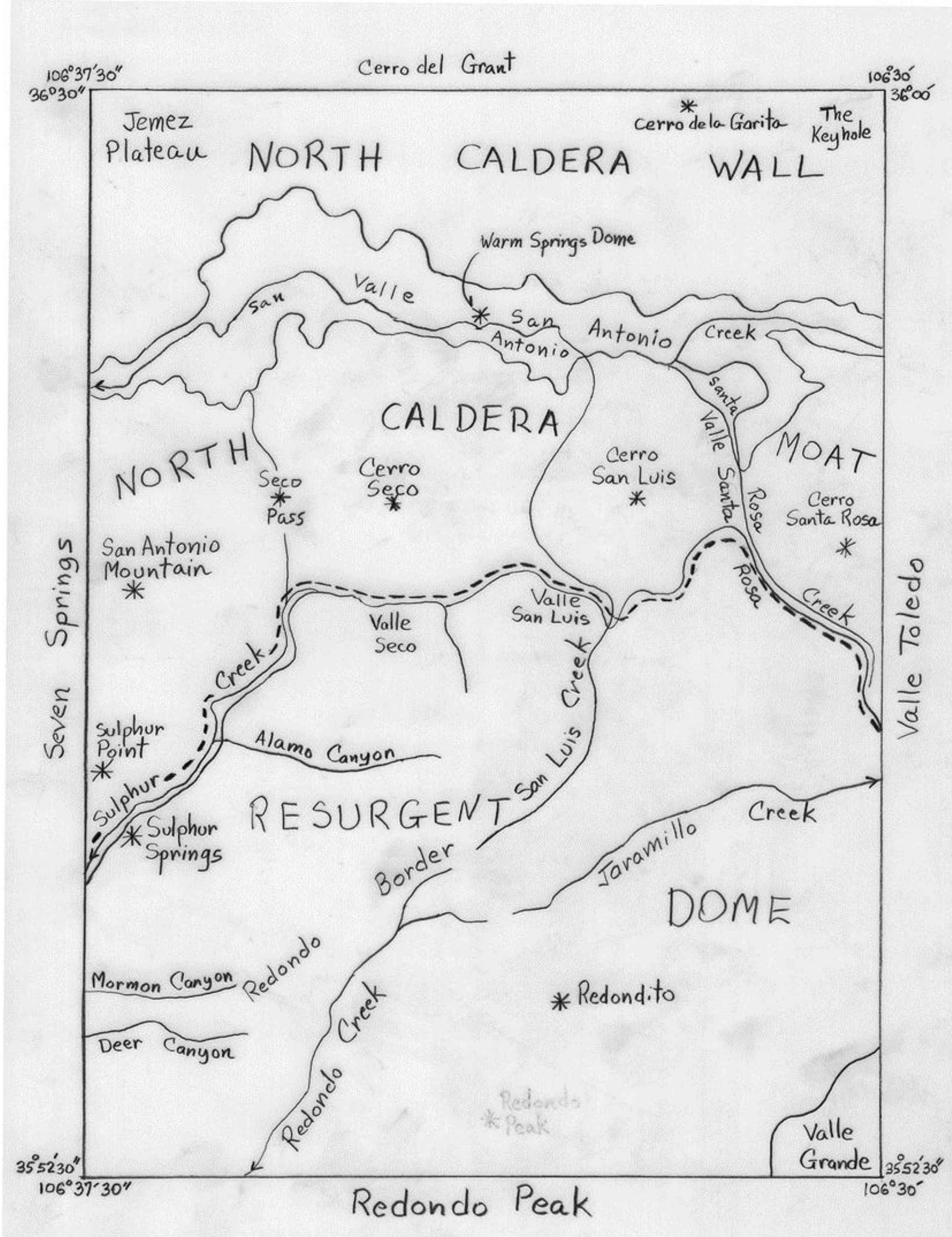

Figure 1: Map of Valle San Antonio 7.5 minute quadrangle showing locations of resurgent dome (south of heavy dashed line), the northern caldera moat, the northern caldera rim (north of Valle San Antonio), and major physiographic features. The names of adjacent 7.5-minute quadrangles are also shown. The Keyhole is local name given to the pass out of Valle San Antonio in the northeastern part of the quadrangle.

STRATIGRAPHY AND EVOLUTION

The oldest exposed rocks in the Valle San Antonio quadrangle consist of caldera wall collapse breccias containing rocks of Pennsylvanian to Miocene age. Often called megabreccias and associated with caldera formation, these units will be described below with rocks of the Valles caldera resurgent dome (see also Goff et al., 2007). Precambrian, Mississippian, Pennsylvanian, Permian, and Miocene (Santa Fe Group) rocks are commonly intersected by geothermal wells at great depth in the resurgent dome area and the south margin of the northern moat (see Description of Units). Geothermal wells within the caldera have not intersected Triassic rocks or strata of the Miocene to Oligocene (?) Abiquiu Formation (Lambert and Epstein, 1980; Nielson and Hulen, 1984; Goff and Gardner, 1994). However, the oldest rocks within the quadrangle that are stratigraphically intact, consist of white to tan, bedded, nearly flat lying, sandstone and siltstone of the Abiquiu Formation (Correlation Chart – see map) and may be part of the upper Abiquiu as described by Kelley et al. (2004). Several exposures of these rocks occur near the bottom of the northwest caldera wall, surrounded by landslide debris of younger rocks. The type locality of the unit occurs roughly 30 km north of the caldera at the village of Abiquiu (Smith, 1938; Smith, 1995; Smith et al., 2002). The type locality contains a significant amount of conglomerate, but the exposures within the caldera, which are only a few meters thick, consist mostly of fine-grained sandstone. Relations with overlying rocks are not exposed but judging from float the Abiquiu is apparently overlain by debris flows and lava flows of Tertiary age.

A sequence of poorly exposed, white to tan to red-orange, sandstone and conglomerate containing a significant amount of quartz, feldspar and intermediate composition volcanic rocks occurs within the northeast corner of the quadrangle in the vicinity of "The Keyhole." The unit is not shown on previous geologic maps of this area, although it is nearly 400 m thick. The sedimentary rocks are interbedded with lava flows of the Paliza Canyon Formation, are overlain by an extensive biotite andesite flow of the La Grulla Formation and are intruded by irregularly shaped dikes and small plugs of the Bearhead Rhyolite. Hydrothermal fluids extensively alter many of these sedimentary rocks, some of which contain copious Fe-oxide cements. Near some of the intrusions, the sandstones are extensively silicified and/or converted to fine-grained hornfels. The origin and provenance of these sedimentary rocks are poorly understood at this time, but because of their stratigraphic position, they are correlated in age with Miocene rocks of the Santa Fe Group, perhaps with the Hernandez Member of the Chamita Formation (Koning et al., 2005).

The next package of rocks consists of intermediate composition lava flows and a tuff of the Paliza Canyon Formation (Keres Group). These rocks are well exposed in the north wall of the caldera beneath Cerro de la Garita. Most of the flows are black to gray two-pyroxene andesite with distinctive plagioclase laths in a glassy groundmass. Flow breccias are common as are vesiculated flow tops. Some flows near the top of the section beneath Cerro de la Garita contain rare, inconspicuous biotite. A lava flow found along the north edge of San Antonio Creek in the eastern part of the quadrangle contains significant biotite and is classified as dacite. Many of these flows contain moderate to intense hydrothermal alteration. Thin sandstone interbeds and/or gravel layers are found between many flows, generally too small to map.

A distinctive greenish gray, lithic-rich tuff (unit Tpdt) underlies andesite lava at the base of the ridge southwest of Cerro de la Garita. This tuff resides within a sub-circular vent that apparently cuts a different andesite lava at hill 8882 due south of Cerro de la Garita. The tuff contains crystal fragments of pyroxene, plagioclase, hornblende and biotite along with pumiceous dacite clasts and fragments of volcanic rocks, sandstones, and rare Precambrian lithologies. Alteration of the tuffaceous matrix is pervasive but it is dated at 8.20 ± 0.39 Ma (WoldeGabriel, 1990). A megabreccia block composed of a similar dacite tuff occurs on the northern side of the resurgent dome of Valles caldera. Biotite from pumice in the megabreccia block is dated at 8.21 ± 0.08 Ma (Phillips, 2004).

In the northwest caldera wall in the headwall scarp of a large landslide complex is a layer of black to gray olivine basalt of the La Grulla Formation (Goff et al., 2011). The basalt underlies a thick sequence of biotite andesite flows (unit Tga). This outcrop is the only exposure of basalt in this part of the Valle San Antonio quadrangle but is petrographically similar to a remnant basalt flow overlying biotite andesite immediately to the north in Cerro del Grant quadrangle (Lawrence et al., 2004). These flows are dated at about 7.80 Ma (Goff et al., 2011). Farther north, basalt flows of the La Grulla volcanic center are dated at 7 to 8 Ma (Lawrence et al., 2004) but correlations among the various basalt flows have not been performed.

An extensive sheet of gray biotite andesite containing two pyroxenes, biotite and abundant, tabular plagioclase phenocrysts (Tga) overlies the Paliza Canyon Formation andesite and above mentioned olivine basalt along most of the north caldera wall. This unit is assigned to the La Grulla Formation because of its distinctive coarser-grained appearance and high stratigraphic position. It may be that it is chemically and mineralogically transitional between Paliza Canyon and Tschicoma formations. The unit probably consists of multiple flows from multiple vents. One of these vents probably occurred at or near the summit of Cerro de la Garita where the andesite is up to 200 m thick. The upper slopes of Cerro de la Garita also contain large quantities of dacitic pumice.

Overlying the biotite andesite is a small, highly eroded La Grulla dacite dome and flow capping the south side of Cerro de la Garita. The flow overlies the west side of the summit. This dacite is distinctive because it is only moderately porphyritic containing small crystals of plagioclase, pyroxene, biotite and hornblende in a glassy groundmass. This dacite is dated by $^{40}Ar/^{39}Ar$ methods at 7.34 ± 0.07 Ma (W. McIntosh, unpub. data).

Next, irregularly shaped dikes and small plugs of high-silica rhyolite intruded volcanic lavas and interbedded Santa Fe-like sediments in the northeast part of the quadrangle. One of the dikes intrudes lowermost La Grulla biotite andesite in the wall of a landslide scar in The Keyhole. These rhyolite intrusions are not recognized on previous geologic maps of the area. The intrusive relations are best exposed in the northwest corner of the adjacent Valle Toledo quadrangle (Gardner et al., 2006) but are also well exposed along the north-trending ravine in the northeastern Valle San Antonio quadrangle. A dike zone of rhyolite also cuts Paliza Canyon Formation rocks on the long ridge extending southeast from Cerro de la Garita. Where not silicified or otherwise altered, the rhyolite contains sparse small phenocrysts of quartz, K-spar and biotite and resembles the ca 7.2 to 6.0 Ma Bearhead Rhyolite in the southeastern Jemez volcanic field (Smith et al., 1970; Justet, 1999). These rhyolites also resemble small rhyolite bodies dated at 5.8 to 7.5 Ma just north in the Polvadera Peak quadrangle (Loeffler et al., 1988) and are thus correlated with Bearhead Rhyolite. Because of the large number of intrusive bodies and widespread alteration, a small stock of rhyolite probably underlies this portion of the quadrangle. This hypothetical stock may resemble the much larger rhyolite stock invading the southeastern Jemez Mountains in the vicinity of the Cochiti Mining District.

For the next 5 Ma or so, the area occupied by the Valle San Antonio quadrangle was volcanically and tectonically inactive. At about 1.6 Ma, a gigantic eruption of high-silica rhyolite ignimbrite formed the Toledo caldera and the Otowi Member of the Bandelier Tuff (Bailey et al., 1969; Smith et al., 1970; Spell and Harrison, 1993; Izett and Obradovich, 1994). The resulting explosions and collapse created a depression at least 15 km in diameter and produced roughly 400 km^3 of ash flow tuff. Because the later but comparably sized Valles caldera formed in nearly the same location as Toledo caldera, most of Toledo caldera was obliterated. Outflow sheets of the Otowi Member are well exposed in the northwest corner of the quadrangle and a thick sequence of intracaldera Otowi Member has been intersected by most deep geothermal wells in the upper Redondo Creek area. At 1.26 Ma, rhyolite lava of Warm Springs dome erupted along the northern ring-fracture zone of Toledo caldera (Goff et al., 1984; Heiken et al., 1986; Stix et al., 1988; Spell et al., 1996). Warm Springs dome is the only remaining rhyolite associated with post-Toledo caldera development in the Valle San Antonio quadrangle.

At ca. 1.25 Ma, Valles caldera formed during the eruption of roughly 400 km^3 of the Tshirege Member of the Bandelier Tuff. Outflow sheets of the Tshirege overlie the Otowi in the northwest portion of the quadrangle. The resulting collapse depression was more than 15 km in diameter. As the caldera formed, caldera-wall collapse breccias (including megabreccias) slid into the developing hole (Lipman, 1976) and were incorporated within intracaldera Tshirege Member ignimbrites. The megabreccia blocks are lithologically varied and range in size from blocks too small to map, to immense masses over 2 km long by 1 km wide (south of Redondito). Most large blocks consist of precaldera andesite, dacite and associated volcaniclastics of the Paliza Canyon and Tschicoma formations. However, large masses of the Otowi Member ignimbrite, and sedimentary rocks of the Santa Fe Group, Abiquiu Formation, Permian redbeds, and at least one block of Pennsylvanian limestone are also mapable within the quadrangle. We have observed many megabreccia blocks exposed as islands on the surface of the resurgent dome, implying that many of the blocks slid late during the formation of the caldera and prior to resurgence.

Soon after the Tshirege eruptions ceased, the caldera depression began to fill with water and erosion of the caldera walls produced extensive colluvial aprons and debris flow deposits. The resulting lacustrine, colluvial, and debris flow deposits are interbedded with small-volume eruptions of Deer Canyon rhyolite lavas and tuffs that were erupted in the central and western caldera. High-precision $^{40}Ar/^{39}Ar$ dates of these rhyolites by Phillips

(2004; Phillips et al., 2007) are indistinguishable in age from the Tshirege Member; thus, these earliest post-caldera sediments and rhyolites were emplaced immediately after the caldera formed.

As these early post-caldera deposits were forming, the central floor of Valles caldera began to rise, forming the resurgent dome (Smith and Bailey, 1968). Multiple eruptions of Redondo Creek rhyodacite lavas occurred within the developing apical grabens (Redondo Creek, Jaramillo Creek, and San Luis Creek grabens), and along developing faults on the west side of the resurgent dome. These lavas overlie Deer Canyon units and may exceed 200 m in thickness on the western resurgent dome, implying that the lavas flowed into and filled the western moat as the resurgent dome rose.

Redondo Creek lavas are interbedded with more debris flow and lacustrine deposits indicating that the resurgent dome emerged from the intracaldera lake. However, the age of Redondo Creek lavas (1.25 to 1.23 Ma; Phillips et al., 2007) is statistically indistinguishable from that of Tshirege Member ignimbrites suggesting that resurgence occurred rapidly. To determine the duration of resurgence, Phillips et al (2007) also dated the first post-caldera moat rhyolite eruption (Cerro del Medio; 1.23 Ma). Because Cerro del Medio does not show any apparent deformation or rotation due to resurgence, it can be argued that the resurgent dome grew within 30 ka after caldera formation (Phillips et al., 2007). Redondo Peak (3450 m), the highest part of the resurgent dome, stands roughly 1000 m above the lowest parts of the present caldera floor, thus the rate of resurgent uplift was roughly 3.3 cm/yr (about 1.3 in/yr).

The northwestern sector of the Valles ring fracture zone provided conduits for eruption of several moat rhyolite lava domes and associated pyroclastic deposits. A 3-m-thick exposure inferred to be an ignimbrite from Cerro del Medio occurs along the road along the central east edge of the quadrangle. Cerro Santa Rosa I and II domes (0.94 Ma, Singer and Brown, 2002; 0.79 Ma, Spell and Harrison, 1993) occur just north of the ignimbrite. Ignimbrite (0.91 Ma) from Santa Rosa I dome underlies the east side of Cerro San Luis dome (0.80 Ma). No pyroclastic phase has been identified from Cerro San Luis. Further west, a radial apron of ignimbrite, dry surge and hydromagmatic surge occurs north of Cerro Seco dome (0.80 Ma). The Cerro Seco pyroclastic deposits locally extend more that 2 km from the lava flows forming the base of the dome. The pyroclastic deposits overlie Cerro San Luis rhyolite lava and cover portions of Warm Springs dome. The Cerro Seco pyroclastic units overlie debris flow deposits from the resurgent dome and some flat-lying lacustrine deposits in the northern caldera moat. White laminated mudstone with apparent desiccation cracks can be found within the hydromagmatic deposits, implying that a lake existed in the Valle San Antonio at approximately 0.8 Ma.

The youngest moat rhyolite in the quadrangle is San Antonio Mountain dome and flow complex (0.56 Ma; Spell and Harrison, 1993). The San Antonio eruption produced two or possibly three flows. San Antonio Mountain lavas overlie debris flow deposits and Redondo Creek rhyodacite from the resurgent dome, and overlie lacustrine deposits in the north caldera moat. No pyroclastic phase has been identified for the San Antonio eruptions.

The San Antonio lavas were viscous and porphyritic, forming dense tough rock within the interior of the flows. As first recognized by Rogers (1996) and Rogers et al. (1996), and confirmed by Reneau et al. (2004; 2007), these lavas buried San Antonio Creek and abutted the west wall of the caldera, forming a substantial dam. Although Rogers et al. (1996) proposed that the resultant lake was restricted to Valle San Antonio, mapping in this study and in the adjacent Valle Toledo quadrangle (Gardner et al., 2006) indicates that the lake extended into Valle Toledo, with major arms extending up Valle San Luis and Valle Santa Rosa. Maximum depth of the closed basin exceeded 100 m, although actual lake depth at any time is uncertain. Lacustrine deposits associated with this lake are well exposed in the Valle San Antonio quadrangle, and generally consist of finely laminated to more thickly bedded clay, silt, and sand, and are variably diatomaceous. Inferred deltaic sediments are also exposed near the east side of Valle San Antonio and in Valle Santa Rosa, recording partial filling of the lake with coarser fluvial sediment.

Before the San Antonio lake basin completely filled with sediment, San Antonio Creek cut an outlet around the west side of the San Antonio Mountain lava flows, draining the lake. A series of stream terraces formed on top of the lacustrine deposits and older rock units as the creek incised to its present grade, and many remnants of these terraces are preserved in the quadrangle. Local deformation of lacustrine deposits was observed in Valle San Antonio and Valle Santa Rosa. This deformation is inferred to be from subaqueous land sliding, possibly associated with earthquakes, and includes faulting, tilting, and folding of sediments and development of flame structures.

STRUCTURE AND TECTONICS

The structure and tectonics of rocks within the Valle San Antonio quadrangle are completely dominated by faults within the Valles resurgent dome. Only a few faults were observed cutting tuffs in the north caldera wall or cutting deposits within the northern moat. These faults have no consistent trend. An arcuate fault with down to the south displacement cuts La Grulla and Paliza Canyon andesites on the north caldera wall. This fault may be an incipient landslide block. Presumably, this fault post-dates formation of Valles caldera. A conspicuous north trending fault cuts the Bandelier Tuff and some moat deposits in the northwestern portion of the quadrangle. It displaces the Otowi Member Bandelier Tuff by about 25 m and juxtaposes the Abiquiu Formation (west) against Tertiary volcaniclastic deposits (Tpv). However, lavas of San Antonio Mountain are not displaced by the fault, indicating that movement occurred some time between 1.25 and 0. 56 Ma. Possibly, this is a reactivated, but minor, Rio Grande rift fault. Two faults located to the east of the north-south fault have east-west to northeast trends and down to the south displacements suggesting they are reactivated caldera collapse faults.

A single fault southeast of San Antonio Mountain appears to offset a small patch of the San Antonio Mountain Rhyolite just above Sulphur Creek. This is the youngest fault offset documented on the quadrangle (<0.56 Ma) and suggests reactivation of a previous resurgence fault.

The structure of the Valles resurgent dome contains a primary set of north to northeast-trending faults associated with three prominent grabens: Redondo Creek, Jaramillo Creek and San Luis Creek (Fig. 2). These grabens are approximately on trend with the northeastern fabric of the Rio Grande rift within this part of New Mexico and mirror the gravity structure beneath the caldera (Goff et al., 1989). Many of the fault blocks within the grabens are quite slender compared with their length and offsets may exceed several hundred meters. The grabens split the resurgent dome as it grew, apparently along reactivated Rio Grande rift structures.

Although the northeast-trending structural grain is most obvious, the resurgent dome is crosscut by a multitude of smaller faults that formed as the dome grew. There is no dominant trend to these faults. Rather, the resurgent dome appears to be broken into many blocks and each block has its own fault domains. The three largest blocks are the Redondo Peak, Redondo Border and San Luis blocks (Fig. 2). Interestingly, the three largest blocks display very different amounts of resurgent uplift. Redondo Peak block was uplifted the most and, as a result, retains very few post-caldera sedimentary and volcanic deposits except on the northeast end of the block (see geologic map). San Luis block was uplifted the least and is overlain by the thickest deposits of old caldera fill (Qdf), which cover underlying units. Redondo Border displays an intermediate amount of uplift. Because of this, the best information on the evolution of resurgence is preserved on the west and northwest flanks of Redondo Border.

Because of the tremendous amount of resurgent uplift, some faults display impressive shear, gouge and breccia zones. Particularly impressive are the shattered rocks along portions of the faults defining the three major grabens, the faults cutting across Deer and Mormon canyons in the southwest, the faults bordering the west, northwest and southwest portions of the Sulphur Creek fault block, the fault parallel to Alamo Canyon and the faults along Sulphur Creek north of Alamo Canyon.

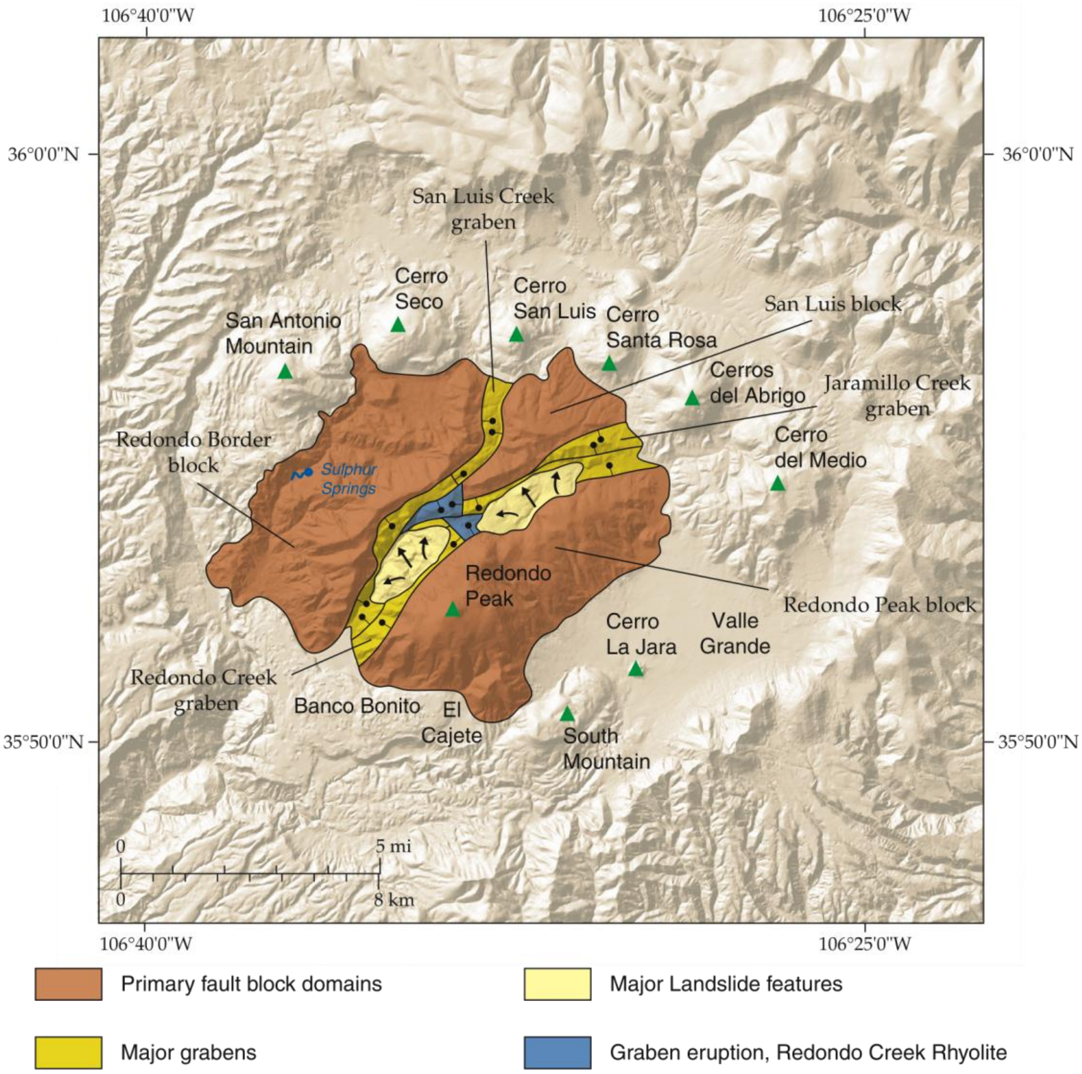

Figure 2: Map of the Valles caldera resurgent dome (from Goff et al., 2011) showing positions of major blocks, the orientation of major grabens, the position of central Redondo Creek rhyodacite, and major landslides off northwest side of the Redondo Peak block (arrows show direction of movement). The resurgent dome is encircled by ring fracture rhyolites (vent locations shown with green triangles).

HYDROTHERMAL ALTERATION AND MINERALIZATION

Four zones with several types of hydrothermal alteration and mineralization occur in the Valle San Antonio quadrangle: a zone of moderate-temperature argillic alteration associated with Bearhead Rhyolite intrusions in the north caldera wall, a zone of low-temperature zeolitic alteration associated with the upper part of the resurgent dome and the oldest post-Valles caldera lake, a zone of moderate-temperature acid-sulfate alteration associated with the Redondo Creek graben and the Redondo Border structural block, and localized silicification associated with some faults on the resurgent dome.

Bearhead intrusions in the northeast corner of the quadrangle have caused widespread silicification and clay alteration of host andesite and dacite lavas and Santa Fe Group sedimentary rocks. The alteration is associated with deposition of pyrite and possibly other sulfides that have been oxidized to red and orange Fe-oxides. Many of the rhyolite dikes and plugs are so thoroughly silicified that they resemble massive quartz veins. Within lavas at higher elevations, the alteration is associated with silica, clay, chlorite, and occasional calcite. No epidote or alunite was observed during field mapping but these rocks are worthy of detailed study as they have not been previously recognized. Previous prospectors dug many shallow excavations in this area and similar areas in the adjacent Valle Toledo quadrangle. Presumably they were looking for precious metals but found none. Some of the associated rocks around the intrusions consist of angular breccias cemented with copious amounts of Fe- and Mn-oxides and resemble hot-spring terrace breccias. We found little or no sinter so it appears that the hydrothermal system that formed the mineralization had a reservoir temperature of ≤150°C (Hochstein, 1982).

Valles caldera presently contains a 260 to 300°C liquid-dominated geothermal system that has been in existence since the caldera formed at ca. 1.25 Ma (Goff et al., 1988; WoldeGabriel and Goff, 1992; Goff and Gardner, 1994). This system was undoubtedly more potent when the caldera formed than it is today and probably discharged hydrothermal fluid into the first intracaldera lake. In a separate study (Chipera et al., 2007), we have identified widespread zeolite, clay, and silica alteration in lacustrine deposits, interbedded Deer Canyon rhyolite lavas and tuffs, and uppermost Bandelier Tuff on the resurgent dome. Where found, the zeolite alteration only affects the upper 10 m or so of the Bandelier Tuff and is localized. It does not affect the entire resurgent dome. The primary zeolites are clinoptilolite and mordenite. Clinoptilolite is most common in the lacustrine rocks while mordenite is most common in the lavas and tuffs. Presence of mordenite indicates that the first Valles lake was locally warm to moderately hot (≤100°C).

The Redondo Creek graben and the Redondo Border block contain localized, structurally controlled acid-sulfate alteration, some of which is related to present hydrothermal activity and some of which appears to be related to an earlier hydrothermal event. The alteration is best expressed at Sulphur Springs on the west side of the resurgent dome (Goff et al., 1985; Goff and Janik, 2002) where active boiling-point fumaroles and acid hot springs occur. But low-temperature fumaroles and gas vents are also widespread occurring along the Alamo Canyon and Redondo Creek graben faults and along faults between Sulphur Springs and Redondo Creek graben. The alteration consists of silica, kaolinite, alunite, pyrite, sulfur, jarosite, gypsum, smectite and Fe-oxides. Fumaroles may contain sulfur and various soluble sulfates (Charles et al., 1986). However, surrounding the alteration zone at Sulphur Springs and extending north into Valle Seco and the southern margin of Valle San Antonio, is a zone of widespread silicification (quartz, chalcedony and opal) that includes associated kaolinite, alunite and minor smectite. This alteration affects some lacustrine deposits from the initial (1.25 Ma) Valles lake and some lacustrine deposits that overlie older caldera fill (Qdf) but underlie Cerro Seco pyroclastic deposits (Qvset, about 0.8 Ma). Apparently, more widespread acid-sulfate alteration occurred in the west and northwest portions of the caldera than seen today and may have been active until after 0.8 Ma. This hypothesis requires further substantiation.

Finally, localized silicification occurs along some faults of the resurgent dome quite distant from active hydrothermal areas. The alteration usually consists of quartz to opal deposition in gouge zones about 0.5 m wide and, rarely, of massive quartz replacement of Bandelier Tuff and other rocks up to 3 m wide. The silicification may be associated with Fe-oxide staining, particularly in the opal. Good exposures occur along faults bordering the west side of San Luis graben adjacent to down-faulted Redondo Creek rhyodacite, the poorly exposed fault on the east nose of Cerro Piñon, and in cross faults cutting the Redondo Peak block northeast of Redondito. This fault-controlled silicification may represent conduits for rising hydrothermal fluids during the growth of the resurgent dome.

Alteration, mineralization and fluid composition within the present Valles geothermal system has been discussed by Laughlin (1981), Smith and Kennedy (1985), Hulen and Nielsen (1986), Truesdell and Janik (1986), White (1986), Goff and Gardner (1994) and Goff and Janik (2002) among others.

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), Goff and Gardner (2004), Gardner et al. (2010), and Goff et al. (2007, 2011). Field names of volcanic rocks are based on hand specimens and petrography and may differ from names based on chemical classifications (Wolff et al., 2005). Minor yet significant changes in regional stratigraphy and nomenclature have occurred here since this map was first compiled and are described in the ***Geologic Map of the Valles caldera, Jemez Mountains, New Mexico*** (Goff, et al., 2011).

Quaternary Deposits

Qdi **Disturbed areas—**Anthropogenically disturbed areas consisting of underlying rock units at each site; unit mapped only where extensive at unused electric power plant site west of Redondo Creek; not shown in correlation chart; maximum thickness less than 5 m.

Qal **Alluvium—**Deposits of sand, gravel and silt in main valley bottoms; locally includes stream terraces, alluvial fans, canyon wall colluvium, and bog deposits; mostly Holocene in age; ^{14}C age on basal bog deposits in Alamo Canyon is 4595 ± 105 yBP (Stearns, 1981); more recent ^{14}C age of 7940 ± 40 yBP was obtained from a different site at depth of roughly 490 cm (Brunner, 1999; S. Anderson, personal communication, 2006); ^{14}C date of 8110 ± 40 yBP was obtained at depth of roughly 175 cm in Santa Rosa bog (S. Anderson, personal communication, 2006); maximum thickness of various alluvium deposits is uncertain but may exceed 15 m.

Qc **Colluvium—**Poorly sorted slope wash and mass wasting deposits from local sources; mapped only where extensive or where covering critical relations; unit is commonly gradational into Qoaf; thickness can locally exceed 15 m.

Qalo **Slightly older alluvium**—Deposits of gravel, sand, silt and minor lacustrine beds along the edges of Sulphur Creek in the southwest corner of the quadrangle; Holocene or slightly older in age; maximum thickness probably 15 m.

Qaf **Alluvial fans—**Typically fan-shaped deposits of coarse to fine gravel and sand, silt, and clay within and at the mouths of valleys and in the Valle San Antonio; associated with present drainages and usually not incised; grades into alluvial deposits along main channels; probable age late Holocene to late Pleistocene; maximum exposed thickness about 15 m.

Qt **Younger stream terraces—**Deposits of sand, gravel, and silt that underlie young terraces bordering present streams; inferred to be largely Holocene or late Pleistocene in age; maximum thickness uncertain.

Qls **Landslides—**Poorly sorted debris that has moved chaotically down steep slopes; 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; some landslides in Valle San Antonio involve lacustrine deposits (Ql) and post-date incision of the inner valley; thickness varies considerably depending on the size and nature of the landslide.

Qrx **Boulder fields—**Areas covered with boulders as large as 3 m derived from subjacent rock units; generally devoid of vegetation; many appear to be rock glaciers, exhibiting flowage features such as arcuate pressure ridges (Blagbrough, 1994); thickness unknown.

Qto **Older stream terraces—**Deposits of sand, gravel, and silt that underlie higher terraces and generally post-date lake that occupied Valle San Antonio, Valle San Luis, and Valle Santa Rosa; includes multiple Pleistocene-age surfaces that formed during incision of main streams through lake deposits, and locally includes fluvial deposits associated with deltas that filled the upper parts of the lake in Valle San Antonio and Valle Santa Rosa; in Valle San Antonio, terrace remnants occur up to 45 m above present channel; commonly overlies strath surfaces cut into lake deposits, and also overlies older rock units; typical thickness is 1 to 2 m, but may locally exceed 10 m in thickness.

Qlso **Older landslides—**Older slide deposits that are overlain by several types of younger deposits; maximum exposed thickness about 25 m.

Qafo **Older alluvial fans—**Older deposits of coarse to fine gravel and sand, silt, and clay derived mostly from the volcanic domes, resurgent dome, and caldera walls; deposits commonly post-date the lake that occupied Valle San Antonio, Valle San Luis, and Valle Santa Rosa, and have been incised; mainly Pleistocene in age although, typically, portions are still active; contacts with Qc, particularly around flanks of volcanic domes, are gradational; thickness is unknown.

Ql **Lacustrine deposits—**Finely laminated deposits of clay, silt, and very fine sand with subordinate fine to coarse sand and gravel; deposited in lakes formed by blockage of drainages by post-resurgence eruptions from the ring-fracture vents (Reneau et al., 2004; 2007); deposits sometimes tuffaceous, and diatomaceous facies occur; some deposits north of Cerro Seco contain what appear to be insect impressions, fossil reeds, and other organic materials; interbedded with and overlain by older alluvial fans (Qoaf); overlies older landslides (Qols) and underlies older terrace deposits (Qot); deposits in the upper (east) part of the valley generally overlie the lavas of Cerro San Luis (Qvsl); some deposits in the lower (west) part of valley underlie the tuffs and tuffaceaous sediments of Cerro Seco (Qvset) and lavas of San Antonio Mountain (Qvsa); deposits beneath Qvset and Qvsa may display considerable silicification from low-temperature hydrothermal alteration; maximum exposed thickness about 20 m.

Qso **Older Sandstone—**Weakly-indurated to unconsolidated, moderate to well sorted, subrounded, medium grained, reddish-tan quartz lithic sand with scattered pumice clasts up to 2 cm diameter. Locally thinly cross-bedded. Pumice clasts are crystal poor, with rare phenocrysts of quartz and biotite. Volcanic lithics are coarse sand to granule size. Unit overlies northerly portions of Cerro Seco lava dome at high elevations; maximum exposed thickness about 20 m.

Qvs/Qvsc **Early caldera fill lacustrine and fluvial deposits—**White to buff, laminated to thinly bedded, diatomaceous mudstone and siltstone, and generally white to gray to tan, cross-bedded to normally graded sandstone and conglomerate; sandstone and conglomerate beds contain mostly fragments of rhyolite pumice, tuff and lava but also contain some grains of precaldera volcanic rocks; may contain Precambrian crystalline fragments and materials eroded from Miocene to Permian sandstone; some beds contain ripple marks, flute casts and plane laminations and may be deltaic deposits near margins of initial caldera lake; beds generally display zeolitic or less commonly acid sulfate alteration (Chipera et al., 2007; Goff et al., 2007); beds generally deformed by uplift of resurgent dome; beds in Valle San Antonio are nearly horizontal; Qvs usually underlies Deer Canyon lavas (Qdc) and Deer Canyon tuffs (Qdct). Unit Qvsc contains abundant biotite and is locally derived by erosion of significant amounts of Redondo Creek Rhyolite (Qrc); Qvsc overlies Redondo Creek rhyolite; Qvs and Qvsc are interbedded with early caldera fill sedimentary rocks (Qdf) and overlie Bandelier Tuff (Qbt); maximum exposed thickness about 30 m; maximum drilled thickness in well Baca-7 on northeast side of resurgent dome is nearly 300 m (Lambert and Epstein, 1980).

Qdf **Early caldera fill alluvial, debris flow, landslide, and colluvial deposits—**Dark gray to buff, matrix-supported beds containing clay to boulders of various early post-caldera rhyolites, Bandelier Tuff, precaldera volcanic rocks, Miocene to Permian sandstone, Pennsylvanian limestone and Precambrian crystalline rocks (Goff et al., 2007); unit contains fluvial sand and gravel deposits; cobbles of older lithologies are more abundant in the lower beds; upper beds generally contain more precaldera volcanic rocks; rare beds contain mostly Bandelier Tuff; formed during rapid slumping and erosion of caldera walls, erosion of megabreccia blocks (Qx), and erosion of previously formed beds during uplift of the resurgent dome; finer-grained matrix is generally not exposed; resembles eroded alluvial fans at some locations on lower flanks of resurgent dome and may represent remnants of original alluvial landforms; weathering produces a lag of boulders on landscape; lower part of unit displays extensive, low-grade hydrothermal alteration; extensively faulted but fault relations in this unit are often difficult to determine where deposits are extensive; interbedded with and overlies all other units on resurgent dome; maximum exposed thickness in map area is 70 m; maximum drilled thickness in well Baca-7 on northeast side of resurgent dome is over 400 m (Lambert and Epstein, 1980).

Qst **Sinter Deposits—**Massive to banded, white to dark gray, silica-rich hot spring deposits from early hydrothermal activity on resurgent dome; may contain Fe-oxides; may contain fossil reeds and other organic remains; exposed only on fault blocks in widely scattered locations on resurgent dome; overlies Redondo Creek Rhyolite (Qrc), Deer Canyon Rhyolite (Qdc), and Bandelier Tuff (Qbt); maximum exposed thickness about 3 m.

Tewa Group
Valles Caldera and Resurgent Dome
Valles Rhyolite

Qvsa **San Antonio Mountain Member—**Flow-banded, massive to slightly vesicular rhyolite lava containing phenocrysts of sanidine, plagioclase, quartz, biotite, hornblende, and clinopyroxene in a pale gray, perlitic to white, devitrified groundmass; rarely glassy; contains no identifiable pyroclastic deposits; consists of two main flow units (oldest to youngest $Qvsa_1$ to $Qvsa_2$) erupted from San Antonio Mountain; a third flow and peripheral vent may also occur at Sulphur Point ($Qvsa_3$); buried ancestral drainage of San Antonio Creek in western Valles caldera; overlies caldera fill deposits (Qdf), lacustrine and fluvial deposits (Qvs, Qvsr and Ql) and

Redondo Creek rhyolite (Qrc); $^{40}Ar/^{39}Ar$ age is 0.557 ± 0.004 Ma on two samples from $Qvsa_2$ (Spell and Harrison, 1993); maximum exposed thickness at least 510 m.

Qvse/Qvset **Cerro Seco Member—**Flow-banded, massive to slightly vesicular rhyolite lava containing phenocrysts of quartz, sanidine, biotite and rare hornblende in a gray to pale pink devitrified groundmass; sanidine is often chatoyant; contains some vitrophyre near summit of Cerro Seco and other locations; consists of two flow units (oldest: $Qvse_1$; youngest: $Qvse_2$); flows overlie Cerro Seco pyroclastic deposits, caldera fill deposits (Qdf), and lacustrine and fluvial deposits (Qvs); $^{40}Ar/^{39}Ar$ age is 0.800 ± 0.007 Ma (Spell and Harrison, 1993), probably from flow $Qvse_2$; maximum exposed thickness is 375 m. Various pyroclastic deposits from Cerro Seco (Qvset) underlie the dome and flow complex and are combined as one map unit. The deposits consist of ignimbrite and dry surge near the vent, to probable hydromagmatic surge and derivative pumice-rich sediments distally. Where both types of deposits are visible, hydromagmatic surge generally overlies or laps on the ignimbrites; ignimbrites are buff to pale pink containing clasts of pumice (≤20 cm), vitrophyre, and pre-caldera lithologies in massive to rarely layered groundmass of ash, crystals, and fine rock fragments; surge deposits show cross-bedding and undulating dips of winnowed crystals, ash and pumice; hydromagmatic and derivative deposits contain quenched angular to subangular pumiceous rhyolite, crystal fragments and abundant foreign lithic fragments in plane-laminated to cross-bedded layers (see Fisher and Schmincke, 1984); contains rare layers of rhyolitic silt and clay with occasional mud crack features suggesting deposition in a shallow lake; overlies caldera fill deposits (Qdf), lacustrine deposits (Ql), Cerro San Luis rhyolite lava (Qvsl), and portions of Warm Springs dome (Qcws); date on sanidine from pumice lump in ignimbrite is 0.77 ± 0.03 Ma; date on sanidine from hydromagmatic deposit is 0.78 ± 0.04 Ma (W. McIntosh, unpub. data); thickness of all pyroclastic deposits is roughly 75 m at edge of Cerro Seco dome complex to <1 m at distal sites; run out distance is roughly 2 km north of edge of dome.

Qvsl **Cerro San Luis Member—**Flow banded, massive to slightly vesicular porphyritic rhyolite lava containing about 10% phenocrysts of sanidine, quartz and biotite in a gray to pale pink devitrified groundmass; rarely glassy; occasionally spherulitic; eruption produced no identifiable pyroclastic deposits but these may underlie flows on north and east side of dome complex. Contains local zones of opalization on north side of dome. Consists of possibly two eruptive pulses ($Qvsl_1$ and $Qvsl_2$). Fills paleocanyon cut into early caldera fill deposits (Qdf and Qvs) on west side of dome. Overlies Santa Rosa ignimbrite and caldera fill deposits on northeast side of dome and underlies pyroclastic deposits from Cerro Seco (Qvset). $^{40}Ar/^{39}Ar$ date is 0.800 ± 0.003 Ma (Spell and Harrison, 1993); maximum exposed thickness is 325 m.

Qvsr/Qvsrt **Cerro Santa Rosa Member—**(note on terminology: this entire dome complex was originally referred to as Cerro Santa Rosa [for example, Doell et al., 1968; Smith et al., 1970] and this terminology remains entrenched in the literature [for example, Spell and Harrison, 1993; Singer and Brown, 2002]. We retain this usage, but, unfortunately, recently revised topographic maps (including this USGS base map) restrict the name Cerro Santa Rosa to what we map as $Qvsr_2$, and label the entire chain of northeast trending domes including the Santa Rosa complex and Trasquilar dome "Cerros de Trasquilar.") Pyroclastic flow (Qvsrt) and two dome and flow complexes (Qvsr) of petrographically and chemically similar, but temporally and magnetically dissimilar, rhyolite. Qvsrt consists of pale gray to pale pink massive ignimbrite having pumice, ash, crystal shards and rare lithic fragments. Pumice lumps may be as much as 20 cm long and contain roughly 10% phenocrysts of quartz, sanidine and biotite in a highly vesicular groundmass; $^{40}Ar/^{39}Ar$ date on sanidine is 0.91 ± 0.03 Ma (W. McIntosh and L. Peters, NMBG&MR). Ignimbrite is not exposed beneath Santa Rosa dome complex but is exposed beneath the northeast part of Cerro San Luis west of source, and in small outcrop to south of dome. Maximum thickness is about 15 m. The oldest lava ($Qvsr_1$) consists of white to grey porphyritic rhyolite with 10 to 15 % fine (1 to 2 mm) to coarse (4mm) phenocrysts of abundant quartz, subordinate sanidine, and sparse, small biotite; groundmass glassy and pumiceous; dome exhibits a breccia apron around summit; west flank of unit includes petrographically similar flows, with chatoyant sanidine, that may be of different age; dated by $^{40}Ar/^{39}Ar$ at 0.914 Ma +/- 0.004 (one sigma error, Spell and Harrison, 1993) and 0.936 +/- 0.008 (two sigma error, Singer and Brown, 2002); maximum thickness over 240 m. The younger dome ($Qvsr_2$) consists of white, porphyritic rhyolite with 15 to 20 % phenocrysts (up to 4 mm) of abundant pink quartz, subordinate sanidine, and trace biotite euhedra; groundmass glassy and pumiceous; outcrops massive to flow banded; dated by $^{40}Ar/^{39}Ar$ at 0.787 Ma +/- 0.015 (one sigma error, Spell and Harrison, 1993); maximum thickness about 150 m.

Qvdmt **Cerro del Medio Member, ignimbrite—**Massive, white to pale gray rhyolitic ignimbrite containing pumice, ash, crystal fragments, obsidian, and rare lithic fragments; pumice contains tiny, rare quartz and sanidine phenocrysts; some outcrops show reworking by later erosional processes; exposed only along east-central edge of quadrangle underlying colluvium; source not immediately obvious from outcrop but is correlated with Cerro del Medio based on pumice chemistry, sparse phenocrysts and presence of obsidian (J. N. Gardner, unpub. data); unit as mapped is not dated; maximum exposed thickness is about 3 m.

Qrc **Redondo Creek Member—**Massive to flow-banded, gray to black to pale pink porphyritic rhyodacite containing plagioclase, conspicuous biotite, clinopyroxene and subordinate sanidine in a perlitic to devitrified groundmass (Goff et al., 2007, 2011); occasionally black and glassy to slightly vesicular; commonly spherulitic; contains substantial flow breccia; only rhyolite in Valles caldera that does not contain quartz; erupted from multiple sources in central and west resurgent dome; western flows filled paleovalley and/or paleocanyon in western moat as resurgent dome grew and probably created dam that formed lakes in ancestral drainage of San Antonio creek; central flows occupy faulted "keystone" in approximate center of resurgent dome; unit displays extensive hydrothermal alteration, particularly in west and northwest; contains no recognizable pyroclastic deposits; $^{40}Ar/^{39}Ar$ ages of different domes and flows range from 1.21 to 1.24 Ma (n=4; Phillips et al., 2007).; maximum exposed thickness is about 180 m.

Qdc **Deer Canyon Member, lava unit—**Massive, to flow-banded gray to pale pink, porphyritic to aphyric rhyolite lavas usually containing phenocrysts of sanidine and quartz (Bailey et al., 1969); phenocrysts are large and abundant in western flows but are tiny and sparse in eastern flows; some sanidine is chatoyant; groundmass is generally silicified; flow breccias are often opalized and iron-stained; most exposures are highly deformed by uplift and faulting on the resurgent dome of Valles caldera; many exposures show extensive zeolitic alteration (Chipera et al., 2007); overlies Deer Canyon tuffs (Qdct); interbedded with old caldera fill (Qdf) and generally overlies fluvial and lacustrine deposits (Qvs); overlies Bandelier Tuff (Qbt); $^{40}Ar/^{39}Ar$ ages of three different flows range from 1.25 to 1.28 Ma (n=3; Phillips et al., 2007); maximum exposed thickness about 40 m.

Qdct **Deer Canyon Member, tuff unit—**White to cream to pale buff lithic-rich rhyolitic tuffs; pumice fragments usually contain phenocrysts of quartz and sanidine; lithic fragments generally consist of Bandelier Tuff and precaldera volcanics; tuff beds usually deformed by faulting; beds often extensively altered to zeolites, silica, Fe-oxides, and clay (Chipera et al., 2007); beds occasionally graded; beds occasionally contain accretionary lapilli and hydromagmatic surge; interbedded with Deer Canyon lava (Qdc), old caldera fill (Qdf), and lacustrine and fluvial deposits (Qvs); overlies Bandelier Tuff (Qbt); $^{40}Ar/^{39}Ar$ ages of different tuff beds range from 1.23 to 1.27 Ma (n=5, Phillips et al., 2007); maximum exposed thickness about 30 m.

Bandelier Tuff

Qbx **Bandelier Tuff vent and/or hydrothermal breccia—**Widely scattered, lenticular to nearly circular outcrops of mosaic breccia, usually located along faults or within faults; usually less than 300 m in diameter; composed primarily of rounded to subrounded fragments of Tshirege Member Bandelier Tuff (Qbt) in matrix of fine-grained tuff; may also contain abundant to rare fragments of precaldera lithologies; may be hydrothermally altered; breccias of this type do not display gouge and shear typical of fault breccia; thickness usually not measurable; some exposures occur on major graben-bounding faults; breccia origins are probably variable.

Qbt **Bandelier Tuff, Tshirege Member—**Multiple flows of white to orange to dark gray, densely welded to non-welded rhyolitic ash-flow tuff (ignimbrite); pumice and matrix contain abundant phenocrysts of sanidine and quartz, sparse microphenocrysts of clinopyroxene and orthopyroxene and extremely rare microphenocrysts of fayalite (Warshaw and Smith, 1988; Warren et al., 1997; 2007); in more welded portions, sanidine typically chatoyant (blue iridescence); upper flow units generally more welded than lower ones. Intracaldera flow units are highly welded with well-developed fiamme and rare vitrophyre; locally contains a thin (<2 m) laminated, pumice fall and surge deposit at base of unit (Tsankawi Pumice) that contains roughly 1% of hornblende dacite pumice (Bailey et al., 1969); locally contains accidental lithic fragments of older country rock entrained during venting and pyroclastic flow; Qbt is major unit of the Valles caldera resurgent dome; forms plateau capping ignimbrite in northwest part of quadrangle; erupted during formation of the Valles caldera; most recent $^{40}Ar/^{39}Ar$ age is 1.25 ± 0.01 Ma (Phillips et al., 2007); maximum observed thickness within caldera over 900 m.

Qx **Caldera collapse breccia—**Caldera-wall landslide breccias (megabreccias) that accumulated synchronously during caldera formation (Lipman, 1976); incorporated in and interbedded with intracaldera Tshirege Member of the Bandelier Tuff (Goff et al., 2007); individual blocks mapped if more than 30 m across; within Valle San Antonio quadrangle, this unit consists of: 1. Silicified and brecciated, brownish-red, Otowi Member of the Bandelier Tuff (Qxbo) with phenocrysts of quartz and sanidine; much of the brecciated texture in this unit is not obvious; 2. Tschicoma Formation rhyodacite, dacite and coarse volcaniclastic materials (Qxt); 3. Paliza Canyon Formation biotite dacite tuff (Qxpt); 4. Paliza Canyon Formation andesite and volcaniclastic materials (Qxp); 5. Santa Fe Group tan to white well-sorted sandstone (Qxsf); 6. Abiquiu Formation white, non-indurated sandstone and conglomerate rich in Precambrian cobbles and pebbles (Qxab); 7. Permian Abo and Yeso Formation brick red to orange sandstone, siltstone, and shale (Qxa); 8. Pennsylvanian Madera Formation gray limestone, micrite and shale (Qxm); blocks of Qx may be difficult to distinguish from older caldera fill (Qdf) because of poor exposures; breccia blocks generally show baking and/or disaggregation textures around margins if contacts with enclosing Bandelier Tuff (Qbt) are preserved; Qx volcanic breccias are dated at 1.68 to 8.21 Ma (n=3; Phillips, 2004); maximum exposed thickness is highly variable; not shown in cross sections for clarity.

Toledo Caldera

Qcws **Warms Springs rhyolite (Cerro Toledo Rhyolite)—**Massive to flow banded, gray to pale pink porphyritic rhyolite lava containing phenocrysts of quartz, sanidine and biotite; groundmass is devitrified; exposed only in small bluff at Warm Springs in Valle San Antonio; overlain by hydromagmatic pyroclastic deposits from Cerro Seco (Qvset); $^{40}Ar/^{39}Ar$ age is 1.26 ± 0.01 Ma (Spell et al., 1996); maximum exposed thickness is 25 m.

Qbo **Bandelier Tuff, Otowi Member—**White to pale pink to orange, generally moderately welded rhyolitic ash-flow tuff; pumice and matrix contains abundant phenocrysts of sanidine and quartz, and sparse mafic microphenocrysts; sanidine may be chatoyant (blue iridescence); contains abundant accidental lithic fragments (Eichelberger and Koch, 1979); consists of multiple flow units in a compound cooling unit; contains a stratified pumice fall and surge deposit at its base (Guaje Pumice; Griggs, 1964); may form tent rocks; Qbo discontinuously fills in rugged topography on a volcanic surface of pre-Toledo caldera age; very difficult to distinguish from upper Bandelier Tuff in hand samples and thin sections; best distinguished by poorer degree of welding, greater tendency to form slopes instead of cliffs, more abundant lithic fragments, less abundant iridescent sanidine, and stratigraphic position beneath the Tsankawi Pumice; 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 60 m.

Tertiary (Pliocene-Oligocene?) Deposits

Keres Group (Pliocene-Miocene)

Ttd **Dacite and rhyodacite, undivided (only on cross section B-B')—**Gray to pale pink to pale blue, massive to sheeted, flows of dacite and rhyodacite exposed in the Sierra de los Valles east of quadrangle; flows are generally highly porphyritic containing phenocrysts of plagioclase, orthopyroxene, clinopyroxene, opaque oxides ± quartz ± sanidine ± hornblende ± biotite in a trachytic groundmass; underlies lower Bandelier Tuff (Qbo); overlies Paliza Canyon Formation andesite (Tpa) and Santa Fe Group (Ts); sources of various flows unknown; may be equivalent to dacitic flows vented near Tschicoma Peak northeast of quadrangle (5.34 to 3.21 Ma; WoldeGabriel et al., 2006), to dacitic flows exposed in the walls of Santa Clara Canyon (3.91 to 3.79 Ma; WoldeGabriel et al., 2006), and to domes vented east of map area near Cerro Rubio and Sierra de los Valles (roughly 2 to 5 Ma; Goff and Gardner, 2004); thickness in cross section is speculative; thickness in Sierra de los Valles east of map area exceeds 500 m.

Tghd **Hornblende dacite of Cerro de la Garita (La Grulla Formation)—**Dark gray, massive to sheeted, sparsely porphyritic dacite with phenocrysts of plagioclase, conspicuous hornblende, sanidine, biotite, and minor clinopyroxene in a devitrified groundmass containing tiny microlites of plagioclase, hornblende, and pyroxene; vent caps southern part of Cerro de la Garita and flows spread west of vent; overlies biotite andesite (Tta); date on biotite is 7.34 ± 0.07 Ma (W. McIntosh, unpub. data); maximum exposed thickness is 30 m.

Tga **Biotite andesite of Cerro de la Garita (La Grulla Formation)—**Gray to pale pink, massive to sheeted, porphyritic andesite lavas with phenocrysts of plagioclase, biotite, clinopyroxene, orthopyroxene, opaque oxides, sparse hornblende and rare resorbed quartz in a groundmass containing microlites of plagioclase, pyroxene, and opaque oxides; hornblende and biotite are commonly oxidized; contains plagioclase-pyroxene-biotite clots; groundmass is trachytic; most samples are devitrified; contains substantial amounts of flow breccia; distinguishable from other volcanic rocks on north caldera rim by abundant, equant feldspar crystals and conspicuous biotite; overlies sandstone (Ts) and Paliza Canyon andesite (Tpa) and overlain by hornblende dacite (Tthd); intruded by altered rhyolite dike (Tbh) in northeast corner of quadrangle and displays weak hydrothermal alteration to silica, clay and Fe-oxides near intrusive contacts; vent area believed to be at Cerro de la Garita; flows apparently filled paleo-depression or paleocanyon south of Cerro de la Garita that predated formation of Toledo caldera; date on biotite is 7.61 ± 0.07 Ma (W. McIntosh, unpub. data; maximum exposed thickness is about 330 m.

Tgb **Olivine basalt (La Grulla Formation)—**Black to gray lava flow exposed at base of slope in northwestern portion of caldera wall; contains abundant phenocrysts of olivine, clinopyroxene and plagioclase in glassy, intersertal groundmass of plagioclase, pyroxene and opaque oxides. Olivine is altered to complex mixture of Fe-oxides, silica and clay (iddingsite). Flow contains abundant vesicles near top; underlies biotite andesite of La Grulla Formation (Tga); base of unit not exposed; age is 7.80 ± 0.13 Ma; maximum exposed thickness is about 30 m.

Tpv **Volcaniclastic deposits—**Black to gray to pale pink volcaniclastic unit consisting predominately of gravelly fluvial deposits, lahars, block and ash flows, and other debris flows; mostly formed contemporaneously with Paliza Canyon (and La Grulla?) Formations but may extend into Pliocene as shown in correlation chart (Fig 2); locally contains hyper-concentrated flow and fluvial deposits, scoria and cinder deposits, and pyroclastic fall deposits; contains andesite flow-breccias too small or thin to map; unit accumulated in small basins, topographic lows, and canyons cut into Paliza Canyon Formation volcanoes; most of unit mapped according to the definition of Cochiti Formation described by Bailey et al., (1969) and Gardner et al. (1986) with stratigraphic interpretation extended to Pliocene (Lavine et al., 1996; Smith and Lavine, 1996); overlies Abiquiu Formation

(Tab) and underlies Otowi Member Bandelier Tuff (Qbo) along San Antonio Creek in west edge of map; age of Tpy is bracketed between roughly 3 and about 13 Ma; maximum exposed thickness about 70 m.

Tbh **Rhyolite intrusive rocks (Bearhead Rhyolite)—**White to gray to pale orange dikes, plugs and flows (?) of slightly porphyritic, devitrified to completely silicified rhyolite containing sparse phenocrysts of quartz, sanidine, plagioclase, biotite and opaque oxides in a groundmass containing abundant microlites of feldspar and biotite; rarely flow-banded; dikes not uniformly tabular and may display complicated intrusive relations with country rocks; widths of individual dikes shown on map are commonly exaggerated to be shown at 1:24,000, and may consist of many smaller sub-parallel dikes; pervasive, hydrothermal alteration consists primarily of quartz, chalcedony and/or opal, illite, Fe and Mn oxides, pyrite and possibly other sulfides, alunite, jarosite and gypsum; intrudes other Paliza Canyon Formation rocks, Tertiary sedimentary rocks (Ts) and Tschicoma andesite (Tta) on the north caldera rim; probably equivalent to the early and intermediate rhyolite of Loeffler et al. (1988) dated at 7.5 to 5.8 Ma and located north of the map area; dates on various Bearhead units in Jemez Mountains range from about 4.81 to 7.83 Ma (Justet and Spell, 2001; Kempter et al., 2007; Goff et al., 2011); maximum observed thickness about 100 m.

Tpdt **Porphyritic dacite tuff (Paliza Canyon Formation)—**Distinctive unit of pale green to gray, massive, lithic-rich tuff with conspicuous crystals of biotite and tiny hornblende, and crystals of plagioclase; contains lithic fragments of andesite, dacite, rhyolite, possible intrusive rocks and sandstone in altered matrix of dense to vesicular dacite; alteration consists of silica, clay, Fe-oxides and probable chlorite; exposed only in lower central caldera wall area; underlies andesite lava (Tpa); intrudes andesite in possible vent area located in fault block south of caldera wall; may be correlative with similar looking dacite tuff found as megabreccia block in northern part of resurgent dome (Qxpt); K-Ar date of altered tuff is 8.20 ± 0.29 Ma (WoldeGabriel, 1990); maximum exposed thickness about 40 m.

Tpbd **Porphyritic biotite dacite (Paliza Canyon Formation)—**Eroded flows of gray, glassy to devitrified porphyritic dacite with phenocrysts of potassium feldspar, plagioclase, biotite, clinopyroxene, orthopyroxene and rare hornblende in a trachytic groundmass of plagioclase, pyroxene, biotite, and opaque oxides; exposed only along north edge of San Antonio Creek in eastern map area in fault contact with altered andesite (Tpa); vent area unknown; unit not dated; maximum exposed thickness is 12 m.

Tpa **Two-pyroxene andesite, undivided (Paliza Canyon Formation)—**Flows and flow breccia of andesite from unknown sources; individual units are slightly porphyritic to very porphyritic; flows dense to platy to highly vesicular; fresh units may contain up to 20% phenocrysts of plagioclase, orthopyroxene, and clinopyroxene in an intersertal or slightly trachytic groundmass; groundmass usually contains abundant opaque oxides; plagioclase phenocrysts are commonly fritted and complexly zoned; most specimens contain plagioclase-pyroxene clots ≥ 1 mm in diameter; some units contain mafic enclaves of plagioclase-pyroxene a few centimeters in diameter; some flows contain minor hornblende and/or biotite; visible alteration varies from slight to extremely intense; alteration generally consists of silica, Fe-oxides, clay ± chlorite ± illite ± pyrite; underlies and is interbedded with sandstone (Ts); intruded by rhyolite (Tbh); vent areas not known; flows in map area not dated; fresh flows of Tpa in southern Jemez Mountains range from 8.8 to 9.4 Ma (Gardner et al., 1986; Goff et al., 2005a; 2005b); altered flows in north caldera wall are dated at 6.96 to 7.07 Ma (WoldeGabriel, 1990); stack of flows in northern caldera wall has maximum exposed thickness of about 490 m. Tpa shown in cross section B-B' is interpreted from the geothermal well intercepts listed in Nielson and Hulen (1984); thickness is wells is highly variable.

Santa Fe Group (Miocene)

Ts/Tsf **Volcaniclastic deposits (Pliocene to Miocene)—**Thick sequence of sedimentary deposits, intercalated with Paliza Canyon and Tschicoma formation volcanic and volcaniclastic deposits; exposed in northeast corner of map and best exposed on Valle Toledo quadrangle to west (Gardner et al., 2006); sequence is dominantly arkosic sandstone, but interbeds of pebbly conglomerate, wacke, subangular gravel of intermediate composition volcanics, debris flows, and angular breccias occur; intense silicification is widespread, and unit deposits are additionally locally altered to iron oxides, clays, and chlorite; volcanic fragments originate from sources in the Paliza Canyon Formation; Ts is interbedded with andesite lavas (Tpa) and is overlain by biotite andesite (Tta); intruded by rhyolite dikes and plugs (Tbh). Assignment of Ts is problematic; may be equivalent to portions of the Santa Fe Group (Chamita Formation), Puye Formation, and volcaniclastic deposits of the Keres Group (Tpy, Cochiti Formation of Gardner 1985; Gardner et al., 1986; Goff et al., 1990). Gardner and Goff (1996) point out that Ts represents basin-fill deposits at the eastern margin of the volcanic field, allowing interbeds of arkosic sandstone in volcanic and volcaniclastic material; maximum exposed thickness in map area is roughly 100 m. Unit Tsf is recognized in drill holes such as VC-2b, Baca-16, Baca-13, etc. (Nielsen and Hulen, 1984; Goff and Gardner, 1994) and consists of well-sorted, non-indurated quartz-rich sandstone; thickness in well VC-2b is 48 m; thickness in other holes may be as much as 75 m.

Abiquiu Formation (Miocene to Oligocene?)

Ta **Sandstone and siltstone**—White to buff well-bedded sandstone and siltstone; contains grains of rounded to subangular quartz, plagioclase, potassium feldspar, quartzite, and crystalline rocks; contains rare grains of diopside and possible tremolite; cement is commonly opaline; thus beds are sometimes very indurated; calcite and limonite cement less common; exposures on Valle San Antonio quadrangle look different from typical exposures (e.g., Goff et al., 2005a; Kelley et al., 2004) in that they contain substantial amounts of laminated silt and clay of possible lacustrine origin; maximum observed thickness is 40 m in northeast caldera wall; not recognized in any deep wells drilled around and within resurgent dome or northern moat; $^{40}Ar/^{39}Ar$ age on ash bed in upper Abiquiu Formation to south is 20.6 ± 0.1 Ma (Osburn et al., 2002).

Paleozoic Rocks

Permian

Pu **Permian rocks, undivided (only on cross sections)**—Sedimentary rocks consisting of (top to bottom) the Glorieta Sandstone, the Yeso Formation, and the Abo Formation; well-exposed to west and southwest in adjacent quadrangles; Glorieta Sandstone consists of white to reddish white, well-sorted, generally plane to cross-bedded quartz arenite with some mica; forms fractured cliffs; Yeso Formation is composed of orange red, well-sorted, medium-grained quartzofeldspathic sandstone and minor siltstone; Abo Formation is made up of brick red to brownish red quartzofeldspathic sandstone, siltstone and mudstone; contains some obvious mica; contains minor conglomerate and limestone; Yeso and Abo are usually indurated in geothermal wells (cross section A-A'), displaying considerable greenish hydrothermal alteration and minor calcite and quartz veining; contact of Pu with underlying Madera Formation is sharp to gradational depending on location; thickness is 498 m in VC-2b (Goff and Gardner, 1994); thickness is 501 m in Baca-12 just south of quadrangle boundary (Nielson and Hulen, 1984).

Mississippian-Pennsylvanian

MIPu **Mississippian-Pennsylvanian rocks, undivided (only on cross sections)**—Light to dark gray, fossiliferous limestone and micrite with subordinate gray to buff arkose, sandstone, shale and mudstone (Madera and Sandia Formations); displays considerable hydrothermal alteration, veining, faulting, fracturing and brecciation in geothermal wells (Goff and Gardner, 1994 and references therein); thickness in VC-2b is 262 m; thickness is 293 m in Baca-12 (Nielson and Hulen, 1984); the Sandia Formation is not identified in Baca-12 but is probably present.

Precambrian Rocks

pCu **Precambrian rocks, undivided (only on cross sections)**—Highly variable unit of crystalline rocks throughout Jemez Mountains region (Goff et al., 1989, Table 2); displays minor to severe hydrothermal alteration; in VC-2b the upper Precambrian consists of roughly 204 m of gray to green to pink, hydrothermally altered, coarse-grained, biotite quartz monzonite; alteration minerals are epidote-illite-phengite-chlorite-quartz-pyrite-calcite (Goff and Gardner, 1994); in Baca-12 consists of 90 m (Nielson and Hulen, 1984) of white to green, altered quartz monzonite containing epidote-chlorite-pyrite-actinolite-quartz-calcite (Hulen and Nielson, 1988); age is 1.62 to 1.44 Ga (Brookins and Laughlin, 1983).

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