Geologic Map of the Jemez Springs Quadrangle, Sandoval County, New Mexico

By

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Open-file Digital Geologic Map OF-GM 073

Scale 1:24,000

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Geology of the Jemez Springs 7.5 minute quadrangle, Sandoval County, New Mexico

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Topographic Setting

The Jemez Springs 7.5 minute quadrangle is in the southwestern Jemez Mountains of north-central New Mexico. Rugged Cañon de San Diego, with 500 to 600 m of relief and scenic red sedimentary slopes capped by cliffs of orange-tan tuff, is a notable southwest-trending canyon crossing the area.. The upper reaches of the canyon south of the village of La Cueva are along San Antonio Creek; the canyon continues along the Jemez River south of the confluence of San Antonio Creek and the East Fork of the Jemez River. Well-known and oft-visited landmarks located in the Jemez Springs quadrangle within Cañon de San Diego include Soda Dam and Spence Springs, which are geothermal features, and Battleship Rock, which is a prominent outcrop of young tuff at the confluence of San Antonio Creek and the East Fork of the Jemez River. Mesas capped by Bandelier Tuff separated by steep sided canyons cut into the tuff are the dominant landforms on west and east sides the quadrangle (Figure 1). Lake Fork, Schoolhouse, Stable, Holiday, and Virgin mesas are bounded by west to southwest trending Lake Fork Canyon, Cañon Cebolla, and Virgin Canyon in the western part of the map area. Cañon de la Cañada, San Juan Canyon, Cat Mesa, and San Juan Mesa are in the southwestern quadrant of the quadrangle.

Regional Geologic Setting

The quadrangle is on the southwestern flank of the 15 Ma to 40 ka Jemez volcanic field, which lies at the intersection of the Rio Grande rift and a NE-trending alignment of < 10 Ma volcanism known as the Jemez lineament (Aldrich et al., 1986). The < 1.61 Ma Bandelier Tuff of the Jemez volcanic field caps mesas across map area. The southwestern margin of the Valles caldera crosses the northeastern corner of the quadrangle just north of La Cueva. The quadrangle straddles the western margin of the Rio Grande rift, a late Oligocene-Holocene, northerly-striking extensional feature that bisects the state of New Mexico. Two northeast- to north-striking rift-related normal fault systems, including, from west to east, the Jemez fault zone and the Cat Mesa fault zone are exposed in southern Virgin Canyon, in Cañon de San Diego, and along the East Fork of the Jemez River. The southeastern flank of the broad Sierra Nacimiento Laramide highland lies within the quadrangle and is exposed in the major canyons. Compressive Laramide deformation started in this area about 75 Ma, with activity peaking about 50-55 Ma (Cather, 2004; Pazzaglia and Kelley, 1998).

Previous Work

Wood and Northrop (1946), Smith et al. (1970), and Kelley (1977) produced regional-scale geologic maps that include the Jemez Springs quadrangle. Renick (1931) described rift-fill sediments and volcanic rocks exposed along the Jemez River. Terraces along the Jemez River were mapped and discussed by Rogers et al. (1996), Formento-Trigilio (1997), and Formento-Trigilio and Pazzaglia (1998).

Important new observations made during this study include: (1) identification of a Pliocene (?) debris avalanche deposit that controls the location of major springs on the west side of Cañon de San Diego; and (2) recognition of previously unmapped, early rift fault strands along the eastern wall of Cañon de San Diego that intersect the canyon of the East Fork of the Jemez River.

Geologic History

Rocks exposed in the Jemez Springs quadrangle contain a rich, but fragmentary, geologic record spanning ~ 1.7 billion years of Earth's history (Fig. 2). The youngest volcanic rocks in the Jemez Mountains are exposed in the upper part of Cañon de San Diego in the northeast part of the quadrangle, while older rocks, including Proterozoic granitic gneiss, are exposed downstream near Soda Dam in the central part of the quadrangle. This description of the geologic history of the Jemez Springs quadrangle is modified from Kelley et al. (2007).

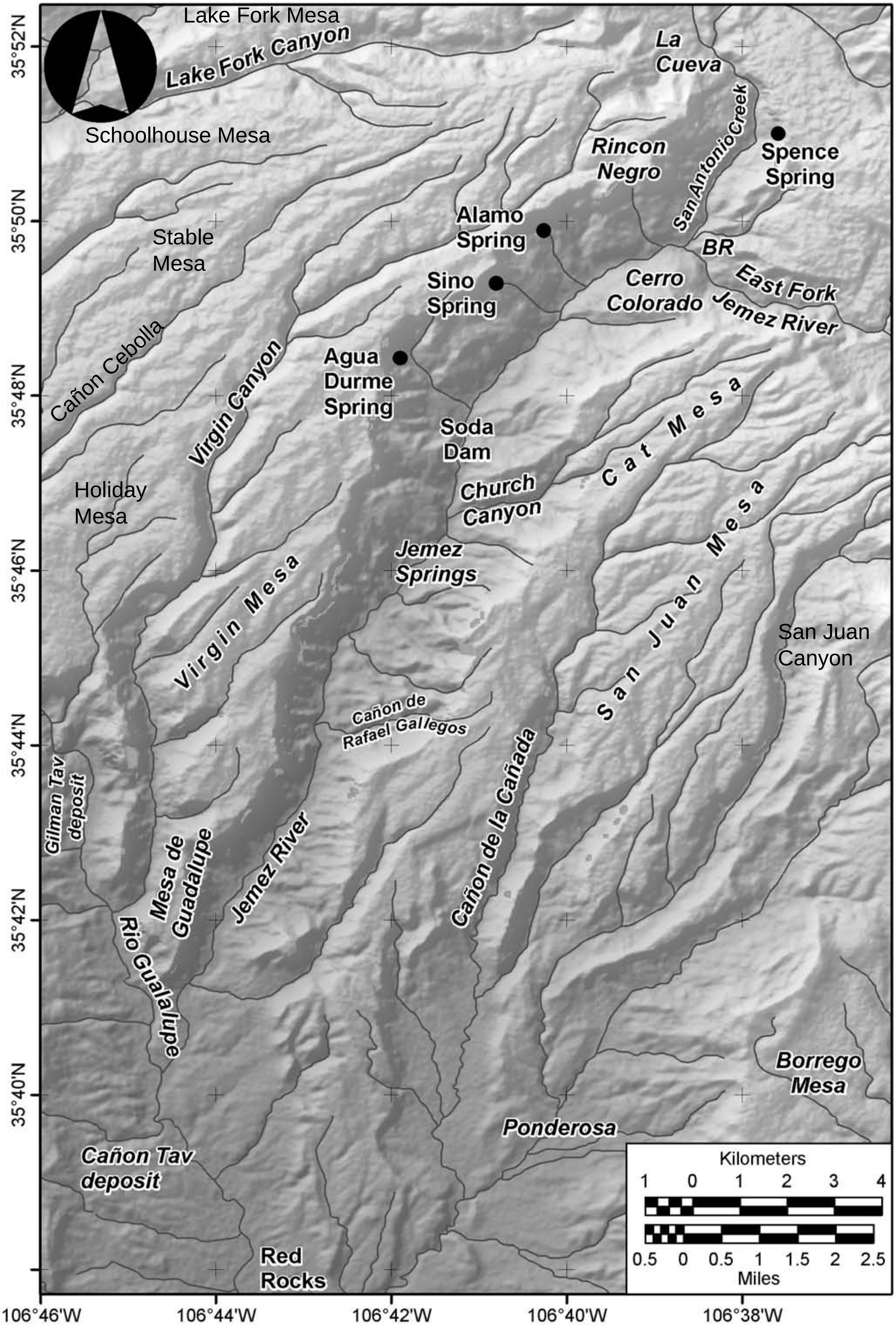
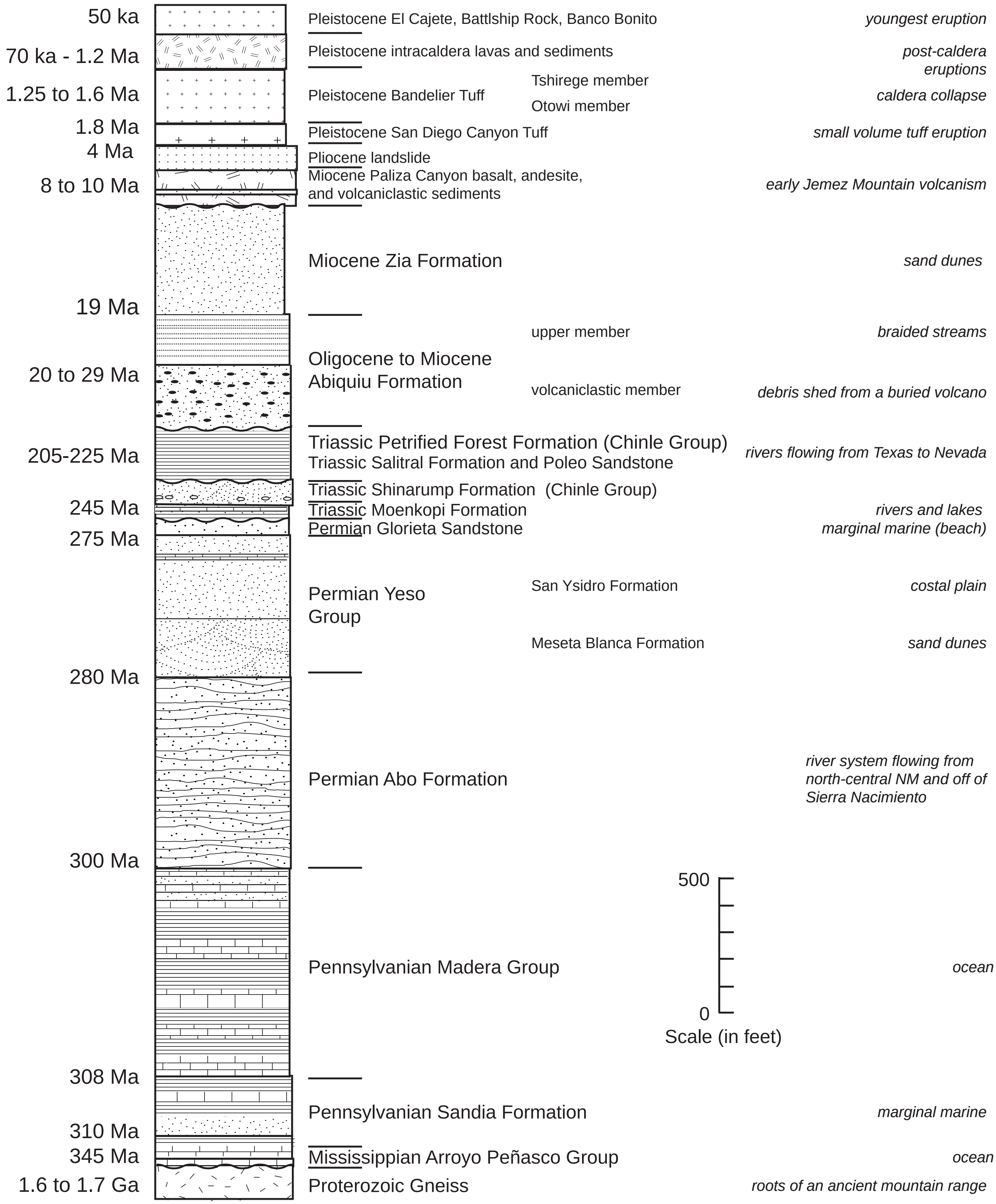


Figure 1. Index map of key geographic points in the southwestern Jemez Mountains.

Figure 2

Rock Units Exposed in Cañon de San Diego



ka = thousands of years
Ma = millions of years
Ga = billions of years

Proterozoic rocks

The oldest rocks in Cañon de San Diego are fractured and altered granitic gneiss exposed on the footwall of the Jemez fault zone in the vicinity of Soda Dam. Although no absolute age data are available for these Proterozoic rocks, this gneiss likely correlates to a 1695 ±14 Ma orthogneiss in the Sierra Nacimiento (U-Pb zircon age, Premo and Kellogg, 2005). Rb-Sr ages of 1.62 to 1.44 Ga were determined for Proterozoic rocks encountered in drillholes at Fenton Hill near La Cueva just north of the quadrangle boundary (Brookins and Laughlin, 1983). The NE-striking strands of the Jemez fault zone exposed at Soda Dam do not appear to have a Mesoproterozoic ancestry because the strike of the foliation in the gneiss is at a high angle with respect to the strike of the fault zone.

Paleozoic

Starting at ~345 Ma (Osagean), an oceanic shoreline moved back and forth across the Jemez Mountains region, depositing the coarse-grained quartz arenite and marine limestone of the Mississippian Espiritu Santo Formation of the Arroyo Peñasco Group on the Proterozoic gneiss at Soda Dam (Armstrong, 1955; Armstrong and Mamet, 1974; Armstrong et al., 2004). Approximately 1.35 billion years of Earth's history is missing across the "Great Unconformity" in this area. The Arroyo Peñasco Group is overlain by a distinctive redbed unit called the Log Springs Formation on the east side of the Jemez River at Soda Dam. The Chesterian (~320 Ma) Log Springs Formation rests on a karsted unconformity that developed atop the Arroyo Peñasco Group. This deposit heralds the early stages of Ancestral Rocky Mountain deformation in the Peñasco uplift (Armstrong et al., 2004), which occupied the approximate current position of the Sierra Nacimiento to the west (Woodward et al., 1987).

Pennsylvanian rocks unconformably overlie the Mississippian section. Quartzose sandstone interbedded with shale, thin-bedded fossiliferous limestone, and chert belonging to the Pennsylvanian (Atokan, ~310 Ma) Sandia Formation is gradationally overlain by fossiliferous limestone, arkosic sandy limestone, and black shale that were deposited between latest Atokan (~308 Ma) and late Virgilian (~300 Ma) time (Wood and Northrop, 1946; Read and Wood, 1947; Lovejoy, 1958; Sutherland and Harlow, 1967; DuChene, 1974; Swenson, 1977, 1996; Kues, 1996). These limestones and clastic rocks were deposited along the shore of a shallow ocean that once covered the southern two-thirds of New Mexico during late Pennsylvanian time (Kues and Giles, 2004). Wood and Northrop (1946) assigned this unit to the Madera Limestone of the Magdalena Group and divided the sequence into a lower gray limestone member and an upper arkosic limestone member. The arkosic material in the upper part of the Pennsylvanian section in the canyon was derived from the Peñasco highland to the west. Kues (2001) suggested correlating the Pennsylvanian units in the Jemez Mountains with those exposed in the Lucero uplift (Kelley and Wood, 1946) about 100 km south of Cañon de San Diego. He assigned the lower gray limestone to the Gray Mesa Formation and the upper arkosic limestone to the Atrasado Formation and put both formations in the Madera Group. The fossiliferous Jemez Springs Shale Member of Sutherland and Harlow (1967) is included in the Atrasado Formation. Several well-known invertebrate fossil collecting sites in the Jemez Springs Shale Member are located in Cañon de San Diego (Sutherland and Harlow, 1967; Kues, 1996). Krainer et al. (2005) more recently applied the name Guadalupe Box Formation to the upper arkosic limestone member and have abandoned the name Madera Group. The Guadalupe Box Formation of Krainer et al. (2005) is further subdivided into the San Diego Canyon Member and the Jemez Springs Shale Member. In this study, we provisionally use Madera Group, pending further detailed work on this package of rocks in Cañon de San Diego. . The upper contact of the Pennsylvanian limestone and clastic rock sequence with the overlying Abo Formation is transitional in this area. The gradational contact between the Madera Limestone and the overlying Abo Formation is exposed north of Soda Dam near Hummingbird Music Camp on the Jemez Springs quadrangle. Marine limestone and shale are interbedded with red micaceous siltstone and arkosic sandstone deposited by south-flowing rivers, recording N-S shoreline movement back and forth across the Cañon de San Diego region for a time before the sea finally retreated south at ~ 300 Ma (Kues, 1996; Krainer et al., 2005).

The latest Pennsylvanian to Permian Abo Formation, a red siltstone interbedded with red to white arkosic sandstone, was deposited by a south-flowing river system during the latest Virgilian through Wolfcampian time (~ 280-300 Ma). Lucas et al. (2005a) note that the basal portion of the Abo Formation is dominated by mudstones and that channel sands become thicker and more abundant in the upper part of the formation. The upper Abo Formation is exposed southeast of the Jemez fault zone and the lower Abo is exposed northwest of the fault zone on the Jemez Springs quadrangle. Abo Formation sandstone contains pebbles of quartz, quartzite, potassium feldspar, and granite derived in part from the Peñasco highland to the west and from the Uncompaghre uplift to the north (Eberth and Miall, 1991). Abo Formation locally contains malachite and azurite in the channel sandstones at several localities in Cañon de San Diego. These minerals formed when copper-rich fluid moved through the sandstones long after deposition (McLemore, 1996).

The Permian Yeso Group forms orange cliffs in the walls of Cañon de San Diego south of Soda Dam. The contact between the Wolfcampian Abo and the overlying Leonardian Yeso is conformable (Woodward, 1987; Stanesco, 1991). An overall drying trend at ~280 Ma is recorded at the contact between the fluvial Abo and the eolian basal part of the Yeso (Mack and Dinterman, 2002). The Yeso has traditionally been assigned formational status and has been divided into two members in the southwestern Jemez Mountains, the lower Meseta Blanca Member and the upper San Ysidro Member (Wood and Northrop, 1946; Stanesco, 1991). Lucas et al (2005b), following the work of Baars (1962), applied the name De Chelly Sandstone to the Meseta Blanca Member and elevated the Yeso Formation to group status. The De Chelly Sandstone is a distinctive eolian sandstone characterized by meter-scale, tabular-planar, wedge-planar and trough cross-beds that record a paleo-transport direction generally to the south (Stanesco, 1991; Lucas et al., 2005 a,b). The San Ysidro Formation of the Yeso Group is primarily medium-bedded, tabular sandstone that is orange red near the base and red near the top. A discontinuous 1 to 2 m thick limestone bed is present near the top of the unit.

The contact between the upper part of the Yeso Group and the overlying yellow-white Permian Glorieta Sandstone is gradational. The medium-bedded sandstone of the Glorieta Sandstone is locally cross-bedded. A south to north marine transgression at ~275 Ma is recorded across the contact, as sand-dominated coastal plain and rare carbonate deposits of the San Ysidro Formation gave way to the coastal sand bar deposits of the Glorieta Sandstone (Kues and Giles, 2004).

Mesozoic

Triassic Moenkopi Formation (early Anisian) unconformably overlies Glorieta Sandstone; at least 26 m.y. of rock record is missing across this unconformity between Permian and Triassic rocks. The Moenkopi Formation is composed of reddish-brown micaceous shale, silty shale, and thin-bedded feldspathic sandstone. The unit is often shaly at the base and sandy at the top. The Moenkopi Formation was deposited by north- to northwest- flowing rivers sourced in the Mogollon highlands to the south and the Ouachita mountain belt to the east and southeast at ~245 Ma (Lucas, 2004).

Upper Triassic Chinle Group, a thick interval of brick-red to red siltstone and mudstone and white to tan sandstone, was deposited by rivers flowing from Texas toward Nevada between 205 and 225 Ma (Lucas, 2004; Lucas et al., 2005). The Chinle Group unconformably overlies the Moenkopi Formation, with an ~20 m.y. hiatus in the rock record between the units. The basal Shinarump Formation (formerly called Agua Zarca Sandstone by Wood and Northrop, 1946) is yellowish brown, medium- to coarse-grained, trough-cross-stratified, conglomeratic quartzose sandstone with well-rounded pebbles of quartz and chert. Petrified wood is common. Shinarump Formation is overlain by < 5-m of red Salitral Formation shale, <5 m of conglomeratic Poleo Sandstone, and <5m of ripple-laminated Mesa Montosa Sandstone. The Petrified Forest Formation of the Chinle Group is not exposed on the Jemez Springs quadrangle, but it may underlie the colluvial-covered slope on the south side of the East Fork of the Jemez River.

Oligocene to Miocene structures and rift fill sedimentary rocks

One of the most significant structures in the Jemez Springs quadrangle is the northeast-striking Jemez fault zone, a down-to-the-southeast, rift-related, normal fault that offsets Pennsylvanian-Permian rocks 200-250 m and 1.25 Ma Tshirege Member of the Bandelier Tuff 15 m near Soda Dam. The stratigraphic offset across the Jemez fault zone decreases dramatically toward the northeast; Abo is juxtaposed against Abo across the fault in the valley of the East Fork of the Jemez River. Several fault splays north of the Jemez fault zone strike northeast, parallel to the strike of the main fault. South of the Jemez fault zone, a fault zone on the east side of Cañon de San Diego has a more NNE-strike. This fault zone, the Cat Mesa fault zone, parallels the western edge of Cat Mesa, and offsets the Permian Yeso Formation ~240 m down to the east where the fault crosses the East Fork of the Jemez River. Stratigraphic offset of the Permian and Triassic rocks across the Cat Mesa fault zone appears to increase toward the north. The fault offsets Paliza Canyon Formation andesite < 10 m in the south wall of the East Fork of the Jemez River and the Bandelier Tuff < 2 m east of Jemez Springs; thus the Cat Mesa fault zone is primarily an early rift fault.

The Abiquiu Formation in the southwestern Jemez Mountains is a white to tan, medium-grained, tabular bedded sandstone that is interbedded with thin (0.1-0.3 m) fine-grained ash-fall deposits. The upper Oligocene to lower Miocene Abiquiu Formation, which covers a broad region of north-central New Mexico, was deposited by southward-flowing sandy braided streams. Clasts from the Latir volcanic field are common in the Abiquiu Formation in the northern and southeastern Jemez Mountains, but are absent in the southwestern Jemez Mountains. Near the southern edge of the map area (UTM 347659, 3957351, NAD 27), the Abiquiu Formation is ~6 m thick. The base of the unit consists of 0.5 m of red volcaniclastic sandstone, 1 to 1.5 m of thin to medium bedded tan sandstone and 0.3 m of limestone. The upper 4 m of the exposure above the limestone consists of red to tan medium bedded sandstone, overlain by thin Guaje Pumice Bed tephra and Otowi Member of the Bandelier Tuff. North of this point, the basal unit is dominantly an arkosic fluvial sandstone with abundant pebble-sized Proterozoic granite, quartzite and schist clasts, with few limestone, sandstone and intermediate-composition volcanic clasts of uncertain origin. The volcanic clasts can be pebble to cobble in size and can be abundant in local channels.

Miocene volcanic rocks

Some of the oldest rocks of the Jemez volcanic field are beautifully exposed in Church Canyon high in the eastern walls of Cañon de San Diego. Two basalt flows interbedded with volcaniclastic sediments belonging to the Paliza Canyon Formation are preserved here. The 3-5 m thick, vesicular lower flow contains phenocrysts of plagioclase and olivine. The upper flow is also vesicular and contains abundant olivine and small phenocrysts of plagioclase. The stratigraphy of the basalts here is similar to that on Borrego Mesa to the east of Cañon de San Diego, where $^{40}Ar/^{39}Ar$ ages of ~9.9 Ma have been determined for the oldest basalt and ages of ~9.1 Ma have been determined for the olivine basalt (Chamberlin et al., 1999; Osburn et al., 2002; Kempter et al., 2003; Chamberlin and McIntosh, 2007). The volcaniclastic sediments consist of alternating beds of tan, cross-bedded conglomeritic sandstone and pebble to boulder conglomerate with abundant andesite, basalt and minor rhyolite clasts. A dark gray, porphyritic andesite flow with clinopyroxene and zoned plagioclase phenocrysts was erupted from a vent just to the north of Church Canyon on the east side of Cañon de San Diego (Smith et al., 1970). This flow sits on volcaniclastic sediment of the Paliza Canyon Formation above the basalts, and sills from the andesitic center intrude the underlying Abiquiu Formation sandstone in Church Canyon. Andesite is also exposed in San Juan Canyon in the southwest corner of the map area, and in the La Cueva area. Although we have no radiometric age data for andesite on the Jemez Springs quadrangle, Paliza Canyon Formation andesite along San Antonio Creek north of La Cueva yielded a $^{40}Ar/^{39}Ar$ age of 8.20 ± 0.09 Ma (Kelley et al., 2004).

Figure 3. Aerial photograph of Rincon Negro on the west side of CdSD. IPm = Pennsylvanian Madera Group; Pa = Permian Abo Formation; Tls = Pliocene(?) debris avalanche; Tsd = San Diego Canyon Tuff; Qbo = Otowi Member, Bandelier Tuff; and Qbt = Tshirege Member, Bandelier Tuff. The line in the upper left marks the east edge of a paleovalley cut on Qbo. The top and base of the Tls deposit are also marked with yellow lines. The contact between Madera and Abo is shown as a dashed line.

Pliocene sedimentary units

Debris avalanche deposits. One of the most interesting units in the quadrangle forms imposing black cliffs on the west side of Cañon de San Diego between a point just south of La Cueva and a point just south of Agua Durme Springs, a distance of 6.5 km (Figure 3). Andesitic flows to the north are juxtaposed abruptly against rubbly deposits to the south across a small drainage just south of La Cueva. This rubbly deposit is composed primarily of 0.1 m to 3 m angular boulders of Paliza Canyon Formation porphyritic andesite; basaltic andesite clasts with iddingsite-altered olivine are also present near the base of the rubbly deposit. Multiple debris flow units, ranging from clast-supported to matrix-supported flows, in some cases including an ashy component, are present in the rubbly unit. A house-sized (60 m by 30 m) block of a white pyroclastic flow containing clasts of devitrified rhyolite is included within the rubbly andesite deposit just south of Alamo Spring. This block is apparently overlain by a brown andesitic lapilli tuff and a fine-grained, flow-banded, andesite flow, but all contacts around this block are sharp and cut across the fabric of the rhyolite flow. The top of the unit has considerable, long-wavelength, relief (up to 60 m); 1.85 Ma San Diego Canyon tuff (Spell et al., 1996) filled in the lows, while the 1.61 Ma Otowi Member of the Bandelier Tuff (Izett and Obradovich, 1994) rests on the high spots (see cross-section). The bulk of the deposit terminates just south of Agua Durme Springs (cross-section, Figure 3), although thin remnants are preserved as far south as the south end of Virgin Mesa, and as far west as the Rio Guadalupe. At Agua Durme, the rubbly andesite deposit overlies a reddish tan, matrix-supported debris flow deposit dominated by clasts of upper Abiquiu Formation sandstone, Paliza Canyon Formation andesite, Abo Formation sandstone, and Tschicoma (?) Formation dacite. The gray biotite- and hornblende-bearing Tschicoma (?) dacite clasts in the debris flow superficially resemble a dacite flow exposed on the west side of San Antonio Creek north of La Cueva that has has a K-Ar age of 4.2 ± 1.3 Ma (Gardner et al., 1986) and a $^{40}Ar/^{39}Ar$ age of 3.86±0.08 Ma (Justet, 2003).

The rubbly nature of the deposit, the presence of an allothononous block, the undulating top contact, and the presence of a basal debris flow deposit suggest this unit represents a large debris avalanche (Siebert, 1984; Smith and Lowe, 1991) potentially derived from the flanks of a Paliza Canyon andesite volcano that has since collapsed into the Toledo-Valles caldera complex. Although exposures are poor, this deposit appears to extend southwest, cropping out in the bottom of Virgin Canyon. Debris flow deposits are also present to the southwest in Cañon Cebollita on the adjoining San Miguel Mountain quadrangle. If the hornblende- and biotite-bearing dacite in the basal debris flow was derived from the ~4 Ma dacite flow to the north, then the deposit is <4 Ma. This deposit contains an important perched aquifer because all of the major springs on the upper west side of Cañon de San Diego -- Alamo Spring, Sino Spring, and Agua Durme Spring--issue from the base of the debris avalanche deposit where it rests on impermeable Abo Formation mudstone.

Other Pliocene deposits. Two sedimentary deposits, one lacustrine and one fluvial, locally rest on the debris avalanche deposit. A 5-m thick, white, diatomaceous (?), fine-grained lacustrine sandstone fills a low in the undulating top of the debris avalanche deposit in a limited area north of Rincon Negro. The margins of the lake deposit are silicified, preserving finely laminated, alternating light and dark layers. The upper contact relationship is uncertain, but the unit appears to underlie the 1.85 Ma San Diego Canyon tuff. Thin (<0.1 m) deposits of finely laminated lacustrine sediments are also discontinuously present on Paliza Canyon andesite on the south wall of the East Fork of the Jemez River beneath the Otowi Member of Bandelier Tuff.

Thin deposits (<12 m) of fluvial gravel and sandstone overlie Permian redbed or Pliocene (?) debris avalanche deposits and underlie the 1.85 Ma San Diego Canyon Tuff or the 1.61 and 1.25 Ma Bandelier Tuff in Virgin Canyon, Cañon de San Diego, and San Juan Canyon. Pebble to boulder clasts in the fluvial deposits are generally sub-rounded to well rounded Paliza Canyon Formation volcanic rocks with few granite, Permian sandstone, Permian conglomerates, and rare Pedernal chert supported in a silt to sand matrix. Paleocurrents based on pebble imbrications indicate that a southerly flowing drainage network was present in the southwestern Jemez Mountains prior to the caldera eruptions (Scholle and Kelley, 2003; Appendix 1). An early, previously unrecognized, eruption appears to be recorded by abundant pumice clasts with chemistry comparable to the San Diego Canyon tuff (N. Dunbar, personal comm., 2003) that are incorporated in a red sandstone at least 5 m below the lowest recognized unit of the tuff. These deposits are, in part, stratigraphically equivalent to the Cochiti Formation in the southeastern Jemez Mountains (Smith and Lavine, 1996).

A deposit in Church Canyon consists of fluvial gravels at the base that grade up into a matrix-supported debris flow deposit. Rounded Paliza Canyon andesite, rounded upper Abiquiu sandstone, and angular Pedernal chert clasts dominate the 10-m-thick unit in Church Canyon. This gravel underlies the Otowi Member of the Bandelier Tuff.

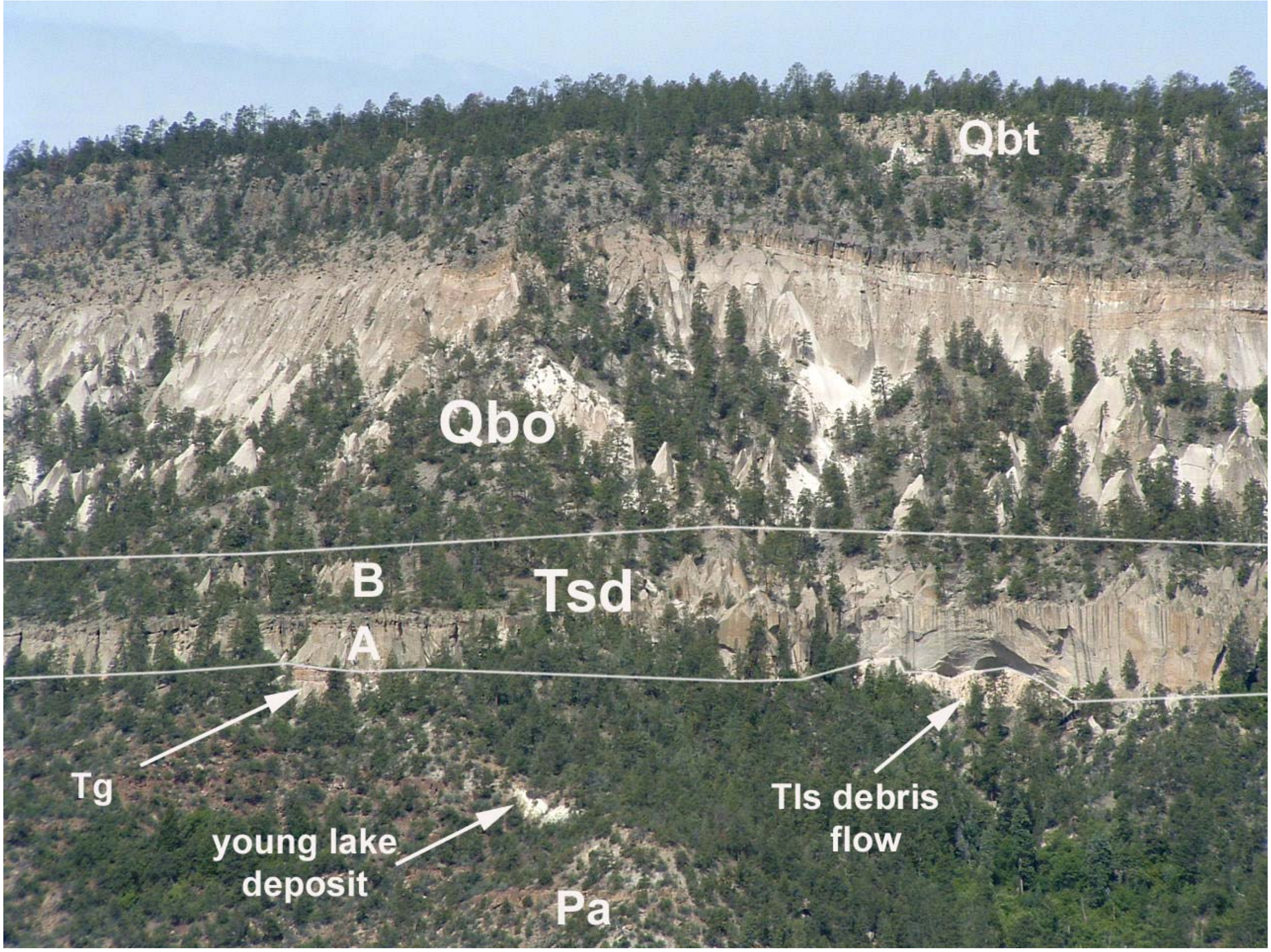


Figure 4. Photograph of Agua Durme area on the west side of CdSD. Pa = Permian Abo Formation; Tls = Pliocene debris avalanche deposit; Tg = fluvial deposits; Tsd = San Diego Canyon Tuff (units A and B of Turbeville and Self., 1988); Qbo = Otowi Member, Bandelier Tuff; and Qbt = Tshirege Member, Bandelier Tuff.

Latest Pliocene to Quaternary volcanic and volcaniclastic deposits

San Diego Canyon tuff is a nonwelded to poorly welded ash flow tuff that is exposed only on the west side of Cañon de San Diego between La Cueva and the south edge of the quadrangle. The source of the small-volume 1.85 Ma San Diego Canyon tuff (Spell et al., 1996) has been obscured by younger caldera-forming eruptions. This tuff is characterized by phenocrysts of quartz and sanidine with trace pyroxene and magnetite. The tuff consists of two (Tuberville and Self, 1988), or possibly three units. The San Diego Canyon tuff obviously filled an active stream channel in the northern Jemez Springs quadrangle positioned slightly west of modern Cañon de San Diego because gravel is interbedded with the two (or three) ignimbrite flows. Fluvial deposition was re-established after the eruption of the San Diego Canyon tuff (Appendix 1).

The landscape of the Jemez Mountains changed dramatically with the collapse of the Toledo caldera and the eruption of the Otowi Member of the Bandelier Tuff at 1.61 Ma (Izett and Obradovich, 1994; Spell et al., 1996). During the early stages of the eruption, the plinian tephra, the Guaje Pumice, was blown toward the east and northeast (Self et al., 1986) and is not preserved or is very thin (<20 cm) in the Jemez Springs quadrangle. The ignimbrite from the eruption blanketed the countryside, filling in valleys and overtopping ridges. The Otowi Member is generally thicker on the west side of Cañon de San Diego compared to the east side, filling in the paleovalley that preserves the older San Diego

Canyon tuff. The Otowi Member is typically a white to pale pink, generally poorly welded rhyolitic ash-flow tuff containing phenocrysts of sanidine and quartz, and abundant lithic fragments.

Figure 5. Photograph of tuff units on the west side of CdSD south of Jemez Springs. Pa = Permian Abo Formation; Py= Permian Yeso Group; Tsd = San Diego Canyon Tuff; Qbo = Otowi Member, Bandelier Tuff; and Qbt = Tshirege Member, Bandelier Tuff. Qbt cooling units 1g, 1v, 2, and 3 are also shown

During the ~400 k.y. between eruptions, west to southwest-trending drainages developed on top of the Otowi Member and in a few places, fluvial gravel is preserved between the members of the Bandelier Tuff. Four southwest-trending paleovalleys and one west-trending are present in the map area. The first is in the northwestern corner of the quad, approximately paralleling the Rio Cebolla. This paleovalley intersects the west-trending Lake Fork paleovalley, which is well exposed just north of the village of La Cueva. The third is west of Cañon de San Diego; in fact, the eastern margin of the paleovalley is well exposed on the western rim of the canyon west of Rincon Negro and above Alamo Spring. A fourth paleovalley cut into the Otowi Member is on Cat Mesa; this valley contains a thin gravel with clasts of Yeso Group sandstone. A fifth paleocanyon is on the east side of San Juan Canyon in the southeastern corner of the map area.

Formation of the Valles caldera at 1.25 Ma (Phillips, 2004) led to the deposition of the plinian Tsankawi Pumice Bed, which averages 1-1.5 m thick, but locally can be up to 3 m thick, in the southwestern Jemez Mountains. Paleovalleys cut on the Otowi Member were filled by the ignimbrites of the Tshirege Member. The cooling unit stratigraphy for the Tshirege Member that has been developed for the Pajarito Plateau (e.g., Broxton and Reneau, 1995) appears to be

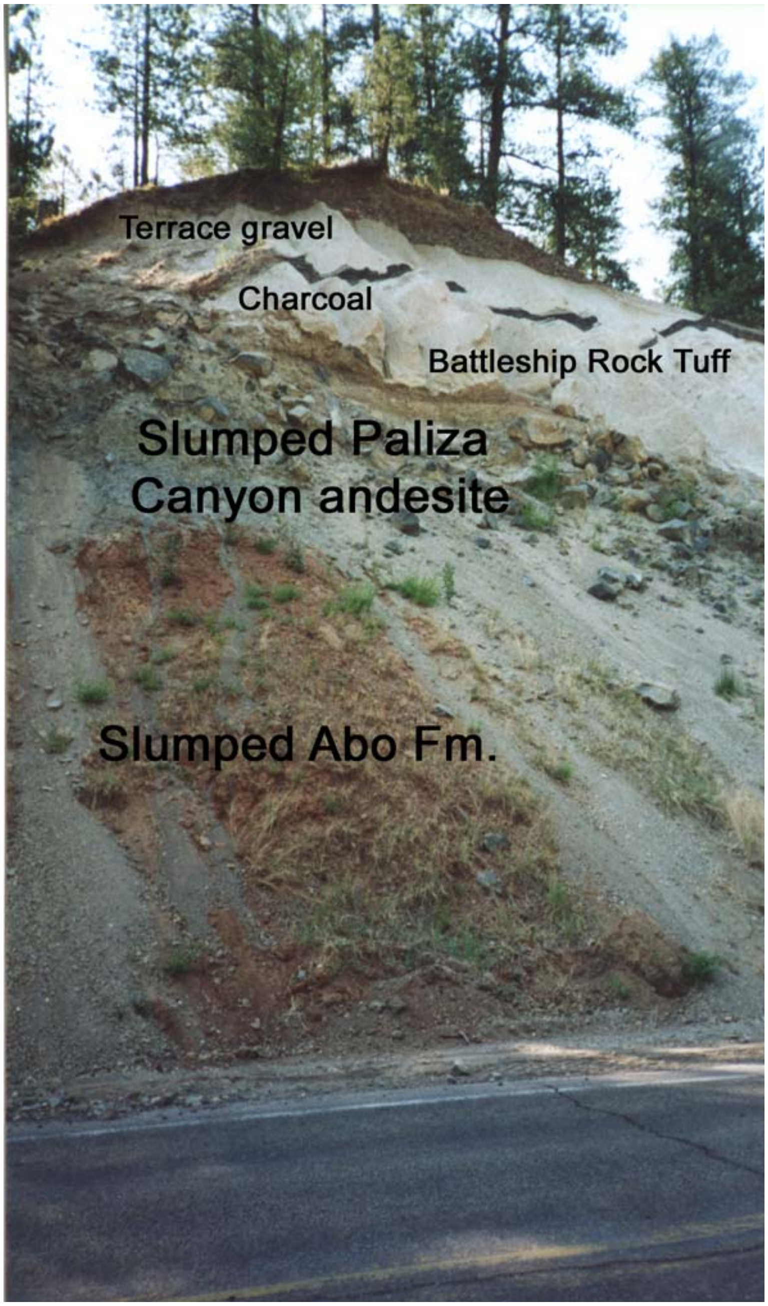


Figure 6. Roadcut along NM Highway 126 north of La Cueva exposing caldera debris flow deposits overlain by Battleship Rock Tuff with a curious charcoal deposit within the tuff. The outcrop is capped by terrace gravel.

present in the walls of Cañon de San Diego (Figure 5), although more work is need to confirm the correlations. The conspicuous dark gray band in Cañon de San Diego in the Tshirege Member cliffs corresponds to unit 2 of Broxton and Reneau (1995), although the unit is more strongly welded here compared to the Pajarito Plateau. Lithic fragments are relatively rare in the Tshirege Member in general, but outcrops of unit 3 on the mesas above Cañon de San Diego can have fragment abundances of 5-10% (e.g., Smith and Bailey, 1966).

Post-caldera lava flows of the 1.208 ± 0.017 to 1.239 ± 0.017 Ma (^{40}Ar/^{39}Ar sanidine ages; Phillips, 2004) Redondo Creek Rhyolite, a moderately phenocryst-rich (10-15%) plagioclase-sanidine-biotite-pyroxene rhyolite, crop out north and east of La Cueva. The Redondo Creek Rhyolite erupted from multiple vents north-northeast of La Cueva. Fine-grained, white, lacustrine beds and debris flows deposits containing angular to subrounded fragments of Bandelier Tuff, Paliza Canyon Formation andesite and dacite, upper Abiquiu Formation sandstone, Pennsylvanian limestone, Permian sandstone, Proterozoic granite and gneiss, chert, lacustrine clasts, and rhyolite clasts are interbedded with Redondo Creek flows near La Cueva and underlie the Battleship Rock Tuff near Battleship Rock (Figure 6, Kelley et al., 2004). These debris flows were derived from the resurgent dome of Valles caldera to the east (Goff et al., 2007).

Rhyolite flows from South Mountain, located ~9 km east of Cañon de San Diego, crop out below the Battleship Rock Tuff just northeast of Battleship Rock. The 0.52 ± 0.01 Ma (sanidine ^{40}Ar/^{39}Ar age; Spell and Harrison, 1993) South Mountain Rhyolite, with phenocrysts of quartz, biotite, hornblende, clinopyroxene, sanidine, and plagioclase, is one of the younger ring fracture domes in the Valles caldera.

The youngest volcanic units in the Jemez volcanic field were erupted from the El Cajete crater along the southwest ring fracture zone of the Valles caldera. The 50-60 ka El Cajete pumice (Gardner and Wolff, 1995) covers San Juan Mesa in the northeastern corner of the quadrangle and is preserved in pockets on Cat Mesa (not mapped) and on the east side of the quadrangle. The youngest volcanic units in the Jemez volcanic field were erupted from centers along the southwest ring fracture zone of the Valles caldera. The 50-60 ka El Cajete Pumice (Gardner and Wolff, 1995), which erupted from the El Cajete crater east of Cañon de San Diego, covers Cat Mesa and San Juan Mesa to the south and southeast of the caldera. The Battleship Rock Tuff, which is age equivalent to the El Cajete Pumice (Self et al., 1988, 1991), is a distinctive pink to gray tuff. This tuff consists of at least two flow units; the base of each flow is non-welded, but the center is usually densely welded (Ross and Smith, 1961). An ESR age on quartz phenocrysts from the Battleship Rock Tuff is 55 ± 6 ka (Toyoda et al., 1995). Debris-flow deposits are preserved between Battleship Rock Tuff and overlying Banco Bonito lavas in cliffs east of San Antonio Creek. The Banco Bonito Rhyolite is a glassy to devitrified rhyolite with phenocrysts of quartz, biotite, hornblende, pyroxene, and plagioclase that consists of at least two flow units (Manley and Fink, 1987; Gardner et al., 1986). An ESR age on quartz phenocrysts from the flow is about 40 ± 4 ka (Ogoh et al., 1993). A ^{21}Ne exposure age on quartz phenocrysts from samples collected on pressure ridges is 37 ± 5 ka (Phillips et al., 1997). The Banco Bonito Rhyolite fills three west-trending paleovalleys cut into the Battleship Rock Tuff.

Drainage Development

A south- to- southwest-trending drainage system has persisted in the vicinity of Cañon de San Diego since late Pliocene time. A valley that was located slightly to the west of modern Cañon de San Diego was filled by San Diego Canyon tuff at ~1.85 Ma. An active stream was present in the valley south of the modern position of Sino Spring at the time of the eruption and a channel was re-established shortly after the small volume eruption of this tuff. The voluminous Otowi Member of the Bandelier Tuff also filled in this valley at 1.61 Ma and totally disrupted the drainage pattern in the Jemez Mountains. The Tshirege Member filled in paleochannels on both sides of the modern Cañon de San Diego at 1.25 Ma. For example, a southwest-trending paleovalley on the west side of Rincon Negro was filled by the Tshirege Member; the west-dipping contact between the Otowi and Tshirege is preserved in the canyon wall between Rincon Negro and the point just south of Alamo Spring (Fig. 3). The Tshirege Member also filled a south-trending paleovalley with an active stream channel to the southeast of Jemez Springs (Scholle and Kelley, 2003).

Rogers et al. (1996) reviewed previous work that considers the timing of the development of Cañon de San Diego. Obviously, incision began after eruption of the 1.25 Ma Tshirege Member. Clearly, the caldera wall on the east side of Cañon de San Diego between Battleship Rock and La Cueva was breached sometime before the emplacement of the 0.5 Ma South Mountain Rhyolite flow and the 50 ka Battleship Rock Tuff. Smith and Bailey (1968) argued that the caldera wall breach and Cañon de San Diego formed within 100 ka of the eruption of the Tshirege Member, when a post-caldera lake drained as the resurgent dome rose. Deposits of this lake are interbedded with Redondo Creek lava flows just northeast of La Cueva. In contrast, Goff and Shevnell (1987) and Goff et al. (1992) proposed that the breach in the caldera wall did not form until ~0.5 Ma, based on pressures in the Valles hydrothermal system and U-Th disequilibrium dates on the travertines at Soda Dam. Rogers et al. (1996) noted that if the earliest lake did catastrophically drain through the Cañon de San Diego area, the tuff would be easily incised, but the underlying sandstone and limestone would be harder to remove. Several lakes may have formed and drained over the last 1.2 m.y. (Rogers et al., 1996; Goff et al., 2007; Reneau et al., 2007), so it seems more likely that Cañon de San Diego has had a protracted and episodic incision history.

During the course of mapping in Cañon de San Diego, we looked for deposits high in the landscape that might provide clues as to the incision history of the canyon. We found two sets of deposits at intermediate levels in the canyon that record episodes of aggradation during the development of the canyon. First, unconsolidated gravel deposits sit on Abo Formation on Cerro Colorado about 306 m above the bottom of Cañon de San Diego and about 195 m below the canyon rim. The gravel consists of 50% round to subround Permian to Triassic sandstone clasts, many with slickensides or deformation bands, 40% Paliza Canyon andesite and basalt clasts, and 10% Proterozoic granite and Pedernal Chert. These clasts were likely eroded from the Cat Mesa fault zone just upstream along the EFJR. Bandelier Tuff and intracaldera-volcanic-rock clasts that might indicate deposition by a stream with headwaters in the caldera are not present in this deposit. Similarly, gravel deposits on Abo Formation west of Battleship Rock about 75 m above the canyon bottom contain abundant rounded Abo and Yeso sandstone clasts that were probably derived from an ancestral EFJR. Again, intracaldera clasts are not present. A terrace deposit about 60 m above the canyon bottom on the north side of Cerro Colorado does contain cobbles to pebbles of intracaldera rocks, including dacite, green lava, tuff, and Banco Bonito obsidian, recording the presence of a stream with a headwaters within the caldera draining into Cañon de San Diego in this vicinity.

Second, a lake deposit that is 280 m above the canyon bottom and 70 m above the highest travertine at Soda Dam is preserved on the west side of Cañon de San Diego (cross-section, Fig. 4). This deposit north of Soda Dam in the Agua Durme area consists of a basal yellowish-orange sandstone that is <0.5 m thick with no obvious sedimentary structures overlain by ~1 m of white to gray laminated sandstone. The unit is capped by 2 m of white, finely laminated silt to shale that contains gastropods and woody stems. The deposit is overlain by a debris flow containing Bandelier Tuff clasts and rests on Abo Formation. A similar, but smaller, deposit is present west of Jemez Springs, inset into the San Diego Canyon tuff at UTM coordinates 346310 3959660 (NAD 27). These deposits likely record blockage of the canyon, probably by landslides, early in its incision history. Further work is need to determine the age of these important deposits, which hold the key to understanding one of the final chapters of the fascinating geologic story preserved in Cañon de San Diego.

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