GEOLOGY OF CAÑON DE SAN DIEGO, SOUTHWESTERN JEMEZ MOUNTAINS, NORTH-CENTRAL NEW MEXICO

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ABSTRACT — Cañon de San Diego (CdSD) provides an important window into the Proterozoic to Pleistocene geologic history of the Jemez Mountains region. Portions of oceanic shorelines and continental-scale river systems are preserved in the late Paleozoic to middle Mesozoic sedimentary rocks in the canyon. Recent mapping in the area has revealed the northern extent of an Oligocene to Miocene Rio Grande rift basin that developed against, and then overlapped, the Jemez fault zone. The older part of this basin, which is exposed on the hanging wall of the Jemez fault zone, is dominated by cobbles and boulders of Oligocene intermediate composition volcanic clasts from an unknown, but nearby, volcanic center. Offset on the Jemez fault zone decreases toward the northeast, and early rift displacement was taken up along a second NNE-striking fault, the Cat Mesa fault, located east of the Jemez fault zone in the eastern wall of CdSD. An apparent Pliocene (?) debris avalanche deposit composed of a basal debris flow deposit overlain by as much as 240 m of rubbly Paliza Canyon Formation andesite is exposed for 6.5 km along the western wall of CdSD; this unit controls the hydrology of the western side of the canyon. A river was present to the west of the modern CdSD prior to the eruption of the small volume 1.85 Ma San Diego Canyon tuff and that river system persisted until the eruption of the Otowi Member of the Bandelier Tuff at 1.61 Ma. Lake and fluvial deposits preserved 280 to 300 m above grade suggest that modern CdSD has had a protracted, episodic incision history.

INTRODUCTION

Scenic Cañon de San Diego (CdSD), with vibrant red and orangish-red sedimentary slopes capped by cliffs of orange-tan tuff, is a significant SW-trending drainage in the southwestern Jemez Mountains (Fig. 1). Tuff outflow sheets, lava flows, and a volcanic center exposed high in the canyon walls are part of the 15 Ma to 40 ka Jemez volcanic field that straddles the transitional margin between the extensional Oligocene to Miocene Rio Grande rift to the east and the transpressional, Proterozoic-cored, Paleocene to Eocene Sierra Nacimiento to the west. The Jemez volcanic field lies at the intersection of a NE-trending alignment of < 10 Ma volcanism known as the Jemez lineament, which is thought to have a Mesoproterozoic ancestry (Aldrich, 1986; Karlstrom and Humphreys, 1998), and the eastern margin of the Rio Grande rift. Cañon de San Diego is one of several major drainages (e.g., Santa Clara Canyon, Cañones Canyon) that cut through the eruptive products of the Jemez volcanic field to reveal the rocks that lie below, but this canyon is unique in that it dissects the flanks of the Sierra Nacimiento Laramide highland, as opposed to the rift-related Española Basin sediments in canyons to the northeast and east (Fig. 1). 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 (EFJR) (Fig. 2). The youngest volcanic rocks in the Jemez Mountains are exposed in the upper part of the canyon, while older rocks, including Proterozoic granitic gneiss, are exposed downstream. New Mexico Highway 4 provides easy access to CdSD from Albuquerque. Well-known and oft-visited landmarks in CdSD 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 EFJR.

Renick (1931), Wood and Northrop (1946), Smith et al. (1970), Kelley (1977), and Woodward (1987) established the regional geologic framework of the southwestern Jemez Mountains and southern Sierra Nacimiento, but little detailed work was done in the area until the geothermal boom in the 1980s. Several targeted geologic studies in and around CdSD were designed to determine the magnitude and extent of the geothermal system in the southwestern Jemez Mountains (e.g., Goff and Kron, 1980; Goff et al., 1981, 1986, 1988, 1992; Goff and Shevnell, 1987).

This paper highlights elements of the geologic and structural development of the area that came to light during recent 1:24,000 scale mapping in the area (Pazzaglia et al., 1998, Osburn et al.,

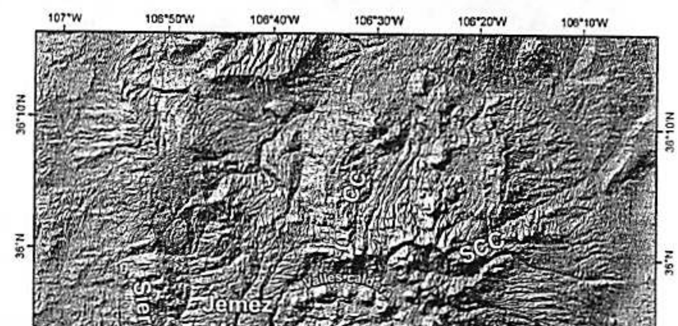

FIGURE 1. DEM of the Jemez Mountains and Sierra Nacimiento. CdSD = Cañon de San Diego; CC= Cañones Canyon; SCC=Santa Clara Canyon.

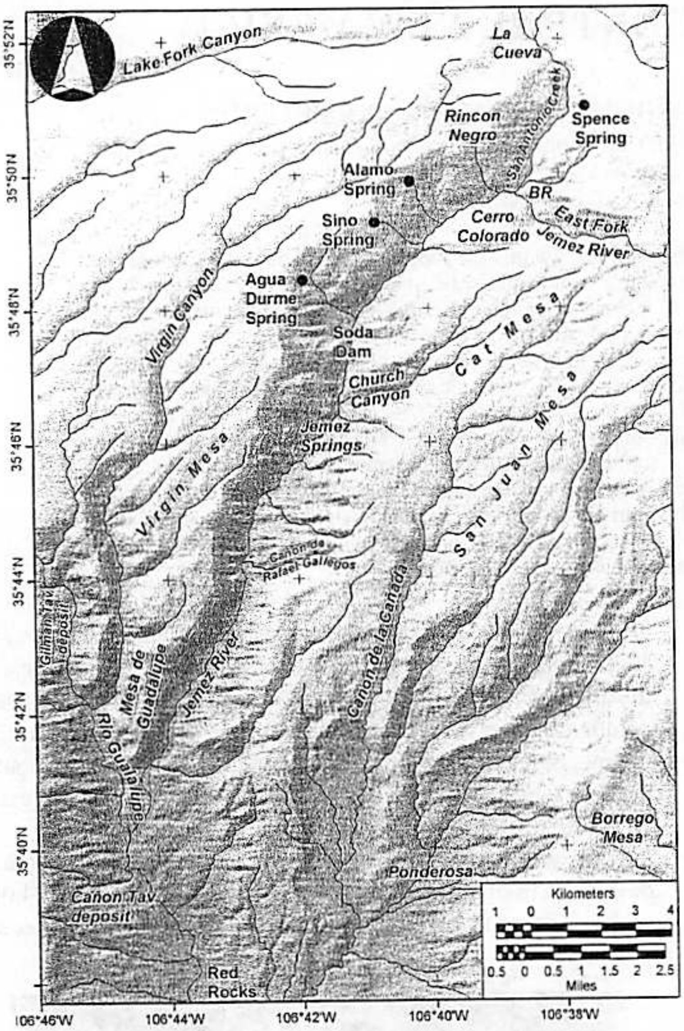

FIGURE 2. Index map of geographic features in Cañon de San Diego. BR is Battleship Rock. Tav is the Oligocene-Miocene volcaniclastic unit..

2002, Kelley et al., 2003, 2004). We use the geological time scale of Gradstein et al. (2005) in our narrative of the geological history of CdSD in this paper. Important observations derived from recent work include: (1) delineation of a late Oligocene to early Miocene basin adjacent to the Jemez fault zone that is filled with intermediate composition Oligocene volcanic cobbles and boulders of unknown origin; (2) identification of a spectacular Pliocene (?) debris avalanche deposit that controls the location of major springs on the west side of CdSD; and (3) recognition of previously unmapped, early rift fault strands along the eastern wall of CdSD that intersect the EFJR.

THE ROCK RECORD IN CAÑON DE SAN DIEGO

Proterozoic rocks

Rocks exposed in CdSD contain a rich, but fragmentary, geologic record spanning ~ 1.7 b.y. of Earth's history (Fig. 3). The oldest rocks in CdSD are fractured and altered granitic gneiss exposed on the footwall of the Jemez fault zone, a rift-related normal fault, 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 (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 foliation strike in the gneiss is at a high angle with respect to the strike of the fault zone.

Paleozoic to Mesozoic sedimentary rocks

Starting at ~345 Ma (Mississippian, Osagean), an oceanic shoreline moved back and forth across the CdSD 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 b.y. 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 Late Mississippian (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 of CdSD (Woodward, 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. 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 CdSD. 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. 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

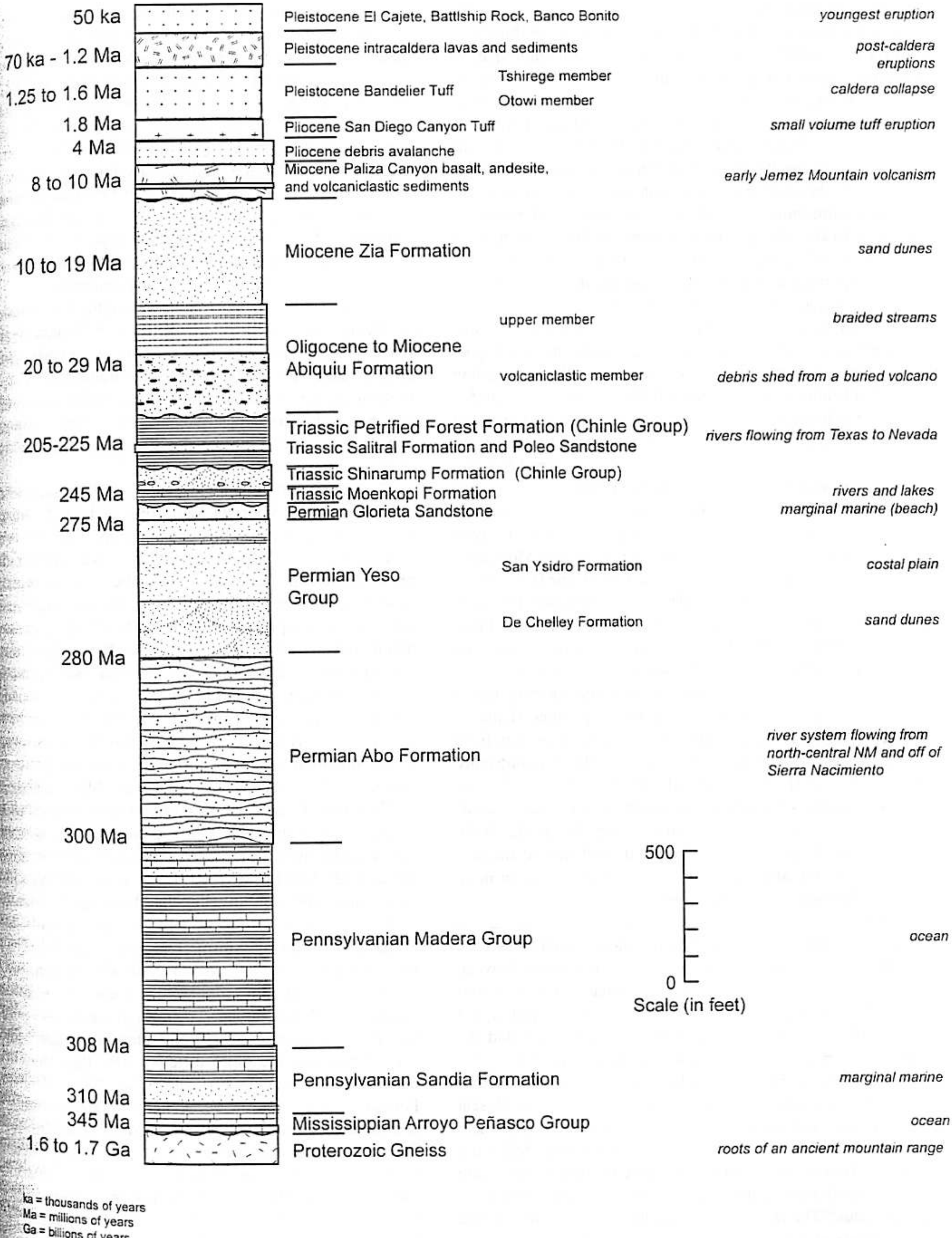

FIGURE 3. Composite stratigraphic section of the rocks exposed in Cañon de San Diego.

Jemez Springs Shale Member. In this study, we provisionally use Madera Group, pending further detailed work on this package of rocks in CdSD. The arkosic material in the upper part of the Pennsylvanian section in the canyon was derived from the Peñasco highland to the west. Several well-known invertebrate fossil collecting sites within the Jemez Springs Shale Member are located in CdSD (Sutherland and Harlow, 1967; Kues, 1996). The upper contact of the Pennsylvanian limestone and clastic rock sequence with the overlying Abo Formation is transitional in this area. 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 CdSD 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. (2005c) noted 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. This trend has also been noted in central and west-central New Mexico (Lucas and Zeigler, 2004). The Abo Formation is temporally equivalent to the Arroyo del Agua Formation and the upper El Cobre Canyon Formation of the Cutler Group in the northern Jemez Mountains (see Day 1 road log, this volume), and the Guadalupe Box Formation of Krainer et al. (2005) correlates with the lower El Cobre Canyon Formation (Lucas et al., 2005a). Thin pedogenic limestone beds within the Abo Formation are common on and just south of Cerro Colorado (Fig. 2); pedogenic calcite is characteristic of the Arroyo del Agua Formation in the northern Jemez Mountains. 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). The Abo Formation locally contains malachite and azurite in the channel sandstones at several localities throughout CdSD (Kelley et al., 2003). These minerals formed when copper-rich fluid moved through the sandstones long after deposition (e.g., Spanish Queen mine near Jemez Springs, McLemore, 1996).

The Permian Yeso Group forms orange cliffs in the canyon walls south of Jemez Springs and is the most conspicuous rock unit in the Red Rocks area on Jemez Pueblo. 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 between the fluvial Abo and the eolian basal part of the Yeso (Mack and Dinterman, 2002). The Yeso has traditionally been assigned formation status and has been divided into two members in the CdSD region, the lower Meseta Blanca Member and the upper San Ysidro Member (Wood and Northrop, 1946; Stanesco, 1991). Lucas et al (2005a), 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 in the vicinity of Red Rocks consists of thin-bedded, cross-bedded, orange sandstone, reddish-orange medium- to thick-bedded tabular sandstone with thin shale interbeds, occasional fluvial channel structures, and rare mudcracks, and a distinctive eolian sandstone characterized by meter-scale, tabular-planar, wedge-planar and trough cross-beds that record a transport direction generally to the south (Stanesco, 1991; Lucas et al., 2005a, c). The upper sandstone contains a thin discontinuous pedogenic carbonate horizon near the upper contact. 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 continuous 1 to 2 m-thick limestone bed is present near the top of the unit. Sandstone immediately under the limestone is bleached, due to weathering prior to the deposition of the limestone. The limestone exhibits soft-sediment deformation and fills in low spots in the underlying sandstone.

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 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).

The Triassic Moenkopi Formation (early Anisian) unconformably overlies the 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 in the Red Rocks area is unique in that it contains a 1 m-thick layer of sandy limestone intercalated with cross-bedded red sandstone; the basal part of the limestone contains abundant unionid pelecypod shells (fossils identified by S.G. Lucas, personal comm., 2005). The Moenkopi Formation was deposited by north- to northwest-flowing rivers with a source in the Mogollon highlands to the south and the Ouachita mountain belt to the east and southeast at ~245 Ma (Lucas, 2004).

The 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., 2005b). The Chinle Group unconformably overlies the Moenkopi Formation, with a ~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. The Shinarump Formation and its basal contact relations are quite different here than they are in the northern Jemez Mountains (Kelley et al., 2006). The Shinarump Formation to the north is white and primarily contains quartzite and metasedimentary cobbles. In addition, the Shinarump Formation and the underlying rocks are deeply pedogenically altered to the north; this alteration is not present in the southern Jemez Mountains. The Shinarump Formation is overlain by red shale of the Salitral Formation. Locally along the south side of the EFJR, the Salitral Formation is overlain by a <5 m thick section of black conglomerate with abundant quartz and chert pebbles belonging to the Poleo Sandstone. The Petrified Forest Formation of the Chinle Group does not crop out in CdSD, but this unit may be covered by colluvium in the EFJR. This unit is exposed to the east near the village of Ponderosa.

Jurassic and Cretaceous sedimentary rocks that are preserved beneath Jemez volcanic field rocks in the northern Jemez Mountains (see Day 1 road log) and to the south near San Ysidro were eroded from the western Jemez Mountains prior to the deposition of the early rift-fill sediments, the Abiquiu Formation. Evidence for transpressive Laramide deformation comes principally from the *absence* of the middle to upper Mesozoic section in this part of the Jemez Mountains. The eastern flank of the broad Sierra Nacimiento high lies east of CdSD, where the upper part of the Triassic Chinle Group and Jurassic Entrada and Todilto Formations are exposed near the village of Ponderosa. The Permian to Triassic rocks in the southern part of the canyon dip about 7° to the south on the southern flank of the Laramide high. Laramide deformation started in this area about 75 Ma, with activity peaking about 50-55 Ma (Pazzaglia and Kelley, 1998; Cather, 2004).

Rift-fill sedimentary rocks

Oligocene-early Miocene

One of the most significant structures in CdSD is the NE-striking Jemez fault zone (JFZ; Fig. 4), a down-to-the-southeast, rift-related, normal fault that offsets the Pennsylvanian-Permian rocks 200-250 m and the 1.25 Ma Tshirege Member of the Bandelier Tuff 15 m west of Soda Dam. The stratigraphic offset across the JFZ decreases dramatically toward the northeast; Abo is juxtaposed against Abo across the fault in the valley of the EFJR. Several fault splays north of the JFZ strike northeast, parallel to the strike of the main fault. South of the JFZ, a fault zone on the east side of CdSD has a more NNE strike. This fault zone, herein named the Cat Mesa fault zone (CMFZ, Fig. 4), parallels the western edge of Cat Mesa, and offsets the Permian Yeso Formation ~240 m down to the east where the fault crosses the EFJR. Stratigraphic offset of the Permian and Triassic rocks across the CMFZ appears to increase toward the north. The fault offsets Paliza Canyon Formation andesite <10 m in the south wall of the EFJR and the Bandelier Tuff <2 m east of Jemez Springs, so the CMFZ is primarily an early rift fault.

Deposits related to an Oligocene phase of extension along the Jemez fault zone are preserved in the southern reaches of CdSD (Connell et al., 2007). A greenish gray volcaniclastic deposit containing rounded clasts of andesitic, basaltic, and rhyolitic rocks from an unknown volcanic center lies on the hanging wall of the Jemez fault zone (Kelley and Connell, 2004; Connell et al., 2007). DuChene (1973) and DuChene et al. (1981) initially described this unit in the vicinity of Gilman. Most of the cobble-sized volcanic clasts are intermediate in composition, contain phenocrysts of plagioclase and pyroxene, and are <20 cm in diameter. Some clasts have hornblende and biotite; rare clasts contain quartz as phenocrysts. Two clasts yield groundmass $^{40}Ar/^{39}Ar$ ages of 28.55±0.07 and 28.63±0.10 Ma; two different clasts have biotite $^{40}Ar/^{39}Ar$ ages of 29.38±0.59 and 29.22±0.58 Ma. Granules and pebbles of Proterozoic granite and quartz are concentrated in the basal 3 to 10 m and in the upper 10 m of the deposit; overall, the volcaniclastic deposit contains <5% Proterozoic granite, quartz, and schist. The volcaniclastic deposit is about 59 m thick in an unnamed drainage on the west side of the Jemez River, west of Jemez Valley High School in the village of Cañon, and is about 56 m thick near Gilman (Fig. 2). The volcaniclastic unit thins dramatically to the north, east, and south of the Gilman-Cañon area and generally is only 0.5 to 1.5 m thick in the canyon walls on the east side of CdSD between Cañon del Raphael Gallegos and Church Canyon (Fig. 2). The volcaniclastic unit typically rests on Permian Yeso Group sandstone and underlies medium-bedded white sandstone assigned to Abiquiu Formation by previous workers (Smith et al., 1970, DuChene, 1973). The volcaniclastic unit appears to be stratigraphically equivalent to the Proterozoic-clast-dominated lower Abiquiu Formation exposed in the northern Jemez Mountains (Smith et al., 2002; Day 1 Road Log, this guidebook). The age and composition of the volcanic clasts support a possible source in the San Juan or the Mogollon-Datil volcanic fields, but both centers are over 100 km from the deposit. The Ortiz volcanic field is closer, but the clast composition does not match volcanic rocks exposed there (G. Smith, personal comm., 2005). Thus, we speculate, based on the size of the clasts and the distribution of the deposit, that the clasts were eroded from a previously unrecognized Oligocene volcanic center that may be buried under the southern Jemez Mountains.

The upper Abiquiu Formation in the southwestern Jemez Mountains is a white to tan, tabular-bedded, medium-grained sandstone that is alternately well cemented and poorly cemented and is interbedded with thin (0.1-0.3 m) fine-grained ash-fall deposits. A few thin-bedded and laminated calcareous siltstones are in this unit. A biotite-rich ash bed from the upper Abiquiu Formation in Cañon de la Cañada located east of CdSD yields a $^{40}Ar/^{39}Ar$ age of 20.61 ± 0.07 Ma, within the age range of the 18 to 27 Ma upper Abiquiu Formation in the northern Jemez Mountains near Cerro Pedernal (Tedford et al., 1993; Smith et al., 2002). This unit is quite variable in thickness, ranging from 50 to 62 m in the Cañon-Gilman area (Connell et al., 2007) to <1 m thick on the south side of the EFJR. Although the Pedernal Chert Member of the Abiquiu Formation is not present in the southwestern Jemez Mountains, chert lenses in sandstones of the upper Abiquiu Formation are common, particularly in exposures north of Church Canyon. A carbonate-cemented sandstone is locally preserved at the base of the upper Abiquiu Formation at several localities in the east wall of CdSD as far north as the EFJR.

Miocene

The northern edge of a basin preserving the Miocene Zia Formation laps onto south-dipping Permian rocks in the vicinity of Jemez Pueblo. In the unnamed drainage west of Jemez Valley High School, a white, poorly cemented sandstone conformably overlies the upper Abiquiu Formation (Connell et al., 2007). This sandstone, which generally is cross-bedded and locally contains fluvial deposits, likely correlates to the Piedra Parada Member of the Miocene Zia Formation (Tedford and Barghoorn, 1999).

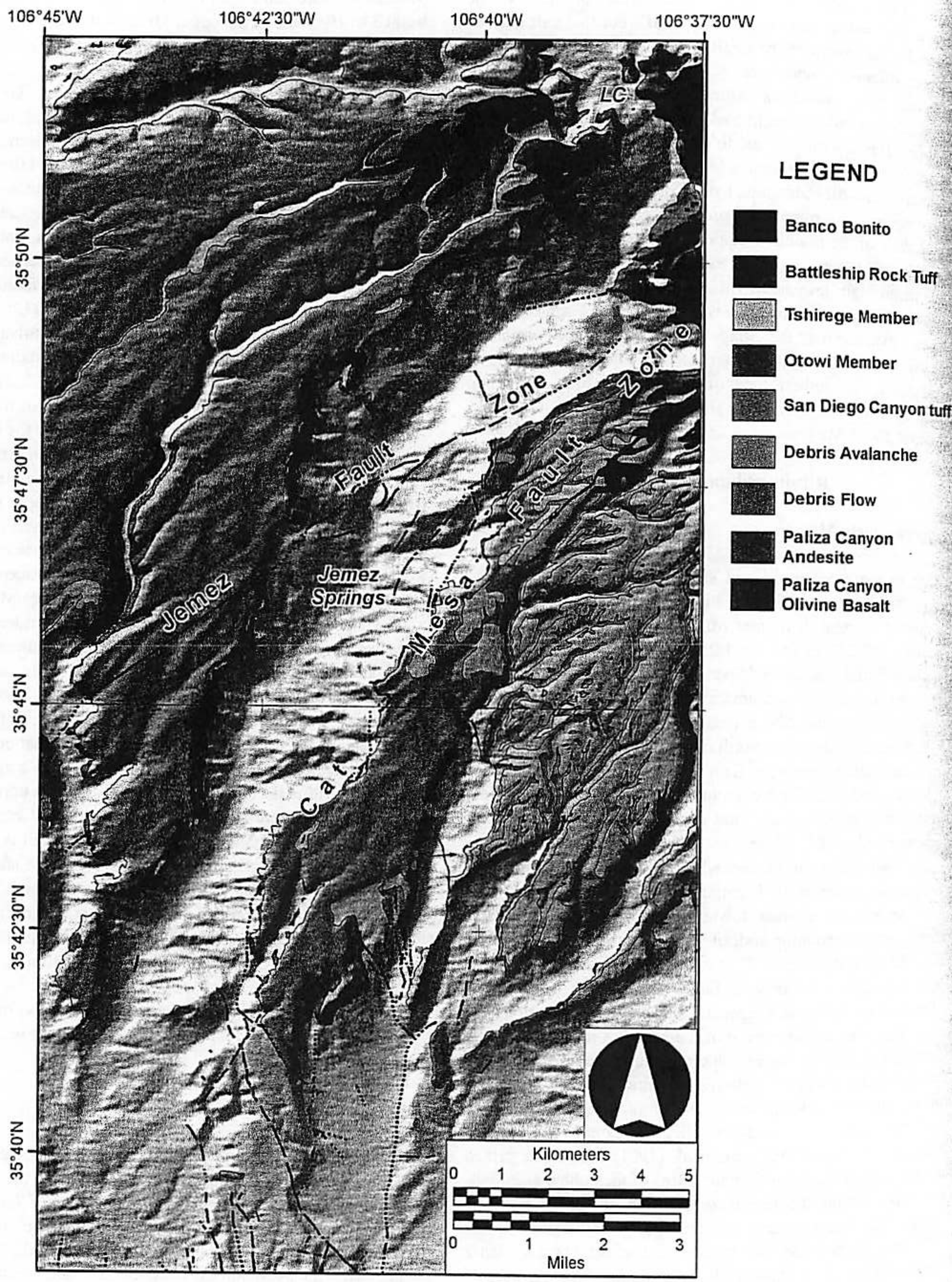

FIGURE 4. Geologic map of Cañon de San Diego. LC is the village of La Cueva. See Plate 8 on page 138 for a color version of this figure.

Jemez volcanic field rocks

Pre-Toledo and Valles caldera rocks

Some of the oldest rocks of the Jemez volcanic field are beautifully exposed in Church Canyon high in the eastern walls of CdSD. 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 CdSD (Fig. 2), where $^{40}Ar/^{39}Ar$ ages of ~9.9 Ma have been determined for the oldest basalt and ~9.1 Ma 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 erupted from a vent just to the north of Church Canyon on the east side of CdSD (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 upper Abiquiu sandstone in Church Canyon. Although we have no radiometric age data for this flow, 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).

One of the most interesting units recognized during this study forms imposing black cliffs on the west side of CdSD between a point just south of La Cueva and and a point just south of Agua Durme Springs, a distance of 6.5 km (Figs 2, 5, 6). Andesitic flows to the north are juxtaposed abruptly against rubbly deposits to the south across a small drainage just south of La Cueva (Figs. 2, 6). This rubbly deposit is composed primarily of 0.1 m to 3 m-wide 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 x 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 rubbly 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 (Fig. 6). The bulk of the deposit terminates just south of Agua Durme Springs (Figs. 6, 7), 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).

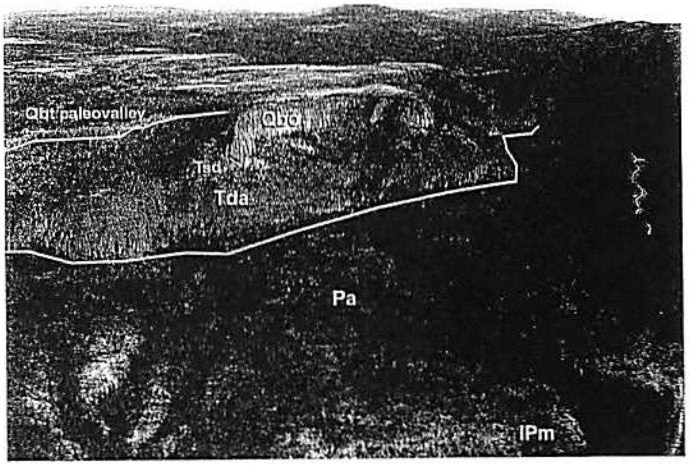

FIGURE 5. Aerial photograph of Rincon Negro on the west side of CdSD. IPm = Pennsylvanian Madera Group; Pa = Permian Abo Formation; Tda = Pliocene(?) debris avalanche; Tsd = San Diego Canyon Tuff; Qbo = Otowi Member, Bandelier Tuff; and Qbt = Tshirege Member, Bandelier Tuff. The line in the upper left marks the east edge of a paleovalley cut on Qbo. The base of the Tda deposit is also marked with lines.

The rubbly nature of the deposit, the presence of an allothonous block, the undulating top contact, and the presence of a basal debris flow deposit suggest that 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. 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 CdSD— 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.

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 (Figs. 6, 8). 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

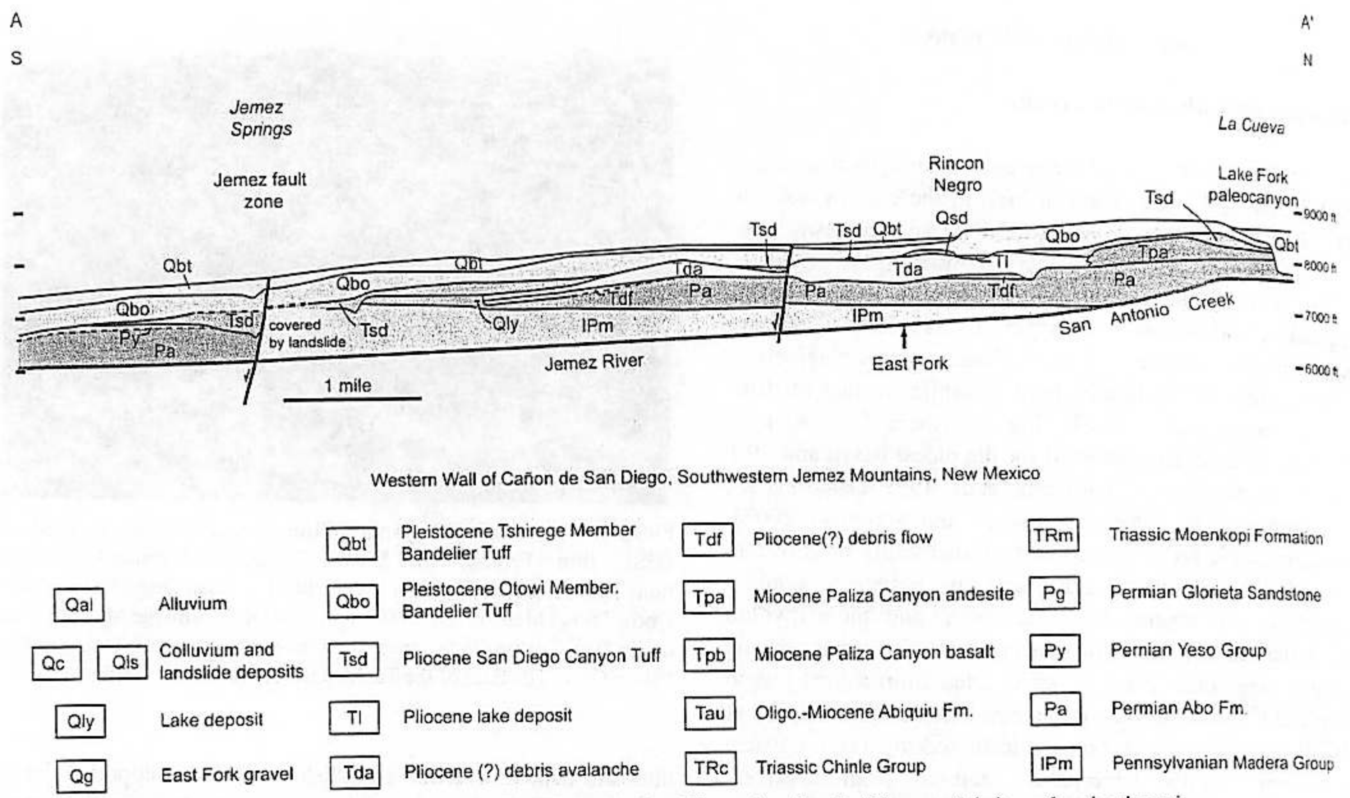

FIGURE 6. North-south cross-section of the west wall of Cañon de San Diego showing the Pliocene debris avalanche deposit.

south wall of the EFJR beneath the Otowi Member of Bandelier Tuff.

Fluvial gravel and sandstone overlie Permian Yeso or Abo sandstone or Pliocene (?) debris avalanche deposits and underlie the San Diego Canyon tuff or the Bandelier Tuff on the west side of CdSD. Pebble to boulder clasts in the fluvial deposits are generally subrounded to well-rounded Paliza Canyon Formation volcanic rocks with a few granite, Permian sandstone, Permian conglomerates, and rare Pedernal chert clasts supported in a silt to sand matrix. Paleocurrents based on pebble imbrications indicate southerly paleoflow (Scholle and Kelley, 2003). These deposits could be temporally equivalent to the Cochiti Formation in the southeastern Jemez Mountains (Smith and Lavine, 1996). 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 commun., 2003) that are incorporated in a red sandstone at least 5 m below the lowest recognized unit of the tuff. 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.

The San Diego Canyon tuff is a gray to white, nonwelded to poorly welded ash flow tuff that is exposed only on the west side of CdSD between La Cueva and the south end of Virgin Mesa. This tuff is characterized by phenocrysts of quartz and sanidine with trace pyroxene and magnetite. The tuff consists of two units (Turbeville and Self, 1988). The lower unit (A) is nonwelded and includes abundant lithic fragments of basalt and andesite from the underlying Paliza Canyon Formation, with minor Proterozoic plutonic and metamorphic components (Turbeville and Self, 1988). The maximum clast size is 25 cm. The upper unit (B) is nonwelded to slightly welded and contains large pumice clasts characterized by vesicles with high aspect ratios. The two units are separated by reworked pumice and debris flow deposits at the

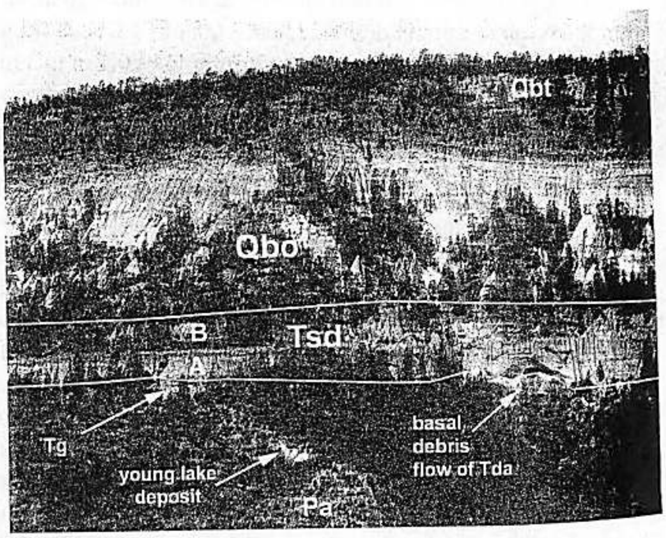

FIGURE 7. Photograph of Agua Durme area on the west side of CdSD. Pa = Permian Abo Formation; Tda = Pliocene debris avalanche deposit; Tg = fluvial deposits; Tsd = San Diego Canyon Tuff (units A and B of Turbeville and Self., 1988); Qbo = Otowi Member, Bandelier Tuff; and Qbt = Tshirege Member, Bandelier Tuff.

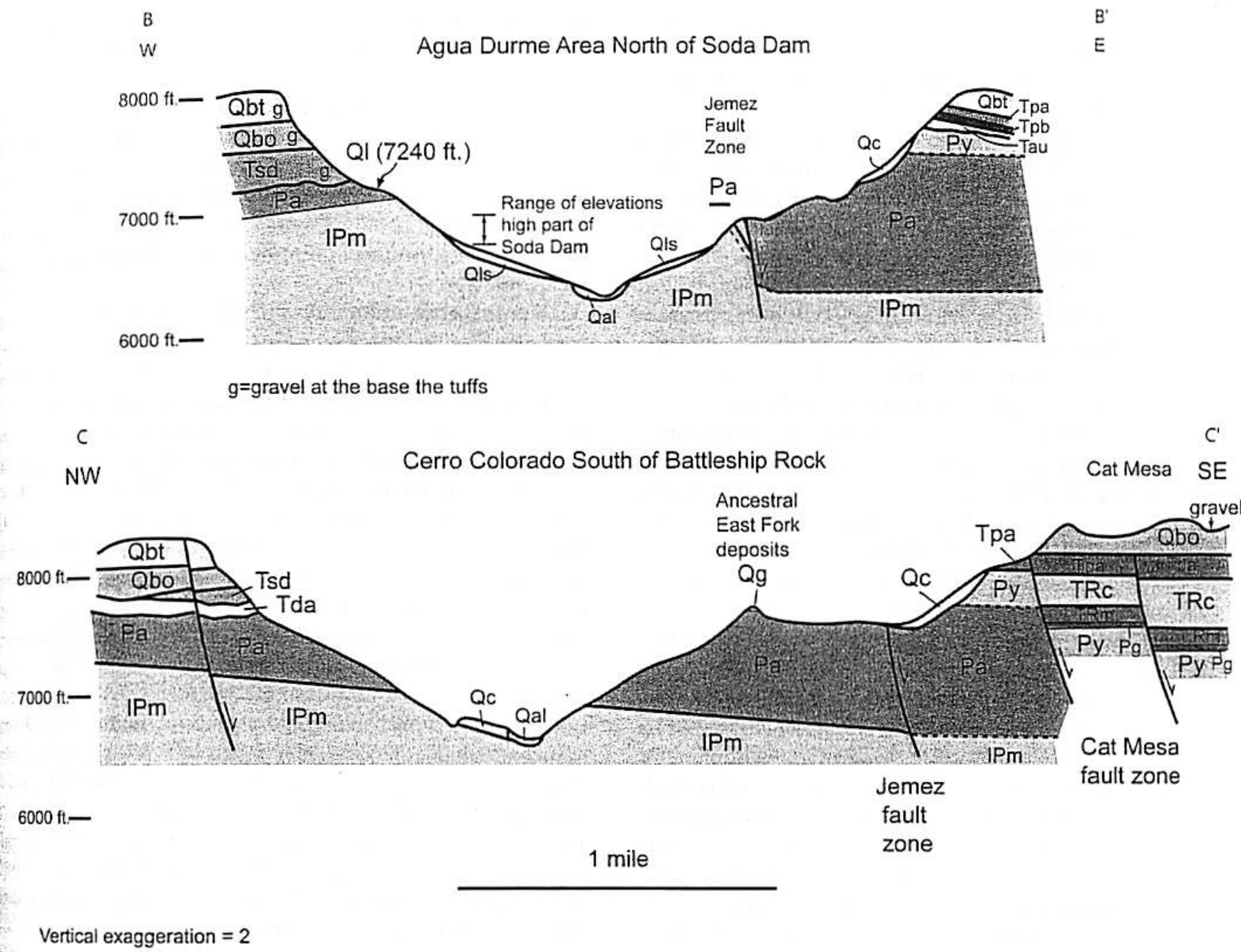

FIGURE 8. East-west cross-sections of Cañon de San Diego highlighting the presence of the pre-1.85 Ma paleodrainage west of the modern canyon. For unit abbreviations see Fig. 6.

north end of the exposure, and by fluvial gravels and mudstones at the south end of the exposure. The tuff is underlain by the Pliocene (?) debris avalanche deposit in the northern part of the canyon and by fluvial gravels in the southern part of the area. The San Diego Canyon tuff obviously filled an active stream channel positioned slightly west of the modern canyon and south of Agua Durme Spring because gravel is interbedded with the two ignimbrite flows. Fluvial deposition continued after eruption of the tuff because fluvial gravel is preserved between the San Diego Canyon tuff and the overlying Otowi Member of the Bandelier Tuff southwest of Jemez Springs.

Large caldera-forming eruptions

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 Bed, was blown toward the east and northeast (Self et al., 1988) and is not preserved or is very thin (<20 cm) in the southwestern Jemez Mountains. The ignimbrite from the eruption blanketed the country side, filling in valleys and overtopping ridges. The Otowi Member is generally thicker on the west side of CdSD compared to the east side, filling in the paleovalley that preserves the older San Diego Canyon tuff. The Otowi Member also filled paleocanyons cut into the Permian rocks, such as the oft-photographed paleocanyon on the east side of CdSD that can be seen looking southeast from Jemez Springs. 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. On Cat Mesa, which is proximal to the caldera margin, the characteristic lithic-rich tuff is overlain by a more welded, pink, lithic-poor tuff. The Otowi Member formed a prominent paleohigh just west of La Cueva (Fig. 5).

During the ~400 k.y. between eruptions, W to SW-trending drainages developed on top of the Otowi Member and in a few places, gravel is preserved between the members of the Bandelier Tuff. A gravel with clasts of Yeso Group sandstone is preserved on top of Cat Mesa. Gravel with Paliza Canyon andesite and basalt, reworked lithic fragments from the Otowi Member, and trace Abo, Yeso, and Glorieta sandstone is present between the tuffs on both sides of CdSD in the vicinity of Jemez Springs (Scholle and Kelley, 2003). These gravels correlate with the Cerro Toledo interval of Broxton and Reneau (1995) on the Pajarito Plateau (Fig. 1).

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 present in the walls of CdSD (Fig. 9), although more work is need to confirm the correlations. Units 1g, 1v, 2, and 3 of Broxton and Reneau (1995) are visible in CdSD canyon walls from the village of Jemez Springs (Fig. 9). The conspicuous dark gray band 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 CdSD can have fragment abundances of 5-10% (e.g., Smith and Bailey, 1966).

Postcaldera 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 flow 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

FIGURE 9. 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.

near Battleship Rock (Kelley et al., 2003, 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 CdSD, 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 erupted from centers along the southwest ring fracture zone of the Valles caldera. The 50-60 ka El Cajete Pumice (Wolff and Gardner, 1995), which erupted from the El Cajete crater east of CdSD, 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 nonwelded, 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 (Kelley et al., 2003).

DRAINAGE DEVELOPMENT IN THE SOUTHWESTERN JEMEZ MOUNTAINS

A S- to SW-trending drainage system has persisted in the vicinity of CdSD since late Pliocene time. A valley that was located slightly to the west of modern CdSD 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 CdSD at 1.25 Ma. For example, a SW-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. 5). 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 CdSD. Obviously, incision began after eruption of the 1.25 Ma Tshirege Member. Clearly, the caldera wall on the east side of CdSD 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 CdSD formed within 100 ka of the eruption of the Tshirege Member, when a postcaldera 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 CdSD 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 CdSD has had a protracted and episodic incision history.

During the course of mapping in CdSD, 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 the Abo Formation on Cerro Colorado about 306 m above the bottom of CdSD 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 the 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 CdSD 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 CdSD (Figs.7, 8). 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 diatoms, gastropods, and woody stems. The deposit is overlain by a debris flow containing Bandelier Tuff clasts and rests on the 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 needed 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 CdSD.

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