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Geologic Framework of a Groundwater System on the Margin of a Rift Basin, Pajarito Plateau, North-Central New Mexico

David E. Broxton and David T. Vaniman

Abstract

The Pajarito Plateau is an important source of abundant high-quality groundwater for Los Alamos National Laboratory (LANL) and communities in the western part of the Española basin. Geologic investigations were undertaken as part of a plateau-wide hydrogeological investigation to develop conceptual models of the groundwater system and to provide a framework for numerical simulations of groundwater flow. The geology of the plateau reflects the interplay of tectonism, volcanism, and sedimentation along the western margin of the Española basin of the Rio Grande rift over the last 21 Ma. In the vicinity of LANL, the plateau is a geomorphic feature formed by Pleistocene ash-flow tuffs erupted from the Valles caldera complex in the adjacent Jemez volcanic field. Pre-Bandelier stratigraphy includes a complex assemblage of interfingering sedimentary and volcanic rocks including Miocene and Pliocene volcaniclastic deposits, intermediate to felsic lavas of the Jemez volcanic field, mafic lavas of the Cerros del Rio volcanic field, riverine deposits of the ancestral Rio Grande, and Miocene rift sediments. The hydrogeology of the Pajarito Plateau is typical of the Basin and Range region in which thick vadose zones and deep aquifer systems develop in rift sediments filling arid to semiarid basins flanked by mountainous recharge areas. Groundwater of the Pajarito Plateau has three principal modes of occurrence: 1) groundwater in canyon-floor alluvium, 2) deep perched groundwater in bedrock units of the vadose zone, and 3) groundwater associated with the regional zone of saturation. Geologic conditions favor the formation of deep perched water bodies beneath wet canyons where well-developed alluvial groundwater systems are fed by natural and/or anthropogenic surface water. The sizes of bedrock perched groundwater bodies vary across the plateau. Most appear to be relatively small in size, but thick perched groundwater bodies occur in the southwest part of LANL near Cañon de Valle and in the eastern part of LANL in Los Alamos and Sandia Canyons. The regional aquifer is primarily made up of thick west- to southwest-dipping, lithologically-complex, sedimentary rocks. In the west, the aquifer is dominated by westward-thickening alluvial fan deposits derived from the Jemez volcanic field. Eastern aquifer rocks consist for the most part of partly consolidated silts and sands derived primarily from the Sangre de Cristo Range. Intermediate and mafic lavas interbedded with the sedimentary rocks are important components of the regional aquifer locally. The presence of anthropogenic chemicals in deep perched and regional groundwater indicates that surface water on the plateau contributes to the recharge of these deep groundwater systems and that groundwater travel times along some pathways from the surface to deep groundwater systems occur within a time frame of decades.

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Introduction

The Pajarito Plateau covers about 622 km^2 (240 mi^2) in north-central New Mexico. The plateau abuts the east side of the Jemez Mountains for a distance of about 48 km (30 mi) and is about 15 km (9 mi) wide at its widest point (Fig. 1). When discussing the Pajarito Plateau in this paper, we are referring to the 233 km^2 (90 mi^2) area in the central part of the plateau that includes the Los Alamos National Laboratory (LANL) and the adjacent communities of Los Alamos and White Rock.

Groundwater drawn from beneath the plateau is the primary source of municipal and industrial water used by LANL and by adjacent communities. The regional zone of saturation lies about 180 m (590 ft) below the east rim of the plateau and more than 365 m (1200 ft) below mesas on the western side. Water supply wells on the plateau are commonly 610 to 762 m (2000 to 2500 ft) deep, and they tap groundwater in Miocene and Pliocene sedimentary and volcanic rocks. Although numerous wells penetrate the top of the regional zone of saturation, none fully penetrate the aquifer.

Water quality is typically good, but there are concerns about potential impacts of LANL operations on groundwater systems. In some areas, shallow and intermediate perched groundwater systems contain elevated concentrations of mobile contaminants such as tritium, nitrate, high explosives, and perchlorate. The regional groundwater system is much less impacted by contamination, but low concentrations of tritium, nitrate, and perchlorate are found in several test and water supply wells.

In 1998, a Hydrogeologic Workplan was prepared in response to New Mexico Environment Department concerns that effects of LANL activities on groundwater quality needed further characterization and that groundwater flow beneath the 111 km^2 (43 mi^2) area of LANL was not adequately understood. A major component of the Hydrogeologic Workplan is installation of up to 32 deep characterization wells in the regional aquifer. Since 1998, 21 new regional wells have been installed (Fig. 2).

The Workplan goals are to:

- Provide a refined understanding of the hydrogeologic framework at LANL, including recharge areas, hydrologic interconnections, flow paths, and flow rates, synthesized by modeling simulations;
- Collect information sufficient to design and implement a detection monitoring program that meets applicable requirements and/or to demonstrate that groundwater monitoring requirements can be waived; and
- Define areas of existing or potential groundwater contamination, and the potential pathways of contaminant transport from the surface to the regional aquifer, with predictions of directions and rates of movement and of risk based on modeling simulations.

Ongoing investigations to complete the Workplan collect stratigraphic, lithologic and geophysical data; identify and characterize perched water zones; collect water quality and water-level data; collect moisture and contaminant profiles through the vadose zone;

perform in-situ hydrologic tests in wells; and characterize the mineralogy and geochemistry of key hydrogeologic units. In addition, groundwater is collected from installed wells on a quarterly basis to determine spatial and temporal variations in water quality across the plateau.

This paper describes the geologic framework of groundwater systems beneath the Pajarito Plateau, and it provides a hydrogeologic framework for discussions by other papers in this special volume. The physical and geologic setting of the plateau are described, and the influence of geology on hydrology is discussed. Information about the regional setting is summarized from literature sources and from site-specific information based on Hydrogeologic Workplan investigations conducted over the past six years. These data support refinement of the hydrogeologic conceptual model, and they provide a framework for the site-wide geologic model, geochemical models, and numerical flow and transport models.

Regional Geographic Setting

The Pajarito Plateau lies at the volcanically and seismically active boundary between the Colorado Plateau and the Rio Grande rift (Fig. 3). The Southern Rocky Mountains extend into the area from the north as two prongs that terminate a short distance to the south of the study area (Griggs, 1964). The eastern prong consists of the Sangre de Cristo Mountains, which contain the highest peaks in New Mexico (e.g. 3994 m [13,102 ft] at Truchas Peak). The western prong consists of discontinuous uplifts that include the Sierra Nacimiento with elevations of up to 3125 m (10,251 ft). The faulted west face of the Sierra Nacimiento marks the eastern boundary of the Colorado Plateau. The Sangre de Cristo and Sierra Nacimiento ranges are separated by the Española basin, a structural component of the Rio Grande rift of the Basin and Range province.

The Rio Grande rift is a major geologic feature of the Rocky Mountain region that consists of north-trending, fault–bounded basins extending from central Colorado to northern Mexico. The local area of subsidence, termed the Española basin of the Rio Grande rift, is a graben between two larger basins—the Albuquerque basin to the south and San Luis basin to the north (Kelley, 1978). The Española basin is about 70 km (44 mi) long and 60 km (37 mi) wide.

The Jemez Mountains are a circular volcanic field 72 km (45 mi) in diameter that overlaps and covers the boundary between the Sierra Nacimiento and the Española basin. The Jemez Mountains are made up of a central mountainous mass containing the central bowl-like depression of the Valles caldera which is 24 km (15 mi) in diameter. The elevation of the caldera floor is about 2591 m (8500 ft). The Sierra de los Valles is the arc of mountains that make up the east side of the Jemez Mountains. These mountains, which lie between the Valles caldera and the Pajarito Plateau, include a number of peaks over 3048 m (10,000 ft) in elevation. Water table maps indicate that the Sierra de los Valles is an important recharge area for the Pajarito Plateau groundwater system (Purtymun, 1984). Aprons of silicic tuff form plateaus, including the Pajarito Plateau, that dip away from the central volcanic highlands.

The Pajarito Plateau is an east-sloping tableland bounded on the west by the eastern Jemez Mountains (Sierra de los Valles) and on the east by the Rio Grande (Figs. 1 and 2). The plateau is deeply-dissected, and it consists of numerous fingerlike mesas separated by deep canyons containing east- to southeast-trending ephemeral and intermittent streams. Mesa top elevations range from approximately 2377 m (7,800 ft) on the flanks of the Jemez Mountains to about 1890 m (6,200 ft) at their eastern termination above the Española valley. The eastern margin of the plateau stands 91 to 305 m (300 to 1000 ft) above White Rock Canyon, a 23-km (14-mi) long gorge cut by the Rio Grande that separates the Pajarito Plateau from the Cerros del Rio volcanic field (Fig. 1). Elevations along the Rio Grande range from 1676 m (5500 ft) at Otowi to 1634 m (5360 ft) at the mouth of Frijoles Canyon 18.5 km (11.5 mi) downstream (Fig. 2).

The crest of the Sierra de los Valles forms the surface-water divide for the Pajarito Plateau area. Streams on the east slopes of the Sierra de los Valles and on the Pajarito Plateau flow eastward to the Rio Grande, the master drainage for the region. Streams west of the divide flow west through the Valles caldera via the Jemez River which flows into the Rio Grande south of the Jemez Mountains. The Rito de los Frijoles, located south of LANL, is the only perennial stream on the Pajarito Plateau that flows into the Rio Grande. Other streams on the plateau support short reaches of perennial flow fed by springs or by releases of treated municipal and industrial waste water. Within these reaches surface water travel down canyon for short distances before infiltrating the channel beds. Ephemeral and intermittent flow occurs in canyons due to snowmelt and to runoff from rain. Runoff from large snowmelt or precipitation events occasionally flows into the Rio Grande.

Los Alamos has a semiarid, temperate mountain climate. The annual precipitation ranges from about 14 in (35.6 cm) on the east side of the plateau to about 18 in (45.7 cm) on the west side (Bowen, 1990). Forty percent of the annual precipitation normally occurs from thundershowers during July and August. Winter precipitation falls primarily as snow, with accumulations of about 130 cm (51 in) annually. Winter temperatures typically range from about –9 to –4°C (15°F to 25°F) during the night and from –1 to 10°C (30°F to 50°F) during the day (Bowen, 1990). Occasionally, temperatures drop to –18°C (0°F) or below. Summers are generally sunny, with moderate, warm days and cool nights. Maximum daily temperatures are usually below 32°C (90°F). Brief afternoon and evening thundershowers are common, especially in July and August. High altitude, light winds, clear skies, and dry atmosphere allow night temperatures to drop to between 10 and 16°C (50 and 60°F) after even the warmest day.

Regional Geologic Framework

The geology of the Pajarito Plateau reflects the contemporaneous nature of volcanism, tectonism, and sedimentation near the western margin of the Española basin from the Miocene through the Quaternary. Bandelier Tuff makes up the surface deposits of the plateau at LANL and gives the area its distinctive tableland appearance. The Bandelier Tuff overlies a diverse assemblage of Miocene and Pliocene sedimentary and volcanic rocks with complex, interfingering relations. Shifting foci of tectonism and volcanism over time strongly affected the distribution and thicknesses of these subsurface units.

Structural Setting

The Española basin is superimposed on an eroded terrane of Cretaceous-Eocene uplifts and basins that extended into the area from the north (Baltz, 1978). These uplifts, including the present-day Sangre de Cristo Mountains and Sierra Nacimiento, were modified and re-activated to their current high elevations by late Cenozoic tectonism associated with the Rio Grande rift.

Structural development of the Española basin was similar to other basins in the Rio Grande rift (Chapin, 1979, Baldridge et al., 1980 and 1984, Seager et al., 1984). Initial subsidence began over a broad area and resulted in a shallow basin filled with Oligocene through early Miocene sedimentary deposits of the Santa Fe Group. Early rift deposits, exposed in outcrops west of the Valles caldera and penetrated by deep boreholes within the caldera, indicate the early basin was wider than the faulted boundaries of the present basin. From middle to late Miocene until early Pliocene, the Española basin developed into a west-tilted, half graben (Kelley, 1952 and 1978) that filled with additional Santa Fe Group sediments derived from highlands located primarily to the north and east (Galusha and Blick, 1971; Cavazza, 1989; Ingersoll et al, 1990). The thickness of these basin-fill deposits beneath the Pajarito Plateau is poorly known but may be as much as 2700 m (~9000 ft) (Kelly, 1978). A prominent, northeast-trending gravity low beneath the Pajarito Plateau was interpreted as a sediment-filled graben within the western part of the Española basin (Ferguson et al., 1995).

Through much of the Pliocene until the early Quaternary, Santa Fe Group beds within the Española basin were tilted westward and broken by north-trending normal faults (Galusha and Blick, 1971, Kelley, 1978). Basin-fill sediments were deeply eroded during this time although alluvial fan deposits continued to accumulate adjacent to highlands such as the Jemez Mountains. Late Pliocene to early Pleistocene pedimentation resulted in a broad, flat valley floor spotted with numerous volcanoes in the Cerros del Rio area (Kelley, 1978). The present-day youthful badlands topography was brought about by incision of drainages caused by Pleistocene uplift of the Española basin relative to the Albuquerque basin to the south (Kelley, 1978).

For most of their development, basins of the Rio Grande rift were closed hydrologic systems. These isolated basins became integrated into regional drainage system by a through-flowing perennial river, the ancestral Rio Grande, prior to 7 Ma (Smith et al., 2001). The ancestral Rio Grande became the master drainage for the region, linking the Española basin with the San Luis basin to the north and the Albuquerque basin to the south. Since establishment of the Rio Grande as the master drainage system for the region, as much as 30% of the original basin-fill deposits have been removed from the Española basin (Galusha and Blick, 1971, Kelley, 1978).

The eastern border of the Española basin is the Sangre de Cristo uplift (Fig. 3). In the vicinity of the Pajarito Plateau, the western structural margin of the Española basin is largely covered by rocks of the Jemez volcanic field. From 13 to 7 Ma the western margin of the Española basin coincided with the Cañada de Cochiti fault zone (CCF2, Fig. 3), a broad zone of north-trending faults with over 500 m (1640 ft) of down-to-the-

east displacement in the south-central part of the volcanic field (Gardner and Goff, 1984). The Cañada de Cochiti fault zone became inactive sometime prior to about 6 Ma. The present active boundary of the Española basin is the Pajarito fault zone, a narrow band of north- and northeast-trending normal faults that occur along the western margin of the Pajarito Plateau (Fig. 3) (Griggs, 1964, Smith et al., 1970, Gardner and Goff, 1984). Displacement along the Pajarito fault zone is dominantly down to the east with episodic faulting indicated by progressively larger offsets in older rock units (Griggs, 1964). Golombek (1983) and Gardner and Goff (1984) suggest that the Pajarito fault zone became active about 4 to 5 Ma.

The Pajarito fault zone and its associated structures are the most prominent tectonic features of the study area (RCF and GMF, Fig. 4). The fault, which forms a 122-m (400-ft) high escarpment on the western margin of the plateau, has the surface expression of a large, north-trending, faulted monocline (Gardner et al., 1999, 2001). Along strike the fault varies from a simple normal fault to broad zones of small faults, faulted monoclines, and unfaulted monoclines. These varied styles of deformation are all considered expressions of deep-seated normal faulting (Gardner et al., 1999). The amount of fault displacement for older rock units is not known because critical relations are covered by thick deposits of Bandelier Tuff. Stratigraphic separation on the Tshirege Member of the Bandelier Tuff (1.22 Ma) ranges between 80 and 120 m (260 to 400 ft) along the segment of the fault west of LANL (Gardner et al., 1999). Continuing displacement along this fault system is reflected by Holocene movement and historic seismicity (Gardner and House, 1987; Gardner et al., 1990).

Other major faults on the Pajarito Plateau include the Rendija Canyon and Guaje Mountain faults (Fig. 4). The Rendija Canyon fault, located in the northern part of the plateau, is a north-trending normal fault with down-to-the-west displacement. The Diamond Drive graben (DDG, Fig. 4), formed by displacement of the Bandelier Tuff, is bounded by the main trace of the Pajarito fault on the west and the Rendija Canyon fault on the east (Gardner et al., 1999). The Rendija Canyon fault dies out as a simple normal fault on the north side of LANL. Southward across LANL it is replaced by a broad arc of small-displacement faults that trend in a southwesterly direction towards the main trace of the Pajarito fault (Fig. 4) (Gardner et al., 1999, 2001). The Guaje Mountain fault lies east of and is generally parallel to the Rendija Canyon fault (Fig. 4). It is also a north-trending normal fault with down-to-the-west displacement. Surface traces of the Guaje Mountain fault die out north of LANL.

Volcanic Setting

Jemez Volcanic Field

Volcanism over the last 13 Ma built up the highlands area of the Jemez Mountains, while contemporaneous tectonic rifting resulted in subsidence of the area extending from the eastern side of the Sierra Nacimiento to the western margin of the Sangre de Cristo Mountains. During this interplay of volcanism and rifting, the volcanic highlands were a source of Miocene and Pliocene volcaniclastic sediments that were deposited as alluvial

fans in the rifted lowlands. To the east these alluvial fan deposits interfinger with basin-fill sediments derived predominantly from Precambrian sources to the east and north.

The Jemez volcanic field began to develop ~13 to 10 Ma with the eruption of predominantly basaltic and rhyolitic rocks of the Keres Group (Gardner et al., 1986). The stratigraphy of the volcanic field is shown schematically in Fig. 5. Basalts of Chamisa Mesa, which are one of the oldest units in the field, are interbedded with Santa Fe Group basin-fill gravels in the southern part of the Jemez Mountains. The Canovas Canyon Rhyolite of the Keres Group consists of rhyolite domes and their associated pyroclastic deposits that were erupted from vents aligned along faults of the Cañada de Cochiti fault zone. From 10 to 7 Ma, 1000 km^3 (240 mi^3) of andesite and subordinate basalt and rhyodacite were erupted as part of the Paliza Canyon Formation (Gardner and Goff, 1984, Gardner et al., 1986). High-silica rhyolite plugs, domes, and tuffs of the Bearhead Rhyolite, including thick tuffaceous deposits of the Peralta Canyon Member, were erupted ~6.15 to 7.06 Ma (Smith, 2001) along faults of the Cañada de Cochiti fault zone. The period from 6 to 7 Ma also coincided with a transition to predominantly dacitic volcanism throughout the volcanic field (Gardner et al., 1986). Dacitic lavas of the Tschicoma Formation of the Polvedera Group were erupted from large, overlapping dome complexes typified by the extensive exposures of this formation in the highlands of the Sierra de los Valles.

Activity in the volcanic field reached a climax with eruption of the Bandelier Tuff (Griggs, 1964; Smith and Bailey, 1966; Bailey et al., 1969; Smith et al., 1970). The Bandelier Tuff has two members, each consisting of a basal pumice fall overlain by a petrologically related succession of ash-flow tuffs (Bailey et al., 1969). Eruption of the two members was accompanied in each case by caldera collapse. The Otowi Member (1.61 Ma; Izett and Obradovich, 1994 and Spell et al., 1996) was erupted from the earlier of the two calderas. This early caldera was coincident with and was largely destroyed by the younger Valles caldera that formed during the eruption of the Tshirege Member (1.22 Ma; Izett and Obradovich, 1994; Spell et al., 1990 and 1996). About 300 km^3 (72 mi^3) of high-silica rhyolite magma was erupted for each of the two Bandelier Tuff members. Deposits of Bandelier Tuff are distributed as a radial belt of flat-topped tuff plateaus that dip away from the central volcanic highlands. The Pajarito Plateau at LANL is made up of Bandelier Tuff that flowed more than 21 km (13 mi) eastward across the western Española basin.

An interval of about 400,000 years separated eruption of the two Bandelier members. During this interval, domes of Cerro Toledo Rhyolite were emplaced northeast and southeast of the Otowi caldera. Tephras from these domes were deposited as ash and pumice falls over the Sierra de los Valles and Pajarito Plateau. Reworking of these tephras resulted in deposition of tuffaceous sediments over broad areas of the Pajarito Plateau.

Post-Valles caldera volcanic vents were restricted to the floor of the Valles caldera. Rhyolitic domes, lava flows, and tuffs of the Valles Rhyolite erupted from >1.133 Ma (Spell and Harrison, 1993) until about 50 to 60 Ka (Toyoda et al., 1995, Reneau et al., 1996). Valles Rhyolite pumice falls and their reworked equivalents were deposited across

large parts of the Pajarito Plateau. These deposits were largely removed by stream incision across the plateau, but erosional remnants are locally present on mesa tops.

Cerros del Rio Volcanic Field

The Cerros del Rio volcanic field forms a hilly basalt plateau on the east side of the Rio Grande (Fig. 1). The volcanic field extends 42 km (26 mi) from La Bajada Hill on the south to Los Alamos Canyon on the north. Black Mesa, located 5.6 km (3.5 mi) north of Los Alamos Canyon, is an erosional outlier of this volcanic field (WoldeGabriel et al, 2001). The main part of the volcanic field is 6.4 to 8 km (4 to 5 mi) wide in its southern part and 12.9 to 19.3 km (8 to 12 mi) wide in its central and northern parts. The surface of the plateau ranges in elevation from 1829 to 2254 m (6000 to 7396 ft). The exposed portion of the volcanic field is made up of about a dozen volcanoes and >70 vents of cinder cones, plugs, and tuff rings (Kelley, 1978). Basalts and their differentiates are the predominant rock types, and most were erupted between 2.3 and 2.8 Ma (WoldeGabriel et al, 1996, 2001). The Rio Grande cuts a south-southwesterly course through the northwestern part of the basalt plateau, forming the 305-m (1000-ft) deep, 1.1- to 2-km (0.7- to 1.25-mi) wide White Rock Canyon. The Cerros del Rio volcanic field extends 11.3 km (7 mi) west of the Rio Grande, beneath the central portion of the Pajarito Plateau where it is covered by Bandelier Tuff.

Stratigraphy of the Pajarito Plateau

A generalized diagram showing the stratigraphic sequence of rock units of the Pajarito Plateau is shown in Fig. 6. Rock units are described below from oldest to youngest. An east-west interpretive cross section across the plateau is shown in Fig. 7. A geological map published by Smith et al., (1970) shows the distribution of these bedrock units across the Pajarito Plateau. Other general geological maps covering the area are those by Griggs (1964), Kelley (1978), Goff et al. (1990), Kimpter and Kelley (2002), and Dethier (1997, 2003). More detailed geological maps covering portions of the LANL include those by Baltz et al. (1963), Rogers (1995), Vaniman and Wohletz (1990), Reneau et al. (1995), Goff (1995), Goff et al., 2002, Lewis et al., 2002, and Lavine et al., 2003.

Santa Fe Group

Rocks of the Santa Fe Group crop out along lower Los Alamos and Guaje Canyons and in White Rock Canyon. Spiegel and Baldwin (1963) subdivided the Santa Fe Group into formations and Galusha and Blick (1971) further subdivided the Tesuque Formation of the Santa Fe Group into members based on geologic mapping and fossil assemblages of late Tertiary mammals. In the vicinity of the Pajarito Plateau, the stratigraphy and geochronology of the Santa Fe Group is poorly understood because near-continuous deposits of Bandelier Tuff cover pre-Bandelier rock units. Based on exposures near the Rio Grande, the Santa Fe Group beneath the Pajarito Plateau is believed to include, in ascending order, the Tesuque Formation and the Chamita Formation. The total thicknesses of the Santa Fe Group in the eastern and northern part of the Española Basin is as much as 1463 m (4800 ft) (Galusha and Blick, 1971). Cross sections by Kelly (1978) show up to 2743 m (9000 ft) of Santa Fe Group deposits in the central and

western parts of the Española basin.

Tesuque Formation

The Miocene Tesuque Formation was penetrated by deep wells in the eastern part of the Pajarito Plateau and is the most important aquifer throughout the Española basin (Purtymun, 1995). It is primarily made up of thick fluvial deposits consisting of partly lithified sediments derived from Precambrian granite, pegmatite, and sparse sedimentary rocks of the Sangre de Cristo Range and from Tertiary intermediate to felsic volcanic rocks from southern Colorado (Cavazza, 1989, Dethier, 2003). Individual beds are generally less than 3 m (10 ft) thick and consist of massive to planar- and cross-bedded light pink-to-buff siltstone, sandstone, lacustrine sediments, and subordinate lenses of pebbly conglomerate (Fig. 8). The age of the Tesuque Formation ranges from about 7 to 21 Ma (Manley, 1979; Cavazza, 1989). In well PM-5, a 110-m (360-ft) thick series of basalt flows within the upper part of the Tesuque Formation yielded an Ar/Ar date of 11.39 Ma (WoldeGabriel et al., 2001). Macintosh and Quade (1995) report an Ar/Ar age of 15.45 Ma for the Skull Ridge Member of the Tesuque Formation near Pojoaque.

Chamita Formation

The Chamita Formation overlies and interfingers with the Tesuque Formation (Galusha and Blick, 1971). It consists of arkosic siltstones, sandstones, pebbly conglomerate, and includes prominent beds of white ash. This formation is thickest in the northern part of the Española basin; because of early Pliocene erosion linked to incision of the ancestral Rio Grande it thins to less than 9.1 m (30 ft) or is absent under most of LANL. Tephras dated by McIntosh and Quade (1995) yielded an age of about 6.75 to 7.67 Ma for the middle and lower parts of the formation, respectively.

Older fanglomerate unit

In this paper, we use the informal term "older fanglomerate unit" to describe a thick sequence of late Miocene fan deposits that were shed from the Jemez volcanic field into the western Española basin. These deposits, which are found only in deep boreholes, are important for the development of high-yield, low-draw-down municipal and industrial water supply wells on the Pajarito Plateau (Purtymun, 1995). Based on the results of a dynamic spinner log at supply well PM-4, the older fanglomerates are among the most productive rocks in the regional aquifer (Koch et al., 1999).

These deposits were called the "Chaquehui Formation" by Purtymun (1995) who assigned them a post-Chamita and pre-Puye age. As originally defined for a type section in Chaquehui Canyon, the Chaquehui Formation consist of up to 457 m (1500 ft) of gravels, cobbles, and boulders derived from the Jemez volcanic field and volcanic, metamorphic, and sedimentary rocks derived from highlands to the north and east (Purtymun, 1995). However, recent stratigraphic studies indicate the type section consists of late Pliocene phreatomagmatic deposits that do not correlate with the Miocene deposits identified as Chaquehui Formation in deep wells (WoldeGabriel et al., 2001). Apparently the Miocene deposits are present only in the subsurface in this area. Given their uncertain

stratigraphic status, we prefer use of the informal term older fanglomerate unit when referring to these deposits until additional dating of intercalated tephras and lavas can better establish their relation to other rocks in the region.

Characterization wells recently installed on the Pajarito Plateau indicate the older fanglomerate unit is generally similar to but older than the Puye Formation. The older fanglomerate is mostly made up of proximal and relatively unaltered volcanic detritus derived from the Jemez volcanic field. These Miocene sediments are characterized by abundant rhyolitic pumice and ash interspersed with crystalline dacitic detritus. Ar/Ar ages of 7.2 Ma and 7.5 Ma (WoldeGabriel, personal communication) obtained on silicic pumice separates from these pumiceous deposits suggest a source region made up of Keres Group rocks. Basalt flows intercalated with the older fanglomertes have Ar/Ar ages of 8.4 to 9.3 Ma (WoldeGabriel et al., 2001). Upper older fanglomerate deposits probably interfinger eastward with the lower Chamita Formation and may be temporally equivalent to the Cochiti Formation deposits found in the southeast part of the Jemez volcanic field. These older fanglomerates indicate that Miocene Keres-Group volcanoes were sources of volcaniclastic deposits beneath LANL similar to the thick Puye deposits that were later produced from Tschicoma volcanic sources. The age break between older fanglomerates and Puye deposits is placed at about ~5.3 Ma based on Ar/Ar ages the oldest dated Tschicoma rocks in the Sierra de los Valles (WoldeGabriel, 2002, personal communication).

The older fanglomerates form a trough that extends 11.3 to 12.9 km (7 to 8 mi) from the northeast to the southwest across the central plateau (Purtymun, 1995). The stratigraphic differences encountered in the Miocene deposits across the plateau indicate that the eastern boundary of this trough may be very sharp. The western boundary of the trough is poorly defined, but recent drilling suggests that these rocks extend at least as far west as well R-25. An interpretive cross section (Fig. 7) shows this trough as fault-bound basin that is covered by younger Puye Formation and Cerros del Rio basalt. An alternative interpretation of the data is that older fanglomerate unit accumulated in a paleovalley incised into the Tesuque Formation.

Miocene basalts

Miocene basalts are intercalated with Santa Fe Group deposits in the east-central part of the Pajarito Plateau. WoldeGabriel et al. (1996, 2001) divided these basalts into two age groups based on Ar/Ar dates. The older group ranges in age from 10.9 to 13.1 Ma and is largely found in the vicinity of Guaje Canyon. The younger group ranges in age from 8.4 to 9.3 Ma and is found over a wide area that extends from Bayo Canyon on the north to Ancho Canyon on the south and from PM-1 on the east and PM-5 to the west (Fig. 2). Results for a dynamic spinner log in PM-4 suggest that these Miocene basalts are less productive than the sedimentary rocks making up the regional aquifer (Koch et al., 1999). These spinner log results are in general agreement with lithologic descriptions which indicate these basalts are altered, with much of the permeability associated with fracture and interflow-breccias plugged by secondary minerals.

Puye Formation

The Puye Formation is a large apron of overlapping alluvial and pyroclastic fans that were shed eastward from the Jemez volcanic field into the western Española basin (Griggs, 1964; Bailey et al., 1969). The Puye Formation unconformably overlies rocks of the Santa Fe Group west of and along the Rio Grande, and it is unconformably overlain by the Otowi Member of the Bandelier Tuff throughout the Pajarito Plateau. The Puye Formation is intersected by most deep wells on the Pajarito Plateau, and it crops out along White Rock Canyon, in lower Los Alamos Canyon, and in canyons to the north. Turbeville et al. (1989) estimated its areal distribution at 518 km^2 (200 mi^2) and its volume at ~15 km^3 (~3.6 mi^3). Because its primary source area was Tschicoma volcanic domes in the Sierra de los Valles, the Puye Formation overlaps and post-dates the Tschicoma Formation in age.

The Puye Formation is largely made up of conglomerates, gravels, and sands consisting of subangular to subrounded dacitic and andesitic lava clasts in a sandy matrix. At least 25 ash beds of dacitic to rhyolitic composition are interbedded with the conglomerates and gravels (Turbeville et al. 1989), and basaltic ash and lacustrine layers are present along the eastern margins of this formation. Because of its deposition as alluvial fans, the Puye Formation shows considerable vertical and lateral lithological variability. The formation reaches a maximum thickness of >333 m (>1093 ft) in R-25 on the western side of the Laboratory (Broxton et al., 2002a) but thins to 15 m (50 ft) in areas north of the Pajarito Plateau (Dethier and Manley 1985). In the central and eastern portions of the Laboratory, it is ~180 m (~600 ft) thick and is interbedded with basaltic lavas of the Cerros del Rio volcanic field. The Puye Formation is subdivided into an axial facies (called the "Totavi Lentil" by Griggs, 1964), a fanglomerate facies, and a lacustrine facies (generally equivalent to the "older alluvium" of Griggs).

The axial facies of the Puye Formation represent axial-channel deposits of the ancestral Rio Grande. The axial facies crops out at Totavi in Los Alamos Canyon and along the east side of the Pajarito Plateau (Griggs, 1964). It is generally ~15 m (~50 ft) thick near the Rio Grande but thickens in a northwest direction. An unusually thick sequence of axial facies rocks (>98 m [>323 ft]) was penetrated in well R-31 located in the southeast part of the Laboratory. These deposits consists of poorly consolidated sands and conglomerate containing well-rounded cobbles and gravels of Precambrian quartzite, granite, and pegmatite with subrounded to subangular cobbles and boulders of silicic to intermediate and rarer basaltic volcanic rocks (Fig. 9). The Precambrian clasts were derived from highland sources to the north and northeast of the Española basin. The source of the volcanic rocks was the northern part of the Jemez volcanic field.

The axial facies forms the oldest deposits in the Puye Formation in many areas, but it also interfingers with the lower part of the fanglomerate facies along the Rio Grande and in drill holes on the eastern side of the Pajarito Plateau. Based on its irregular distribution in deep wells, it is evident that the axial facies is not a continuous, sheet-like deposit at the base of the Puye Formation, as suggested by some earlier investigations. Instead, this facies appears to be comprised of discontinuous deposits of limited lateral extent that

represent the course of the ancestral Rio Grande at different points. The westernmost axial facies rocks occur in well H-19 on the western side of the plateau where a 3-m (10-ft) thick bed of quartzite pebbles is interbedded with Tschicoma lavas (Griggs, 1964). In general it appears that the course of the ancestral Rio Grande was displaced eastward over time by prograding Puye fans. The eastward migration of the Rio Grande was halted by the development of the Cerro del Rio volcanic field, which formed an area of elevated terrane to the east.

The fanglomerate facies is the dominant unit of the Puye Formation. It is widespread beneath the Pajarito Plateau and caps the prominent cliffs (Puye Escarpment) along the Rio Grande north of Otowi. It is interbedded with basaltic rocks of the Cerros del Rio volcanic field in the eastern and central part of the plateau. Fanglomerate is a general term meaning a rock unit composed of conglomerates, gravels, and sands deposited in an alluvial fan setting. The fanglomerate facies contains angular-to-subangular cobbles and boulders of latite, quartz latite, dacite, rhyolite, and tuff in a matrix of silts, clays, and sands (Fig. 10). Lenses of silt, clay, and dacitic pumice are common. Consolidated mudflow deposits are common throughout the unit, and tend to be cliff-forming units (Bailey et al., 1969). Primary and reworked pumiceous tuffs and lithic lapilli tuffs are also important components of the unit. These pumiceous deposits typically contain abundant unaltered volcanic glass, except in an area defined by wells R-5, R-8, R-9, and R-12 where most volcanic glass has altered to smectite. The fanglomerate facies also contains mixed deposits containing >85% dacitic detritus and trace to 15% quartzite and subordinate granite pebbles and gravels. The origin of nonvolcanic components in these fanglomerate deposits is not known with certainty, but may represent reworking of older Puye fan deposits that include older axial facies rocks.

The lacustrine facies includes lake and riverine deposits in the upper part of the Puye Formation. These deposits are characterized by lacustrine fine sand, silt, and clay up to 10 m (30 ft) thick. Basaltic ash beds (maar deposits) up to 3 m (10 ft) thick are locally present above or below the lacustrine deposits. The lacustrine facies includes some well-rounded riverine gravels of Precambrian quartzite and gneiss that fill channels cut into the fanglomerates. The lacustrine facies crops out in lower Los Alamos Canyon and extends both northward and southward in discontinuous outcrops for several miles. Apparently, it is of limited extent beneath the Pajarito Plateau, being found only in R-9, R-12, and R-16 near the eastern edge of the plateau.

Tschicoma Formation

The Tschicoma Formation of the Polvadera Group makes up the rugged Sierra de los Valles highlands west of Los Alamos. The Tschicoma Formation was encountered in wells TW-4, H-19, CDV-16-3(i) and CDV-R-37-2 in the western part of the Pajarito Plateau but is absent in boreholes to the east.

The Tschicoma Formation is made of numerous thick dacite to rhyodacite lava flows erupted from large overlapping dome complexes. Major peaks in the Sierra de los Valles, including Cerro Grande, Pajarito Mountain, Caballo Mountain, and Tschicoma Mountain,

are compositionally distinct domes that represent separate volcanic source areas. Fragmental deposits of ash and lava debris occur in the distal parts of the formation. The Tschicoma Formation has a variable thickness due to the lenticular shapes of its lava flows, and it is at least 762 m (2,500 ft) thick in the Sierra de los Valles. The Tschicoma Formation thins eastward under the western Pajarito Plateau where it interfingers with the Puye Formation.

Outcrops of the Tschicoma Formation in the Sierra de los Valles are primarily gray to purplish gray lavas that are characterized by pronounced jointing. The tops and bottoms of individual flow units are commonly marked by blocky breccia. Flow interiors are commonly devitrified to form a microcrystalline groundmass, giving the rocks a stony appearance. Chilled volcanic glass is sometimes preserved in flow tops and bottoms.

Dated rocks from the domes in the Sierra de los Valles range in age between 2.91 and 5.03 Ma (WoldeGabriel, 2001, personal communication). Turbeville et al. (1989) report an age of 2.53 Ma for a Tschicoma ignimbrite within the Puye Formation. In the northern part of the Jemez volcanic field, the Tschicoma Formation is bracketed in age by the underlying Lobato Basalt (7.4 Ma) and the overlying El Rechuelos Rhyolite (2.0 Ma) (Loeffler et al., 1988).

Basaltic Rocks of the Cerros del Rio Volcanic Field

Basaltic rocks of the Cerros del Rio volcanic field crop out primarily in White Rock Canyon and east of the Rio Grande (Griggs, 1964, Smith et al., 1970). In the subsurface, these basalts extend westward to the central part of the Pajarito Plateau (Broxton and Reneau, 1996). Cerros del Rio basalts interfinger with the Puye Formation west of the Rio Grande and overlie the Santa Fe Group in the Cerros del Rio east of the Rio Grande. Bandelier Tuff unconformably overlies the basalts near White Rock.

Cerros del Rio basalts typically form thick sequences of stacked lava flows separated by interflow breccia, scoria, sediment, and ash (Fig. 11). These rocks are mostly basalts and basaltic andesites, but subordinate dacite is present in the east and central plateau (e.g. Ball et al., 2002) or occurs as separate flows on the west side of the volcanic field. Cerros del Rio lavas were erupted from vents located east and west of the Rio Grande. On the Pajarito Plateau, the top of these basalts (Fig 12) formed a broad north-south trending highland that was buried by Bandelier Tuff (Broxton and Reneau, 1996). Cerros del Rio deposits are generally 61 to 183 m (200 to 600 ft) thick and reach a maximum thickness of 300 m (983 ft) at R-22 (Fig. 12). The thickest deposits generally coincide with a north-northeast-trending basin that is defined by structure contours at the base of the unit (Fig. 13).

Individual flows typically range in thickness from about a meter to more than 30 m (100 ft). The internal structure of flows is generally similar to that described by Swanson et al. (1979) and Whiteman et al. (1994) for the Columbia River Basalt Group in Washington, Oregon, and Idaho. In descending order, the flows typically are characterized by: 1) a flow top of vesicular basalt with scoria and clinker, 2) entablature, a complex zone of overlapping fan-shaped fractures, 3) colonnade, a zone made up of vertical, large-

diameter columns bound by cooling joints, and 4) a flow base, which is characterized by vesicular basalt with clinker and scoria (Fig. 14). The terms flow breccia and interflow zone are used to describe zones where a flow base directly overlies the flow top of an underlying flow. In the eastern part of the plateau, where the basalts interacted with surface water, flow bases commonly include porous pillow-palagonite complexes.

The basaltic rocks of the Cerros del Rio volcanic field include buried remnants of maar volcanoes in White Rock Canyon (Aubele, 1978; Heiken et al., 1989). The aprons of fragmental debris surrounding these buried craters consist of thin layers of basaltic ash and sediments. The maar deposits resulted from steam explosions that occurred where basalt erupted through an aquifer or standing body of water. Thin maar deposits were identified at the base of the Cerros del Rio basalt in R-9 and R-12.

Bandelier Tuff

The Bandelier Tuff consists of the Otowi and Tshirege Members, which are stratigraphically separated in many places by the tephra and volcaniclastic sediments of the Cerro Toledo interval (Fig. 5). The Bandelier Tuff was erupted from the Valles caldera complex between 1.61 and 1.22 Ma ago (Izett and Obradovich, 1994; Spell et al., 1996). Griggs (1964), Smith and Bailey (1966), Bailey et al. (1969), and Smith et al. (1970) summarize the nature and extent of the Bandelier Tuff.

Otowi Member

The Otowi Member crops out in several canyons but is best exposed in Los Alamos Canyon and in canyons to the north. It consists of moderately consolidated, porous, and nonwelded vitric ash-flow tuffs (ignimbrite) that form gentle, colluvium-covered slopes along the base of canyon walls (Fig. 15). The Otowi ignimbrites contain light gray-to-orange pumice supported in a white to tan ashy matrix of glass shards, broken pumice, crystals, and rock fragments (Broxton et al. 1995a; Goff, 1995). The Otowi Member is made up of multiple ash flows, but individual ash-flow deposits can not be traced in the subsurface using core and cuttings from widely-spaced boreholes. In some drill holes, a shift in borehole gamma measurements in the central part of the unit provides a useful datum for correlations between drill holes. The nonwelded ash-flow tuffs of the Otowi Member collectively form a relatively homogenous rock unit throughout the plateau.

The Otowi Member was probably deposited throughout the Pajarito Plateau as an eastward-thinning wedge of tuffs. However, 400,000 years of subsequent pre-Tshirege erosion removed a significant thickness of the Otowi Member in some areas. The present maximum thickness of Otowi Member occurs in two lobes in the western part of the plateau where the deposits are about 107 to 122 m (350 to 400 ft) thick (Fig. 16). The two lobes are separated by deposits only <30 to 91 m (<100 to 300 ft) thick. These thin Otowi deposits underlie unusually thick Cerro Toledo deposits (Fig. 17). The Cerro Toledo deposits apparently accumulated in a broad east-southeast-trending drainage incised into the top of the Otowi Member. On the eastern side of the plateau, the Otowi Member is 0 to 30 m (100 ft) thick. Thinning of the deposits eastward reflects both the general

thinning of the Otowi Member away from its caldera source and thinning of the ash-flow tuffs over the Cerros del Rio highland on the east side of the plateau. Structure contours indicate that Otowi ash-flow tuffs filled a broad north-trending paleovalley west of the Cerros del Rio basaltic highland (Fig. 16).

The Guaje Pumice Bed occurs at the base of the Otowi Member as a significant and extensive marker horizon in outcrop and coreholes (Fig. 15, bottom photograph). The Guaje Pumice Bed (Bailey et al., 1969; Self et al., 1986) contains layers of well-sorted pumice fragments whose mean size varies between 2.0 and 4.1 cm (0.8 and 1.6 in). It has an average thickness of ~8.5 m (~28 ft) over much of the plateau. Geophysical logs show that the Guaje Pumice Bed has a higher porosity than overlying Otowi ash-flow tuffs and underlying Puye deposits or Cerros del Rio lavas.

Tephra and Volcaniclastic Sediments of the Cerro Toledo Interval

The Cerro Toledo interval is an informal name given to a stratified sequence of volcaniclastic sediments and tephra of mixed provenance that separates the Otowi and Tshirege Members of the Bandelier Tuff on the Pajarito Plateau (Fig. 15, top and middle photographs) (Broxton et al., 1995a; Goff, 1995; Broxton and Reneau, 1995). Although it is intercalated between the two members of the Bandelier Tuff, the Cerro Toledo interval is not considered part of that formation, a usage consistent with the nomenclature for the Cerro Toledo Rhyolite (Bailey et al., 1969).

The Cerro Toledo interval unconformably overlies the Otowi Member in Los Alamos Canyon and in canyons to the north. The Cerro Toledo interval is also found in boreholes across the plateau, but its thickness is highly variable, ranging from several feet to 120 m (393 ft). Structure contours for the base of the Cerro Toledo indicate that this unit filled a broad southeast-trending paleovalley in the southwest part of LANL (Fig. 17). The thickest Cerro Toledo deposits coincide with the axis of this paleovalley.

The predominant rock types in the Cerro Toledo interval are rhyolitic tuffaceous sediments and tephra (Stix et al., 1988; Heiken et al., 1986; Broxton et al., 1995a; Goff 1995). The tuffaceous sediments, which contain crystal-poor ash and pumice, clasts of rhyolite lava, and obsidian, are the reworked equivalents of Cerro Toledo Rhyolite tephra that erupted from the Cerro Toledo and Rabbit Mountain dome complexes located in the Sierra de los Valles (Smith et al.,1970). Primary pumice-and ash-falls and their reworked equivalents occur in most locations. In some areas, Cerro Toledo sediments include reworked tuffs derived from the Otowi Member.

Clast-supported gravel, cobble, and boulder deposits made up of porphyritic dacite derived from the Tschicoma Formation are interbedded with the tuffaceous rocks. In some deposits, the dacitic detritus is volumetrically more important than the tuffaceous detritus. These coarse dacitic deposits commonly define the axial portions of paleochannels incised into the underlying Otowi Member.

The Cerro Toledo interval contains a large component of crystal-rich tuffaceous detritus in the western part of the plateau. These tuffaceous sediments represent reworked Otowi

tuff that accumulated in paleovalleys that were incised into the Otowi Member prior to emplacement of the Tshirege Member. These reworked Otowi deposits are interbedded with other volcaniclastic deposits derived from Cerro Toledo and Tschicoma sources.

Tshirege Member

The Tshirege Member is the upper member of the Bandelier Tuff and is the most widely exposed bedrock unit of the Pajarito Plateau (Griggs, 1964; Smith and Bailey, 1966; Bailey et al., 1969; Smith et al., 1970). Emplacement of this unit occurred during eruptions of the Valles caldera at 1.22 Ma (Izett and Obradovich, 1994; Spell et al., 1996). The Tshirege Member is a multiple-flow, ash-and-pumice sheet that forms the prominent cliffs throughout the Pajarito Plateau (Fig. 15). It also underlies canyon floors in all but the middle and lower reaches of Los Alamos Canyon and in canyons to the north. The Tshirege Member is generally over 61 m (200 ft) thick in the north-central part of the Laboratory and is over 183 m (600 ft) thick near the southern edge of the Laboratory at TA-49 (Broxton and Reneau, 1996).

The Tshirege Member differs from the Otowi Member most notably in its generally greater degree of welding compaction (Fig. 15). Time breaks between the successive emplacement of flow units caused the tuff to cool as several distinct cooling units. For this reason the Tshirege Member is a compound cooling unit, consisting of at least four cooling subunits that display variable physical properties vertically and horizontally (Smith and Bailey, 1966; Crowe et al., 1978, Broxton and Reneau, 1995). These variations in physical properties reflect zonal patterns of varying degrees of welding and glass crystallization that accompany welding (Smith 1960a, 1960b). The welding and crystallization zonation in the Tshirege Member produce vertical variations in properties such as density, porosity, hardness, composition, color, and surface weathering patterns. The degree of welding in each of the cooling units generally decreases from west to east, reflecting higher emplacement temperatures and thicker deposits closer to the Valles caldera.

The Tsankawi Pumice Bed forms the base of the Tshirege Member. Where exposed, it is commonly 51 to 76 cm (20 to 30 in) thick. This pumice-fall deposit contains moderately well sorted pumice lapilli (diameters reaching about 6.4 cm [2.5 in]) in a crystal-rich matrix. Several thin ash beds are interbedded with the pumice-fall deposits. Perched groundwater is generally not associated with the Tsankawi Pumice Bed.

Because the thick Tshirege deposits make up a significant portion of the upper vadose zone, brief descriptions are provided below for the major subunits of the member. These subunits form widespread mappable units across the Pajarito Plateau and represent tuffs with distinctive lithologic characteristics. A photograph of Tshirege Member subunits in the central part of the plateau is shown in Fig. 15.

Qbt 1g is the lowermost subunit of the thick ignimbrite sheet overlying the Tsankawi Pumice Bed. It consists of porous, nonwelded, and poorly sorted ash-flow tuffs. The "g" in this designation stands for "glass" because none of the glass in ash shards and pumices shows crystallization by devitrification or vapor phase alteration. This unit is poorly

indurated but nonetheless forms steep cliffs because of a resistant bench near the top of the unit that forms a harder, protective cap over the softer underlying tuffs (Fig. 15, top and middle photographs). A thin (10 to 25 cm [4 to 10 in]), pumice-poor, surge deposit is sometimes present at the base of this unit.

Qbt 1v forms alternating cliff-like and sloping outcrops composed of porous, nonwelded, but crystalline tuffs. The "v" stands for vapor-phase crystallization that together with crystallization of glass in shards and pumices (devitrification) transformed the rock matrix into microcrystalline aggregates of silica polymorphs and sanidine. The base of this unit is a thin, horizontal zone of preferential weathering that marks the abrupt transition from glassy tuffs below to crystallized tuffs above. This feature forms a widespread mappable marker horizon (locally called the vapor-phase notch) throughout the Pajarito Plateau. In some locations the vapor-phase notch grades laterally into a prominent bench developed on top of the glassy tuff (Fig. 15, top photograph). The lower part of Qbt 1v, which is designated Qbt 1vc, is a colonnade tuff that is orange brown, resistant to weathering, and has distinctive columnar cooling joints. The upper part of the unit, designated Qbt 1vu, consists of white, variably indurated, alternating cliff- and slope-forming tuffs. The tuffs of Qbt 1v are generally nonwelded and have an open, porous structure.

Qbt 2 forms a distinctive, medium brown, vertical cliff that stands out in marked contrast to the slope-forming, lighter colored tuffs above and below (Fig. 15, top photograph). A series of surge beds commonly mark its base in the eastern part of the Laboratory. In the central and western part of the Laboratory, the boundary between Qbt 2 and Qbt 1v is gradational and the distinction between the two units is somewhat arbitrary. Qbt 2 is typically the most strongly welded tuff in the Tshirege Member. Welding tends to increase upsection through the subunit. On the western side of the plateau, a partial cooling break occurs in the middle of the densely-welded portion of the unit. Qbt 2 is characterized by lower porosity and higher density relative to the other units of the Tshirege Member, and because of its brittle nature, it is typically more fractured. Vapor-phase crystallization of flattened shards and pumices is extensive in this subunit.

Qbt 3 is a nonwelded to partly welded, vapor-phase altered tuff that forms the caprock of mesas in the central part of the Pajarito Plateau (Fig. 15, top photograph). Its base consists of a purple gray, unconsolidated, porous, and crystal-rich nonwelded tuff that underlies a broad, gently sloping bench developed on top of strongly welded Qbt 2. This basal, nonwelded portion forms relatively soft outcrops that weather into low, rounded outcrops with a white color, which contrast with the partly-welded cliff-forming tuffs in the middle and upper portions of the subunit. Qbt 3 becomes moderately- to densely-welded in the western part of the plateau. In the extreme western part of the Laboratory, an additional subunit, Qbt 3t, is present above Qbt 3 (Gardner et al., 2001). Qbt 3t is a moderately- to densely-welded ash-flow tuff that has petrographic and geochemical characteristics that are transitional between Qbt 3 and Qbt 4.

Qbt 4 is a complex unit consisting of nonwelded to densely-welded ignimbrite. The lower part of the subunit is made up of nonwelded to partly-welded ash-flow tuffs characterized by small, sparse pumices and intercalated surge deposits. The upper part of the subunit

includes pumiceous, densely-welded ash-flow tuffs that cap mesas in the western part of the Laboratory. Devitrification and vapor-phase alteration are typical in this unit, but thin zones of vitric ignimbrite occur locally. The occurrence of Qbt 4 is limited to the western part of the Pajarito Plateau. Lewis et al. (2002) divide Qbt 4 into local subunits and provide detailed descriptions of this heterogeneous unit.

Relation Between Geologic and Hydrogeologic Frameworks

The complex geologic system of the Pajarito Plateau has been organized into more generalized hydrogeological units that form the framework for flow and transport numerical models. Hydrogeological units were subdivided based on lithological characteristics that are believed to reflect differences in hydrological properties. A comparison of geologic and hydrologic frameworks for the plateau region is provided in Fig. 6. Carey et al. (this volume) discuss how the 3-dimensional hydrogeologic model was developed for modeling the groundwater system. The hydrologic framework supports both vadose zone and regional aquifer modeling efforts. Definition of hydrogeological units is an iterative process, and further refinement of hydrogeological units is expected as additional hydrological measurements for rock units become available.

Units of the Bandelier Tuff occur almost exclusively in the vadose zone. The stratigraphic divisions of Tshirege subunits were retained for the hydrologic model because the subunits capture widespread stratification of rock properties imparted by variations in welding, fracturing, and post-emplacement alteration. Except for Qbt 4 and Qbt 3t, which occur only in the west, subunits of the Tshirege Member are aerially extensive and can be traced laterally over the entire plateau area.

Within the Tshirege Member alternating sequences of welded and nonwelded tuffs form distinctive cooling units with welded interiors separated by porous, poorly indurated, nonwelded tuffs. Because of their brittle nature, the welded portions of subunits Qbt 2, Qbt 3, Qbt 3t, and Qbt 4 are typically denser and more highly fractured than the nonwelded tuffs that separate them. Fractures originating in welded zones, which include both cooling joints and tectonic fractures, commonly die out in overlying and underlying nonwelded tuffs. Fracture-filling materials, including illuviated detritus from the surface, clay minerals, and carbonate, are common in near-surface fractures, but decrease with depth.

Subunit Qbt 3 is strongly welded in the western part of the plateau, but welding decreases significantly eastward towards the more distal part of the unit. Higher bulk densities and lower porosities characterize the strongly welded interior of this unit (Fig. 18). Qbt 2 is characterized by higher bulk densities and lower porosities than other subunits of the Tshirege Member (Fig. 18), and it is a prominent cliff-forming unit throughout the plateau. Qbt 2 is most strongly welded near its top, and welding generally decreases downsection. Density and porosity profiles indicate the presence of a partial cooling break in the center of Qbt 2 in the western part of the plateau, but this cooling break is absent towards the east. Subunit Qbt1vu, which underlies Qbt 2, is generally nonwelded to partly welded. In the eastern part the plateau, stratified surge beds up to 0.3m (1 ft)

thick mark the contact between Qbt 2 and Qbt 1v. Westward, however, surge beds are absent, and the contact between Qbt1vu and Qbt 2 is gradational (Fig. 18). Subunit Qbt1vc is a well-indurated, cliff-forming unit, but it is not strongly welded; it is also characterized by a well-developed system of columnar cooling joints. Qbt 1g is mineralogically unique in that it is the only part of the Tshirege Member where the original volcanic glass of ash and pumices is extensively preserved. Except for local deposits in Qbt 4, volcanic glass in other Tshirege subunits was transformed to silica minerals and alkali feldspars following emplacement. The hydrological effects of devitrification and vapor-phase crystallization are not completely understood, but these processes affect grain-size distributions and may affect the effective porosity of the tuffs. Qbt 1g is nonwelded and generally has uniform lithological characteristics throughout the plateau.

The hydrogeological unit Qct is equivalent to the Cerro Toledo interval. These highly-stratified, volcaniclastic deposits provide a sharp contrast to the massive ignimbrite deposits that characterize the two members of the Bandelier Tuff. Variations in grain size, sorting, and bedding thicknesses result in strong vertical anisotropy. Juxtaposition of beds with contrasting lithologic characteristics may provide favorable settings for perched groundwater and for its lateral diversion. Qct mostly occurs in the vadose zone throughout the plateau.

Hydrogeological units Qbo and Qbog are equivalent to the ash-flow tuffs and fall deposits of the Otowi Member and the Guaje Pumice Bed, respectively. Unlike the Tshirege Member, the ash-flow tuffs making up the Otowi Member are nonwelded throughout, and the original volcanic glass is unaffected by post-emplacement devitrification and vapor-phase crystallization. These characteristics result in more uniform lithological characteristics than the Tshirege Member. In the western part of the plateau, Qbo shows some variability in vertical density and porosity profiles (Fig. 18). Abrupt vertical changes in density and porosity probably reflect successive episodes of ash-flow tuff emplacement. Qbo is relatively uniform in the central and eastern parts of the plateau. Qbog is treated as a separate hydrogeological unit because of its strongly stratified nature and because it is better sorted than other Bandelier Tuff units. Both Qbof and Qbog generally occur in the vadose zone throughout the plateau.

Hydrogeological unit Tpf is largely equivalent to the fanglomerate and lacustrine facies of the Puye Formation. Tpf is an important component of both vadose zone and regional aquifer models. Rocks making up Tpf are a complex assemblage of stratified volcaniclastic sediments and tephras characterized by significant vertical and lateral heterogeneity. Vertical heterogeneity in hydrologic properties results from the stacking of sedimentary deposits with contrasting lithologic characteristics. Lateral heterogeneity is due to the limited lateral extent and cross-cutting relationships of fluvial deposits in an alluvial fan setting. Heterogeneity occurs at scales ranging from hand specimen to outcrop in extent, and it arises from a number of factors including but not limited to grain-size variations, sorting characteristics, variations in bedding thicknesses, and lateral continuity of individual beds.

Tpt represents the axial facies of the Puye Formation. These riverine deposits represent

channel deposits of the ancestral Rio Grande and include sand, gravel, and cobble beds that are generally better sorted and locally much thicker than those of Tpf in the eastern part of the plateau. Tpt tends to be a good producer of groundwater in water-supply wells on the Pajarito Plateau (Purtymun, 1995). For example, a spinner log for supply well PM-4 indicated that Tpt produces 18% of the water even though it accounts for only 2.5 % of the screen interval (Koch et al., 1999). Drillers commonly report high water production and flowing sands when drilling through this unit. Tpt represents discontinuous deposits of limited lateral extent that mark the course of the ancestral Rio Grande at different points in time.

Channel deposits of the ancestral Rio Grande are also an important source of groundwater in the Albuquerque basin (Hawley et al., 1995). Fluvial sands and gravels form a stacked sequence of braided river-channel deposits in a zone as much as 5 km (3 mi) wide beneath the eastern heights of Albuquerque. The channel deposits of the Albuquerque basin are temporally equivalent and lithologically similar to the axial facies rocks of the Española basin. However, ancestral Rio Grande deposits in the Albuquerque basin are generally much thicker (>300 m [>1000 ft]) than equivalent rocks in the Española basin (<100 m [<300 ft]).

Tppu represents pumice-rich deposits in the lower part of the Puye Formation. These deposits are similar to other fanglomerates of the Puye Formation but include a significantly higher percentage of reworked tuffaceous sediments and primary ash and pumice falls. Preliminary results from borehole hydrologic tests suggest that the hydraulic conductivity of Tppu is generally greater than the crystalline-rich detritus of Tpf (Stone and McLin, 2003). Tppu is differentiated from similar pumice-rich deposits (Tppl) that occur in the older fanglomerates. Tppu includes those pumice-rich deposits that overlie Tpt, and thus are contemporaneous with the Puye Formation. Tppl includes pumice-rich deposits that underlie Tpt or that are shown to be contemporaneous with the older fanglomerate through radiometric age dating of primary fall deposits or intercalated basalts. Bedding orientations for rocks beneath the water table were determined by oriented formation microimager (FMI) logs in open boreholes. FMI logs indicate that Tppu and Tppl primarily dip 5° to 15° towards the southwest and west.

Hydrogeological unit Tb4 is largely equivalent to the Cerros del Rio basalt, but includes fanglomerate and rarer lake deposits where the Puye Formation interfingers with the basalt. Tb4 hosts perched water at a number of locations in the central and eastern part of the plateau, and it forms the top of the regional aquifer in the southeast part of LANL. It is a heterogeneous unit containing stacked lava flows separated by breccia zones, cinder deposits, and interbedded sediments. The internal structure of individual flows contributes to the vertical and lateral variability of this unit. Studies of similar sequences of stacked basalt on the Columbia Plateau concluded that groundwater is most readily transmitted through the highly-interconnected pore space provided by the broken and scoriaceous rocks of the interflow breccia zones (Whiteman et al., 1994). The interflow breccias are separated by fractured, but more massive rocks of the entablature and colonnade. Rocks of the entablature and colonnade are typically denser and less porous than interflow breccias, and fractures control water movement. In the vadose zone,

vertical movement of water between interflow breccias is probably controlled by fractures of the entablature and colonnade.

Hydrogeological units Tt1, Tk, Tb1, and Tb2 are volcanic units primarily made up of stacked lavas flows. Tb2 is the most extensive of these units beneath the plateau. Tb1 and Tb2 consist of basalt flows and interbedded sedimentary rocks of the Santa Fe Group. Tt1 and Tk represent the intermediate to silicic lavas of the Tschicoma Formation and Keres Group, respectively. Tt1 and Tk are primarily located within the Jemez Mountains, but may be locally important near the western margin of the plateau.

Hydrogeological units Tf and Ts represent the lowermost sedimentary rocks of the regional aquifer. Until recently the pre-Puye stratigraphy was believed to consist of, in descending order, the Chaquehui, Chamita, and Tesuque Formations of the Santa Fe Group. However, collection of new borehole data and review of old borehole logs suggest that these stratigraphic assignments were inconsistently applied among earlier investigators and that the nomenclature required modification. Revisions to the stratigraphic nomenclature will be undertaken when on-going investigations are completed. In the meantime, pre-Puye deposits are simplified into two main hydrogeologic units in the 3-D geologic model: the older fanglomerates of Tf and the silts and sands of Ts. The older fanglomerates of Tf are generally similar to, but distinctly older than the Tpf fanglomerates based on radiometric ages from interbedded tephras and basalts. Tpt and/or Tppu commonly separate Tpf and Tf in boreholes. Ts is largely equivalent to the Tesuque Formation, but may include sandy deposits of the Chamita Formation. The contact between Tf and Ts was placed where lithologic logs indicate a transition from predominantly coarse-grained deposits (gravels and cobbles) above to predominately fine-grained deposits (silt and sand) down section. In R-16 (Fig. 2), FMI logs indicate that Ts beds generally dip westwards, but dip directions range from west-northwest to west-southwest. Dips angles generally range between 5° to 10° for the upper part of Ts in R-16 and 10° to 20° in the lower part of the borehole.

Basement rocks beneath the Santa Fe Group sediments are not penetrated by any of the wells on the Pajarito Plateau. Based on outcrops along the margins of the Española basin, pre-Santa Fe Group rocks are likely to include Oligocene Espinoza and Gallisteo Formations, Mesozoic and Paleozoic sedimentary rocks, and Precambrian metamorphic and granitic rocks. These pre-Miocene rocks are grouped together and treated as the basement confining layer in the 3-D geologic model.

Geologic Setting of Groundwater Occurrences

Groundwater of the Pajarito Plateau has three principal modes of occurrence: 1) groundwater in canyon-floor alluvium, 2) deep perched groundwater in bedrock units of the vadose zone, and 3) groundwater associated with the regional zone of saturation. These three modes of occurrence are shown conceptually in Fig. 19. Contaminant distributions in groundwater strongly suggest that the groundwater from the plateau alluvial systems are in communication with deep perched and regional groundwater to varying degrees.

Alluvial Groundwater

Alluvial groundwater occurs primarily in the large watersheds that head in the Sierra de los Valles and in smaller watersheds on the plateau that receive liquid discharges from LANL or municipal sources. Canyon bottom alluvium is a complex geologic unit consisting of fluvial sands, gravels, cobbles that interfinger laterally with colluvium derived from canyon walls. The fluvial deposits represent cross-cutting active and inactive channels and active and inactive floodplains. Canyons that head on the plateau contain detritus of Bandelier Tuff; canyons that head in the Sierra de los Valles also contain dacitic detritus derived from the Tschicoma Formation.

The thickness of alluvial deposits is variable across the plateau. In Pueblo Canyon alluvium is about 3.4 m (11 ft) thick on the west side of the plateau and about 5.5 m (18 ft) thick near the confluence with Los Alamos Canyon. Mortandad Canyon has 0.3 to 0.6 m (1 to 2 ft) of alluvium near its headwaters and more than 30 m (100 ft) of alluvium near the eastern LANL boundary. Where present, alluvial groundwater commonly occurs near the base of the alluvial sequence atop weathered Bandelier Tuff. However, perched water is also found above permeability barriers within thick sequences of stratified alluvial deposits.

The saturated thickness and lateral extent of alluvial groundwater is strongly affected by seasonal variations in snow-melt and in storm runoff. In Los Alamos Canyon, perennial alluvial groundwater extends from the Sierra de los Valles to about a mile east of the Pajarito fault zone, even in drought years. During the peak snow-melt months of April through early June, surface flow and alluvial groundwater commonly extends an additional 6.4 to 9.7 km (4 to 6 mi) down canyon. Storm runoff, particularly associated with monsoonal thunderstorms in July and August, is also an important source of recharge for alluvial groundwater systems.

Deep Perched Groundwater

Identification deep perched systems beneath the Pajarito Plateau comes mostly from direct observation of saturation in boreholes, borehole geophysics, or by the installation of wells or piezometers. Additional information is provided by surface-based electrical geophysics although these types of investigations are generally limited by their relatively shallow depths of investigation and poor vertical resolution. Identification of larger perched groundwater bodies in boreholes is generally reliable, but use of drilling fluids, which is necessary in most boreholes, may mask smaller or relatively unproductive zones. Defining the lateral extent of saturation is more problematical because of the costs associated with installing wells to such great depths. Despite these limitations, substantial new information has been gathered about deep perched zones on the plateau.

Table 1 lists 27 occurrences of deep perched groundwater detected in boreholes across the Pajarito Plateau. Perched groundwater is widely distributed across the northern and central part of the plateau (Fig. 20) with depth to water ranging from 36 to 272 m (118 to 894 ft). The principal occurrences of perched groundwater occur in 1) the large, relatively wet Los Alamos and Pueblo Canyon watersheds, 2) the smaller watersheds of Sandia and

Mortandad Canyons that receive significant volumes of treated effluent from LANL operations, and 3) in the Cañon de Valle area in the southwestern part of LANL. Perched water is most often found in Puye fanglomerates, the Cerros del Rio basalt, and in units of the Bandelier Tuff (Fig. 19). There are few reported occurrences of perched water in the southern part of LANL, but few deep boreholes are located there and additional perched zones are likely beneath the large wet watersheds of Pajarito and Water Canyons.

In the western part of Los Alamos Canyon, perched groundwater occurs at depths of 89 to 137 m (293 to 450 ft) in the Guaje Pumice Bed and in underlying Puye Formation fanglomerate. Saturated thicknesses for these occurrences range from about 6.7 (22 ft) in the west to about 1 m (3 ft) in the east. These groundwater occurrences may represent a related groundwater system because of their similar geologic and geographic settings, however, in one well, R-7 (Fig. 20), perched groundwater occurs in the underlying Puye Formation. The east-west extent of perched groundwater in the Guaje Pumice Bed is about 5.6 km (3.7 mi). Little is known about the extent of perched groundwater beneath the adjacent mesas, but a dry borehole extending to the Guaje Pumice Bed suggests that saturation does not extend beneath the mesa north of Los Alamos Canyon. The perched groundwater is free of LANL contamination in the central part of the canyon (e.g. well LAO(I)A-1.1, Fig. 20) but contained 3000 pCi/L tritium in 1995 at LADP-3 (Broxton et al, 1995b), the easternmost well penetrating this groundwater body. The movement of groundwater in the Guaje Pumice Bed may be controlled by paleotopography on top of the underlying Puye Formation. Structure contours indicate that the down-dip direction for the base of Guaje Pumice Bed beneath Los Alamos Canyon is towards the south and east (Fig. 16).

Eastward in Los Alamos Canyon, perched zones are generally thicker and occur at multiple depths. In well R-9 for example, three perched systems were encountered: 1) in the central part of the Cerros del Rio basalt, 2) in the basal part of the Cerros del Rio basalt, and 3) in pumice-rich deposits in the lower part of the Puye Formation. Saturated thicknesses for the top and bottom zones range from about 13.7 to 31.4 m (45 to 103 ft), and the middle zone was 2.1 m (7 ft) thick. The top and middle perched zones in R-9 are also present in well LAWS-1, located 396 m (1300 ft) to the east (Fig. 20), but their lateral extent is likely to be much greater. The occurrence of more extensive perched groundwater in the eastern part of Los Alamos Canyon may be due to enhanced infiltration where the canyon floor is underlain by Puye fanglomerate and Cerros del Rio basalt rather than by Bandelier Tuff. Tritium activities of 69 to 246 pCi/L for these perched groundwaters are elevated relative to the cosmogenic baseline of 1 pCi/L, suggesting that these zones contain a component of young water that postdates the advent of atmospheric nuclear testing 60 years ago (Longmire, 2002).

In Pueblo Canyon perched water was identified in four wells. At wells TW-2a and R-5, perched water occurs within fanglomerate of the Puye Formation and has a saturated thickness of >7 and about 11.3 m (>23 and about 37 ft), respectively. Depth to water is 33.5 m (110 ft) at TW-2a and about 115.8 m (380 ft) at R-5. These perched zones probably represent relatively small, unrelated water bodies because of their distance from one another (4 km [2.5 mi]), the lateral heterogeneity of Puye Formation deposits, and their varying depths beneath the canyon floor. Wells TW-1a and POI-4 encountered

perched water at depths of 36 to 48.8 m (118 to 160 ft), respectively, in Cerros del Rio basalt. The saturated thickness is >1m (>3 ft) at TW-1a and 6.4 m (>21 ft) at POI-4. Saturation is associated with interflow breccia and sediments in TW-1a and with fractured basalt at POI-4.

In Sandia and Mortandad Canyons deep perched water was found in two wells in each canyon. The water quality of these perched zones includes a component of treated waste-water effluent released to the canyons via outfalls (Longmire et al., 2001, Longmire, 2002; Broxton et al., 2002b). Depth to water is also similar, ranging from 129 to 183 m (424 to 601 ft) in Sandia Canyon and 150 to 197 m (493 to 646 ft) in Mortandad Canyon.

In Sandia Canyon, perched water in wells R-11 and R-12 is associated with the lower part of the Cerros del Rio basalt and extends into the underlying Puye Formation. The saturated thickness of this zone increases eastward towards well R-12. In R-12, perched groundwater was encountered from depths of 135 to 158 m (443 to 519 ft). Saturation occurs in the lower part of the Cerros del Rio basalt and extends downward into underlying riverine deposits of the lacustrine facies (Broxton et al., 2001a). The perched water in this zone may be confined because the borehole was dry until a depth of 135 m (443 ft) was reached, but the water level rose to a depth of 129 m (424 ft) once saturation was encountered. The apparent confining layer at the top of this zone is a massive basalt flow with few fractures. An alternative explanation for the observed rise in water level is that the groundwater is unconfined, but water-bearing interconnected fracture systems were not intersected by the borehole until a depth of 135 m (443 ft). The perching layer consists of clay- and silt-rich lacustrine deposits 5 m (16.5 ft) thick. The saturated thickness of this groundwater body is at least 23 m (75 ft), making it the thickest intermediate-depth perched groundwater body identified in the eastern Pajarito Plateau.

In Mortandad Canyon perched water was encountered in two boreholes. At well MCOBT-4.4, the top of perched groundwater zone occurs at a depth of about 150 m (493 ft), within pebble gravel made up of dacitic volcanic detritus in the Puye Formation. The saturated thickness of this zone is between 3 and 6 m (10 and 30 ft). The perching layer includes one or more of the following lithologies: 1) silty sands and gravels in the lower part the Puye sequence (153.3 to 157.6 m [503 to 517 ft]), 2) clay-rich brecciated rubble at the top of Cerros del Rio basalt (157.6 to 159.3 m [517 to 522.5 ft]), or 3) massive, unfractured interior of the uppermost Cerros del Rio flow (approximately 159.3 to 163.1 m [522.5 ft to 535 ft]). At well R-15, located 347 m (1140 ft) down canyon of MCOBT-4.4, perched water occurs within the lower part of a thick sequence of Cerros del Rio basalts. The depth to water is 197 m (646 ft) and saturation occurs in fractured lava flows. The saturated thickness is about 30 m (99 ft), and the perching horizon is clay-rich flow-base rubble or underlying silty basaltic sands. Because of their different geologic settings, the perched groundwater at MCOBT-4.4 and R-15 probably represent unrelated groundwater bodies of limited lateral extent. Other deep boreholes in Mortandad Canyon did not encounter perched groundwater. Based on the distribution of available boreholes, the lateral extent of individual perched groundwater bodies is probably less than 460 m (1500 ft).

Both perched water occurrences in Mortandad Canyon contain elevated tritium, nitrate, and perchlorate. The highest contaminant levels occur in MCOBT-4.4, which contains 14,750 pCi/L tritium, 12.5 mg/L nitrate plus nitrite (as N), and 179 ppb perchlorate (Longmire, 2002, personal communication). Since 1963, these contaminants were released to the canyon as liquid effluent by a waste treatment facility in the upper part of the canyon. The presence of contaminants in deep perched groundwater beneath Mortandad Canyon indicates that vertical transport through the vadose zone occurs on the timescale of decades.

A large area of complex perched groundwater occurrences is found in the region bounded by Cañon de Valle on the north and Water Canyon on the south in the southwest part of LANL. Five deep boreholes encountered significant zones of groundwater over a 2.6 km^2 (1 mi^2) area located just east of the Pajarito fault zone. These boreholes included R-25, R-26, CdV-16-1(i), CdV-16-2(i), and SHB-3 (Fig. 20). Depth to water in these perched zones range from about 183 m (600 ft) just east of the Pajarito fault to about 244 m (800 ft) 2.3 km (1.4 mi) farther east of the fault. Only wells R-25 and R-26 fully penetrate the perched water zones.

At R-26, a water-level measurement of 184 m (604 ft) was obtained when the borehole was 219 m (720 ft) deep. The borehole was eventually completed to a total depth of 454.3 m (1490.5 ft) with the regional water table occurring at a depth of approximately 291 m (954 ft). Borehole neutron, magnetic resonance, and induction logs indicate that high moisture contents occur in rocks below 175 m (575 ft), with perched water most likely at depths of 177 to 202 m (580 to 662 ft) and 238 to 252 m (780 to 827 ft). These perched zones occur within volcaniclastic sediments of the Cerro Toledo interval. Low-porosity sediments within the Cerro Toledo interval probably provide the perching horizons.

R-25, located 1524 m (5000 ft) east of R-26, has two distinct zones of saturation separated by 47 m (154 ft) of partially saturated rocks. The upper zone, which is interpreted as a perched zone, occurs between depths of about 217 to 345 m (711 to 1132 ft) within the Otowi Member and in the upper part of the Puye Formation. An interval of partial saturation occurs below the perched zone from 345 to 392 m (1132 to 1286 ft) depth. Partial saturation was defined by casing off the perched zone and drilling through alternating zones of dry and wet rocks by coring and air-rotary methods. From 392 m (1286 ft) to the total depth of 592 m (1942 ft), continuous saturation representing regional groundwater was encountered within Puye deposits. R-25 was constructed with 9 screens separated by packers using a Westbay sampling system. Hydraulic head measurements in isolated screens decrease with depth, indicating downward vertical gradients. Isotopic and water quality data suggest the upper and lower zones of saturation at R-25 represent separate groundwater systems (Longmire, 2003, personal communication).

A deep-sounding surface-based magnetotelluric survey conducted in the Cañon de Valle/Water Canyon area suggests that perched groundwater is discontinuous laterally, occurring instead as vertical, finger-like groundwater bodies. These geophysical interpretations are currently being tested by additional drilling.

Perched groundwater in the Cañon de Valle/Water Canyon area may be the result of focused recharge beneath canyons crossing the Pajarito fault zone. These canyons may act as line sources of recharge due to infiltration of surface and alluvial water. Welded tuffs in the vicinity of the fault are brittle and highly fractured. These fractures may provide pathways for deep infiltration in the near-surface environment. Elsewhere on the plateau fractures in welded tuffs of the Tshirege Member tend to die out at depth in underlying nonwelded tuffs and poorly consolidated volcaniclastic deposits. The porous nature of the nonwelded tuffs and the stratified nature of the volcaniclastic deposits probably facilitates the lateral spreading of groundwater in perched zones.

Regional Groundwater

Over 50 active and inactive water-supply and test wells intersect regional groundwater across the Pajarito Plateau. Depth to water is greatest at mesa-top locations in the western part of the plateau. At well CdV-R-15-3, for example, depth to water is 379.5 m (1245 ft). Water depths are shallower in the eastern part of the plateau. In Los Alamos Canyon near the Rio Grande, supply wells LA-1, -2, and -3 (Fig. 2) flowed at the surface when installed. Springs believed to discharge regional groundwater occur throughout White Rock Canyon. Well R-16, located near the rim of White Rock Canyon (Fig. 2), encountered regional groundwater at a depth of about 187.1 m (614 ft). The regional water table in R-16 is about 65 m (210 ft) higher than the Rio Grande, which is located one kilometer (0.6 mi) to the east.

Regional groundwater moves generally eastward across the plateau towards the Rio Grande (Purtymun, 1995). The Sierra de los Valles is a major source of recharge for the groundwater system. Water table maps, hydraulic gradients, permeability data, and groundwater velocities are discussed by Keating et al. (this volume).

The distribution of bedrock units at the top of regional saturation is shown in Fig. 21. Regional groundwater enters the Pajarito Plateau by underflow through the rocks that underlie the Sierra de los Valles (Griggs, 1964; Purtymun, 1984). This underflow is supplemented by recharge from drainages that cross the plateau (Kwickless et al., this volume). West of the Pajarito fault zone, dacitic Tschicoma lavas make up the surface geologic units. Geologic units that underlie the Tschicoma Formation are poorly constrained because of the lack of borehole data. Based on the tectonic and volcanic history of the region, it is likely that the Puye Formation, older fanglomerate, and Santa Fe Group sediments underlie Tschicoma lavas west of the Pajarito fault zone. In the western part of the plateau, the regional water table occurs within Tschicoma lava flows in the vicinity of Pueblo Canyon to the north and Water Canyon to the south. Down-dropped sequences of these lavas extend up to 3.2 km (2 mi) to the east of the Pajarito fault zone. Groundwater flow through dacite most likely occurs as fracture flow in lavas and porous matrix flow in interflow breccias and interbedded clastic deposits. West of the Pajarito fault zone, most of the significant groundwater flow may occur in the pre-Tschicoma sedimentary deposits of Tertiary age.

The Puye Formation forms the uppermost rock unit of the regional aquifer throughout much of the western and central part of the plateau (Fig. 21). The Puye Formation includes the relatively coarse-grained deposits of the fanglomerate facies as well as the riverine deposits of the axial facies. Older fanglomerates, older basalts, and Santa Fe Group sediments underlie the Puye Formation. Some of the most productive municipal supply wells on the plateau have well screens that span the lower part of the Puye Formation and the underlying older fanglomerates.

The top of regional saturation coincides with basalts in two areas. The most extensive area is located in the south-central part of the plateau where Cerros del Rio basalts straddle the water table. As much as 59.4 m (195 ft) of saturated basalt occurs at the top of the aquifer at well DT-10 and 88.4 m (290 ft) at R-22 (Fig. 21). A smaller region of basalts at the water table occurs in a north-trending zone extending from wells R-12 to R-5. These basalts are late Miocene in age and are interbedded with Santa Fe Group sediments. The northern and southern extent of this zone is poorly constrained.

The Tesuque Formation of the Santa Fe Group is the primary rock unit making up the regional aquifer throughout much of the eastern part of the plateau and in the city of Santa Fe's Buckman Well Field east of the Rio Grande (Fig. 2 and 21). Miocene basalts are interbedded with the siltstones and sandstones of the Tesuque Formation beneath parts of the plateau, but are apparently absent east of the Rio Grande. Most of the production from municipal supply wells in Guaje Canyon and in lower Los Alamos Canyon comes from the Tesuque Formation.

Conclusions

The hydrogeology of the Pajarito Plateau is typical of the Basin and Range region in which thick vadose zones and deep aquifer systems develop in rift sediments that fill arid to semiarid basins flanked by mountainous recharge areas. The plateau is located on the west side of the Española basin, a north-trending structural trough that is a major segment of the Rio Grande rift. The Española basin is a west-tilted half graben with the down-to-the-east displacement occurring along a system of master faults that migrated eastward over time. Subsidence of the Española basin began more than 21 Ma.

Rocks making up the Pajarito Plateau reflect changing patterns of tectonism, volcanism, and sedimentation within the Española basin over time. The early basin was a closed hydrologic system that accumulated thick deposits of Miocene fluvial and lacustrine sediments of the Santa Fe Group as the basin subsided. The Tesuque Formation is the primary rift deposit in the Pajarito Plateau area. The aquifer characteristics of these rocks are controlled by siltstones, silty sandstones, conglomerates and lacustrine beds that were derived primarily from distal Precambrian basement and Tertiary volcanic sources to the east and northeast.

About 10 Ma, the Jemez volcanic field became the primary source of sediments for the western part of the Española basin. Intermediate to felsic volcaniclastic sediments of the older fanglomerate unit accumulated as alluvial fan complexes that extended eastward and northeastward over the western Española basin. About 5 Ma, the Pajarito fault zone

became the active rift margin, and the Pajarito Plateau area became the focus of subsidence within the basin. About 5 to 3 Ma dacitic domes of the Tschicoma Formation formed in the Sierra de los Valles, and volcaniclastic sediments shed from this mountainous highland were deposited eastward as prograding alluvial fans over the actively subsiding basin. Axial riverine deposits are interbedded with the Puye Formation, indicating that the ancestral Rio Grande was established as a through-going river by this time. Together, the older fanglomerate unit and the fanglomerate and axial facies of the Puye Formation form a stacked sequence of relatively coarse-grained deposits that is the most productive part of the regional aquifer in the western part of the Española basin.

Basalts are interbedded with rift sediments in the Pajarito Plateau area. These basalts were erupted primarily during three episodes at approximately 13.1 to 10.9 Ma, 9.3 to 8.4 Ma, and 2.8 to 2.3 Ma. Basalts from the earlier two episodes are extensively altered and appear to be relatively poor producers of groundwater, although data are limited. The youngest basalts belong to the Cerros del Rio volcanic field occur mostly above the water table, but form the upper part of the regional aquifer in the south-central part of the plateau. These basalts are mostly fresh, and highly porous zones such as interflow breccias and interbedded sediments may be important groundwater pathways.

The vadose zone of the Pajarito Plateau ranges in thickness from several hundred feet on the east side of the plateau to more than 1200 feet on the west side. Perched groundwater is found in canyon-floor alluvium and in bedrock units at a number of widespread locations across the plateau. Conditions are most favorable for the formation of perched groundwater in drainages that support prolonged periods of surface water flow during periods of snow melt or rain water runoff. Generally the most favorable canyons for the formation of perched water are those whose headwaters extend into the highlands of the Sierra de los Valles. Perched water is also associated with smaller drainages that receive liquid effluent from sanitary and waste treatment facilities. Bedrock perched groundwater bodies are found in a variety of geologic settings but occur most commonly in the Cerros del Rio basalt, Puye Formation, and Bandelier Tuff. The bedrock occurrences of perched groundwater vary greatly in size across the plateau, but most appear to be relatively small. However, thick zones of perched groundwater bodies occur within Cerro Toledo, Otowi Member, and Puye deposits in the southwest part of LANL near Cañon de Valle. Thick zones of perched groundwater are also found within Cerros del Rio basalt in the eastern part of LANL in Los Alamos and Sandia Canyons. The presence of anthropogenic chemicals in deep perched and regional groundwater indicates that surface water on the plateau contributes to the recharge of these deep groundwater systems and that groundwater travel times along some pathways from the surface to deep groundwater systems occur on a time frame of decades.

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Tables

Table 1. Occurrences of Deep Perched Groundwater Beneath the Pajarito Plateau.

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Fig. 2 Location map of the central Pajarito Plateau. Shaded area is the Los Alamos National Laboratory. Also shown are the municipalities of Los Alamos and White Rock. East and southeast trending canyons are incised into the plateau. Water supply wells are shown as blue stars. Major water-supply well fields include the Los Alamos well field (LA-1 through LA-6), the Pajarito well field (PM-1 through PM-5), the Otowi well field (O-1 and O-4), the Guaje well field (GR-2 and additional wells located just north of this map), and the Buckman well field, which provides water to Santa Fe. Water supply wells LA-1 through LA-6 are no longer used for municipal water production. Characterization and monitoring wells installed to date as part of Hydrogeologic Workplan and Environmental Restoration investigations are shown as red dots. Pre-workplan test wells are shown as black dots.

Fig. 3 Map of the major tectonic features in northern New Mexico. Major fault systems are shown schematically with ball on downthrown side. VC is the Valles caldera complex, NFZ is the Nacimiento fault zone, CCFZ is the Cañada del Cochiti fault zone, and PFZ is the Pajarito fault zone. Figure is modified from Gardner and Goff (1984).

Fig. 4 Map showing main elements of the Pajarito fault zone in the west-central part of the Pajarito Plateau. Yellow-shaded area is the western part of Los Alamos National Laboratory. PFZ is the main trace of the Pajarito fault zone, RCF is the Rendija Canyon fault, GMF is the Guaje Mountain fault, and DDG is the Diamond Drive graben. Figure is modified from Gardner et al. (2001) and Lewis et al. (2002).

Fig. 5 Stratigraphic nomenclature for the main rock units of the Jemez volcanic field.

Fig. 6 Stratigraphic chart for the Pajarito Plateau with correlation of geologic framework with hydrogeologic framework.

Fig. 7 Interpretive east-west cross section showing stratigraphic relations for geologic units of the Pajarito Plateau. Line of section is shown in Fig. 1.

Fig. 8 The Tesuque Formation of the Santa Fe Group is the principal rock unit of the regional aquifer in the Española basin. The Tesuque Formation is typically made up of fluvial and lacustrine deposits of pink to buff siltstone and silty sand. Lenses of pebble conglomerate and clay are also present. Top photograph shows typical outcrop of stratified Tesuque deposits. Middle photograph is close up view of silts and silty sands that are the predominant rock types. The bottom photograph shows channels of pebble conglomerate interbedded with silty sands.

Fig. 9 Axial ancestral Rio Grande deposits interbedded with the lower part of fanglomerate deposits in the Puye Formation. Top photograph shows typical coarse deposits made up of subrounded silicic to intermediate volcanic rocks and rounded

Precambrian quartzite, granite, and pegmatite. Middle photograph shows unconsolidated, cross-bedded, arkosic sands. The bottom photograph is a close up view of well-rounded, clast- and matrix-supported cobbles and gravels.

Fig. 10 Fanglomerate facies of the Puye Formation. Top photograph shows outcrop made up of alternating beds of light-colored, ash-rich fluvial deposits and gray gravels and cobble deposits made up of crystalline dacite. Middle photograph shows gray, heterogeneous, fluvial deposits overlying light-colored, ash-rich reworked tuffaceous sediments. Bottom photograph is unsorted mudflow deposit with crystalline dacite clasts supported in a silty to sandy matrix.

Fig. 11 Cerros del Rio basalt is largely buried by Bandelier Tuff on the Pajarito Plateau. Top photograph shows the stacked nature of multiple flows at the mouth of Frijoles Canyon. Individual flows are separated by interflow breccia, scoria, sediment, and ash. Middle photograph shows the highly fractured nature of flows. Bottom photograph was taken by video camera in borehole R-31. It shows highly-porous, oxidized interflow breccia that is commonly found between individual lava flows.

Fig. 12 Structure contour for the top of Cerros del Rio basalt with isopachs showing the cumulative thickness of flows. Green dashed line indicates the northern and western boundary of the Cerros del Rio volcanic field. Blue line indicates western extent of dacitic lavas that were contemporaneous with the basalts. Top of Cerros del Rio basalts formed broad north-trending highland on east side of plateau. This highland was buried by deposition of the Bandelier Tuff.

Fig. 13 Structure contour for the base of Cerros del Rio basalt with isopachs showing the cumulative thickness of flows. Green dashed line indicates the northern and western boundary of the Cerros del Rio volcanic field. Blue line indicates western extent of dacitic lavas that were contemporaneous with the basalts. The maximum thickness of basalt corresponds with structural-contour lows suggesting that the basalts accumulated in topographic basins.

Fig. 14 Generalized diagram showing the typical internal structure of a Cerros del Rio basalt flow. These structures are generally present, but their degree of development varies laterally within flows and vertically among flows. The pillow-palagonite complex occurs only near the eastern margin of the plateau where lava flowed into lakes formed by lava dams along the Rio Grande. Figure modified from Whiteman et al. (1994).

Fig. 15 Thick Bandelier Tuff deposits form the mesas of the Pajarito Plateau. Upper photograph shows, in ascending order, the Otowi Member (Qbo), the Cerro Toledo interval (Qct), and the Tshirege Member (Qbt 1g to Qbt 3, see text). Subunits of the Tshirege Member represent changes in welding and crystallization characteristics in this compound cooling unit. Middle photograph shows stratified Cerro Toledo tuffaceous sedimentary deposits (Qct) between light-colored, slope-forming glassy, nonwelded tuffs of the Otowi Member (Qbo, foreground) and subunit Qbt 1g of the Tshirege Member (background). Bottom photograph shows stratified pumice-fall deposits of the Guaje

Pumice Bed (Qbog) below Otowi Member ash-flow tuffs (Qbo, massive light-colored deposits in slope) and above Cerros del Rio basalt (Tb4).

Fig. 16 Structure contour and isopach map for the Otowi Member of the Bandelier Tuff. Structure contours are for base of Guaje Pumice Bed. The structure contours show the paleotopography prior to eruption of the Otowi Member. Otowi tuffs filled a broad north-trending paleovalley bound by the Sierra de los Valles highlands on the west and the Cerros del Rio basaltic highland on the east. The variable thickness of the Otowi Member represents deep erosion of these poorly consolidated nonwelded tuffs prior to eruption of the Tshirege Member.

Fig. 17 Structure contour and isopach map for the Cerro Toledo interval. Structure contours for base of unit indicate that Cerro Toledo filled a broad southeast-trending paleovalley incised into the Otowi Member (see isopach map for Otowi Member in Fig. 16). The thickest Cerro Toledo deposits coincide with the axis of the paleovalley.

Fig. 18 Natural gamma, density, and porosity logs for the CdV-16-2(i) borehole located in the western part of the plateau. The rhyolitic Tshirege and Otowi Members of the Bandelier Tuff have elevated gamma signatures relative to the dacitic sedimentary deposits of the Puye Formation. The large density and porosity variations in the Tshirege Member reflect vertical welding variations in this compound cooling unit. The Otowi Member shows less variability, but density and porosity shifts suggest a small increase in welding below 625 ft depth. The relatively high density and low porosity of the Puye Formation reflects the high percentage of crystalline dacite gravels, cobbles, and boulders embedded in a silty matrix that diminishes porosity.

Fig. 19 Conceptual model of groundwater occurrences beneath the Pajarito Plateau. Groundwater occurs as shallow perched systems in canyon-floor alluvium, as bedrock perched systems within the thick vadose zone (primarily beneath wet canyons), and as regional saturation associated with the basin-wide groundwater system.

Fig. 20 Locations of wells and boreholes that have penetrated perched groundwater systems in bedrock. See Table 1 for descriptions of these perched zones. Shallow perched groundwater in canyon-floor alluvium and shallow zones of perched water issuing from bedrock springs are not included here and in Table 1.

Fig. 21 Map showing distribution of geologic units at the top of the regional zone of saturation beneath the Pajarito Plateau. The wells that provided geologic control for this map are indicated by red dots.

Table 1. Characteristics of deep perched groundwater zones encountered in wells on the Pajarito Plateau.

Watershed	Well Name	Depth to Water (ft)	Saturated Thickness (ft)	Groundwater Host Rock	Nature of Perching Layer	Anthropogenic Chemicals Detected	Comments
Pueblo Canyon	TW-2a	110	>23	Puye Fm. fanglomerate	Within Puye Fm. fanglomerate; perching lithology not known	Tritium, nitrate	A canyon-floor well was installed with a single screen in the perched zone (Griggs, 1964, Purtymun, 1995).
	R-5	~380	~37	Puye Fm. dacitic sands and gravels mixed with 5-15% rounded quartzite and granite river gravels	Within Puye Fm. fanglomerate; perching lithology not known	Nitrate, fluoride, chloride, uranium, and sulphate	A canyon-floor well was installed with four isolated screens (LANL, 2003). Screen #2 is completed in this perched zone. The vertical extent of this zone is poorly known.
	TW-1a	118	>3	Interflow breccia and silt in Cerros del Rio basalt	Massive basalt	Nitrate, phosphate, chloride, boron, and uranium	Groundwater was first encountered within a stack of Cerros del Rio basalts in an interflow zone from 212- to 215-ft-depth (Griggs, 1964). Groundwater may be confined because the water level stabilized at 118 ft (Purtymun, 1995). A canyon-floor well was installed with a single screen in the perched zone.
	POI-4	160	>21	Cerros del Rio	Confining layer	Nitrate,	A canyon-floor well was

				fractured basalt	not penetrated	phosphate, chloride, boron,	installed with a single screen in the perched zone. Groundwater occurs in massive basalt cut by high-angle fractures.
Los Alamos Canyon	H-19	450	22	Tephras in the Guaje Pumice Bed	Tschicoma Fm. lava flow top	No data but contaminants are unlikely at this upgradient site.	Saturation in this zone was noted while drilling to reach the regional aquifer (Griggs, 1964). The perched zone was not screened, and the well was later abandoned.
	LAOI(A)1.1	293	22	Tephras in the Guaje Pumice Bed	Top of Puye Formation; possible clay-rich soil horizon – see description for well LADP-3	None	A canyon-floor well was installed with a single screen in the perched zone.
	R-7	373	9	Puye Fm. silty, clayey, and sandy gravels	Clay-rich gravels from 382-397 ft depth in the Puye Formation	None	A canyon-floor well was installed with three isolated screens (Stone et al., 2002). Screen #1 in well R-7 is completed in this perched zone.
	R-7	744	~23	Puye Fm. sandy gravel with abundant pumice clasts	Puye Fm.; possible perching layer from 767 to 772 ft in silty pebble gravel or from 772-777 in	None	Screen #2 in well R-7 is completed in this zone. Geophysical logs and borehole videos suggest additional perched groundwater zones were

				clayey pumiceous sands.		encountered when the R-7 borehole was drilled.
LADP-3	325	3	Tephras in the Guaje Pumice Bed	Smectite- and kaolinite-rich soil a few inches thick at top of Puye Formation	Tritium	Soil development has been noted at top of the Puye Formation in outcrops and in boreholes elsewhere. Soil at the top of the Puye Fm. may be a widespread feature across the plateau. A canyon-floor well was installed with a single screen in the perched zone (Broxton et al., 1995b).
Water Supply Well Otowi 4	~253	Not known	Puye Fm. gravel bed	Within Puye Fm. fanglomerate; perching lithology not known	No data	Saturation in this zone was noted while drilling to install a municipal supply well in the regional aquifer (Stoker et al. (1992). The geologic log notes: "Some perched water was visible in a video log of the 48-in hole at about 253 ft where water cascaded in from a large gravel". The perched zone is not screened.
R-9i and LAWS-01	137	45-99	Cerros del Rio interflow breccia and highly fractured basalt	Massive basalt with few fractures	Tritium	Groundwater was first encountered at a depth of 180 ft, but the water level quickly rose to 137 ft, indicating possible

						confinement. At R-9i a canyon-floor well was installed with two isolated screens (Broxton et al., 2001b). Screen #1 of R-9i is completed in this zone. In LAWS-01, this zone is sampled via a flexible liner with sampling ports (Stone and Newell, 2002).
R-9i and LAWS-01	275	7	Cerros del Rio basalt breciated flow base	Clay-rich, stratified, basaltic tephra (maar deposits) from 282-289.8 ft	Tritium	Water first encountered at 275 ft. The water level stabilized at 264 ft and may be confined. Screen #2 in well R-9i is completed in this zone. In LAWS-01, this zone is sampled via a flexible liner with sampling ports.
R-9	524	48 to 103	Puye Formation sands and gravels	Clay-rich tuffaceous sands and gravels	Tritium	Three stringers of sands and gravels at 579-580.5 ft, 615 ft, 624-626.8 ft produced groundwater while drilling to the regional aquifer. These stringers probably constitute a single saturated zone because, when isolated, each yielded the same water level of 524 ft. The water bearing stringers are enclosed by clay-rich

							tuffaceous sands and gravels that may be confining units or may simply be unproductive. This saturated zone was not screened.
Sandia Canyon	R-11	601	9+ (?)	Cerros del Rio basalt breciated flow base and/or underlying Puye Fm. sands and gravels.	Not known	None	Saturation in this zone was noted while drilling to reach the regional aquifer. Little is known about the vertical extent of this perched zone. Water level readings stabilized at 601 ft depth when the borehole was at a depth of 643 ft in the Puye Fm. The groundwater may be produced from the base of the basalt and/or from the underlying fanglomerate. This perched zone was not screened.
	R-12	424	76-95	Fractured Cerros del Rio basalt, underlying fluvial sands and silts, and riverine gravels of the lacustrine facies of the Puye Fm.	Clay-rich lake beds of the lacustrine facies of the Puye Fm. from 519-535 ft	Tritium, nitrate	Groundwater was first encountered at a depth of 443 ft, but the water level quickly rose to 424 ft before stabilizing, indicating possible confinement. A canyon-floor well was installed with three isolated screens

							(Broxton et al., 2001a). Screens #1 and #2 are completed in this perched zone.
Mortandad Canyon	MCOBT-4.4	493	10-30	Puye Fm. pebble gravel	See comments	Tritium, nitrate, perchlorate	This perched zone occurs in Puye Formation sediments that overlie Cerros del Rio basalt. The perching layer is uncertain but occurs within a rock sequence comprised of: 1) Puye silty sands, 2) clay-rich basalt flow-top rubble, and 3) massive, unfractured Cerros del Rio basalt. A canyon-floor well was installed with a single screen in the perched zone (Broxton et al., 2002b).
	R-15	646	~99	Fractured Cerros del Rio basalt	Clay-rich flow-base rubble or underlying silty basaltic sand (745-746.7 ft)	Tritium, nitrate, perchlorate	Saturation in this zone was noted while drilling to reach the regional aquifer (Longmire et al., 2001). Saturation was first encountered at a depth 646 ft, but a zone of increased water production was noted by the driller from 707-717 ft. This perched zone was not screened.
Pajarito	R-23	Not	Not known	Cerros del Rio	Not known	No data	Perched groundwater was

Canyon		known		basalt			probably encountered while drilling R-23 to the regional aquifer. Water accumulated in the annulus between the drill casing and the borehole wall above a clay-rich bridge. The accumulated water is probably from a perched zone within the Cerros del Rio basalt. The perched zone was not screened.
	R-19	894	18	Puye Fm. sand and gravel beds	Puye Fm. low-porosity sedimentary deposits.	None	R-19 was installed on a mesa south of Threemile Canyon. A perched zone was encountered in Puye Formation fanglomerate overlying Cerros del Rio basalt. Borehole geophysical logs indicate the perched zone is made up of high-porosity sediments overlying a confining layer of low-porosity sediments. A well was installed with seven isolated screens at this site (Broxton et al., 2001c). Screen #2 is completed in this perched zone.
Cañon de	R-25	723	~409	Otowi ash-flow	Confining layer	High-explosive	This large saturated zone is

Valle				tuff, Guaje Pumice bed, and Puye Fm. fanglomerate	occurs in Puye Fm. sedimentary deposits. From 1132-1137 ft, cuttings of fine-grained sand and silt are interbedded with gravels and cobbles. Alternating wet and dry sediments occur below this zone to a depth of 1286 ft.	compounds and their degradation products, trichloroethene, tetrachloroethene	separated from the regional aquifer (depth at 1286 ft) by 154 ft of alternating wet and dry fanglomerate deposits. This upper saturated zone is currently interpreted as a perched zone with a leaky confining layer. The top of the same upper saturated zone was penetrated in nearby well CDV-16-1(i) which is located in adjacent Cañon de Valle. A multi-screen mesa-top well was installed at R-25 (Broxton et al., 2002a). Four screens are completed in this thick perched zone.
	CDV-16-1(i)	563	Not fully penetrated	Otowi ash-flow tuff	Perching horizon not known; below drill hole depth	High-explosive compounds	Because of the proximity of CDV-16-1(i) and R-25 (~375 ft), the upper saturated zone in these wells is probably laterally connected. The top of the upper saturated zone is 28 ft higher in CDV-16-1(i) (elev. 6821 ft) compared to R-25 (elev. 6793 ft). A canyon-floor well was installed with a single

						screen in the perched zone.
CDV-16-2(i)	827 (?)	Not known	Puye Fm. fanglomerate	Within Puye Fm. fanglomerate; perching lithology not known	High-explosive compounds	The nature of this perched zone is currently under investigation. Borehole video logs, water level measurements, and the presence of high explosives in groundwater samples indicate that perched water is present. However, efforts to install a well in this zone(s) have not been successful.
R-26	173	Zones of thin, dis-continuous saturation associated with fractures.	Fractured densely-welded tuff in unit Qbt 3t of the Tshirege Member	Water production associated with fractures	Analyses pending	A piezometer was installed in a borehole adjaent to well R-26 to monitor water levels in this perched zone. The piezometer is screened from 175 to 185 ft depth and the depth to water is 173 ft. Saturation appears to be associated with low-angle platy fractures in the ash-flow tuff.
R-26	About 604	See comments	Cerro Toledo interval	See comments	Analyses pending	R-26 was recently drilled and interpretation of perched water in this zone is preliminary. Borehole geophysical logs suggest high moisture contents

							below 575 ft to the top of of regional saturation at 954 ft. Perched water appears most likely at depths of 580 to 662 ft and 780 to 827 ft. A water level at 604 ft depth was measured during drilling while the borehole was at a depth of 720 ft. Well R-26 was completed with two isolated well screens with the upper screen placed within the perched zone and the lower screen in the regional zone of saturation.
Water Canyon	SHB-3	663	> 197 ft. Not fully penetrated.	Otowi ash-flow tuff, Guaje Pumice bed, and Puye Fm. fanglomerate	Confining layer not penetrated	None	Saturation occurs in the lower Bandelier Tuff and upper Puye Formation. The zone of saturation was not fully penetrated before drilling was terminated. A temporary mesa-top well was installed in the perched zone (Gardner et al., 1993).

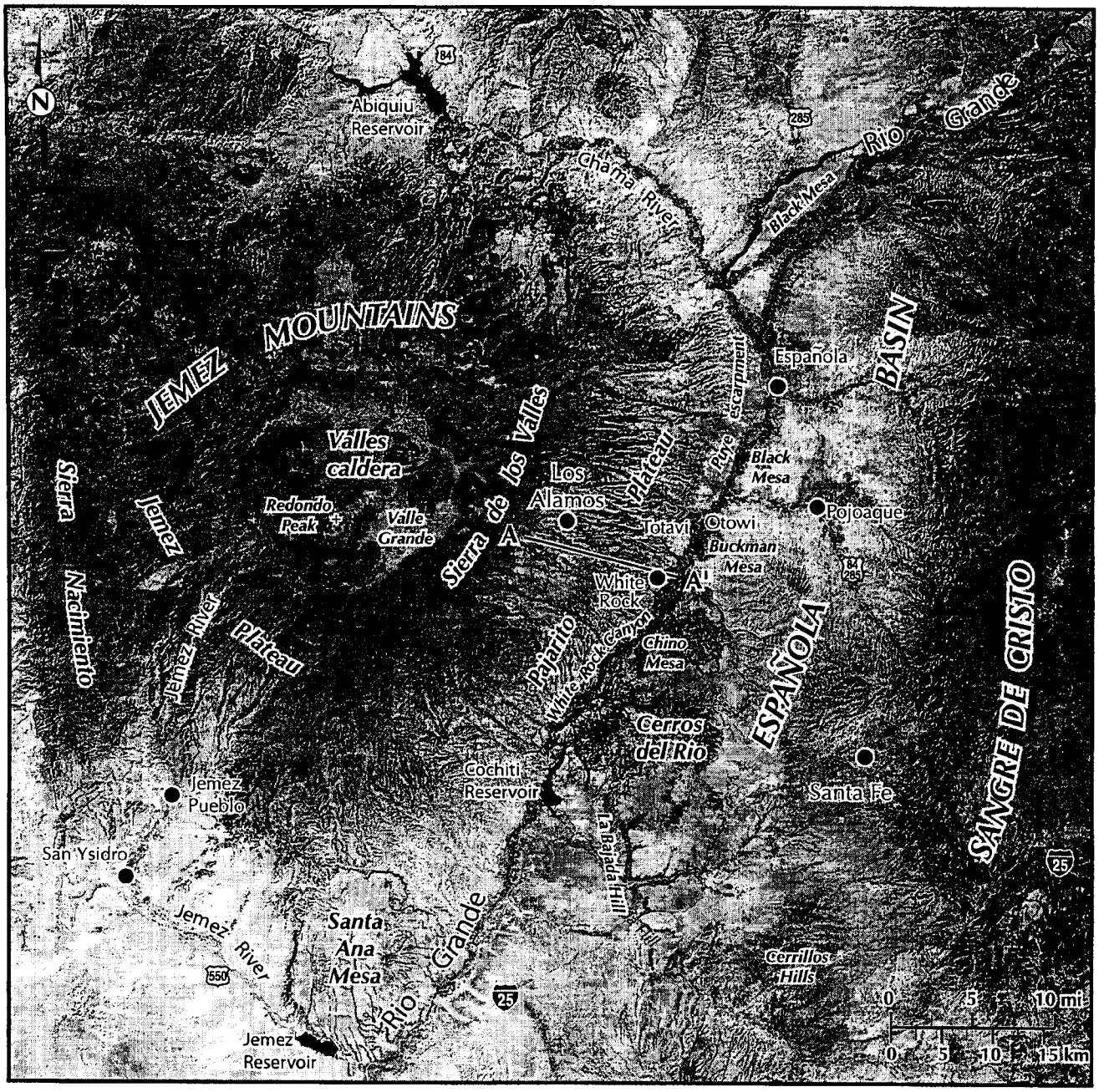

N
Abiquiu Reservoir
Chama River
Rio Grande
Black Mesa
JEMEZ MOUNTAINS
Española
BASIN
Pueblo escarpment
Valles caldera
Los Alamos
Plateau
Black Mesa
Pojoaque
Sierra de los Valles
Redondo Peak
Valle Grande
Totavi
Otowi
Buckman Mesa
A
A'
White Rock
Sierra Nacimiento
Jemez
Jemez River
Plateau
Pajarito
White Rock Canyon
Chino Mesa
ESPAÑOLA
SANGRE DE CRISTO
Cerros del Rio
Cochiti Reservoir
Jemez Pueblo
Santa Fe
La Bajada Hill
San Ysidro
Jemez River
Santa Ana Mesa
Rio Grande
Cerrillos Hills
Jemez Reservoir
0 5 10 mi
0 5 10 15 km

Figure 1

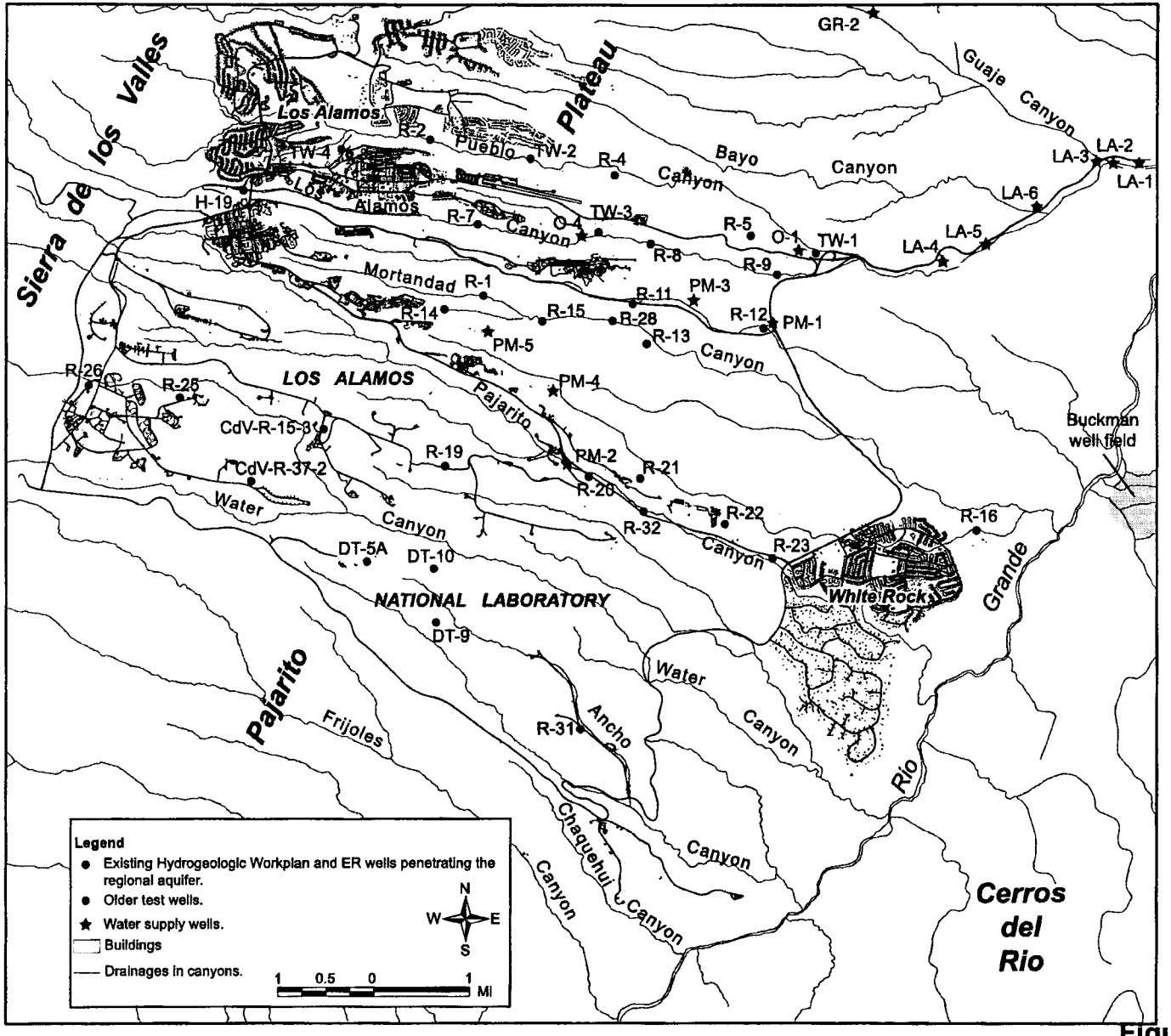

Sierra de los Valles
Plateau
Los Alamos
Pueblo
Canyon
Bayo
Canyon
Guaje Canyon
Los Alamos
Canyon
Mortandad
Canyon
Pajarito
Canyon
LOS ALAMOS
NATIONAL LABORATORY
Water
Canyon
Water
Canyon
Ancho
Canyon
Chaquehui
Canyon
Canyon
Frijoles
Pajarito
Rio
Grande
White Rock
Buckman well field
Cerros del Rio
GR-2
LA-1
LA-2
LA-3
LA-4
LA-5
LA-6
TW-1
TW-2
TW-3
TW-4
O-1
O-4
R-1
R-2
R-4
R-5
R-7
R-8
R-9
R-11
R-12
R-13
R-14
R-15
R-16
R-19
R-20
R-21
R-22
R-23
R-25
R-26
R-28
R-31
R-32
PM-1
PM-2
PM-3
PM-4
PM-5
H-19
CdV-R-15-3
CdV-R-37-2
DT-5A
DT-10
DT-9
Legend
Existing Hydrogeologic Workplan and ER wells penetrating the regional aquifer.
Older test wells.
Water supply wells.
Buildings
Drainages in canyons.
N
W
E
S
1
0.5
0
1
Mi

Figure 2

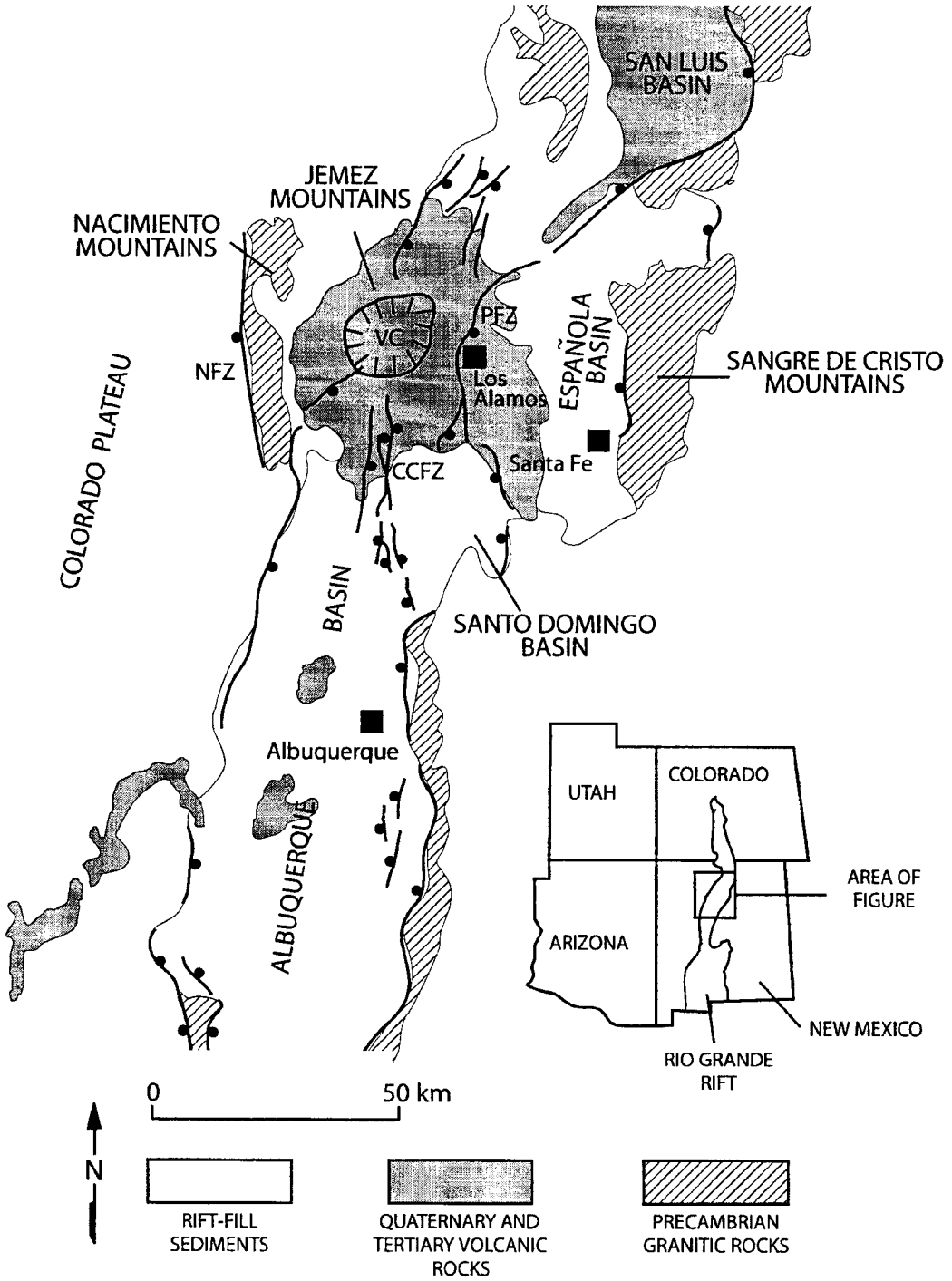

SAN LUIS BASIN
JEMEZ MOUNTAINS
NACIMIENTO MOUNTAINS
VC
PFZ
ESPAÑOLA BASIN
SANGRE DE CRISTO MOUNTAINS
NFZ
Los Alamos
COLORADO PLATEAU
CCFZ
Santa Fe
BASIN
SANTO DOMINGO BASIN
Albuquerque
ALBUQUERQUE
UTAH
COLORADO
AREA OF FIGURE
ARIZONA
NEW MEXICO
RIO GRANDE RIFT
0
50 km
N
RIFT-FILL SEDIMENTS
QUATERNARY AND TERTIARY VOLCANIC ROCKS
PRECAMBRIAN GRANITIC ROCKS

Figure 3

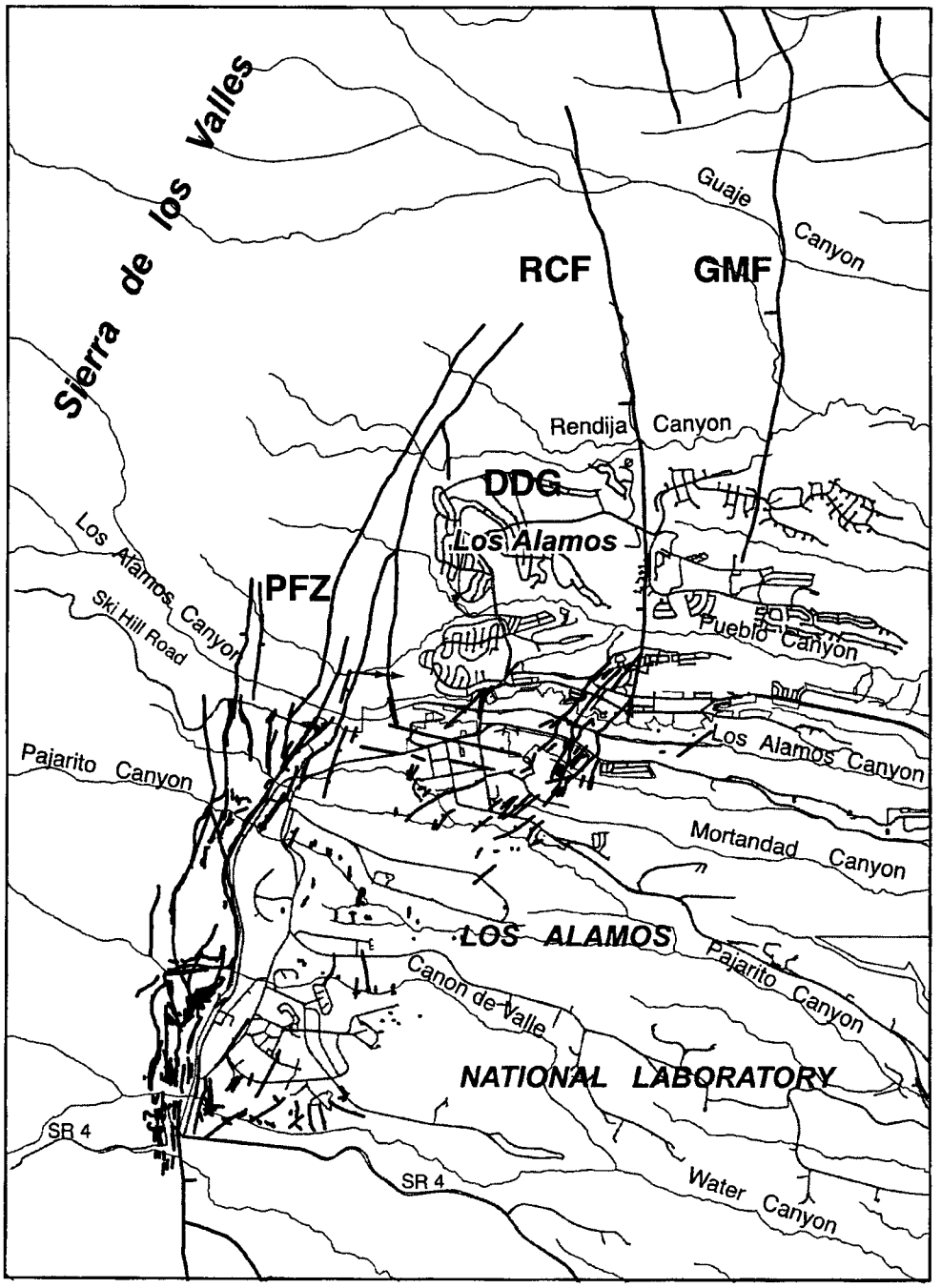
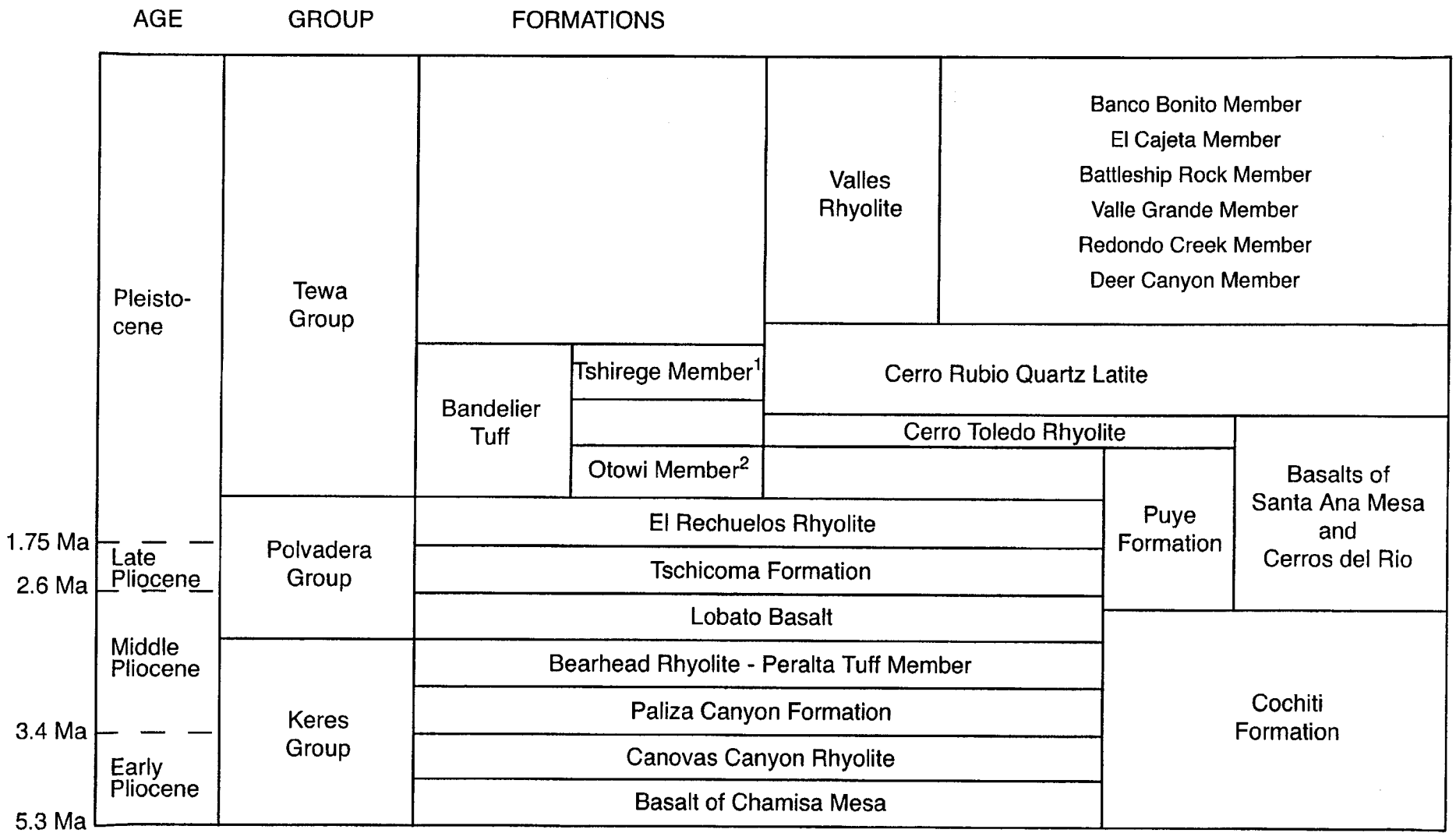

Sierra de los Valles
Guaje Canyon
RCF
GMF
Rendija Canyon
DDG
Los Alamos
PFZ
Los Alamos Canyon
Ski Hill Road
Pueblo Canyon
Los Alamos Canyon
Pajarito Canyon
Mortandad Canyon
LOS ALAMOS
Pajarito Canyon
Canon de Valle
NATIONAL LABORATORY
SR 4
SR 4
Water Canyon

Figure 4



[1] includes Tsankawi Pumice Bed
[2] Includes Guaje Pumice Bed

from Bailey et al., 1969

Figure 5

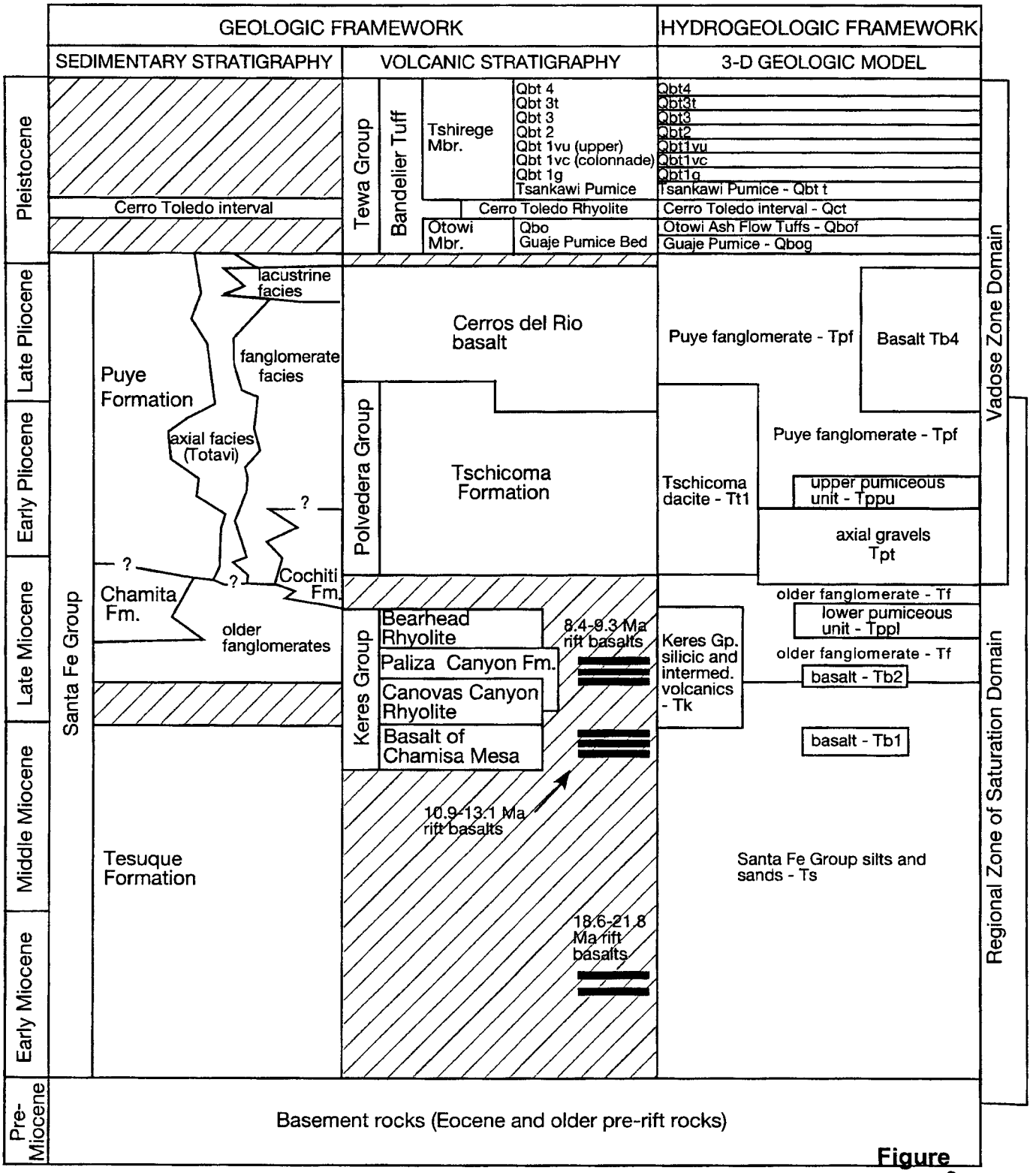

GEOLOGIC FRAMEWORK
HYDROGEOLOGIC FRAMEWORK
SEDIMENTARY STRATIGRAPHY
VOLCANIC STRATIGRAPHY
3-D GEOLOGIC MODEL
Pleistocene
Late Pliocene
Early Pliocene
Late Miocene
Middle Miocene
Early Miocene
Pre-Miocene
Cerro Toledo interval
Tewa Group
Bandelier Tuff
Tshirege Mbr.
Qbt 4
Qbt 3t
Qbt 3
Qbt 2
Qbt 1vu (upper)
Qbt 1vc (colonnade)
Qbt 1g
Tsankawi Pumice
Cerro Toledo Rhyolite
Otowi Mbr.
Qbo
Guaje Pumice Bed
Qbt4
Qbt3t
Qbt3
Qbt2
Qbt1vu
Qbt1vc
Qbt1g
Tsankawi Pumice - Qbt t
Cerro Toledo interval - Qct
Otowi Ash Flow Tuffs - Qbof
Guaje Pumice - Qbog
Vadose Zone Domain
Regional Zone of Saturation Domain
Santa Fe Group
lacustrine facies
fanglomerate facies
Puye Formation
axial facies (Totavi)
Chamita Fm.
Cochiti Fm.
older fanglomerates
Cerros del Rio basalt
Polvedera Group
Tschicoma Formation
Keres Group
Bearhead Rhyolite
Paliza Canyon Fm.
Canovas Canyon Rhyolite
Basalt of Chamisa Mesa
8.4-9.3 Ma rift basalts
10.9-13.1 Ma rift basalts
18.6-21.8 Ma rift basalts
Tesuque Formation
Puye fanglomerate - Tpf
Basalt Tb4
Puye fanglomerate - Tpf
Tschicoma dacite - Tt1
upper pumiceous unit - Tppu
axial gravels Tpt
older fanglomerate - Tf
lower pumiceous unit - Tppl
older fanglomerate - Tf
basalt - Tb2
Keres Gp. silicic and intermed. volcanics - Tk
basalt - Tb1
Santa Fe Group silts and sands - Ts
Basement rocks (Eocene and older pre-rift rocks)

Figure 6

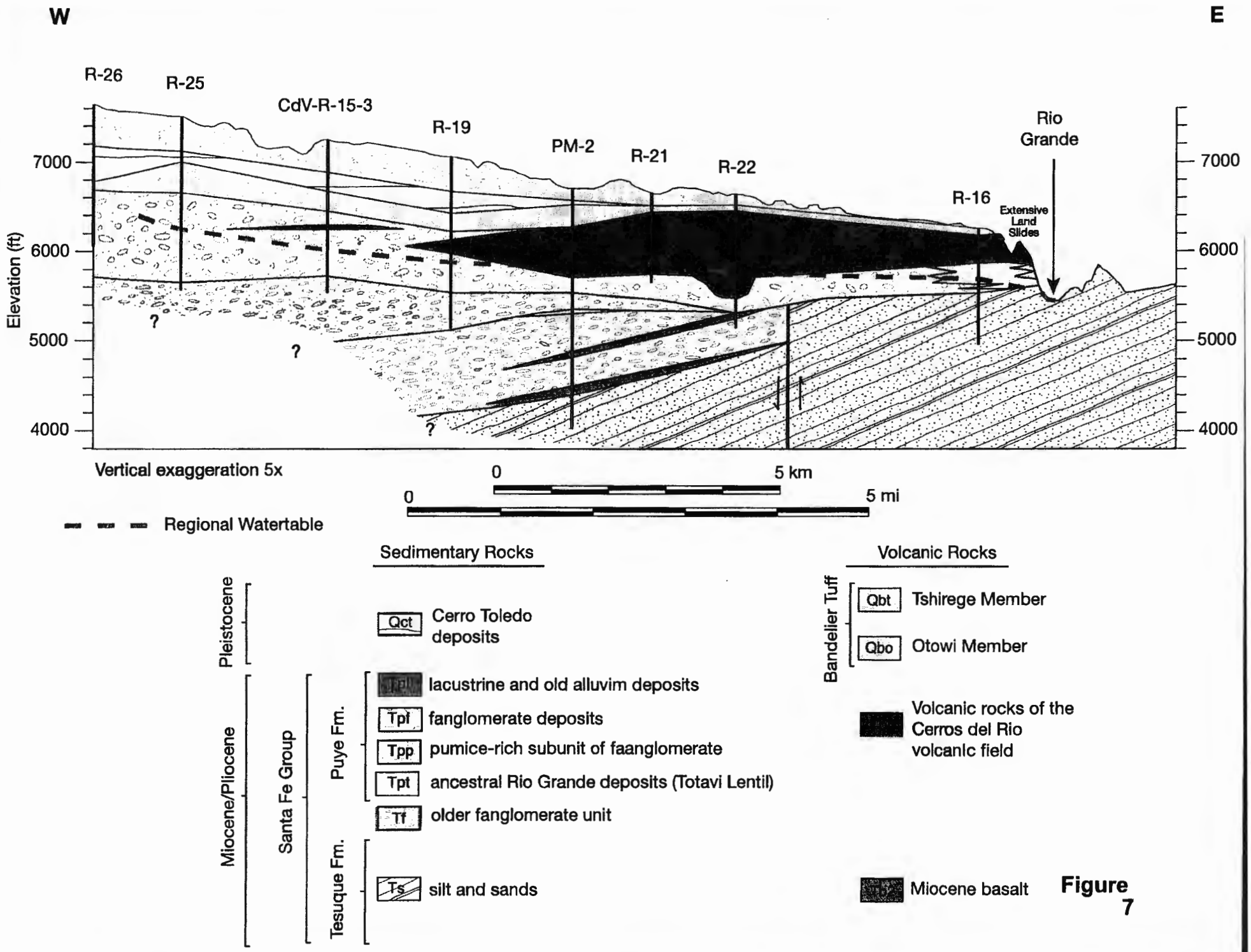

W
E
R-26
R-25
CdV-R-15-3
R-19
PM-2
R-21
R-22
R-16
Rio Grande
Extensive Land Slides
Elevation (ft)
7000
6000
5000
4000
Vertical exaggeration 5x
0
5 km
0
5 mi
Regional Watertable
Sedimentary Rocks
Pleistocene
Qct Cerro Toledo deposits
Miocene/Pliocene
Santa Fe Group
Puye Fm.
Tpl lacustrine and old alluvim deposits
Tpf fanglomerate deposits
Tpp pumice-rich subunit of faanglomerate
Tpt ancestral Rio Grande deposits (Totavi Lentil)
Tf older fanglomerate unit
Tesuque Fm.
Ts silt and sands
Volcanic Rocks
Bandelier Tuff
Qbt Tshirege Member
Qbo Otowi Member
Volcanic rocks of the Cerros del Rio volcanic field
Miocene basalt

Figure 7

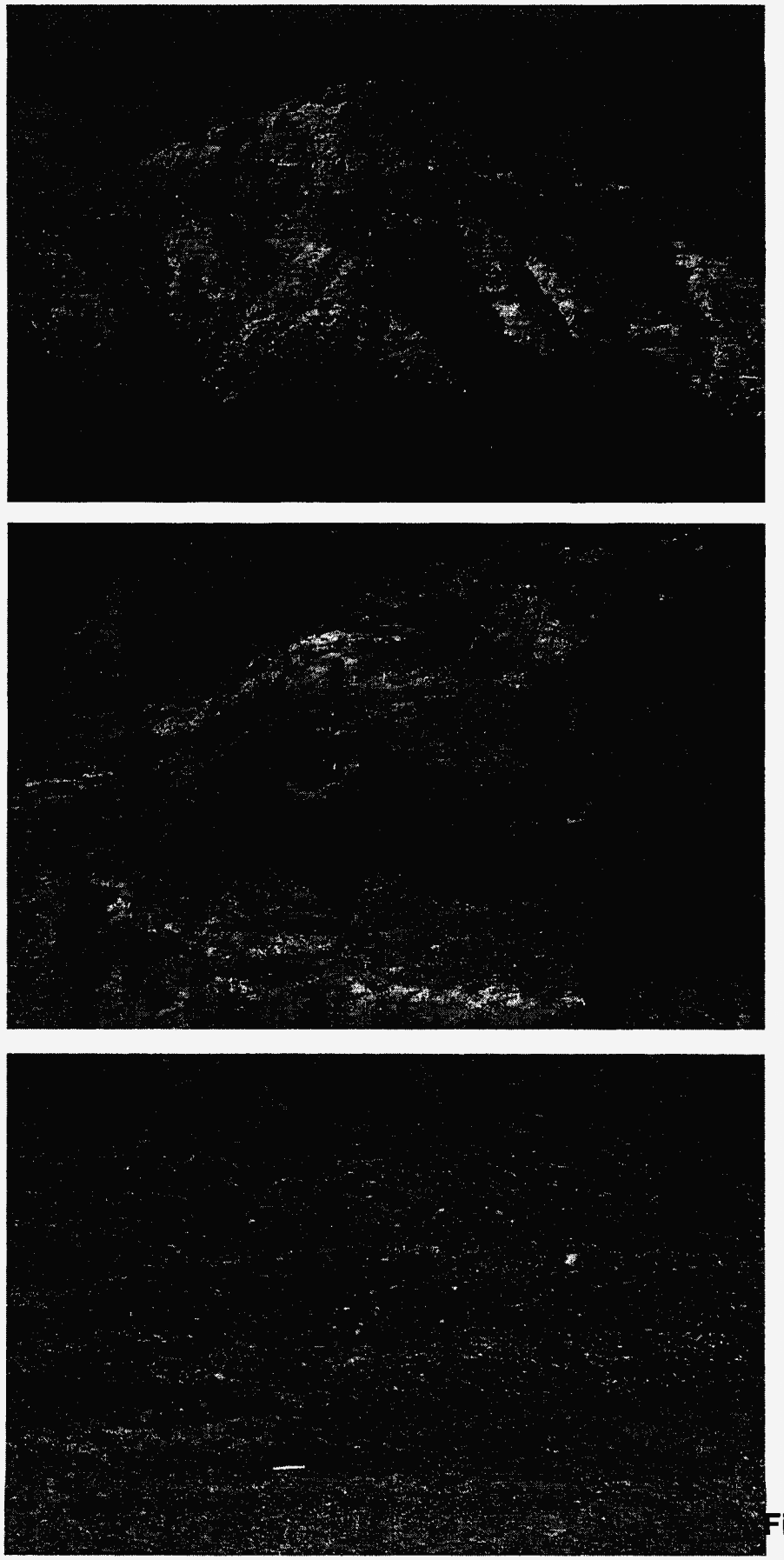


Figure 8

Figure 9

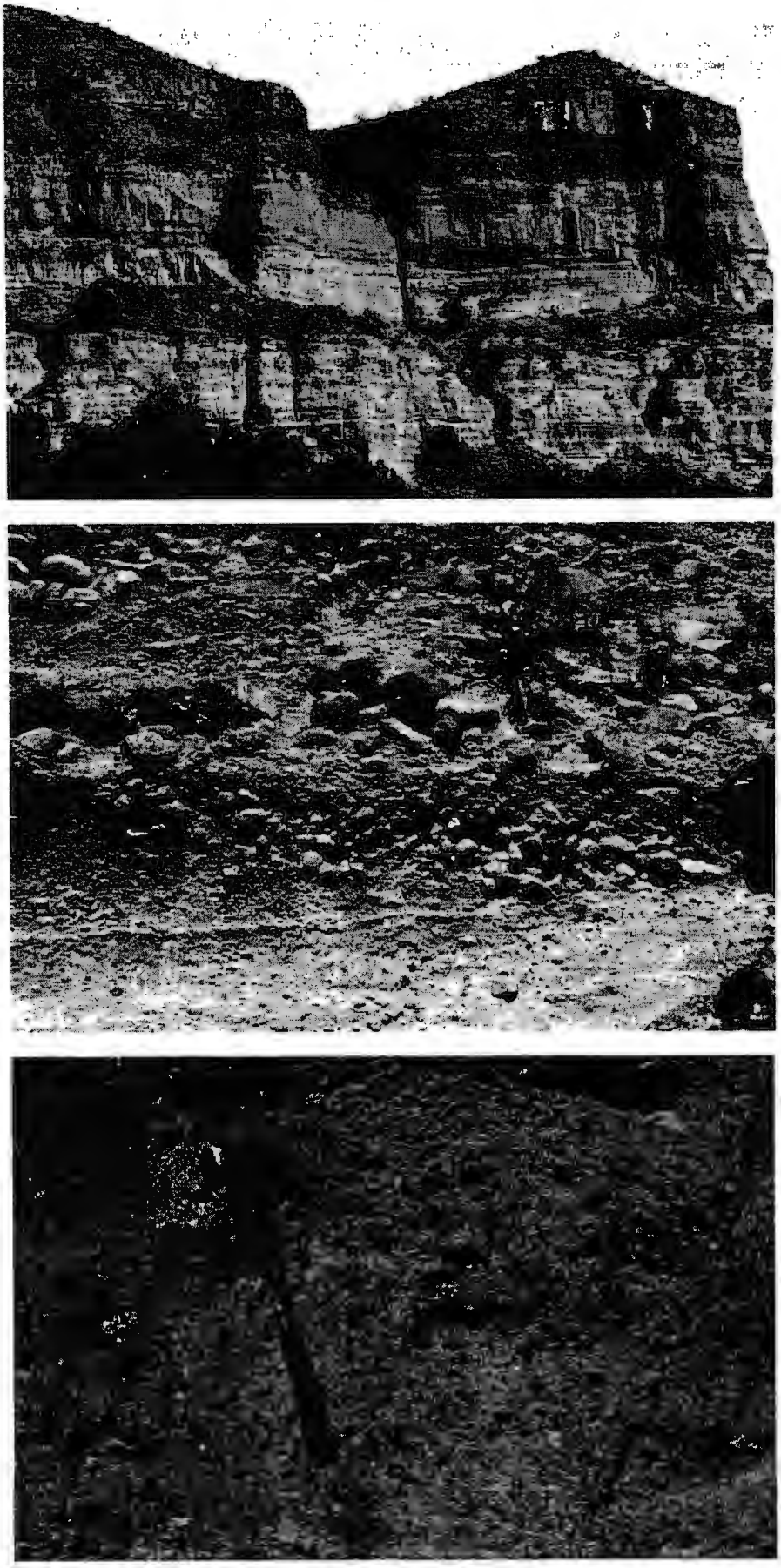
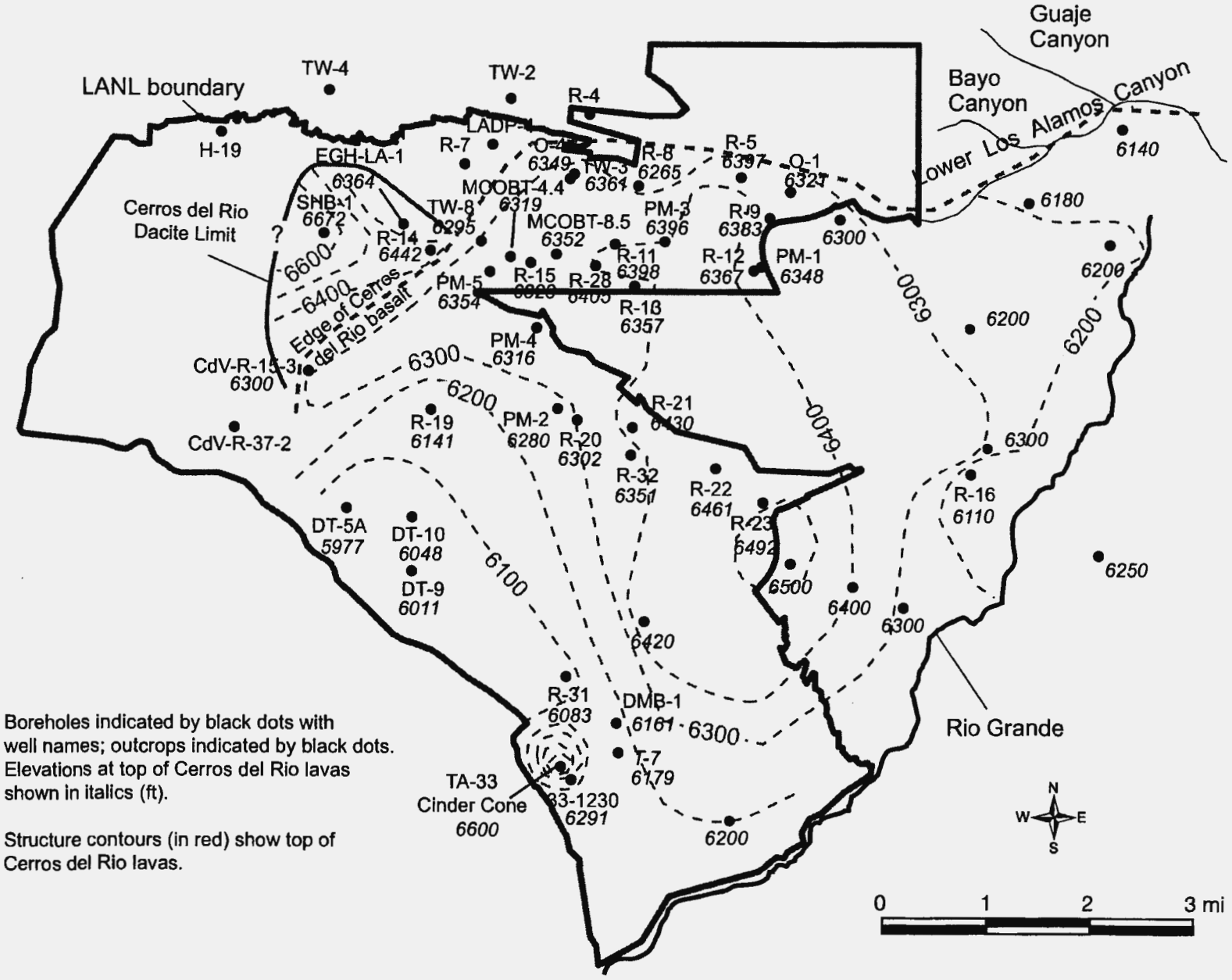


Figure 10

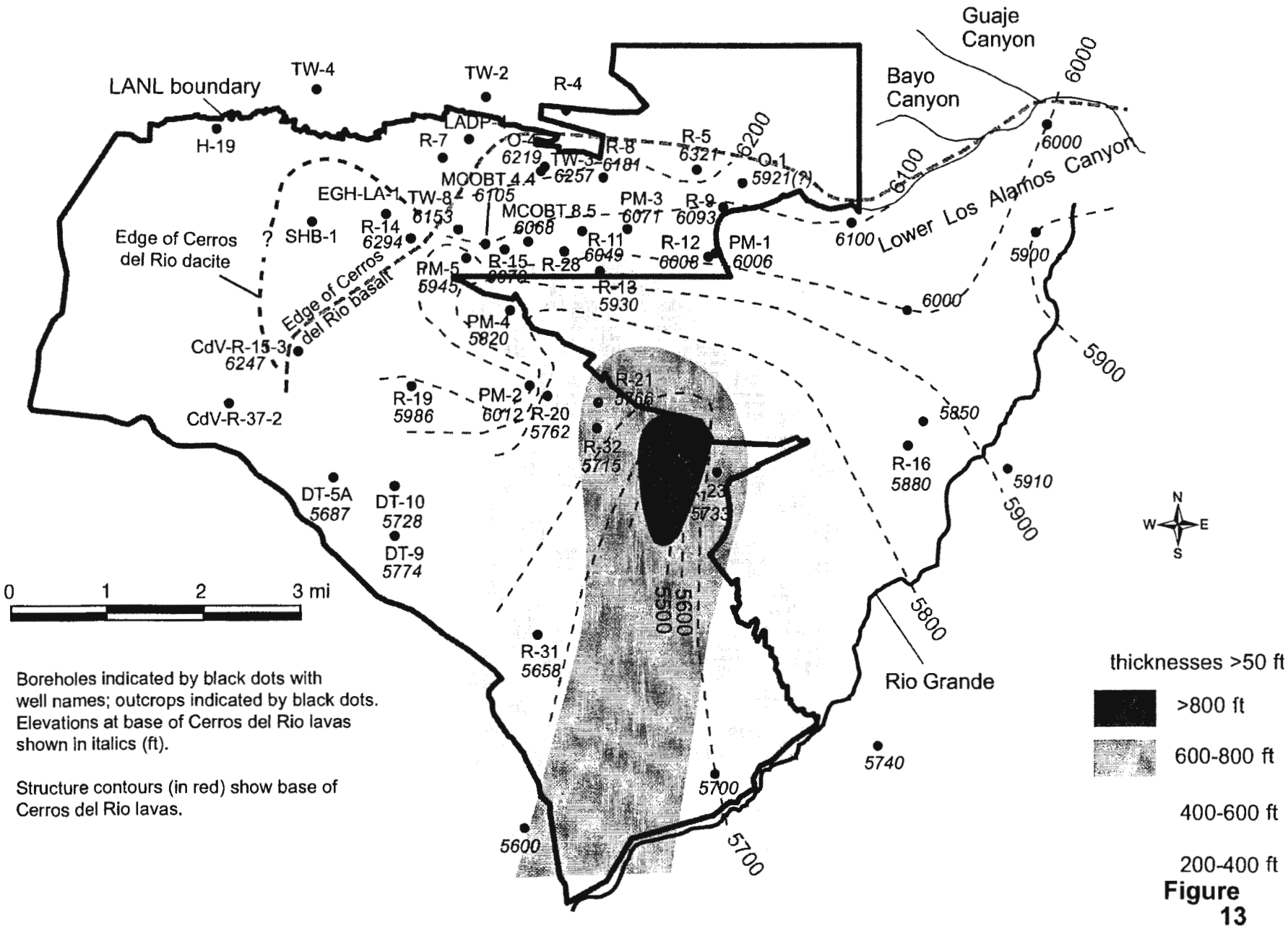
Figure 11



Boreholes indicated by black dots with well names; outcrops indicated by black dots. Elevations at top of Cerros del Rio lavas shown in italics (ft).

Structure contours (in red) show top of Cerros del Rio lavas.

Figure 12



Boreholes indicated by black dots with well names; outcrops indicated by black dots. Elevations at base of Cerros del Rio lavas shown in italics (ft).

Structure contours (in red) show base of Cerros del Rio lavas.

Figure 13

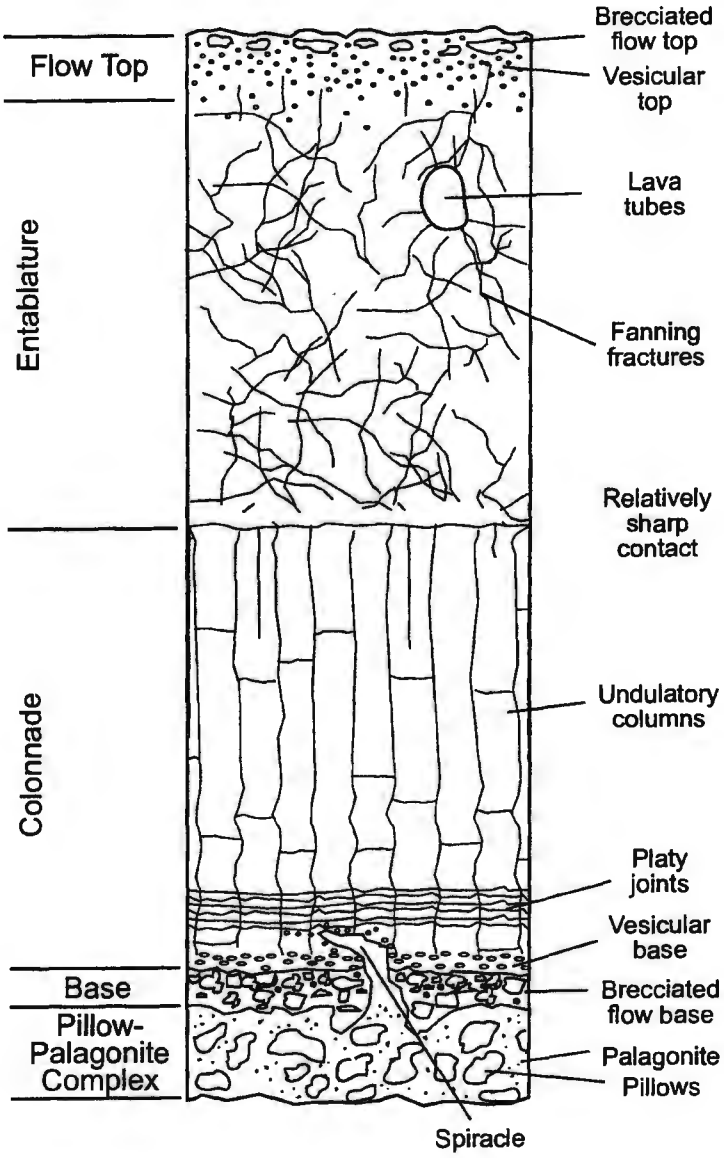

Flow Top
Entablature
Colonnade
Base
Pillow-
Palagonite
Complex
Brecciated
flow top
Vesicular
top
Lava
tubes
Fanning
fractures
Relatively
sharp
contact
Undulatory
columns
Platy
joints
Vesicular
base
Brecciated
flow base
Palagonite
Pillows
Spiracle

Figure 14

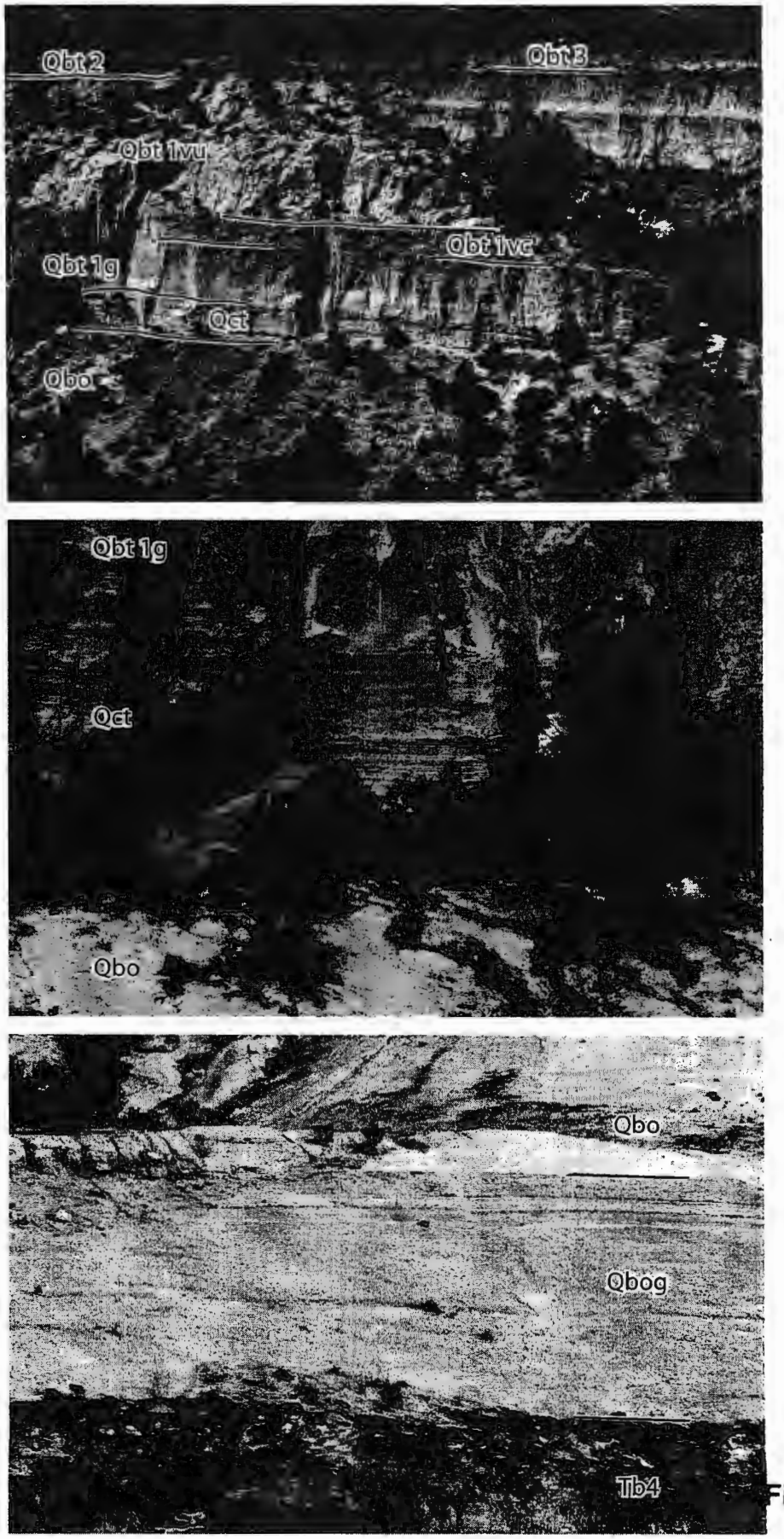

Qbt 2
Qbt 3
Qbt 1vu
Qbt 1vc
Qbt 1g
Qct
Qbo
Qbt 1g
Qct
Qbo
Qbo
Qbog
Tb4

Figure 15

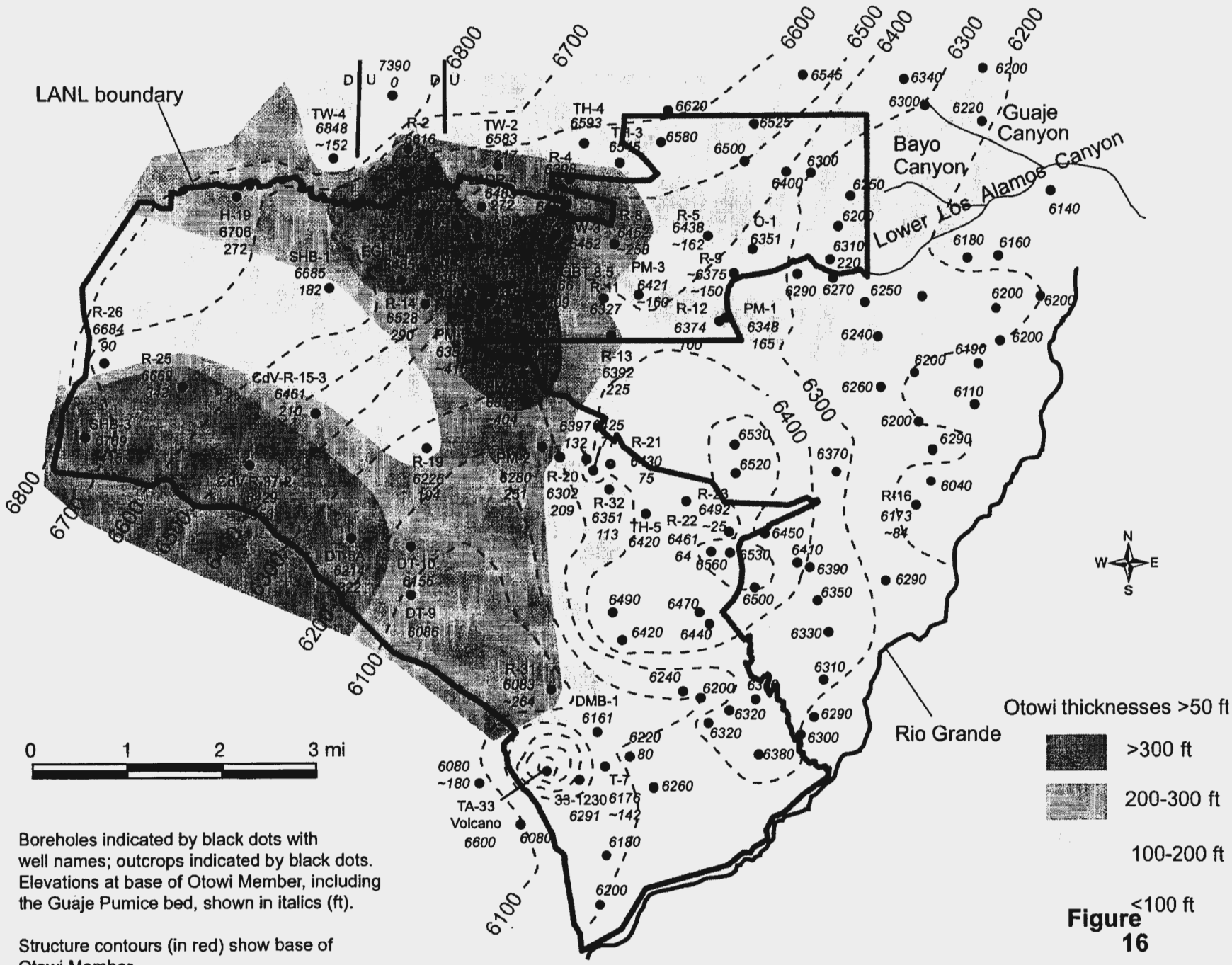
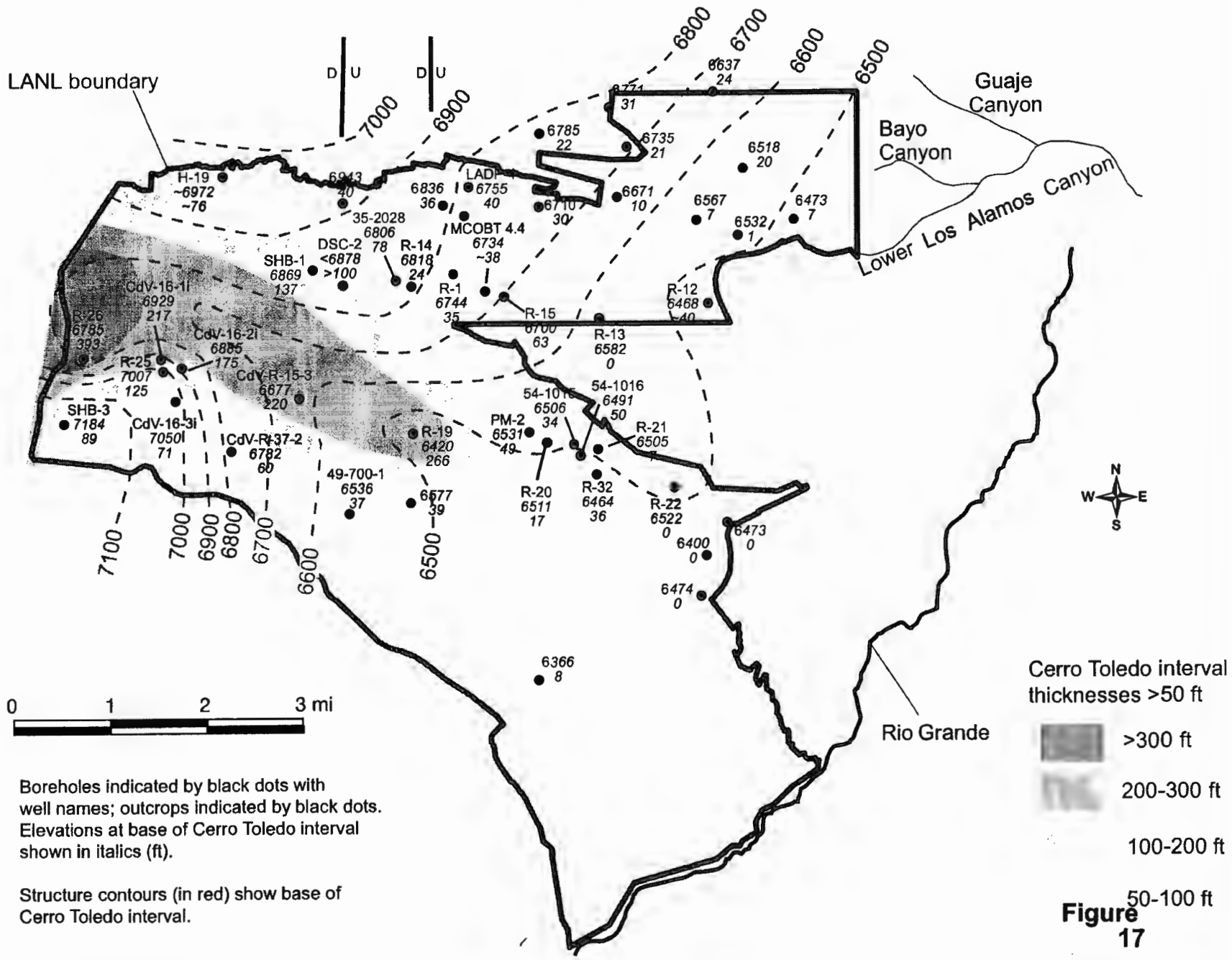

LANL boundary
Guaje Canyon
Bayo Canyon
Lower Los Alamos Canyon
Rio Grande
Otowi thicknesses >50 ft
>300 ft
200-300 ft
100-200 ft
<100 ft
0 1 2 3 mi
N
W
E
S
Boreholes indicated by black dots with well names; outcrops indicated by black dots. Elevations at base of Otowi Member, including the Guaje Pumice bed, shown in italics (ft).
Structure contours (in red) show base of Otowi Member.

Figure 16



Boreholes indicated by black dots with well names; outcrops indicated by black dots. Elevations at base of Cerro Toledo interval shown in italics (ft).

Structure contours (in red) show base of Cerro Toledo interval.

Figure 17

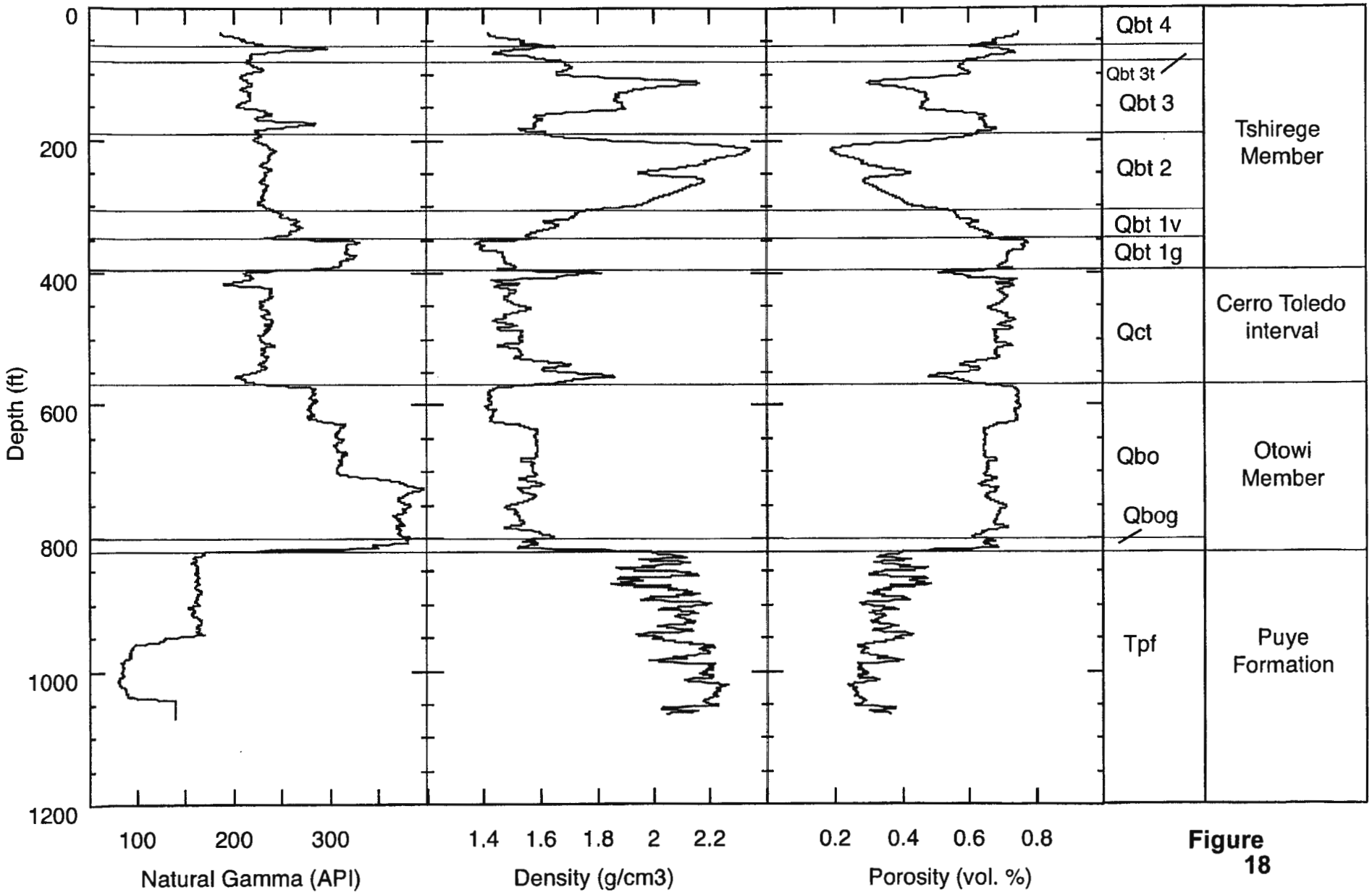
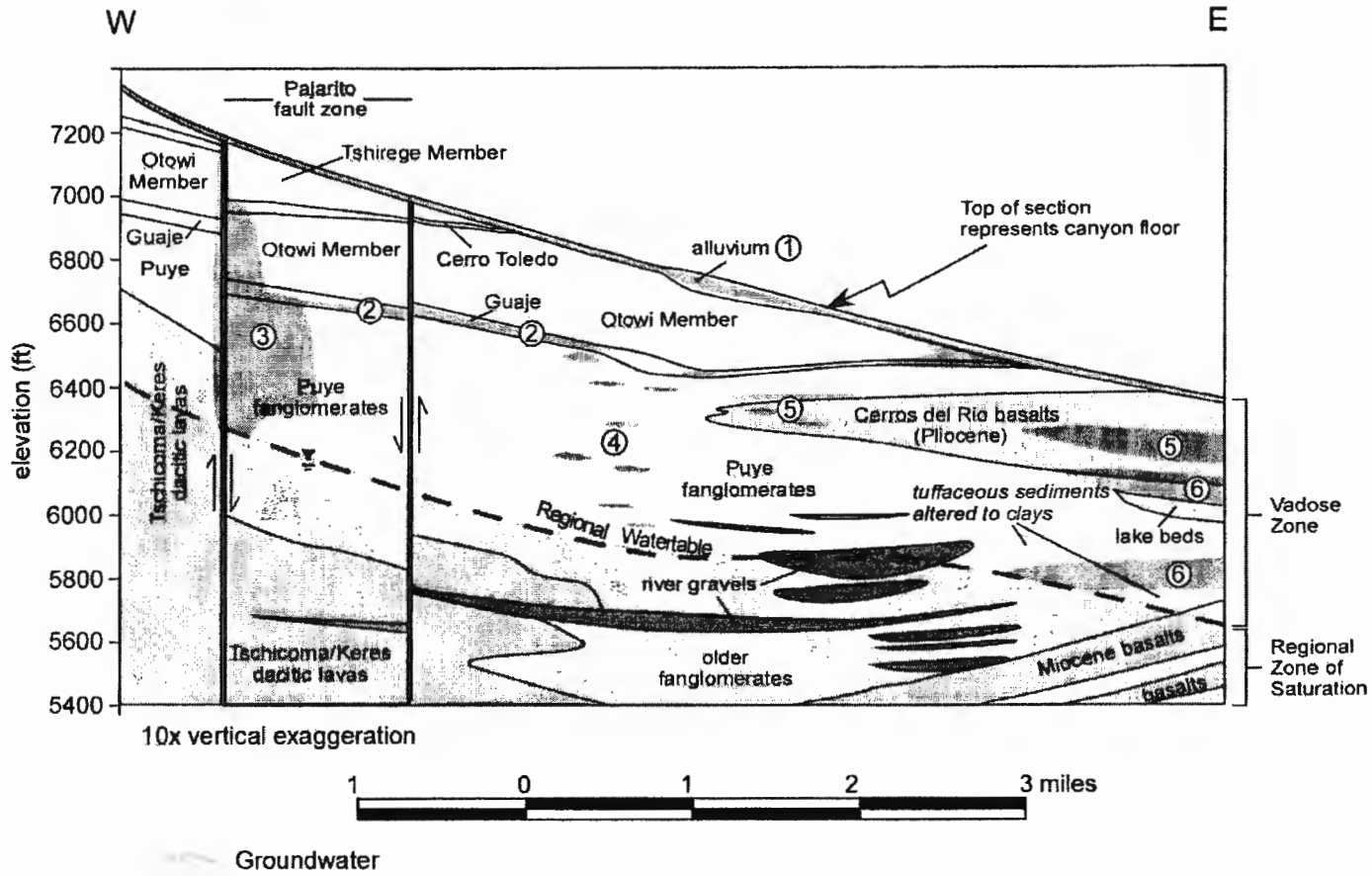

Depth (ft)
0
200
400
600
800
1000
1200
100
200
300
Natural Gamma (API)
1.4
1.6
1.8
2
2.2
Density (g/cm3)
0.2
0.4
0.6
0.8
Porosity (vol. %)
Qbt 4
Qbt 3t
Qbt 3
Qbt 2
Qbt 1v
Qbt 1g
Tshirege Member
Qct
Cerro Toledo interval
Qbo
Qbog
Otowi Member
Tpf
Puye Formation

Figure 18



① Canyon-floor alluvial groundwater - most commonly found in large, wet watersheds with significant snow and storm runnoff or in smaller watershed that recieve liquid effluent from waste water treatment plants. Saturated thickness and down-canyon extent varies seasonally.

② Perched groundwater is associated with the Guaje Pumice Bed in Los Alamos Canyon. This perched water body has a lateral extent of up to 3.7 mi. Guaje Pumice Bed has a high moisture content but is not fully saturated in most other locations.

③ Canon de Valle area in the southwest part of LANL. This is the largest perched zone identified on the plateau. A deep-sounding surface-based magnetotelluric survey suggests that this perched zone is discontinuous laterally, occurring as vertical, pipe-like groundwater bodies. One interpretation of this zone is that it represents groundwater mound(s) formed in response to local recharge beneath a wet canyon floor. Recharge may be enhanced across the Pajarito fault zone where shallow, densely-welded tuffs rocks are highly fractured.

④ Small zones of perched water formed above stratigraphic traps in Puye fanglomerate. These perched zones tend to be more numerous beneath large wet canyons and less frequent beneath dry mesa tops.

⑤ Perched groundwater associated with Cerro del Rio basalt. Saturation occurs in fractured basalt flows and in interflow breccias and sediments.

⑥ Perched zones form in response to local geologic conditions on the eastern side of the plateau. These include perch zones within clay-altered tuffaceous sediments and above lake deposits.

Figure 19

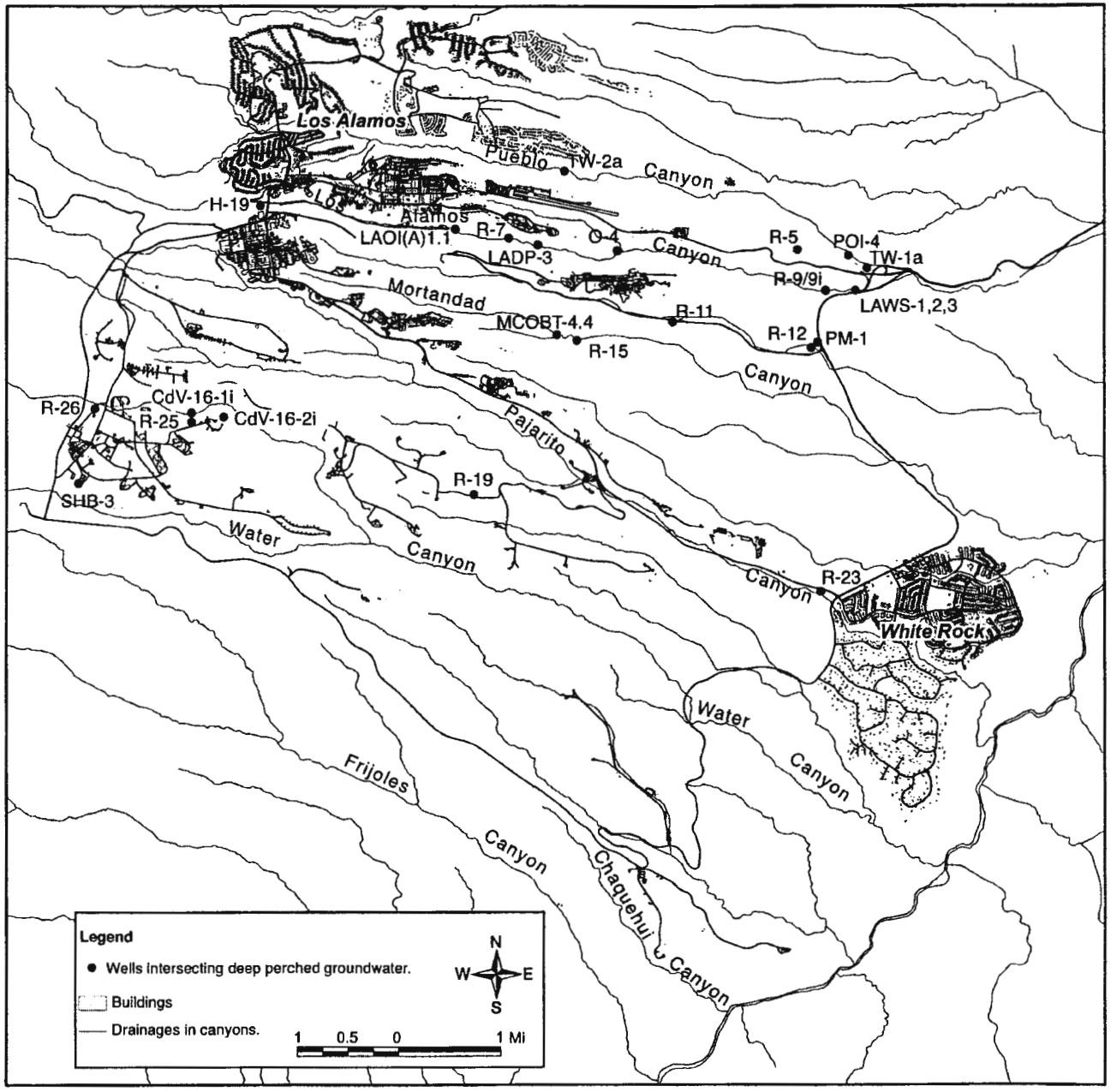
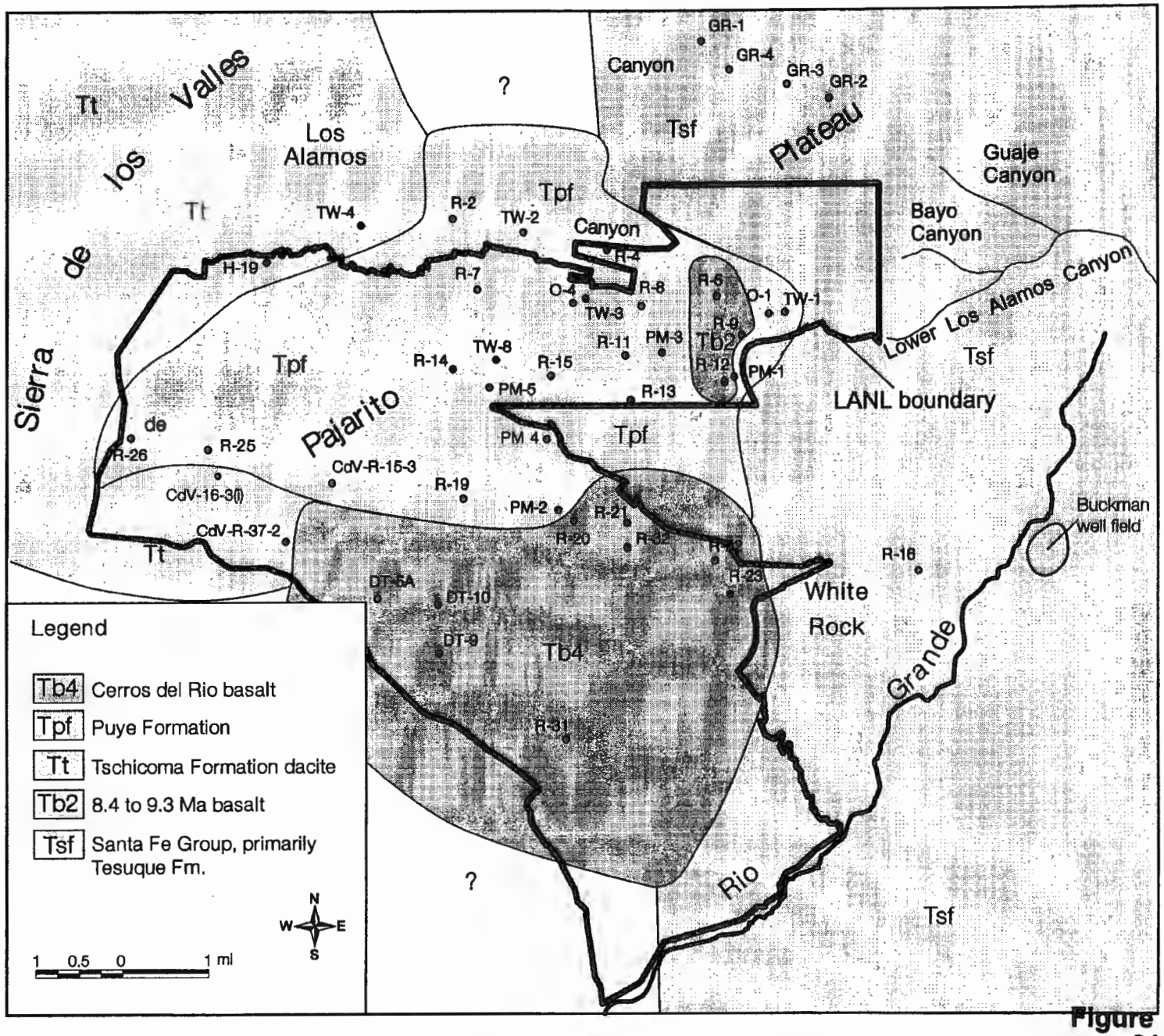

Los Alamos
Pueblo
Canyon
TW-2a
H-19
Los
Alamos
LAOI(A)1.1
R-7
O-4
Canyon
R-5
POI-4
TW-1a
LADP-3
R-9/9i
LAWS-1,2,3
Mortandad
MCOBT-4.4
R-11
R-12
PM-1
R-15
Canyon
CdV-16-1i
R-26
R-25
CdV-16-2i
Pajarito
R-19
SHB-3
Water
Canyon
Canyon
R-23
White Rock
Water
Canyon
Frijoles
Canyon
Chaquehui
Canyon
Legend
Wells intersecting deep perched groundwater.
Buildings
Drainages in canyons.
N
W
E
S
1
0.5
0
1 Mi

Figure 20



Legend

- Tb4 Cerros del Rio basalt
- Tpf Puye Formation
- Tt Tschicoma Formation dacite
- Tb2 8.4 to 9.3 Ma basalt
- Tsf Santa Fe Group, primarily Tesuque Fm.

N W E S

1 0.5 0 1 mi

Figure 21