APPENDIX E

CURRENT UNDERSTANDING OF THE GROUNDWATER REGIME AT LOS ALAMOS NATIONAL LABORATORY

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This appendix summarizes the current understanding of groundwater flow at Los Alamos National Laboratory (LANL) and the conceptual models that have been developed for the purpose of numerical modeling of groundwater flow and contaminant transport. This appendix presents the components by which researchers develop their concepts of the geohydrologic system at LANL.

E.1 Introduction

A comprehensive study of the geology, hydrologic processes, and site characteristics of an area must be understood to formulate a conceptual model of a groundwater flow system. Geologic information must be used in conjunction with the hydrologic data to define hydrostratigraphic units. A geologic unit can be used as a model layer or several units can be combined into model layers if their hydrologic characteristics are similar. Knowledge of the geology is required to define the areal extent of the units. Inferences about the flow system's hydraulic behavior and transport characteristics are drawn from information about geologic structures, lithologic properties, and groundwater geochemistry.

The setting occupied by LANL is geologically and hydrologically complex. Before recent drilling activities were implemented, conceptual models and numerical simulations of regional groundwater flow that had been developed were based on sparse data (Keating, Robinson, and Vesselinov 2005). The knowledge base regarding recharge, discharge, and how waterborne contaminants interact with and move through rock fractures and rock matrix in the vadose zone into perched water zones and the regional aquifer below LANL is growing. In 2005, the LANL contractor was regularly sampling 74 surface monitoring stations and 137 groundwater-monitoring locations based on agreements with the New Mexico Environment Department and the U.S. Environmental Protection Agency. These activities have resulted in modification of the conceptual models (Newman and Robinson 2005). As a result of further agreements, the LANL contractor will be expanding its data collection activities while conducting further analysis of existing data. This understanding of the hydrologic and chemical components at the site will aid in the development of sound conceptual models of flow and transport through the fractures and the matrix of the vadose zone into the saturated zone. It is anticipated that the new data, coupled with improvement in numerical flow and transport models and improved calculational techniques, will enable better prediction of flow and transport of groundwater in the LANL region and more accurately define the ultimate impacts on the regional groundwater resources below LANL.

This appendix provides a framework for understanding the geohydrology and the development of numerical models. In 2005, a series of reports of investigations in the *Vadose Zone Journal* developed conceptual models and discussed flow and transport through the vadose zone to perched groundwater bodies and the regional aquifer below LANL. Some of the reports from this series are discussed. The descriptions are brief and references are provided.

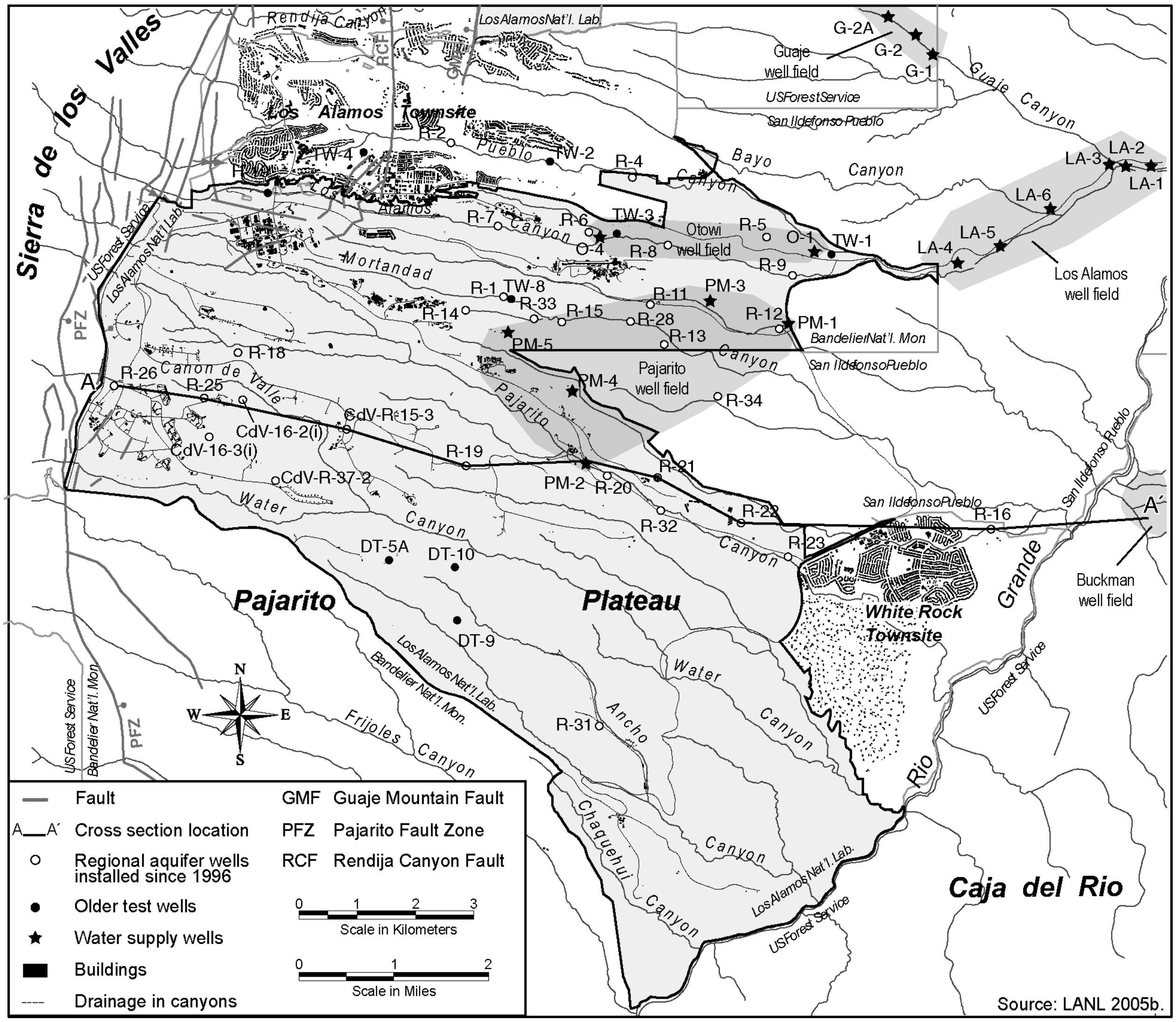
E.2 Regional Setting

LANL and the adjacent communities of Los Alamos and White Rock are located on the Pajarito Plateau (**Figure E–1** and Chapter 4, Figure 4–9). The plateau is an accumulation of east-sloping volcanic material that lies over the western part of the Española Basin and extends from the Sierra de los Valles on the eastern rim of the Jemez Mountains to White Rock Canyon and the Española Valley west of the Rio Grande. The plateau covers an area of about 240 square miles (620 square kilometers), of which about 90 square miles (230 square kilometers) is in the central part of the plateau and includes the area covered by LANL (Broxton and Vaniman 2005) (Figure E–1). The plateau is drained by easterly flowing ephemeral and intermittent streams that have formed deeply incised canyons separated by elongated mesas. The mesas range in elevation from west to east from 7,700 feet (2,350 meters) on the slopes of the Sierra de los Valles to 6,200 feet (1,900 meters) at their ends overlooking the Española Valley (Broxton and Vaniman 2005).

The drainage of the high slopes of the Jemez region (Sierra de los Valles) extends across the tuff outcrops of LANL. Precipitation potential in the north-central part of New Mexico is strongly altitude-dependent. Precipitation in the form of rainfall and snowfall at the higher elevations is about 18 inches (46 centimeters) and about 14 inches (36 centimeters) on the semiarid lower slopes of the area (Broxton and Vaniman 2005). Flow across the Pajarito Plateau from the higher elevations to the Rio Grande has resulted in the mesa and canyon landscape of the area. The steeply cut canyons slope eastward from the Jemez Mountains toward the Rio Grande and are the cumulative result of the alternating humid and arid climatic cycles of the past 2.8 million years (Pleistocene glacial and interglacial). The canyon bottoms are covered with a relatively thin layer of alluvium. The mesa tops display little soil formation and are sparsely vegetated with water-efficient plants. Devitrification of the tuffs on the surface of the plateau has generated a nutrient-poor soil with smectitic clays as its principal argillaceous component. The mesa surfaces are generally quite flat and receive no runoff from the higher elevations. Soil moisture infiltration and runoff is controlled by plant growth and downward transport of precipitation that falls on the mesa surfaces.

E.3 Structural Setting

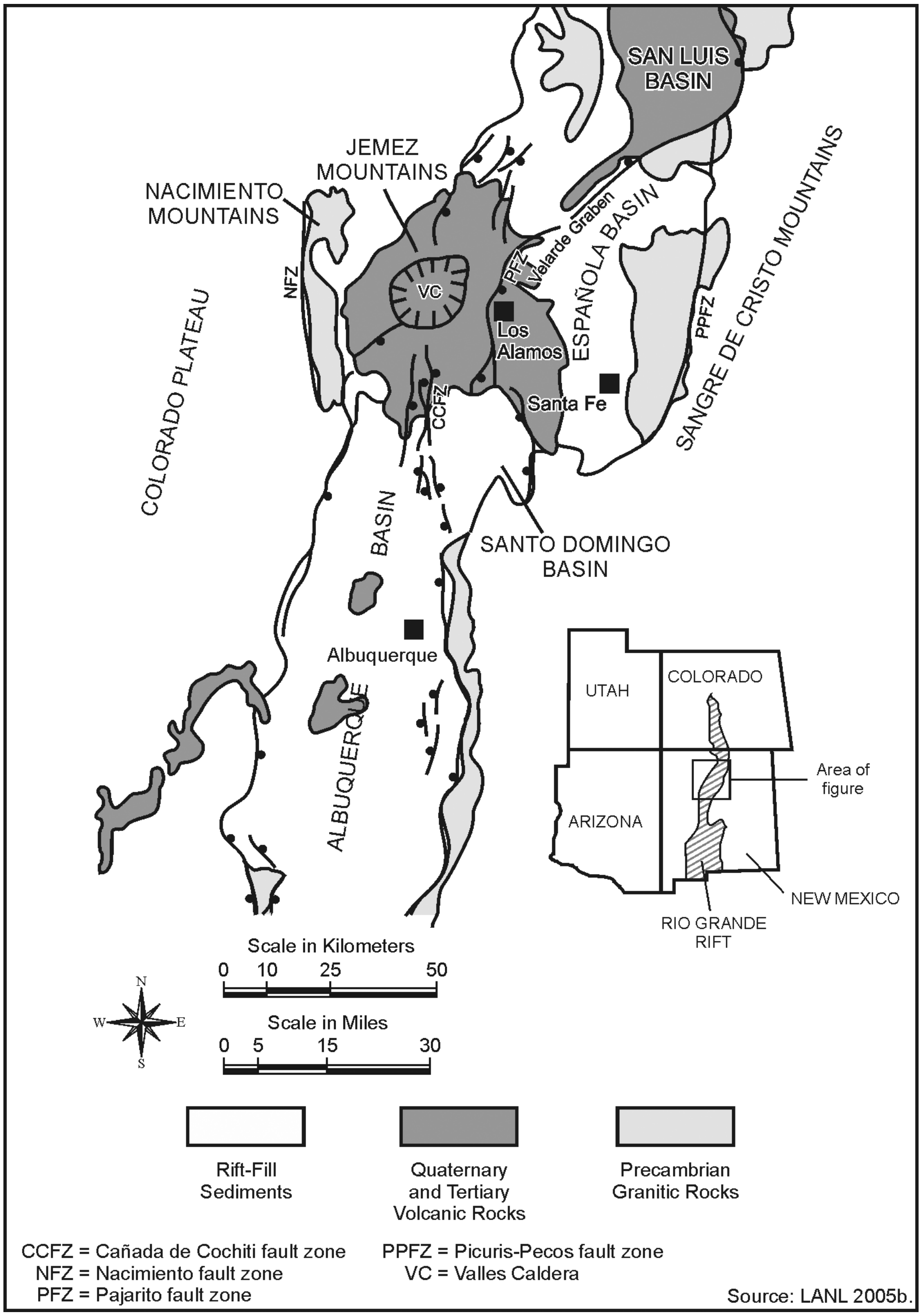
The tectonic episodes that occurred in southern Colorado and north-central New Mexico from the late Campanian stage of the Cretaceous Period (approximately 75 million years ago) through the Eocene Epoch (about 35 million years ago) formed the Rocky Mountains (Cather 2004). The mountain building (termed the Laramide orogeny) was caused by compression of the Earth's crust and formed two large basins that are separated by an uplifted area in north and central New Mexico and extend into southern Colorado. The structures formed were the San Juan Basin to the west and the Raton Basin to the east, which are separated by the San Luis Uplift. The southern part of the San Luis Uplift in the LANL vicinity has been called the Pajarito Uplift (Cather 2004). The Pajarito Uplift is bounded by the Picuris-Pecos fault zone in the Sangre de Cristo Mountains to the east and the Pajarito fault zone to the west (Broxton and Vaniman 2005).



Source: LANL 2005b.

Figure E–1 Location Map of the Central Pajarito Plateau

At the end of the Eocene Epoch, three large-scale processes began and continued until the late Pleistocene Epoch: (1) widespread volcanism, (2) extension of the crust (rifting) from Colorado through New Mexico to west Texas, and (3) extensive erosion of the High Plains east of a rift zone that is delineated by the Rio Grande (from which the zone's name is derived) and the Colorado Plateau west of the Rio Grande rift (Smith 2004). The Pajarito Uplift and other uplifts began to undergo extensional inversion (lowering) along the rift zone. In northern New Mexico, the Rio Grande Rift formed a series of semi-coaxial, elongated, oppositely tilted grabens that became narrow, sediment-filled basins (Smith 2004, Broxton and Vaniman 2005, LANL 2005a) (**Figure E–2**). The basins along the axis of the rift are flanked by a series of discontinuous mountains (Smith 2004). The Española Basin is flanked by the Nacimiento Mountains and the Jemez Mountains to the west and the Sangre de Cristo Mountains to the east. The western margin of the basin is obscured by Jemez volcanics and the margin may be further west at the Laramide Nacimiento Uplift (Smith 2004).



Source: LANL 2005b.

Figure E–2 Locations of Major Structural and Geologic Elements in the Vicinity of Los Alamos National Laboratory

Basins along the Rio Grande Rift are bounded by normal faulting that occurs along the margins and within the basins. The Española Basin is a west-tilting half graben bounded on the west edge by north-trending faults called the Pajarito fault zone (Figure E–2); on the north by northeast-trending transverse faults of the Embudo fault zone; and on the south by northwest-trending transverse faults called the Bajada fault zone (LANL 2005a). Gravity evidence indicates that deep within the Española Basin are three buried grabens associated with the Pajarito and Embudo fault zones (Smith 2004, Broxton and Vanimin 2005). One graben forms the north-trending Los Alamos sub-basin and is near Los Alamos. It is bounded by the Pajarito fault zone on the west and by the buried faults that lie east of the southern projections of Rendija Canyon and Guaje Mountain (Smith 2004, Broxton and Vaniman 2005).

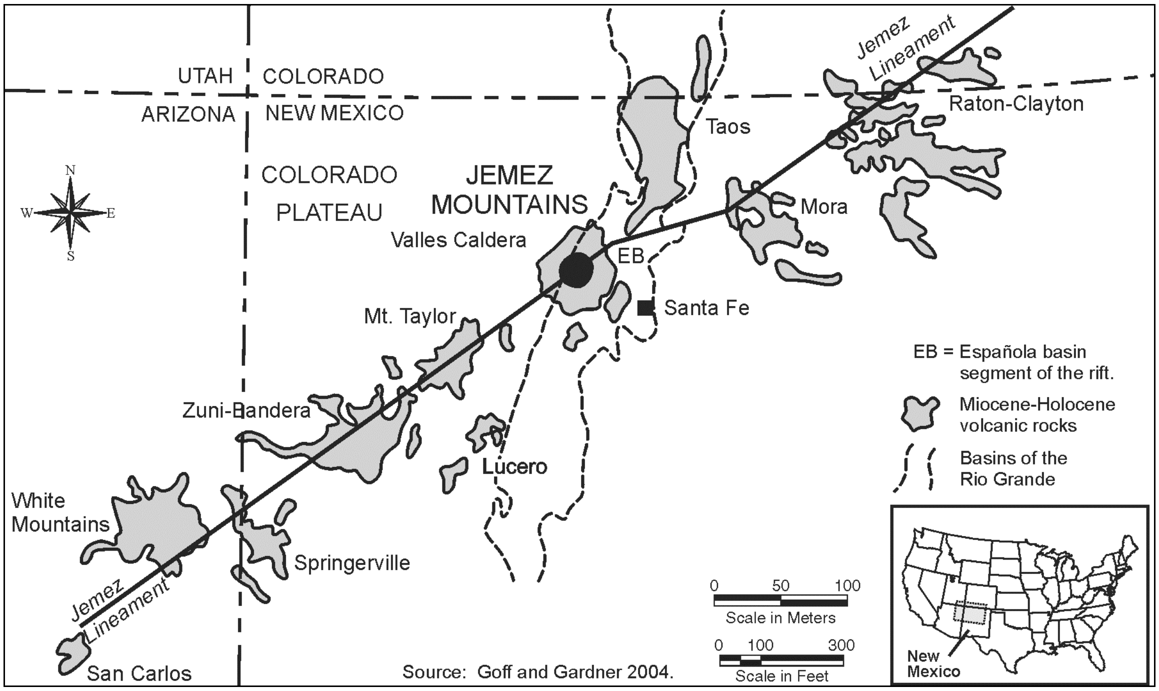
The Pajarito fault zone forms a 400-foot (120-meter)-high escarpment on the western margin of the plateau that looks like a monocline, but examination along the strike reveals a simple normal fault, several small normal faults, and faulted and unfaulted monoclines (Broxton and Vaniman 2005).

Other major fault zones in the LANL area include the north-trending Rendija Canyon fault that is down-to-the-west, and the north-trending Guaje Mountain fault that is also down-to-the-west (Broxton and Vaniman 2005). The faults are parallel in the northern part of the plateau. Additional faults are buried beneath or within the Bandelier Tuffs under the Pajarito Plateau. Faulting also occurs in the older Santa Fe Group rocks on the eastern side of the Española Basin.

E.4 Volcanic Setting

Jemez Volcanic Field

The Jemez Mountains were formed by rift-related volcanism along the Jemez lineament (**Figure E–3**) where the Colorado Plateau abuts the Española Basin. The lineament is a feature that may be a reactivated zone of ancient crustal weakness that trends northeast from eastern Arizona through the Jemez Mountains into southeastern Colorado (Goff and Gardner 2004, Broxton and Vaniman 2005). The volcanic zone that forms the Jemez Mountains overlaps the Colorado Plateau and western Española Basin (Broxton and Vaniman 2005). The region around the Valles Caldera in the Jemez Mountains west of the Pajarito Plateau is the source of most of the volcano-derived material that forms the Pajarito Plateau (Broxton and Vaniman 2005).



Source: Goff and Gardner 2004.

Figure E–3 Location Map of the Jemez Mountains and Valles Caldera with Respect to the Jemez Volcanic Lineament, the Colorado Plateau, and the Rio Grande Rift

For the past 14 million years, the structural province of this region has been extensively affected by tectonic forces. Volcanic activity and subsidence due to rifting were contemporaneous. The early Española Basin was the depositional site of alluvium derived from the Colorado Plateau and later from the Jemez Mountain volcanic field (to the west) and the Sangre de Cristo Mountains (to the east). The volcaniclastics from the Jemez Mountain volcanic field and the Precambrian basement rocks to the east and north formed large alluvial fans that intertongued, forming a vertical intergradation of wedge-shaped layers (Goff and Gardner 2004; Smith 2004; and Broxton and Vanimin 2005).

The Jemez Mountain volcanic field is divided into three groups. The oldest groups are the Keres Group in the south and the Polvadera Group in the north. These are succeeded by the Tewa Group in the central part and on the flanks of the Jemez Mountain volcanic field (Goff and Gardner 2004). This is not to imply that some of the volcanic eruptions that formed these three groups did not occur at the same time. Eruptions in different areas can overlap in time. The Lobato Basalt of the Polvadera Group was somewhat synchronous with the Keres Group basalts (Broxton and Vaniman 2005). LANL staff is conducting detailed examination of basalt and rhyolite outcrops and drill-hole data from beneath the Pajarito Plateau. The new data provide insight into the ages of the rocks and are being used to determine whether the rocks can be correlated throughout the volcanic field.

Knowledge gained from the study of the rock materials present in the LANL area is important to understanding hydrologic and chemical properties when developing conceptual models of groundwater flow and transport. A summary of the units present in the region, including their approximate ages and short descriptions, is given in **Table E–1**. Further descriptions and the relationships of these units with the alluvial units under the Pajarito Plateau are provided in Section E.5, Stratigraphic Framework of the Pajarito Plateau.

In the LANL area, on the east side of the Rio Grande, is the Caja del Rio Basalt Plateau (Figure E–1). It is an exposed part of the Cerros del Rio volcanic field that extends westward 7 miles (11 kilometers) underneath the Pajarito Plateau where it is covered by Bandelier Tuff (Goff and Gardner 2004; Broxton and Vaniman 2005). These volcanics are dissected by the Rio Grande, forming the steep-sided White Rock Canyon.

Caldera formation and subsequent collapse during the Late Pliocene to Late Pleistocene Epochs formed the Jemez Mountains and resulted in significant chemical evolution of the magma-, ash-, and tuff-forming phases. The Bandelier Tuff Formation consists of ashfalls, pumiceous beds, and flow tuffs and ranges up to tens of feet thick in the plateau area and is spread widely east and south of the main caldera. These tuffaceous deposits of the Bandelier Tuff, the Otowi, Cerro Toledo interval, and Tshirege define the geomorphology of the plateau and control the development of the terrain of canyons and mesas at LANL.

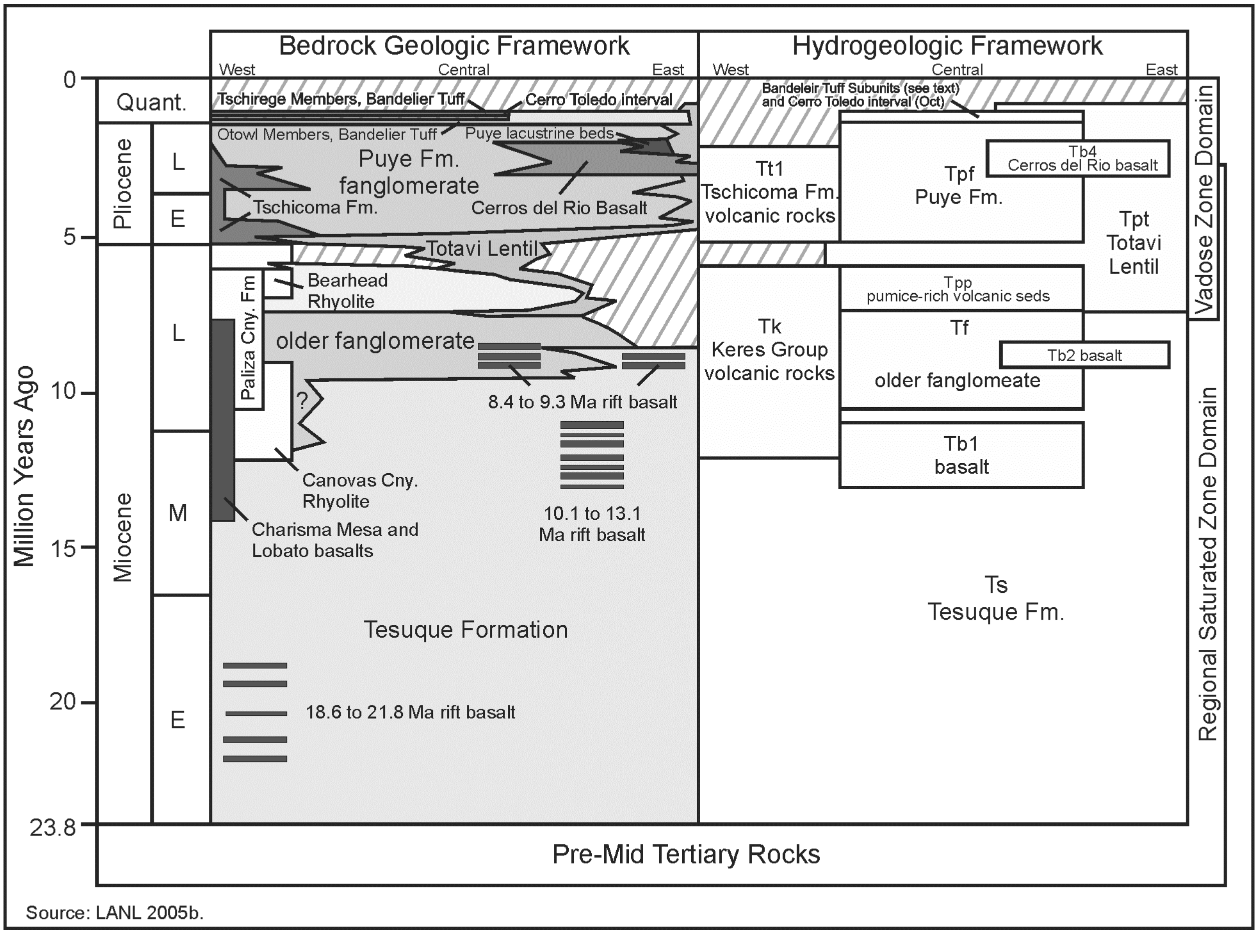
Table E–1 Summary of Jemez Mountain Volcanic Field Names, Rock Types, and Rock Ages

Group Name	*Unit Name*	*Description*
Middle Miocene Units		
Polvadera Group (Oldest unit in north part of LANL. Contemporaneous with parts of the Keres Group.)	Lobato Basalt (14 to 7.6 million years ago)	Multiple flows and cinder deposits coeval with Chamisa Mesa Basalt. Primarily olivine; dikes intruded Santa Fe Formation; interbedded with Santa Fe Formation.
Keres Group (Oldest unit in south part of LANL. Contemporaneous with parts of the Polvadera Group.)	Chamisa Mesa Basalt (13 to 9 million years ago)	Thin flows of basaltic lavas and cinder deposits that overlie rhyolitic tuff; forms mesa tops to the south and northeast of LANL. May be oldest unit in the Jemez Mountain volcanic field.
	Canovas Canyon Rhyolite (12.4 to 8.8 million years ago)	Domes, plugs, and pyroclasts (tuff, ash); weathered; intrudes Paliza Canyon Formation; rhyolite and basalt.
	Paliza Canyon Formation (10.6 to 7.1 million years ago)	Thick flows, domes, and pyroclasts; basalt, andesite and dacite composition.
	Peralta Member (6 to 7.1 million years ago)	Thick, tuffaceous deposits.
	Bearhead Rhyolite (6 to 7.1 million years ago)	Domes, intrusions, and pyroclasts; high silica rhyolites, plugs, domes, and tuffs.
	Cochiti Formation. (< 13 to < 6 million years ago)	Volcaniclastic rocks derived from Keres group rocks and interfingers with Santa Fe Group, Canovas Canyon Rhyolite, and Paliza Canyon Formation.
Late Miocene to Late Pliocene Units		
Polvadera Group	Tschicoma Formation (5 to 3 million years ago)	Large, overlapping domes and flows of dacite, rhyodacite, and andesite.
Late Pliocene to Late Pleistocene Units		
Tewa Group	Bandelier Tuff Pumice fall covered by ash-flow – High silica Rhyolite tuff; exposures at Pajarito Plateau in canyons; forms Pajarito Plateau east of and Jemez Plateau west of the Jemez Mountain Volcanic Zone.	
	Otowi Member (1.61 million years ago)	Guaje Pumice – Eruption formed the Toledo caldera, which was destroyed; less welded than Tshirege Member; basal pumice fall overlain by ash-flow tuffs.
	Cerro Toledo Interval	Cerro Toledo Rhyolite, Rhyolite domes.
	Tshirege Member (1.22 million years ago)	Tsankawi Pumice – Eruption formed the Valles Caldera that subsequently collapsed; basal pumice fall overlain by ash-flow tuffs.
Peripheral Lavas	Basalts of the Cerros del Rio (2.8 to < 1 million years ago)	Basalt lavas and dikes; relationship to Otowi unclear (Goff and Gardner 2004).

Source: Summarized from Broxton and Vaniman 2005 and Goff and Gardner 2004.

E.5 Stratigraphic Framework of the Pajarito Plateau

This section describes the stratigraphy of the Pajarito Plateau and shows how the volcanics described above fit in the sequence of deposition (**Figure E–4**). As mentioned above, volcaniclastics and sediments derived from the volcaniclastics from the Jemez Mountain volcanic field to the west of the Pajarito Plateau and sediment from the Precambrian basement rocks to the east and north formed alluvial fans that intertongued, forming a vertical intergradation of wedge-shaped layers.



Source: LANL 2005b.

Figure E–4 Pajarito Plateau Stratigraphy and Hydrogeologic Units

E.5.1 Santa Fe Group

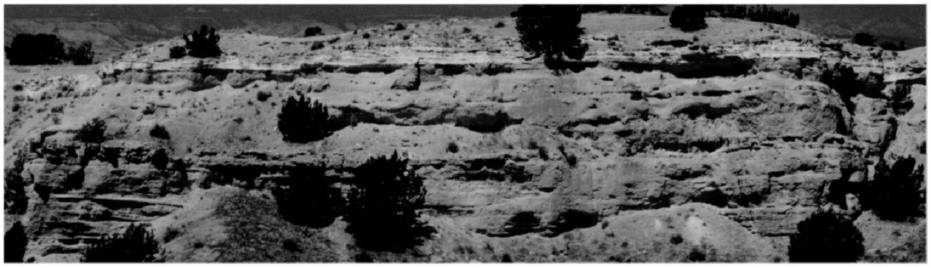
The basins along the Rio Grande Rift average several tens of miles long and are filled with sediments that reach depths of a few tens of thousands of feet. This thick accumulation of sediments in the Española Basin was derived from Precambrian rocks exposed in the highlands north and east of the basin. The basin sediments in north-central New Mexico were first collectively termed the Santa Fe Formation, but the formation was later elevated to a group name and subdivided into several formations. The Tesuque Formation is subdivided into, in ascending order, the Bishop’s Lodge, Nambe, Skull Ridge, Pojoaque, Chama-El Rito, and Ojo Caliente Members and the Chamita Formation. The Puye Formation was added and the Ojo Caliente was elevated to a formation (Broxton and Vaniman 2005). The age of the Tesuque ranges from about 30.45 to 8.48 million years ago. The name Tesuque Formation was used for the youngest formation of the Santa Fe Group in the Española Basin because it was felt that some of the members and formation designations could not be mapped properly because they were not defined over a large enough area (Smith 2004). Interfingered into these sediments are volcaniclastic sediments from the Jemez volcanic field (Broxton and Vaniman 2005).

Most of the rocks that were pre-Española Basin were stripped away in the Pajarito Plateau vicinity. Denudation of Paleozoic and Mesozoic rocks may have been due to erosion of the Pajarito Uplift (Cather 2004, Smith 2004), resulting in the absence of pre-Eocene rocks.

Mesozoic units may be present under the Pajarito Plateau, but at this time there is no supporting evidence (Broxton and Vaniman 2005). There are no exposures of the Santa Fe Group within the LANL boundaries; but on the eastern margins of the Pajarito Plateau and north of LANL, there are exposures in deep canyons such as Rendija Canyon and lower Los Alamos Canyon (**Figure E–5**). East of the Pajarito fault, the Santa Fe Group may be 6,650 feet (2,000 meters) thick, but much thinner (less than 1,640 feet [500 meters]) west of the fault, as indicated by examination of outcrops and drill-hole data (Goff and Gardner 2004, Broxton and Vaniman 2005). Because of the thickness of the Santa Fe Group, not much is known about units that are of hydrologic significance and are older than the Tesuque in the LANL region. Most of what is known about the Tesuque Formation's lithologic and hydrologic properties comes from drill holes.

Outcrop of the Puye Formation, Rendija Canyon (North of LANL).

Outcrop of the Santa Fe Group, Lower Los Alamos Canyon (East of LANL).



Outcrop of the Santa Fe Group, near Española.

Source: LANL 2005b.

Figure E–5 Deep Canyon Exposures

New drill hole data and exposures of rocks near the Rio Grande provide much of what is known about the stratigraphy, lithology, and ages of the Santa Fe Group in the LANL area. A recent attempt to address controversies dealing with stratigraphy and mechanisms that formed the Española Basin is reported in a synthesis of work performed up to the present (Smith 2004). Units believed to be of significance in the Pajarito Plateau area, in ascending order, are the Tesuque Formation, older fanglomerate deposits of the Jemez Mountain volcanic field, the Totavi Lentil and older river deposits, pumice-rich volcaniclastic rocks, and the Puye Formation (Broxton and Vaniman 2005).

Tesuque Formation

The Miocene Tesuque Formation has been characterized from data taken from partially penetrating water production wells for local communities west of the Rio Grande on the eastern edge of the Pajarito Plateau and from exposures east of the Rio Grande. The Tesuque Formation below the plateau is derived from arkosic sediments from the Precambrian Eon and sedimentary rocks of the Sangre de Christo Range to the east, and from Tertiary volcanic material to the north. The partly lithified fluvial sediments are thin-bedded (less than 10 feet, [3 meters]), massive to planar, cross-bedded, light pink to buff sandstones (Smith 2004; Broxton and Vaniman 2005). West of Española, the Tesuque Formation is interbedded with Lobato Basalt (Smith 2004). The Tesuque Formation dips to the west-northwest at about 11 degrees on the east side of the plateau (Broxton and Vaniman 2005).

Miocene Basalts

There are two groups of Miocene basalts underneath the east edge of the Pajarito Plateau. One group is 10.9 to 13.1 million years old near Guaje Canyon north of LANL, and the other is 8.4 to 9.3 million years old and extends from Bayo Canyon on the north end of the eastern part of the plateau to almost the southern end of LANL.

Older Fanglomerate

This unit of the Santa Fe Group is important because high-yield municipal water supply wells with low drawdown have been developed in these rocks. Recent data indicate that the older fanglomerates are widespread below the Pajarito Plateau (Broxton and Vaniman 2005). The unit is made up of volcanic detritus from the Keres Group and possibly from the Tschicoma Formation of the Polvadera Group. Data for the Otowi-4 well show that the older fanglomerate is a thick (1,650 feet [500 meters]) unit made up of dark, lithic sandstone with gravel and cobbles (Broxton and Vaniman 2005). An interpretive cross-section was developed using well data that indicate the older fanglomerate interfingers with the upper Tesuque Formation (Broxton and Vaniman 2005). This is consistent with data from Guaje Canyon wells that suggest that the fanglomerate may have accumulated as the Los Alamos sub-basin subsided (Broxton and Vaniman 2005).

Totavi Lentil and Older River Deposits

The Totavi Lentil (**Figure E–6**) is made up of poorly consolidated and well-rounded sands, gravels, and cobbles formed by the ancestral Rio Grande (Broxton and Vaniman 2005; Goff and Gardner 2004) and is used as a marker bed for supply wells beneath the Pajarito Plateau. The deposits at some locations are conformable with the Puye Formation and are used by some workers to delineate the base of the Puye Formation (Broxton and Vaniman 2005). The Totavi Lentil is highly variable in thickness and ranges from 50 feet (15 meters) to more than 323 feet (98 meters). New well data show a range in thickness of 30 to 100 feet (10 to 30 meters), but data from Well H-19 at the western limit of the Totavi Lentil indicate that the unit is only 10 feet (3 meters) thick.


Source: LANL 2005b.

Figure E–6 Outcrop of Totavi Lentil Along SR 304

New well data show that the unit is coeval with several stratigraphic units and late Miocene river gravels and put the age of through-going rivers (rivers that are regional in nature with origins outside of the study area) at about 6.96 million years (Broxton and Vaniman 2005).

Pumice-Rich Volcaniclastic Rocks

The pumice-rich volcaniclastic rocks have well-bedded horizons of light-colored, reworked tephra-rich sedimentary deposits and subordinate primary ash- and pumice-fall deposits. The rocks consist mainly of tuffaceous sandstones with a few beds of gravels made of reworked lava (Broxton and Vaniman 2005). The deposits of pumice-rich volcaniclastic rocks become thinner eastward over the Pajarito Plateau and are made up of subangular to rounded lapilli (30 percent) and ash and lithic sands (70 to 90 percent). Samples of material from the saturated zone taken from wells in and near the Otowi Well Field (R-5, R-8, R-9, R-12) at the northeastern edge of LANL contained diagenetically altered volcanic glass replaced by smectite, but in other areas the lapilli are still vitric with only some surface oxidation and minor clay development (Broxton and Vaniman 2005). The source rocks may be from the Keres Group volcanism.

Tschicoma Formation

The Tschicoma Formation consists of thick dacite and low-silica rhyolite lava flows erupted from major peaks of the Sierra de los Valles highlands north and east of Valles Caldera and west of Los Alamos (Broxton and Vaniman 2005). The formation interfingers with the deposits of the Puye Formation, becomes thinner eastward across the Pajarito Plateau, and is absent at the eastern end of the plateau (Goff and Gardner 2004, Broxton and Vaniman 2005). The Tschicoma

Formation is lenticular, resulting in variable thicknesses (up to 2,500 feet [762 meters] in the Sierra de los Valles) (Broxton and Vaniman 2005).

Puye Formation

The Puye Formation is a large complex of alluvial fans made up of volcanic material and alluvium. It is well exposed north of the Pajarito Plateau; unconformably overlies the Santa Fe Group; and is intersected by most deep wells on the Pajarito Plateau (Goff and Gardner 2004, Broxton and Vaniman 2005). The formation's source rocks are the domes and flows of the Sierra de los Valles; consequently, the formation overlaps and postdates the Tschicoma Formation (Broxton and Vaniman 2005). The unit has two facies, fanglomerate and lacustrine. The fanglomerate is a widespread intertonguing mixture of stream flow, sheet flow, debris flow, block and ash fall, pumice fall, and ignimbrite deposits and may be up to 1,100 feet (330 meters) thick (Goff and Gardner 2004). The lacustrine facies include lake and riverine deposits in the upper part of the Puye; consist of fine sand, silt, and clay; and may be up to 30 feet (9 meters) thick. The lacustrine deposits are discontinuously exposed along Los Alamos Canyon (Broxton and Vaniman 2005).

Basaltic Rocks of the Cerros Del Rio Volcanic Field

These thick sequences of stacked lava unconformably overlie the Tesuque Formation and intertongue with the upper Puye under the Pajarito Plateau. Basalt outcrops occur east of the river and in Frijole Canyon and White Rock Canyon (Broxton and Vaniman 2005). The features are typical of basalt flows; that is, there is a flow base of vesicular basalt with scoria and clinkers, a collonade structure, a complex overlapping fractured zone, and a flow top with clinkers and scoria. The cooling rates of the basalts influenced the different zones of materials. The lower part of the interior units cooled more slowly than the upper part and formed columnar structures separated by vertical fractures. As cooling rates increased upward, the upper part developed into an array of web-like random fractures. The interflows consist of clastics, ash, and sedimentary deposits. The flows are generally 200 to 300 feet (61 to 183 meters) thick and reach a maximum of 983 feet (300 meters). There are some maar deposits formed when molten basalt encountered water (Broxton and Vaniman 2005).

E.5.2 Upper Pliocene and Quaternary Units

Bandelier Tuff

The Bandelier Tuff comprises the surface and near surface materials in the LANL area. It is an extensive, wedge-shaped pyroclastic unit that gets thinner as it extends eastward from Sierra de los Valles toward the eastern edge of the Pajarito Plateau and was deposited during a recent eruptive phase of the Jemez volcanic complex (1.6 to 1.2 million years ago) (Goff and Gardner 2004; Broxton and Vaniman 2005). The Bandelier Tuff is made up of two similar units, the Otowi Member (the oldest) and the Tschirege Member. The two members are divided into subunits, a basal pumice layer overlain by multiple tuff layers, and their characteristics are based mostly on thermal and depositional features. The two members are separated by a layer of tephras and volcaniclastics and make up the Cerro Toledo interval (Birdsell et al. 2005, Goff and Gardner 2004, Broxton and Vaniman 2005).

Otowi Member of the Bandelier Tuff

The Otowi Member (equivalent to the Qbo hydrologic unit discussed in Section E.6.3) is exposed in Los Alamos Canyon, the deeper canyons to the north at the edge of the Pajarito Plateau, and in the deeper canyons at the edge of the Jemez Plateau west of the Jemez Mountains (Goff and Gardner 2004; Birdsell et al. 2005; Broxton and Vaniman 2005). The basal layer of the Otowi Member, the Guaje Pumice (equivalent to the Qbog hydrologic unit discussed in Section E.6.3), is a pumice layer, ranges in thickness from about 7 to 50 feet (2 to 15 meters) (Birdsell et al. 2005), and averages about 30 feet (9 meters) (Broxton and Vaniman 2005). The pumice, a distinctive marker bed, is overlain by a series of poorly welded rhyolitic ash-flow units that collectively form an extensive, homogeneous rock unit. The Otowi Member is wedge-shaped and thins eastward away from its source, the caldera, over the central part of the plateau. The Otowi Member on the western part of the Pajarito Plateau has two thick zones ranging from 350 to 400 feet (100 to 125 meters) separated by an elongated zone ranging from less than 100 to 300 feet (30 to 90 meters). The thin zone is overlain with a thick deposit of Cerro Toledo sediments (equivalent to the Qct hydrologic unit discussed in Section E.6.3). Erosion removed a large amount of the Otowi Member in some parts of the plateau, leading to a suggestion that the thin zone is indicative of an east-trending drainage incised into the surface of the member (Broxton and Vaniman 2005).

Cerro Toledo Interval

The Otowi and Tshirege Members of the Bandelier Tuff are separated by a stratified sequence of volcaniclastics informally named the Cerro Toledo interval (Goff and Gardner 2004, Broxton and Vaniman 2005). The unit is exposed in Los Alamos Canyon and the deeper canyons to the north at the edge of the Pajarito Plateau. The Cerro Toledo is variable in thickness, ranging from 3 to 390 feet (1 to 120 meters) (Broxton and Vaniman 2005), and is composed of rhyolites that are representative of the Toledo caldera before it collapsed (Goff and Gardner 2004). Dacite and andesite detritus from the Tschicoma Formation are intertongued with reworked Otowi deposits and Cerro Toledo interval rhyolites (Goff and Gardner 2004, Broxton and Vaniman 2005).

Tschirege Member of the Bandelier Tuff

The Tschirege Member is the most distinctive and widely exposed unit on the Pajarito Plateau. It is somewhat more resistant to weathering and erosion in the western part of the plateau because the tuffs are strongly welded and form steep, narrow canyons that become wider downgradient where the tuff is not as strongly welded (Goff and Gardner 2004, Broxton and Vaniman 2005, Birdsell et al. 2005). Like the Otowi, the Tschirege Member has a basal pumice layer, the Tsankawi Pumice, that unconformably overlies the Cerro Toledo sediments (Goff and Gardner 2004; Broxton and Vaniman 2005). The pumice layer is much thinner than the Guaje Pumice and ranges in thickness from 20 to 30 inches (50 to 75 centimeters). The Tsankawi Pumice is overlain by a compound cooling sequence of four welded ash-flows (Goff and Gardner 2004). The thickness of the four units ranges from 200 feet (61 meters) in the north-central part of LANL to 600 feet (183 meters) at the southern edge of LANL (Broxton and Vaniman 2005). The degree of welding in the Tschirege increases westward on the plateau as one approaches the caldera that is the source of the tuff (Broxton and Vaniman 2005). The high temperatures were maintained longer due to the thicker deposits, which increases welding.

Cooling joints in the Otowi tuffs and poorly welded portions of the Tschirege are mostly lacking (Birdsell et al. 2005).

The four mappable cooling units of the Tschirege tuffs have been subdivided into subunits based on distinctive lithologic characteristics because the units occupy a "significant portion of the vadose zone" (Broxton and Vaniman 2005). The unit names are also used for the hydrologic units discussed in Section E.6.3. Briefly, from the oldest to the youngest, the designations for the units are:

> **Qbt 1g**. This unit is a porous, nonwelded tuff with no devitrification or vapor phase alteration of the glass (g). The unit has a resistant caprock that protects the soft tuffs underneath, forming steep cliffs.
>
> **Qbt 1v**. This unit is nonwelded, porous, crystalline tuff that has undergone vapor-phase (v) crystallization of pumice and glass shards. The lower part (Qbt 1vc) is a collonade tuff with columnar cooling joints. The tuff alternates between cliff-forming and slope-forming units.
>
> **Qbt 2**. This unit is a series of surge beds, forming brownish vertical cliffs. The unit conformably overlies Qbt 1v in some parts of LANL. The unit is dense and porosity is lower than the other units. Welding increases upward.
>
> **Qbt 3**. This unit is a nonwelded to partly welded, vapor-phase tuff that forms the cap rock of mesas. It grades upward from a soft basal unit that is a purple-gray, porous, unconsolidated, crystal-rich, nonwelded tuff to a partly welded, white cliff-forming tuff that becomes moderately to densely welded in the western part of LANL. Qb 3t, a subunit of Qbt 3, is moderately to densely welded ash-flow tuff in the far-western part of LANL and is transitional to Qbt 4.
>
> **Qbt 4**. This unit is a complex unit in the western part of LANL made up of nonwelded to partly welded ash-flow tuffs with pumice and surge deposits in the lower part of the unit and densely welded ash-flow tuffs that form caprocks. The unit has mostly undergone devitrification and vapor phase alteration, but locally there are thin rhyolitic, vitric ash-flow tuff deposits.

Alluvium

Alluvium of the Holocene and Pleistocene occurs on the canyon floors at LANL. Continuous alluvial deposits from the Pleistocene occur at the foot of the eastern slopes of Sierra de los Valles and on the Pajarito Plateau on top of the Bandelier Tuff (Broxton and Vaniman 2005). The alluvium on the floors of small canyons that head (begin) on the Bandelier Tuff consists of Bandelier Tuff detritus. Canyons that have headwaters farther west in the Sierra de los Valles have detritus from the Bandelier and the Tschicoma Formations. The alluvium consists of unconsolidated fluvial sands and gravels and forms stratified lenticular-shaped deposits along the canyon floors and at the mouths of canyons. The alluvium deposits intertongue with the colluvium, which may have blocks of material up to 10 feet (3 meters) in cross-section at the bases of the walls of the canyons. The deposits are cross-cut by the ephemeral or intermittent streams, forming complex deposits on the canyon floors and at the mouths of the canyons. The alluvial deposits vary in thickness within the canyons and from canyon to canyon. Alluvium thickness in Pueblo Canyon ranges from 11 feet (3.4 meters) on the west side of the plateau to about 18 feet (5.5 meters) at the confluence with Los Alamos Canyon (Broxton and Vaniman 2005; Robinson et al. 2005); at Mortandad Canyon, the range is from 1 to 2 feet (0.3 to 0.6 meters) at its headwaters to 100 feet (30 meters) at the eastern margin of LANL.

E.6 Hydrogeology

E.6.1 Comparison of the Bedrock Geologic Framework with the Hydrologic Framework

Cross-sections that represent subsurface geology result from the integration of:

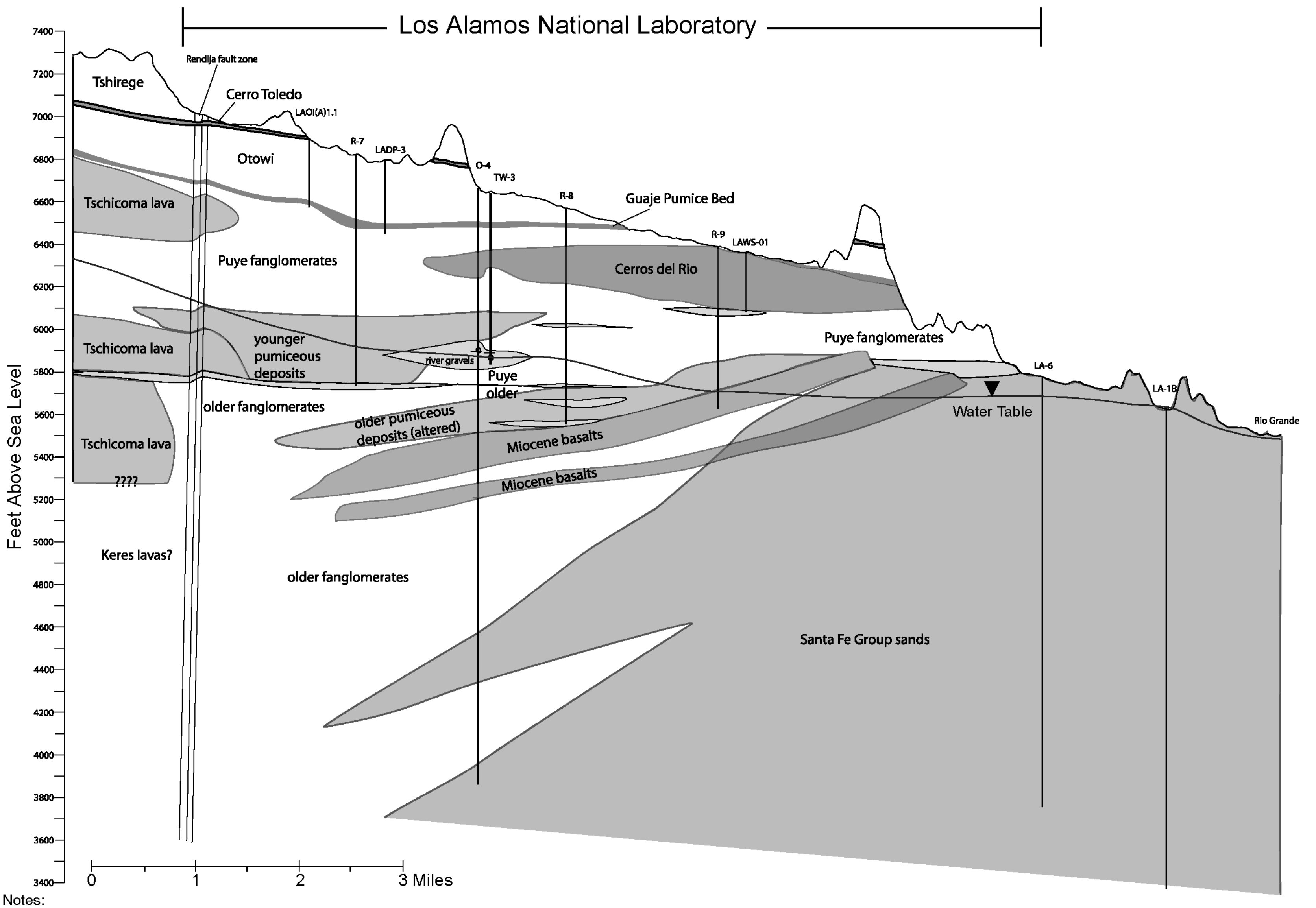
- Structural geologic observations consisting mostly of the elevations of contacts between rock bodies of different character measured in wells,
- Stratigraphic descriptions of the character and thickness of individual rock bodies from wells and the study of outcrops, and
- Down-hole geophysical studies.

The observations from wells define the fundamental data necessary to accurately construct cross-sections. The cross-sections, structural contour maps, and interpreted character of the rocks around LANL serve as the framework for flow and transport models (Figure E–4). Cross-sections drawn from west to east across the Pajarito Plateau are presented in **Figures E–7** (along Los Alamos Canyon) and **E–8** (along Pajarito Canyon).

The comparison shows how the geologic units differ from the hydrologic units. The geologic units are combined because they possess similar hydrologic properties, which allows for modeling efficiency. This does not imply that the hydrologic units are homogeneous regions of unvarying properties. Large local internal variations in hydrologic properties have been noted and are due to rock texture, composition, and structure. The basis for defining the hydrologic units is that the gross character of a unit can be modeled relatively consistently. The following discussion compares the geologic and hydrologic frameworks (Broxton and Vaniman 2005).

E.6.2 Groundwater Occurrence

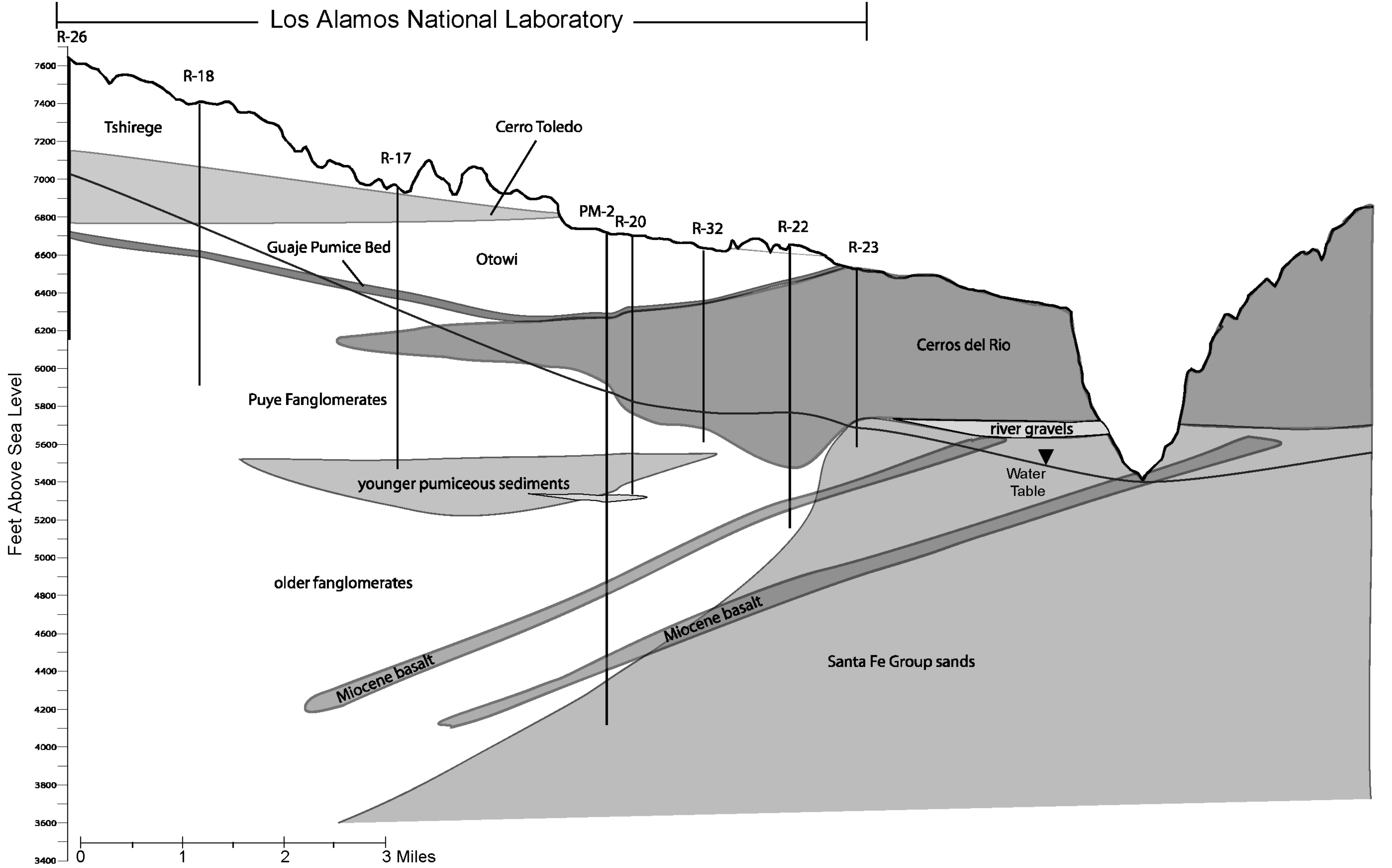
There are three modes of groundwater occurrence in the Pajarito Plateau: (1) perched alluvial groundwater in canyon bottoms; (2) zones of intermediate-depth perched groundwater whose location is controlled by availability of recharge and by subsurface changes in permeability; and (3) the regional aquifer beneath the Pajarito Plateau (Broxton and Vaniman 2005). In wet canyons, stream runoff percolates through the alluvium until downward flow is impeded by less permeable layers, maintaining shallow bodies of perched groundwater within the alluvium. Contaminant distributions in the groundwater under the Pajarito Plateau suggest that the three systems may be in communication under certain conditions (Robinson, McLin, and Viswanathan 2005). The hydrogeology of the Pajarito Plateau is typical of the semi-arid, sediment-filled basins along the Rio Grande Rift in that the basins receive recharge from mountain ranges along the margins (Broxton and Vaniman 2005). This section discusses alluvial, perched, and regional groundwater.



Notes:
1. The thickness of geologic units has been exaggerated on this figure to illustrate unit relationships and topography.
2. To convert feet to meters, multiply by 0.3048.

Source: LANL 2005b.

Figure E–7 Conceptual Cross-Section Across the Pajarito Plateau Along Los Alamos Canyon



Notes:
1. The thickness of geologic units has been exaggerated on this figure to illustrate unit relationships and topography.
2. To convert feet to meters, multiply by 0.3048.

Source: LANL 2005b.

Figure E–8 Conceptual Cross-Section Across the Pajarito Plateau Along Pajarito Canyon

The geology of the regional aquifer was discussed above. Knowledge of the origin and depositional history of the rocks at LANL, coupled with groundwater sampling and aquifer testing, helps to determine the hydraulic properties of the regional aquifer. Single well tests of small volumes of rock have been conducted by withdrawing water from or injecting water into a well and measuring the rate of recovery of the original water surface. Multiple-well tests of large volumes of rock involve pumping a well and then making observations of the effects on nearby wells completed in the same interval. Extensive downhole geophysical studies are also a part of the deep-well program. Studies of rock properties and geochemical information with hydrologic testing results provide a basis for evaluating travel times and transport in the vadose zone (Keating, Robinson, and Vesselinov 2005). Summaries of these properties obtained from well tests, sampling programs, and analyses have been reported previously (Keating, Robinson, and Vesselinov 2005; Robinson, McLin, and Viswanathan 2005; Birdsell et al. 2005). Potentiometric maps, hydraulic gradients, and permeability data for the regional aquifer have also been discussed (Keating, Robinson, and Vesselinov 2005).

E.6.2.1 Alluvial Groundwater

Alluvial groundwater in the LANL area primarily occurs in canyons that originate in the Sierra de los Valles or in the Pajarito Plateau watersheds. Groundwater in the canyons is supported by seasonal runoff from the mountains, by episodic precipitation events on the plateau, perennial springs, and by discharge from LANL outfalls. Liquid wastewater from LANL released to the outfalls above the canyons was responsible for contamination of alluvial groundwater in the past. The wastewater also plays a part in the hydrogeology of the canyons.

As mentioned above in the stratigraphy section, the canyon floors are covered with alluvium of variable thickness and consist of fluvial sands, gravels, and cobbles. The alluvium is derived from the mountains to the west and from rocks that have been incised by the ephemeral and intermittent streams that formed the canyons (parts of some canyon streams have perennial flow). The alluvium is intermingled laterally with colluvium from the canyon walls. Groundwater in the canyons occurs above permeability barriers at the base of the alluvium above the Bandelier Tuff or above well-sorted tight sequences of canyon floor alluvium. Seasonal variation in the amount of snowmelt or storm runoff affects the saturated thickness and lateral extent of alluvial groundwater.

E.6.2.2 Deep Perched Groundwater

The extent and nature of deep perched water beneath Pajarito Plateau has been investigated to determine whether the alluvial systems on the plateau are in communication with the deep perched water or the regional aquifer and whether there is a potential for contaminants to travel to the regional groundwater (Robinson, Broxton, and Vaniman 2005). At the time of the investigation, 33 perched water zones had been identified in 29 wells. The study defined perched water "as a hydrologic condition in the rock or sediment above the regional aquifer in which the rock pores are completely saturated with water." Perched water may occur because of capillary barriers or because of low permeability barriers coupled with structures in the stratigraphic section. For example, faults may intersect hydraulically conductive zones with low permeability materials and block flow paths. Another cause may be that, when a saturated zone becomes unsaturated due to a decline in water level, water may become trapped in a zone of high permeability where it is unable to move to the new level.

The perched zones at LANL do not have enough water to warrant putting in municipal water supply wells, but the perched groundwater zones are important for four reasons: (1) the water is protected under state law; (2) transport rates through the unsaturated rocks are affected by the chemistry of the perched zones; (3) the zones restrict vertical movement of groundwater or may indicate the presence of fast-paths; and (4) the zones can be used for monitoring movement of groundwater toward the regional aquifer (Robinson, Broxton, and Vaniman 2005). The deep, perched zones get water from surface and alluvial groundwater associated with the large canyons that head in the Sierra de los Valles; deep, perched water below the smaller canyons on the plateau can also be recharged by liquid effluent from LANL. The deep, perched water zones have a saturated thickness ranging from 100 to 400 feet (30 to 120 meters) (Robinson, Broxton, and Vaniman 2005).

Perched water bodies are important elements of the hydrogeology of the site for several reasons. There is a probability that the zones can intercept contaminants being transported downward through the vadose zone. The perched water can be a permanent or long-term residence for contaminants because the chemical makeup of the rocks may result in adsorption. Perched water can also serve as a place where dilution occurs, lowering the concentration of contaminants. There is a possibility that perched zones may be intersected by streams in the lower parts of the canyons, resulting in lateral flow under the influence of gravity out of the canyon walls into the alluvial aquifer and subsequently to the Rio Grande.

E.6.2.3 Regional Groundwater

The regional aquifer below LANL is very deep (up to 1,200 feet [360 meters]) and is separated from the surface by a thick vadose zone with some perched water zones (Keating, Robinson, and Vesselinov 2005). The depth to the water of the regional aquifer on the eastern part of the plateau near the rim of White Rock Canyon is about 614 feet (200 meters), about 210 feet (65 meters) above the level of the Rio Grande (Broxton and Vaniman 2005). It has been reported that a well drilled in the lower Los Alamos Canyon near the Rio Grande flowed to the surface when installed in the regional aquifer, indicating confined or semi-confined conditions, and that there are seeps and springs in White Rock Canyon (Broxton and Vaniman 2005).

Sedimentary bedrock units at the top of regional saturation zones below the Pajarito Plateau at LANL include the Puye Formation (Tpf), pumiceous deposits (Tpp), older fanglomerate (Tf), and Tesuque Formation (Ts). The volcanic rocks in which groundwater occurs are the Cerros del Rio basalts (Tb4), the Tschicoma Formation (Tt), and Miocene basalt (Tb2) (Broxton and Vaniman 2005). Groundwater recharge to the regional aquifer under the Pajarito Plateau comes from underflow from the Sierra de los Valles and from drainages across the plateau (Kwicklis et al. 2005). The stratigraphy of the rocks is discussed in Section E.5. The most productive wells on the plateau occur in the central part of the plateau within the basin fill deposits consisting of the Puye Formation, the pumiceous deposits, the Totavi Lentil, the older fanglomerates, and the Tesuque Formation. The wells have screens up to 1,600 feet (500 meters) long spanning these units (Broxton and Vaniman 2005). The Tesuque is the primary productive unit in the eastern part of the plateau, in Guaje Canyon, and in the lower Los Alamos Canyon.

E.6.3 Hydrogeologic Units

Basal Confining Units

The rock units that occur below the regional aquifer are considered to be all of the units below the Tesuque Formation, including Precambrian igneous and metamorphic rocks, Paleozoic and Mesozoic sedimentary rocks, and mid-to-upper Tertiary terrestrial sediments.

Santa Fe Group Rocks

Hydrologic unit Ts is generally considered to be equivalent to the Tesuque Formation. The lithology of the unit is silty to sandy with some basalt and flow breccias (Tb1). The basalts are about 11 to 13 million years old and have intercalated sedimentary units. Water supply wells in the lower Los Alamos Canyon completed in this unit yield about 600 gallons per minute (2,200 liters per minute), and in the western part of LANL where the Ts is coarser, supply wells yield about 1,000 gallons per minute (3,800 liters per minute). Flow in the volcaniclastics and altered basalts is associated with fractures; the interflow breccias are plugged with secondary minerals (Broxton and Vaniman 2005).

Older Fanglomerate

This hydrogeologic unit (Tf) is a thick sequence of gravel and cobble beds and interbedded sandstones. It has been identified as the most productive zone (1,000 gallons per minute [3,800 liters per minute]) in the LANL area. The Tf is vertically heterogeneous and anisotropic because of the bedding, but may be strongly isotropic in the lateral direction. Reinterpretation of earlier well logs puts the contact with the Ts at the transition zone where coarse grain gravels and cobbles overlay sands and silts (Broxton and Vaniman 2005). Basalts (8.4 to 9.3 million years old) and intercalated sedimentary rocks in the Tf are designated as Tb2. Hydrologic unit Tk is intertongued with the Tf and is made up of Keres Group volcanic rocks.

Hydrologic unit Tpt represents the Totavi Lentil and older river deposits that make up a poorly consolidated conglomerate. Data from one water production well completed in this interval show that 18 percent of the water produced comes from only 2.5 percent of the screened interval (Broxton and Vaniman 2005). The hydrologic unit Tpp below the Tpt is a well-stratified, heterogeneous, pumice-rich, volcaniclastic rock. It is fine grained and more porous than the more coarsely grained overlying and underlying hydrologic units. The unit is anisotropic because, vertically, the alternating fine grained bedding is less hydraulically conductive than in the lateral direction. These pumice rich rocks also have a lower bulk density than Tpt and Tf (Broxton and Vaniman 2005; Birdsell et al. 2005).

Beneath the pumice deposits is the hydrologic unit Tpf that is similar to, but predates, the lacustrine deposits of the Puye Formation (Birdsell et al. 2005). The lacustrine deposits are equivalent, which may indicate that the rocks are contemporaneous (Broxton and Vaniman 2005). The Tpf is a deposit of coalesced alluvial fans and consists of much coarser material than the Tpp; like the Tpp, however, it is heterogeneous and anisotropic. Vertically, heterogeneity is due to layering; laterally, it is due to cross-cutting and variable grain size characteristic of fluvial deposits in an alluvial fan environment. It has been hypothesized that the hydraulic conductivity in the vertical direction is less than the hydraulic conductivity in the horizontal direction parallel to the bedding planes (Broxton and Vaniman 2005).

Basaltic Rocks of the Cerros del Rio Volcanic Field

The heterogeneous hydrologic unit Tb4 basalts are intercalated with subordinate amounts of upper Puye Formation and constitute the top of the regional aquifer at the southeast corner of LANL (Birdsell et al. 2005; Broxton and Vaniman 2005). As noted above, these basalts are exposed on the east side of the Rio Grande. In the LANL region, the basalts are located under the central and eastern part of the Pajarito Plateau. The connected porosity of the highly brecciated clinker and scoria zones and sediments at the tops and bottoms of the stacked lavas may extend for hundreds of yards or may be limited in some areas where the voids are filled with clay minerals (Birdsell et al. 2005; Broxton and Vaniman 2005). The dense lava flow interiors are impermeable, with flow of gases and liquid water restricted to fractures. Flow in the scoriated breccia zones is lateral along the beds and mostly vertical in the interflow zones.

Bandelier Tuff

The stratigraphic divisions presented in Table E–1 were retained for the hydrologic units because the rock properties for the stratigraphic subunits are laterally ubiquitous and traceable throughout the plateau (Broxton and Vaniman 2005). This section presents the hydrologic units of the Bandelier Tuff with descriptions from oldest to youngest (Broxton and Vaniman 2005, Birdsell et al. 2005, Springer 2005).

Ash-flow tuffs and fall deposits (the Guaje Pumice Bed) of the Otowi Member are hydrologic units Qbog and Qbo, respectively. Qbo is uniform with respect to vertical density and density-porosity profiles in the central and eastern parts of the plateau, but is more variable in the west where changes are more abrupt (Broxton and Vaniman 2005). The ash-flow tuffs of the Otowi do not have pervasive cooling joints found in the welded tuffs in the upper Bandelier (Birdsell et al. 2005). The Guaje Pumice Bed (fall deposits) at the base of the Otowi Member is designated hydrologic unit Qbog. It is well sorted and stratified; has less matrix ash than the other Bandelier units; and is an excellent marker bed between the Bandelier Tuff and the units below it.

The stratified volcaniclastic deposits of the Cerro Toledo Interval are designated as hydrologic unit Qct. Because the unit consists of rocks that are variable in grain size, sorting, and bedding thickness, a strong vertical anisotropy exists above Qct within the Bandelier (Broxton and Vaniman 2005). These characteristics provide a favorable setting for perched groundwater.

The upper Tshirege Member is a complex hydrologic unit of welded ash-flow tuffs separated by poorly welded tuffs and a basal unit of pumice fall deposits. The welded tuffs have joints and fractures caused by cooling and tectonic processes that die out in the nonwelded layers (Birdsell et al. 2005). The basal hydrologic unit Qbt t is equivalent to the Tsankawi Pumice Bed (Broxton and Vaniman 2005). Unit Qbt t is overlain by hydrologic subunits Qbt 1g and Qbt 1v. Qbt t and Qbt 1g are the only ash and pumice falls in the Tshirege that are made up of similar, unaltered volcanic glass.

Volcanic glass above Qbt 1g in hydrologic unit Qbt 1v has undergone post-depositional devitrification and vapor-phase crystallization. These processes may affect grain size and decrease effective porosity by creating poorly connected pore spaces (Broxton and Vaniman 2005). Unit Qbt 1vc is indurated and poorly welded with a system of well-developed columnar joints. Unit Qbt 1vu is generally nonwelded to partly welded, but lacks extensive jointing (Broxton and Vaniman 2005, Birdsell et al. 2005).

Hydrologic unit Qbt 2 is separated from the altered beds of unit Qbt v by a thin pyroclastic surge bed in the eastern part of the Pajarito Plateau; but in other parts of the plateau, Qbt 1v grades into Qbt 2. In the western part of the plateau, density and density-porosity profiles indicate that Qbt 2 has a cooling break present at its center. The break is not present in the eastern part of the plateau. Upper Qbt 2 is strongly welded, becomes less welded down-section, and has higher bulk densities than other Tshirege units.

Hydrologic unit Qbt 3 is strongly welded in the western part of the plateau and becomes less welded eastward. The strongly welded interior of Qbt 3 has a high bulk density and low density porosity. Hydrologic unit Qbt 4 is a nonwelded to strongly welded unit and is present only in the western Pajarito Plateau.

E.7 Conceptual Models

Potential contamination of the regional aquifer below LANL is of major concern. It is the responsibility of LANL to determine whether past contaminant releases pose a threat to human health. Flow and transport mechanisms through the vadose zone are being examined. This section discusses recent papers in the *Vadose Zone Journal* published on August 16, 2005. The papers collectively describe the work that has been completed or contemplated for the purpose of developing conceptual models of the hydrogeology and numerical models of groundwater flow and transport under the Pajarito Plateau in general and under LANL in particular. The journal articles summarize extensive observational data regarding deep perched water on the plateau and discuss the controls on the distribution of deep perched water and the ways perched zones may develop (Robinson et al. 2005). There is a description and a numerical model of the regional aquifer below the Pajarito Plateau that is used for determining fluxes and transport (Keating, Robinson, and Vesselinov 2005). There is a report on net infiltration on the plateau, which is a major concern when modeling groundwater flow under LANL and streamflow on the plateau (Kwicklis et al. 2005). A comprehensive discussion of a statistical analysis of hydrologic properties also is presented (Springer 2005). Several articles discuss the roles of matrix and fracture flow within the Bandelier Tuffs and basalts (Robinson, Broxton, and Vaniman 2005, Levitt et al. 2005, Stauffer and Stone 2005). There is also a summary paper that describes the hydrogeologic setting and site history of LANL (Newman and Robinson 2005).

Conceptual models constantly change as knowledge about hydrologic processes and events that control groundwater movement increases for a particular site. The following section includes a discussion of the conceptual models, numerical model development, modeling results, and conclusions. The papers are presented in the order of the hydrostratigraphy of the region: the vadose zone; the deep perched zones; and the regional aquifer.

E.7.1 Geochemical Conceptual Model

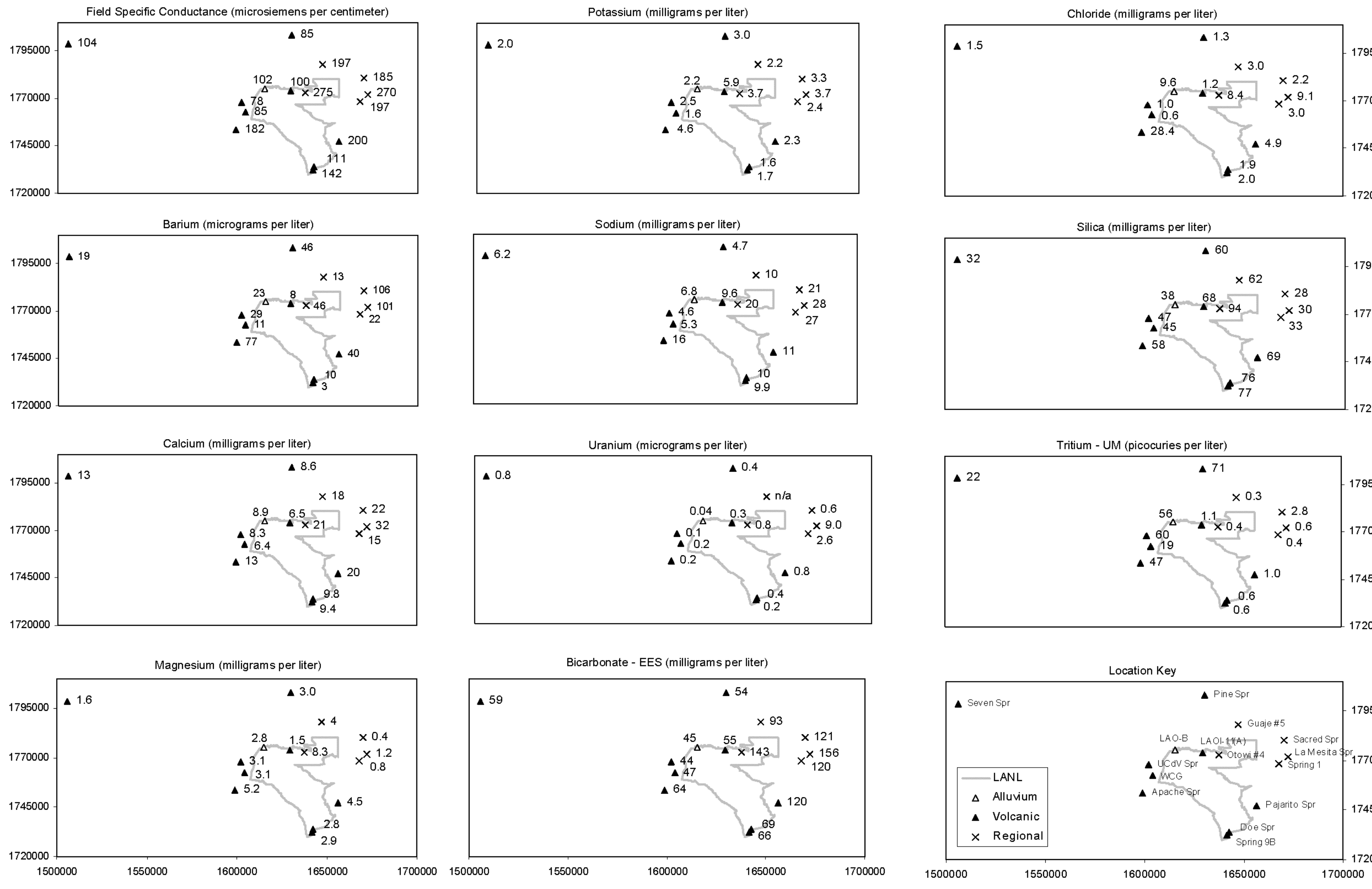
This section is a discussion of the geochemistry of the groundwater in the LANL region as presented in *Los Alamos National Laboratory's Hydrogeologic Studies of the Pajarito Plateau: A Synthesis of Hydrogeologic Workplan Activities (1998-2004) (Hydrogeologic Synthesis Report)* (LANL 2005b). First, the *Hydrogeologic Synthesis Report* discusses a geostatistical methodology of reducing the data from many sources outside the area that might have been contaminated and develops a groundwater chemistry baseline. Second, it presents conceptual models of each reach of canyon drainage that is thought to be unique in its natural and artificial flow and its contaminant transport history. Third, alternative models of contaminant transport to the perched water bodies and the regional groundwater are presented to relate the contaminant concentrations, recharge, and transport processes to probable sources, predominantly the canyon bottom alluvial aquifers. Last, it presents a discussion of conceptual models of the hydrogeology and geochemistry of the canyon springs.

The discussion of the components of geochemical conceptual models was broken into seven parts in the *Hydrogeologic Synthesis Report*. The components are:

- Natural geochemical composition of groundwater,
- Residence time of contaminant ions in the perched alluvial aquifer and the rocks of the vadose zone,
- Reactive minerals controlling groundwater composition and solute mobility,
- Adsorption and precipitation reactions,
- Redox conditions,
- Chemical speciation, and
- Colloids.

Natural Composition of Groundwater

Groundwater sampling to establish a baseline (background) of the chemistry of groundwater in the LANL area was conducted from 1997 to 2000. The composition of natural groundwater in the LANL area ranges from calcium-sodium bicarbonate water at the Sierra de los Valles to sodium-calcium bicarbonate water east and northeast of LANL. Sodium bicarbonate groundwater occurs in deep wells in the lower Los Alamos Canyon and along the Rio Grande and in springs in White Rock Canyon (LANL 2005b). This characterization of the natural groundwater permits the discrimination of natural components in the groundwater from manmade contaminants. **Figure E–9** shows the average concentrations of solutes, including specific conductance, major cations and anions, silica, tritium, and several trace elements such as uranium and barium from six sampling rounds.



Source: LANL 2005b.

Figure E–9 Average Spatial Distribution (n=6) for Key Analytes in Los Alamos National Laboratory Background Wells and Springs

Residence time

Residence time refers to the distribution of the ages of groundwater in the various groundwater environments under the Pajarito Plateau. Determining the residence time helps determine transport rates through the rocks. The residence time of natural major ions and trace elements in natural groundwater under the Pajarito Plateau increases from west to east and with depth in all modes of groundwater occurrence. Measurements of tritium in groundwater from within the Sierra de los Valles fractured volcanic rocks indicate that the groundwater is less than 60 years old; however, groundwater in the discharge area at White Rock Canyon ranges from 3,000 to 10,000 years old (LANL 2005b). Carbon-14 dating of regional groundwater in the LANL area indicates that a component of the groundwater is several tens of thousands of years old, becoming older from west to east. The presence of tritium indicates that younger water is mixing with the older water. Future studies are planned to determine the fractions of young and old water (LANL 2005b).

Reactive minerals

Groundwater reacts with the minerals in rocks through which it passes or in which it is stored. These reactions control basic chemical conditions such as pH and influence mineral precipitation and dissolution, as well as sorption of ions from groundwater by minerals. These are important controls on the evolution of groundwater as it migrates and on the mobility of contaminant ions.

In the natural groundwater, sodium, calcium, and bicarbonate are the most abundant major ion solutes. Silica is the second most abundant due to the interaction of volcanic glass with the groundwater. Average concentrations of natural arsenic and fluoride were highest in the Cerros del Rio basalts. Average concentrations of dissolved natural barium, boron, bromide, strontium, and uranium in the regional aquifer were highest at La Mesita Spring. Silica-rich rocks such as the Bandelier Tuffs contain more natural uranium than the basalts, which are silica-poor. Uranium in trace minerals such as zircon may exceed 1,000 parts per million, but zircon is highly refractory and has a low aqueous solubility ($10^{-15.4}$ molar at pH 7); consequently, it does not dissolve readily in the natural groundwaters at LANL. Some uranium is associated with volcanic glass in the Bandelier Tuff. In comparison with zircon, volcanic glass has a higher aqueous solubility ($10^{-27.1}$ molar at pH 7), but a low concentration of uranium. Therefore, even though the leachability is higher for volcanic glass, the concentration of uranium in perched water in the Bandelier Tuff is low (LANL 2005b).

Dissolved organic carbon is a component of groundwater derived from leaching solid organic matter from forests and grasslands. At LANL, organic matter is found in the perched water in the intermediate zones and in the regional aquifer and is typically less than 2 milligrams of carbon per liter. Higher concentrations are found in alluvial groundwater, soil, and surface water (20 milligrams of carbon per liter) (LANL 2005b). Ash from the Cerro Grande Fire in May 2000 increased the amount of leachable carbon in the LANL area. The increased concentration of total organic carbon can be used as a tracer for tracking recharge. Perched zones in the Cellos del Rio basalt in Los Alamos Canyon have exceeded 300 milligrams of carbon per liter.

Calcite, smectite, hydrous ferric oxide, manganese hydroxide, and zeolites are highly adsorptive for trace elements including chromium, lead, strontium, and thorium. As groundwater flows through the intermediate perched zones, the soluble silica glass that is present reacts with the groundwater and forms clay minerals, including kaolinite and smectite. Smectite increases the adsorption capacity of aquifer material under circumneutral (6.5 to 7.5) pH conditions. These interactions are only partially known in the specific groundwater environments beneath the Pajarito Plateau, but knowledge is expanding as new programs are being incorporated.

Adsorption and Precipitation

Adsorption and precipitation are the principal mechanisms that retard the transport of contaminants and keep them in residence in the vadose zone. These reactions are well documented for most of the contaminant ions present under the Pajarito Plateau. The specific groundwater environment in terms of pH and parallel mineral reactions are important controls on sorption and precipitation reactions. Definition of those relationships is an interactive process that is underway in the areas of specific concern at LANL (LANL 2005b). Geochemical processes increase concentrations (measured as total dissolve solids) of trace elements downward from the alluvial aquifer to perched water and on to the regional aquifer from west to east due to residence time and rock and water interactions such as adsorption-desorption (LANL 2005b). Relatively fresh water in the form of precipitation recharges the groundwater at the Sierra de los Valles and reacts with the rocks as it moves along flow paths, becoming more mineralized toward its discharge points. Notice in Figure E-9 that tritium decays along the flow path from west to east and that the concentration decreases within the noncontaminated intermediate perched water and the regional aquifer.

Redox Conditions

Redox condition refers to whether the local groundwater conditions are oxidizing or reducing. This influences mineral stability and sorption reactions and is another aspect of groundwater chemistry that controls contaminant mobility. As mentioned above, uranium is a naturally occurring trace element found in groundwater below the Pajarito Plateau. It is processed at LANL and is discussed at length in the *Hydrogeologic Synthesis Report* (LANL 2005b). As stated above, some other natural components of groundwater are calcium, bicarbonate, and silica compounds. The *Hydrogeologic Synthesis Report* (LANL 2005b) concludes that the temperature, pH, redox potential, and dissolved activities of the ions mentioned influence precipitation and dissolution of uranium compounds. These conclusions were based on geochemical calculations and the oxidizing conditions of natural groundwater beneath the Pajarito Plateau. The *Hydrogeologic Synthesis Report* (LANL 2005b) also concluded that, although it is useful to perform saturation index calculations to evaluate mineral equilibrium, most of the deep groundwaters are not in equilibrium with respect to the uranium compounds. Based on the results of the calculations they presented, adsorption processes appear to control dissolved concentrations of uranium in groundwater.

Chemical Speciation

Ions can exist as various stable isotopes and as parts of stable compounds (some organic) in groundwater. The form in which each contaminant ion exists influences its entry into precipitating minerals or sorption, and thus influences its mobility (LANL 2005b).

Colloids

The role of colloids in transport of contaminants at LANL is largely unknown and uninvestigated.

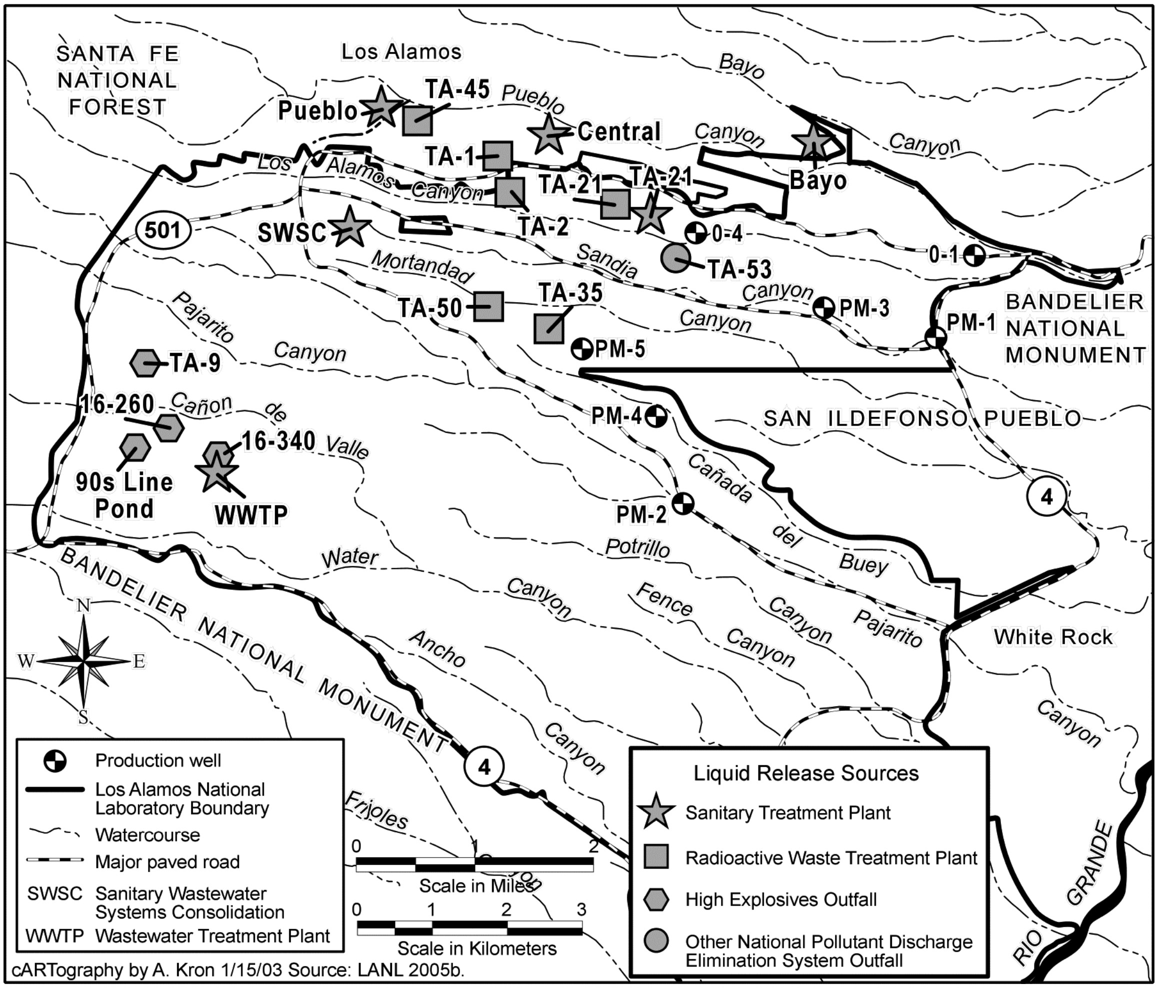
E.7.1.1 Contaminant Distributions

Anthropogenic contaminants in the groundwater at LANL generally derive from liquid effluent disposal into canyons or from surface impoundments on the mesa tops rather than from solid waste disposal. (Most solid waste disposal sites are located on mesa tops where there is little natural or artificial percolation to carry anthropogenic constituents to groundwater.) These effluents have degraded shallow perched water in some canyons (LANL 2005b). Canyons that have received radioactive effluent include Mortandad Canyon, Pueblo Canyon from its tributary Acid Canyon, and Los Alamos Canyon from its tributary DP Canyon. Effluents from high explosive processing and experiments contributed effluent to Water Canyon, its tributary Cañon de Valle, and Pajarito Canyon. Los Alamos County and the LANL contractor have operated sanitary treatment plants over the years (**Figure E–10**).

Effluent releases have impacted alluvial groundwater and in a few cases perched groundwater at depths of a few hundred feet. Little contamination from the perched groundwater zones under the mesas reaches the deep regional groundwater because the perched water is separated from the deep aquifer by hundreds of feet of unsaturated rock. LANL contaminants are found in groundwater below the alluvial aquifers in some canyons or below mesa tops where large retention ponds were located or where there were large-quantity discharges to the surface (LANL 2005b). The *Hydrogeologic Synthesis Report* (LANL 2005b) contains a summary of monitoring data by watershed and groundwater zone.

Observation of contaminant data and knowledge of geochemistry and the history of releases of contaminants provides a method of determining the rates and modes of groundwater flow through the subsurface to the regional aquifer. Nonreactive chemicals and compounds like tritium, perchlorate, and nitrate are used to determine how groundwater moves through the rocks. Some compounds or constituents (uranium, strontium-90, barium, some high explosive compounds, and solvents) are slowed by adsorption, precipitation-dissolution, oxidation-reduction, or radioactive decay, and some constituents (americium-241, plutonium) are strongly absorbed onto sediment and are nearly immobile (LANL 2005b).

Alluvial groundwater does not extend beyond LANL boundaries and has a short residence time. Tritium studies have shown that there is a rapid turnover of alluvial groundwater volume in the alluvial aquifers in the canyons and that contaminants do not accumulate. Since effluent limits were adopted in 2001, LANL has improved effluent quality and the once high values of tritium contamination are not present today. Since that time, tritium activity is barely detectable in Pueblo Canyon, DP Canyon, and Los Alamos Canyon and is below the maximum contaminant level in Mortandad Canyon.



cARTography by A. Kron 1/15/03 Source: LANL 2005b.

Figure E–10 Major Liquid Release Sources that have Potentially Affected Groundwater at Los Alamos National Laboratory (most of these are now inactive)

As mentioned above, perched groundwater is separated from alluvial groundwater by several hundred feet of unsaturated rock; even though recharge occurs slowly, contaminants in alluvial groundwater may reach the intermediate perched groundwater. Contaminant concentration data from the perched water zones below Mortandad Canyon indicate alluvial groundwater is the source of recharge to the intermediate groundwater by a process of infiltration (LANL 2005b).

The regional aquifer is separated from the intermediate perched groundwater by hundreds of feet of unsaturated rock. Recharge through these rocks to the regional aquifer occurs over a longer time than under the alluvial aquifers. Contaminants are found below alluvial groundwater in canyon bottoms or in perched water below mesa-tops where large amounts of effluents had been discharged to the surface. Tritium concentrations are much lower than values found in alluvial or intermediate groundwater due to dilution or to radioactive decay (LANL 2005b). Some high values are found in conjunction with effluent discharges near the liquid radioactive waste treatment plants shown in Figure E–10, at a past tritium disposal site (R-22 near Material Disposal Area G), and at a spring that had a value of 45 picocuries per liter, which may be due to a component of surface water because it is similar to rainfall and Rio Grande data (LANL 2005b).

Four alternative models are presented in the *Hydrogeologic Synthesis Report* (LANL 2005b). The models are described and examined to identify the strengths and weaknesses of the possible interpretations of available data. There is also a discussion of how the alternative models would change the current conceptual model and how the alternatives could be tested.

E.7.2 Geohydrologic Conceptual Model

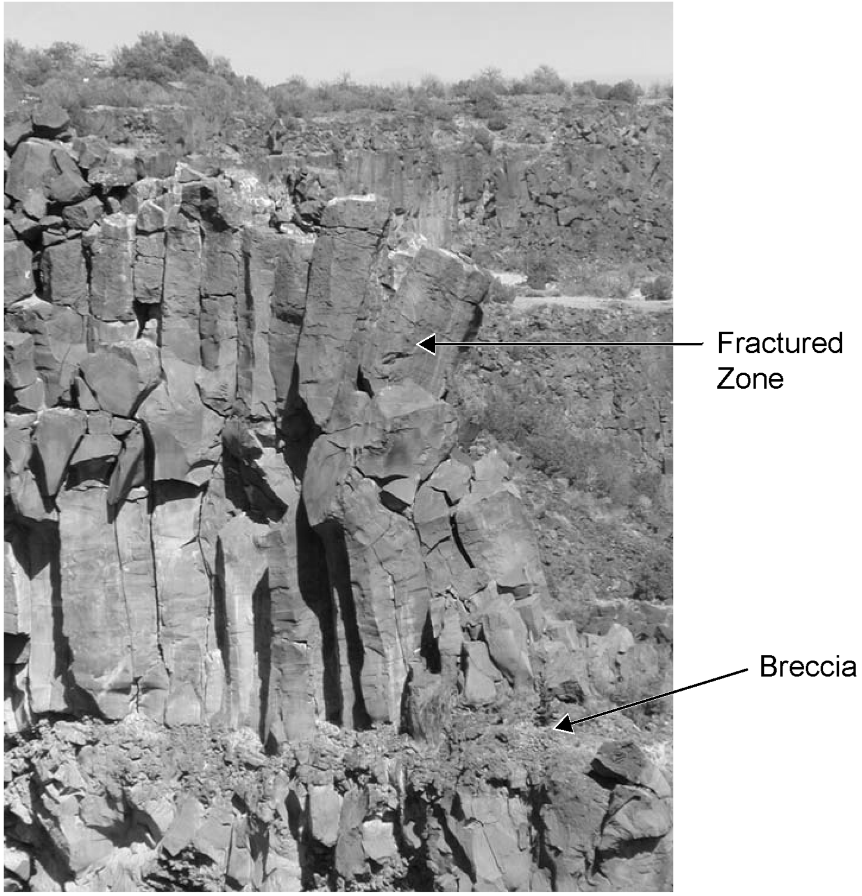
A conceptual model of the geohydrologic system at LANL is used for most numerical simulations by LANL workers and others (Robinson et al. 2005; Robinson, McLin, and Viswanathan 2005; Robinson, Broxton, and Vaniman 2005; Birdsell et al. 2005; Stauffer and Stone 2005; LANL 1995). The conceptual model was developed and supported based on field data. This section describes the components of the conceptual model and how they fit into the conceptual model.

Topography and Surface Water Setting. Deep canyons that begin in the Sierra de los Valles have large catchment areas, frequent surface flow, and perched alluvial groundwater (Birdsell et al. 2005). The wet canyons receive discharge from outfalls and wastewater treatment (anthropogenic water), as well as from infiltration of water from precipitation and shallow groundwater flow in the alluvium. Dry canyons originate on the plateau and have small catchment areas, infrequent flows, and no saturated alluvium in their floors. The dry canyons may display characteristics of the wet canyons if they receive anthropogenic water. In contrast to the wet canyons, there is little infiltration from these canyons. Mountain fronts receive more infiltration and this gives rise to localized perched water. Mountain front groundwater also flows laterally through fractures to nearby canyon walls, forming springs. As evidence for this conceptual model component, there are water budget studies (Kwicklis et al. 2005); moisture profile measurements and model simulations; major ion, stable-isotope, and contaminant concentration studies; and tracer tests in perched water for the mountain front case.

Anthropogenic Impacts. A second conceptual model component examines how anthropogenic activities significantly modified canyons and the intervening mesas of the Pajarito Plateau (Birdsell et al. 2005). Asphalt pavements have reduced evapotranspiration and built up subsurface moisture underneath. In addition, asphalt may focus runoff or may crack and cause infiltration where it may not have normally occurred. Effluent discharges to canyons from LANL or Los Alamos County sources have increased surface and groundwater flows, which have increased the infiltration rate to the vadose zone. In support of this component, water content measurements, contaminant transport measurements, and numerical simulations of paved areas and canyons influenced by LANL facilities are cited.

Flow and Transport Mechanisms. A third conceptual model component examines matrix and fracture flow transport mechanisms through the vadose zone to the regional aquifer (Robinson, McLin, and Viswanathan 2005; Birdsell et al. 2005; Springer 2005). Two principal hydrostratigraphic units with respect to vadose zone flow are the Bandelier Tuff and the Cerros del Rio basalts. Water movement in tuffs and basalts was examined. In poorly welded and fractured areas of the Bandelier Tuff, water moves into the fractures and is quickly absorbed into the high-permeability matrix; as a result, fractures play only a minor role in groundwater movement (Robinson, McLin, and Viswanathan 2005).

It was stated above that, at the Sierra de los Valles mountain front above the Pajarito fault zone west of LANL, the Bandelier tuffs are more densely welded than they are eastward under LANL toward the Rio Grande. Wellbore injection testing shows that water moves primarily in fractures of densely welded tuffs and basalts and is not absorbed as readily into the low-permeability rocks as it is into the fractures of poorly welded tuff (Robinson, McLin, and Viswanathan 2005; Birdsell et al. 2005). Typically, groundwater flow through basalts is controlled by cooling structures. Groundwater flow is vertical through the interior basalts where slow cooling occurred and columnar structures were formed with pronounced vertical fractures. **Figure E–11** is a photograph of the Cerros del Rio basalts below the Bandelier Tuff Otowi Member. Note the vertically fractured, dense interior columnar section and the more porous horizontal breccia zone. Groundwater flow is horizontal through these rapidly cooled breccias that make up the tops and bottoms of the basalt-flows. Groundwater flow is also horizontal in the interflow sediments. Perched water occurs in these porous brecciated zones underlying highly fractured basalt that overlies a massive unfractured flow interior (Birdsell et al. 2005). This conceptual model is supported by cited reports of water content measurements, major ion measurements, contaminant transport measurements, numerical simulations, field measurements at instrumented sites, and fluid injection tests (Birdsell et al. 2005).



Source: LANL 2005b.

Figure E–11 Outcrop of Cerros del Rio Basalt at White Rock Overlook (East of Los Alamos National Laboratory)

Vadose Zone Travel Times. Travel times in the vadose zone at LANL vary from several years to several decades. Travel time is shortest in fractured basalts, decades long where there are significant thicknesses of Bandelier Tuff, and in excess of thousands of years in dry canyons (Birdsell et al. 2005). The conceptual model was supported by numerical modeling of wet canyons (Robinson et al. 2005, as discussed in Section E.8.1), contaminant profiles in vadose zone boreholes, chloride and isotope profiles, and groundwater surveillance reports.

These conceptual model components provide a basis for numerical simulations of groundwater flow and transport through the vadose zone at LANL. Summaries of numerical modeling research at LANL are provided below.

E.8 Numerical Modeling Studies

This section describes numerical modeling activities by LANL workers. The numerical simulations mainly incorporate the conceptual model developed by Birdsell et al. (2005), as presented in the previous section.

E.8.1 A Vadose Zone Flow and Transport Model for Los Alamos Canyon, Los Alamos, New Mexico (Robinson et al. 2005)

Purpose: The purpose of this effort was to develop a large-scale numerical model to advance understanding of vadose zone flow and the transport of contaminants to the regional aquifer. This required applying a conceptual model to knowledge of the hydrostratigraphy, hydrologic conditions, and field measurements. Primarily, the purpose was to develop a numerical simulation of flow; but the transport of tritium in the form of tritiated water beneath Los Alamos Canyon was also modeled. Tritiated water is a good tracer and acted as a constraint on the numerical model (Robinson et al. 2005).

Conceptual Flow Model: The hydrologic system was characterized as an equivalent continuum model; that is, the model captured the characteristics of both the fractures and the matrix. The fractures are predicted to be dry until the capillary pressure of the matrix is a low value (saturated), fracture flow begins, and liquid permeability rises. The equivalent continuum model then behaves like a single continuum model (Robinson et al. 2005).

The infiltration rates used for the canyons and mesa tops were based on the Birdsell et al. (2005) conceptual model outlined above for wet canyons. Infiltration rates used in the simulation were calculated from previous studies using the rates from direct drainage from the alluvium to the vadose zone along the floor of Los Alamos Canyon (Birdsell et al. 2005). The highest rate (42.4 inches [1,076 millimeters] per year) occurs in the upper reaches of the canyon near the Guaje Fault zone where it is probably highly fractured due to faulting.

The source of contaminants used for this model was the Omega West reactor site that was used from 1943 to 1994 to house various reactors. Tritium was one of various radionuclides released into the canyon from a cooling water system leak discovered in 1993 that may have started in late 1969 or early 1970 (Robinson et al. 2005). It is used as a tracer because of its chemical state as a water molecule; it is not readily sorbed; and it does not precipitate out of solution or have complicated speciation processes.

Model Development: Information from 20 geological units was integrated into computational grids using a three-dimensional framework. Site-specific data from LANL's program of site characterization and their comprehensive drilling program, coupled with previous numerical modeling activities, were used for the framework. The accepted stratigraphic designation described previously was used (Broxton and Vaniman 2005). Los Alamos Canyon cuts deep into the Bandelier Tuff with the result that the Tshirege Member is not very thick at the canyon head and absent at the lower reach of the canyon. The Otowi Member is the first unit encountered below the canyon alluvium in much of the model domain. In the lower reach of the canyon, the Cerros del Rio basalts (Tb4) are below the alluvium.

Numerical Grids: The numerical model incorporated both two- and three-dimensional finite element grids. The model used was the Finite Element Heat and Mass code. This code was used because it was used in previous numerical modeling efforts at LANL for saturated and unsaturated flow and the code solved the equations needed for two-phase flow of air and water (Robinson et al. 2005; Birdsell et al. 2005). A two-dimensional grid was used for scoping and sensitivity analysis because it has a smaller number of nodes and elements and is computationally efficient.

Results: Model results suggest that the nonwelded and partially welded Bandelier Tuffs dampen episodic infiltration events; that is, the steady-state model shows that, if infiltration occurs all at once or is averaged over a year, the result yields a similar water content profile. Transients caused by anthropogenic activities over a decade or longer significantly affect predicted water content. Tritium transport modeling indicates that tritium has decayed and that most other contaminants released reside in the vadose zone. The model also suggests that, where the tuffs are absent, such as the lower Los Alamos Canyon near the confluence with Pueblo Canyon, there is a risk of contaminants getting to the regional groundwater.

E.8.2 Hydrologic Behavior of Unsaturated, Fractured Tuff: Interpretation and Modeling of a Wellbore Injection Test (Robinson, McLin, and Viswanathan 2005)

Purpose: This study interprets and models a reported injection test in the Tshirege Member of the Bandelier Tuff and examines different conceptual models. Four conceptual models were developed for flow and transport in fractured tuffs utilizing data from an early injection test in the Tshirege Member of the Bandelier Tuff.

Model Development: The first conceptual model tested was a single continuum model where fractures play no role in flow and transport. A second conceptual model was an equivalent continuum model that captures characteristics of both fractures and matrix. The third conceptual model was a dual-permeability model where it is assumed that the fractures and matrix represent two separate, but coupled, continua. The fourth conceptual model was a discrete fracture model that represents the fractures with distinct hydrologic properties within a model domain that includes the rock matrix. A numerical simulation was then run for each conceptual model. For kilometer-scale simulations, basalts are considered by some workers as a homogeneous continuum with a high permeability and low porosity (Stauffer and Stone 2005).

The same numerical grid, boundary conditions, and hydrologic properties were used for all of the numerical simulations of the conceptual models except for the discrete fracture model. For the discrete fracture model, idealized calculations were performed to develop a mechanistic explanation of how the hydrologic behavior of the tuffs changes when water is injected into a dry fracture.

Results: The study results suggest that flow and transport in the tuffs is through the matrix rather than fractures. This is the result of the high matrix permeability of the tuff. The matrix-dominated flow decreases travel velocities and increases retardation by sorption. Sorption is increased because more water comes in contact with the rock by absorbtion into the rock rather than by contact with the walls of a fracture. Rocks with rather high capillary suction properties would be expected to result in more lateral movement and spreading of a plume.

E.8.3 Development and Application of Numerical Models to Estimate Fluxes through the Regional Aquifer beneath the Pajarito Plateau (Keating, Robinson, and Vesselinov 2005)

Purpose: This study integrates new site-wide data into a model of the regional aquifer beneath the plateau and provides new insight into large-scale aquifer properties. This aquifer is the primary source of water for Santa Fe, Española, Los Alamos, various Pueblos, and LANL. There is a concern about dropping water levels because in 2002 there was a decrease in baseflow to the Rio Grande. There is also a concern that water quality is decreasing because of contamination from LANL sources. This study provides a comprehensive literature review for the aquifer and supplements it with interpretations of new data. This appendix synopsis of the study includes other supporting citations.

Recharge and Discharge: This study (Keating, Robinson, and Vesselinov 2005) discusses and cites various concepts of recharge to the regional aquifer. Early workers thought recharge occurred at various places: Sierra de los Valles, along stream channels on the western edge of the Pajarito Plateau, and in Valles Caldera. Water chemistry did not support these concepts. It was then proposed by various workers that recharge areas were either from the Sangre de Cristo Mountains to the east or from the north and east, but not from the west. Water balance and chloride mass-balance analyses indicate that basin recharge does occur in the mountains at the margins of the basins. Findings based on stable isotope ratios suggest that recharge to groundwater under Pajarito Plateau is from Sierra de los Valles and very little is from Valles Caldera (LANL 2005a). Some recharge is also from streamflow infiltration along arroyos and canyons on the plateau and some recharge, although volumetrically small compared to mountain recharge, is from the surface of the mesas. This study (Keating, Robinson, and Vesselinov 2005) reports that tritium data indicate that water below LANL is relatively young and derives from fast-path flow through the vadose zone. Tritium studies in groundwater discharging from springs within the Sierra de los Valles indicate that the water is about 60 years old. However, groundwater from springs in White Rock Canyon has no tritium and probably ranges in age somewhere between 3,000 to 10,000 years (LANL 2005a).

Discharge of groundwater from under the plateau is assumed by many workers to be to the Rio Grande at White Rock Canyon and may occur as lateral flow, upward flow, or flow from springs. One hypothesis being explored is that the springs come from draining perched aquifers. A second hypothesis is that discharge of groundwater from the regional aquifer may also be southeasterly to the lower Albuquerque Basin, but a structural high at the boundary of the

Española Basin and the Albuquerque Basin may be impeding flow. This would cause interflow upward to the surface. This hypothesis has not been resolved because no studies have been conducted in the lower part of the Española Basin (Keating, Robinson, and Vesselinov 2005).

Aquifer Properties: The hydrostratigraphic units were described above. It is apparent that the units are complex because of the tectonic, volcanic, and sedimentary processes that occurred in the LANL region. Santa Fe Group and Puye Formation rocks are made up of intertonguing alluvial fans separated by layers of volcaniclastics, lava deposits, breccia zones, and other materials, resulting in vertically anisotropic conditions. This is supported by short-term well tests where permeability data are derived from production wells with large screened intervals. The well test results show permeability perpendicular to bedding planes is less than permeability parallel to bedding planes (Keating, Robinson, and Vesselinov 2005). Anisotropy may also be the result of the numerous north-south faults in the basin interfering with spatial continuity of low- or high-permeability rocks. For instance, a layer may look as if it has good permeability, but when tested on a large scale, it may appear to have a poor hydraulic connection to other parts of the same unit because it is interrupted by a low-permeability fault zone.

Several conceptual models regarding the regional aquifer have been developed. The complex geologic structures and data from well tests have several interpretations. Earlier workers postulated the Santa Fe Group is under water table conditions near the Sierra de los Valles and becomes confined eastward. Specific storage data indicate that parts of the aquifer exhibit "leaky-confined" conditions because of semi-confining layers of rocks. Another conceptual model proposes that the anisotropic condition of the aquifer interferes with vertical movement of groundwater, making it appear to be confined during short-term pumping tests. A third conceptual model is that a laterally extensive low-permeability layer confines the lower part of the aquifer and is overlain by groundwater under water table conditions.

Model Development: Three numerical models were integrated: a three-dimensional hydrostratigraphic framework model, a three-dimensional numerical flow and transport model (based on the Finite Element Heat and Mass Transfer Model discussed above), and a model of recharge based on precipitation data. The model incorporates no-flow boundaries at the Santa Clara River to the north, the Valles Caldera to the west, the Rio Frijoles to the south, and the Rio Grande to the east. The upper boundary represents the top of the saturated zone, which has a constant thickness throughout the simulation. The eastern edge of the upper boundary of the model is the Rio Grande and has a specified head. The Buckman well field is a transient flux (sink) to simulate production.

Results: Groundwater flow in the numerical model was to the south-southeast and generally fits the conceptual models of flow. Calculated heads near wells R-9, R-12, R-22, and R-16 were not matched well with actual heads. The model showed that transport calculations would benefit from a refinement of the hydrostratigraphic framework. It was felt that a low-permeability layer separating the upper aquifer from the lower aquifer would allow a closer match of the calculated heads and fluxes with actual data. Calculated total recharge to the aquifer was within the range of early estimates and does occur to the west. The simple recharge model demonstrated that production water is coming from storage from the deeper zones in the aquifer rather than from the shallow zones that receive water from local recharge. Parameter uncertainty impacts the ability to make predictions of fluxes and velocities through individual units downgradient from

LANL. Estimated pore-water velocities varied from 3.3 feet per year (1 meter per year) to 415 feet per year (125 meters per year) in the deep Miocene basalt unit Tb2. This makes predictions of lateral contaminant movement difficult where the basalts are present and brings up the possibility that contaminants may have traveled a significant distance laterally (Keating, Robinson, and Vesselinov 2005). Uncertainties about porosity and permeability also lead to model uncertainty.

E.8.4 Observations and Modeling of Deep Perched Water beneath the Pajarito Plateau (Robinson, Broxton, and Vaniman 2005)

Purpose: The purpose of this study was to perform numerical simulations using vadose zone flow models of two deep perched water zones. One zone is relatively stagnant and the other more dynamic.

Conceptual Model: The conceptual model is also presented in Section E.7.2. Much has been learned about perched water in spite of some difficulties encountered. Small perched bodies are not easily identified because of the drilling techniques required. The lateral extent of deep perched water bodies is also difficult to determine because of the cost of drilling wells. Identification of perched water systems is mostly from observation of saturation in open boreholes using video logs, water measurements, electric logs, neutron logs, wells, and piezometers. Thirty-three occurrences of deep perched water across the Pajarito Plateau are reported (Robinson, Broxton, and Vaniman 2005). The depth to perched water ranges from 118 to 894 feet (36 to 272 meters). The principle occurrence of perched groundwater is in the large wet canyons (Los Alamos and Pueblo Canyons), the smaller watersheds (Sandia and Mortandad Canyons), and Cañon de Valle. Perched water is found in the Puye Fanglomerates, Cerros del Rio basalts, and Bandelier Tuffs (Robinson, Broxton, and Vaniman 2005). Perched water is less common under the dry mesas.

Some deep perched water contains mobile (nonsorbing) anthropogenic chemicals, but no direct measurements have been made to determine how the chemicals reached the perched water. Two conceptual models that are at present untestable are presented to explain the process: a low-velocity, stagnant water resting in a depression above the perching horizon and a high-velocity, laterally migrating fluid that travels on top of the perching horizon (Robinson, Broxton, and Vaniman 2005). Perching horizons in the low-velocity model slow the downward percolation of water, but seem to become dry when penetrated by a borehole and not recharged. In the high-velocity model, water percolates into a deep perched zone; then moves laterally to where the zone pinches out or reaches another vertical, permeable pathway; and then moves downward. This is repeated until it can no longer move downward or it reaches the regional aquifer. These two scenarios can occur together. Deep perched water does not appear to extend far below the dry mesas (Robinson, Broxton, and Vaniman 2005).

Model Development: A model that considers perching horizons as interfaces between hydrostratigraphic units was developed. It uses an interface reduction factor method to account for perched water. When mean values for hydraulic conductivity are used in a model, the water will move through the unsaturated zone and will not perch or move laterally. The derivation of an equation called the permeability reduction factor was added to the Finite Element Heat and Mass Transfer code. The reduction factor allows the user to enter a multiplier that will reduce the permeability at the interface of two hydrostratigraphic units and allow increased saturation. A two-dimensional model was then run using permeability reduction factors for simulating the perched zone. Models without the low-permeability barrier were run for comparison.

Results: The results were compared to information from wells LADP-3 and LAOI(A)-1.1, which penetrate the Guaje Pumice Bed-Puye Formation interface. The Guaje Mountain fault zone was used as the high-infiltration zone. The base case had no permeability reduction factor, but showed a slight increase in saturation at the Guaje Pumice Bed; however, no perching occurred. When the reduction factor was used, perching occurred and increased as the factor was lowered. Particle tracking showed that, as the reduction factor was decreased, migration of contaminants moved laterally. Some contaminants moved through the interface.

Perched water zones in the Pajarito Plateau and Yucca Mountain, Nevada, are being extensively studied and have some similarities. Both places have the low-permeability zones required for perching to occur. The low-permeability zone at Yucca Mountain is an extensive low-permeability zone of zeolites. At Pajarito Plateau, the low-permeability zones are limited in area and are associated with stratified sedimentary units and dense basalts.

Fluid velocity in the perched zones is unknown and hydrologic testing, tracer tests, or groundwater dating methods are required to determine the age of the groundwater. Anthropogenic chemicals found in perched zones in some wet canyons allow for some estimates of travel times that may be only on the order of decades.

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