Road Geology of selected sections in the Pajarito Plateau and the Jemez Mountains, North Central New Mexico

Well exposed geologic sections and spectacular panoramic views are characteristic features of the Pajarito Plateau and the Jemez Mountains of north central New Mexico. Five locations on State Roads NM4 and NM502 that are frequently visited by geologists and the general public are briefly described below (Fig. 1). The geologic descriptions are adapted from a field guide for the Valles caldera and the Jemez Mountains (Goff et al., 1989) with minor modifications and additions on the White Rock Overlook (Stop 2).

The Los Alamos National Laboratory is located in the central part of the Pajarito Plateau along the eastern part of the Jemez Mountains in north central New Mexico. The plateau is part of the Espanola Basin of the Rio Grande rift and is separated from the Jemez Mountains by the Pajarito fault system. The major rock types underlying the Laboratory, the town site, and the surrounding mesas are exposed in 200- to 300-m deep, steep-sided canyons that cut the Pajarito Plateau into finger-like mesas before they merge with the White Rock Canyon of the Rio Grande along the eastern part of the plateau (Fig. 2) The oldest rocks exposed in the Pajarito Plateau consist of the Santa Fe Group sedimentary rocks deposited by rivers in the Rio Grande rift floor between 8 and 17 Ma (million years). In the subsurface below the Los Alamos National Laboratory, the town site, and the adjacent mesas, volcanic lava flows ranging in age from 8 to 13 Ma are intercalated within the Santa Fe Group sedimentary deposits. The Santa Fe Group is overlain by the Puye Formation sedimentary sequence deposited between 2.5 and 5 Ma. These rocks were eroded from the Jemez Mountains and accumulated along the foothills of the western margin of the Rio Grande rift. Widespread volcanic flows erupted between 2.4 and 3 Ma overlie and partially intercalated within the upper part of the Puye Formation (WoldeGabriel et al., 1996). These volcanic rocks belong to the Cerros del Rio volcanic field and are exposed on both sides of the [3] 300-m deep White Rock Canyon, clearly visible from the White Rock Overlook.

STOP 1: The Bandelier Tuff and late Tertiary stratigraphy

Park in large turn-out on road cut near Twin Tanks, right side of highway as you start climbing toward Los Alamos. The Guaje Pumice Bed of the Otowi Member (1.62 Ma) of the lower Bandelier Tuff overlies 2.4 Ma old basalt flow of the Cerros del Rio volcanic eruptions in road cut on right (Figs. 3 and 3a). Note soil developed on top of basalt. In the slopes and cliffs above the basalt, about 100 m of Bandelier Tuff is exposed. The Guaje Pumice Bed is about 7 m thick here, but the bed is commonly as much as 10 m thick on the east side of the mountains. Underlying the slopes and exposed in gullies to the base of the cliffs are about 50 m of nonwelded Otowi ash flows.

A thin layer of bedded pumice fallout and reworked tuffaceous sediments of the Cerro Toledo Rhyolite (1.23 to 1.59 Ma, Spell et al., 1996) crops out on top of the Otowi ash flows. The bedded pumice and ash fallout were vented from domes within the Toledo caldera and Toledo embayment (Smith et al., 1970; Heiken et al., 1986; Stix et al., 1988; Spell et al., 1996). A thicker section of the bedded Cerro Toledo Rhyolite is exposed on the north side of NM502 in Pueblo Canyon about 2 km west of the NM502 and NM4 intersection (Fig. 4).

At the base of the cliff directly above the Cerro Toledo Rhyolite is 1 m of fine-grained ash and pumice fallout of the Tsankawi Pumice Bed of the upper Tshirege Member, and above are 50 m of partly welded Tshirege ash flows (Fig. 3). In the upper 30 m of columnar- jointed tuff, distinct flow units separated by sandy partings and pumice concentrations are discernible.

Rocks exposed in lower Los Alamos Canyon (south side of road between Stop 1 and the Espanola turn off) are typical of sequences along the length of White Rock Canyon. They record interfingering stratigraphic relations between lavas and tuffs of the Cerros del Rio volcanic field with rift-basin sedimentary units (especially those derived from the Jemez volcanic field), regional tilting, uplift, and erosion of the Espanola Basin in the late Cenozoic, and the Quaternary pyroclastic deposits erupted from the Valles and Toledo calderas. Locally, there were interactions between magma and meteoric/surface waters resulting in phreatomagmatic tuff rings; lava flows erupted within the course of the ancestral Rio Grande repeatedly dammed it to produce lakes in which lacustrine-deltaic sedimentary sequences were deposited.

Sedimentary units of the lower Puye Formation (Waresback, 1986) comprise a volcaniclastic apron shed from the northeastern margin of the Jemez volcanic field. The road cuts along NM-502 expose coarse debris-flow and fluvial facies (plus minor tuff and lacustrine facies) containing a high proportion of Tschicoma andesite to dacite clasts (about 0.5 km east of Stop 1). The Totavi Formation, which is at the base of the Puye Formation, is similar but also contains a significant fraction of Precambrian clasts, carried southward by the ancestral Rio Grande. Transport directions of fluvial-sediment systems were dominantly south-southeast. The debris-flow dominated unit is abruptly succeeded in this area by a lacustrine sequence that overlies an erosion surface and grades upward from dark, thinly laminated silts, through lighter colored sandy beds, to fluvial gravels with southerly transport directions and dominantly Precambrian clasts (derived from reworking of the Totavi). This sequence records the damming of the ancestral Rio Grande and filling of the consequent lake basin. The basalt flow that formed the drainage obstruction is exposed to the southeast on the rim of Los Alamos Canyon. The paleotopography of the lake basin is recorded by the geometry of this sediment package, which thins to the east, north, and west from a maximum local thickness of 30 m.

At 2.4 to 3 Ma, (Baldridge, 1979; WoldeGabriel et al., 1996), basaltic eruptions south and west of the road cut along the Rio Grande produced lava flows and associated dark-green, thinly laminated basaltic tuff (< 1 m) that spread across a braided-stream system in the area. Where the basaltic ash was deposited within channels, it was reworked, mixed with clastic sediment, and filled these paleochannels to thicknesses >3 m. As the basalt flow moved eastward, it overrod the tuff, which exhibits both brittle and soft-sediment deformation. The river became dammed to the south by the lava and the flow front became a pillow-palagonite (altered basalt) delta. Eastward-dipping foreset beds of this delta are spectacularly exposed in Los Alamos Canyon south of the water tanks. Ashy sediment, forming the green lacustrine shale unit, filled the lake to a level which locally topped the lava flow.

The Bandelier section is in place where it rests on the basalt flow, but northeast of the flow front it is thinned by erosion of the Otowi Member prior to eruption of the Tshirege Member and it is allochthonous (i.e., moved from its original position), having slumped extensively. The green lacustrine shales have acted as a highly deformable decollement; the underlying basaltic tuff is virtually undeformed by post-Bandelier slumping.

STOP 2: White Rock Overlook

At the White Rock Overlook, the cliff below the pedestal is made up of different lava flows and the upper two layers gave similar ages of 2.50 Ma (WoldeGabriel et al., 1996). These two flows have different compositions and originated on opposite sides of the White Rock Canyon. The lava flows increase in age to 2.8 Ma downstream from the White Rock Overlook in the vicinity of the Frijoles Canyon (downstream from the Bandelier National Monument Visitor Center) (Fig. 5). Upstream from the White Rock Overlook and on the right side of the Rio Grande south of the Otowi Bridge, the Buckman Mesa volcanic centers erupted lavas and basaltic tuffs that are exposed on top of the Santa Fe Group sedimentary deposits (Figs. 6 and 6a). An age of 2.6 Ma was obtained on two lava flows that erupted from one of the centers on the mesa. Upstream from the Buckman Mesa, a deeply-eroded volcanic center known as the Black Mesa at San Ildefonso represents a distinct landmark. Although it forms an isolated center, it probably occurs along the northern edge of the widespread Cerros del Rio volcanic field that forms the highland across from the Laboratory on the east side of the White Rock Canyon. The Black Mesa volcanic center overlies the Santa Fe Group sedimentary rocks. An age of 2.7 Ma was obtained on one of the flows.

The Los Alamos National Laboratory and the town site were built on the Bandelier Tuff. This volcanic deposit erupted as fallout and ignimbrite ash clouds at 1.2 and 1.6 Ma from the Valles and Toledo calderas, respectively, a major superimposed circular depression in the central part of the Jemez Mountains. The deposits form vertical cliffs on both sides of the canyons that dissect the Pajarito Plateau (Figs. 2 and 3). The Bandelier Tuff crops out on top of the Cerros del Rio lava flows and the poorly-sorted gravel-rich sedimentary deposits of the Puye Formation sedimentary deposits. This stratigraphic relationship is clearly indicated on along the road east of the NM4 (White Rock) and NM502 (Los Alamos) intersection or the "Y" (Fig. 1). At places, the Bandelier Tuff is covered by younger ash deposits, recent sediments, and soils.

STOP 3: Valles Grande Overlook into Valles caldera

Park in turnout on right side of road adjacent to sign. The Valles caldera formed 1.2 Ma during catastrophic eruption of approximately 300 km^2 of ignimbrite of the Tshirege Member of the Upper Bandelier Tuff. By comparison, the amount of ash released during the May 1980 eruptions of Mt. St. Helens is estimated at <2 km^2. From this vantage (Fig. 7), you can gaze across the Valles Grande, the eastern section of the caldera "moat," toward the broad mountain of Redondo Peak (3460 m), forming the eastern segment of the resurgent dome. This segment is really a northeast-trending ridge that includes the knob of Redondito on the north side. The resurgent dome is composed primarily of densely welded Bandelier Tuff that was uplifted during post-caldera tumescence or swelling of the volatile-depleted Bandelier magma chamber (Smith and Bailey, 1968; Smith, 1979). Dips on foliations in the ignimbrite are generally south to southeast on the Redondo Peak segment of the dome. The relations between the tilted ignimbrites of the resurgent dome, overlying volcaniclastic rocks and lacustrine deposits, and postcaldera rhyolites indicate that resurgence probably occurred within 50,000 to100,000 years after caldera formation (Doell et al., 1968; Smith et al., 1970; Hulen et al., 1987).

Visible postcaldera, ring-fracture rhyolites of the Valles Rhyolite that partly surround the resurgent dome are from right to left: Cerro del Medio (1.21 Ma), Cerro del Abrigo (1.004 Ma), Cerro Santa Rosa (0.92 Ma), Cerro la Jara (0.53 Ma), and South Mountain (0.52 Ma) in anti clockwise order (Spell and Harrison, 1993; Izett and Obradovich, 1994). These rhyolites range from crystal-poor (Cerro del Medio) to coarsely porphyritic (South Mountain), but all are high-silica rhyolites (e.g., San Antonio Mtn. Rhyolite). Geochemical data presented by Spell (1987) indicate that they were derived from Bandelier parental magma.

Geothermal development and the cooperative agreement between UNOCAL and the U.S. Department of Energy have provided drill-hole and geophysical data that gave interesting picture of subsurface caldera structure. The gravity model of Segar (1974) indicates the floor of the caldera is very asymmetrical, being shallow on the west and deep in the east; this model is verified by drill-hole data in the western and central caldera. The model also indicates a series of steep, northeast-trending gravity gradients that are probably precaldera structures inherited from the Rio Grande rift (Goff, 1983; Nielson and Hulen, 1984; Heiken et al., 1986; Aldrich, 1986). Depth to Precambrian basement west of the ring-fracture zone beneath Valles Grande is estimated at 5000 m.

If one looks northwest between the extension of the resurgent dome and Cerro del Medio (Fig. 8), one can see the northwest wall of the caldera (about 18 km distant) formed primarily of Tschicoma Formation dacites overlying hydrothermally altered Paliza Canyon Formation andesite and dacite (WoldeGabriel, 1990). The caldera wall immediately to the right is formed of Tschicoma Formation, but to the left is formed mostly of Paliza Canyon Formation. The exception is Rabbit Mountain (1.43 Ma), part of the Cerro Toledo Rhyolite that was vented after the formation of Toledo caldera (1.62 Ma).

Several lines of evidence indicate that the Toledo caldera, which erupted 300-400 km^2 of the Otowi Member of the Lower Bandelier Tuff, is coaxial with the Valles caldera. This evidence includes isopachs on the Guaje Pumice Bed (Self et al., 1986), radial distribution of the Otowi Member around the present Valles caldera (Smith et al., 1970), flow-direction indicators in the Otowi Member (Potter and Oberthal, 1983), an arc of post-Toledo-age rhyolite domes exposed in the northern moat of Valles caldera (Goff et al., 1984), and the thick sequence of Otowi Member beneath the Valles resurgent dome (Nielson and Hulen, 1984). The feature denoted as Toledo caldera on the northeast margin of Valles caldera by Smith et al. (1970) represents some other structural feature (see Self et al., 1986, and Heiken et al., 1986) and has been renamed the Toledo embayment (Goff et al ., 1984).

STOP 4: West caldera overlook; corehole VC-1 and Hot Dry Rock project

From La Cueva follow NM126 west for about 4 miles to the top of the ridge. Turn left onto paved drive to picnic area. Park at end of drive and walk east toward overlook. From this vantage point (elev. 2615 m) on the southwest topographic rim of Valles caldera, you can gaze across the caldera moat toward Redondo Peak (elev. 3460 m), the resurgent dome occupying the approximate center of the caldera (Fig. 9). The nearer and lower ridge to the left of Redondo Peak is Redondo Border, which forms the western half of the resurgent dome. The valley between the two is the northeast-trending Redondo Peak graben.

To the northeast, in the middle distance, are San Antonio Mountain and Cerro Seco, two post-resurgent moat-rhyolite domes (Valles Rhyolite) dated at 0.54 and 0.73 Ma, respectively. A thick rhyolite flow from San Antonio Mountain overlies Redondo Creek Rhyolite on Thompson Ridge in the caldera moat in the immediate background. Another flow of rhyolitic obsidian (Banco Bonito Member, Valles Rhyolite) fills the caldera moat to the right (age ~60,000 years).

On the distant skyline to the northeast, on the northern rim of the caldera, is Cerro de la Garita formed of dacite of the Tschicoma Formation. On the skyline to the southeast is the crest of Los Griegos (on the south rim of the caldera), formed mainly of andesites of the Paliza Canyon Formation.

Continental Scientific Drilling Project corehole VC- 1 was drilled in August 1984 on the southern side of the Banco Bonito flow on strike with the southwest projection of the Redondo Creek graben (Fig. 10). Objectives were: (1) to intersect a hydrothermal outflow plume from the geothermal reservoir near its source, (2) to study the structure and stratigraphy near the intersection of the ring-fracture zone and the precaldera Jemez fault zone, and (3) to study the petrology of the youngest moat volcanics in the caldera. Total depth is 856 m and the bottom-hole temperature is about 185°C. Fluid chemistry of aquifers at 400-600 m depth in VC- 1 resembles, but is more dilute than, reservoir waters in the caldera. More information on the outflow plume will be given at Stop 5.

VC- 1 core was found to be altered and structurally disrupted below 335 m, particularly the lowermost interval of brecciated Precambrian rocks and Sandia Formation (Hulen and Nielson, 1988; Keith, 1988). Molybdenite was also found in this breccia zone along with chalcopyrite, sphalerite, galena, pyrite, and barite. Fluid inclusion work suggests that the molybdenite was deposited from dilute water at temperatures as high as 280°C (Hulen and Nielson, 1988; Sasada, 1988). A K-Ar age of 1.0 Ma was obtained on hydrothermal illite in Madera Limestone (Ghazi and Wampler, 1987; WoldeGabriel, 1990), while Sturchio and Binz (1988) obtained ages of 95,000 to >400,000 years on calcite veins using the U-Th disequilibrium technique. Geissman (1988) found that the paleomagnetic character of Paleozoic rocks in the corehole was overprinted by a reversed magnetic signature and concluded that major hydrothermal activity at about 300°C occurred between 1.62 and 0.97 Ma.

The location of the first Hot Dry Rock (HDR) demonstration project is a scant 0.5 km to the west of this overlook. In the HDR concept, two wells are drilled into hot, impermeable-rock units and connected by man-made fractures. Cold surface water is pumped down one well, where it is heated by the rock adjacent to the fracture, and removed up the second well. A heat exchanger or turbine is used to extract the heat or energy from this circulation system, after which the water is pumped down the first well for another cycle. The first (research) system was constructed at a depth of 3 km where the ambient temperature is 195°C. This system demonstrated technical feasibility (Heiken et al., 1981; Laughlin, 1981; Smith, 1983). The second system, constructed at depths of 3.7 km and a temperature of about 250°C, is designed to demonstrate commercial feasibility. Small volumes of relatively concentrated fluids (=20,000 mg/kg TDS) have been encountered in Precambrian rocks in both the HDR wells (Grigsby et al., 1984) and in the WC23-4 well on Thompson Ridge in the western caldera moat (Shevenell et al. 1987, 1988). The origin of these fluids and their relation to more dilute but voluminous "reservoir" fluids is not yet resolved, but an association can be seen in the isotope plot.

STOP 5: Soda Dam and Jemez fault zone

Park in turnout on right side of road before crossing cattleguard. Walk up path to ledge overlooking the right (west) side of highway. The travertine dam (Figs. 11 and 11a) across the gorge in Precambrian granite gneiss was built by carbonated thermal waters that discharge from a strand of the Jemez fault zone. There are roughly 15 springs and seeps discharging in this area. About 20 years ago water discharged along the central fissure parallel to the trend of the dam, but the New Mexico State Highway Department eliminated the hump in the paved road by dynamiting a notch in the west end of the dam. This forever changed the plumbing of hot spring water and today Soda Dam is slowly disintegrating.

The travertine deposits of Soda Dam proper have been dated by the U-Th technique and have a maximum age of about 5000 years (Goff and Shevenell, 1987). Two older deposits at slightly higher elevation occur across the Jemez River (age=60,000-110,000 years). On the west side of the gorge, roughly 30 m above the road, occurs an extremely large deposit of travertine that has an age range of about 0.48-1.0 Ma by evaluation with the U-U dating method. These older deposits do not overlie Bandelier Tuff; instead they lie directly on Paleozoic/Precambrian rocks. A discontinuous deposit of ancestral Jemez River gravels can be seen beneath the travertine and a large cave is located along the contact.

Hot-spring waters at Soda Dam have a maximum temperature of 48°C and contain about 1500 mg/kg Cl and substantial As, B. Br, Li, etc. They chemically resemble, but are more dilute than, reservoir water inside Valles caldera, and isotopically they appear to be mixtures of meteoric and reservoir water. Several people have claimed that the hot waters follow the trace of the Jemez fault zone out of the caldera and mix with dilute ground waters (Dondanville, 1971; Trainer, 1984; Goff et al., 1981). By combining geochemistry of hot springs and aquifers throughout the southwestern perimeter of the caldera with other geologic data, Goff et al. (1988) showed that a major subsurface tongue of reservoir water flows out of the caldera on either side of the Jemez fault zone. During lateral flow, the waters dissolve Paleozoic limestone and become relatively rich in Ca and HCO3. When these data are combined with the information on the travertine deposits, the age of the Valles hydrothermal system is estimated to be about 1.0 Ma.

The Jemez fault zone is very complex in this area. The main trace trends northeast across the highway and creates a 15 m scarp along the north side of the older travertine. Generally, displacement along the fault in Paleozoic rocks is about 200-250 m down-to-the-east. At Soda Dam, a local horst of sheared Precambrian granite-gneiss is uplifted and overlain by distorted Paleozoic rocks. The granite/gneiss is hydrothermally altered and contains secondary barite, galena, and sphalerite in veins and fracture fillings. The Jemez fault zone continues to the southwest and displaces the Tshirege Member of the Bandelier Tuff by about 50 m in the canyon wall.

If you gaze carefully at the upper east wall of San Diego Canyon, you can see a white band of Abiquiu Formation (late Oligocene, =30 Ma) overlying orange Permian Yeso Formation sandstone and shale. The Abiquiu is overlain by volcanic units of the Paliza Canyon Formation (8-10 Ma?) and the mesa is capped by a thin layer of Tshirege Member, Upper Bandelier Tuff. Looking northwest, the canyon wall is composed of Pennsylvanian Madera Limestone, Abo Formation, Abiquiu Formation, Paliza Canyon Formation, and both members of the Bandelier Tuff. The canyon is partly controlled by erosion along the Jemez fault zone and the stratigraphy is different on either canyon wall.

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Ecology

Geology and climate present opportunities and constraints for life to exist on the Pajarito Plateau. Geological formations are modified by physical, chemical, and biological processes to produce soils. Chemical and physical characteristics of soils and climate help to determine the forms of life that persist in and on those soils. These collections of interacting life forms are called ecological communities. When we also consider interactions between nonliving (abiotic) components and the living (biotic) components we have an ecosystem.

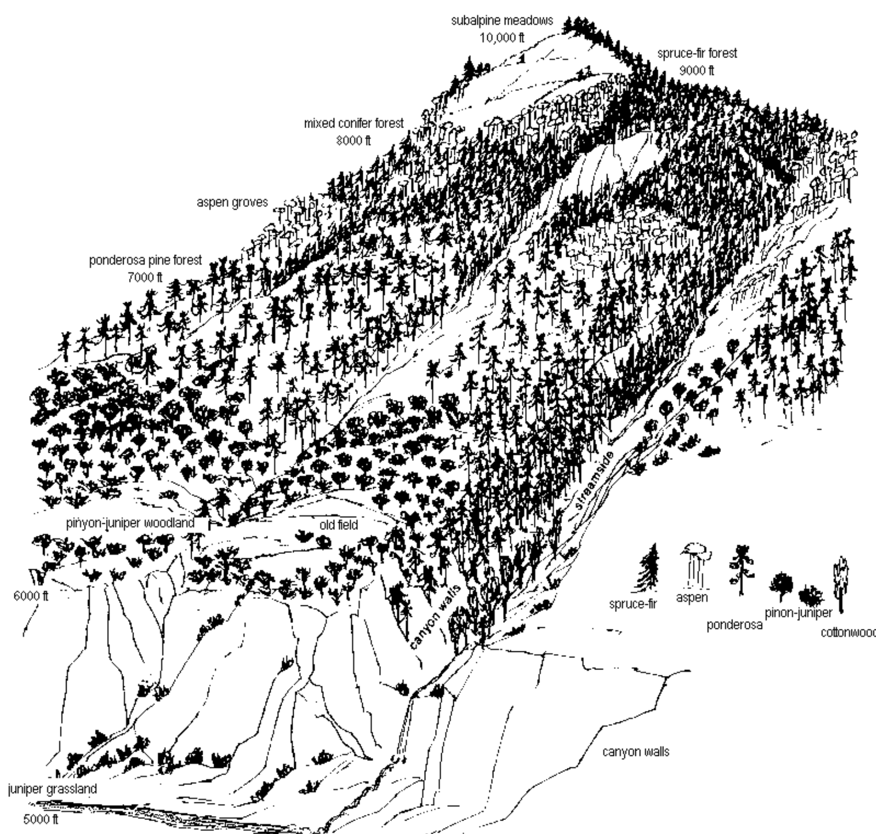

Figure 1. Ecological communities at Los Alamos.

One way to classify ecological communities in the Los Alamos area is on the basis of vegetation. One may find local examples of riparian and wetland communities, juniper-grassland savannas, piñon-juniper woodlands, and forests composed of ponderosa pine, aspen, or mixed conifer species (Figure 1).

Juniper-grassland savannas form an ecotone between grasslands and juniper woodlands. These savannas are dominated by one-seed juniper with an undergrowth of warm season grasses, such as blue grama. Shrubs such as wavyleaf oak, snakeweed, big sagebrush, and rabbitbrush are also found in this habitat. Juniper woodlands are found at elevations between about 5400 and 6500 feet. Piñon-Juniper woodlands occupy areas above the juniper woodlands. The major tree species are piñon pine and one-seed juniper. Shrubs like Gambel and wavyleaf oak, mountain mahogany, and big sagebrush are common, and common grasses are blue grama, galleta, and little bluestem. Between about 7000 to 8000 feet one finds forests of ponderosa pine, although thin fingers of ponderosa pine forest follow north-facing slopes and canyon bottoms down to about 6500 feet. Here one may also find mountain muhly, pine dropseed, and little bluestem grasses. Mixed conifer forests occur primarily between 8000 and 9500 feet. Douglas fir, Englemann spruce, and white fir are characteristic overstory species in these forests. One may also find aspen, oaks, chokecherry, serviceberry, bearberry, and a variety of grasses here. Stands of aspen are interspersed with the mixed conifer type where fires or other disturbances have removed the mixed conifer overstory. Prior to when fire control practices began in the late 1800's, higher elevation mixed conifer forests on north-facing slopes burned every 15 - 20 years. These fires usually had a low intensity so that large stands of trees were not eliminated. Lower elevation stands on south-facing slopes had an interval of about 8 - 10 years between fires. Ponderosa pine forests burned even more frequently. Modern forest management uses controlled burns to restore historical fire regimes that these forests evolved under. Riparian and wetland habitats may include springs, river and stream banks, marshes, and outfalls. They contain vegetation that is dependent upon moist conditions, like narrowleaf cottonwood, boxelder, alder, or Rocky Mountain maple.

Plant communities create habitats used by many wildlife species. More than 100 bird species breed in Los Alamos County. Species like broad-tailed hummingbird, northern flicker, violet-green swallow, western bluebird, and American robin may breed in most habitats on the Pajarito Plateau. Ash-throated flycatcher, Say's phoebe, bushtit, piñon jay, scrub jay, Bewick's wren, blue-gray gnatcatcher, black-throated gray warbler, canyon towhee, spotted towhee, and house finch may be found breeding in piñon-juniper woodlands. Ponderosa and mixed-conifer forests provide breeding habitats for spotted owl, band-tailed pigeon, Cooper's hawk, pygmy nuthatch, Virginia's warbler, Grace's warbler, solitary vireo, Williamson's sapsucker, downy woodpecker, hairy woodpecker, mountain chickadee, Steller's jay, hermit thrush, Townsend's solitaire, house wren, pine siskin, and many other species. Cliff faces create suitable habitats for turkey vulture, white-throated swift, rock wren, and canyon wren.

About 60 species of mammals may be found locally. Included among the mammals are 15 carnivore species, such as black bear, mountain lion, bobcat, fox, and coyote. There are about 15 species of bats, and more than 20 species of rodents-mice, ground squirrels, tree squirrels, pocket gophers, chipmunks, voles, and porcupines inhabit the area. Deer and elk can be observed and sometimes create road hazards.