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New Mexico’s geology affords us the chance to see a wide variety of igneous features and landscapes. On our trip we will explore igneous features that range in age from millions of years old to those that erupted within the last 3000-4000 years. Some of the volcanoes we will visit, such as the Albuquerque Volcanoes, were relatively quiescent in their eruptive character. On the other hand, the eruption that formed the Valle Grande caldera was so horrific it ranks that event in the class known as a “Supervolcano”\(^1\) – capable of hemispheric or even global impact.

Many people are surprised to learn that there are so many volcanoes in New Mexico, or even that there are volcanoes within the continental United States outside of the Cascades or Alaska. In fact, there are volcanoes that have been active in the Holocene epoch\(^2\) found in every state west of the Rocky Mountains with the exception of Montana (fig.1).

Figure 1 - Volcanoes of Western North America (from Smithsonian Volcano World)

Large red triangles show volcanoes with known or inferred Holocene eruptions; small red triangles mark volcanoes with possible, but uncertain Holocene eruptions or Pleistocene volcanoes with major thermal activity. Yellow triangles distinguish volcanoes of other regions.

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\(^1\) Though there is no well-defined minimum explosive size for a "supervolcano", there are at least two types of volcanic eruption that have been identified as supervolcanoes: large igneous provinces such as the Deccan Traps and the flood basalts of Iceland, and massive eruptions. Massive eruptions with a Volcanic Explosivity Index of 8 (VEI-8) are colossal events that throw out at least 1,000 km\(^3\) Dense Rock Equivalent (DRE) of ejecta; VEI-7 events eject at least 100 km\(^3\) (DRE).

\(^2\) For this discussion it is accepted that the Holocene started approximately 10 ka (thousand years) Before Present.
WHY ARE THEY HERE?

Since the advent of Plate Tectonic theory, over forty years ago, the location and distribution of igneous features has been much better understood and explained. For instance, the Cascade volcanoes of the Pacific Northwest are the product of the subduction of the Juan de Fuca plate beneath North America. Similarly, the Sierra Nevada Mountains were produced by the subduction of the Farallon plate beneath the western margin of North America 75-45 Ma. Like the Cascades, the Sierra Nevada range was formed as a volcanic arc (figure 2).

![Figure 2 - Volcanic Arc (USGS)](image)

The volcanoes of the interior west have been somewhat more problematic in fitting the standard explanations offered by Plate Tectonic theory. While there is some good evidence supporting a so-called “hotspot” passing beneath the continent serving as the source of some of the volcanism trending from the Pacific Coast to the Yellowstone caldera (figure. 3), the volcanoes peripheral to the Colorado Plateau have been less easily explained (figure. 3b).

![Figure 3 Proposed hotspot trace (USGS)](image)
Recent work by Dr. Hans-Peter Bunge, of Princeton University\(^3\), has offered an explanation that explains this southwestern interior volcanism and also provides a mechanism for the construction of the Rocky Mountains - another geologic conundrum.

The Rocky Mountains do not fit the typical model offered for the construction of a large compressional mountain belt. In the conventional model, the collision of lithospheric plates bearing continental crust, or the accretion of sufficiently massive terranes\(^4\) by collision with continental crust at a subduction zone, are offered as explanations for the orogenetic circumstances giving rise to complex-folded mountain belts. The Alps, Urals, Himalayas and Hindu Kush all fit this paradigm, as do the Appalachians of North America’s East Coast (figure 4).

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\(^3\) HPCC Insights Magazine, NASA Goddard Space Flight Center (http://ct.gsfc.nasa.gov/insights/vol14/story1.htm)

\(^4\) In paleogeography, a terrane is the accreted block that has sutured to a craton (continental nucleus) and that contains distinct rock strata of distinct genesis.
Bunge, collaborating with Dr. John Baumgardner of NASA High Performance Computing and Communication Program (HPCC), reconfigured the TERRA software developed at the Los Alamos National Laboratory for modeling the Earth’s mantle to run on parallel supercomputers. By scaling up the ability of the software to do deep mantle simulations, the research team assembled by Bunge could effectively probe the behavior of subducted lithospheric plates as they plunged deep into the mantle. Coupled with detailed seismic data provided by University of Texas seismologist Stephan Grand, the reconfigured TERRA software began to offer a surprising new look at the post-subduction history of the Farallon plate and its role in the geologic events that have shaped the American West.

The powerful TERRA software “rediscovered” the Farallon plate, gone from the Earth’s surface for more than 60 million years. Amazingly, Farallon now is located deep beneath the East Coast of the United States. Its journey, detailed in the software’s simulations, show that as the plate initially subducted, the partial melting of the plate generated the magma that fueled the development of the Sierra Nevada mountains. As the subduction of the Farallon plate, and the adjacent Kula plate to the north began, the two plates began to diverge (figure 5).

![Figure 5 Western continental margin plate interactions (NASA-GSFC)](image-url)

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5 Faculty Bio and research work: http://www.geo.utexas.edu/faculty/grand.htm
The Farallon plate apparently began its subduction at the “normal” angle of about 45 degrees but then “leveled off” (figure 6). Scrapping along the bottom side of the North American plate for more than 1000 miles, the Farallon plate exerts drag on the North American plate from below (figure 6b), creating compressive forces and shear features aligned with its passage.⁶

Figure 6  Farallon passing beneath N.A. (NASA-GSFC)

Figure 6b Eastward extent of Farallon Plate induced compression (NASA-GSFC)

Volcanism associated with the Colorado Mineral Belt and the southwestern New Mexico Santa Rita lineament between about 75 Ma and 45 Ma seems to be associated with the low angle subduction of the Farallon Plate triggering partial melting in the North American lithosphere (figure 6). Previously discovered structural trends in the lithosphere in this area, related to Proterozoic accretion of terranes, seems to have been a controlling factor in the trending of the magmatism and volcanism of this time period, as the alignment of major igneous activity parallels the accretionary structural grain (figure 8).
By about 45 Ma, the subduction rate of the Farallon Plate decreased, interpreted to be a result of a change in the relative direction of the Farallon, Kula, and North American Plates. Subsequent to this time, regional igneous activity changes in character and location. Andesitic\(^7\) volcanism becomes dominant in the southwestern New Mexico Mogollon-Datil volcanic field, spreading eastward into the Sierra Blanca field. The reason for this change is subject to considerable debate, however, the sinking of the Farallon plate coupled with its partial disintegration may have triggered a change in the thermal gradient and afforded the opportunity for magmatic differentiation and fractionalization\(^8\).

Around 37-36 Ma, the andesitic volcanism gives way to the first major ignimbrite\(^9\) “flare-up” extending from Tran-Pecos Texas into Colorado. Subsequent episodes of ignimbrite volcanism continue periodically until approximately 23 Ma, concurrent with an increase in mafic\(^10\) volcanism believed to be related to the transition from compressional to extentional forces acting on the region. A northwestward retreat of part of the North American Plate at about 17 Ma seems also to be a factor in the increase of mafic magmatism as this triggered increased extension of the Rio Grande Rift.

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\(^7\) Andesite is a gray to black volcanic rock with between about 52 and 63 weight percent silica (SiO\(_2\)). Andesites contain crystals composed primarily of plagioclase feldspar and one or more of the minerals pyroxene (clinopyroxene and orthopyroxene) and lesser amounts of hornblende.

\(^8\) When early-formed crystals are separated from magma, the overall composition of the melt changes the process is called magmatic differentiation (or fractional crystallization aka fractionalization)

\(^9\) Ignimbrite is a compact volcanic pyroclastic (fragmental) rock typically of rhyolitic (high silica) composition. Ignimbrite is primarily composed of fine-grained igneous fragments with a medium to high percentage of volcanic glass.

\(^10\) Igneous rocks that are rich in dark-colored minerals and that contain magnesium and iron and a comparatively low level of silica (45-55 wt% SiO\(_2\)). Generally synonymous with “basaltic.”
Evidence continues to mount that supports the hypothesis that the major control of volcanism in the region is the changing motions of the tectonic plates impinging on the western margin of North America. A change in the motion of the Pacific Plate at about 10 Ma is reflected by the most recent phase of igneous activity in New Mexico - primarily associated with the Jemez lineament.

The Jemez lineament will be the focus of most of our attention during our field trips. Here we will find the most recent volcanism in the region, dated at about 3 Ka (McCarty's Flow) as well as representative examples of a wide variety of igneous features. The lineament is believed to follow the Mazatzal-Yavapai province boundary, a Proterozoic\(^{11}\) terrane suture (figure 10). This boundary was inactive

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\(^{11}\) The period of Earth's history that began 2.5 billion years ago and ended 543 million years ago.
during the northeastward compression of the Laramide orogeny\textsuperscript{12} but seems to have become activated by the northwestward expansion of the Great Basin.

\textsuperscript{12} The Laramide orogeny was a period of mountain building in western North America, which started in the Late Cretaceous, 70 to 80 million years ago, and ended 35 to 55 million years ago.
WHERE NEXT?

Where will the next eruption be? The best evidence points to continued activity on the Jemez lineament in the vicinity of recent activity around El Malpais. Activity is also likely in areas where the Jemez and other lineaments intersect the Rio Grande Rift, such as the Socorro volcanic center, located at the intersection of the Morenci and Capitan lineaments with the Rio Grande Rift (figure 11). Geophysical data strongly indicate the presence of magma bodies at depth in these areas.

Determining the recurrence interval of igneous activity at anything other than the broadest time frames is a difficult task. Work in the El Malpais volcanic field has indicated about 100 eruptions have occurred in the past million years. A crude calculation of frequency would indicate an eruption should occur about every 10,000 years. More precise dating of specific events in the El Malpais field have given intervals of about 5000 to 8000 years between successive eruptions in the late Pleistocene and Holocene epochs. On that basis, given the eruption of McCarty’s Crater about 3000 years ago, an eruption may not be expected for a few millennia – however with active magma chambers known to exist beneath the state, we should certainly consider that a rough estimate.

One thing we know is that the eruption would be preceded by tell-tale signs that magma was making its way to the surface. Bulging of the landscape and swarms of low magnitude earthquakes would announce the arrival of the magma just below the surface, and then we would expect to see an event not unlike that witnessed by Dionisio Pulido, and his wife Paula on February 20, 1943. The Pulidos farmed a small plot in rural Mexico. On that day, they were burning shrubbery in their cornfield when they observed the earth in front of them swell upward and crack to form a fissure 2-2.5 m across. They heard hissing sounds and later described the rise of "smoke"
from the fissure, which had the repugnant smell of rotten eggs. The "rotten egg" smell is a hallmark of H₂S gas, and the crack that opened in front of them would, within hours, develop into a small volcano. Three weeks before the eruption, the people near Paricutin village heard the rumbling noises that resembled thunder, yet they were confused because the skies were clear of clouds. The noises were associated with earthquakes at depth near Paricutin.

Like the cinder cones of El Malpais such as Bandera (figure 13), Paracutin was a monogenetic volcano, reaching its full height of about 1300 feet (425 m) in just under 10 years and subsequently becoming inactive, with no expectation of future activity (figure 14).

Figure 11 Paracutin - 1943

Figure 12 Google Earth view of the Bandera Field

Figure 13 Google Earth View of Paracutin


1 Faculty Bio and research work:  http://www.geo.utexas.edu/faculty/grand.htm

13 A monogenetic volcano is one which erupts once only and then becomes extinct.
Albuquerque's Natural Environment

Geology and Geological History

The Rio Grande Rift

The physiography of Albuquerque is controlled by a diverse group of geologic features, each with a unique origin. Most of the high mountain country lies along a north-south line which bisects the state. This physiographic demarcation is formed by the Rio Grande Rift, a great fracture in the earth's surface that extends more than 450 miles from Leadville, Colo., to Las Cruces, N.M. The Rift was formed by down-dropping of a large block of the earth's crust, yielding an elongated trough bounded on either side by mountains. Many small earthquakes along the faults bounding the Rift tell us that the Rift is still actively evolving. These faults provide avenues for magma to follow as it rises, which produces volcanoes at the surface along the edges of the Rift. Other manifestations of geothermal energy along the Rift margins include hot springs and seeps. This down-dropped block also provides a low spot in the topography for streams and rivers to flow, such as the Rio Grande, which follows the Rift from Del Norte, Colo., to Las Cruces.

Albuquerque lies in the central part of the Rio Grande Rift. The faulted western margin of the Rift lies along the Rio Puerco, approximately 20 miles west of the city center. The eastern edge of the rift lies at the base of the Sandia Mountains.
The Sandia Mountains

The most impressive feature in the Albuquerque area is the lofty mountain range which flanks the eastern city limits. The Sandia Mountains are a great block of granite and limestone which was uplifted during the formation of the Rio Grande Rift. The rise of this immense fragment of the earth's crust is somewhat analogous to opening a trap door; the open door is marked by the gently sloping eastern side of the Sandias (fig. 15), whereas the hinge is found in the intensely crumpled rocks of the Cedar Crest area (fig. 16). The light-colored granite which makes up the majority of the rock in the Sandia Mountains was formed from a magma which solidified one and one-half billion years ago. About 300 million years ago this granite was covered by limey material deposited in an ocean that spread across much of New Mexico. This lime hardened and became the well-layered, fossil-bearing limestone that caps the Sandia Mountains. It was not until relatively recently, about seven to ten million years ago, that the great fault along the western edge of the Sandias began to move, and the Sandias slowly rose to their present commanding height. The total vertical movement on this fault probably exceeds five miles. The same rocks that we see on Sandia Crest lie buried beneath Albuquerque about 15,000 feet below sea level!
Figure 14 Google Earth view of Sandia Mountain looking north. Arrow indicates tip of plunging anticline also shown in fig. 16 below.

Figure 15 Google Earth view of eroded anticline east of Sandia Mountain
Porous Bedrock Means Water Storage

Turning to the valley of the Rio Grande, we see the effects of the subsidence of the huge crystal block west of the Sandias. Most of Albuquerque lies on an apron of material that has been eroded from the mountains surrounding the Rift zone and deposited within it. Many thousands of feet of sediment have consolidated to form the underpinnings of the city. We are particularly fortunate that this material is porous, for great quantities of water are stored in the soft sediments of the Rift valley.

West Mesa Moves

Below Mount Taylor in the western vistas near Albuquerque are the West Mesa and the Albuquerque Volcanoes. The West Mesa, or Llano de Albuquerque, is a remnant of the broad floor of the Rio Grande Rift which developed about 600,000 years ago. This smooth surface formed during a time when there was little movement along the Rio Grande

Figure 16 Google Earth view of the West Mesa

Rift in the Albuquerque Area.

This surface is now more than 400 feet above the present flood plain of the Rio Grande; thus either the West Mesa has been uplifted or the Rio Grande Rift has subsided in its central part in the last 600,000 years. This is a significant amount of movement for such a short period of geologic time.
The Significant Rift

The physiography of the Albuquerque area is thus the sum of many geologic features. The grand design is determined by the Rio Grande Rift, one of the most impressive rift zones on earth. The Rift has fractured the earth’s crust and caused the mountainous margins to rise thousands or tens of thousands of feet relative to the subsiding inner valley. As the fractures developed, they acted as conduits for rising magma which produced the volcanic landforms which border the city. These magmas brought with them mineral resources and heat energy. Erosion of the flanking mountains has slowly filled the rift valley with thousands of feet of porous sediment, and with time this sediment has soaked up rain and river water to become a huge underground reservoir. Thus Albuquerque has been blessed with both scenic and natural resources in abundance; it is a perfect place to spend a moment or a lifetime.

This material was abstracted from an article, "Grand Designs: A Mini Lesson in Local Geology" by Professor Jon Callender (*Albuquerque Magazine*, 1978, Vol. 3, No. 1, p. 32-41), and reprinted with the permission of the author.

The Rio Grande Valley south of Albuquerque
The Zuni-Bandera Volcanic Field and El Malpais National Monument

The Zuni-Bandera volcanic field, in northwest New Mexico, has had many episodes of basaltic eruptions over the last million years (Laughlin et al., 1993). The youngest lava flow in the field is the McCartys flow, which is only 3000 years old, one of the youngest volcanic features in the 48 contiguous United States! The Zuni-Bandera volcanic field has produced many basaltic lava flows, some with a-a characteristics, and some that are paheohoe. There are also a number of well-preserved cinder cones that can be visited, as well as many lava tubes, some of which contain perennial ice. The Zuni-Bandera volcanic field is an excellent site for studying physical volcanology of basaltic magmatic systems.

The geologic map shown below covers about 100 km (60 miles) from north (top of image) to south (bottom of image). The basaltic lava flows appear as black to grey to reddish-brown areas on the satellite image, and different lava flows appear as different colors on the geologic map.

![Geologic map of El Malpais and surrounding area, New Mexico.](image)
The Zuni-Bandera volcanic field consists of a large number of basaltic lava flow and cinder cones, and exhibits a number of striking features of Hawaiian-style volcanism. Pahoehoe and a-a lavas are both represented, along with well-developed lava tube systems. Nichols (1946) mapped and catalogued the geomorphic features of the apparently-young McCartys basalt flow and recognized many features of Hawaiian-style volcanism, including pahoehoe flow patterns, small spatter cones, gas cavities, large wedge-shaped cracks, collapse depressions, large pressure ridges and tumescences. These types of features are also present in other, apparently-older flows, although in some cases are obscured by erosion. At least 100 vents have been recognized in the volcanic field (Luedke and Smith, 1978), and the flows cover a large aerial extent of 2,460 km2. Combined flow thickness is as great as 145 m in some places, and the total volume of all flows is at least 74 km3 (Laughlin et al., 1993).

**Tectonic setting and Geochemistry**

The Zuni-Bandera volcanic field volcanism occurs along the Jemez linament, a zone of apparent crustal weakness defined by a concentration of late-Cenozoic volcanism (Laughlin et al., 1982). The Zuni Bandera volcanic field also occurs in a "transition zone" between the Colorado Plateau, with crustal thicknesses of over 40 km to the Rio Grande Rift where the crust is much thinner. The Jemez linament trends north-northeast, and includes the Zuni-Bandera volcanic field, the Mt. Taylor volcanic field, and the Jemez volcanic field. The Jemez linament apparently has been a long-lasting tectonic feature that penetrates the lithosphere to great depth, and the basaltic lavas of the Zuni-Bandera volcanic field appear to be mantle-derived melts (Laughlin et al., 1982).

Geochemically, the lava flows of the Zuni-Bandera volcanic field include both tholeiitic, alkaline basalts as well as minor basaltic andesites and one basanite (Menzies et al., 1991). Observed phenocryst mineralogy includes small olivine crystals, plagioclase crystals and pyroxene. Groundmass contains the same phenocrysts phases, as well as opaque oxides (Laughlin et al., 1972). Feldspar megacrysts, composed either of anorthoclase or oligoclase, are present in some of the alkali basalt flows. These megacrysts can be up to 2 cm in diameter (Laughlin et al., 1974).

Perry et al. (1987), suggest that late Cenozoic basaltic rocks from the Colorado Plateau-Basin and Range transition area show isotopic characteristics of both enriched and depleted mantle, and may come from the boundary between these two mantle types. Menzies et al. (1991) suggest that although the chemical composition of the Zuni-Bandera lavas is typical of intraplate volcanism, and that chemical signatures typical of both enriched and depleted mantle sources are present.

**Geochronology**

The chronology of lava flows in the Zuni-Bandera volcanic field has been difficult to determine due to the composition of the lava flows. A summary of flow ages is given
below. For details, see the listed references. For details on the McCartys and Bandera flows, see information below table, or click on links below.

Summary of lava flows in the El Malpais area (from Mayberry et al., 1999; Laughlin et al., 1993; Laughlin et al., 1994; Dunbar and Phillips, 1994; Phillips et al., 1997).

<table>
<thead>
<tr>
<th>NAME</th>
<th>VENT</th>
<th>TYPE OF FLOW</th>
<th>AGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>McCartys</td>
<td>McCartys shield</td>
<td>Pahoeohoe sheet flows, aa</td>
<td>2,500-3,900</td>
</tr>
<tr>
<td>Bandera</td>
<td>Bandera Crater</td>
<td>Aa and tube fed pahoeohoe</td>
<td>9,500-10,900</td>
</tr>
<tr>
<td>Cerro Hoya</td>
<td>Cerro Hoya shield</td>
<td>Pahoeohoe sheet flows</td>
<td></td>
</tr>
<tr>
<td>Lava Crater</td>
<td>Lava Crater shield</td>
<td>Tube fed pahoeohoe</td>
<td>18,000</td>
</tr>
<tr>
<td>Lost Woman Crater</td>
<td>Lost Woman cinder cone</td>
<td>Channelized and tube fed pahoeohoe</td>
<td></td>
</tr>
<tr>
<td>Twin Craters</td>
<td>Twin Craters cinder cone</td>
<td>Channelized aa and tube fed pahoeohoe</td>
<td>15,800-17,800</td>
</tr>
<tr>
<td>Laguna</td>
<td>El Calderon</td>
<td></td>
<td>33,400</td>
</tr>
<tr>
<td>Bluewater flow</td>
<td>El Tinitero cinder cone</td>
<td></td>
<td>35,600-79,000</td>
</tr>
<tr>
<td>Candelaria</td>
<td>Candelaria</td>
<td></td>
<td></td>
</tr>
<tr>
<td>El Calderon</td>
<td>El Calderon cinder cone and shield</td>
<td>Aa flowed by pahoeohoe</td>
<td>115,000</td>
</tr>
<tr>
<td>Zuni Canyon</td>
<td>Paxton Springs cinder cone</td>
<td>Channelized aa</td>
<td>Older than Bandera and younger than Bluewater and Laguna flows</td>
</tr>
<tr>
<td>Oso Ridge</td>
<td>Oso Ridge cinder cone</td>
<td>Aa</td>
<td>Older than Zuni Canyon, younger than El Calderon</td>
</tr>
<tr>
<td>Plagioclase lava</td>
<td>South Rendija shield</td>
<td>Pahoeohoe sheet</td>
<td></td>
</tr>
<tr>
<td>Cerro Rendija</td>
<td>Cerro Rendija shield</td>
<td>Tube fed pahoeohoe</td>
<td></td>
</tr>
<tr>
<td>Cerro Encliarro</td>
<td>Cerro Encliarro shield</td>
<td>Tube fed pahoeohoe</td>
<td></td>
</tr>
<tr>
<td>Remah Navajo</td>
<td></td>
<td></td>
<td>7.85 million years</td>
</tr>
<tr>
<td>Fence Lake flow</td>
<td>unknown</td>
<td></td>
<td>0.6-0.7 million years</td>
</tr>
<tr>
<td>North Plains basalts</td>
<td>unknown</td>
<td></td>
<td>0.6-0.7 million years</td>
</tr>
</tbody>
</table>

McCartys flow is the youngest basalt flow within the Zuni-Bandera volcanic field. Its source is a low shield volcano located about 40 km south of the intersection of I-40 and NM-117. A small cinder cone about 8 m high sits on top of this broad shield. Although some of the lava flowed southwestward 8 to 9 km, most followed the preexisting drainage and flowed northward about 40 km before turning to flow eastward 10 km down the Rio San Jose valley. The McCartys flow overlies older basalts of the Zuni-Bandera volcanic field and Holocene alluvium.

The McCartys flow is typically a vesicular, porphyritic basalt. Carden and Laughlin (1974) examined chemical and petrographic variations along the length of the flow and reported that within 4 km of the source the basalt is characterized by plagioclase
phenocrysts 0.20 to 1.5 cm in length. At greater distances from the source, large plagioclase phenocrysts are absent and olivine phenocrysts are present. Plagioclase is the dominant mineral in samples of McCartys flow.

Prior to work of Laughlin et al. (1994) and others, the age of McCartys flow was poorly constrained. Nichols (1946), on the basis of Indian legends and archeological and faunal evidence concluded that the McCartys eruption probably took place after 700 A.D. Since then, accelerator mass spectrometer radiocarbon dates of 2970±60 and 3010±70 years B.P. were obtained on samples of burnt roots. The surface of the flow has also been dated using 3He and 36Cl cosmogenic techniques (Laughlin et al., 1994; Phillips et al., 1997). The determined ages are 2.5±1.1 and 2.4±0.6 ka (3He from Laughlin et al., 1994) and 3.9±1.2 (36Cl, Phillips et al., 1997).

Bandera Crater Flow

The Bandera flows originated from Bandera Crater, a double cinder cone about 150 m high and 1 km in diameter. The eruption of Bandera Crater and its associated flows was the second youngest volcanic event in the ZBVF. Like many other cinder cones in the ZBVF, Bandera Crater is breached to the southwest, probably due in part to local prevailing winds. A large lava tube, intermittently collapsed, extends about 29 km south from the breach in the crater wall and a commercial ice cave is located in a collapsed portion of the tube near the Candelaria Trading Post. Causey (1970) recognized seven stages in the development of Bandera Crater and its associated flows, culminating in the eruption of the black cinders that cap the cinder cone and blanket the hills to the north. Two
small commercial cinder pits have been opened in the cinders covering the hills to the north of NM Highway 53 where the cinder blanket is thickest. A variety of crustal and mantle xenoliths and anorthoclase megacrysts have been found in these cinder pits (Laughlin et al., 1971, 1974; Gallagher, 1973). The Bandera lavas are nepheline normative, holocrystalline, microporphyritic and vesicular near the surface. Both aa and pahoehoe surfaces are common on the flows.

Five different dating techniques have been used to date the Bandera flows or to constrain their ages: conventional K/Ar, 3He, 36Cl, 14C, and 40Ar/39Ar. Two K/Ar dates (Laughlin et al., 1979) have been obtained on flows that immediately underlie flows from Bandera Crater. These dates of 0.199±0.042 and 0.148±0.87 Ma provide maximum ages for the Bandera flows. These ages were suspected of being too old due to the possible presence of excess Ar in the samples. Since then, charcoal collected from under the cinders, and presumably carbonized by the eruption, yielded ages of 10.05-10.07 ka (Laughlin et al., 1994). The cosmogenic 3He and 36Cl techniques yielded ages of 11.2±1.1 and 9.5±0.9 ka (Laughlin et al., 1994; Dunbar and Phillips, 1994). The 40Ar/39Ar technique yielded an age of 41±7 ka, probably much older than the actual eruption age due to excess Ar in the samples. In summary, the Bandera crater cinders and lava flows probably erupted around 10,000 years ago.

This list wide range of references dealing with the Zuni-Bandera and other New Mexican basaltic volcanic fields, processes of basaltic volcanism, and also some papers addressing the tectonic setting of basaltic volcanism within New Mexico. Many of these can be found in the "Natural history of El Malpais National Monument" which is available at the New Mexico Bureau of Geology and Mineral Resources publication department. This, and most other references on this list should be available at a college or university library.

References

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LAVAS TUBES WITHIN THE ZUNI-BANDERA LAVA FLOWS

Lava tubes are a very interesting feature of basaltic lava flows. As basaltic lava cools, the outer part can solidify to form a shell around the inner, still molten and flowing part. The cool crust acts as a very effective insulator for the inner, hotter lava, allowing it to flow for very great distances. Single lava tubes up to 10 km in length have been recognized in Hawaii. Lava tubes have been recognized in many parts of the world, and also may have been recognized on the flanks of the giant Martian volcanoes. The following photos illustrate a number of features observed in a lava tube called Junction Cave near Grants, NM.

El Malpais National Monument Closes Caves to Visitors

Submitted by Kurt Repanshek

ALL CAVES AT EL MALPAIS NATIONAL MONUMENT ARE CLOSED TO PREVENT THE SPREAD OF WHITE-NOSE SYNDROME.

All caves at El Malpais National Monument in New Mexico have been closed to humans due to concerns over white-nose syndrome, a deadly disease that is sweeping through bat colonies in the eastern United States.

While nearly all of the caves in the park have been closed for some time, Superintendent Kayci Cook Collins says the five caves - Junction, Xenolith, Big Skylight, Four Windows and Braided - that have remained opened are now closed to the public.

“Federal and state agencies in New Mexico are very concerned about the spread of the fungus, Geomyces destructans, which causes white-nose syndrome in bats,” said the superintendent in a prepared release. “The disease has already killed more than 1 million bats in the northeastern United States and has spread from New York State all the way to northwest Oklahoma in four years.”

Officials aren't entirely sure what causes the fungal disease or how to manage it. Nor do they know whether the disease originated in the United States or came over from Europe, where a similar fungus exists on bats, or whether there are pockets of naturally immune bat populations.
“Researchers believe bat-to-bat contact is one of the ways the disease moves from cave to cave, however the disease may also be spread from cave to cave by humans on their caving gear,” the El Malpais superintendent said.

The recent discovery of the disease in Oklahoma could easily threaten bat populations at El Malpais, she said.

“The (bat) species that tested positive in Oklahoma, the Cave myotis, is the first uniquely western species to contract the Geomyces fungus,” Superintendent Collins said. “And, more importantly, the Cave myotis is found at El Malpais.”

Research is under way to see if the fungus might already be present in monument caves.

“We have no evidence that the fungus is present in our caves, however we have been doing research over the summer and are currently testing cave soil samples to see if the Geomyces strain is here,” she said. “There are several other bat and cave research projects we hope to get under way later this year and next spring that will add to the information we are currently collecting.”

While testing for the fungus and monitoring cave environments is the prime focus of the ongoing and future research efforts, Superintendent Collins said the monument is also seeing which caves do not have bat colonies.

“Caves that have maternal colonies, are bat hibernating sites or have agency species of concern must be closed,” she said. “Once we have more solid information from our researchers, we will look at recreational caving options.”
Bandera Crater is the largest volcano in the region. It erupted around 10,000 years ago. There were two stages of the eruption: first the cinder cone developed, then a massive lava flow broke out on its side. Bandera's lava flow is nearly 23 miles long. At the end of the Bandera eruption, the lava suddenly fell back down the main vent making the bottom of the cone deeper than the outside lava flow. The crater that remains is nearly 1200 feet wide at the top and roughly 750 feet deep. Over time, erosion and gravity take their toll on the crater and slowly fill it with cinders and rocks.

**Lava Tubes**

The Bandera lava tube complex at one time extended for over seventeen miles. Today, much of the tube is collapsed, but many segments of these spectacular caves remain to be seen.

The Bandera lava tubes formed during the phase of molten lava flow from the volcano. The surface of the lava hardened, while below, the lava continued to flow. The hardened, porous lava acted as an excellent insulator and kept the lava beneath the surface hot and runny. The insulated lava so flowed through natural pipelines appropriately known as lava tubes. When the flow from Bandera came to an end, the lava tubes drained and left caves that we can explore today.
Ice Cave

The Ancient Lava Trail leads you to Ice Cave, the partially collapsed remains of a lava tube. The temperature at Ice Cave never rises above 31 degrees Fahrenheit. It is floored with natural layers of perpetual ice that glisten blue-green in the reflected rays of sunlight. The green tint is caused by unusual forms of Arctic algae.

As rain water and snowmelt seep into this cave, the ice floor thickens. The floor of the ice is now approximately 20 feet thick. The deepest ice is the oldest and dates back to the year 170 AD. The back wall was carved in the early days when Pueblo Indians, who knew the cave as the "Winter Lake", and early settlers mined the ice. In 1946, ice removal was stopped, at which time the ice wall was nearly 12 feet high. Since then, the ice floor has risen relative to the back wall. The rate of ice accumulation varies with annual precipitation.

Ice Cave serves as a natural ice box due to its peculiar geometry. A restricted entrance leads downward twenty feet into an enclosed chamber. During the winter, cold, dense air sinks into the cave. During the summer, little air exchange takes place, and the cave is insulated from the sun's heat by porous lava rock. The cave thus maintains frigid winter temperatures all year round.
Mount Taylor volcano, a prominent landmark that can be seen on the skyline west of Albuquerque, is located about 15 miles northwest of the town of Grants, New Mexico. Mount Taylor Peak, at an elevation of 11,301 feet, stands approximately one mile above the Rio San Jose 12 miles to the south (Hunt, 1938). Mount Taylor volcano is part of a larger, northeast-trending volcanic field that includes Mesa Chivato, a broad plateau located northeast of the cone (Figure 1), and Grants Ridge (Keating and Valentine, 1998; WoldeGabriel et al., 1999), located southwest of the cone. Basalt that caps Mesa Chivato and other mesas surrounding Mount Taylor makes up about 80% of the volume of the volcanic field (Perry et al., 1990). The Mount Taylor volcanic field lies on the southern flank of the San Juan Basin on the Colorado Plateau and straddles the extensional transition zone between the Colorado Plateau and the Rio Grande rift (Figure 1). The Mount Taylor volcanic field is considered to be part of the Jemez Lineament, a zone of young (< 5 million years old, Figure 3) volcanism aligned along an ancient suture in the 1.7 to 1.6 billion year old Proterozoic basement (Mayo, 1958, Laughlin et al., 1976; Lipman and Moench, 1972; Perry et al., 1990).

Although Mount Taylor volcano is the feature that dominates the landscape near Grants, the earlier history of the region prior to the eruption of the volcanic rocks is well preserved in the bold cliffs below the volcanic rocks, particularly around the southern margin of the volcanic field. Sandstone and shale deposited along a shoreline, thick deposits of black shale deposited in an open ocean and tan sandstone with interbedded shale and coal deposited by a northeast-draining river system record the oscillation of the northwest-trending shoreline of the Cretaceous Western Interior Seaway back and forth across the area ~84 to 99 million years ago. The Cretaceous rocks exposed around Mount Taylor include the Dakota Sandstone, Mancos Shale, Gallup Sandstone, and Crevasse Canyon Formation (Lipman et al., 1979; Dillinger, 1990).

Following deposition of the Cretaceous rocks, the area was gently folded by Laramide compression starting about 80 million years ago (Cather, 2004). Mount Taylor is on a broad regional downwarp called the Acoma Sag (Crumpler, 1982). The McCarty syncline, a north-plunging broad symmetrical fold that extends from the east end of the Zuni Mountains north-northeast (N20°E) into the southern San Juan Basin, underlies the Mount Taylor volcanic field. At the south end of the field, the northward
plunge of the fold dramatically increases and the west flank of the fold becomes a monocline, but at the north end of the field the syncline is no longer visible. (Hunt, 1938).

Mount Taylor is a composite rhyolitic to intermediate (latitic) composition stratovolcano that was active >3.3 to 1.5 million years ago (Perry et al., 1990). Composite stratovolcanoes are usually made of lava flows interbedded with ash flow tuffs and pumice that form during explosive eruptions and volcaniclastic sediment (sediment related to erosion of the cone). Mount Taylor is a classic composite cone in nearly every respect (Figure 4) except that only 10% of the cone is made of tuff and pumice, a low volume compared to other volcanoes of this type (Perry et al., 1990). A 3.73 ± 0.09 million year old basanite flow sitting on Cretaceous sandstone at the north end of Horace Mesa is the oldest volcanic unit dated so far in the Mount Taylor field (Lipman and Moench, 1972). The oldest volcanic unit exposed in the bottom of the cone's amphitheater is a 3.3 million year old trachyte dome or flow. This trachyte dome is most likely related to trachytic volcanism to the northeast on Mesa Chivato (Crumpler, 1980, Lipman and Mehnert, 1979) and is not directly associated to the formation of the Mt. Taylor cone (Perry et al., 1990). After these initial eruptions, rhyolite (70 to 75% silica) lava erupted during the early history of the buildup of the volcanic cone, followed by quartz latite (63 to 70 % silica), and finally latite (58-63% silica) (Perry et al., 1990). In general, the composition of the lavas on the cone
became more mafic through time. Most of the cone formed between 3 and 2.6 million years ago and quartz latite makes up more than 65% of the cone (Baldridge et al., 1989). Basalt eruptions occurred through the lifetime of the volcano, although relatively little basalt erupted prior to the main formation of the cone. Most of the basalt in the Mount Taylor volcanic field erupted after the cone formed, erupting from vents around the volcano, with the basalt flows lapping onto the edge of the cone and spreading out over erosion surfaces (Hunt, 1938). Most of the basalt is hawaiite, but flows ranging from basanite to trachyte in composition are also present (Lipman and Moench, 1972; Crumpler, 1977).

An east-facing amphitheater is a prominent feature in the central part of the volcano (Figures 1, 3, and 5); Mount Taylor Peak is the highest point on the west rim of the amphitheater. Underlying Cretaceous sedimentary rocks and the oldest volcanic rocks in the cone are exposed in the lower elevations of the amphitheater. Crumpler (1982) suggested that the east side of Mount Taylor collapsed, leading to a lateral eruption like the 1980 eruption of Mount St. Helens in Washington state; however, no clear debris avalanche deposits indicative of a lateral eruption have been found on Mount Taylor (Perry et al., 1990). A mudflow deposit containing boulders and cobbles of volcanic rock mantles the east side of the volcano (Lipman et al., 1979). Hunt (1938) and Perry et al. (1990) propose that the amphitheater is the result of erosional enlargement of a crater on Mount Taylor volcano.
Mt Taylor cross section

Figure 4. Diagramatic cross-section of Mt. Taylor volcano, modified from Lipman and Mehnert (1979) using the ages of Perry et al. (1990), Laughlin et al. (1993), and Dunbar and Phillips (2004).

Perry et al. (1990) use spatial and temporal trends in the geochemistry of the lavas in conjunction with thin section and field observations to argue that several successive short-lived magma chambers, rather than one large chamber, fed Mount Taylor volcano. The trend of increased mafic content through time may be due to low rates of extension early in the history of the field, which may have allowed magma coming up from the mantle to pond in the crust and differentiate. Later in the history of the field, increased extension allowed more magma to pass through the crust with little time to differentiate. In fact, many of the later basalts contain abundant pieces of mantle rock (xenoliths) that were entrained in the magma, suggesting a relatively quick trip from the source in the mantle to eruption at the surface. These eruptions provide a wonderful opportunity to examine pieces of the Earth's mantle that formed at depths of 50 to 62 miles (80 to 100 km) below the surface (Pocerra et al., 2004).

Mesa Chivato

Mesa Chivato, located northeast of Mount Taylor, is the site of numerous fissure vents, collapse craters, maars, and trachyte domes (Aubele et al., 1976, Crumpler, 1980). Fissure vents are linear volcanic vents through which lava erupts, usually without any explosive activity. The vents are usually a few meters wide and may be many kilometers long. Maars are broad, low-relief volcanic craters formed by shallow explosive eruptions that are usually caused by the heating and boiling of groundwater when magma invades the groundwater table. Maars often subsequently fill with water to form a lake. Mesa Chivato is dotted by hundreds of basaltic vents that are aligned in both northeast and west-northwest directions (Figure 3). The orientation of the vents is thought to be controlled by underlying basement structures (Crumpler, 1982; Laughlin et al., 1982). In places, faults on the mesa follow northeast trending fissure vents and thus postdate the basalt. Elsewhere, fissure eruptions postdate faulting (Crumpler, 1980, 1982). The east side of the field is bounded by the Rio Puerco fault zone, including the Alamosa fault, San Ignacio monocline and Reservoir fault (Hunt, 1938), which form part of the eastern boundary of the Rio Grande rift.
A trachyte dome on Mesa Chivato yields a K-Ar age of 3.3 ± 0.2 million years (Lipman and Mehnert, 1979). This dome predates a 7.4 mile (12 km) wide zone of normal faulting that trends north-northeast across the mesa. As mentioned above, a trachyte flow or dome that is 3.3 ± 0.08 million year old (Perry et al., 1990) is exposed in the bottom of the Mount Taylor amphitheater. The domes on Mesa Chivato and Mt. Taylor formed at the same time and are compositionally similar, and thus may be related. Interestingly, the trachyte is not the oldest unit on Mesa Chivato. Several basalt flows and a basal rhyolite tuff lie below the dated flow, so the timing of the initiation of volcanism on Mesa Chivato is unconstrained.

![Mt. Taylor Shaded Relief Map](image)

**Figure 5 – Mt. Taylor Shaded Relief Map**

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The Kasha-Katuwe Tent Rocks National Monument is a remarkable outdoor laboratory, offering an opportunity to observe, study, and experience the geologic processes that shape natural landscapes. The national monument, on the Pajarito Plateau in north central New Mexico, includes a national recreation trail (see “Activities” below) and ranges from 5,570 feet to 6,760 feet above sea level.

The cone-shaped tent rock formations are the products of volcanic eruptions that occurred 6 to 7 million years ago and left pumice, ash and tuff deposits over 1,000 feet thick. Tremendous explosions from the Jemez volcanic field spewed pyroclasts (rock fragments), while searing hot gases blasted down slopes in an incandescent avalanche called a “pyroclastic flow.” In close inspections of the arroyos, visitors will discover small, rounded, translucent obsidian (volcanic glass) fragments created by rapid cooling. Please leave these fragments for others to enjoy.

Precariously perched on many of the tapering hoodoos are boulder caps that protect the softer pumice and tuff below. Some tents have lost their hard, resistant caprocks and are disintegrating. While fairly uniform in shape, the tent rock formations vary in height from a few feet to 90 feet.

As the result of uniform layering of volcanic material, bands of gray are interspersed with beige and pink-colored rock along the cliff face. Over time, wind and water cut into these deposits, creating canyons and arroyos, scooping holes in the rock, and contouring the ends of small, inward ravines into smooth semi-circles.
**Historical & Cultural Perspective**

The complex landscape and spectacular geologic scenery of the national monument has been a focal point for visitors for centuries. Before nearby Cochiti Reservoir was built, surveys recorded numerous archaeological sites reflecting human occupations spanning 4,000 years. During the 14th and 15th centuries, several large ancestral pueblos were established and their descendants, the Pueblo de Cochiti, still inhabit the surrounding area. Kasha-Katuwe means “white cliffs” in the traditional Keresan language of the Pueblo.

In 1540, the Spanish explorer Francisco Vasquez de Coronado encountered the Pueblo de Cochiti. Throughout the 17th century, settlers would follow Juan de Oñate’s route along the Rio Grande Valley, bringing trade, farming and domestic animals, and claiming land grants from the Spanish Crown. In 1680, the Cochiti people joined other pueblos in a rebellion that drove the Spaniards south to El Paso, Texas, but the Spanish returned permanently in 1692. By 1870, iron rails stretched into the territory of New Mexico bringing loggers, miners and others to enjoy its rich natural resources.
Cabezon Peak

Cabezon Peak’s dramatic volcanic formation is one of the most well known landmarks in northwest New Mexico. With an elevation of 7,785 feet, the Peak is part of the Mount Taylor volcanic field and is the largest of 50 volcanic necks rising from the Rio Puerco Valley. Dramatic basaltic cliffs on Cabezon provide a close view of an ancient volcano. To the south, the land rises sharply to Mesa Chivato, with cool pine forests and elevations over 8,000 feet. Mesa Chivato is composed of basaltic lava flows that erupted from Mount Taylor 3.3 to 1.5 million years ago. The colorful Cretaceous shoreline and marine rock layers expose lava cap ends and the elevation drops quickly to the Arroyo Chico to the north. The Rio Puerco flows through Cabezon Country, passing close by Cerro Cuate before making a dramatic bend to the south.

The name “Cabezon” is derived from the Spanish noun “cabeza,” meaning “head,” and “Cabezon” translates as “big head.” The peak is believed to have religious significance for the Pueblo and Navajo Indians, and remnants of their visits still exist. The Navajos have various myths associated with Cabezon, one of which explains that the peak and local lava flows came from a giant who was slain upon Mount Taylor. The giant’s head became Cabezon Peak and his blood congealed to form the Malpais, or the “bad land” volcanic flow to the south.
Coronado State Monument is located about 15 miles north of Albuquerque in Bernalillo. Drive north on I-25 from Albuquerque, take the Highway 550 exit (Exit 242), drive west 1.7 miles, then turn north (right) on Kuaua Road, following the signs to the monument.

Coronado State Monument is named after Francisco Vasquez de Coronado, a Spanish explorer who was in New Mexico in the mid-16th century. Coronado supposedly wintered at Kuana Pueblo, the large pueblo preserved at the state monument, between late 1540 and early 1541; however, recent excavations indicate that the Spaniards camped nearby at Santiago Pueblo, located about 2 miles to the southwest of Coronado State Monument. Nonetheless, the preserved pueblo is impressive and the kivas at Kuana Pueblo are decorated with remarkable murals that can be viewed at the Visitor's Center.

Geologic Setting

Coronado State Monument, which is on the western bank of the Rio Grande in Bernalillo, offers spectacular views of the Sandia Mountains, a mountain range that exposes one of the most complete records of the geologic history of northern New Mexico (Kelley and Northrop, 1975; Pazzaglia et al., 1999a). Coronado State Monument lies in the Albuquerque Basin (Kelley, 1977), one of several basins that form the Rio Grande rift, a northerly-trending zone of continental extension that runs between central Colorado and west Texas (Figure 1). The dramatic mountains on the east side of Albuquerque, which on average are about 4000 feet higher that the valley, formed as the result of Rio Grande rift extension starting about 25 million years ago (Roy et al., 1999; Karlstrom et al., 1999; House et al., 2003).
The Sandia Mountains dip about 15° to the east. As a result, the oldest rocks in the range are exposed in the western escarpment; the craggy spires on the west side of the Sandia Mountains are made of 1.7 billion year old igneous and metamorphic rocks and 1.4 billion year old granitic rocks (Figure 2). These ancient rocks are overlain by nearly 11,500 feet (3.5 km) of sedimentary and volcanic rocks that are exposed on the east side of the Sandia Mountains and in the Hagan basin to the northeast of the Sandia Mountains. The sedimentary and volcanic rocks, which are ~330 million to ~30 million years old, tell a tale of oceans rising and falling, great sand dune fields accumulating, and ancient river systems flowing, and volcanoes erupting across the area. Only the oldest rocks near the base of this great stack of sedimentary and volcanic units, the limestones of the Mississippian Arroyo Peñasco Group, and the sandstone, limestone, and shale of the Pennsylvanian Sandia Formation and Madera Group, are visible as a thin, layered, gray band on the skyline capping the pink granitic rocks (Figure 3). These Mississippian and Pennsylvanian rocks were deposited in a shallow ocean that once covered much of the state of New Mexico. More than 1 billion years of Earth's history is missing across the boundary between the pink granite and the gray limestone; this huge gap in the rock record is called the Great Unconformity. The younger rocks of the 11,500-foot (3.5 km) section, which are not easily discernible from the monument, can be viewed along
highways on the northern and eastern side of the Sandia Mountains (Kelley and Northrop, 1975; Pazzaglia et al., 1999b; Lucas et al., 1999; Bauer et al., 2003).

Coronado State Monument overlooks the modern flood plain of the Rio Grande. The pueblo is built on young, poorly-consolidated deposits of sand, sandy clay, and gravel associated with a broad alluvial fan derived from areas west of the river. Two older deposits are exposed in the banks of the river in the vicinity of the monument. A moderately consolidated deposit of gravel, sand, and minor sandy clay derived from an ancestral Rio Grande (<156,000 years old) overlies a well-consolidated <4 to 6 million year old gravelly sandstone with gravel clasts of red granite, basalt, light-gray tuff, and minor sandstone derived from the northwestern margin of the Albuquerque Basin and eastern slope of the Sierra Nacimiento (Connell et al., 1995).

“Francisco Vásquez de Coronado and His Entrada Into New Mexico”

(Excerpted from the Southwest Crossroads Spotlight)

Francisco Vásquez de Coronado was born in Salamanca, Spain in 1510. He arrived in New Spain after the Fray Marcos de Niza expedition had returned from the north with descriptions of the golden Seven Cities of Cibola. Coronado organized an expedition of 300 Spanish soldiers and 1000 Tlaxcalan Indian allies and set out from Compostela along the west coast of Mexico on February 23, 1540. They retraced Fray Marcos de Niza's route and reached Zuni, only to discover that the pueblos were made of adobe, not gold. The expedition visited the Rio Grande pueblos and those to the east and west. They saw the Grand Canyon, the Pacific Ocean, and the eastern plains, but nowhere did they find riches. Coronado's expedition, that had suffered many hardships and disrupted the lives of the native populations, was considered a failure. Coronado returned to New Spain and died in poverty in Mexico City in 1554. Pedro Casteñeda de Najera, a soldier on the expedition, wrote an account of their journeys.
References


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.

Figure 1 Route map of selected road geology sections and panoramic views in the Pajarito Plateau and the Jemez Mountains, north central New Mexico.
STOP 1: 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.

**STOP 2: 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

![Image](image_url)
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.

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 km² 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 km². 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 to 100,000 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 anticlockwise 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 km2 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: 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 5: The Bandelier Tuff and late Tertiary stratigraphy

Park in large turn-out on road cut near Twin Tanks. 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 left (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. 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 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 volcanioclastic 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
overrode 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.

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.
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Petroglyph National Monument is located on Ceja Mesa on the west side of Albuquerque. (Figure 1).

The Volcanoes Day Use area can be reached by driving west from Albuquerque on I-40 and exiting at Atrisco Vista – formerly Paseo del Volcan (Exit 149). The Volcanoes Day Use area is 4.8 miles north of I-40 on the east side of the road (Figure 1).

Petroglyph National Monument is best known for the estimated 25,000 rock art images carved into basalt erupted from the approximately 200,000-year-old Albuquerque volcanic field (Figure 2). Using stone chisels and hammer stones, the ancestors of the Puebloan Indians cut most of the petroglyphs into the desert varnish coating the basalt between 1300 and 1680 A.D. A few of the markings are much older, dating back to perhaps 2000 B.C. Spaniards and later generations of Albuquerque inhabitants have produced younger petroglyphs with more modern themes. The monument, created in 1990, includes about 17 miles of petroglyph-covered basalt cliffs and five extinct volcanoes.
Figure 1 – Location and geologic map for Petroglyph National Monument. Geology from Connell (2008).

Figure 2 – Petroglyphs etched in desert varnish on basalt flows in the northern geologic window section of Petroglyph National Monument.
Regional Geologic Setting

The Albuquerque volcanic field is only seven miles west of downtown Albuquerque. The volcanic field is in the western Albuquerque Basin of the Rio Grande rift (Figure 3). This basin is just one of a series of linked basins between central Colorado and west Texas that formed when the earth's crust extended or stretched in an east-west direction starting about 36 million years ago in the southern part of the rift. As extension was accommodated by normal faults, deep basins and prominent rift-flank uplifts formed. The monument offers spectacular views of the Sandia Mountains directly to the east and Manzanita and Manzano Mountains to the southeast (Figures 3 and 4). These east-tilted rift-flank ranges on the eastern margin of the Albuquerque Basin rise as much as 5700 feet above the elevation of the Rio Grande, exposing Precambrian granitic and metamorphic rocks on the west side, with Pennsylvanian limestone and shale capping the mountain blocks. The western margin of the Albuquerque Basin is a subtle topographic feature that lies about 12 miles to the west of the monument on the west side of the Rio Puerco, where Cretaceous marine sedimentary rocks are faulted against rift-fill sediments. The volcanoes formed along faults near the center of the basin, perhaps in a place where the crust is most thinned by extension.
Figure 4 – Manzano Mountains, a rift-flank uplift southeast of Petroglyph National Monument. Photograph by Richard Kelley.

Figure 5 – Albuquerque Volcanoes Map
Figure 6 – View of Volcan cone, looking toward the northwest.

About 210,000 to 155,000 years ago (Peate et al., 1996; Smith et al., 1999), basaltic magma from deep within the earth migrated up along the fractured rock in the vicinity of a significant rift-related fault; the fault is named the County Dump fault for good exposures of this feature at the local landfill (Bauer et al., 2003). The weakened, fractured rocks around the fault acted as conduits, allowing the molten rock to come to the surface. The fault has not moved significantly in the last 20,000 years, but a small earthquake (magnitude 4.4) was recorded along this fault in 1971 (Bauer et al., 2003).

Five large cones and at least 10 small volcanoes and spatter cones have been recognized in the Albuquerque volcanic field (Kelley and Kudo, 1978; Crumpler, 1999; Smith et al., 1999). Three of the largest cones are connected by the trails of the Petroglyph/Albuquerque Volcanoes National Monument (Figure 5). Six basalt flows erupted from the aligned spatter cones and fissures that developed along two en echelon north-south striking fault segments (Lambert, 1968; Kelley and Kudo, 1978). The fissures and spatter cones shot fountains of ash, cinders, and lava about 30 feet into the air (Smith et al., 1999). The first eruption along the fissures sent lobes of fluid lava that moved slowly (5-10 mph; Bauer et al., 2003) downslope to the east and southeast into the Rio Grande valley, covering the Llano de Albuquerque surface and the younger terrace and valley alluvium deposits. The lava from the second eruption covered a larger area than the first flow, rolling toward the northeast, east, and southeast, again into the river valley. There was a pause in
activity and thin sediments were deposited. When activity was renewed in the Albuquerque volcanic field, the style of eruption changed. The magma was slightly more viscous (i.e. more sticky), so that the lava flowed both east and west of the main fissure, but the lava did not flow very far (Figures 1 and 6). The flows from the final three eruptions were localized around the vents (Figure 1).

Geologic Features

Several of the basalt flows that erupted from the cones contain abundant white plagioclase crystals that are easily visible to the naked eye (Figure 7). Generally the tops and bottoms of the individual flows are full of holes called vesicles, which formed as gas bubbles escaping from the cooling lava were trapped and preserved in the rock (Figure 7). The tops of the flows variably have a ropy (pahoehoe) or a rubbly (aa) texture. Wind-blown spatter and cinder deposits, frozen lava lakes, and small lava tubes are among the well-preserved volcanic features that can be viewed in the monument (Smith et al., 1999; Crumpler, 1999).

Figure 7 – Close-up of the surface of one of the lava flows. The small elongate features are phenocrysts of plagioclase and the small black dots are vesicles. The circular object is a Lifesaver candy, which is included in the photograph for scale.
The volcanoes on Ceja Mesa are aligned along two segments that trend in slightly different directions. The southern segment, which strikes 2° east of north, includes, from south to north, the JA, Black, and Vulcan cones (Kelley and Kudo, 1978). The trail system of the Volcano Day Use area meanders through this southern set of cones. One of the southern-segment cones named Cinder, which was south of JA cone, has been mined out of existence. Cinder from the cones was mined for railroad bed material, cinder blocks, and landscaping material. The northern set of cones, including Butte and Bond cones, is offset to the west of the southern segment by about 650 feet and strikes 3° east of north (Kelley and Kudo, 1978). These cones are harder to visit because there are no trails.

The largest of the cones in the Albuquerque volcanic field is Vulcan (Figures 6 and 8), named after the Roman god of fire. From a vantage point on top of the cone 200 feet above mesa, the alignment of the 5-mile-long chain of vents is particularly noticeable. Vulcan is a spatter cone, formed primarily by fire fountains that were active in the central vent and in smaller vents on flanks of the cone (Smith et al., 1999). Spatter forms when blobs of lava are emitted from a vent. The blobs cool as they fly through the air, and the partially molten blobs then land on the side of the cone to weld together to form a hard crust. Fragmental cinder and spatter material and lava flows dip at angles as high as 55° away from the central vent on the eastern and southern side of the Vulcan (Figure 8; Smith et al., 1999). The spatter material is thickest on the southeastern side of Vulcan, indicating that it was blown by the wind toward the south and east during the fountaining events. A solidified lava pond that consists of a massive gray basalt with weakly-developed columnar jointing occupies the crater of Vulcan (Figures 9 and 10). Modern graffiti has been carved into this flow on the west side of the cone. Radial, sinuous lava tubes 8 to 20 inches across and 300 feet long are preserved on the northeast and northwest flanks of Vulcan.

![Figure 8](image_url) – Steeply dipping fire fountain spatter deposits on the east side of Vulcan. A classic example of inverted topography is preserved on the east side of the monument.
Basalt from the Albuquerque volcanoes once filled in low spots along the edge of Rio Grande valley about 200,000 years ago. Subsequent downcutting by the Rio Grande has now formed a mesa capped by basalt. Erosion of the soft sediments under the hard basalt has caused large blocks of basalt from the two older flows to tumble down the eastern escarpment of the mesa. Most of the petroglyphs are on these large basalt blocks. The petroglyphs are chiseled into a black, metallic-looking patina on the basalt called desert varnish. This coating forms in arid environments on protected surfaces that are resistant to weathering. Desert varnish is composed mainly of clay mixed with manganese and iron oxides. Organic processes and the evaporation of dew, which causes the concentration of manganese oxide, enhance the formation of desert varnish. The best petroglyphs are along trails in Rinconada Canyon to the south of the Visitor Center and along trails in Boca Negra Canyon and Piedras Marcadas Canyon to the north of the Visitor Center.

Figure 9 – View to the north of Volcan. A solidified lava lake is shown in the foreground. The white arrows highlight the aligned Bond and Butte cones.

Figure 10 – Closer view of the solidified lava lake on north side of Volcan.
Two small erosional windows cut by streams through the basalt flows are included within Petroglyph National Monument (Figures 1 and 11). There are no formal trails or parking areas to access these windows, but the erosional windows can be reached by hiking along arroyos. The northern window can be accessed via dirt roads located south of Paseo del Norte NW or by walking up North Boca Negra Arroyo. The southern window can be reached by walking along South Boca Negra Arroyo. The basalt flows are thin in the vicinity of these windows compared to areas to the north and south, suggesting that there might have been small hills on top of the Ceja Formation prior to the eruption of the Albuquerque volcanoes. Basal flow features and flow breaks are well-exposed in these windows. Although the Ceja Formation is poorly exposed in these drainages, pebbles and cobbles of granite, quartzite, and chert litter the slopes below the lava flows (Figure 5). A few petroglyphs were carved into the basalt flows of the geologic windows (Figure 2).

Figure 11 – Rubble covered slopes of the northern geologic window section of Petroglyph National Monument, Photograph by Richard Kelley.

The Cat Hills – located south of the Albuquerque Volcanoes, are slightly younger, but similar in origin and morphology.
Petroglyph National Monument protects a variety of cultural and natural resources including volcanos, archeological sites and an estimated 20,000 carved images. Many of the images are recognizable as animals, people, brands and crosses; others are more complex. These images are inseparable from the cultural landscape, the spirits of the people who created, and who appreciate them.

Rinconada Canyon offers insight into the geologic, cultural and natural resources of Petroglyph National Monument. Follow the path of past inhabitants of this landscape along silent volcanic boulders yearning to speak to those willing to listen. Enter a narrow valley that seems to have frozen in time, carrying you over sand dunes and alongside a volcanic escarpment abundant with plant and animal desert life. As you walk into the canyon the sounds and sights of the city fade away and may be replaced with the coo of a mourning dove or a collared lizard sunning itself on a basalt boulder.

Human Connections

Around A.D. 1300 there was a population increase in the Middle Rio Grande Valley by ancestors of today’s Pueblo Indians and other Southwestern tribes. The Ancestral Puebloans lived in adobe villages along the Rio Grande, utilizing Albuquerque’s West Mesa for hunting, gathering, dry-farming, cultural and religious activities.

Spanish explorers and Mexican natives arrived in the Southwest in 1540, meeting groups of people along the Rio Grande who lived in what they described as pueblos, or towns, hence the name Pueblo people. Rinconada Canyon exhibits remnants of
Spanish activity including rock shelters, rock wall alignments (possible sheep corrals), Christian crosses, and petroglyph's of livestock brands. These shepherders were likely descendants of the Atrisco Land Grant holders who were granted an 82,000 acre parcel in 1692 by Governor Don Diego de Vargas. Local Native peoples have a long and enduring relationship with the land and its resources.

The Petroglyphs

Most of the petroglyphs were made by pecking. An early method of pecking may have been accomplished by striking the basalt boulder directly with a hammerstone removing the dark, desert varnish on the boulders surface. Later, a more controlled execution was developed by using two stones, in much the way a chisel is used, to peck boulders. This “hammer and chisel” method gave petroglyph makers the ability to peck images with detail.

Archeologists believe Ancestral Puebloans made most of the 1200 petroglyph's in Rinconada Canyon four to seven hundred years ago. Pueblo elders believe the images are as old as time. They also believe that the petroglyphs choose when and to whom they reveal themselves. You may not see them all. The images include anthropomorphs—human-like figures, concentric circles/spirals, animal figures, and geometric designs. Pueblo Indians use petroglyphs to teach their children about their history, culture, and spiritual beliefs.

Petroglyphs offer the opportunity to think about how human inhabitants interacted with nature and with each other. Many Southwest Indians are able to claim cultural relationships to past inhabitants of this area because they recognize the images as having deep cultural and spiritual significance.

As you view the images, consider how they fit into the landscape and how the images might be important in Southwest Indian, Spanish, and Mexican cultures and religious beliefs. Also recognize that petroglyph images have varied interpretations or meanings to different people. Please respect the importance of petroglyphs to the inhabitants, both past and present, of this sacred land.

The Hike

The trail along the base of the north side of the canyon allows you to view a variety of petroglyphs. The trail is 1.25 miles long to the head of the canyon (2 1/2 miles round trip) and is moderately strenuous. You may return by backtracking along the north side of the canyon or continue the trail loop down the middle of the canyon. This route is devoid of petroglyphs but your chance of seeing an Earless Leopard Lizard or hearing the cascading song of a Canyon Wren is worth the trip.

As you watch a turkey vulture soar above the canyon or a desert millipede walk across the trail, take the time to let your imagination wander and experience the beauty of this compelling landscape.
References

New Mexico History

New Mexico's past is long, diverse and very much storied. Human existence as long as 25,000 years ago has been verified at Sandía Cave near Albuquerque and near Folsom in northeastern New Mexico where man thrived some 15,000 years ago. Also, evidence of humans possibly pre-dating that of Sandía Cave recently was discovered near Orogrande in southern New Mexico, while other evidence of man was found at Blackwater Draw near Portales.

Since prehistoric man roamed our expansive vistas, the ancestors of our modern Native American inhabitants lived in many areas of the state shortly after the time of Christ. They lived in pit houses, which were holes dug in the ground with roofs fashioned from wood and branches. Some of these ancient Indians also dwelled in cliffside caves and later they built impressive stone structures at Chaco Canyon, among other sites that reveal similar architecture.

The ancestors of these early Indians known as the Anasazi are believed to be the modern Pueblo Indians of today. They lived in virtual isolation in pueblos mostly along the Río Grande and in western New Mexico and eastern Arizona until the arrival of the Spanish in the 1500s.

While the Native Americans continued to exist as they had for centuries, the Spanish colonized in 1598 and interrupted the spiritual world of the natives. They forced them to conform to the inflexible tenets of Christianity. The Pueblos rebelled against the Spanish and expelled them from New Mexico during the Pueblo Revolt of 1680.

The Spanish didn't return until a dozen years later and they learned to respect the centuries-old customs of their entrenched neighbors. Eventually, the Pueblos willfully adopted many Christian values and they were no longer forced to abandon their traditional beliefs.
Albuquerque

Founded in 1706 by Francisco Cuervo y Valdez along the Rio Grande River, Albuquerque is now home of a million people. Economics of this part of New Mexico is driven by retail, commercial business, and industry. Residents proudly show off what remains of Route 66 in and around the community. Old Town, the historic district, is filled with gift shops, restaurants, galleries, and San Felipe de Neri Church. Albuquerque events include International Balloon Fiesta, Fiery Food Show, Rio Grande Arts & Crafts Festival, Fiestas De Albuquerque, and numerous ethnic and cultural festivals.

Old Town—the area where Albuquerque began in the 1700s—comes first: a large square lined with well-preserved (and partially adobe) buildings from that Spanish era including two major churches, two museums of both the history and natural history of the city, charming authentic restaurants of the Southwest, and many crafts shops and galleries. It ranks well with the far more extensive adobe, earth-colored areas of Santa Fe, which somehow seem less authentic, more artificial and contrived. Most visitors, early in their stay, take the Sandia Peak Tramway to the highest mountaintop area overlooking the city, Sandia Peak, from which they enjoy a view of many hundreds of square miles. Hang gliders often take off from this 10,000-foot altitude, sometimes to their grief.

The outstanding museum of the Albuquerque area is the large Indian Cultural Center operated by a consortium of Native American tribes. It relates the history, and describes the culture, of the inhabitants of the New Mexico "pueblos" in a way that has never successfully been done before, and it is an indispensable stop during your Albuquerque stay. For anthropological exhibits, go to the campus of the University of New Mexico, within the city, and visit its distinguished Museum of Anthropology, which deals with some of the same themes presented at the Indian Cultural Center.

Just on the outskirts of Albuquerque, the Coronado State Park reveals excavations of an ancient Indian pueblo, its wall murals largely intact. This, too, makes for an important Albuquerque visit.
But even more important, at some point of your stay, is a visit to a modern "Indian Reservation," of which two prominent ones are within 30 miles of Albuquerque. The doleful history of our treatment of the Native Americans is reflected in the conditions of those reservations, and all of us need to know of the shortcomings of our policies—and of the prejudices still directed against this much-suffering people.
Get Your Kicks on Route 66

There is not much of original Route 66 in New Mexico, sadly rather less than in neighboring Arizona. The road used to cross the state east-west through Tucumcari, Albuquerque and Gallup but most has now been converted into I-40. Apart from a few short stretches through several towns to the east such as San Jon and Endee, the only significant parts are from the Arizona border to Laguna, 30 miles west of Grants. This stretch makes for an interesting drive – a now almost ghostly quiet road with many reminders of the recent history of this region.

Gallup: The first appearance of Route 66 after the Arizona border is through the small town of Manuelito, then there is a 26 mile section either side of Gallup, a major trading town for the Navajo and Zuni tribes. The route forms the main street through town and has a fine collection of old buildings and craft shops. There is then a gap of 14 miles, and continuing east requires traveling on I-40 for a few junctions, across
the continental divide. The original road may be rejoined at exit 53 - starting from Thoreau it then crosses generally empty prairie land through several small towns for an uninterrupted 65 miles to Laguna, an historic Indian pueblo village.

**Prewitt - Milan**: Particularly evocative is the section between Prewitt and Milan. The road is wide but little used a reminder of busier days now forever past. Abandoned motels and empty gas stations are scattered at intervals, with faded decor typical of the 60s and 70s. The BNSF railway (formerly known as the Santa Fe) runs alongside to the north. The surrounding land is not particularly scenic, but seems somehow appropriate; distant low hills, grayish in color, in keeping with the drab abandoned buildings. There are several lava flows in the region, associated with the much larger deposits of the nearby El Malpais National Monument.
The Pueblo Indians have lived in the southwestern part of this country for at least 12,000 years. They may have originally been a nomadic tribe but between the years of 400 and 700, they learned to grow corn or maize and they settled down. They built homes of sun-baked earth, called adobe, in the caves and cliffs of the rocky area. These ancient people were called the Anasazi or "the Basket Makers" or sometimes "Cliff Dwellers." They flourished and spread out in the Four Corners region and built roads connecting their villages. Their homes usually consisted of one room for each family with many shared village areas for food storage and outside plazas for working together. They built bigger and better apartment style homes, some as high as thirty stories, which were reached by ladders. Most villages had one or more "kivas" or sacred chambers built underground and entered by a ladder pushed through a hole in the roof. These were the centers of religious life for the Pueblos. They became expert craftsmen and farmers and made simple, but beautifully decorated pottery. Anthropologists have found much evidence of their way of life. Then suddenly, around 1276, the villages started to be abandoned. It is speculated that long droughts forced the Anasazi to leave for other areas. By 1540, when the Spanish arrived, most of the old dwellings had been emptied. The Indians rebuilt the same style of villages in other, adjacent regions. Coronado, the Spanish explorer came looking for gold and also tried to Christianize the Indians. The invaders burned villages, mistreated the people and took many of their possessions. Many Indians died from lack of immunity to white diseases. The Pueblo country was soon colonized by the Spanish who tyrannized them and continued to attempt to convert them from their native religion. There were uprisings and revolts but the Spanish held on to the area until 1821 when Mexico claimed ownership. By 1848, in the Treaty of Guadalupe Hidalgo, the Pueblo lands became part of the United States. The U. S. government began a program of assimilation and many Indian children were taken away from their families and sent away to white-run boarding schools so they would learn new ways. Gradually, the Pueblo Indians gained some political control over themselves and the land but still today the Pueblo Indians generally struggle to find a comfortable way of life between the old and new.
General Geology of the
Carrizozo Malpais

The Carrizozo malpais consist of two basaltic lava flows that erupted from within the Tularosa Basin, in south-central New Mexico. A geological map of the Carrizozo Malpais and associated areas is shown below. The vent area for the lava flows, Little Black Peak, falls on the Capitan lineament, a zone of crustal weakness that extends across eastern New Mexico. The Capitan lineament is defined by a number of igneous features, including the Capitan Pluton, the Carrizozo lava flow, Broken Back Crater and associated lava flow (seen in dark green color, just to the NW of the main Carrizozo flows). The Capitan lineament is interpreted as a deeply penetrating zone of crustal weakness along which magmas have been able to rise and erupt (Chapin et al., 1978).

The total eruptive volume of the Carrizozo lava flows is estimated to be 2.8 to 4.3 km$^3$ (Allen, 1952); thickness averages 10-15 m, and the total length of the flow field is 75 km (Keszthelyi and Pieri, 1993). The flows are interpreted as tube-fed (Keszthelyi and Pieri, 1993), and are characterized by pahoehoe textures, such as ropey flow tops, smooth lava sheets, toes, tumuli, and pressure ridges. The flow top of the lava is very well-preserved, and in some places even retains an iridescent appearance, typical of young lava flows. Two distinct lava flows have been identified in the Carrizozo field (Renault, 1970). The lower flow is extends for the full 75 km length. The central part of the flow is narrow, whereas the lower part spreads to a width of nearly 8 km. The upper flow extends approximately 25 km from the vent, is wider, on average, than the lower flow and, where both flows can be observed, is typically thicker (Weber, 1964). The contact between the upper and lower flows is brecciated, but shows no evidence of erosion or soil development (Faris, 1980), suggesting that the time between eruption of the two flows was relatively short.
The lava that forms the Carrizo lava flows is alkaline to transitional olivine basalt (Faris, 1980) and the rock is typically unaltered. Anthony et al. (1998) note that the lava that forms the Carrizo flows is transitional between hypersthene and nepheline-normative, and that it is likely to be derived from mantle that is either enriched in incompatible elements, or has undergone some crustal contamination. Faris (1980) suggests that the Carrizo basalts were formed from 4-6% partial melting of a spinel-peridotite parent. Although some compositional trends are observed within the Carrizo lavas, consistent with a small degree of fractionation of olivine +/- pyroxene, the chemical composition of the lower flow is, on average very close to the upper (Faris, 1980; Renault, 1970).
References


Cooper, J. B., 1958, Ground-water conditions in the vicinity of Carrizozo, Lincoln County, New Mexico: U.S. Geological Survey open-file report, p. 45.


Little Black Peak (circled) is the source for the Carrizozo lavas.
The Manzano Mountains are a north-south elongate, east-tilted fault block that formed as part of the eastern flank of the Rio Grande rift during Miocene time, about 20–15 m.y. ago. The oldest rocks exposed in the highest peaks of the Manzano Mountains are Proterozoic quartzites, mica schists, metasiltstones, phyllites, metarhyolite, amphibolite, and basic schist. These rocks were subsequently metamorphosed (Marcoline et al., 2000) and then intruded locally by granitic rocks of the Ojita, Monte Largo, and Priest plutons. The Ojita pluton is 1,527 m.y. old, the Monte Largo pluton is 1,656 m.y. old and the Priest pluton is 1,427 m.y. old (Bauer et al., 1993). The metamorphic rocks are clearly older than the 1,656 m.y.-old Monte Largo pluton and may be as old as 1,700 m.y. (Bolton, 1976; Bowring et al., 1983). Boulders of these metamorphic rocks are scattered throughout the State Park.

Regional uplift occurred, and several thousand feet of erosion followed forming a regional erosional surface that records no deposition in the Manzano Mountains until Late Mississippian, a gap in the geologic record of about 1.1 m.y. The contact between the substantially older Proterozoic rocks and younger Mississippian rocks is called an “unconformity.” This particular unconformity was recognized in the Grand Canyon area and was called the Great Unconformity by John Wesley Powell.

Marine seas began to cover New Mexico during late Paleozoic time and deposited Mississippian- and Pennsylvanian-age sediment unconformably on the Proterozoic
rocks (Myers, 1982). The Mississippian Caloso Formation of Myers (1982) and the Pennsylvanian Sandia Formation represent the first stage of marine deposition and consist of a mixture of thin nonmarine limestones, siltstones, sandstones, and conglomerates and marine limestones and shales (Myers, 1982). The Caloso Formation is poorly exposed, consists of local, thin (less than 22 ft thick), nonfossiliferous limestones, and is probably part of the Arroyo Peñasco Group (Broadhead, 1997). The Sandia Formation is approximately 90–320 ft thick, and most of the sediment was probably derived from the Pedernal uplift, which forms the eastern edge of the Estancia Basin. These rocks were probably deposited about 320 m.y. ago, based on fossil evidence (Myers, 1982), and are exposed along the western foothills of the Manzano Mountains.

The Madera Group overlies the Sandia Formation and represents the major marine sequence of the Pennsylvanian and Early Permian. The Madera Group is 1,200–1,270 ft thick and consists of the Los Moyos Limestone (oldest), Wild Cow Formation, and Bursum Formation (Broadhead, 1997). Many of the limestone boulders found in the state park belong to these formations. The Los Moyos Limestone and Wild Cow Formation consist of marine limestones with interbedded siltstones, shales, sandstones, and conglomerates. The Bursum Formation is the last phase (Early Permian) of marine deposition during the Pennsylvanian–Permian and consists of alternating sequences of red arkosic sandstones, red and green shales and siltstones, and greenish-gray marine limestones. Carbon dioxide (CO2) was discovered in the Pennsylvanian rocks near Estancia in 1925 (McLemore, 1984). Carbon dioxide was produced from 1932 to 1942 and was converted into dry ice.

The brick red sandstones, shales, and mudstones of the Permian Abo Formation were deposited on top of the Madera Group after the Pennsylvanian seas retreated about 250 m.y. ago. The lower units of the Abo Formation were deposited in high-energy alluvial-fan and pediment environments, and the upper units were deposited in low-energy fluvial floodplain and shallow-water lake environments (Hatchell et al., 1982). Abo sandstones were used at Abó and Quarai by the Pueblo Indians to build their homes and later the churches. The area of the State Park has been stripped of younger rocks by erosion and is underlain by the Abo Formation. Rocks eroding from the Manzano Mountains form a thin veneer on top of the Abo and other Permian and Pennsylvanian rocks in the surrounding Manzano area. The younger Yeso Formation, at one time overlying the Abo Formation, also has been eroded in the Manzano area and is only exposed to the east in the Estancia Basin.

The state park lies on the western edge of a closed basin, called the Estancia Basin (Fig. 6), which initially formed as a depositional basin during the Early Pennsylvanian with the deposition of the Sandia Formation and Madera Group. The present structural basin formed when the Sandia, Manzano, Manzanita, and Los Pinos Mountains were uplifted during formation of the Rio Grande rift about 20–15 m.y. ago (McLemore, 1999; Bauer et al., 2003). The Sandia, Manzano, Manzanita, and Los Pinos Mountains form the western boundary, the Pedernal Hills form the eastern boundary, Chupadera Mesa forms the southern boundary, and Lobo Hill separates the Estancia Basin from the Española Basin to the north (Broadhead, 1997).
During the last ice age between 24,000 and 12,000 yrs B.P., a large pluvial lake filled the basin (Bachhuber, 1982; Smith and Anderson, 1982; Allen and Anderson, 2000). The maximum extent of the lake was approximately 40 mi long, 23 mi wide, and it would have covered the towns of Estancia and Willard with nearly 100 ft of water (Allen, 1994). Shore features, cliffs, terraces, beach ridges, and other lake features, preserved in the Estancia Basin east of the state park, record a series of changing water levels in the lake from 24,000 to 12,000 yrs B.P. caused by rapid shifts in climate. Lake Estancia gradually dried up after about 12,000 yrs B.P., and the floor became exposed (Allen and Anderson, 1993, 2000). A return to wetter conditions resulted in the filling of the basin again by a younger lake (called Lake Willard by some geologists) at about 10,000 yrs B.P. (Bachhuber, 1982; Allen and Anderson, 2000). These lakes did not have any outlets to the Rio Grande or anywhere else, and the water became saline over time, in part as a result of evaporation and also as a result of contributions from underlying Yeso evaporites.

Today, a complex of playa lakes and surrounding gypsum and clay dunes remain following excavation or deflation of the ancient lake bottom since about 8,000 yrs B.P. by southwesterly wind. An overall rise in the water table and return to a slightly wetter climate have reversed the trend from deflation to sediment filling of the lakes (Allen, 1994). As saline water in some of the playas evaporated, a residue of halite (salt) and minor sodium sulfates and magnesium sulfates precipitated. The deposits of halite became valuable commodities to the Pueblo Indians that settled at Abó, Quarai, and Gran Quivira and later to the Spanish and Anglo settlers. Today, the playa lakes in Estancia Basin range in size from a few acres to more than 12 mi long.

References

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The Spanish gave this Anasazi village the name of Pueblo de Las Humanas (a thriving pueblo) when Oñate first approached it in 1598 to accept the oath of allegiance to Spain. Largest of the Salinas pueblos, it was occupied for nearly nine centuries, 800 A.D. to 1672 A.D. Later, Spaniards called it Gran Quivira, the object of Coronado's and Oñate's futile search for gold.

Coronado had taken his search for gold, rumored to be possessed by the Quiviras, almost to present-day Kansas City. According to "The Land of Poco Tiempo" by Charles F. Lummis, written in 1893, the Quivira was a Teton nomad, a cousin of the Sioux, moving wherever there were buffalo, planting a little corn, and moving on, an aboriginal Gypsy. Lummis says, "it was not the end of the chimera" (wild or fantastic conception), because Oñate also chased the "Seven Cities of Cibola" story of gold. Lummis insists Gran Quivira was the pueblo of Tabira, one of the larger pueblos with about 1,500 inhabitants, and one of the three pueblo ruins in the Salinas National Monument. The other two, Abo and Quarai, are northwest of Gran Quivira.

The Gran Quivira was an important trade center before and after the Spanish entrada. Although the people resisted the newcomers representing Spain, they reconciled and borrowed freely from their culture. However, documents of the 1600s indicate strife between the Franciscan missionaries and the encomenderos. The latter were ranking citizens appointed by the Governor to provide protection, aid and education to Indians and military support for the government in return for collecting tribute. As is often the case, the system was abused.

In 1627, Father Alonso de Benavides toured the Saline Pueblos, so called because of the lakes where Indians once mined their salt. He called the Gran Quivira the Pueblo de los Jumanos, pueblo of the striped ones, because the natives decorated themselves with a stripe across their noses. Father Benavides claimed he converted all the Indians after one sermon in the plaza. A church was built in 1629, but it was replaced in 1659 by Father Diego Santander, who supervised the building of the huge church of San Buenventura with an adjoining convent. It was never completed.

Dwellings had evolved from pit-houses to adobe and finally to masonry communal buildings. One account says Gran Quivira was a group of three and four story stone
houses separated by narrow alleys or streets. Apache raids, droughts and famine reduced the population to less than 500 in the 1670s and the pueblo was abandoned. The three pueblos are known variously as "The Cities that Died of Fear" or "Cities that Were Forgotten."

Fodor's New Mexico Travel Guide points out these churches are a century and a half older than the oldest missions in California, Arizona or Texas. It adds there were seven missions built before the Indian rebellion of 1680, and two have been restored and are in use in Acoma and Isleta Indian pueblos. The Jemez and Pecos missions are state and national monuments and Abo, Quarai and Gran Quivira are the other three.

The latter has been extensively excavated by teams from the University of New Mexico, and visitors can see the way generations of Indians lived. The ruins are huge walls of stone resembling some of the crumbling cathedrals in the United Kingdom. As you walk through the ruins you can sense the presence of these people who enjoyed the "sea of grass" of the plains and the dwellings built with their own blood, sweat and tears. To have had to abandon them must have been a bitter moment - and the question still lingers, where did the Anasazi go?

"The natural and civilized worlds must live together or perish separately."
Henry David Thoreau
APPENDIX - A

Volcanic and Geologic Terms

'A'a: Hawaiian word used to describe a lava flow whose surface is broken into rough angular fragments. Click here to view a photo of 'a'a.

Accessory: A mineral whose presence in a rock is not essential to the proper classification of the rock.

Accidental: Pyroclastic rocks that are formed from fragments of non-volcanic rocks or from volcanic rocks not related to the erupting volcano.

Accretionary Lava Ball: A rounded mass, ranging in diameter from a few centimeters to several meters, [carried] on the surface of a lava flow (e.g., 'a'a) or on cinder-cone slopes [and formed] by the molding of viscous lava around a core of already solidified lava.

Acid: A descriptive term applied to igneous rocks with more than 60% silica (SiO2).

Active Volcano: A volcano that is erupting. Also, a volcano that is not presently erupting, but that has erupted within historical time and is considered likely to do so in the future.

Agglutinate: A pyroclastic deposit consisting of an accumulation of originally plastic ejecta and formed by the coherence of the fragments upon solidification.

Alkalic: Rocks which contain above average amounts of sodium and/or potassium for the group of rocks for which it belongs. For example, the basalts of the capping stage of Hawaiian volcanoes are alkalic. They contain more sodium and/or potassium than the shield-building basalts that make the bulk of the volcano.

Andesite: Volcanic rock (or lava) characteristically medium dark in color and containing 54 to 62 percent silica and moderate amounts of iron and magnesium.

Ash: Fine particles of pulverized rock blown from an explosion vent. Measuring less than 1/10 inch in diameter, ash may be either solid or molten when first erupted. By far the most common variety is vitric ash (glassy particles formed by gas bubbles bursting through liquid magma).

Ashfall (Airfall): Volcanic ash that has fallen through the air from an eruption cloud. A deposit so formed is usually well sorted and layered.

Ash Flow: A turbulent mixture of gas and rock fragments, most of which are ash-sized particles, ejected violently from a crater or fissure. The mass of pyroclastics is
normally of very high temperature and moves rapidly down the slopes or even along a level surface.

**Asthenosphere:** The shell within the earth, some tens of kilometers below the surface and of undefined thickness, which is a shell of weakness where plastic movements take place to permit pressure adjustments.

**Aquifer:** A body of rock that contains significant quantities of water that can be tapped by wells or springs.

**Avalanche:** A large mass of material or mixtures of material falling or sliding rapidly under the force of gravity. Avalanches often are classified by their content, such as snow, ice, soil, or rock avalanches. A mixture of these materials is a debris avalanche.

**Basalt:** Volcanic rock (or lava) that characteristically is dark in color, contains 45% to 54% silica, and generally is rich in iron and magnesium.

**Basement:** The undifferentiated rocks that underlie the rocks of interest in an area.

**Basic:** A descriptive term applied to igneous rocks (basalt and gabbro) with silica (SiO2) between 44% and 52%.

**Bench:** The unstable, newly-formed front of a lava delta.

**Blister:** A swelling of the crust of a lava flow formed by the puffing-up of gas or vapor beneath the flow. Blisters are about 1 meter in diameter and hollow.

**Block:** Angular chunk of solid rock ejected during an eruption.

**Bomb:** Fragment of molten or semi-molten rock, 2 1/2 inches to many feet in diameter, which is blown out during an eruption. Because of their plastic condition, bombs are often modified in shape during their flight or upon impact.

**Caldera:** The Spanish word for cauldron, a basin-shaped volcanic depression; by definition, at least a mile in diameter. Such large depressions are typically formed by the subsidence of volcanoes. Crater Lake occupies the best-known caldera in the Cascades.

**Capping Stage:** Refers to a stage in the evolution of a typical Hawaiian volcano during which alkalic, basalt, and related rocks build a steeply, sloping cap on the main shield of the volcano. Eruptions are less frequent, but more explosive. The summit caldera may be buried.

**Central Vent:** A central vent is an opening at the Earth's surface of a volcanic conduit of cylindrical or pipe-like form.

**Central Volcano:** A volcano constructed by the ejection of debris and lava flows from a central point, forming a more or less symmetrical volcano.
**Cinder Cone:** A volcanic cone built entirely of loose fragmented material (pyroclastics.)

**Cirque:** A steep-walled horseshoe-shaped recess high on a mountain that is formed by glacial erosion.

**Cleavage:** The breaking of a mineral along crystallographic planes, that reflects a crystal structure.

**Composite Volcano:** A steep volcanic cone built by both lava flows and pyroclastic eruptions.

**Compound Volcano:** A volcano that consists of a complex of two or more vents, or a volcano that has an associated volcanic dome, either in its crater or on its flanks. Examples are Vesuvius and Mont Pelee.

**Compression Waves:** Earthquake waves that move like a slinky. As the wave moves to the left, for example, it expands and compresses in the same direction as it moves.

**Conduit:** A passage followed by magma in a volcano.

**Continental Crust:** Solid, outer layers of the earth, including the rocks of the continents.

**Continental Drift:** The theory that horizontal movement of the earth's surface causes slow, relative movements of the continents toward or away from one another.

**Country Rocks:** The rock intruded by and surrounding an igneous intrusion.

**Crater:** A steep-sided, usually circular depression formed by either explosion or collapse at a volcanic vent.

**Craton:** A part of the earth's crust that has attained stability and has been little deformed for a prolonged period.

**Curtain of Fire:** A row of coalescing lava fountains along a fissure; a typical feature of a Hawaiian-type eruption.

**Dacite:** Volcanic rock (or lava) that characteristically is light in color and contains 62% to 69% silica and moderate amounts of sodium and potassium.

**Debris Avalanche:** A rapid and unusually sudden sliding or flowage of unsorted masses of rock and other material. As applied to the major avalanche involved in the eruption of Mount St. Helens, a rapid mass movement that included fragmented cold and hot volcanic rock, water, snow, glacier ice, trees, and some hot pyroclastic material. Most of the May 18, 1980 deposits in the upper valley of the North Fork Toutle River and in the vicinity of Spirit Lake are from the debris avalanche.

**Debris Flow:** A mixture of water-saturated rock debris that flows downslope under the force of gravity (also called lahar or mudflow).
**Detachment Plane:** The surface along which a landslide disconnects from its original position.

**Devonian:** A period of time in the Paleozoic Era that covered the time span between 400 and 345 million years.

**Diatreme:** A breccia filled volcanic pipe that was formed by a gaseous explosion.

**Dike:** A sheetlike body of igneous rock that cuts across layering or contacts in the rock into which it intrudes.

**Dome:** A steep-sided mass of viscous (doughy) lava extruded from a volcanic vent (often circular in plane view) and spiny, rounded, or flat on top. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome.

**Dormant Volcano:** Literally, "sleeping." The term is used to describe a volcano which is presently inactive but which may erupt again. Most of the major Cascade volcanoes are believed to be dormant rather than extinct.

**Drainage Basin:** The area of land drained by a river system.

**Echelon:** Set of geologic features that are in an overlapping or a staggered arrangement (e.g., faults). Each is relatively short, but collectively they form a linear zone in which the strike of the individual features is oblique to that of the zone as a whole.

**Ejecta:** Material that is thrown out by a volcano, including pyroclastic material (tephra) and lava bombs.

**Episode:** An episode is a volcanic event that is distinguished by its duration or style.

**Eruption:** The process by which solid, liquid, and gaseous materials are ejected into the earth's atmosphere and onto the earth's surface by volcanic activity. Eruptions range from the quiet overflow of liquid rock to the tremendously violent expulsion of pyroclastics.

**Eruption Cloud:** The column of gases, ash, and larger rock fragments rising from a crater or other vent. If it is of sufficient volume and velocity, this gaseous column may reach many miles into the stratosphere, where high winds will carry it long distances.

**Eruptive Vent:** The opening through which volcanic material is emitted.

**Evacuate:** Temporarily move people away from possible danger.

**Extinct Volcano:** A volcano that is not presently erupting and is not likely to do so for a very long time in the future.

**Extrusion:** The emission of magmatic material at the earth's surface. Also, the structure or form produced by the process (e.g., a lava flow, volcanic dome, or certain pyroclastic rocks).
**Fault:** A crack or fracture in the earth’s surface. Movement along the fault can cause earthquakes or—in the process of mountain-building—can release underlying magma and permit it to rise to the surface.

**Fault Scarp** A steep slope or cliff formed directly by movement along a fault and representing the exposed surface of the fault before modification by erosion and weathering.

**Felsic:** An igneous rock having abundant light-colored minerals.

**Fire fountain:** See also: lava fountain

**Fissures:** Elongated fractures or cracks on the slopes of a volcano. Fissure eruptions typically produce liquid flows, but pyroclastics may also be ejected.

**Flank Eruption:** An eruption from the side of a volcano (in contrast to a summit eruption.)

**Fluvial:** Produced by the action of flowing water.

**Formation:** A body of rock identified by lithic characteristics and stratigraphic position and is mappable at the earth's surface or traceable in the subsurface.

**Fracture:** The manner of breaking due to intense folding or faulting.

**Fumarole:** A vent or opening through which issue steam, hydrogen sulfide, or other gases. The craters of many dormant volcanoes contain active fumaroles.

**Geothermal Energy:** Energy derived from the internal heat of the earth.

**Geothermal Power:** Power generated by using the heat energy of the earth.

**Graben:** An elongate crustal block that is relatively depressed (downdropped) between two fault systems.

**Guyot:** A type of seamount that has a platform top. Named for a nineteenth-century Swiss-American geologist.

**Hardness:** The resistance of a mineral to scratching.

**Harmonic Tremor:** A continuous release of seismic energy typically associated with the underground movement of magma. It contrasts distinctly with the sudden release and rapid decrease of seismic energy associated with the more common type of earthquake caused by slippage along a fault.

**Heat transfer:** Movement of heat from one place to another.

**Heterolithologic:** Material is made up of a heterogeneous mix of different rock types. Instead of being composed on one rock type, it is composed of fragments of many different rocks.
**Holocene:** The time period from 10,000 years ago to the present. Also, the rocks and deposits of that age.

**Horizontal Blast:** An explosive eruption in which the resultant cloud of hot ash and other material moves laterally rather than upward.

**Horst:** A block of the earth’s crust, generally long compared to its width, that has been uplifted along faults relative to the rocks on either side.

**Hot Spot:** A volcanic center, 60 to 120 miles (100 to 200 km) across and persistent for at least a few tens of million of years, that is thought to be the surface expression of a persistent rising plume of hot mantle material. Hot spots are not linked to arcs and may not be associated with ocean ridges.

**Hot-spot Volcanoes:** Volcanoes related to a persistent heat source in the mantle.

**Hyaloclastite:** A deposit formed by the flowing or intrusion of lava or magma into water, ice, or water-saturated sediment and its consequent granulation or shattering into small angular fragments.

**Hydrothermal Reservoir:** An underground zone of porous rock containing hot water.

**Hypabyssal:** A shallow intrusion of magma or the resulting solidified rock.

**Hypocenter:** The place on a buried fault where an earthquake occurs. (Also known as the focus.)

**Ignimbrite:** The rock formed by the widespread deposition and consolidation of ash flows and Nuees Ardentes. The term was originally applied only to densely welded deposits but now includes non-welded deposits.

**Intensity:** A measure of the effects of an earthquake at a particular place. Intensity depends not only on the magnitude of the earthquake, but also on the distance from the epicenter and the local geology.

**Intermediate:** A descriptive term applied to igneous rocks that are transitional between basic and acidic with silica (SiO2) between 54% and 65%.

**Intrusion:** The process of emplacement of magma in pre-existing rock. Also, the term refers to igneous rock mass so formed within the surrounding rock.

**Joint:** A surface of fracture in a rock.

**Juvenile:** Pyroclastic material derived directly from magma reaching the surface.

**Kipuka:** An area surrounded by a lava flow.

**Laccolith:** A body of igneous rocks with a flat bottom and domed top. It is parallel to the layers above and below it.

**Lahar:** A torrential flow of water-saturated volcanic debris down the slope of a volcano in response to gravity. A type of mudflow.
Landsat: A series of unmanned satellites orbiting at about 706 km (438 miles) above the surface of the earth. The satellites carry cameras similar to video cameras and take images or pictures showing features as small as 30 m or 80 m wide, depending on which camera is used.

Lapilli: Literally, "little stones." Round to angular rock fragments, measuring 1/10 inch to 2 1/2 inches in diameter, which may be ejected in either a solid or molten state.

Lava: Magma which has reached the surface through a volcanic eruption. The term is most commonly applied to streams of liquid rock that flow from a crater or fissure. It also refers to cooled and solidified rock.

Lava Dome: Mass of lava, created by many individual flows, that has built a dome-shaped pile of lava.

Lava Flow: An outpouring of lava onto the land surface from a vent or fissure. Also, a solidified tongue like or sheet-like body formed by outpouring lava.

Lava Fountain: A rhythmic vertical fountainlike eruption of lava.

Lava Lake (Pond): A lake of molten lava, usually basaltic, contained in a vent, crater, or broad depression of a shield volcano.

Lava Shields: A shield volcano made of basaltic lava.

Lava Tube: A tunnel formed when the surface of a lava flow cools and solidifies while the still-molten interior flows through and drains away.

Limu O Pele (Pele Seaweed): Delicate, translucent sheets of spatter filled with tiny glass bubbles.

Lithic: Of or pertaining to stone.

Lithosphere: The rigid crust and uppermost mantle of the earth. Thickness is on the order of 60 miles (100 km). Stronger than the underlying asthenosphere.

Luster: The reflection of light from the surface of a mineral.

Maar: A volcanic crater that is produced by an explosion in an area of low relief, is generally more or less circular, and often contains a lake, pond, or marsh.

Mafic: An igneous composed chiefly of one or more dark-colored minerals.

Magma: Molten rock beneath the surface of the earth.

Magma Chamber: The subterranean cavity containing the gas-rich liquid magma which feeds a volcano.

Magmatic: Pertaining to magma.
**Magnitude**: A numerical expression of the amount of energy released by an earthquake, determined by measuring earthquake waves on standardized recording instruments (seismographs.) The number scale for magnitudes is logarithmic rather than arithmetic. Therefore, deflections on a seismograph for a magnitude 5 earthquake, for example, are 10 times greater than those for a magnitude 4 earthquake, 100 times greater than for a magnitude 3 earthquake, and so on.

**Mantle**: The zone of the earth below the crust and above the core.

**Matrix**: The solid matter in which a fossil or crystal is embedded. Also, a binding substance (e.g., cement in concrete).

**Miocene**: An epoch in Earth's history from about 24 to 5 million years ago. Also refers to the rocks that formed in that epoch.

**Moho**: Also called the Mohorovicic discontinuity. The surface or discontinuity that separates the crust from the mantle. The Moho is at a depth of 5-10 km beneath the ocean floor and about 35 km below the continents (but down to 60 km below mountains). Named for Andrija Mohorovicic, a Croatian seismologist.

**Monogenetic**: A volcano built by a single eruption.

**Mudflow**: A flowage of water-saturated earth material possessing a high degree of fluidity during movement. A less-saturated flowing mass is often called a debris flow. A mudflow originating on the flank of a volcano is properly called a lahar.

**Nuees Ardentes**: A French term applied to a highly heated mass of gas-charged ash which is expelled with explosive force and moves hurricane speed down the mountainside.

**Obsidian**: A black or dark-colored volcanic glass, usually composed of rhyolite.

**Oceanic Crust**: The earth's crust where it underlies oceans.

**Pahoehoe**: A Hawaiian term for lava with a smooth, billowy, or ropy surface.

**Pali**: Hawaiian word for steep hills or cliffs.

**Pele Hair**: A natural spun glass formed by blowing-out during quiet fountaining of fluid lava, cascading lava falls, or turbulent flows, sometimes in association with pele tears. A single strand, with a diameter of less than half a millimeter, may be as long as two meters.

**Pele Tears**: Small, solidified drops of volcanic glass behind which trail pendants of Pele hair. They may be tear-shaped, spherical, or nearly cylindrical.

**Peralkaline**: Igneous rocks in which the molecular proportion of aluminum oxide is less than that of sodium and potassium oxides combined.

**Phenocryst**: A conspicuous, usually large, crystal embedded in porphyritic igneous rock.
**Phreatic Eruption (Explosion):** An explosive volcanic eruption caused when water and heated volcanic rocks interact to produce a violent expulsion of steam and pulverized rocks. Magma is not involved.

**Phreatomagmatic:** An explosive volcanic eruption that results from the interaction of surface or subsurface water and magma.

**Pillow lava:** Interconnected, sack-like bodies of lava formed underwater.

**Pipe:** A vertical conduit through the Earth's crust below a volcano, through which magmatic materials have passed. Commonly filled with volcanic breccia and fragments of older rock.

**Pit Crater:** A crater formed by sinking in of the surface, not primarily a vent for lava.

**Plastic:** Capable of being molded into any form, which is retained.

**Plate Tectonics:** The theory that the earth's crust is broken into about 10 fragments (plates,) which move in relation to one another, shifting continents, forming new ocean crust, and stimulating volcanic eruptions.

**Pleistocene:** A epoch in Earth history from about 2-5 million years to 10,000 years ago. Also refers to the rocks and sediment deposited in that epoch.

**Plinian Eruption:** An explosive eruption in which a steady, turbulent stream of fragmented magma and magmatic gases is released at a high velocity from a vent. Large volumes of tephra and tall eruption columns are characteristic.

**Plug:** Solidified lava that fills the conduit of a volcano. It is usually more resistant to erosion than the material making up the surrounding cone, and may remain standing as a solitary pinnacle when the rest of the original structure has eroded away.

**Plug Dome:** The steep-sided, rounded mound formed when viscous lava wells up into a crater and is too stiff to flow away. It piles up as a dome-shaped mass, often completely filling the vent from which it emerged.

**Pluton:** A large igneous intrusion formed at great depth in the crust.

**Polygenetic:** Originating in various ways or from various sources.

**Precambrian:** All geologic time from the beginning of Earth history to 570 million years ago. Also refers to the rocks that formed in that epoch.

**Pumice:** Light-colored, frothy volcanic rock, usually of dacite or rhyolite composition, formed by the expansion of gas in erupting lava. Commonly seen as lumps or fragments of pea-size and larger, but can also occur abundantly as ash-sized particles.

**Pyroclastic:** Pertaining to fragmented (clastic) rock material formed by a volcanic explosion or ejection from a volcanic vent.
**Pyroclastic Flow:** Lateral flowage of a turbulent mixture of hot gases and unsorted pyroclastic material (volcanic fragments, crystals, ash, pumice, and glass shards) that can move at high speed (50 to 100 miles an hour.) The term also can refer to the deposit so formed.

**Quaternary:** The period of Earth's history from about 2 million years ago to the present; also, the rocks and deposits of that age.

**Relief:** The vertical difference between the summit of a mountain and the adjacent valley or plain.

**Renewed Volcanism State:** Refers to a state in the evolution of a typical Hawaiian volcano during which --after a long period of quiescence--lava and tephra erupt intermittently. Erosion and reef building continue.

**Repose:** The interval of time between volcanic eruptions.

**Rhyodacite:** An extrusive rock intermediate in composition between dacite and rhyolite.

**Rhyolite:** Volcanic rock (or lava) that characteristically is light in color, contains 69% silica or more, and is rich in potassium and sodium.

**Ridge, Oceanic:** A major submarine mountain range.

**Rift System:** The oceanic ridges formed where tectonic plates are separating and a new crust is being created; also, their on-land counterparts such as the East African Rift.

**Rift Zone:** A zone of volcanic features associated with underlying dikes. The location of the rift is marked by cracks, faults, and vents.

**Ring of Fire:** The regions of mountain-building earthquakes and volcanoes which surround the Pacific Ocean.

**Scoria:** A bomb-size (> 64 mm) pyroclast that is irregular in form and generally very vesicular. It is usually heavier, darker, and more crystalline than pumice.

**Seafloor Spreading:** The mechanism by which new seafloor crust is created at oceanic ridges and slowly spreads away as plates are separating.

**Seamount:** A submarine volcano.

**Seismograph:** An instrument that records seismic waves; that is, vibrations of the earth.

**Seismologist:** Scientists who study earthquake waves and what they tell us about the inside of the Earth.

**Seismometer:** An instrument that measures motion of the ground caused by earthquake waves.
**Shearing:** The motion of surfaces sliding past one another.

**Shear Waves:** Earthquake waves that move up and down as the wave itself moves. For example, to the left.

**Shield Volcano:** A gently sloping volcano in the shape of a flattened dome and built almost exclusively of lava flows.

**Shoshonite:** A trachyandesite composed of olivine and augite phenocrysts in a groundmass of labradorite with alkali feldspar rims, olivine, augite, a small amount of leucite, and some dark-colored glass. Its name is derived from the Shoshone River, Wyoming and given by Iddings in 1895.

**Silica:** A chemical combination of silicon and oxygen.

**Sill:** A tabular body of intrusive igneous rock, parallel to the layering of the rocks into which it intrudes.

**Skylight:** An opening formed by a collapse in the roof of a lava tube.

**Solfatara:** A type of fumarole, the gases of which are characteristically sulfurous.

**Spatter Cone:** A low, steep-sided cone of spatter built up on a fissure or vent. It is usually of basaltic material.

**Spatter Rampart:** A ridge of congealed pyroclastic material (usually basaltic) built up on a fissure or vent.

**Specific Gravity:** The density of a mineral divided by the density of water.

**Spines:** Horn-like projections formed upon a lava dome.

**Stalactite:** A cone shaped deposit of minerals hanging from the roof of a cavern.

**Stratigraphic:** The study of rock strata, especially of their distribution, deposition, and age.

**Stratovolcano:** A volcano composed of both lava flows and pyroclastic material.

**Streak:** The color of a mineral in the powdered form.

**Strike-Slip Fault:** A nearly vertical fault with side-slip displacement.

**Strombolian Eruption:** A type of volcanic eruption characterized by jetting of clots or fountains of fluid basaltic lava from a central crater.

**Subduction Zone:** The zone of convergence of two tectonic plates, one of which usually overrides the other.

**Surge:** A ring-shaped cloud of gas and suspended solid debris that moves radially outward at high velocity as a density flow from the base of a vertical eruption column accompanying a volcanic eruption or crater formation.
**Talus:** A slope formed at the base of a steeper slope, made of fallen and disintegrated materials.

**Tephra:** Materials of all types and sizes that are erupted from a crater or volcanic vent and deposited from the air.

**Tephrochronology:** The collection, preparation, petrographic description, and approximate dating of tephra.

**Tilt:** The angle between the slope of a part of a volcano and some reference. The reference may be the slope of the volcano at some previous time.

**Trachyanidesite:** An extrusive rock intermediate in composition between trachyte and andesite.

**Trachybasalt:** An extrusive rock intermediate in composition between trachyte and basalt.

**Trachyte:** A group of fine-grained, generally porphyritic, extrusive igneous rocks having alkali feldspar and minor mafic minerals as the main components, and possibly a small amount of sodic plagioclase.

**Tremor:** Low amplitude, continuous earthquake activity often associated with magma movement.

**Tsunami:** A great sea wave produced by a submarine earthquake, volcanic eruption, or large landslide.

**Tuff:** Rock formed of pyroclastic material.

**Tuff Cone:** A type of volcanic cone formed by the interaction of basaltic magma and water. Smaller and steeper than a tuff ring.

**Tuff Ring:** A wide, low-rimmed, well-bedded accumulation of hyalo-clastic debris built around a volcanic vent located in a lake, coastal zone, marsh, or area of abundant ground water.

**Tumulus:** A doming or small mound on the crest of a lava flow caused by pressure due to the difference in the rate of flow between the cooler crust and the more fluid lava below.

**Ultramafic:** Igneous rocks made mostly of the mafic minerals hypersthene, augite, and/or olivine.

**Unconformity:** A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession, such as an interruption in continuity of a depositional sequence of sedimentary rocks or a break between eroded igneous rocks and younger sedimentary strata. It results from a change that caused deposition to cease for a considerable time, and it normally implies uplift and erosion with loss of the previous formed record.
Vent: The opening at the earth's surface through which volcanic materials issue forth.

Vesicle: A small air pocket or cavity formed in volcanic rock during solidification.

Viscosity: A measure of resistance to flow in a liquid (water has low viscosity while honey has a higher viscosity.)

Volcano: A vent in the surface of the Earth through which magma and associated gases and ash erupt; also, the form or structure (usually conical) that is produced by the ejected material.

Volcanic Arc: A generally curved linear belt of volcanoes above a subduction zone, and the volcanic and plutonic rocks formed there.

Volcanic Complex: A persistent volcanic vent area that has built a complex combination of volcanic landforms.

Volcanic Cone: A mound of loose material that was ejected ballistically.

Volcanic Neck: A massive pillar of rock more resistant to erosion than the lavas and pyroclastic rocks of a volcanic cone.

Vulcan: Roman god of fire and the forge after whom volcanoes are named.

Vulcanian: A type of eruption consisting of the explosive ejection of incandescent fragments of new viscous lava, usually on the form of blocks.

Water Table: The surface between where the pore space in rock is filled with water and where the the pore space in rock is filled with air.

Xenocrysts: A crystal that resembles a phenocryst in igneous rock, but is a foreign to the body of rock in which it occurs.

Xenoliths: A foreign inclusion in an igneous rock.

Glossary compiled from:

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