ROCKS in the CHIRICAHUA National Monument and the FORT BOWIE National Historic Site

By John V. Bezy - National Park Service

Arizona Geological Survey
DOWN-TO-EARTH 11
Ruins of Fort Bowie. The Apache Pass fault bisects the peak in the background from left to right. Horquilla limestone (Pennsylvanian age) crops out on the front side of the peak, whereas the light-colored rock on the crest and back side is a quartzite of Precambrian age.
Rocks in the Chiricahua National Monument and the Fort Bowie National Historic Site

by

John V. Bezy
National Park Service

Photographs by
Larry D. Fellows
Arizona Geological Survey

Arizona Geological Survey
Down-to-Earth 11
ACKNOWLEDGMENTS

The author expresses sincere gratitude to Drs. George Davis and Douglas B. Hall, the University of Arizona; Drs. John S. Pallister, Edward A. du Bray, and Harold Drewes, U.S. Geological Survey; Dr. Arthur Trevena, UNOCAL Corporation; and Drs. Larry D. Fellows and Jon E. Spencer, Arizona Geological Survey (AZGS), for technical review of this publication. Special thanks are due to Dr. Fellows for his contributions to the organization of this publication and the many photographs that grace its pages. Thanks are also given to AZGS employees Mr. John A. Birmingham for design and layout of this book and Ms. Rose Ellen McDonnell for editing. Appreciation is also extended to Ms. Gretchen A. Graham, Pima Community College, and to Mr. Andrew William Amann, Jr., Ms. Marjorie Bengtson, Ms. Carol Kruse, Mr. Walt Saenger, Ms. Suzanne Moody, and Mr. Larry Ludwig of the National Park Service for valuable editorial suggestions.

Dr. John C. Dohrenwend graciously granted permission to use his satellite images in this publication. Poster-sized satellite image maps (1:100,000 scale) of the Chiricahua National Monument area can be ordered from John C. Dohrenwend, P.O. Box 141, Teasdale, UT 84773; Phone: (435) 425-3118; E-mail: Dohrenwend@rkyimtnhi.com
## CONTENTS

<table>
<thead>
<tr>
<th>CHIRICAHUA NATIONAL MONUMENT</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>6</td>
</tr>
<tr>
<td>GENERAL GEOLOGY</td>
<td>7</td>
</tr>
<tr>
<td>ORGAN PIPE ROCKS</td>
<td>8</td>
</tr>
<tr>
<td>GEOLOGIC FEATURES ALONG</td>
<td>12</td>
</tr>
<tr>
<td>SUGARLOAF MOUNTAIN TRAIL</td>
<td>14</td>
</tr>
<tr>
<td>Welded tuff</td>
<td>14</td>
</tr>
<tr>
<td>Joints</td>
<td>15</td>
</tr>
<tr>
<td>Lichens</td>
<td>16</td>
</tr>
<tr>
<td>Rock varnish</td>
<td>17</td>
</tr>
<tr>
<td>Surge beds</td>
<td>18</td>
</tr>
<tr>
<td>Fossil fumaroles</td>
<td>19</td>
</tr>
<tr>
<td>Dacite caprock</td>
<td>20</td>
</tr>
<tr>
<td>Turkey Creek caldera</td>
<td>21</td>
</tr>
<tr>
<td>Willcox Playa</td>
<td>22</td>
</tr>
<tr>
<td>Basin and range topography</td>
<td>23</td>
</tr>
<tr>
<td>GEOLOGIC FEATURES ALONG</td>
<td>24</td>
</tr>
<tr>
<td>ECHO CANYON LOOP</td>
<td></td>
</tr>
<tr>
<td>Exfoliation shingles</td>
<td>24</td>
</tr>
<tr>
<td>Solution pans</td>
<td>25</td>
</tr>
<tr>
<td>Chicken heads</td>
<td>26</td>
</tr>
<tr>
<td>Horizontal ribs</td>
<td>27</td>
</tr>
<tr>
<td>Tafoni</td>
<td>28</td>
</tr>
<tr>
<td>Case hardening</td>
<td>29</td>
</tr>
<tr>
<td>Slot canyons</td>
<td>30</td>
</tr>
<tr>
<td>Talus cones</td>
<td>31</td>
</tr>
<tr>
<td>Spherulites</td>
<td>32</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FORT BOWIE NATIONAL HISTORIC SITE</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>35</td>
</tr>
<tr>
<td>APACHE PASS FAULT ZONE</td>
<td>35</td>
</tr>
<tr>
<td>APACHE SPRING</td>
<td>37</td>
</tr>
<tr>
<td>OVERLOOK RIDGE</td>
<td>38</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>40</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SELECTED READINGS</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiricahua National Monument</td>
<td>45</td>
</tr>
<tr>
<td>Fort Bowie National Historic Site</td>
<td>48</td>
</tr>
</tbody>
</table>
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Monument roads and trails</td>
<td>6</td>
</tr>
<tr>
<td>2.</td>
<td>Crustal plates</td>
<td>8</td>
</tr>
<tr>
<td>3.</td>
<td>Block diagram showing overriding crustal plates, magma chamber, and Turkey Creek caldera</td>
<td>9</td>
</tr>
<tr>
<td>4.</td>
<td>Basins and ranges in southeastern Arizona</td>
<td>11</td>
</tr>
<tr>
<td>5.</td>
<td>Organ Pipe Rocks</td>
<td>12</td>
</tr>
<tr>
<td>6.</td>
<td>Diagram that shows how pinnacles develop</td>
<td>13</td>
</tr>
<tr>
<td>7.</td>
<td>Rhyolite Canyon Tuff</td>
<td>14</td>
</tr>
<tr>
<td>8.</td>
<td>A joint in the Rhyolite Canyon Tuff</td>
<td>15</td>
</tr>
<tr>
<td>9.</td>
<td>Lichens</td>
<td>16</td>
</tr>
<tr>
<td>10.</td>
<td>Rock varnish</td>
<td>17</td>
</tr>
<tr>
<td>11.</td>
<td>Surge bed</td>
<td>18</td>
</tr>
<tr>
<td>12.</td>
<td>Rockfall</td>
<td>18</td>
</tr>
<tr>
<td>13.</td>
<td>Fossil fumarole</td>
<td>19</td>
</tr>
<tr>
<td>14.</td>
<td>Dacite caprock on Sugarloaf Mountain</td>
<td>20</td>
</tr>
<tr>
<td>15.</td>
<td>Approximate location of Turkey Creek caldera</td>
<td>21</td>
</tr>
<tr>
<td>16.</td>
<td>Satellite image of Willcox Playa</td>
<td>22</td>
</tr>
<tr>
<td>17.</td>
<td>Basins and ranges in southern Arizona</td>
<td>23</td>
</tr>
<tr>
<td>18.</td>
<td>Exfoliation shingles</td>
<td>24</td>
</tr>
<tr>
<td>19.</td>
<td>Solution pan</td>
<td>25</td>
</tr>
<tr>
<td>20.</td>
<td>Chicken head texture to rock surfaces</td>
<td>26</td>
</tr>
<tr>
<td>21.</td>
<td>Horizontal ribs</td>
<td>27</td>
</tr>
<tr>
<td>22.</td>
<td>Tafoni</td>
<td>28</td>
</tr>
<tr>
<td>23.</td>
<td>Case hardening</td>
<td>29</td>
</tr>
<tr>
<td>24.</td>
<td>Slot canyon</td>
<td>30</td>
</tr>
<tr>
<td>25.</td>
<td>Talus</td>
<td>31</td>
</tr>
<tr>
<td>26.</td>
<td>Spherulites</td>
<td>32</td>
</tr>
<tr>
<td>27.</td>
<td>Map of Fort Bowie National Historic Site</td>
<td>34</td>
</tr>
<tr>
<td>28.</td>
<td>Geologic map of the Fort Bowie area</td>
<td>36</td>
</tr>
<tr>
<td>29.</td>
<td>Geologic cross section through Fort Bowie area</td>
<td>38</td>
</tr>
<tr>
<td>30.</td>
<td>Apache Spring</td>
<td>39</td>
</tr>
<tr>
<td>31.</td>
<td>Block diagram showing geology of Apache Spring area</td>
<td>39</td>
</tr>
<tr>
<td>32.</td>
<td>Fort Bowie</td>
<td>41</td>
</tr>
<tr>
<td>33.</td>
<td>Rattlesnake Point granodiorite in fault contact with the Horquilla Limestone on Overlook Ridge</td>
<td>41</td>
</tr>
<tr>
<td>34.</td>
<td>Overlook Ridge</td>
<td>43</td>
</tr>
</tbody>
</table>
Figure 1. Roads and trails in the Chiricahua National Monument. © is the Organ Pipe rocks, ® is the Sugarloaf Mountain Trail and ℓ is the Echo Canyon Loop. Map is modified from National Park Service brochure.
Chiricahua National Monument is best known for spectacular rock pinnacles or columns. These features were shaped, in large part, by freezing, thawing, and running water during the last Ice Age, when climatic conditions were cooler and wetter than they are now. More subtle processes are currently modifying the pinnacles and related features. Today’s scenery is, therefore, a mosaic of relict and modern geologic features, each of which contributes its unique form, color, and texture to the landscape.

The purpose of this guide is to provide an understanding of the dynamic processes that have shaped this exceptional landscape. The guide was written for the visitor who has not had formal training in geology, but will also be useful to those who have. Please take it with you as you hike the Monument’s trails.

To set the stage, I have briefly described the area’s geologic history. In the following pages emphasis is given to descriptions of features that can be observed along the Sugarloaf Mountain Trail and Echo Canyon Loop (Figure 1), which were chosen because they offer the greatest variety of geologic features. You should be able to identify these features easily by studying the photographs in the guide. None of the features described in the guide are designated by markers along the trail.

You may encounter a number of these features when you travel in other parts of the Southwest. I hope that your experience at Chiricahua National Monument will enhance the pleasure of future explorations. Please help preserve the features in the monument for future generations by not collecting samples.
The earth's crust is broken into plates that are in motion (Figure 2). In some areas the plates are colliding; in others they are sliding past or overriding each other. Chiricahua National Monument's present landscape is directly related to plate movement.

About thirty million years ago, the westward-moving North American plate was overriding a plate beneath the Pacific Ocean to the west (Figure 3). The heavier ocean-basin rock sank beneath the lighter continental rock of the North American plate. The temperature of the subsiding oceanic rock increased with depth, causing the rocks to melt.

The ocean rock also carried water to great depth. This water accelerated melting when it mixed with the hot mantle rock. The molten rock (magma) slowly migrated upward and formed magma chambers a few miles below the surface.

About 27 million years ago, a magma chamber was present just south of what is now the Chiricahua National Monument. The compressed water vapor, carbon dioxide, and molten rock within the chamber ruptured the overlying rocks with a series of violent eruptions. Steam and gas explosions blew the magma into massive clouds (called nuee ardente) of red-hot gas, pumice, and ash, which cascaded down the slopes at speeds of up to 100 miles (160 kilometers) per hour. When the eruptions stopped, more than 1,200 square miles (3,100 square kilometers) of the surround-

---

**Figure 2.** Crustal plates. Movement of these plates is responsible for earthquakes and volcanic eruptions throughout the world.
Figure 3. Depiction of the North American plate over­riding the Pacific plate. Water in seafloor sediment and the oceanic crust was carried into the subduction zone. Water at these depths and temperatures caused the crustal and mantle rocks to melt. Molten rock, less dense than solid rock, rose toward the surface. When it reached the surface, a volcanic eruption, such as that at Turkey Creek 26.9 million years ago, took place.

Water in seafloor sediment and the oceanic crust was carried into the subduction zone, causing the crustal and mantle rocks to melt. Molten rock, less dense than solid rock, rose toward the surface. When it reached the surface, a volcanic eruption, such as that at Turkey Creek 26.9 million years ago, took place.

ing landscape had been blanketed with volcanic ash. These deposits, known by geologists as tuff, slowly compressed, fused together, and cooled to form rock. The rock, named the Rhyolite Canyon Tuff, is the most extensive bedrock in the monument area. It is more than 800 feet (245 meters) thick.

As magma was ejected, the top part of the magma chamber collapsed and formed a caldera, a huge crater-like depression, that was about 12 miles (19 kilometers) across and 5,000 feet (1,524 meters) deep (Figure 3). The caldera, subsequently buried by pumice and ash and altered by faulting and erosion, is no longer a recognizable landform. Its presence is known from interpretation of detailed geologic maps. Geologists named it the Turkey Creek caldera after a major stream that drains the area.

Dozens of other calderas also formed during this same volcanic flare up, which lasted about 10 million years and built a vast plateau, the Sierra Madre Occidental, in northwestern Mexico. Other volcanic rocks of about the same age are present in New Mexico, Colorado, and other parts of Arizona.

As the ash deposit cooled and contracted, a series of horizontal and vertical cracks, called joints, developed. Water, plant roots, and organic acids penetrate to the heart of the rock along joints. Deep slot-like canyons were eventually cut along the major joint sets by frost wedging and running water.
Between 25 and 5 million years ago changes in plate motion caused the crust beneath western North America to stretch and fracture. Movement along the fractures (faults) resulted in the development of the San Andreas fault system along the west coast. Farther inland, stretching caused the crust to thin and break into linear, north-trending blocks, some of which were uplifted to become mountains and others that were down-dropped to form valleys. This basin-and-range topography is characteristic of much of western North America from central Mexico to Oregon. The Chiricahua, Dos Cabezas, and Dragoon Mountains are fault-bounded blocks that are adjacent to the Sulphur Springs and San Simon valleys (Figure 4).

During the cooler, wetter glacial periods of the Ice Age, which began 1.6 million years ago, frost wedging and erosion by running water carved the Rhyolite Canyon Tuff into a maze of narrow canyons separated by angular pinnacle-lined ridges. During the warmer, drier interglacial periods, slow small-scale chemical and organic weathering processes smoothed the contours of the columns into their present cylindrical form. Today's landscape is a product of plate collision, explosive volcanism, crustal stretching, basin-and-range faulting, Ice Age frost wedging and stream erosion, along with active weathering and erosion in today's arid climate.
Figure 4. Mountain ranges (shaded) and basins in southeastern Arizona.
From the Visitor Center, follow the main park road 0.5 mile (0.8 kilometer) northeast. The Organ Pipe Rocks are straight-ahead (Figure 5). This is the first place within the monument where you get a close look at the pinnacles or columns, for which the monument is best known. Joints separate the pinnacles, which have developed in the Rhyolite Canyon Tuff. If you'd like to stop for a better view or a photograph, a small parking area is provided.

Figure 5. Pinnacles or columns formed in the Rhyolite Canyon Tuff by weathering and erosion along joints (arrow) in the rocks. These pinnacles have developed to a stage between b and c in Figure 6.
Pinnacles composed of the Rhyolite Canyon Tuff are relict landforms from the last glacial period. Originally angular and blocky, they were smoothed to their present cylindrical and hourglass shapes by chemical weathering, repeated freezing and thawing, lichen attack, and other processes during the last 10,000 years (Figure 6).

Weathering by clay and salt particles also plays a role in shaping the columns. Certain clay minerals, such as kaolinite and smectite, absorb large quantities of water and, as a result, increase in volume by several hundred percent. Drying results in contraction. This shrink-swell cycle, repeated over time, causes bedrock to disintegrate.

Salt particles have a similar effect. Sodium sulfate, sodium carbonate, magnesium sulfate, halite, and anhydrite, blown in as dust from Willcox Playa and other areas, become concentrated in protected rock hollows and crevices by rain and dew. As salt crystals grow they loosen and dislodge adjacent rock fragments. Over long periods of time this shedding of small rock fragments softens the sharp, angular shape given to the columns by frost wedging during the glacial period.

It appears that earthquakes, wind gusts, or gravity could easily topple these tall, slender pinnacles, notched where weathering has attacked horizontal joints. Studies indicate, however, that the rock columns could withstand 12 to 13 times their weight in stress before they would fail. Their stability is substantiated by the fact that they withstood the 7.2-magnitude Pitaycachi earthquake in 1887. This northern Sonora earthquake, which shook all of southeastern Arizona, caused rockslides as far away as the Santa Catalina Mountains north of Tucson. Even if you look carefully within the monument, you will see few pinnacles that have toppled.

Figure 6. Diagram that shows how pinnacles developed in the Rhyolite Canyon Tuff.
Continue eastward 4.5 miles (7.2 kilometers) from Organ Pipe Rocks to the turnoff to the Echo Canyon and Sugarloaf Mountain Trails. Turn right, drive 0.6 mile (1.0 kilometer) to the Sugarloaf Mountain trailhead, and park. The features described below can be observed along the trail. Plan to spend a minimum of two hours for a round-trip hike.

**WELDED TUFF**

Cuts along this trail give excellent exposure to part of the 26.9-million-year-old deposit of compressed volcanic ash, pumice, rock fragments, and crystals of feldspar and quartz known as the Rhyolite Canyon Tuff (Figure 7). Because of the freshness of the trail cut, small features in the tuff can be easily observed.

The white streaks in the rock are flattened pumice fragments, called fiamme. Pumice is a soft volcanic material permeated by gas bubbles. Pumice fragments were compressed and their bubbles deflated by the weight of the overlying volcanic material when the ash sheet was hot and soft. Most of the material between fiamme is volcanic ash, which is composed of microscopic pieces of volcanic glass and crystal fragments that were produced by the explosive eruption. The eruption produced great billowing clouds of ash, pumice, rock fragments, and gas that glowed with intense heat (more than a thousand degrees). These hot glowing clouds rolled down the slopes of the Turkey Creek caldera (described on page 21) at speeds up to 100 miles (160 kilometers) per hour and blanketed the landscape with thick layers of hot ash and pumice. Intense heat fused the volcanic glass with the pumice, which cooled to form the Rhyolite Canyon Tuff.
Parallel cracks called joints (Figure 8) formed as the volcanic ash beds cooled and contracted. Sets of joints intersect other joints at nearly right angles and break the bedrock into rectangular blocks. Some joints, called master joints, are more extensive and can be traced for great distances. The average spacing between the master joints in this area is 14 to 18 feet (4.3 to 5.5 meters). Minor joint sets have similar spacing.

Joints are significant because chemical and physical weathering processes occur along them. Water from rain and melted snow seeps into joints and freezes during winter nights. The resulting expansion of the ice exerts sufficient pressure to shatter rock and widen joint walls. Plant roots also enter and wedge open the joints. Accumulated soil acts as a sponge, keeping slightly acidic groundwater in contact with joint walls, which decompose by chemical weathering processes.

Working in concert over hundreds of thousands of years, weathering and erosion have widened and deepened the intersecting joint sets to form the rectangular pattern of ridges, pinnacles, and slot canyons of today’s landscape.

Figure 8. A joint (arrow) in the Rhyolite Canyon Tuff. The inset photograph shows tree roots growing in a joint.
Most of the rock around you supports a dense growth of many species of lichens (Figure 9), which speed the decomposition of bedrock. These colonies of plants, consisting of algae and fungi living together in a symbiotic relationship, inhabit rock surfaces and minute cracks.

Lichen colonies weaken rock by both chemical and mechanical weathering. They produce acids that etch minerals such as feldspar and quartz in the rock. Because of their ability to mobilize iron and manganese, lichens concentrate minerals on rock surfaces and contribute to the formation of rock varnish. Lichens are firmly attached to the rock surface on which they grow. Because they expand and shrink when they are wetted and dried, these plants can exert enough pressure to dislodge mineral grains, chip off rock flakes, and enlarge cracks. Their ability to retain water at the surface of the rock also enhances other types of chemical weathering.

Weathering by lichen colonies is effective in the slow, grain-by-grain disintegration of rock. Mineral grains on column surfaces covered by lichens are looser and more easily dislodged than those on surfaces free of lichens. Although the process is too slow to see, it is continuously weakening the surrounding cliffs and columns.
The brown and black blotches (Figure 10) on the buff-colored rock pinnacles are rock varnish. This mineral patina gives the landscape a tan to dark-brown cast. Rock varnish develops best on weathering- and erosion-resistant rocks that have moderately rough surfaces. Sandstone, basalt, and many metamorphic rocks are normally well varnished, whereas siltstone and shale disintegrate too rapidly to retain such a coating. Desert pavement, the pebble-and cobble-covered ground surface so common in arid lands, can also glisten with this mineral varnish.

Desert varnish is a thin coating (typically less than a hundredth of an inch) of clay minerals (illite, montmorillonite, and kaolinite) stained by high concentrations of iron and manganese oxides. The clay minerals settle as dust from the atmosphere. Manganese, also derived from windborne dust and rain, produces a black to dark-brown coloration on surfaces exposed to air. Micro-colonies of lichens and bacteria gain energy by oxidizing the manganese. They anchor themselves to rock surfaces with the clay particles, which provide protection against extremes in temperature and humidity. In the process, the manganese becomes firmly attached to and darkens the clay. Each time the rock surface is wetted by rain, more manganese and clay are added to sustain the slowly growing colony. Colonies thrive where the rock acidity is neutral and the surface is so nutrient poor that competing colonies of lichens and mosses cannot survive.

Scientists are unable to use desert varnish as an age-dating tool, even though older surfaces tend to be more heavily varnished and darker than younger surfaces. The rate at which desert varnish forms is not constant and is affected by many variables, such as climatic change, wind abrasion, biological competition, and abundance of manganese. Some researchers believe that the clay and manganese content of rock varnish reflects past climatic conditions. Because some varnished surfaces may be 1,000,000 years old, they could reveal valuable information about climatic change during and since the last Ice Age.

Well-varnished surfaces have a dull luster that causes entire hillsides to glisten in intense desert sunlight. This mineral coating gives the landscape its warm tones of brown and ebony, often masking brilliantly colored bedrock below. All the earth's deserts have varnished rocks, but in the Southwest these surfaces provoke even greater interest because of their archeological importance. In innumerable locations prehistoric Indians pecked petroglyphs (rock writings) through the mineral skin to the fresh rock below. Today these symbols are being revarnished as the process continues.
The ash-rich, white-to-light-gray layers are surge beds (Figure 11) that were deposited when violent explosions propelled ash clouds down the slopes of the caldera.

Magma behaves much like a carbonated beverage. When pressure is released, gases escape, forming a "foamy" liquid (pumice). The foam, the first liquid to be ejected from the volcano, settles in topographically low areas. Volcanic ash is subsequently deposited on top of the pumice and fine ash.

Surge beds are much softer and more easily eroded than the tuff layers that were deposited on them. This creates a geologically unstable situation. During particularly wet years water moves along joints in the rhyolite and saturates the white ash.

Blocks of the rhyolite break loose and tumble down the slopes of Sugarloaf Mountain. One of these rockfalls occurred in February 2001 about half way up the Sugarloaf Trail (Figure 12). Rockfalls are an important mass-wasting process that, over geologic time, contribute to the wearing down of Earth's highlands.
Locally, ancient steam vents, called fossil fumaroles, have been preserved in the rock (Figure 13). These vertical pipes of coarse ash and crystals mark locations where steam and gases escaped to the surface.

Figure 13. A fossil fumarole preserved in pumice and fine ash. A fossil fumarole is also visible in the right-center portion of Figure 11.
The dark rock (Figure 14) that caps Sugarloaf Mountain is dacite, the youngest rock in the monument. The dacite was once molten and flowed as lava down a valley from higher slopes in the Turkey Creek area just to the south. The flow cooled, solidified, and except for this remnant, was removed by erosion.

Sugarloaf Mountain is an example of topographic reversal. The dacite flow once filled a valley cut into the Rhyolite Canyon Tuff. Erosion has since removed the softer, more easily eroded tuff, leaving this remnant of the dacite flow as a protective cap—forming a mesa where a valley once existed.
The highest peaks of the Chiricahua Mountains, visible on the southern skyline (Figure 15), are remnants of the Turkey Creek caldera, which formed after large quantities of magma (molten rock) were erupted explosively 26.9 million years ago. Magma, together with water vapor, carbon dioxide, and other gases, accumulated in a massive magma chamber a few miles below the land surface and ruptured the overlying rocks. The resulting steam explosions and release of confined gases blew more than $100$ cubic miles of molten rock into the atmosphere as clouds of pumice and ash. This material settled to the ground and eventually blanketed more than $1,200$ square miles ($3,100$ square kilometers). This compacted material became the Rhyolite Canyon Tuff, which has been carved into spectacular pinnacles by weathering and erosion processes.

The volcano ejected more than a thousand times the amount of material that was ejected during the 1980 Mt. St. Helens eruption in Washington State and a hundred times that of the 1991 Pinatubo explosions in the Philippines. The explosion and collapse of the magma chamber formed a giant depression 12 miles (19 kilometers) across and 5,000 feet (1,524 meters) deep.

The circular form of the caldera (refer to Figure 4) has been obliterated because of burial by pumice and ash and by faulting and erosion. The volume of volcanic rocks related to the Turkey Creek eruptions is minuscule when compared with those that form Mexico’s vast plateau, the Sierra Madre Occidental (Figure 4). There, in what must have been one of the earth’s most violent episodes of volcanism, dozens of calderas ejected massive ash sheets that covered much of western Mexico at the same time the Turkey Creek deposits were forming in this area.
Willcox Playa, the gray-white area in the Sulphur Springs Valley west of the monument (Figure 16) is visible from the top of Sugarloaf Mountain. This dry lake is a remnant of Lake Cochise, a shallow, 35-foot-deep (11 meters) Ice Age body of water that was present as recently as 10,500 years ago. The lake level rose and fell during wet and dry periods in the Ice Age. Salinity of the water varied due to changing evaporation rates and fluctuating inflow of water within this closed basin.

Lake Cochise was just one of many lakes that formed in the Southwest during the wetter, cooler climatic conditions of the Ice Age. Fossils and pollen collected from the lake sediment indicate that during the Ice Age the basin supported open stands of ponderosa pine and herds of mammoth, horse, and camel. The white color of the playa is due to mineral salts (such as halite and gypsum) and clay minerals eroded from the Chiricahua Mountains and other ranges that border the Sulphur Springs Valley. Today, wind is returning these fine particles as dust to adjacent areas, including the Chiricahua National Monument, where the particles play a role in weathering the rock pinnacles.

Willcox Playa, just west of Highway 186 south of Willcox, is one of only two active playas in Arizona. The other is the Red Lake playa near Kingman in northwestern Arizona.
Several of the basins and intervening mountain ranges that characterize the topography of southeastern Arizona can be viewed from the top of Sugarloaf Mountain. During the period 25 to 5 million years ago, long after the Turkey Creek caldera had formed and was buried, the western part of North America was severely stretched. As a result, the earth's crust beneath much of the Southwest broke into blocks separated by long fractures, called faults. Some crustal blocks were uplifted to form the mountain ranges of the region. Other blocks subsided as much as 1.25 miles (2 kilometers) to form deep basins (Figure 17). Erosion has since filled the basins with sediment eroded from the adjacent ranges.

Figure 17. The Basin and Range province is well exhibited in southeastern Arizona. Mountain ranges (in green) include the Peloncillo (PL), Chiricahua (C), Pedregosa (PD), Perilla (PR), Swisshelm (SH), Dos Cabezas (DC), Winchester (WN), Little Dragoon (LD), Dragoon (D), Mule (M), Huachuca (H), Whetstone (WH), and Rincon (R). Basins include the San Simon (SNS), Sulfur Springs (SS), and San Pedro (SNP). Highways are shown in red.
Drive back toward the main road and park in the Echo Canyon Loop parking area. The geologic features described below can be observed from this trail.

The narrow, necked portions of many of the pinnacles exhibit blocky features that resemble small shingles (Figure 18). The partings between the shingles are surficial, penetrating only a few inches into the bedrock. The shingles have a heavy coating of rock varnish and are commonly case hardened. Exfoliation shingles protrude from the weathered face of the columns because of these protective mineral coatings. Stress from the weight of the rock mass above the necked portions of the columns may be a factor in their formation. More study is needed to determine their exact origin.

Figure 18. Plate-like features called exfoliation shingles are common on the weathered surfaces of the rock columns in the monument. Lichens are abundant. Note pen for scale.
Many flat-lying areas, including the level tops of many pinnacles, contain flat-bottomed, circular depressions that commonly have overhanging side-walls (Figure 19). These solution pans, up to 3 feet (1 meter) across and 4 inches (10 centimeters) deep, can hold water for weeks after rain and snowmelt.

Pans form at points of rock weakness (a joint, lichen disintegration, or flaked surface) and expand by chemical and lichen weathering. Periodic pooling of water leads to the chemical alteration of the minerals that make up the underlying rock. Some minerals dissolve, some oxidize, and others are changed to clay minerals. Lichens and algae flourish in the more humid environment of the pits and decompose the rhyolite grain by grain. The rock disintegrates slowly and the resulting debris is swept and flushed from the enlarging solution pans by wind and heavy rains.

The rims of many of these pans are covered with orange, iron-rich rock varnish. The minute quantities of iron have oxidized (rustied), giving the orange tint to the mineral coating. The varnish tends to protect the underlying rock from chemical decay, which produces the elevated rim along the edges of the pans.

Figure 19. Solution pans are dish-shaped depressions in rock that form by chemical and physical weathering processes. The pans occasionally fill with rainwater or snowmelt. The pen in the center of the solution pan is for scale.

Solution pans are the best places to observe chemical weathering, because periodic ponding of water in these shallow depressions allows the process to proceed at a more rapid rate.
Near the base of most pinnacles the rock surface has knobby or plate-like protrusions termed chicken heads (Figure 20). These miniature features contain remnant coatings of rock varnish and lichens, and have been case hardened to make them more resistant to weathering than the surrounding fresh rock surfaces. When these protective coatings are worn away, the chicken heads will be weathered to a smooth surface. Meanwhile, they add a distinctive texture to rock columns in the region.

Figure 20. The irregular, knobby surfaces of rock pinnacles are referred to as chicken heads.
Horizontal ribs are common small-scale surface features on the rock pinnacles (Figure 21). Ribs and depressions vary from $\frac{1}{2}$ to 4 inches (about 1 to 10 centimeters) in width and up to 8 inches (20 centimeters) long. The depressions are cavities formed by the weathering of softer ash layers and fiamme (pumice blocks that were flattened and deflated during the welding of the rhyolite). The material interbedded with the soft ash layers and fiamme is more resistant to weathering and stands out as ribs on the surfaces of the columns.
The cavities weathered in the rock walls of the surrounding pinnacles are called tafoni (Figure 22). They occur in many different types of rock and in a great variety of climates, but are particularly visible in deserts where their shapes are not obscured by soil and vegetation.

These cavernous openings, which range up to several yards in diameter, are commonly aligned along joints, bedding planes, or other zones of weakness in bedrock. They are products of several processes acting in concert. Sometimes the rock face develops a hardened crust of mineral salts that were drawn from the interior of the rock. This "case-hardened" outer surface is more resistant and is preserved, while small openings continue to enlarge and penetrate the softer interior of the rock. Within these shaded cavities, higher humidity and lower temperatures cause rock to disintegrate more rapidly than outside. Cavity walls are usually crumbling and flaking, due to the expansion of clay minerals that swell when wet, the growth of ice crystals, and the solution of mineral cement that binds rock grains together.

Some cliffs contain fossil tafoni. Interiors of fossil tafoni are either case hardened or covered with lichens or rock varnish (a clayey, iron-manganese rind). Shaped by processes that have slowed or ceased, these openings are relics from an earlier period when the climate was more humid. Tafoni weathering, common throughout the Southwest, is but one of the numerous processes that reduce solid rock to fragments that are then swept away by erosion.
The surfaces of most of the surrounding pinnacles and cliffs have developed a protective mineral rind by a process called case hardening. It is most easily examined along the edges of tafoni (Figure 23). These case-hardened rock surfaces are coated with a durable film of amorphous (lacking an orderly crystal form) silica (SiO2) that has been drawn from the interior of the rock and reprecipitated on the surface. Although silica is not very soluble in water, small quantities of it are leached from the rhyolite each time the rock is wetted by rain or dew and then deposited on the surface when the moisture evaporates. In time, the rock surface becomes hardened by this buildup of silica, while the rock beneath is weakened by the removal of that mineral.

Case hardening protects rock surfaces from chemical weathering and low energy erosion. Once this protective film is broken, however, the softer, weathered zone is exposed to the elements and quickly develops tafoni.
Slot-like canyons, commonly up to 40 times deeper than their width, have been cut into the rhyolite (Figure 24). Their course is totally controlled by the rectangular joint sets described on page 15. These narrow defiles, and the fin-like, pinnacle-lined walls that separate them, were formed primarily during the wet, cold glacial periods of the last Ice Age (1.6 million to 10,000 years ago). Repeated freezing and thawing of ice along joints and the flushing away of resulting rock fragments by running water “roughed out” these large-scale features. Rock faces were originally angular and blocky. During the warmer, drier interglacial periods (such as our current climate) chemical weathering, lichen colonization, and the development of rock varnish have rounded and tapered these landforms.

One can occasionally see huge rectangular blocks that have toppled from the top of a nearby pinnacle and become wedged between narrow walls high above the floor of the slot. For the most part, however, these slot canyons are free of large rock fragments shed from adjacent pinnacles. This is because frost wedging is no longer as active as it was during the glacial periods.

Today most of the debris falling from these walls consists of rock grains dislodged by small-scale chemical and mechanical weathering.

These slot canyons are relict landforms that were carved by frost wedging and running water along a rectangular system of joints during the last glacial period.
Talus cones, those steep, triangular-shaped piles of rock rubble shown in Figure 25 are common landforms in high mountains and deserts. Wedging by ice and plant roots, chemical decomposition, and other weathering processes loosen angular rock fragments. When dislodged, these chunks fall to the slope below and break into pieces that slide and tumble down the cone built by previous rockfalls. Fresh sliderock lacks the mineral coating called rock varnish and contrasts sharply with the dark color of older debris. Talus cones can be seen best along the Hailstone segment of the Echo Canyon Loop.

Talus cones are the products of weathering and rock movement due to gravity. Both processes are important in reducing highlands and preparing the decomposed rock for removal by running water.

The momentum of falling boulders commonly carries them to the base of the cone; the particles become progressively smaller upslope. This crude sorting is the reverse of that found in river-deposited sediment.

These accumulations of fallen rock collect slowly and at discontinuous rates. During extended periods of climatic cooling, when there is an increased number of daily freeze-thaw cycles, the rate of rock fall and accumulation is greater. Talus cones in the Chiricahua Mountains are relict features produced during the cooler and wetter climatic conditions of the Ice Age (1,600,000 to 10,000 years ago). The cones show little evidence of recent rockfall, are encrusted with lichens, and have been partially stabilized by vegetation.

Talus slopes can be very unstable. Because slope angles normally have reached their upper limit (angle of repose), rock slides can be triggered when one attempts to climb the cones. Caution!
Figure 26. These marble-sized spherulites developed after the volcanic ash was deposited. They are not fossil hailstones.

The bed of rounded rocks (Figure 26) exposed on the trail cut at point A on Figure 1 is composed of spherulites, which were formed as the volcanic ash sheet cooled. The spheroidal shape is due to the radial growth of needle-shaped, secondary crystals of quartz and feldspar from a common center. They were once thought to be volcanic hailstones that formed by the repeated accumulation of concentric ash layers around water droplets or crystals as they rose and fell through volcanic ash clouds—hence the name “hailstone” segment of the Echo Canyon Loop.
The landscape of Chiricahua National Monument, like that of much of the Earth's surface, is a complex mosaic of large and small geologic features. Some of these features were produced by processes that were more active in past geological time but have now slowed or ceased. Other features are the result of past and currently active processes; only a few owe their origin solely to recently active processes. Welded tuff, fiamme, surge beds, fossil fumaroles, and the dacite caprock, for example, were all produced during the eruption of the Turkey Creek caldera, about 27 million years ago. Some joints and spherulites formed as the ash sheet cooled. Other joints and the region's mountain ranges and intervening basins are the result of Basin and Range faulting during the period 25 to 5 million years ago. Willcox Playa, talus cones, pinnacles, and slot canyons were produced by processes that were more active during the wetter, cooler climate of the Ice Age 1.6 million to 10,000 years ago. Tafoni, rock varnish, lichens, case hardened surfaces, chicken heads, exfoliation shingles, horizontal ribs, solution pans, and the rounded form of the columns are all forming today. Unraveling the evolution of such complex landscapes makes geology a particularly challenging science.
Figure 27. Map of Fort Bowie National Historic Site.
INTRODUCTION

Geology has greatly influenced the course of history in the Fort Bowie National Historic Site and surrounding area. Fort Bowie was built to guard Apache Pass, a natural passage between the Dos Cabezas and Chiricahua Mountains that connects the San Simon and Sulphur Springs Valleys (Figure 4). Known as “Puerta Dado” or the “Pass of Chance” during the Spanish and Mexican periods, this strategic corridor exists because of the hardness differences and structure of the bedrock. The site chosen for Fort Bowie is directly related to geologic conditions. The dependable springs, including Apache Spring, that have attracted humans to this narrow passage for thousands of years are also the result of geology, specifically the Apache Pass fault.

Apache Spring, Fort Bowie, and Overlook Ridge, along which the Battle of Apache Pass took place in 1862, can be observed along the foot trail from the parking lot on Apache Pass Road to the visitor center, a round trip distance of 3 miles (4.8 kilometers) (Figure 27).

Apache Spring and the Apache Pass fault are designated by trail markers. One can easily identify all of the features, however, by studying the photographs and maps that accompany the text. Please remember that it is illegal to collect natural or cultural items from Fort Bowie National Historic Site.
Fort Bowie National Historic Site

To Bowie

Parking

Apache Spring Overlook Ridge

Ft. Bowie

To Willcox
The Apache Pass fault zone is the major geologic feature in this area (Figure 28). It is 0.6 to 1.2 miles (1 to 2 kilometers) wide and can be traced across the mountains for nearly 38 miles (60 kilometers). This northwest-trending feature is a belt of Paleozoic and Mesozoic sedimentary strata that separates two masses of igneous and metamorphic rocks of Precambrian and Oligocene age.

The Apache Pass fault zone is a complex system of fractures along which repeated horizontal and vertical movement has occurred. In the vicinity of Fort Bowie the once-horizontal sedimentary layers were also sheared by two other faults, the Fort Bowie and Hidalgo thrust faults. Movement along these high-angle fractures has tilted and broken the sedimentary rocks into elongated slices that dip steeply toward the southwest (Figure 29). Vertical movement along these thrust faults, together with more than 7.5 miles (12 kilometers) of horizontal slippage along the Apache Pass Fault, has juxtaposed rocks of vastly different ages. Overlook Ridge, for example, which dominates the northwestern approach to Fort Bowie, is composed of the Horquilla Limestone of Pennsylvanian age (310 million years old) that was dragged into contact with the Rattlesnake Point granodiorite of Precambrian age (1.36 billion years old).

The narrow, northeastern entrance to Apache Pass, guarded by Fort Bowie, was formed by running water that eroded Siphon and Cutoff canyons into the upturned, erosion-resistant Paleozoic and Mesozoic strata. The fort is situated on one of these slivers of sedimentary strata, in the saddle that separates Siphon Canyon and Bear Gulch.

Drive northeastward almost 1.5 miles (2.4 kilometers) from the parking area for the Fort Bowie trailhead and traverse the Apache Pass fault zone. Observe that the rocks are steeply dipping and contorted. Sandstones and volcanic rocks of Cretaceous age crop out in the vicinity of the parking area. Farther down the road limestones of Paleozoic age are exposed. Turn around and return to the parking area.

(Facing page) Figure 28. Geologic map of the Fort Bowie area (generalized and modified from Drewes, 1984).
From the parking lot on Apache Pass road walk on the trail that leads to the Fort Bowie National Historic Site Visitor Center about one mile. Apache Spring is on the left (north) side of the trail.

Water that feeds Apache Spring (Figure 30) is ground water that flows to the surface where Siphon Canyon has cut across (intersects) the zone of bedrock that was shattered along the Apache Pass Fault. The sedimentary and igneous rocks in the Fort Bowie area are generally impermeable. Water is stored only in fractures created by folding and faulting. Rainwater and snowmelt from the higher parts of this drainage basin percolate through the alluvium of Siphon Canyon into the zone of fault-fractured rock below. This water re-emerges at the surface where streams have intercepted the fault shatter zones (Figure 31).

A masonry box is used to store and divert water from the spring. The flow from the spring, which averages about five gallons (19 liters) per minute, is dependent on precipitation and fluctuates from season to season and year to year. Some of the water must be diverted to a stock tank on private land because of prior water rights.

Apache and other nearby fault-controlled springs are dependable sources of water for humans and other mammals that inhabit or pass through this dry part of the Dos Cabezas and Chiricahua Mountains. Fort Bowie was located here to control Apache Pass and Apache Spring.

Throughout the Basin and Range country of western North America springs are commonly located along fault zones. Along some faults, voids within the fractured rock carry the ground water; other faults contain an impermeable zone of pulverized rock powder, called gouge, that forces subsurface water to the surface in springs and seeps.

Figure 29. Geologic cross section through the Fort Bowie area (modified after Drewes, 1984).
Figure 30. Apache Spring

Figure 31. Block diagram of the Apache Spring area.
OVERLOOK RIDGE

LOCATION

Walk 0.2 mile (0.3 kilometer) north along the Overlook Ridge Trail from the Visitor Center to the bench that overlooks Fort Bowie. Then continue north on the trail an additional 0.2 mile (0.3 kilometer) to the metal trailside exhibit that discusses the Apache Pass fault. After you have viewed the features described below, continue northward on this trail and return to the parking area.

Horquilla Limestone. As you begin to walk up the Overlook Ridge Trail north of the Visitor Center, observe the gray Horquilla limestone. The chemical and crystal makeup of this and other sedimentary layers has been altered throughout extensive areas. This alteration or metamorphism of the rock is due to intense pressure and heat that accompanied the compression and faulting. Heat from nearby intrusions of once-molten rock may have also played a minor role in the alteration. This is a ridge because these altered or metamorphosed rocks are harder and more resistant to erosion.

Fort Bowie. Before you reach the crest of Overlook Ridge look south toward Fort Bowie. Observe the thin fan-like veneer of sediment on which the fort was built (Figure 32). That sediment was derived from the weathering of rocks higher on the slope. This was the only comparative-ly flat surface suitable for a large fort that was close enough to protect Apache Spring. The northwestern (right) edge of the sediment veneer is truncated by the Apache Pass fault. Apache riflemen, positioned on Overlook Ridge, tried to block the passage of the California Volunteers on July 15 and 16, 1862 during the Battle of Apache Pass.

Continue on the trail to the metal trailside fault exhibit.

Apache Pass fault. At the trailside marker look toward the south toward Fort Bowie and observe the distinct color difference between the gray Horquilla limestone on the left side of the fault and the brownish Rattlesnake Point granodiorite on the right (Figure 33). The Apache Pass Fault is a strike-slip fault—a fracture in the Earth's crust where rocks on one side have moved horizontally relative to those on the other side. The shattered sedimentary rocks within this complex fault zone have been dragged in a southeasterly direction by compressional forces. Offset slivers of sedimentary layers within the fault zone and igneous rocks bordering the zone indicate that more than 7.5 miles (12 kilometers) of horizontal displacement has occurred. Rock movement has also had a vertical component. Rocks on the southwest side having moved upward relative to those on the northeast.

The Apache Pass fault system is interpreted to have originally formed during Precambrian time (perhaps 1.4 billion years ago) and experienced an active period of slippage during later geologic time. This ancient fault demonstrates that major structural features can be reactivated and influence the devel-
Figure 32. Fort Bowie sits on a thin veneer of sediment (S) that was formed by weathering of rocks higher on the slope. The Horquilla limestone (H) crops out on the hill behind the fort. The Rattlesnake Point granodiorite (RP) is in contact with the Horquilla along the Apache Pass fault (AP). This fault forms the northwestern margin of the sediment veneer.

Figure 33. The Apache Pass fault (AP) has placed Horquilla limestone (H) (Pennsylvanian age) in contact with the Rattlesnake Point granodiorite (RP) (Precambrian age). View is toward the Fort Bowie ruins from the metal trailside marker.
Development of surface landscapes over long spans of geologic time.

Slippage along strike-slip faults, which can set miles of rock in motion, is an important mechanism in explaining how great slices of land have been added to the western part of North America. Earthquakes from such movement can be catastrophic in areas of dense human population, as California’s 600-mile (966 kilometer)-long San Andreas fault has shown several times this century.

**Rattlesnake Point granodiorite.** Just south of the metal trail marker for the Apache Pass fault, a trail proceeds westward a short distance. The Rattlesnake Point granodiorite crops out along this trail. The rock is a course-grained igneous intrusive rock that has an age of about 1,375 million years (Precambrian). Although the fresh rock is gray, it weathers to a brownish color. The rock has roughly equal percentages (about 30) of quartz, microcline, and plagioclase, with small quantities of biotite, magnetite, apatite, and other minerals. Return to the metal marker.

**Fort Bowie thrust fault.** The principle of superposition—that younger rocks are found above older ones in vertical sequence—is basic to geologic thought. Yet here, along Overlook Ridge, the rocks are not in the order that they were deposited. The elongated slice of Horquilla limestone that forms this ridge was shoved into position by thrust faulting. It was torn from the main mass of the Horquilla limestone about 65-63 million years ago, during late Cretaceous or early Paleocene time, when intense compression broke the rock along a steep fracture called the Fort Bowie thrust fault (Figures 29, 31, and 34).

Continued slippage along the thrust fault moved this sheared off slice of Pennsylvanian age (approximately 310 million years) limestone into contact with the younger Cretaceous (144-65 million years) rocks below and to the northeast. Compression accompanying slippage along the fault zone also folded the limestone.

Aside from creating geologic puzzles such as inverted strata, thrust faulting can be a significant mountain-building process. Larger-scale horizontal displacements of miles of bedrock along thrust faults have built grand ranges such as the Alps and Himalayas.
Overlook Ridge. The Apache Pass fault (solid line) has placed the Rattlesnake Point granodiorite (RP) in contact with Horquilla limestone (H). Apache Spring is within the tree-covered area at the center of the photograph. The Overlook Ridge Trail follows the crest of the ridge. The metal trail marker is on the fault at the ridge crest (arrow). The Battle of Apache Pass took place on this hillside in 1862. View is toward the north from the first Fort Bowie.
SUMMARY

Ancient structural features, when exposed to weathering and erosion at the Earth's surface, determine the development of the modern landscape. In this part of the Chiricahua and Dos Cabezas Mountains the Apache Pass fault zone controls the regional topography. Although much of the rock displacement here was along strike-slip faults, numerous slices of rock were emplaced by compressional movement along thrust faults such as the Fort Bowie thrust fault. Miles of movement along these fractures has folded, upturned, and sheared a great thickness of sedimentary rocks into such slices. Weathering of the harder and more erosion-resistant Horquilla Limestone and other comparable sedimentary rock layers within the Apache Pass fault zone formed steep ridges such as Overlook Ridge. Softer rocks were eroded into the long, narrow valleys that make up Apache Pass. Voids within the shattered rock zones along the faults carry groundwater that feeds Apache and other springs in the Apache Pass area. A gently sloping hillside veneered with sediment near Apache Spring provided a favorable place on which to build a fort. Geology thus played a dominant role in the historical events that took place at this strategic portal.
SELECTED READINGS

CHIRICAHUA NATIONAL MONUMENT


Selected Readings (continued)


Selected Readings (continued)

____, 1979, Mineralogy of manganese dendrites and coatings: American Mineralogist, v. 64, p. 1219-1226.


Selected Readings (continued)

FORT BOWIE NATIONAL HISTORIC SITE


Rock pinnacles in the Chiricahua National Monument have been and are being shaped by a number of chemical and physical processes, including the action of lichens.