U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Geology of Chiricahua National Monument, A Review for the Non-Specialist

By

John S. Pallister, Edward A. du Bray, and Douglas B. Hall

Open-File Report 93-617

1993

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American stratigraphic code. *Technical terms are shown in italics and a glossary is provided as an appendix.*

Introduction

We gather clues about the geologic history of Chiricahua National Monument by examining rocks in the field and in the laboratory and by plotting the distribution of the various rock types to produce geologic maps that show where ancient landforms (rivers, lakes, and volcanoes) used to be. Just as a detective reconstructs the scene of the crime and a sequence of events, we have reconstructed how and when the rocks of the Monument area formed. We are fortunate because these rocks record the natural environment of Southeast Arizona throughout much of Earth history. We see evidence that the region was alternately flooded by ancient seas, uplifted along great fault zones, and covered by lavas and ash from volcanoes. The most dramatic geologic event took place 27 million years ago when a giant volcano, called the Turkey Creek *caldera*, erupted just south of the National Monument (Figure 1). This eruption was 1000 times larger than the 1980 eruption of Mount St. Helens and five to ten times the size of the great explosion of Krakatoa in 1883.

Similar and still potentially hazardous giant volcanoes exist in the United States (e.g., within Long Valley, California and in Yellowstone National Park) and in a number of other places around the Pacific rim; luckily for us, they erupt infrequently. Yet, the very fact that eruptions are infrequent at these calderas makes predicting how and when they will next erupt difficult. This is one of the reasons we study extinct volcanoes like Turkey Creek. We have determined the size and frequency of ancient eruptions that took place here and we can estimate the size of the area that was devastated by the eruptions. Because erosion has cut deep valleys into the volcano, we can also directly examine parts of the subterranean *magma chamber* that fed the eruptions, something that is impossible at active, uneroded, volcanoes. In this way, we develop and refine a general model for caldera-forming eruptions and we compile a series of "case examples" that allow us to better understand the hazards posed by still-active calderas.

Shortly after eruption, the Turkey Creek volcano would have been similar in appearance to Crater Lake caldera, in Crater Lake National Park, Oregon... but twice as large. The Turkey Creek eruption buried the region with a thick layer of hot *ash* and *pumice*, producing a deposit known as *tuff*. The ash and pumice layer was hot enough to fuse together, or weld. As it cooled, the *welded tuff* contracted, forming cracks or *joints*. Water then seeped into the cracks and began eroding out the columns for which the Monument is best known. Assisted by the wedging action of freezing water, stream flow, and erosion by the wind, the cliffs and columns were slowly carved into the thick layer of welded tuff. We will discuss the volcanic rocks of the National Monument in more detail later, but first we will review the more ancient part of the geologic story.

Precambrian time- Arizona "arrives"

The oldest rock in the area is Pinal *Schist*, a *metamorphic rock* that is widely exposed in the Dos Cabezas Mountains, between the National Monument and Willcox, Arizona. The Pinal Schist formed about 1.7 billion-years-ago during the *Precambrian Era*. It is composed of volcanic tuffs (much like those in the Monument) and *sedimentary rocks*. These rocks were *metamorphosed* into schist as they were heated by masses of molten rock, and as a result of being deeply buried for millions of years. However, at places within the schist we can still recognize pumice blocks in the original volcanic rocks, and grains of sand in the sedimentary rocks. And we can begin to reconstruct the local environment 1.7 billion years ago, even before most life appeared on Earth. This appears to have been a time when the Southwest was made up of numerous volcanic belts separated by shallow seas; perhaps, not unlike the western Pacific of today.

These volcanic belts, or *island arcs*, were made up of rocks that were relatively light-weight; they floated on heavier and partly molten *mantle* rocks that moved like a conveyor belt beneath them. The island arcs were swept together and plastered, or *accreted*, to the edge of the North American continent, much as items pile up at the end of a conveyor belt at your local grocery store. This process of continental growth is part of the global process of *plate tectonics*, a unifying theory that explains much of Earth history. As more island arcs were added, the continent grew to the southwest from its previous coastline in Wyoming, such that by 1.4 billion years ago, most of Arizona had been added to North America. About this time, new masses of molten rock *intruded* into the accreted coastal province, effectively "stitching" it to the mainland. An example of one of the resulting *granites*, with feldspar crystals the size of golf balls, is visible in nearby road cuts on Arizona highway 181, about a mile and a half east of Dos Cabezas town.

Little record remains of what happened during the next 800 million years, presumably many rocks were deposited, but virtually all have been eroded away, leaving an *unconformity* surface in the geologic record. This remarkable surface, where 1.4 billion year old rocks are separated from 500-600 million year-old Cambrian rocks is exposed in road cuts 3.6 miles east of Dos Cabezas town. The Cambrian rocks are conglomerate and sandstone, derived from rivers and beaches that record a major advance of the sea at the beginning of Paleozoic time (about 570 Million years ago).

Paleozoic time-- "Under the sea"

Southeast Arizona was covered by an ancient sea throughout Paleozoic time (570 to about 250 million years ago) and thick layers of fossiliferous limestone and sandstone were deposited. These rocks are exposed in the northeastern corner of the National Monument, on the rugged southeastern flank of Timber Mountain. Fossil corals, brachiopods (ancestors of modern clams), echinoid spines (related to modern sea urchins), and gastropods (snail-like shells) are abundant in these rocks and record shallow-water coral reef environments.

Mesozoic time-- "Emergence and volcanic eruptions"

Another gap or unconformity, this time of about 100 million years, occurs in the local geologic record between rocks of Paleozoic and Mesozoic age. The unconformity represents a period of uplift and erosion, such that few rocks of late Paleozoic or early Mesozoic age are preserved in the Chiricahua Mountains. The youngest Paleozoic rock in the area is the Permian Concha Limestone (about 250 million years old), which is overlain by conglomerate, sandstones, and volcanic rock of the Jurassic to Cretaceous Bisbee Group (less than 150 million years old). Conglomerate beds at the base of the Bisbee Group are widely exposed in the hills east of Whitetail Pass. These beds contain cobbles of fossiliferous limestone that were shed from uplifted mountains composed of the underlying Paleozoic rocks. The conglomerate beds are overlain by fine-grained sedimentary rocks, such as silty limestone, shale and sandstone, and by lava flows. Some sandstone beds contain fossilized trees (petrified wood); other beds are dark green or gray due to an abundance of dark volcanic rock fragments. Lava that flowed into water formed pillow-like shapes when the surface of the lava was cooled rapidly by the water, but the interior kept flowing and inflated the rind like a balloon. Such *pillow lava* can be seen along the road across Onion Saddle, between the National Monument and Portal, Arizona; although, it is often difficult to distinguish true pillow lava forms in these rocks from rounded outcrop blocks produced by weathering. The Bisbee Group rocks record the presence of a shallow inland sea, that extended from this region across southern New Mexico and to the Gulf of Mexico.

Numerous volcanoes formed during the Mesozoic Era, as crustal rocks of the Pacific Ocean slid under the Southwest and melted. By this process of *subduction* oceanic crust that is generated at ocean ridges is later destroyed as the underlying mantle cools and sinks at *subduction zones*. Oceanic crustal plates float on the underlying mantle as it moves like a conveyor belt from mid-ocean ridges to subduction zones. The continents drift about the globe as a consequence of being caught between the conveyor belts of spreading ocean ridges and subduction zones. Continents grow, as bits of the oceanic crust, including islands like Hawaii, and island arcs like Japan, are "scraped off" the top of the conveyor belt and accreted to the edges of continents. As described above, this process of continental growth took place in Arizona during Precambrian time, and again in California during Mesozoic time.

Volcanoes form above subduction zones as the oceanic crust is drawn down and heated beneath them. Seawater and other volatile components are "boiled off" in the subduction zone and rise into the overlying hot rocks, where they promote melting, in the same way that addition of a flux allows metals to melt more easily. The melted rock, or *magma* is enriched in volatiles and it rises toward the surface. It may ascend directly to the surface and erupt, or it may pond beneath the surface to form subterranean resevoirs of molten rock, known as *magma chambers*. Magma chambers cool slowly; they eventually crystallize to form coarse-grained rocks such as granite. However, while they are still molten, these chambers often leak magma to the surface above, "feeding" one or more volcanoes. This is the current situation at Mount St. Helens, at Long Valley California, at Yellowstone National Park, and at hundreds of other volcanic fields across the globe. Occasionally, parts of a shallow magma chamber may become unstable and "boil" causing what is, in effect, a huge steam explosion. In this situation, a giant volcano, or *caldera*, forms as tens to hundreds of cubic miles of magma are erupted all at once. Caldera-forming eruptions are the most violent volcanic events known on Earth and many have occurred in the Southwest.

Subduction zones underlay this part of Arizona (and the Southwest) during much of the Mesozoic Era. During this period, the Sierra Nevada *batholith* (including the large granite masses in Yosemite National Park) were intruded, and they fed volcanoes in an arc along the western coast of North America. Huge volcanoes also erupted in southeastern Arizona, first forming calderas in the Huachuca and southern Dragoon Mountains about 160 million years ago, then again during a burst of volcanic activity and faulting at the close of the Mesozoic Era about 65 million years ago. This latter period is known as the *Laramide orogeny*, an episode of mountain building throughout the western US at the end of the Mesozoic. Mountain ranges were built from volcanic rock and uplifted along numerous fault zones. It was during the Laramide orogeny that most of the ores of copper, silver, and gold were deposited in the Southwest. Ore that was deposited during this tumultuous period of Earth history 65 million years ago is removed at the prominent open-pit mines in southeast Arizona. Welded tuff that forms the summit of the Dos Cabezas Mountains was erupted, and mineralizing fluids invaded the surrounding rocks, leaving deposits of metals.

Cenozoic time-- Eruption of the Turkey Creek caldera and Basin and Range faulting

The Cenozoic Era is divided into two periods: the Tertiary (65 million years to about 2 million years), and the Quaternary (about 2 million-years to the present). A subduction zone was present beneath the Southwest during the first half to two thirds of the Tertiary, so volcanism continued. Most of the volcanic activity in the Chiricahuas took place between about 35 and 25 million years ago. This is the interval when small magma chambers were emplaced and cooled to form granite at Cochise Stronghold (across the Sulfur Springs valley to the west) and in several areas of the northern Chiricahua Mountains. Scattered volcanoes erupted lava flows during the same interval. Some of these were dark-colored *basalt*, such as the rocks exposed in the road cuts just uphill from the "Lake Beds" markers on the road to Sugarloaf Mountain and Massai Point in the National Monument. Recent study has shown that the "Lake Bed" deposits are mainly stream and alluvial fan deposits that were laid down about 30 million years ago within a shallow basin that extended to the north across what is now Whitetail Pass. Other small volcanoes produced mainly sticky, or viscous, *rhyolite* lava that piled up around their eruption vents like toothpaste and formed the hills north and south of Faraway Ranch. A vertical *flow ramp* where viscous rhyolite lava piled up on itself is clearly visible as vertical layers in the cliff north of the Faraway Ranch parking lot. Small explosions accompanied the eruption of rhyolite lava and produced *nuée ardente* (glowing cloud and avalanche) deposits consisting of thin beds of rhyolite ash and rock debris. Analagous explosions took place at Unzen volcano in Japan in 1991 when part of a lava dome collapsed; the resulting nuée ardente killed 41 people.

At about 27 million-years ago, a large mass of magma accumulated within a few miles of the surface, just south of the National Monument. Volatiles (mostly water vapor and carbon dioxide) accumulated in the magma chamber, until eventually the strength of the overlying rock was exceeded and it ruptured, allowing the volatiles to come out of the magma, like the bubbles in soda pop or the foam on a glass of beer. The foaming magma formed *pumice*, and expanded up to 50 times in volume, driving a tremendous series of explosive eruptions that blew more than a 100 cubic miles of magma out of the volcano and buried a region of at least 1200 square miles in a thick blanket of incandescent *ash* and pumice. For comparison, the 1980 eruption of Mount St. Helens produced only one tenth of a cubic mile of magma and the 1991 eruption of Mount Pinatubo in the Philippines involved only about one cubic mile of magma. The roof of the magma chamber collapsed as a result of the large volume of magma being withdrawn during the eruption. This produced a large circular depression, 12 miles in diameter and at least 5000 feet deep and located above the magma chamber (Figure 1). The depression, named the Turkey Creek caldera, was partly filled with the just-erupted ash and pumice. Although large, the eruption of the Turkey Creek caldera is not the biggest known; individual eruptions of the same type in the San Juan Mountains of Colorado, and in Yellowstone National Park each vented more than 500 cubic miles of magma.

The magma from the Turkey Creek volcano was rich in silica (about 77% SiO_2); rock of this composition is called *rhyolite*. When bubbles of gas in the magma exploded during the eruption, they liberated gas to drive the eruption and formed billions of microscopic shards of volcanic glass and fragments of crystals; together these particles are known as volcanic *ash*. The eruption produced boiling clouds of very hot (1100°F) ash, pumice, rock fragments, and gas that raced into the atmosphere and across the countryside at speeds of up to a hundred miles an hour, scouring everything in their paths like superheated jets from a sandblaster. It is doubtful if any living creature within 20 miles of the volcano survived. As the clouds lost gas, they became more dense and flowed downslope from the volcano as *pyroclastic flows* that ponded in valleys to form thick deposits of steaming ash and pumice. A rock that is composed mainly of ash and pumice is named *tuff*. If the deposit is thick and the shards of volcanic glass and the pumice fragments are still hot, they fuse together and compact under their own weight to form a rock called *welded tuff*. The Monument was formerly a valley; it was filled to a depth of about 1500 feet by a series of pyroclastic flows during the caldera-forming eruption. Because of the great thickness and dense welding this valley-filling deposit of tuff has not been eroded away during the past 27 million years. It is so well preserved in Rhyolite Canyon that the entire deposit is named the Rhyolite Canyon Tuff. Outcrops of similar rocks that are many miles away and were produced by the same eruption are given the same name. This is the nature of a *stratigraphic unit*, rocks that were produced at about the same time, and are similar in composition are named after places where they are best exposed.

Pumice, ash, rock fragments and crystals of feldspar and quartz are the main constituents of the Rhyolite Canyon Tuff. The pumice is seen as the prominent white streaks (*fiame*) in the rock. These pumices form streaks, instead of angular blocks because they were flattened as the rock welded and the gas bubbles collapsed. Although most of the Rhyolite Canyon Tuff is densely welded, relatively thin zones of poorly welded ash and pumice, and *surge beds* of ash, are visible as horizontal white bands in the cliffs. These white bands mark contacts between successive *pyroclastic flow deposits*. Three such contacts are present within the Rhyolite Canyon Tuff in the National Monument; they divide the Tuff into three layers, or members. All three layers were erupted in rapid succession. White, ash-rich surge beds are well exposed along the trail to the summit of Sugarloaf Mountain. They record explosions that blasted ash from the volcano at high velocity (hundreds of miles an hour). The blasts move laterally along the ground surface, leaving deposits in which individual beds are only a few tenths of an inch thick, and often form low angle *cross bedding* and *inverse grading*. The surge beds along the Sugarloaf trail have been overprinted by chemical banding produced as water boiled in the ash, leaving less-soluble minerals behind in layers, like the residue in a coffee pot. Fossil *fumaroles*, where water boiled and steam blasted to the surface, are preserved in the ash and the overlying welded tuff along the trail. These form irregular vertical pipes in which the fine grained ash material was blown out, leaving the coarser grained ash and crystals behind.

Accretionary lapilli consist of balls of ash that accreted to water droplets in the clouds of ash that rose above the pyroclastic flows. Beds of marble-size accretionary lapilli occur along Hailstone Trail at the contact between the lower and middle members of the Rhyolite Canyon Tuff. These likely record rainstorms that accompanied and followed eruption of the lower member of the Tuff. Volcanic eruptions of this magnitude would have created their own weather systems, both due to the large volume of water vapor added to the atmosphere during the eruptions, and to convection of air that was heated by the newly deposited, and widespread blanket of hot tuff.

The final chapter in the volcanic history in the National Monument is recorded by *dacite* lava atop Sugarloaf Mountain. Volcanic rocks with about 63% to 70% silica (SiO_2) are named dacite. Magma of this composition was present in the lower part of the magma chamber beneath the Turkey Creek caldera; it was erupted immediately after the Rhyolite Canyon Tuff. But, because the dacite contained less water and volatiles, it did not explode into ash, but was erupted as lava. Many of these dacite lava flows were trapped inside the caldera depression. The source area for the Sugarloaf lava flow is about six miles southeast of Sugarloaf Mountain where similar lava is exposed inside the caldera near Ida Peak (Figure 1). Lava from this area flowed out of the caldera and down a former valley into the National Monument. The dacite lava is hard rock that is resistant to erosion. Consequently, it was left standing high as the surrounding tuff was eroded. In this manner an area that was once a valley bottom is now the top of Sugarloaf Mountain. Geologists call this process topographic inversion.

Although the dacite atop Sugarloaf is the youngest volcanic rock in the Monument, caldera development was not yet complete. South of the Monument, the central part of the caldera depression was uplifted, forming a structure known as a *resurgent dome*, as first dacite and then new rhyolite magma rose into the magma chamber and lifted its roof. Uplift of the central part of the depression created a circular valley, or *moat*, between the resurgent dome and the edge of the caldera depression. The new batch of rhyolite magma did not erupt as explosively as the Rhyolite Canyon Tuff, instead it leaked out to form lava flows that were confined within the moat. These lavas were highly viscous, and formed flow ramps similar to those seen in the older rocks near Faraway Ranch. These moat lavas are visible to the south from the lookout atop Sugarloaf Mountain. They form the east-west ridge line south of Pinery Canyon, and extend to the south along the crest of the Chiricahua Mountain range. A dramatic exposure of the flow-ramped moat lava can be seen in the hillside above and just south of Dawings Pass on the Methodist Camp road, a side road south of the Pinery Canyon road between the National Monument and Portal, Arizona.

The topography of the Chiricahua Mountains, and the appearance of the Turkey Creek volcano has changed dramatically over the past 27 million years. Steep faults cut the rocks and dropped large blocks down out of sight to form the San Simon Valley to the east and parts of the Sulfur Springs Valley to the west. The steep Whitetail Valley at the eastern boundary of the Monument (where the paved road to Sugarloaf Mountain and Massai Point turns south after ascending Bonita Canyon) is parallel to a fault zone along which adjacent crustal blocks have repeatedly shifted. The most recent motion appears to have dropped a block on the east side down, forming Whitetail valley and dragging the Rhyolite Canyon Tuff down into the valley, such that the formerly horizontal welded pumice fiame (white streaks in the rocks) now plunge steeply into the valley.

Steep faulting during the past 20 million years is not restricted to the Chiricahua Mountains. This is just a small part of the faulted *Basin and Range Province* of the

Southwest. In essence, subduction off the western coast of North America ceased as the former East Pacific ocean ridge ran into the subduction zone. This shut down the process of subduction, and the motion of the plates shifted to *strike-slip faulting* as the San Andreas fault was born in California. Because subduction ceased, most volcanism in the Southwest waned, and the crust began to extend through thermal relaxation. *Graben blocks* dropped to form valleys between mountain ranges. Because the graben blocks are shaped like keystone blocks in the arches of doorways, the adjacent crust could extend, or be pulled apart, as they sank. This is the kind of structure most common in the Chiricahua Mountains. Nearby, in the Pinalino and Rincon-Santa Catalina Mountains, crustal extension was also accommodated by low-angle faulting, in which adjacent blocks slid laterally as the crust was pulled apart and thinned. Small amounts of basalt magma leaked from the underlying mantle during this extension process, forming the San Bernadino volcanic field along the southeastern flank of the Chiricahua Mountains. These basalt cinder cones, lavas, and small explosion craters are clearly visible from US highway 80 between Rodeo, New Mexico, and Douglas, Arizona.

As noted above, the columns, or pinnacles, for which the National Monument is known, are erosional features that formed as the welded tuff layer was dissected by water and wind. But, why did erosion form such spectacular columns? Geologists agree that systematically spaced fractures, known as *joints*, played a key role. When walking in the Monument, you will recognize the joint planes both as thin planar fractures or veins in the rock, and by the alignment of columns in rows. Erosion was "focussed" along the joint planes, thereby slicing the tuff into columns, as illustrated in the exhibits at Massai Point. But, how did the joints form in the first place? Recent study by geologists from the University of Arizona has shown that contrary to previous ideas, the joints were not produced because the tuff was fractured between faults, as if in a vise. If that were the case, one would expect to see a systematic pattern in the orientation of the joints. Instead, the joint directions vary widely and they curve, features that indicate they resulted mainly from contraction brought about by the original cooling of the tuff. Rock shrinks upon cooling and the space is made up by formation of cracks, or joints. Cooling joints are common in lava flows; a spectacular example is Devil's Postpile National Monument, in California. Similar *columnar joints* are also recognized in welded tuff layers, such as in the rhyolite tuff cliffs of Bandelier National Monument, New Mexico.

How old are the columns, and why don't they fall over? Although the welded tuff and its joints are 27 million years old, the columns we see are thought to be less than three million years old. This age is based on calculating how much material has been removed from the Rhyolite Canyon basin over the past 27 million years to obtain an erosion rate (it works out to about two-thirds of an inch of downcutting per thousand years). Applying this rate to the average column height of 120 feet yields 2.4 million years. Surprisingly, the columns are quite strong, and even the "balanced rocks" are not as fragile or precarious as they appear. Engineering analysis shows that the columns are well within their mechanical failure limits for static load; they are not about to fail under their own weight. In fact, the 187 foot-high Totem Pole could be suspended upside-down like a *stalactite* without breaking. Dynamic failure is more likely, in which columns would be"knocked over" by a lateral force. Lateral forces occur during earthquakes, but surprizingly, few of the columns appear to have been destroyed by the magnitude 7.2 Pitaicachi earthquake of 1887, dispite widespread damage to buildings in the region. Perhaps, a "tuned" frequency of earthquake ground waves is required to get the columns swaying enough to fall?

Glossary

accreted- With respect to plate tectonic theory, the process by which continental crust grows through the addition of smaller fragments of crust to its margins. An *accreted terrane* is a fragment of crust that was transported by plate tectonic processes and added to the margin of a continent. Much of the western US is composed of accreted terranes.

accretionary lapilli- Lapilli are small, approximately 0.1" to 2.5" (2 mm - 64 mm), spherical balls of ash that accrete, or stick, to water droplets or crystals during a volcanic eruption. They are often concentrically layered, like hail balls, as a result of repeated accretion of layers of ash.

ash- Very fine grained volcanic "dust" composed of broken particles of volcanic glass and crystals, and rock fragments. Commonly dominated by microscopic shards of glass produced by breakage of gas bubbles in the source magma.

ash flow- A density current composed dominantly of hot ash and pumice. Moves rapidly due to liberation of gas from pumice and to ingestion of air at flow front. Produces an ash-flow deposit (tuff), that if sufficiently hot may weld to produce *welded-tuff.* A type of *pyroclastic flow.*

basalt-- A dark colored volcanic rock with less than 52% silica (expressed as SiO_2). Basalt is the most common volcanic rock on Earth, as it underlies most of the ocean basins, as well as forming large provinces on the continents, such as the Columbia River plateau of the Pacific Northwest in the US. Basalt is produced by melting of mantle rocks, and is widely viewed as the principal means of transporting mass and heat from the mantle to the crust.

batholith-- A large region of *plutonic* rocks with an area that is typically much greater than 40 square miles, such as the *granite* batholith of the Sierra Nevada in California. Most batholiths consist of many bodies of magma that were intruded during an extended period of time and represent the roots of *island arc* volcanic complexes.

Basin and Range Province-- A physiographic province of the western US composed of north or northwest trending mountain ranges separated by parallel valleys. Includes southeastern California, most of Nevada and Utah, and the southern parts of Arizona and New Mexico, as well as extending south into Mexico. Produced mainly during the last 20 million years by the extension of the crust after *subduction* ceased to the west.

caldera-- A volcanic depression larger than a crater, typically circular in outline, created by collapse of the roof of a magma chamber and brought about by rapid eruption of magma from the chamber. Calderas associated with the eruption of rhyolite tuff range from a few to as many as 60 miles in diameter.

columnar joints-- Planar or curvilinear fractures that bound polygonal columns of rock. Typically form during cooling of volcanic rocks due to contraction. Tend to form at right angles to cooling surfaces, therefore are typically vertical, except near valley walls.

cross bedding-- Bedding in a sedimentary or volcanic rock in which individual beds intersect and truncate one another at outcrop scale. With respect to sedimentary rocks indicate presence of currents (in either wind or water) that scour older beds and deposit new beds across the scoured surface, leading to truncation of the older bedding. With respect to volcanic ash deposits, low angle cross bedding is indicative of high energy transport of particles in a lateral fashion, as seen in *surge* deposits.

dacite-- A volcanic rock with about 63% to 69% silica (expressed as SiO_2). Commonly contains the minerals hornblende and biotite, in addition to feldspar, and rarely quartz. A relatively common rock in volcanic arcs. Forms lava flows as well as pyroclastic rocks, including ash flow deposits.

fiame-- Italian for "flame". Refers to lens-shaped flattened pumice fragments in a welded tuff deposit. In cross-section such fragments commonly have jagged terminations, giving the appearance of flames. In the Rhyolite Canyon Tuff, pumice fiame are typically white and range in size from less than an inch to more than a foot in length and are commonly flattened to plate-shaped bodies with thicknesses less than 1/10 of diameter. The plates are typically horizontal as a result of flattening (deflation) of pumice blocks by gravity during cooling of the tuff.

flow ramp-- A sequence of layers in a lava flow that ramp abruptly upward, truncating layering in the adjacent and underlying lava. Produced in highly viscous materials as shear planes develop and allow transport more readily than internal flowage. Most common in high silica (rhyolite) lavas due to their high viscosity.

fumaroles-- Steam vents within volcanic rocks. Result from degassing after deposition of ash flow deposits, or from steaming of underlying wet ground.

graben block-- A block of rocks, typically more than several square miles in area and bounded by inwardly-dipping fault planes, in which the graben block moved down relative to the adjacent blocks, which are termed *horst* blocks. A keystone graben is a common configuration, in which the block has the general shape of the keystone block in an archway. Extension may be accommodated by formation of a horst and graben structure in which the grabens move down relative to the adjacent horsts, as would the keystone in an archway, if the arch was pulled apart.

graded bedding-- The normal stacking of grains in a sedimentary or volcaniclastic rock in which larger and heavier grains underlie smaller and lighter grains. The result of gravitational settling of particles in a fluid. *Inverse grading* is the opposite sense of stacking, with larger grains above smaller ones. This implies the presence of a boundary layer force that "pushes" large particles upward, such as would be present due to shear forces during rapid lateral flow. Inverse grading is a characteristic feature of base surge deposits.

granite-- A high silica rock (typically with more than 70% silica, expressed as SiO_2) made up mainly of coarse grained crystals of quartz and feldspar. The compositional equivalent of the volcanic rock *rhyolite*, but cooled slowly at depth such that all of the magma crystallized and no glass remains. Magmas that cool slowly and crystallize at depth are termed plutonic rocks. They tend to form large oval masses that cover several square miles or more. Where numerous plutons coalesce, the resultant body of plutonic rock may cover hundreds of square miles, and is termed a *batholith.*

igneous rock-- One of the three major divisions of rock types (*igneous*, *sedimentary*, and *metamorphic*). Refers to rock "born of fire", i.e., crystallized or quenched to glass directly from molten rock (*magma*). When magma is erupted on the surface it cools to fine grained volcanic rocks, when it cools slowly beneath the surface it forms *plutonic* rocks.

intruded-- The process by which a magma is emplaced into other rocks. The overlying or adjacent rocks may break, allowing the magma to move into fractures, or it may be melted and become a part of the advancing magma.

inverse grading-- See *graded bedding*.

island arcs-- Arcuate linear belts of volcanic islands that overlie subduction zones. Where such volcanic bands occur within a continental mass overlying a subduction zone, the term *volcanic arc* is used.

joints-- Planar fractures or cracks along which there has been negligible movement. May be produced by cooling (see *columnar joints*) or by a directed stress due to faulting or folding of the rock.

Laramide orogeny-- A period of mountain building (orogeny) marked by widespread faulting and volcanism at the close of the Mesozoic, about 65 million years ago.

magma-- Molten rock, a suspension of crystals in silicate liquid with dissolved volatiles such as water vapor and carbon dioxide. Common magmas range in composition from basalt, with less than 52% silica to rhyolite, with more than 70% silica.

magma chambers-- Reservoirs of molten rock beneath the Earth's surface. These crystallize at depth to produce coarse grained plutonic rocks.

mantle-- A division of the Earth, lying between the core, and the crust. The upper part of the mantle is composed of magnesium and iron rich silicate minerals, such as olivine and pyroxene. The depth to the mantle varies from less than 6 miles beneath young ocean crust, to as much as 60 miles beneath continents. Mantle rocks, known as peridotites exist at high temperature and deform slowly as if they were plastic. They flow in response to the broad convection currents that drive *plate tectonics*. Where these mantle rocks upwell, they begin to melt, yielding magma that can rise toward the surface to fill magma chambers and feed volcanoes.

metamorphic rock-- One of the three major divisions of rock types (*igneous*, *sedimentary*, and *metamorphic*). Refers to rock that is recrystallized or mechanically reconstituted (metamorphosed) due to the effects of heat and pressure within the Earth.

moat-- A circular depression between the central resurgent dome and the edge of a caldera depression.

nuée ardante-- A "glowing cloud" of hot ash that rises from an avalanche of volcanic ash and rock fragments. The ash cloud and related avalanche are a type of *pyroclastic flow* produced by the collapse of the oversteepened front of a viscous lava dome and from explosions the emanate within the underlying magma. These flows generally produce relatively small-volume, ash- and rock fragment-rich deposits that lack abundant pumice and do not weld. The term was coined to describe the glowing cloud that swept down from the base of the lava dome atop Mount Pelée, Martinique on May 8, 1902 and killed 30,000 people in the town of Saint Pierre. Subsequent avalanches produced clouds of hot ash that glowed dull red at night. Also used to describe the large-volume, pumice-rich, pyroclastic flows produced by much larger caldera-forming eruptions of the type that give rise to welded tuff deposits. However, this usage is now disfavored and the term is restricted to relatively small volume pyroclastic flows produced by collapse of an actively growing lava flow or dome.

porphyry-- A volcanic or plutonic rock that has large crystals set in a finer grained matrix. The dacite porphyry of the Turkey Creek caldera is both a shallow plutonic rock produced by intrusion of dacite magma into the floor of the caldera shortly after it collapsed, and thick lava flows that accumulated in the floor of the caldera *moat.*

pillow lava-- Lava that flowed under water and formed pillow-shaped masses as a consequence of chilling and solidification of the outer surface while the inner part of the lava flow was still flowing. Usually basalt or andesite in composition; the most common type of lava in oceanic crust.

plate tectonics-- A unifying theory that explains how the fundamental processes affecting the Earths crust operate. Based on slow thermal convection of the Earth's mantle, which leads to generation of oceanic crust by decompression melting in zones of upwelling at ocean ridges and destruction of that crust where it and underlying cooled mantle sinks at *subduction zones.* Oceanic crustal plates float on the underlying mantle as it moves like a conveyor belt from mid-ocean ridges to subduction zones. The continents drift about the globe as a consequence of being caught between the conveyor belts of spreading ocean ridges and subduction zones. Mountain belts form where continents collide, and volcanic arcs grow above subduction zones where melting is enabled by dehydration of the downgoing plate. Strike-slip faults, like the San Andreas fault form where the collision of crustal plates is oblique and the plates slide past one another.

plutonic-- Refers to a coarse-grained *igneous* rock that crystallized slowly beneath the Earth's surface.

Precambrian Era- A broad division of geologic time extending from initial formation of the Earth at about 4.5 billion years ago to the beginning of the Cambrian Period at about 570 million years ago.

pumice-- A gas bubble-rich volcanic rock; typically with enough bubbles to allow it to float in water. Also used to describe fiame in welded tuff, which represent pumice blocks that were flattened and deflated during welding.

pyroclastic flow-- A dense cloud of hot ash, rock debris, pumice and gas that moves rapidly downslope from a volcano and leaves an ash-rich deposit (a pyroclastic flow deposit). Pyroclastic flows move rapidly because they are inflated by volcanic gas and by air ingested at the flow front. If sufficiently hot and thick, the resultant deposit may weld. Welded tuff, ash-flow tuff, nuée ardante deposits, and block and ash flows are all types of pyroclastic flow deposits.

resurgent dome-- A domal region of uplift within a caldera depression. Caused by intrusion of new magma into shallow levels within or beneath the caldera.

rhyolite-- A chemical class of volcanic rock or magma with more than about 70% SiO_2. Rhyolite rock is usually light grey or white in color, but may be black if quenched to glass (obsidian), and can be a variety of other colors as a result of alteration. Commonly contains crystals of quartz and alkali feldspar. *Granite* is the *plutonic* equivalent of rhyolite, in which slow cooling produces large crystals.

schist-- A metamorphic rock that is rich in the platy mineral mica. The mica grains are aligned by deformation yielding internal layering and a shiny appearance to the rock.

sedimentary rocks-- One of the three major divisions of rock types (*igneous*, *sedimentary*, and *metamorphic*). Refers to rocks such as sandstone that are made up of mineral grains and rock fragments deposited by water or wind, and rocks such as limestone that precipitated from water.

stratigraphic unit-- A particular rock deposit or group of deposits that are generally similar in composition or type, and were produced at about the same time. Stratigraphic units are the fundamental building blocks for constructing geologic maps.

subduction-- A fundamental component of *plate tectonics* theory. The process by which oceanic crust is destroyed by sinking into the mantle along an inclined *subduction zone.* These zones occur within the ocean basins and along continental margins where they produce numerous earthquakes as the oceanic crustal plate slides down beneath the adjacent oceanic or continental plate. Subduction zones are sometimes marked by ocean trenches, such as the Marianas Trench. Fluids are liberated from the sinking plate as it is heated at depth. These fluids act as a flux to help melt overlying rocks, producing magma that supply volcanoes on the surface. Volcanic arcs overlie subduction zones, typically in a linear belt or arc; arcs form above the area where the subducted plate reaches a depth of about 60 miles..

surge beds-- Ash-rich beds that result from laterally-directed volcanic blasts. Characterized by *inverse grading* and low angle *cross bedding.*

tuff-- A volcanic rock made up of ash, pumice, and rock fragments, typically derived from a *pyroclastic flow*, but may also include deposits that accumulate from the "rain" of ash and debris after an eruption.

unconformity-- A surface separating two rock deposits of distinctly different age, such that a significant period of geologic time is missing from the rock record between the two deposits.

welded tuff-- A *tuff*, typically produced from a *pyroclastic flow* that was sufficiently hot and thick for individual glass shards to have fused together and for pumices to have deflated and to have been flattened under the weight of the deposit.

Acknowledgements

This report is the result of cooperation between the staff of Chiricahua National Monument and scientists from the U.S. Geological Survey and the University of Arizona. We especially thank Dick Anderson, and Carol Kruse for providing logistical and moral support during our work in the Monument, and we thank Roy Simpson for suggesting that we write this report. This report updates and expands unpublished reports written by National Park Service staff members Richard P. Yetman in 1974, and Michelle Lamb in 1992. The discussion of formation of rock joints in this report is based on research by Douglas B. Hall of the University of Arizona. Our work in the Chiricahua Mountains has been made possible through the cooperation of numerous ranchers and landowners. In the National Monument area, we especially thank Jim Riggs for land access.

Suggested additional reading

General geology

Cronic, Halka, 1986, Roadside Geology of Arizona, Mountain Press, Missoula, 321 pages (guide to geologic features in Arizona, *introductory level*).

Press, Frank, and Siever, Raymond, 1974, Earth, W. H. Freeman and Company, San Francisco, 943 pages (geology textbook, *introductory level*).

Rhodes, Frank H. T., 1991, Golden Guide to Geology: Golden Press (Western Publishing Co. Inc., Racine, 160 pages (overview of geology *introductory level*).
Sorrell, C. A., 1973, A guide to field identification of rocks and minerals, Western Publishing Co., Inc., Racine, 280 pages (field guide, *introductory level*).

Volcanology

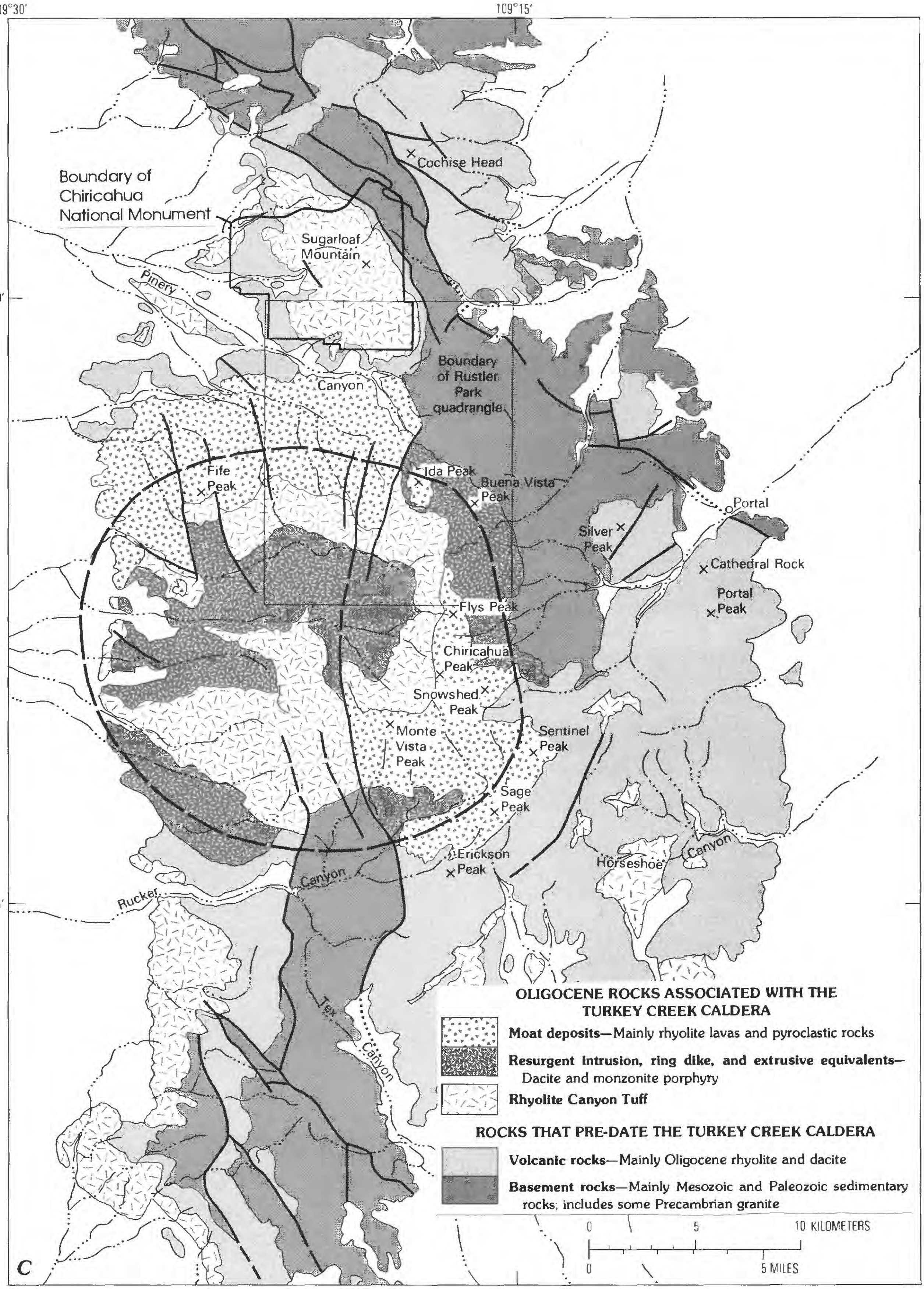
Cas, R. A. F., and Wright, J. V., 1988, Volcanic Successions, Modern and Ancient: Unwin Hyman, Boston, 528 pages (*college level* textbook, emphasis on physical volcanology and sedimentology).
de Golia, Jack, 1989, Fire: The story behind a force of nature, K.C. Publications, Las Vegas, 48 pages (volcanology for the non-specialist, *introductory level*).
Harris, Stephen L., 1990, Agents of chaos, 1990, Mountain Press, Missoula, 260 pages (volcanology for the non-specialist, *introductory level*).
Macdonald, Gordon A., 1972, Volcanoes: Printice Hall, Englewood Cliffs, New Jersey, 510 pages (*introductory level* textbook with narratives of eruptions and numerous examples of volcanologic phenomena).
Williams, H., and McBirney, A. R., 1979, Volcanology, Freeman, Cooper and Company, San Francisco, 397 pages (*college level* textbook, emphasis on petrology, physics and chemistry).

Turkey Creek Caldera

du Bray, E. A., and Pallister, J. S., 1991, An ash-flow caldera in cross section: Ongoing field and geochemical studies of the Mid-Tertiary Turkey Creek caldera, SE Arizona: Journal of Geophysical Research, v. 96, no. B8, p. 13435-13,457 (*technical paper*).
du Bray, E. A., and Pallister, J. S., in press, Geologic Map of the Chiricahua Peak quadrangle: U.S. Geological Survey Geologic Quadrangle Map, scale 1:24,000, 1 plate (*technical* geologic map).
du Bray, E. A., and Pallister, J. S., in press, Geologic Map of the Stanford Canyon quadrangle: U.S. Geological Survey Geologic Quadrangle Map, scale 1:24,000, 1 plate (*technical* geologic map).
Pallister, J. S., and du Bray, E. A., 1989, Field guide to volcanic and plutonic features of the Turkey Creek caldera, Chiricahua Mountains, southeast Arizona: in Chapin, C. E., and Zidek, J., eds., Field excursions to volcanic terranes in the western United States, Volume I: Southern Rocky Mountains region: New Mexico Bureau of Mines and Mineral Resources Memoir 46, p. 138-157 (fieldtrip guidebook, *college level*, for the professional geologist or student).
Pallister, J. S., du Bray, E. A., and Latta, J. S. IV., in press, Geologic Map of the Rustler Park quadrangle, southeast Arizona: U.S. Geological Survey Geologic Quadrangle Map GQ-1696, scale 1:24,000, 1 plate (*technical* geologic map).
Pallister, J. S., and du Bray, E. A., in press, Geologic Map of the Fife Peak quadrangle, southeast Arizona: U.S. Geological Survey Geologic Quadrangle Map, scale 1:24,000, 1 plate (*technical* geologic map).

Pallister J. S., and du Bray, E. A., in prep., Geologic Map and field guide to the geology of Chiricahua National Monument: U.S. Geological Survey Miscellaneous Investigations Map (*introductory level* geologic map of the National Monument with illustrations and notes for the visitor or hiker).

Figure 1. Simplified geologic map of the Chiricahua Mountains and Chiricahua National Monument. The dashed circle outlines edge of the depression formed by the Turkey Creek volcano. The region within this circle was a giant collapse crater, a *caldera,* that formed 27 million years ago during the eruption that produced the Rhyolite Canyon Tuff, which was deposited in Chiricahua National Monument and south of the caldera. *Dacite porphyry* is magma from a deeper part of the same magma chamber that produced the Rhyolite Canyon Tuff. The dacite *magma* intruded and uplifted the floor of the caldera shortly after eruption of the tuff. This uplift produced a *resurgent dome*, and the dacite porphyry is known as a resurgent intrusion. Some of the dacite magma leaked to the surface and formed dacite porphyry lava flows adjacent to the growing resurgent dome. Rhyolite moat lavas were erupted later, after the resurgent dome formed, and filled the topographic *moat* between the dome and the edge of the caldera.



109°30′
109°15′
32°00′
31°45′
Boundary of
Chiricahua
National Monument
Cochise Head
Sugarloaf
Mountain
Pinery
Canyon
Boundary
of Rustler
Park
quadrangle
Fife
Peak
Ida Peak
Buena Vista
Peak
Portal
Silver
Peak
Cathedral Rock
Portal
Peak
Flys Peak
Chiricahua
Peak
Snowshed
Peak
Monte
Vista
Peak
Sentinel
Peak
Sage
Peak
Erickson
Peak
Horseshoe
Canyon
Rucker
Canyon
Tex
Canyon
OLIGOCENE ROCKS ASSOCIATED WITH THE TURKEY CREEK CALDERA
Moat deposits—Mainly rhyolite lavas and pyroclastic rocks
Resurgent intrusion, ring dike, and extrusive equivalents—Dacite and monzonite porphyry
Rhyolite Canyon Tuff
ROCKS THAT PRE-DATE THE TURKEY CREEK CALDERA
Volcanic rocks—Mainly Oligocene rhyolite and dacite
Basement rocks—Mainly Mesozoic and Paleozoic sedimentary rocks; includes some Precambrian granite
0
5
10 KILOMETERS
0
5 MILES
C

Figure 1.