National Park Service
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Natural Resource Program Center

Saguaro National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/233

THIS PAGE:
A Saguaro silhouette stands before the glow of a peerless Arizona sunset.

ON THE COVER:
View from Amole Peak over the Tucson Mountain District. This district of the park offers excellent exposures of the Tucson Mountains Caldera, the eroded remains of a colossal volcanic eruption that occurred approximately 70 to 75 million years ago.

National Park Service photographs.

Saguaro National Park

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Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
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Natural Resource Program Center
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Executive Summary

This report accompanies the digital geologic map data for Saguaro National Park in Arizona, produced by the Geologic Resources Division in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Saguaro National Park consists of two districts, the Tucson Mountain District, west of Tucson, and the larger Rincon Mountain District, east of Tucson. The two districts contain markedly distinct geology, although they experienced the same general types of structural deformation and depositional environments through time. The Tucson Mountain District offers excellent exposures of the Tucson Mountains Caldera, the eroded remains of a colossal volcanic eruption that occurred approximately 70 to 75 million years ago. The Rincon Mountain District provides one of the best exposures of a metamorphic core complex in western North America and contains features critical to understanding how metamorphic core complexes evolved. The regional landscape of both districts evolved as part of the Basin-and-Range province, a tectonic terrain developed during extensional ("pull-apart") faulting about 15 million years ago.

At a Geologic Resource Inventory scoping meeting held at Saguaro National Park in April 2006, geologic issues, features, and processes significant to park management were identified. Priority issues associated with hydrogeology and abandoned mining impact both districts.

Groundwater extraction from sources outside the park poses a potential threat to riparian ecosystems in the Rincon Mountain District and to groundwater availability in the Tucson Mountain District. Riparian areas in the Rincon Mountain District that may be susceptible to groundwater withdrawal include Rincon Creek, lower Box Canyon, and the lower reaches of the drainages feeding Tanque Verde Wash. While the Rincon Mountain District is connected to Tucson Water, Tucson Mountain District's domestic water supply is dependent on a well in the extreme southwestern corner of the park. Water levels in this well are impacted by groundwater extraction from a private well located near the boundary of the park.

Abandoned mineral lands have been identified in the park. The Gould and Mile Wide mines were the two largest operations while the Old Yuma Mine produced world-class mineral specimens. The shafts and adits in the park's database have been mapped, photographed, and measured; however, some mining issues remain. Migration of contaminants from soil to groundwater seems unlikely, but potential migration pathways exist in both surface water runoff and airborne dust. Thus, safety measures have been installed at all three mines.

Other issues affecting Saguaro National Park include: the destruction of tinajas; flooding and debris flows; headcut migration; additional mapping in the Rincon Mountain District; and recognition of archaeology sites. The Rincon Mountain District offers the only exposure of the Santa Catalina Fault that is not located on private land; an interpretive trail that would allow access to this exposure was discussed at the scoping meeting and has been included in the park's 2009 trail management plan. Tinajas, ephemeral pools important for wildlife, fill with sediment from erosion after wildfires, and thus are impacted for many years. Debris flows generated by flash flooding may impact roads. Road construction has led to headcut migration and subsequent erosion issues. Additional data suggest that mapping rock units west of the Santa Catalina Fault might provide better resolution for park managers. Mapping Quaternary deposits in Saguaro National Park could provide a way of identifying potential archaeology sites.

Both the Tucson Mountain District and the Rincon Mountain District contain features distinctive to the geological processes in the southwestern desert environment, such as pediments, alluvial fans, bajadas, and rock varnish. In addition, tectonic and depositional features that represent various plate tectonic episodes are present in both districts. Pre-volcanic, volcanic eruption, caldera collapse, and post-caldera history are recorded in the rocks in the Tucson Mountain District. Intrusive dikes, igneous plutons, and volcanic tuffs are prevalent throughout the park. The Rincon Mountain District exposes the complex history of a metamorphic core complex and contains one of the few exceptional exposures of the Santa Catalina Fault available in the Catalina and Rincon Mountains. Deformation and normal faulting related to the extensional tectonics that formed the present-day Basin-and-Range topography in the southwestern United States left features that impacted all of the previous deformation events in both districts.

Saguaro National Park provides a window into a tectonic and depositional history that spans 1.6 billion years. Rocks in the park reveal the history of a continent being developed in the Precambrian, oceans covering southeast Arizona in the Paleozoic, volcanic upheaval and mountain-building events in the Mesozoic, and continental rifting in the Cenozoic. Recent uplift, downward-cutting streams, faulting, and erosion have revealed this history in Saguaro National Park and record significant past geological processes that continue to impact the park.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service Inventory and Monitoring Program. The GRI is administered by the Geologic Resources Division of the Natural Resource Program Center.

The Geologic Resources Division relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

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Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Saguaro National Park.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The GRI, administered by the Geologic Resources Division of the Natural Resource Program Center, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory web site (http://www.nature.nps.gov/geology/inventory/).

Regional Location and Geologic Setting

Saguaro National Park consists of two physically separate park areas that straddle the city of Tucson (fig. 1). The Tucson Mountain District, west of Tucson, is the smaller of the two units. Wasson Peak, the highest point in the Tucson Mountain District, rises 1,429 m (4,687 ft) above sea level. The larger Rincon Mountain District, located on the eastern outskirts of Tucson, contains the much higher Mica Mountain (2,642 m [8,666 ft]). The two units of Saguaro National Park comprise 37,004.34 ha (91,439.71 ac), which includes 28,694 ha (70,905 ac) of wilderness.

Saguaro National Park lies within the Mexican Highland and Sonoran Desert section of the Basin-and-Range Province, a geological province that extends from southeastern Oregon to northern Mexico (fig. 2). While the two units contain markedly different geology (fig. 3), they experienced the same general types of structural deformation and depositional environments through time—e.g., intrusion of Precambrian granite; deposition of mostly marine sediments during the Paleozoic; extensive erosion in the Mesozoic; compression during the Laramide Orogeny (mountain-building event) of the Late Cretaceous to Tertiary; volcanism, crustal stretching, and fault-block mountain formation from the mid-Tertiary to the present (Kiver and Harris 1999). Tucson has developed on the relatively flat surface of the structural basin that separates the two mountain ranges.

Refer to the glossary for definitions of geologic terms and to fig. 16 for a geologic timescale.

Rincon Mountain District (Saguaro–East)

The Rincon Mountain District lies at the foot of the Rincon Mountains, part of a large three-humped metamorphic core complex. Unique to the mountainous North American Cordillera, metamorphic core complexes consist of metamorphosed basement rocks overlain by unmetamorphosed rock units. The two structures are separated by a shallowly-dipping detachment fault (called a "décollement"), which displaces the overlying units up to several kilometers. Outcrops along Cactus Forest Drive are considered to be the "showpiece" of diagnostic features of metamorphic core complexes, and the geology of the Rincon Mountain District served as the basis for distinguishing and classifying the fundamental structural characteristics of metamorphic core complexes (Davis 1987).

In general, the metamorphic core complex in the Rincon Mountain District consists of a dome-shaped granite pluton overlain by severely stretched and microfractured granitic, sedimentary, and volcanic rocks. The low-angle Santa Catalina detachment fault separates the underlying metamorphic rocks (gneiss) from a variety of rock types including highly faulted, brittle layers of Paleozoic rocks (fig. 4). The convex-up fold ("antiform") in the Tanque Verde Ridge is shaped like a mountain-sized turtle shell, which plunges southwesterly toward the park headquarters (fig. 5) (Davis 1987; Kiver and Harris 1999; Bezy 2005).

Rock layers that once covered the crest of the Rincon Mountains have been eroded by downward cutting streams. Continued erosion by running water along joints and faults have cut canyons into the hard gneiss. Beveled rock platforms, called pediments, formed from erosion of granite at the foot of the mountain. A thin veneer of rock debris, much of it delivered by flash floods, covers most of the pediments (Bezy 2005).

Tucson Mountain District (Saguaro–West)

The Tucson Mountains are part of the Basin-and-Range province, a region of crustal extension in which mountain blocks were pulled apart and sediments filled the basins that formed between the blocks. The 30- by 15-km (19- by 9-mi) Tucson Mountains block separates Avra Valley (to the west) from the Tucson Basin (to the east) (Kring 2002).

The Tucson Mountains are also the eroded remnants of an extraordinary volcanic eruption that occurred about 70 to 75 million years ago (Bezy 2005). The eruption left a gigantic depression (caldera) about 20 to 25 km (12 to 15 mi) wide called the Tucson Mountains Caldera. In comparison, the caldera in Crater Lake National Park is 10 km (6 mi) in diameter.

The volcanic eruption and subsequent collapse of rock units into the Tucson Mountains Caldera left a heterogeneous jumble of large blocks of Precambrian schist, Paleozoic limestone, Mesozoic sedimentary rocks and Tertiary volcanic rocks ("megabreccia") (Lipman 1993; Jon Spencer, Arizona Geological Survey, personal communication, April 4, 2006). Irregular layers of Cretaceous and Tertiary volcanic rocks, deposited after the caldera collapse, overlie the megabreccia (fig. 3). Saguaro National Park offers an exceptional opportunity to study the cataclysmic events associated with this type of volcanic eruption.

A variety of igneous rocks are exposed in the Tucson Mountains. Tertiary volcanic rocks overlie and partly conceal Paleozoic and Mesozoic sedimentary strata that tilt to the east and are cut by high-angle normal faults. Hardened volcanic ash (tuff) forms cliffs from Cat Mountain in the south to Picture Rocks Road in the north (fig. 6). Solidified lava flows can be found in Tumamoc Hill, Twin Hills, and Safford Peak, and around the Yuma Mine.

Granitic exposures exist in the western portion of the Tucson Mountain District (Lipman 1993; Kring 2002). The Cretaceous Amole pluton, a coarse-grained, light-colored granitic intrusion, is exposed just west of both Wasson and Amole Peaks and forms the westward-jutting hills below the peaks. A normal fault separates Proterozoic granite from Paleozoic sedimentary rocks at Twin Peaks, outlying peaks surrounded by Quaternary alluvial fan deposits in the northwest part of the Tucson Mountain District (Lipman 1993).

Time has taken its toll on the Tucson Mountains Caldera. Downcutting streams have exposed the complex internal structures and plumbing system of the ancient volcano and caldera. Erosion has removed the walls of the caldera and most of the lava and volcanic ash that flowed from the caldera and solidified along its flanks. Flash floods and mudflows have transported the eroded rock material into the adjacent basins.

Tucson Basin

The Tucson Basin lies between the Tucson Mountains to the west and the Rincon and Santa Catalina Mountains to the east. It is a portion of the upper Santa Cruz Basin, a valley draining to the northwest. Tucson, Arizona is located in the center of the 2,590-sq-km (1,000-sq-mi) Tucson Basin, and lies at an elevation of 700 m (2,300 ft). A groundwater divide between the upper and lower Santa Cruz Basins exists near the town of Cortaro (Burkham 1970; Mott 1997).

Tertiary and Quaternary basin deposits may be as much as 2,400 m (8,000 ft) thick. Basin fill consists of fluvial, lacustrine, and debris flow deposits eroded from the surrounding mountains and ranges farther up the drainage. Alluvial fan deposits occur along the perimeter of the basin, while river channel and flood plain deposits are common in the center of the basin. The occurrence and movement of groundwater in the basin is controlled by the lithology, porosity, and permeability of the sediments.

Park History

Humans occupied the Saguaro area as long as 10,000 years ago (Clemensen 1987). The area experienced much wetter conditions than currently, so the habitat could support mammoths, bison, and other such mammals. About 2,100 years ago, the Hohokam people settled in the Santa Cruz Basin. The origins of human occupation in the Tucson Mountains are not clear, but the Hohokam developed an extensive community in the area between 1100 and 1300 C.E. (Common Era; "A.D.") (Kring 2002). That community, known as the Marana Platform Mound community, contained a large (45- by 60-m [150- by 200-ft]) structure that provided the Hohokam with a clear view of the Santa Cruz Basin. The Hohokam built farms; quarried rock for tools; built ball courts, irrigation canals, and large firepits around the platform mounds; and carved petroglyphs in the region's cliffs and boulders.

Piman villages replaced the Hohokam communities that were abandoned in the 1400s for obscure reasons. On the eastern edge of the Tucson Mountains, one of these villages was built at the base of Sentinel Peak along the banks of the Santa Cruz River. Another, possibly large, village was built in the vicinity of what is now called the Del Bac Hills or Black Mountain near the south end of the Tucson Mountains.

Padre Eusebio Kenio was the first European to visit the area, in 1694 (Clemensen 1987). The Pima (now Tohono O'odham) communities that he encountered practiced a lifestyle based on cultivation and hunting.

Wanting better control of the territories he claimed, King Carlos II of Spain built presidios (walled garrisons) throughout what is now northern Mexico and the southwestern United States. By 1783, the presidio of Tucson was built along the Santa Cruz River. Tucson is a derivative of the Pima word "Stjukshon," which described the location of their village as a "spring at the foot of a black mountain." The phrase referred to the Santa Cruz River at the base of Sentinel Peak.

The presidio changed hands twice after its completion—first in 1821 when Mexico gained its independence from Spain, and again in 1853 when the United States purchased the region under the terms of the Gadsden Treaty (Kring 2002). With the cessation of the Apache raids, local population increased. Access to the area improved with the arrival of the Southern Pacific Railroad in 1879. Between 1870 and 1890, cattle grazing increased, leading to overgrazing (Clemensen 1987).

Copper was discovered in the nearby Silver Bell Mountains in the 1870s, and this led to mineral exploration in the Tucson Mountains. The mountains are now riddled with prospectors' pits. Several mines were opened including the Gould Mine and the Mile-Wide Mine near King Canyon. By 1912 the Gould Mine was closed. By 1918, the Mile-Wide Mine was closed, although it was reopened briefly in 1943. Fairly extensive mining camps surrounded both of these mines.

Realizing that the natural beauty of the land was worth more than its mineral resources, some Tucson residents began lobbying for a special park. In the 1920s, plans were made to set aside 24,300 ha (60,000 ac) for the park. In 1929, an area of 11,731 ha (28,988 ac) was designated as the Tucson Mountain Park, which was to be administered by Pima County.

On March 1, 1933, the Rincon Mountain District was designated as Saguaro National Monument, and became the first national park or monument established to protect a species of plant: the giant saguaro cactus (inside front cover). The saguaro cactus can grow over 15 m (50 ft) tall and can weigh over 5 tons. President John F. Kennedy added 6,216 ha (15,360 ac) of the Tucson Mountain District to the monument in 1961. Roughly 8,500 ha (21,000 ac) were later added to this district. On October 20, 1976, 28,694 ha (70,905 ac) of the park were designated as a wilderness area. The monument became the nation's 52nd national park in a bill signed by President Bill Clinton on October 14, 1994.

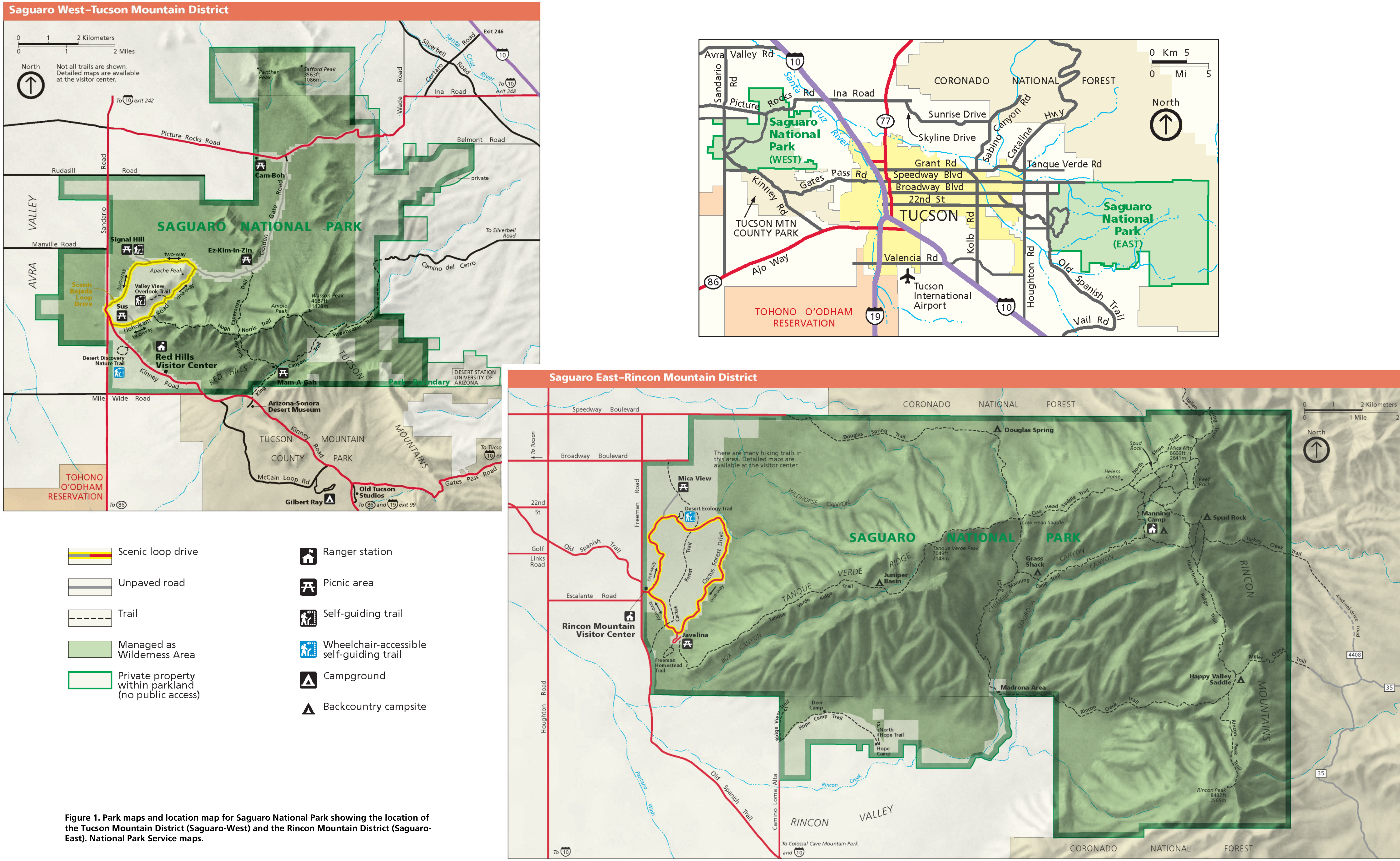


Figure 1. Park maps and location map for Saguaro National Park showing the location of the Tucson Mountain District (Saguaro-West) and the Rincon Mountain District (Saguaro-East). National Park Service maps.

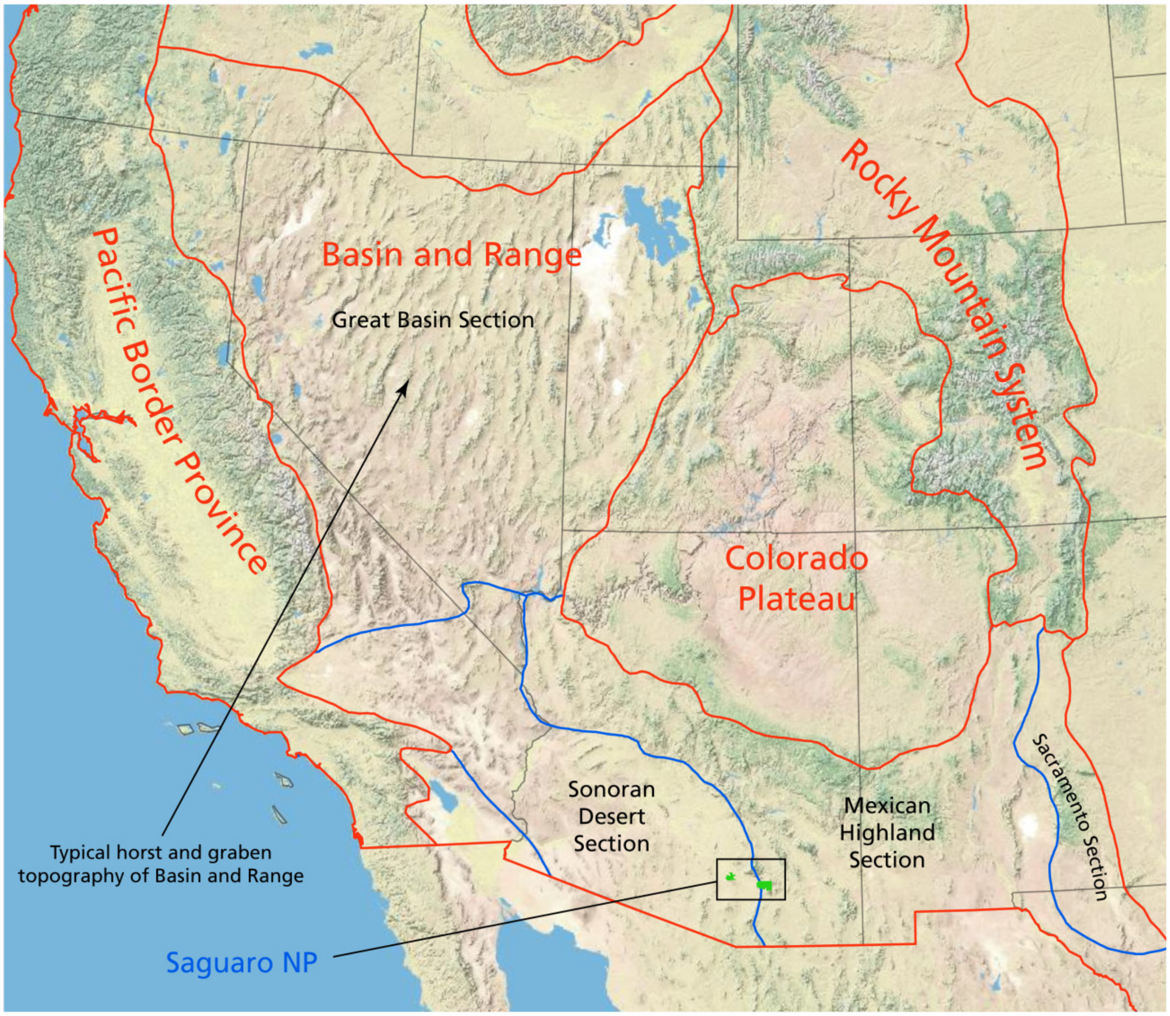
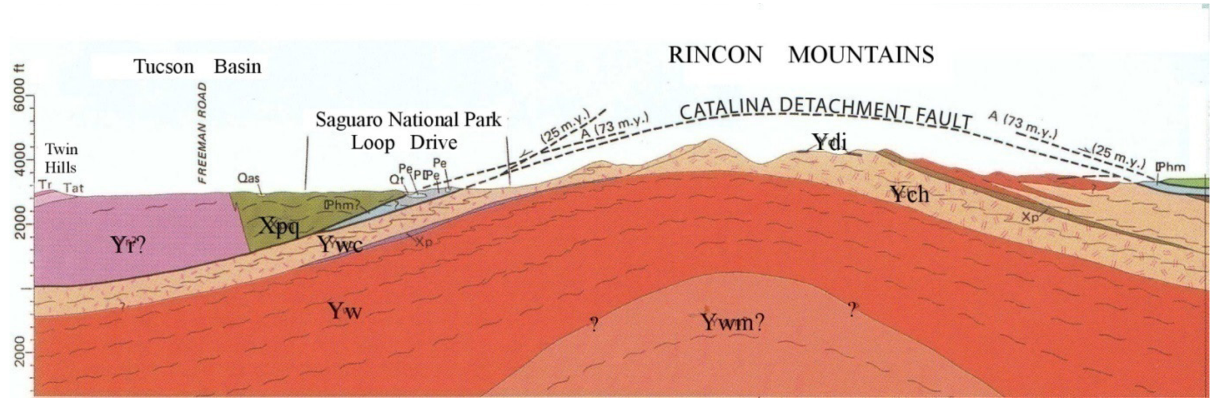


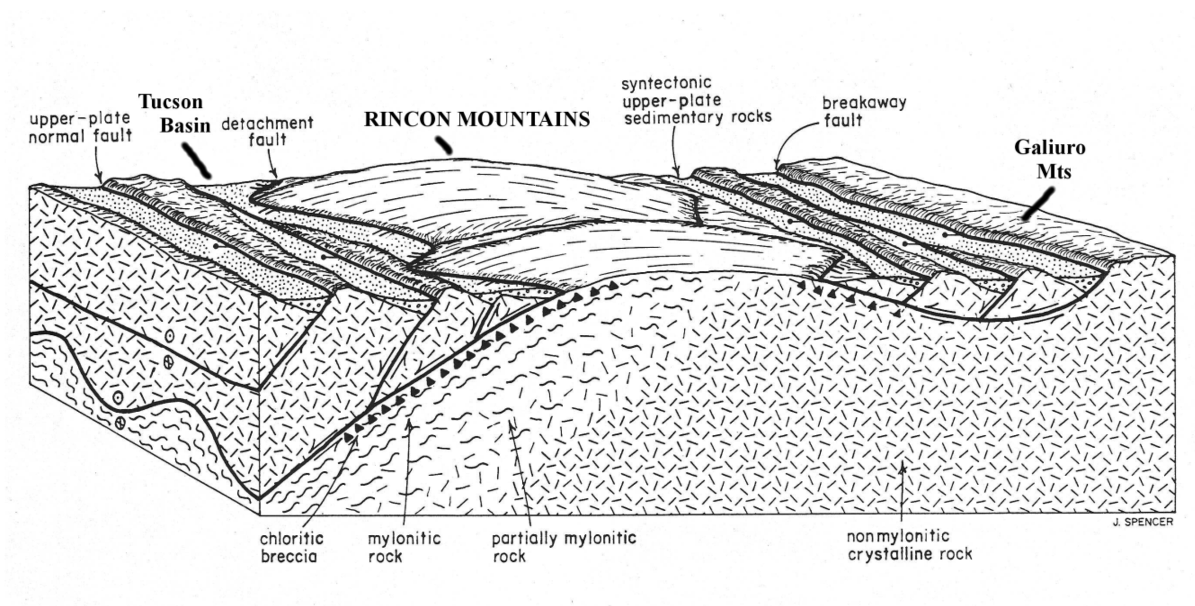
Figure 2. Landform map of the Southwestern United States illustrating the roughly parallel horst (range) and graben (basin) topography typical of the Basin-and-Range Province. Saguaro National Park lies within the Mexican Highland and Sonoran Desert portion of the Basin-and-Range. Compiled by Phil Reiker (NPS Geologic Resources Division) from ESRI Arc Image Service, National Geographic Society TOPO Imagery.

Era	Period (epoch)	Tucson Mountain District Unit Name	Tucson Mountain District General Description	Rincon Mountain District Unit Name	Rincon Mountain District General Description
Cenozoic	Quaternary (Holocene)	Alluvium and colluvium	Unconsolidated silt, sand, gravel.	Alluvium	Unconsolidated silt, sand, gravel.
		Alluvial-fan deposits	Gravel, sand, and silt. Local boulders.		
	Quaternary (Pleistocene)			Terrace gravel deposits	Gravel and sand.
	Neogene (Pliocene and Miocene)			Pediment, terrace and basin deposits	Cobbles, gravel, and sand.
				Pantano Formation	Pebble and cobble megabreccia to claystone.
	Paleogene (Oligocene, to Paleocene)	Safford Dacite	Volcaniclastic and lava units.	Igneous Units	Rhyolite and andesite.
Mesozoic	Cretaceous	Volcanic Units	Andesite dikes.		
		Amole Pluton	Granite, aplite, and granodiorite.		
		Volcanics of Yuma Mine	Rhyolite, dacite, and andesite lava flows.		
		Cat Mountain Tuff	Rhyolite tuff and megabreccia.	Bisbee Group	Shale, sandstone, some limestone.
		Amole Arkose	Feldspar-rich sandstone.		
		Tuff of Confidence Peak	Welded rhyolite tuff.		
		Volcanic Conglomerate	Cobble conglomerate.	Glance Conglomerate	Cobble and pebble conglomerate.
	Jurassic	Rhyolite tuff	Ash-flow tuff.		
		Sandstone	Sandstone		
		Recreation Red Beds	Red-brown mud- and siltstone.		
	Triassic				
Paleozoic	Permian	Scherrer Formation	Quartzite and sandstone.	Scherrer Formation	Quartzite and sandstone.
				Epitaph Dolomite	Cherty dolomite.
				Earp Formation	Marlstone, shale, and siltstone.
		Horquilla Limestone	Cherty limestone and siltstone.	Horquilla Limestone	Cherty limestone and siltstone.
	Pennsylvanian				
	Mississippian	Escabrosa Limestone	Cherty limestone with fossils.	Escabrosa Limestone	Cherty limestone with fossils.
	Devonian				
	Silurian				
	Ordovician				
	Cambrian			Abrigo Formation	Sandstone, shale.
				Bolsa Quartzite	Quartzite.
Precambrian	Proterozoic Eon			Wrong Mountain Quartz Monzonite (Catalina Gneiss)	Quartz monzonite stocks.
				Continental Granodiorite	Porphyritic granodiorite.
				Pinal Schist	Mica schist.
	Archean Eon				

Figure 3. Generalized stratigraphic column for rock units within the borders of Saguaro National Park. For ages of geologic time periods see fig. 16. Gray areas represent missing time between units (unconformity). Modified from Lipman (1993) and Drewes (1974, 1977).



A) Cross section view



B) Block diagram

Figure 4. Cross-sectional view (A) and block diagram (B) of the metamorphic core complex in the western Rincon Mountains. The Rincon Mountains form the "core" of the metamorphic complex. A) The cross-section shows the Catalina Detachment Fault and the rock units above and below the fault. The units that begin with the letters "Y" and "X" are Precambrian rocks. Other units include Permian (P), Pennsylvanian (lP), and Permian-to-Pennsylvanian (PlP) rocks. "Q" represents Quaternary sediments. The detachment fault separates Precambrian rocks below the fault (lower-plate) from Precambrian and younger rocks above the fault (upper-plate). B) Normal faults (where rocks above the fault move down relative to rocks below the fault) have offset rock units in the upper plate but do not penetrate below the detachment fault. "Mylonite" refers to rock that has undergone intense microbrecciation, fracturing, and shearing typically associated with a décollement. The digital geologic data (Appendix A) contains detailed cross-sections through the metamorphic core complex at Saguaro National Park. The Tucson Mountain District is believed to be part of a detached block that slid from the nearby metamorphic core complex. Cross-section view is modified from Bezy (2005). Block diagram courtesy of and modified from Jon Spencer, Arizona Geological Survey, written communication, April 2008.

Figure 5. Tanque Verde Ridge from the Loma Verde Trail, Rincon Mountain District, Saguaro National Park. The rounded turtle-shell shape of Tanque Verde Ridge is typical of the topography formed by a metamorphic core complex. Precambrian Wrong Mountain Quartz Monzonite and Continental Granodiorite (commonly known as Catalina Gneiss) forms the ridgeline. National Park Service photograph by Laura Bolyard (Saguaro National Park).

Figure 6. Welded tuff of the Cat Mountain Tuff forms cliffs at Gates Pass. The Cat Mountain Tuff contains welded tuff, nonwelded tuff, and megabreccia resulting from the Tucson Mountains Caldera. The welded tuff units of the Cat Mountain Tuff form cliffs, while the poorly fused deposits are less resistant to erosion and form slopes. Arizona Geological Survey photograph from Bezy (2005).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Saguaro National Park on April 6, 2006, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers. Contact the Geologic Resources Division for technical assistance.

The geologic issues section addresses geologic issues as they affect the ecosystem, their importance to park management, and the extent to which they are anthropogenically influenced. The following geologic issues, listed in order of priority, were discussed during the April 4, 2006 Saguaro National Park scoping session (Appendix B).

- Hydrogeology
- Abandoned mineral lands
- Establishment of an interpretive trail to the Catalina Fault
- Additional mapping in the Rincon Mountain District

Other geologic issues in the park include the effect of sedimentation on tinajas (ephemeral pools), flooding and debris flows, headcut migration due to past road construction, and recognition of archaeology sites in Quaternary deposits.

Hydrogeology

The most serious potential threat to the water resources of Saguaro National Park is excessive extraction of near surface groundwater from areas adjacent to the park (Mott 1997). Annual precipitation in the Tucson Basin averages 28 cm (11 in). Most of this precipitation occurs during two rainy seasons: July through September, and January through March. Intense thunderstorms take place from July through September, and gentle rains from January to March (Mott 1997; Kring 2002; Baker Jr. 2005). The region is an arid environment with an average potential evaporation of 229 cm (90 in).

Most of the surface water in the park drains into the north-flowing Santa Cruz River. The east flank of the Rincon Mountain District drains into the San Pedro River. The west flank of the Tucson Mountain District drains into Brawley Wash and the Avra Valley. Streams within the park are perennially intermittent or ephemeral. Groundwater often occurs near the surface along these water courses and provides for many areas of riparian habitat (fig. 7).

Tucson relies heavily on groundwater that is pumped from the deep Tucson Basin (Mott 1997). Groundwater occurs under unconfined conditions in alluvial deposits that generally form a single, hydraulically connected, aquifer system. Alluvial fan deposits occur along the perimeter of the basin, while the center of the basin contains river channel and flood plain deposits. In the center of the basin, coarse-grained fluvial deposits of gravel and well-sorted sand contain the highest permeability. Groundwater flows near the land surface along perennial streams; however, along the mountain fronts, groundwater may be more than 90 to 240 m (300 to 800 ft) deep (Mott 1997).

With population growth in the basin, water has become an increasingly valuable (and scarce) resource. In the past, the Santa Cruz River flowed all year through Tucson. Water now only flows in the river after an unusually heavy rain or snowmelt (Kiver and Harris 1999).

Increased temperatures and aridity associated with climate change will exacerbate water-use issues throughout the Southwest. The park has already experienced increases in shallow-rooted vegetation and may see a decrease in the habitable range of the Saguaro cactus (National Park Service 2010; Karl et al. 2009). Refer to Karl et al. (2009) for more detailed information and climate change projections for the Southwest. Also see the NPS Climate Change Response Program website: http://www.nature.nps.gov/climatechange/index.cfm (accessed May 4, 2010).

Drawdown in the wells supplying water to the city and Saguaro National Park is lowering the groundwater levels, causing the land surface to subside, and increasing concerns that large ground cracks will become a serious problem. Between 1947 and 1985, the majority of the Tucson area experienced groundwater declines of 12 to 24 m (40 to 80 ft). Throughout most of the Avra Valley, water levels declined by more than 30 m (100 ft) during the same period. Surface fissures along basin margins resulting from groundwater withdrawal may result in damage to agricultural facilities, roads, utilities and structures. However, because the Rincon Mountain District and the Tucson Mountain District are not located over the alluvial basins where settling would occur, aquifer compaction and land subsidence are not major issues for the park. Only in the extreme eastern and western portions of the Tucson Mountain District is there a potential for subsidence (Mott 1997).

Rincon Mountain District

The distinct and diverse riparian ecosystems in the Rincon Mountain District depend on near-surface groundwater. Thus, small water table declines or increased fluctuation in near-surface groundwater levels can negatively impact riparian habitats, which are especially crucial to avian populations. Riparian habitats have been recognized as some of the most important and most endangered ecosystems in the southwestern desert region (Mott 1997).

Three riparian areas within the Rincon Mountain District are located in areas susceptible to water level declines: 1) Rincon Creek near the NPS expansion area; 2) lower Box Canyon; and 3) the lower reaches of the drainages feeding Tanque Verde Wash (fig. 7) (Mott 1997). As Tucson expands, new well fields in major developments near these three areas could lower water tables and impact deep-rooted phreatophytes and the wildlife that depend on them.

Groundwater reservoirs supporting the riparian areas within the Rincon Mountain District lie east of the Pantano Fault, and are not directly connected to the Tucson Basin aquifer (Mott 1997). Drawdown in the Tucson Basin has already placed the water table beyond the depth where phreatophytic vegetation can access and utilize this resource. Depth to groundwater is 1.5 to 9 m (5 to 30 ft) below Tanque Verde Wash and 3 to 30 m (10 to 100 ft) under Rincon Creek's channel.

The thickness of the saturated alluvium in the three areas varies greatly, but the overall storage capacity is orders of magnitude less than the saturated sediments within the Tucson Basin. Wells developed up–gradient from the Pantano Fault could have an immediate and pronounced effect on water table elevations (Mott 1997). Prior to 1996, Tucson Water located municipal wells outside the Tucson Basin and within the saturated alluvium along Tanque Verde Wash. After these wells were activated, cottonwood trees began to die, and public concern caused the city to halt the pumping (Mott 1997). With increased demand for water in Tucson and the moratorium on the use of Central Arizona Project water allocations, Tucson Water is again expanding its well field into the Tanque Verde area.

Developers of the Rocking K Ranch, a 6,000-house development project proposed for lower Rincon Creek, have been granted a permit by the Arizona Department of Water Resources to withdraw 14,868,295 liters/day (3,927,788 gal/day) from the underlying alluvial aquifer (Halpenny 1985; Mott 1997). The development, however, is on the western side of the detachment fault, so drawdown should not impact the Rincon Creek area where the park is claiming an instream flow water right. As of February 2010, few of the projected homes have been built in the planned community (Meg Weesner, NPS Saguaro National Park, written communication, February 5, 2010).

Drinking water is supplied to the Rincon Mountain District by the city of Tucson. Before connecting to the city's distribution system, the Rincon Mountain District drew over 3 million liters (1 million gallons) annually from a 152-m- (500-ft)- deep well located on government property 1.6 km (1 mi) west of the park boundary.

Groundwater recharge in the Colossal Cave area, south of the Rincon Mountain District, occurs through sinkholes. However, because the Colossal Cave system does not extend into the park, caves and karst are not issues in Saguaro National Park.

Tucson Mountain District

There are no mapped riparian vegetation areas in the Tucson Mountain District, so drawdown is not an issue with regards to riparian habitat (Mott 1997). However, domestic water is provided by a well in the extreme southwest corner of the Tucson Mountain District that taps the Avra Valley aquifer. That well supplies water for three park residences, the visitor center, and administrative operations (Meg Weesner, NPS Saguaro National Park, written communication, August 25, 2006). A new pump delivers about 38 liters (10 gallons) per minute (Colleen Filippone, NPS Intermountain Region, written communication, September 7, 2006). Before the new pump was installed, the park found that sediment had reduced the total depth of the well from 170 m (560 ft) to 160 m (520 ft), which left the old pump resting on top of these solids. Five meters (18 ft) of solids was bailed from the well before the new pump was installed.

The Tucson Mountain District uses about 6,400 liters (1,700 gallons) of water per day and has a 190,000-liter (50,000-gallon) storage tank on site. Runoff and recharge rates are not well understood for the Tucson Mountain District, although recharge occurs wherever washes carry water over alluvial sediments; this would include many sections of washes on the flanks of the Tucson Mountains and in the park (Jon Spencer, Arizona Geological Survey, written communication, April 15, 2008).

The water level in the park's well appears to be impacted by a private well located about 60 m (200 ft) from the park's well (Colleen Filippone, NPS Intermountain Region, written communication, September 7, 2006). The private well is owned by the Sandario Water Company, a local water supplier. The static water level in the Tucson Mountain District's well is 131 m (431 ft) below the top of the casing; however, while the well was being bailed and the pump was out of the ground, a water level of 144 m (474 ft) was recorded. In January 2005, the water level fell to 148 m (487 ft) below the top of the casing. When the Tucson recharge ponds were brought online, water levels rose, but the recharge ponds likely do not provide a long-term solution because the Sandario well is situated between the park and the recharge ponds (Colleen Filippone, NPS Intermountain Region, written communication, September 7, 2006).

Water quality in the park is considered to be good, although little water quality data exists in the U.S. Environmental Protection Agency (EPA) STORET database for the park's two districts (National Park Service 1997). In 1968 and 1981, eight springs were monitored for 19 parameters within the Rincon Mountain District. Except for a pH reading of less than 6.5 for a sample from the Manning Camp Spring, no water quality samples from the park exceeded EPA criteria for freshwater aquatic life or drinking water (National Park Service 1997).

Although relatively recent observations at sampling stations within the park are scarce, the limited water quality data suggest that water quality for Saguaro National Park has not been impacted by human activities. West of the Rincon Mountain District, however, principally along the Santa Cruz River, human activities have impacted water quality (National Park Service 1997). Potential anthropogenic sources of contamination include municipal and industrial wastewater discharges, urban development atmospheric deposition, storm water runoff, mining and quarrying operations, livestock grazing activities, recreational use, and military operations. Surface water quality and groundwater quality are not impacted by Saguaro's septic system. All drain fields have been replaced since 1990.

For more information regarding surface water and groundwater resources in Saguaro National Park, please contact the Water Resources Division of the National Park Service in Fort Collins, Colorado (http://www.nature.nps.gov/water/).

Abandoned Mineral Lands

Mining and mine speculation is an important part of Tuscon-area history, particularly in the late 19th and early 20th centuries (Clemensen 1987). Saguaro National Park contains evidence of this mining history—the NPS Abandoned Mineral Lands (AML) database lists 288 mining-associated features at 146 sites within the park (John Burghardt, NPS Geologic Resources Division, personal communication, August 30, 2010). Most of the mine workings have been fenced off with barbed wire and posted with warning signs. A number of the vertical shafts that are close to public access have been backfilled to eliminate safety hazards. The park tries to have staff visit each site at least annually to determine the sites' status.

Although some mining activity has occurred in both of the park's districts, mining was never widespread or intensive in the Rincon Mountain District (Clemensen 1987). Spanish miners maintained small-scale lime kiln operations between the 1880s and 1910s. In 1902, the Loma Verde Mine reached a depth of 107 m (350 ft), but the mine was not included on a list of mines just five years later. The mine has since been back-filled. The Civilian Conservation Corps filled in 30 prospect holes in the mid-1930s.

Mining activity was more prevalent in the Tucson Mountain District where 150 abandoned mine workings and associated waste rock piles exist, mostly in designated wilderness areas (National Park Service 2005). Quite large waste rock piles are associated with the Gould and Mile Wide mines, the two largest operations (Higgins 1996). Some yellow and red staining, from acid mine drainage, exists in stream channels up to 0.4 km (0.25 mi) below the piles. The streams are ephemeral, however, and the piles have stabilized through time, so the potential of impacting aquatic communities with runoff from the area around the mines now is minimal.

An Environmental Assessment of several Arizona NPS units was conducted with funds from the 2009 American Recovery and Reinvestment Act (ARRA). For Saguaro, the report focused primarily on nine mine openings that are to be closed under ARRA, but sufficient background and field data were collected on all sites and features in the park so that this Environmental Assessment document will be applicable for closure of additional features as funding becomes available. Contact Linda Dansby, National Park Service Intermountain Region Minerals Coordinator and ARRA Program Lead for additional information.

Old Yuma Mine, Tucson Mountain District

When the boundaries of the Tucson Mountain District expanded under the Saguaro National Park Establishment and Expansion Act of 1994, the entire Old Yuma mining claim block (about 67 ha [165 ac]) became part of the park. These were "probably the most famous of the Tucson Mountain claims" (Clemensen 1987). The claimant received a patent on the valid claims from the Bureau of Land Management just before the lands transferred from BLM to NPS management (Comet 1 Lode, Old Yuma #1 Lode, and Old Yuma Placer Mining Claims, which were top-staked on one another and occupied a total of about 9 ha [22 ac]). The claimant never submitted a plan of operations to the National Park Service, and has since passed away. The park has stated that their biggest concern regarding this mine is potential injury due to onsite hazards. (Meg Weesner, NPS Saguaro National Park, personal communication, August 25, 2006). This mine is under a Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA, or "Superfund") investigation, however.

World-renown mineral specimens (particularly wulfenite) have been collected from the Old Yuma Mine (fig. 8), which operated from 1885 to about 1954. Located on a fault that trends east-northeast and dips to the southeast, the Old Yuma Mine contains a broad surface-mined area and a 91-m (300-ft) inclined shaft that dips at an angle of 43°, providing the main access to underground workings (Covington 1996). Horizontal underground workings occur at the 20-, 30-, 61-, and 91-m (65-, 100-, 200-, and 300-ft) levels off the main. An inspection in 2002 revealed caved-in rubble in the lower 30 m (100 ft) of the mine, which blocks access to the 91-m level. Numerous stopes (stepwise, broad excavations) occur along the inclined ore body on either side of the main incline, breaking through into the surface mine workings in what is loosely termed, "the glory hole." The mine is dry at least to the 61-m (200-ft) depth (Baker Jr. 2005).

The Old Yuma Mine produced copper, lead, zinc, silver, gold, and steel hardening agents from wulfenite, molybdenite, and vanadinite (fig. 9) (Covington 1996; Baker Jr. 2005). Molybdenum was produced in 1917 when World War I pushed the price of the metal unusually high (Covington 1996).

In addition to waste rock stashed around the property, approximately 5,400 cu m (7,000 cu yds) of tailings remains stockpiled at the Old Yuma Mill site, although this is only part of the original tailings pile. The other part of the pile was used for road base in the surrounding area (Baker Jr. 2005). The mine site includes a large excavation open to the surface (a "glory hole"), shafts (inclined and vertical), adits (horizontal), a headframe that was used to hoist from the main inclined access shaft, a concrete mill foundation, a solid waste dumping area and a small leach pad. The leach pad was constructed in 1984 for the purpose of reducing gold ore from the remnant mine tailings, but it was never put into operation (Baker Jr. 2005).

Potential Contamination at the Old Yuma Mine

Heavy metal contamination and acid-mine drainage present potential hazards to many parks in the western United States, including Saguaro National Park. A July 2005 Preliminary Assessment/Site Inspection (PA/SI) conducted at the Old Yuma Mine analyzed 17 subsurface soil samples for metals, including a sample from the identified cyanide-leach pad and a composite sample from a private residence located north of the Old Yuma Mine on property adjacent to Saguaro National Park (Baker Jr. 2005). Mine tailings were used as for roadbase and landscaping at the residence.

Criteria and standards used to compare the analytical results included: Preliminary Remediation Goals (PRGs); Soil Remediation Levels (SRLs); and Toxicity Characteristic Leaching Procedure (TCLP) concentrations. PRGs provide an initial screening-level tool for evaluating contaminated sites; they are EPA guidelines, but not legally enforceable standards. SRLs are soil cleanup standards enacted by the State of Arizona for the protection of human health and the environment. TCLP concentrations are maximum concentrations for toxicity characteristics in soil established by the EPA and presented in the Code of Federal Regulations (CFR) 40 CFR 261.

Of the 23 Target Analyte List metals, all but antimony and thallium were detected in the samples. Metals that exceeded SRL and PRG criteria and standards are listed in table 1. The sample from the residence contained metal concentrations exceeding SRL and/or PRG criteria similar to the samples collected from the mine tailings and waste rock (Baker Jr. 2005).

Table 1. Metals exceeding SRL standards and/or PRG criteria in 17 samples.

Metal	SRL	PRG
Lead	All 17 samples	All 17 samples
Arsenic	All 17 samples	All 17 samples
Cadmium	1 sample	1 sample
Iron		All 17 samples
Manganese	16 samples	All 17 samples
Vanadium	1 sample	14 samples
Zinc	9 samples	9 samples

The presence of heavy metals, however, does not necessarily signify a potential hazard to park visitors. As part of the PA/SI, the Old Yuma Mine received a Hazard Ranking System score of 3.15 based on CERCLA 42 United States Code 9601 (Baker Jr. 2005). Only sites that score over 28 are placed on the National Priorities List. The overall Hazard Ranking System score was calculated from scores determined for the following potential contaminant pathways:

- groundwater migration
- surface water migration
- soil exposure
- air migration

Scores for groundwater migration and soil exposure pathways were insignificant. Groundwater is 107 m (350 ft) below ground surface at the residence outside the park, which is a lower elevation than at the mine. Because no residences, daycare facilities, or workplaces exist within 61 m (200 ft) of the site, there was no threat to residential populations through the soil exposure pathway. However, human contact with the soil could occur as a result of hiking on trails through the mine areas and vandalism in fenced areas.

Threats to drinking water, the human food chain, and the environment were used to determine the surface water migration pathway score. A lack of population resulted in a low score for this pathway, also. However, an increase in population served by drinking water, the size of the stream, and an increase in surface water intakes identified within the sampling distance of the Old Yuma Mine site could potentially increase the score (Baker Jr. 2005).

The PA/SI concluded that both surface water runoff and airborne dust are likely migration pathways for contaminants from the Old Yuma Mine (Baker Jr. 2005). The tailings and waste rock piles are bare and loose, and the terrain is relatively steep. Erosion swales at the site suggest that infrequent but heavy rains could transport the loose soil and chemically dissolve metals, although most of the minerals that contain these metals do not dissolve easily in water. In this arid environment, wind also could transport dust.

In general, groundwater contamination by leaching from the tailings and waste rock piles is unlikely because annual precipitation is low and evaporation is high, and recharge provides little input to the underlying aquifers (Mott 1997; Kring 2002; National Park Service 2005). In a 1979 study, the Upper Santa Cruz Basin Mine Task Force concluded that groundwater contamination from mining activities could not be detected in either the Tucson or Avra Valley basins, even from large active mines.

An ephemeral stream is mapped approximately 120 to 150 m (400 to 500 ft) north-northwest of Old Yuma Mine, but no other streams, creeks, rivers, lakes, or other surface water bodies exist within a 0.8 km (0.5 mi) radius of the mine. Even if contaminant migration were to occur during periods of intense thunderstorms when surface runoff could be generated from the tailings piles, dilution during these events would be high, and metals or other contaminants would be carried from the park down to the adjoining Avra Valley or Tucson Basin before significant infiltration could occur.

Because arsenic and lead tend to bioaccumulate through the food web, a biotic pathway is possible. The studies did not address this potential pathway. In its closing section, the PA/SI recommends further study of site contamination.

As part of the ongoing CERCLA investigation, $418,000 in ARRA funding was appropriated for an Engineering Evaluation/Cost Analysis (EE/CA) and removal action to mitigate metals-contaminated soil. That amount will most likely cover the cost of the EE/CA and the drilling of one water well to test whether Old Yuma is affecting groundwater in the area. An additional $135,000 in ARRA funding will be spent on closures (wildlife-compatible where appropriate) of all of the mine entrances at Old Yuma Mine (John Burghardt, NPS Geologic Resources Division, personal communication, August 31, 2010).

Silver Lily Dikes

The Silver Lily Dikes, a swarm of magmatic intrusions that were injected through the floor of the Tucson Mountains Caldera and the overlying sequence of volcanic ashes and breccias, caused local alteration and mineralization at about the same time the ores of the Old Yuma Mine were being deposited. The dikes are only a few meters wide, but cut across the Tucson Mountains for distances up to 6 km (3.7 mi) (Kring 2002). A series of mines were sunk along the contacts between the dikes and adjacent sedimentary rocks.

Safety Measures

A fence now surrounds the Old Yuma Mine. The abandoned Gould Mine is next to a trail, and a grate has been placed over the shaft. A bat gate has been installed at the Wild Horse Mine on the east side of the Tucson Mountain District. The Mile Wide Mine is not on a trail, and the mine is not easily accessible; its deep shaft is fenced. Mile Wide and Gould mines were the subject of a Geologic Resources Division site visit and trip report in 1996 (Higgins 1996). The shafts and adits in the park's database of old mines for the Tucson Mountain District have been mapped, photographed, and measured. The park has begun to develop a comprehensive mine management plan.

A number of mine safety and closure projects within the park were submitted as part of the American Recovery and Reinvestment Act of 2009. Proposals have been submitted to initiate work on a number of the projects (Meg Weesner, NPS Saguaro National Park, personal communication, May 2010). In preparation for ARRA closures, an Environmental Assessment was conducted on all of the park's mines. Certain key mines will be closed, and fences at all of the remaining mine entrances will be reinforced or reconstructed as needed (John Burghardt, NPS Geologic Resources Division, personal communication, August 30, 2010).

Interpretive Trail to the Santa Catalina Fault

One of the most accessible and well-exposed outcrops of the Santa Catalina Fault is located adjacent to Cactus Forest Drive in the Rincon Mountain District of Saguaro National Park (fig. 11). At the scoping meeting in 2006, participants expressed an interest in developing an interpretive trail to the Santa Catalina Fault.

On July 31, 2009, the National Park Service approved Saguaro National Park's Comprehensive Trails Management Plan. As part of the plan, the Lime Falls Trail will be extended eastward from the Cactus Forest Trail to the eastern portion of Cactus Forest Drive, providing access the Santa Catalina Fault. The trail will include new interpretive signs (National Park Service 2009).

Another exposure of the Santa Catalina Fault exists about 1.6 km (1 mi) north of the Loma Alta trailhead in Rincon Valley. Although also within the park's boundaries, this outcrop does not expose the fault as well as the one along the proposed Lime Falls Trail (Jon Spencer, Arizona Geological Survey, written communication, April 15, 2008). Appendix A displays faults mapped within the park as part of the digital geologic data.

Additional Mapping in the Rincon Mountain District

More details are now available for the rock units that Drewes mapped west and south of the Santa Catalina Fault (Drewes 1977). Additional geologic mapping from the Fire Building to the park's headquarters and along Cactus Forest Drive could provide greater resolution of the exposed units. On the other hand, the contacts between granites, gneisses, and other metamorphic rock units exposed east of the Santa Catalina Fault remain difficult to map, so that re-mapping east of the fault may not prove worthwhile.

Other Issues

Sedimentation and Tinajas

Tinajas are ephemeral pools that are important water sources for wildlife, especially the leopard frog, in the Rincon Mountain District (Parker 2006). Tinajas range from 1 to 9 m (3 to 30 ft) in diameter and form in both bedrock and unconsolidated material. Most of the tinajas in Saguaro National Park have been inventoried. If these pools fill with sediment, their use as wildlife habitat is greatly restricted.

Under normal conditions, channels in the Rincon Mountains contain very little sediment in storage, especially channels cut into steep bedrock slopes. Typically, sheetwash and rill erosion are not significant in transporting sediment to stream channels. Large hot wildfires, however, alter watershed conditions such that the amount of sediment delivered to channels can be greatly increased. Fires destroy the vegetation and the layer of decaying leaves and conifer needles that comprise the forest litter. Fires expose the ground surface to the direct effects of precipitation and storm runoff, and they can burn into root systems that ordinarily bind soil to hillslopes. Hot fires can also change the structure of the soil itself, making it resistant to infiltration from precipitation (Parker 2006).

After fires, the amount of surface water runoff from storms increases due to the lack of vegetation and change in soil structure. More sediment is eroded from hillslopes and transported to stream channels. This increased sediment from erosion can fill tinajas, impacting these important water sources for many years. For example, runoff from the Box Canyon fire in 1999 carried large amounts of ash through the ephemeral stream channels of Loma Verde Wash. The ash left the pools inky black and greatly raised water temperatures. Subsequent flows flushed the ash from the pools. Less than two years later, gravel and coarse sand, eroded from the fire-impacted slopes, buried the uppermost pools to depths of 1 to 2 m (3 to 6 ft).

All of the 24 pools identified as breeding pools for the leopard frog were buried by 2005. A large pool in Wildhorse Canyon filled with sediment following the 1989 Chiva fire, and it remains filled as of 2006. Two years after the Helens II fire of 2003, one large pool in Joaquin Canyon was buried by as much as 1 m (3 ft) of coarse sand. Pools downstream had received some coarse-sand deposition but were not yet filled (Parker 2006).

Flooding and Debris Flows

A debris flow is a sediment-rich slurry. Sediment transported in a debris flow can range from the smallest clay, silt, and sand particles to boulders. In summer 2005, several thunderstorms washed out some roads and deposited debris in the Tucson Mountain District (Meg Weesner, NPS Saguaro National Park, personal communication, April 4, 2006). Although paved roads in the park are not often affected by debris flows, dirt roads are impacted every few summers.

An unprecedented number of slope failures and debris flows occurred in southeastern Arizona during the last week of July, 2006. An unusual weather pattern resulted in several days of nocturnal and early morning rainfall in southeastern Arizona. Up to 20 cm (8 in) of rain fell in less than six hours in some mountain areas. Maximum three-day precipitation totals for the southern Santa Catalina Mountains, north of Tucson, were 30.58 cm (12.04 in) (Webb et al. 2008). The estimated recurrence interval for this amount of rainfall is once every 1,200 years. Flash flooding occurred throughout the Tucson area. On July 29, floodwaters in Tanque Verde Wash inundated the Tanque Verde Loop Road, approximately 1.6 km (1 mi) northeast of the Rincon Mountain District (fig. 10). In the southern Santa Catalina Mountains, an estimated 1.5 million tons of sediment were released into the channels of ten drainage basins due to slope failures (Webb et al. 2008). The debris flows of 2006 showed that this geologic hazard can occur in the absence of fire. Other NPS areas in Arizona, including Coronado National Memorial, were also impacted by these 2006 storms.

Erosion Associated with Abandoned Roads

Abandoned mining and ranch roads in the park affect water flow patterns (hydrology) and contribute to erosion. For example, culverts associated with some of the roads contribute to headcut migration issues. The Geologic Resources Division has studied the issue and a report is pending (Dave Steensen, NPS Geologic Resources Division, personal communication, August 20, 2010). The park is investigating the feasibility of converting some of the roads to trails. The Geologic Resources Division completed some rehabilitation project proposals and submitted them to the park (Dave Steensen, NPS Geologic Resources Division, personal communication, August 20, 2010).

Recognizing Archaeology Sites

Saguaro National Park has surveyed 450 archaeological sites in the Rincon Mountain District. Scattered sites in the Tucson Mountain District have also been recognized. At the scoping meeting, detailed mapping of Quaternary deposits was suggested as a way to recognize potential archaeology sites.

Less Significant Issues for Saguaro National Park

Geologic issues that are less significant to Saguaro National park include cryptobiotic soils, fossils, and energy corridors.

Neither livestock grazing nor off-trail hiking is allowed in the park; thus, destruction of cryptobiotic soils is not a significant issue. Soils are addressed in the park's soil survey geographic database (National Park Service 2006). GIS data for soils can be integrated with geologic data (Appendix A) to investigate relationships between soil type and geologic parent material.

Marine invertebrates such as brachiopods and trilobites are occasionally found in Cambrian-aged rocks, but they are not a primary management issue (Tweet et al. 2008). Many of the geologic units mapped within the park are known to preserve fossils outside of the park. Metamorphism and deformation from past faulting and folding have altered the limestone strata in the Rincon Mountain District and significantly reduced the potential for any well-preserved paleontological resources. Packrat middens provide important records of paleoenvironments. Many are known from the Tuscon Mountains area, including at least one from what is now within the park. The midden record spans at least the past 25,000 years. The 2009 Paleontological Resources Preservation Act (Public Law 111-11) outlines a science-based management, education, and interpretation plan for fossil resources, which are nonrenewable.

The impact of power lines in the Tucson Mountain District has become a non-issue because the power lines have not been re-permitted.

Figure 7. Riparian vegetation along Rincon Creek (left) in the Rincon Mountain District compared with Sonoran Desert scrub with Tanque Verde ridge in the background (right). Photograph is the cover photo by Greg Levandowski for U.S. Geological Survey Open-File Report 2006-1075 (Powell et al. 2006).

Figure 8. The Old Yuma Mine (ruins visible in photo) was operational from the 1880s to the 1950s. A variety of minerals were mined at the Old Yuma Mine, some spectacular specimens have been recovered, including the vanadinite specimen in figure 9. National Park Service photograph courtesy John Burghardt (NPS Geologic Resources Division).

Figure 9. Vanadinite is one of many minerals mined from the Old Yuma Mine. Some spectacular specimens, such as this one, were found in the mine. Vanadinite is a source of the element vanadium, an important component of many steel alloys. Arizona-Sonora Desert Museum photograph (specimen ASDM03859), courtesy Christine Conte and Bill Hornbaker (Arizona-Sonora Desert Museum).

Figure 10. Flash flooding in Tanque Verde Wash inundates Tanque Verde Loop Road following a thunderstorm on July 29, 2006. The road dips down where it crosses the normally dry and sandy Tanque Verde Wash, so the water is deeper than it appears. Copyrighted photograph used with permission from T. Beth Kinsey, http://fireflyforest.net/firefly/206/08/01/july-2006-flooding-in-tucson (accessed February 7, 2010).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Saguaro National Park.

Both units of Saguaro National Park contain features representative of a wide variety of geologic processes. Mountain building, earthquakes, volcanism, erosion, landslides, metamorphism, and lithification of both clastic and carbonate sediments are some of the geologic processes that created the modern landscape. Refer to Bezy (2005) for additional photographs and descriptions of geologic features and processes in the park. The glossary contains definitions of many of the technical terms.

Rincon Mountain District

Metamorphic core complexes are geologic features created when overlying unmetamorphosed crystalline, volcanic, and sedimentary rocks—originally burying the mountains' metamorphic core—were moved away by detachment faults, bringing ancient metamorphosed bedrock to the surface (fig. 4). The Rincon Mountains are one of the best examples in the world of a metamorphic core complex, illustrating the processes involved in the formation of domed metamorphic core complexes (Anderson 1988; Davis 1987). More specifically, the metamorphic core complexes include:

- A low-angle detachment fault of extensional (pulling apart) origin separating rock units above the fault surface (upper-plate) from rock units below the fault surface (lower-plate)
- A lower-plate ("core") of metamorphosed crystalline rocks, displaying a shallow-dipping zone of intense shearing ("mylonitic foliation"). These foliated rocks display a consistent orientation ("lineation") truncated by the overlying detachment fault and associated breccias. The mineral chlorite is abundant in the breccias.
- An upper plate of crystalline, sedimentary, and volcanic rocks that lack the intense mylonitic deformation and metamorphism of the lower plate
- An assemblage of normal faults in the upper-plate that have been offset consistent with movement along the detachment fault.

The following features are described in their order of occurrence along the one-way Cactus Forest Drive. Some of the geologic features are located away from the road and are not accessible to visitors. Under the 2009 Comprehensive Trail Management Plan, the Lime Falls Trail will be extended to make the Santa Catalina detachment fault outcrop accessible (National Park Service 2009).

Pinal Schist

The Pinal Schist is the dark gray rock exposed along the east side of a dry wash about 0.8 km (0.5 mi) from the entrance station along Cactus Forest Drive. The oldest rock in southern Arizona, the Pinal Schist is approximately 1.65 to 1.7 billion years old. The Pinal Schist represents a marine environment that received much sand, silt, and clay from a nearby continent (Kring 2002; Bezy 2005). The sediments were buried and lithified, forming sedimentary rocks. Later, increases in temperature and pressure metamorphosed them into schists and phyllites.

Pediment

About 1 km (0.6 mi) from the entrance station, the top of the Pinal Schist forms a surface that gently slopes away from the Rincon Mountains toward the Tucson Basin (Bezy 2005). This surface is part of a more extensive beveled platform called a pediment. In this location, a thin veneer of sand and pebbles, eroded from the Rincon Mountains, covers the pediment; in other locations, however, the pediment is an exposed bedrock surface. Exposed pediments are classic landforms of the Basin-and-Range geologic province.

Triangular Dome Facets

Extensional forces approximately 20 to 30 million years ago stretched, thinned, and fractured the crust along low-angle faults (detachment faults). This allowed masses of rock to dome up as metamorphic core complexes. Streams cut drainages through more easily eroded rock on the crest of the dome and incised deep canyons in the underlying, erosion-resistant, gneiss. This resulted in a series of aligned triangular-shaped rock faces between the mouths of canyons.

These triangular-shaped, convex rock faces separated by V–shaped canyon mouths form the western margin of the Rincon Mountains, and can be seen approximately 1.6 km (1 mi) from the entrance station (Bezy 2005). These landforms, called triangular domed facets, are hallmark features of metamorphic core complexes. They retain the original arched form of the bedrock when it was first exposed to weathering and erosion at Earth's surface.

Upper-Plate Rocks

The Loma Verde trailhead is located on upper-plate rocks, defined as all the rock units that lie above the Santa Catalina Fault surface (fig. 4; Map Unit Properties Table). In Saguaro National Park, these upper-plate rocks include slices of upper Paleozoic and Mesozoic strata as well as Precambrian metamorphic rocks (Drewes 1977). Upper-plate rocks are all deformed, and fold structures can be found at some locations. Some of the fold structures may be compressional features formed during the Cretaceous-Tertiary Laramide Orogeny (mountain-building event). However, the geometry of most of the folds appears compatible with deformation caused by the southwest-directed normal fault movement of the Santa Catalina detachment fault (Davis 1987).

Thin veins of calcite locally penetrate folded and faulted limestones. Strata in the Bisbee Group have been turned upside down from their original depositional sequence and represent an excellent example of inverted stratigraphy. Caves in the Rincon Mountains (e.g., Colossal Cave to the south) are located in deformed upper-plate limestones.

Today, most of the upper-plate rocks that were displaced along the Santa Catalina Fault lie beneath the Tucson Basin. About 0.33 km (0.2 mi) past the Loma Verde trailhead, the road crosses the trace of the Santa Catalina Fault and enters a landscape developed on lower-plate Precambrian units.

Dikes

Along the right side of the road, about 6 km (3.8 mi) from the entrance station, a dike of dark-colored rock is exposed in the lower-plate rocks. Magma migrated under great pressure and wedged open and filled cracks in the older, lighter-colored gneiss (Bezy 2005). Dikes are common features in Saguaro National Park (Appendix A) and are important to the mining history of the area. Recrystallized areas bordering dikes can contain metal and mineral deposits.

Santa Catalina Detachment Fault

About 10 km (6 mi) from the entrance station, the trace of the Santa Catalina detachment fault is exposed at the top of a ledge of cataclasite (fine-grained rock fractured during metamorphism) to the north of the road (fig. 11). The Santa Catalina fault separates rocks above the fault from highly deformed and fractured rocks (called cataclasites, microbreccias, and mylonites) below the fault. The rocks beneath the detachment fault were displaced at least 25 to 35 km (15 to 22 mi) toward the northeast relative to the overlying rocks (Bezy 2005). The limestones that lie above the detachment fault were originally deposited as horizontal layers but have been intricately folded by the fault movement.

The sinuous trace of the Santa Catalina fault can be followed for 70 km (42 mi) along the front of the Santa Catalina, Tanque Verde, and Rincon Mountains (Drewes 1977; Davis 1987). The surface of the fault plunges 15° to 30° to the southwest. The displacement along the fault is the same orientation as the mineral lineation in the mylonites. The Santa Catalina fault appears to be a low-angle, normal-slip fault that helped accommodate crustal extension (pulling apart) during the middle Tertiary (fig. 4) (Davis 1987).

Lower-Plate Rocks

The color-banded metamorphic rock at the Javelina Rocks, the small hills about 10.6 km (6.6 mi) from the entrance station, consist of mylonitic gneiss commonly known as "Catalina Gneiss," but mapped as Wrong Mountain Quartz Monzonite and Continental Granodiorite (figs. 12, 13; Map Unit Properties Table; Appendix A) (Drewes 1977; Davis 1987; Bezy 2005). Catalina Gneiss is the most common rock type in the Rincon Mountains and forms the "lower plate" rocks. Abundant, relatively large feldspar crystals ("porphyroclasts") ranging in size from 0.5 to 6 cm (0.2 to 2 in) are imbedded in the mylonitic gneiss. These feldspar crystals are called "augen" (German for "eyes") because they have been squeezed by increased temperature and pressure into the shape of eyes. They represent relict grains of the original rock, prior to metamorphism, that are partly crushed and lie within the finer-grained matrix of the gneiss.

Rocks originally formed during the Precambrian were metamorphosed into the mylonites much later, during the Tertiary (Davis 1987). A zone of steel gray to black "ultramylonite" that lies east of Cactus Forest Drive provides evidence of the timing of detachment and mylonitization (stop 2 in Davis 1987). Ultramylonite has undergone such severe deformation that the primary structures and porphyroclasts have been obliterated. The rock has become homogeneous and dense. It comprises a shear zone separating corase-grained mylonite gneisses derived from Precambrian quartz monzonite from finer grained mylonite gneisses derived from Tertiary rocks that remain buried beneath the shear zone (Davis 1987).

Granites in Saguaro National Park metamorphosed to gneiss at depths of 10 to 15 km (7 to 10 mi), where temperatures reached 350° C (600° F). The increased temperature and pressure caused the quartz crystals in the granites to behave like hot soft putty and to smear in long ribbons parallel to the southwest-northeast directed stretching. Because they are more brittle at these temperatures, feldspar crystals were rolled, crushed, and smeared in the direction of extension. The stretched feldspars and quartz crystals form the aligned dark and light streaks that give gneiss its unique texture.

Excellent exposures of brecciated and microbrecciated mylonite gneisses are found all along the wash leading to the Santa Catalina detachment fault from Cactus Forest Drive. Different intensities of brecciation are evident in the rocks, and the degree of brecciation suggests that microbrecciation was the result of progressive deformation through time (Davis 1987).

Javalina Fault

Davis (1987) mapped a north-to-northeast trending, gently west-dipping fault that crosses Cactus Forest Drive near the Javelina Rocks (figs. 12, 14). The fault, which he named the Javalina (*sic*) fault, separates mylonite and ultramylonite on the footwall of the fault (to the east) from brecciated mylonites containing chlorite on the hanging wall of the fault.

East of the fault, the rocks are "normal" mylonite gneiss, with large rounded and elliptical feldspar porphyroclasts set in a matrix of mainly quartz and feldspar. Alteration of feldspar is insignificant. In contrast, west of the fault surface, the brecciated mylonite gneisses are marked by extreme fracturing, microfaulting, and alteration. Grain size is greatly reduced.

Fracture-Controlled Drainage, Box Canyon

Box Canyon can be viewed by hiking about 1.6 km (1 mi) up the Tanque Verde Ridge Trail. Canyons in this part of the Rincon Mountains have unusually straight courses because the canyons have developed along fractures. Tributary canyons also tend to join these major canyons at high angles, and are associated with fracture patterns. Chemical and physical weathering processes deepened and widened fractures that eventually formed the deep rectangular system of canyons that cut into the slopes of the Rincon Mountains (Bezy 2005). A fracture system that parallels Box Canyon has not been found, and some geologists suggest the canyon could have formed from a groove in the detachment fault.

Tucson Mountain District

Tucson Mountains Caldera

The Tucson Mountains are the eroded remains of one of at least seven gigantic, explosive volcanoes that were active in southeastern Arizona about 70 to 75 million years ago (Kring 2002; Bezy 2005). The catastrophic eruption that produced the Tucson Mountains Caldera disgorged many cubic kilometers of volcanic debris. In places, the pile of volcanic debris was at least 3,000 to 4,000 m (9,800 to 13,100 ft) thick. Violent explosions ejected enormous blocks of Earth's crust, up to 0.5 km (0.3 mi) in size, which spread out within the caldera to form chaotic debris flows. These debris flows added an estimated 1 km (0.6 mi) to the total thickness of the volcanic deposit (Kring 2002). During the Late Cretaceous (70-75 million years ago), the Tucson area may have resembled today's Yellowstone National Park with geysers and the pungent odor of sulphur.

In the Tucson Mountains, enough magma drained from the magma chamber feeding the volcano that the chamber's roof and overlying volcanic debris collapsed to form the Tucson Mountains Caldera (fig. 15). Prior to erosion, the caldera probably had a height of 1 km (0.6 mi) and was about 20 to 25 km (12 to 15 mi) wide. In comparison, Crater Lake in Oregon, a caldera of similar origin, is 10 km (6 mi) wide. The floor of the caldera subsided like a trapdoor, hinged to the south. The floor to the south subsided only 100 m (300 ft) compared to 4,600 m (15,000 ft) beneath Wasson Peak on the north. Ash-flow tuffs, megabreccia, igneous intrusions, and a series of intrusive dikes associated with this caldera are explained in the following paragraphs.

Cat Mountain Tuff

The Cat Mountain Tuff is a sequence of rhyolitic volcanic ash deposits that now form most of the red cliffs in the Tucson Mountains (fig. 6). This rock is a 73-million-year-old deposit of compressed volcanic ash, pumice, rock fragments, and crystals of feldspar, quartz, and biotite. These ash flow tuffs can be easily identified by the dark lenses of flattened pumice fragments (lapilli) surrounded by the lighter matrix of volcanic ash (Kring 2002). The pumice formed when lava was ejected into the air and rapidly cooled, creating rocks riddled with gas-filled vesicles. The fragments became part of the hot ash and gas mixture flowing across the floor of the caldera before ponding in low areas. The overlying mass of ash compressed and flattened the pumice fragments.

Microscopic features such as broken crystals and flattened volcanic glass shards, along with outcrop features such as massive textures with no discrete layering suggest that the ash flows were rapidly erupted and emplaced by a "nuée ardente" (Kring 2002). Nuée ardentes are exceptionally violent types of ash flow eruptions. Such ash flows are produced when an explosive eruption cloud is so saturated with volcanic fragments to rise very far into the atmosphere, and simultaneously too charged with gas to flow like lava. Heated to more than 1,000° C (1,800° F), the mass of superheated gas and debris forms a glowing avalanche of material that can flow downslope at speeds greater than 200 km/hr (125 mph) (Kring 2002; Bezy 2005). Nuée ardentes burn and bury everything in their path.

Several eruptions produced the Cat Mountain Tuff. Some of the tuff was so hot that the fragments welded together to form the very hard rock known as "welded tuff." In other cases, the tuff was not welded (or was weakly welded) and produced a softer rock; this occurred because either the ash cooled more quickly near the margin of the flow, rock fragments inhibited welding, or the ash was cooler (Kring 2002). The more thoroughly welded zones are more resistant to weathering and erosion and form cliffs. The weakly welded tuff deposits form slopes (fig. 6).

The caldera did not confine all of the ash flows. For example, a 200-m (660-ft) thick ash flow from the Tucson Mountain volcanic center covered the slightly older Silver Bell Caldera and now caps most of the ridges in the Silver Bell Mountains. Similarly, a 100-m- (330-ft) -thick ash flow tuff that erupted from the Silver Bell Caldera covered the Amole Arkose in the Tucson Mountains before the Tucson Mountains Caldera erupted. Remnants of this ash flow can be found along the Norris Trail, northwest of the Gould Mine (Lipman 1993; Kring 2002).

Cat Mountain Megabreccia (Tucson Mountains Chaos)

A jumble of large, unsorted rock fragments are exposed about 46 m (150 ft) north and northwest of the Gates Pass parking lot. This chaotic mix of welded tuff, Amole Arkose, Paleozoic limestone, and Recreation Red Beds is a megabreccia that was produced when the steep mile-high caldera walls collapsed after the caldera floor had subsided (Lipman 1993; Kring 2002; Bezy 2005). Some of the blocks are as long as 490 m (1,600 ft)—e.g., Gates Pass is cut through a single block of Amole Arkose that sits in a matrix of volcanic rock fragments, pumice, and ash.

The interlayering of the Cat Mountain megabreccia and the Cat Mountain Tuff suggest that they were deposited simultaneously or in repeated episodes of successive deposition (Lipman and Fridrick 1990; Lipman 1993). The combined thickness of the megabreccia and Cat Mountain Tuff increases from south to north, supporting the hypothesis that the caldera floor dipped downward like a trap door hinged in the south (fig. 15). About 4,000 to 5,000 m (13,000 to 16,000 ft) of ash and breccia ponded in the north end of the caldera (Lipman 1993; Kring 2002; Bezy 2005). In the south end, only 100 to 200 m (330 to 660 ft) of ash and breccia accumulated.

Post-Collapse Lava Flows

Lava erupting from volcanic vents began to fill the caldera after its floor had collapsed and the megabreccia and tuffs were emplaced (Kring 2002). The magma contained less gas, so the eruptions were less explosive than the ash flow eruptions. The extruded lava flows were often up to 150 m (500 ft) thick. The first lava flows reached toward the northwest, as far as Panther Peak, from what is now the Yuma Mine (Lipman 1993; Kring 2002). Interfingering with volcaniclastic sediments, they form a sequence of rocks that is 2,500 m (8,200 ft) thick in the north end of the mountain range.

Small vents in the southeastern portion of the caldera extruded dark-colored andesite lava flows, dacite lava flows, and dacite tuffs. Dacite is composed of interlocking, irregularly shaped crystals of feldspar (white) and mica (brownish-black). Due to their mineral composition, dacite lavas are more viscous than basalt flows (such as those seen on Hawaii); thus, they move more slowly—more like toothpaste squeezed from a tube than like hot wax from an overturned candle—and form impressive features that can be several hundred feet thick (Kring 2002). Because the lava cooled rapidly. the minerals did not grow very large. Aligned lens-shaped cavities that were once gas bubbles preserve the flow layers in the rock.

Dacite flowed down valleys that existed at the time of the eruptions; however, because dacite is more resistant to erosion than the surrounding rock, the flows now form cliffs and peaks, such as Safford Peak and Panther Peak. The dacite flows are excellent examples of the process of topographic reversal due to differential erosion where highlands stand where a lowland once existed.

An andesite lava flow is exposed near John F. Kennedy Park, and a dacite tuff is exposed at Beehive Peak. Lava flows also form a large fraction of Twin Hills. Remnants of dacite lava flows and volcanic vents that cooled about 25 to 30 million years ago are exposed near the Box Canyon parking area off the Picture Rocks Road (Bezy 2005). The flows range in thickness from 25 m (80 ft) to more than 100 m (300 ft).

Columnar Joints

When the dacite erupted, the flowing lava was in direct contact with relatively cool rocks underneath and cool air above, so the lava cooled and solidified rapidly. As the lava cooled, the rock contracted and a network of polygonal cracks formed perpendicular to the upper and lower cooling surfaces of the flow. At the Box Canyon location, these vertical columnar joints are approximately 0.6 to 0.9 m (2 to 3 ft) wide.

Columnar joints are common in basalt and other volcanic rocks, worldwide. Excellent examples of columnar jointing include the Devils Postpile (Devils Postpile National Monument in California; Graham 2010), Devils Tower (Devils Tower National Monument in Wyoming; Graham 2008), and the Giant's Causeway in Northern Ireland.

Amole Pluton and Other Plutonic Intrusions

Circular fault or fracture patterns ("ring faults" or "ring fractures") commonly form in association with caldera subsidence. After the eruption of the lava flows, the Amole Pluton intruded along a ring fracture on the northwest flank of the caldera. Domal uplift caused by the intrusion tilted the overlying lava flows and volcaniclastic sediments in the vicinity of the Old Yuma Mine (Kring 2002). The pluton covers approximately 50 sq km (140 sq mi) in the northern Tucson Mountains today, mostly in the Tucson Mountain District of Saguaro National Park.

The Amole Pluton consists primarily of granite and granodiorite (Kring 2002; Bezy 2005). Approximately equal amounts of quartz, alkali feldspar (rich in potassium and sodium), and plagioclase feldspar compose the granite, which forms the interior of the pluton. The granite also contains small amounts of biotite (black mica) and muscovite (silver mica). The upper margin of the magma chamber crystallized to form granodiorite. The granodiorite is darker in color and contains crystals of biotite, hornblende (greenish-black), plagioclase feldspar (white), and quartz (gray) (Bezy 2005).

Tan outcroppings of granite and granodiorite are exposed in low hills on the road to the Sus Picnic Area. Other magma bodies were emplaced beneath Saginaw Hill and the Sedimentary Hills. Granite and granodiorite cool and solidify deep below Earth's surface. A substantial thickness of overlying rocks had to erode for these plutonic rocks to now be exposed at the surface.

Dikes

A light gray, dacite dike that intruded into the Cretaceous Amole Arkose about 73 million years ago is exposed in the hillside about 0.8 km (0.5 mi) west of the King Canyon Trailhead. The dike forms part of a group of silica-rich intrusions called the Silver Lily dike swarm (Lipman 1993; Kring 2002; Bezy 2005). The Silver Lily dike swarm crosscuts the plutonic intrusions and trends easterly across this part of the Tucson Mountains. These ribs of light colored rock are up to 20 m (66 ft) wide and can be traced along the surface for up to 6,000 m (19,700 ft). Precious and industrial metals have been found in some areas where the dacite is in contact with the arkose.

Precambrian Granites and Schists

Small remnants of the 1.65- to 1.7- billion-year-old Pinal Schist and 1.4- billion-year-old porphyritic granite are exposed in the vicinity of Twin Peaks and as clasts in the ash flow tuffs and megabreccias (Kring 2002). Although only small amounts are exposed in the Tucson Mountains today, these Precambrian rocks, as well as the Paleozoic rocks discussed below, formed much of the mountains that once bordered a large lake (Amole Lake, see "Geologic History" section). The lake existed during the Cretaceous Period, prior to the eruption that produced the Tucson Mountains Caldera.

Paleozoic Sedimentary Rocks

A few Paleozoic sedimentary rocks, mostly limestone, are exposed in a north-south series of normal fault-bounded blocks along the western fringe of the Tucson Mountains (Lipman 1993; Kring 2002). The largest of these blocks is the Twin Peaks block. The limestone is mined to produce cement. Blocks of Paleozoic rocks are also present in the Cat Mountain megabreccia.

The oldest Paleozoic formation in the area is the Cambrian Bolsa Quartzite, a common marker for the Phanerozoic sequence of rocks that began about 540 million years ago (fig. 3). The shales and sandstones of the Abrigo Formation, another Cambrian unit, overlie the Bolsa Quartzite. No Ordovician or Silurian rocks exist in the region. Devonian dolomite of the Martin Formation unconformably overlies the Abrigo Formation.

The gray Horquilla and Escabrosa limestones are exposed to the west of the Sus Picnic Area parking lot. The Permian and Pennsylvanian Horquilla Limestone and the older Mississippian Escabrosa Limestone were deposited in a shallow sea that covered this part of North America. The Escabrosa Limestone contains chert and fossil crinoids. Fault movement has juxtaposed these limestones against much younger Jurassic- or Cretaceous- aged sedimentary rocks (Lipman 1993; Bezy 2005). Paleozoic limestones similar to the Horquilla and Escabrosa limestones are exposed in the mountain ranges across southern Arizona.

The youngest Paleozoic units include: the quartzite or recrystallized sandstone of the Permian Scherrer Formation; the cherty and fossiliferous Permian Concha Limestone; and the limestone, dolomite, and sandstone of the Permian Rainvalley Formation. Exposures of these units are up to only a few tens of meters thick (Kring 2002).

Recreation Red Beds

The reddish rocks of the Recreation Red Beds dominate Brown Mountain and the Red Hills along Kinney Road (Kring 2002; Bezy 2005). The formation was originally limited to the massive, fine-grained, brick-red sandstone, but was later expanded to include a tuff member and a volcanic conglomerate member (Brown 1939; Colby 1958; Lipman 1993; Kring 2002). A small amount of iron oxide derived from the volcanic debris in the bedrock colored the outcrops. Stratigraphic features in the sandstone and siltstone include thin- and thick-beds and cross-stratification. Massive beds of volcanic conglomerate over 4.25 m (14.8 ft) thick contain clasts greater than 0.5 m (1.5 ft) in diameter.

Questions remain concerning the age and thickness of the Recreation Red Beds. The age has been estimated to be as old as Upper Triassic and as young as Upper Cretaceous (Kring 2002). An andesite dike intruded and deformed the redbeds at the north end of Brown Mountain 159 million years ago (Upper Jurassic); thus, the redbeds must be at least that old (Kring 2002; Bezy 2005). The stratigraphic thickness has been measured at approximately 500 m (1,640 ft), but has also been estimated to be about 1,500 m (5,000 ft) thick (Colby 1958; Dickinson 1991; Kring 2002).

The volcanic tuff contains veins of the reddish-brown or reddish-black mineral piedmontite (also called piemontite) (Kring 2002). Because of this, Brown Mountain used to be called the Piedmontite Hills.

Amole Arkose

The Amole Arkose comprises a sequence of alluvial fan, stream, delta, and lake sediments deposited in a northwest-southeast oriented basin surrounded by highlands about 100 million years ago in the Cretaceous Period (Risley 1987; Kring 2002; Bezy 2005). About 1,000 m (3,300 ft) of the formation's silty mudstone, siltstone, and feldspar-rich sandstone (arkose) unconformably overlies the Permian Rainvalley Formation and the Jurassic Recreation Red Beds. The Amole Arkose also contains minor amounts of conglomerate and limestone.

The finer- grained mudstone and siltstone are often thinly bedded and horizontally laminated. The arkose, a sandstone containing at least 25% feldspar grains, may be thinly bedded as well, but also occurs in massive beds over 4 m (13 ft) thick. These massive beds sometimes fill ancient channels and are sorted (graded) with the coarser debris on the bottom and the finer debris on the top of the deposit. The sandstone can be cross-bedded, contain lenses of pebbles, and have ripple marks on the top surfaces of the beds. All of these features help geologists determine the depositional environment of the sandstone.

The Amole Arkose contains two varieties of conglomerate rocks. The first is a conglomerate containing cobbles and boulders in lenses less than 2 m (6 ft) thick. The second type is dominated by pebbles. Limestone in the formation is typically laminated in beds usually less than 50 cm (20 in) thick. The laminations have been interpreted as algal mats. Desiccation cracks in the laminae suggest that the algal mats were occasionally exposed to dry air. Fossil gastropods (snails) and pelecypods (bivalves) are found in laminae-free limestone. Rare shell beds represent shell accumulations from storm waves.

About 0.8 km (0.5 mi) from the King Canyon Trailhead, sandstone exposures of Amole Arkose contain high quantities of feldspar crystals. At Earth's surface, feldspar is more easily broken than quartz, so quartz grains tend to dominate sedimentary deposits as distance from the source increases. Deposits containing abundant feldspar grains indicate a nearby source area. Arkose sands are commonly derived from decomposed granite. The numerous large feldspar grains in the Amole Arkose indicate that the sandstone was derived from the weathering and erosion of nearby outcrops of granite.

The Amole Arkose is a good example of sedimentary processes that sort particles according to size. The coarse cobble-filled conglomerates formed alluvial fans at the base of the mountains that bordered the Amole basin. Streams flowing through the alluvial fans carried finer-grained sand, silt, and clay farther into the basin. Sand was deposited in braided streams and deltas associated with Amole Lake. Fine-grained silt and clay settled in quiet waters farther from the mountain front, either in stream channels or in the lake.

Mid-Tertiary Volcanic Rocks

A series of smaller volcanic systems erupted lavas and relatively low-volume tuffs in the Tucson Mountains about 20 to 30 million years ago, long after the volcanic system that produced the Tucson Mountains Caldera had shut down. Remnants of a dacitic lava field, known as the Safford Dacite, are exposed in the northern part of the Tucson Mountains on Safford Peak and south of Panther Peak (Lipman 1993; Kring 2002). The dacite lava flows are 25 to 100 m (82 to 328 ft) thick.

Exposures of basaltic lavas and rhyolitic tuffs occur on the east side of the Tucson Mountain range in Tumamoc Hill and Sentinel Peak (also called A-Mountain) (Kring 2002). The basaltic lava is vesicular and contains the mineral olivine. At one time, basaltic andesite lava was quarried and used for building stone in many homes in the downtown area of Tucson and in stone walls on the University of Arizona campus. The entire sequence is about 100 m (328 ft) thick, with individual lava flows up to 25 m (82 ft) thick.

Minerals

Most of the mineralization occurred in the Tucson Mountains during the caldera cycle of the Late Cretaceous. Hot, metal-laden groundwater originating from magmas or heated by magmas produced primary mineral deposits of gold, silver, and copper (Kring and Domitrovic 1996; Kring 2002). The Amole granite and granodiorite in the Tucson Mountain District represents the largest magma intrusion in the area following caldera collapse. Before cooling, the magma altered the surrounding rocks near King Canyon, Amole Peak, Wasson Peak, and elsewhere in a process called "contact metamorphism."

When magma encounters limestone, the contact metamorphism produces a "skarn" deposit. Large garnet crystals can be found in these zones. Garnet and epidote are found in the vicinity of the Sedimentary Hills, and crystalline (specular) hematite and magnetite are found around Amole and Wasson peaks. In the early 20th century, the Gould Mine opened near King Canyon in a contact metamorphic zone involving blocks of altered limestone. The mine recovered copper sulfide minerals with traces of silver (Kring 2002; Bezy 2005).

Mineralization also occurred beyond the zone of contact metamorphism in the Tucson Mountains. Magmatic fluids from the Amole pluton penetrated and altered a thick sequence of lava flows and sedimentary rocks that had collected in the north end of the collapsed caldera. Fluids produced lead- and vanadium-rich mineral deposits.

Heat from the cooling magma that formed the Amole pluton drove the underground circulation of hot, mineral-rich fluids that flowed through cracks in the granite and adjacent rocks. As these migrating fluids cooled and reached the low-pressure environments of surface rocks, silver, gold, copper, lead, vanadinite, wulfenite, and other minerals crystallized and filled the cracks. Subsequent injections of molten rock filled cracks in the granite and granodiorite, forming dikes. In the recrystallized zones along the margins of some dikes, precious and industrial metals formed.

The Old Yuma Mine (fig. 8) is the most famous mine with this type of mineralization in this area. Galena was the primary ore-bearing lead mineral, but spectacular vanadinite and wulfenite crystals were found in pockets carved by corrosive fluids. Additionally, the exotic assemblage of minerals found at the site included: anglesite; calcite; cerussite; chrysocolla; descloizite; fornacite; kermesite; malachite; mimetite; mottramite; palygorskite; plattnerite; quartz; and willemite (Kring 2002).

The sulfide minerals chalcopyrite, galena, pyrite, pyrrhotite, and sphalerite were found associated with similar but smaller magmatic intrusions at Saginaw Hill and the Sedimentary Hills (Kring 2002). At Saginaw Hill, the primary sulfide minerals were often oxidized to copper oxides, carbonates, and phosphates. Brightly colored secondary minerals from these reactions include turquoise and malachite. The oxidized zone at Saginaw Hill is one of the few localities in the world in which peacock-blue and copper-bearing cornetite are found, along with atacamite, brochantite, chrysocolla, covellite, libethenite, malachite, pseudomalachite, and quartz.

Tucson Mountains Dinosaur

The "Tucson Mountains dinosaur" was found near the park in a megabreccia block of the Amole Arkose approximately 550 m (1,800 ft) north-northwest of Gates Pass (Lucas et al. 2005). Historically thought to be an Early Cretaceous iguanodont, the dinosaur has been reinterpreted as a large hadrosaur (duck-billed dinosaur) that is restricted to strata of Late Cretaceous age in the American West (Lucas et al. 2005; Lucas and Heckert 2005).

Interpreting the dinosaur as Late Cretaceous has important stratigraphic significance. Prior to the re-designation, blocks of Amole Arkose were all thought to be freshwater equivalents of the marine members of the Lower Cretaceous Bisbee Group (Kring 2002). However, the sandstone matrix of the hadrosaur fossil represents a block derived from a younger, Upper Cretaceous horizon in the upper Amole Arkose. Finding an Upper Cretaceous megabreccia suggests that the caldera was still a depression and subject to landslide deposits well into the Upper Cretaceous.

Basin-and-Range Topography

Avra Valley, seen from the ridge along the Valley View Overlook Trail, is an example of a "graben," a sediment-filled basin typical of the Basin-and-Range Province (fig. 2). The uplifted block of rock that contains the Valley View Overlook Trail is called a "horst." Horsts form companion geologic structures to adjacent grabens (fig. 16). Rather than a basin carved by running water, Avra Valley is a tectonic basin formed by normal faulting. About 15 million years ago, the crustal rocks of this western part of North America were pulled apart in a northeast-southwest direction. As extension continued, some blocks of rocks subsided to form grabens, while others were uplifted, creating a landscape of relatively short narrow mountain ranges (i.e., the Tucson and Silverbell Mountains) separated by broad basins (i.e., the Avra Valley and Tucson Basin).

Total vertical movement on some of the normal faults is more than 3 km (2 mi). Thousands of feet of gravel, sand, silt, and clay eroded from the adjacent Tucson and Silverbell Mountains filled the Avra Valley graben. Later, the basin's sediments became saturated with rainfall and snowmelt. Today, this ancient groundwater is being extracted and pumped to Tucson.

Bajada

Flash floods and mudflows during the past several million years have transported gravel, sand, and silt from the canyons of the Tucson Mountains and deposited the rock debris as alluvial fans at the mouth of each canyon. As erosion continued to wear back the mountain front, these fan-shaped deposits coalesced to form a bajada, a continuous apron of alluvial material adjacent to the Tucson Mountains. The plain that slopes gently toward the Avra Valley is a bajada.

Desert Varnish

Petroglyphs on the Petroglyph Trail at the Signal Hill Picnic Area are etched on desert varnish, the black-colored substance on the surface of some of the harder rocks like granodiorite, basalt, and sandstone. Siltstone and shale tend to disintegrate too quickly to retain desert varnish. Typically less than 0.25 mm (0.01 in) thick, desert varnish is a coating formed by colonies of microscopic bacteria. The bacteria absorb trace amounts of manganese and iron from the atmosphere and precipitate the minerals as a black layer of manganese oxide or reddish iron oxide on the rock surface. Thin layers of desert varnish include clay particles that help shield the bacteria against desiccation, extreme heat, and intense solar radiation.

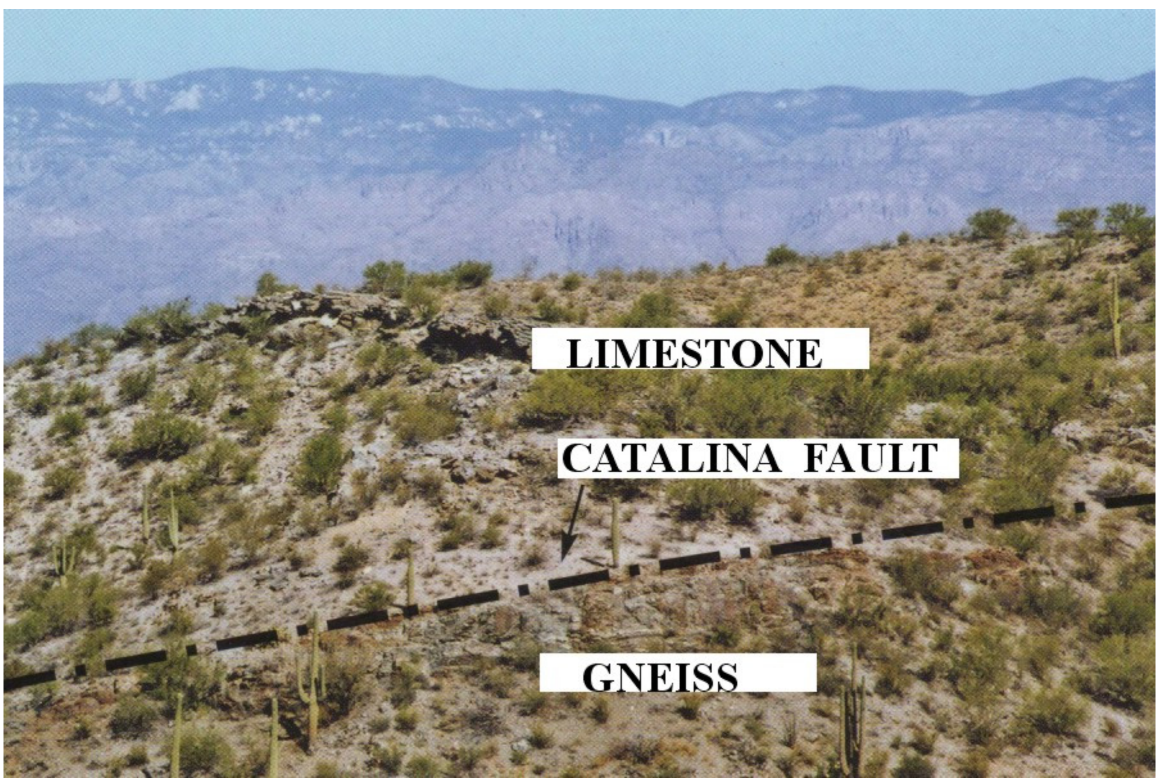


Figure 11. Santa Catalina Fault surface exposed near Cactus Forest Drive in the Rincon Mountain District, Saguaro National Park. The fault separates overlying, gray, Paleozoic-aged limestone from underlying, Precambrian gneiss. The Lime Falls Trail will be extended so that visitors may appreciate this rare exposure of the Santa Catalina Fault. Photograph modified from Bezy (2005).

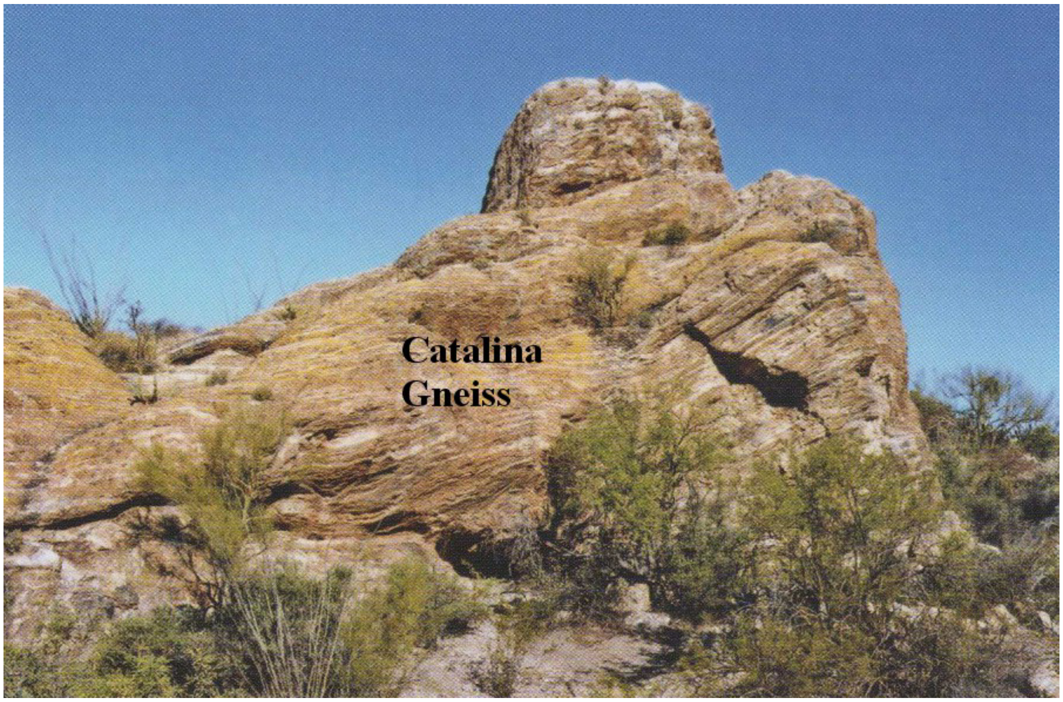


Figure 12. Lower-plate rocks of Catalina Gneiss (Wrong Mountain Quartz Monzonite and Continental Granodiorite) at the Javelina Rocks, Rincon Mountain District, Saguaro National Park. Photograph modified from Bezy (2005).

Figure 13. Minerals in the Catalina Gneiss are conspicuously banded, a characteristic of gneiss. National Park Service photograph by Kalyca Spinler (Saguaro National Park) courtesy of Laura Bolyard (Saguaro National Park).

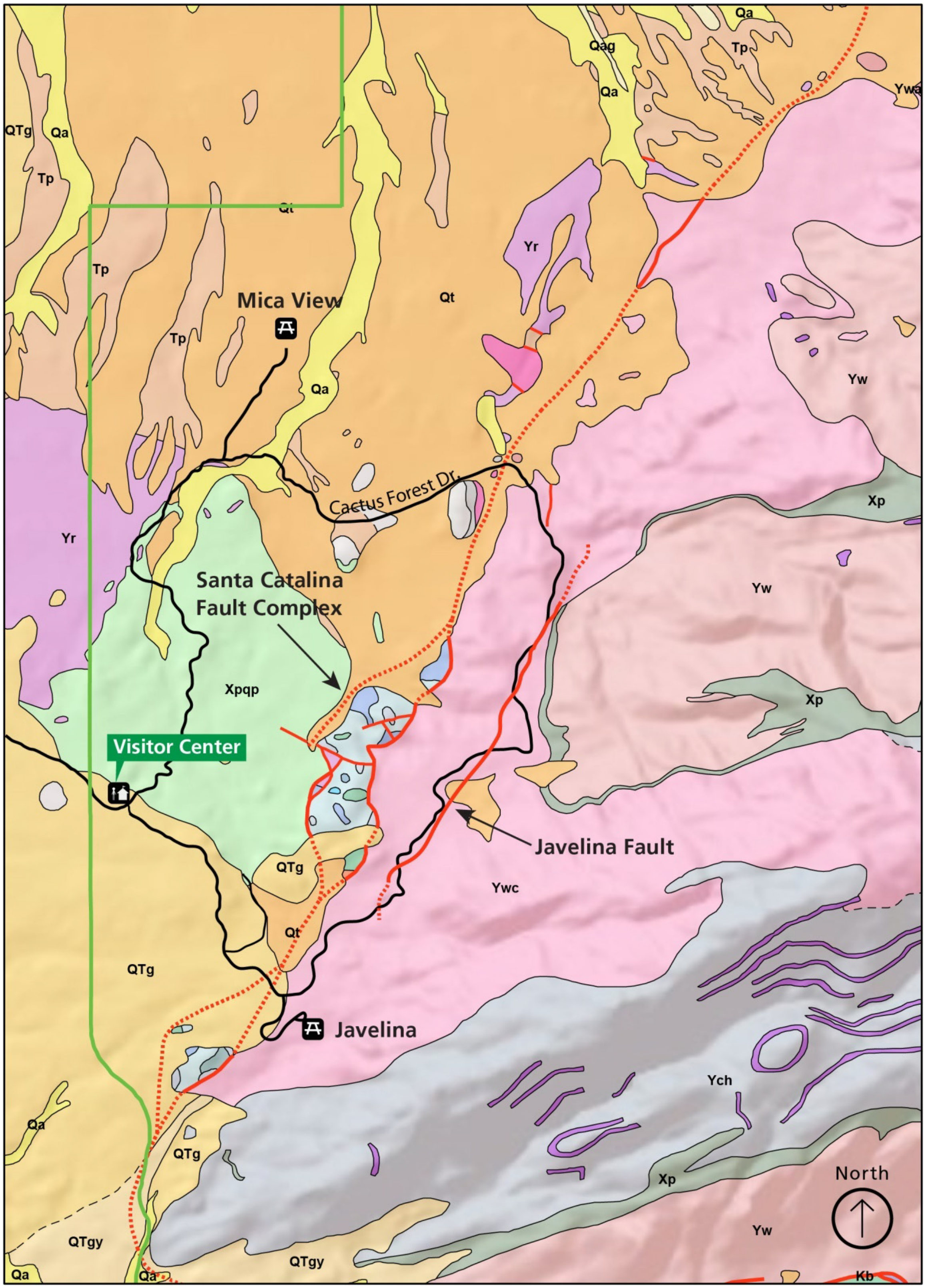


Figure 14. Location of the Javelina Fault in relation to the Santa Catalina Fault Complex, Rincon Mountain District, Saguaro National Park. Red lines represent the approximate location of each fault, dashed where not exposed on the surface. Geologic map unit symbols are described in the Map Unit Properties Table. Green line represents park boundary. Graphic by Phil Reiker (NPS Geologic Resources Division), compiled from GRI Digital Geologic Data of Saguaro National Park (Appendix A).

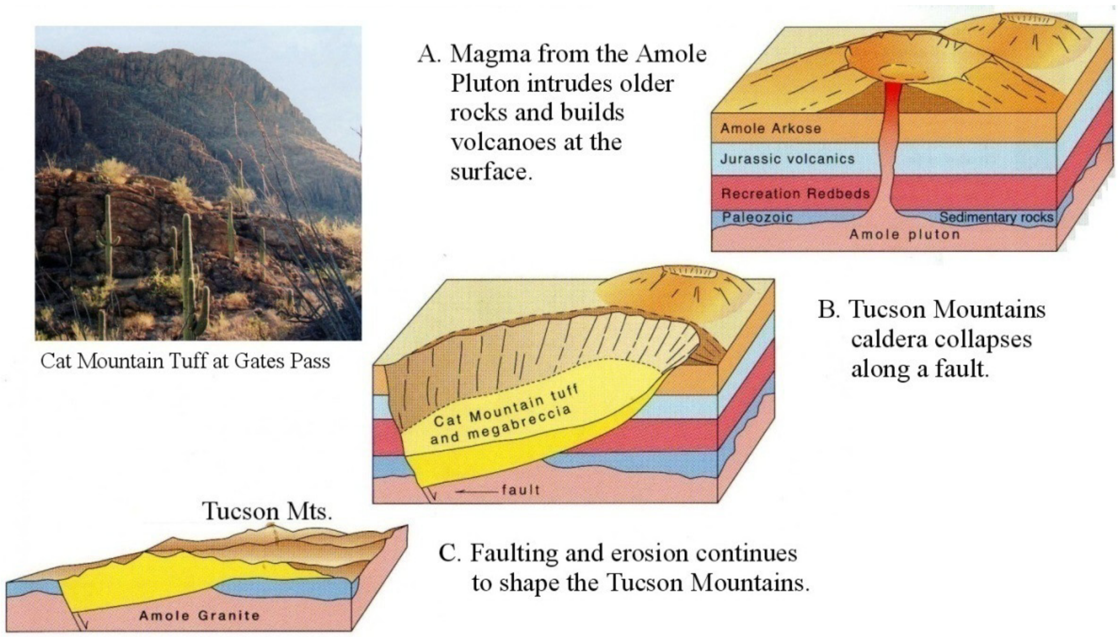


Figure 15. Evolution of the Tucson Mountains Caldera and deposition of the Cat Mountain Tuff. After the walls of the caldera collapsed, the caldera filled with hot glowing clouds of ash and pumice along with great slabs of older rock (megabreccia) eroded from the sides of the caldera. Intense heat fused the ash and pumice, which cooled to form the Cat Mountain Tuff. Diagram and photograph modified from Bezy (2005).

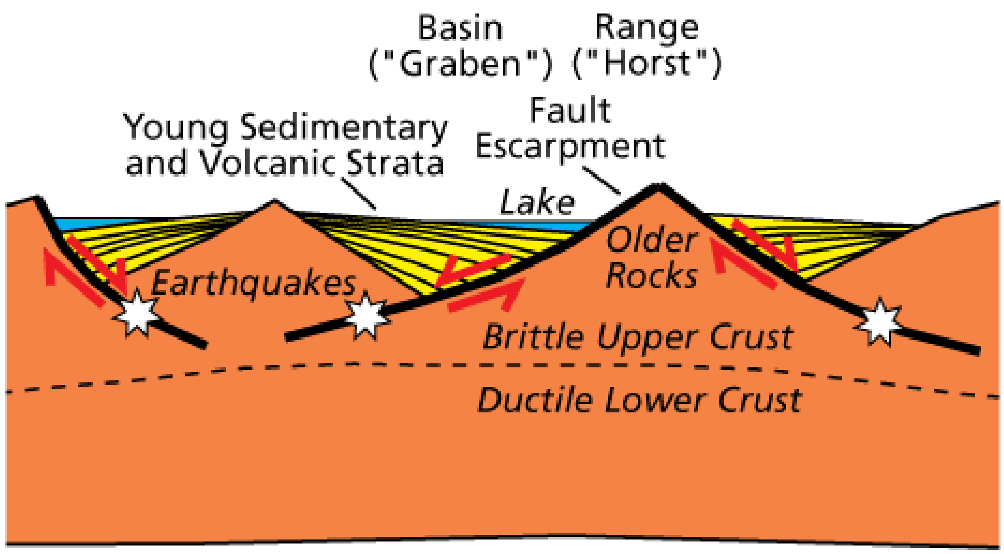


Figure 16. Horst and graben structure of the Basin-and-Range province. In this idealized cross-section, continental rifting forms horst (range) and graben (basin) topography typical of the southwestern United States. Sedimentary and volcanic strata tilt toward escarpments representing zones of normal faulting that bound grabens. The land surface also tilts, which may allow lakes to form against the fault escarpments. Since continental rifting began in the Miocene, the basins have filled with thousands of feet of unconsolidated sediment. Diagram courtesy of Dr. Robert Lillie, Oregon State University.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Saguaro National Park. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Saguaro National Park provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships among geologic features, other natural resources, and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps are not soil maps, and do not show soil types, but they do show parent material—a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 17) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table is conjectural and meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following references are the sources for the GRI digital geologic data for Saguaro National Park:

Drewes, H. 1977. *Geologic map and sections of the Rincon Valley quadrangle, Pima County, Arizona*. Scale 1:48,000. Miscellaneous Investigations Series Map I-997. Reston, VA: U.S. Geological Survey.

Drewes, H. 1974. *Geologic map and sections of the Happy Valley quadrangle, Cochise County, Arizona*. Scale 1:48,000. Miscellaneous Investigations Series Map I-832. Reston, VA: U.S. Geological Survey.

Lipman, P. W. 1993. *Geologic map of the Tucson Mountains Caldera, southern Arizona*. Scale 1:24,000. Miscellaneous Investigations Series Map I-2205. Reston, VA: U.S. Geological Survey.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, and increases the overall utility of the data. GRI digital geologic map products include data in coverage and shapefile GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map and connects the help file directly to the map document.
GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/). Data will be available on the Natural Resource Information Portal when the portal goes online. As of August 2010, access is limited to NPS computers at http://nrinfo/Home.mvc.

Eon	Era	Period	Epoch	Ma		Life Forms	North American Events
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Age of Mammals	Modern humans	Cascade volcanoes (W)
			Pleistocene	2.6		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary: Neogene	Pliocene	5.3		Large carnivores	Sierra Nevada Mountains (W)
			Miocene	23.0		Whales and apes	Linking of North and South America Basin-and-Range extension (W)
		Tertiary: Paleogene	Oligocene	33.9			
			Eocene	55.8		Early primates	Laramide Orogeny ends (W)
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic		199.6		First mammals	Elko Orogeny (W)
		Triassic		251		**Mass extinction** Flying reptiles First dinosaurs	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic	Permian		299	Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant	Ancestral Rocky Mountains (W)
		Mississippian		359.2		Variety of insects First amphibians	
		Devonian		416	Fishes	First reptiles **Mass extinction** First forests (evergreens)	Antler Orogeny (W) Acadian Orogeny (E-NE)
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian		542		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of proto-North America (Laurentia)
Proterozoic		Precambrian		2500		First multicelled organisms Jellyfish fossil (670 Ma)	Supercontinent rifted apart Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				≈4000		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean				4600		Origin of life? Formation of the Earth	Oldest moon rocks (4–4.6 billion years ago) Formation of Earth's crust

Figure 17. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Radiometric ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/ with additional information from the International Commission on Stratigraphy. http://www.stratigraphy.org/view.php?id=25.

Map Unit Properties Table: Saguaro National Park-Tucson Mountain District (Saguaro West)

Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Holocene)	Alluvium (Qal)	Sand, silt, and gravel. Locally includes small alluvial fan and colluvial deposits (**Qf**, **Qc**) at margins of valley bottoms. Deposited along streams and valley floors in the northern part of the park.	Low.	Low. Located in floodplains.	Flash flooding?	Potential animal remains.	Possible American Indian sites.	Sand and gravel.	Ephemeral stream channels susceptible to flooding.	Hiking ephemeral stream beds.	None.
	Colluvium (Qc)	Poorly sorted silt- to boulder-sized material. Grades downslope into **Qf**. Near-surface caliche zones locally well developed. Located on slopes and in steep valleys.	Silt: low. Caliche: high.	Limited areal extent; on slopes.	Unknown.	Potential animal remains.	Unknown. Outcrops limited in areal extent.	None documented.	Mix of boulders and lowland desert scrub.	Pack trails; Mam A-Gah Picnic Area.	None.
QUATERNARY (Pleistocene–Holocene)	Alluvial-fan deposits (Qf)	Gravel, sand, and silt in variable dissected fans. Locally contains moderately rounded to well-rounded boulders. Near-surface caliche zones locally well developed. Forms fan-shaped topography along the margins of valley bottoms.	Silt: low. Caliche: high.	Heavily developed with buildings (Old Tucson), roads, and pipelines.	Erosion may impact roads.	Potential animal remains.	Possible American Indian sites.	Sand and gravel.	Variety of lowland desert scrub plants (saguaro, cholla, prickly pear, barrel, ocotillo, creosote bush).	Arizona-Sonora Desert Museum; Desert Discovery Nature Trail; other trails.	None.
QUATERNARY (Pleistocene)	Older alluvial-fan deposits (Qfo)	Gravel, sand, and silt. May include some upper Tertiary fan deposits.	Low.	Roads and jeep trails build on fan deposits.	Erosion may destabilize structures.	Potential animal remains.	Possible American Indian sites.	Sand and gravel.	Variety of lowland desert scrub plants (saguaro, cholla, prickly pear, barrel, ocotillo, creosote bush).	Jeep trails; hiking; roads.	None.
TERTIARY (Oligocene)	Intrusive andesite (Tai)	Dark –gray andesite containing sparse small phenocrysts of plagioclase and pyroxene. Limited exposures.	High.	Not mapped in park.	Limited exposure.	None.	Not mapped in park.	Plagioclase, pyroxene.	Not mapped in park.	Not mapped in park.	None.
	Intrusive dacite (Tdi)	Gray to brown porphyritic dacite containing 10% to 20% phenocrysts of blocky plagioclase and altered biotite. Intrusion at Beehive Peak possibly related to similar dacite lava flow complex (**Tdr**) along the southern margin of USGS map I-2205 (Lipman 1993).	High.	Not mapped in park.	None documented.	None.	Not mapped in park.	Plagioclase, biotite.	Not mapped in park.	Not mapped in park.	None.
	Intrusive rhyolite (Tri)	Light tan to gray rhyolite; locally flow layered near contacts. Contains small phenocrysts of plagioclase and biotite, commonly altered.	High.	Linear features; not applicable.	Very limited exposures.	None.	Very limited exposures.	Plagioclase, biotite.	Very limited exposures.	Very limited exposures.	None.
	Volcanics of Tumamoc Hills (Tba, Tr, Tdr)	**Tba**: Basaltic andesite. Dark-gray, vesicular, olivine-bearing flows. Individual flows up to 25 m (82 ft) thick; overall thickness about 100 m (300 ft). Layered with **Tr** and **Tvs**. Basal flow at eastern margin of quadrangle is plagioclase "turkey-track" andesite. Potassium-Argon (K-Ar) radiometric ages are 20 to 29.5 million years old. **Tr**: Rhyolitic ash-flow tuff. Tan, partly welded silicic rhyolite; sparse small lithic frags, and a few quartz sanidine phenocrysts. K-Ar sanidine ages are 26 to 30 million years old. 25 m (82 ft) thick. **Tdr**: Dacite-rhyolitic lava flows or domes. Massive, grayish-brown, with about 15% phenocrysts of plagioclase and oxidized biotite. Unconformably overlies several units of Cat Mountain Tuff and postcaldera lava flows. Similar to **Tdi** dike at Beehive Peak. Exposed southeast of the park.	High.	Not mapped in park.	Rockfall?	None.	Not mapped in park.	Olivine; **Tba**: once used as building stone.	Not mapped in park.	Not mapped in park.	**Tba**: In part erupted from spatter cone 0.5 km (0.3 mi) east of map. **Tdr**: Younger than **TKb**.
	Safford Dacite (Tsf, Tsv, Tss, Tst, Tsm)	**Tsf**: Lava flows. Gray to light-brown dacite and rhyolitic lava flows with 10% to 20% phenocrysts of plagioclase, biotite, and augite. Individual flows are 25 to 100 m (82 to 300 ft) thick; most sections have only 1 or 2 flows; interflow contacts are mapped; flow horizons are numbered from oldest to youngest (**Tsf1** to **Tsf4**). K-Ar biotite ages are 39.5 million years old (**Tsf1**), 26.7 to 28.6 million years old (**Tsf2**), 25.1 million years old (**Tsf4**). Argon-Argon radiometric age (Ar/Ar) biotite age is 26.6 million years old (**Tsf1**). **Tsv**: Vent intrusions. K-Ar biotite age on **Tsf4** is probably valid for this vent. **Tss**: Vent splatter. Intermixed black glassy and red-brown devitrified lenses of near-vent dacitic splatter at head of Sunset Road. Vent concealed beneath alluvial-fan deposits to east. **Tst**: Tuffaceous rocks. White to light-gray and tan, nonwelded ash-flow tuff, airfall tuff, tuff breccia, and minor tuffaceous sedimentary rocks. Thickness 0 to 20 m (66 ft). K-Ar biotite age 25.9 ±1.4 million years old. **Tsm**: Mudflow deposits. Red-brown indurated conglomerates containing predominantly rounded clasts of Safford Peak dacitic lavas as much as 0.5 m (1.6 ft) in diameter. As much as 50 m (160 ft) thick in outcrops along the ridge between Panther and Safford Peaks.	High.	Unknown. Rugged terrane with ridge crests and steep slopes.	Unknown. Possible rockfall and landsliding.	Potential plant fossils in interbedded sedimentary layers.	American Indian pictographs; other sites possible.	Plagioclase, augite, biotite.	Lowland communities of desert scrub and desert grasslands.	Pictographs near Picture Rocks Road; pack trails.	**Tsv**; 2 necks were probably feeder for uppermost flow preserved only on east side of Safford Peak (**Tsf4**) and lowermost widespread flow (**Tsf1**).

Map Unit Properties Table: Saguaro National Park-Tucson Mountain District (Saguaro West). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
TERTIARY (Oligocene)	Volcaniclastic sedimentary rocks (Tvs)	Light gray to tan, bedded, reworked tuffaceous sediments; includes conglomerate containing clasts derived from **TKd** of Twin Hills. Interlayered with **Tba** and **Tr** lava flows. Broadly correlative with volcaniclastic units of the Safford Dacite. Thickness 0 to 30 m (98 ft). Exposed on Tumamoc Hill.	Variable.	Slope exposures; not in park.	Unknown.	None.	Not mapped in park.	None documented.	Not mapped in park.	Not mapped in park.	None.
TERTIARY (Oligocene and Eocene?)	Tertiary colluvium (Tc)	Indurated red-brown breccia and conglomerate, containing angular clasts of Cretaceous and Tertiary lavas; probably more widespread beneath lava flows than mapped. Poorly exposed beneath and between Tertiary lavas.	Low to moderate. Forms ledges.	Limited, insignificant slope exposures in northern part of park.	Possible minor rockslides.	None.	Unknown. Limited exposures.	None documented.	Limited exposures on slopes.	Insignificant to recreation use.	None.
		ROCKS OF THE TUCSON MOUNTAINS CALDERA CYCLE									
LOWER TERTIARY/ UPPER CRETACEOUS	Dikes and irregular intrusions (TKai, TKap, TKs, Kgp)	**TKai**: Andesite dikes. Dark-gray, sparsely porphyritic and aphanitic, containing small phenocrysts of plagioclase and augite. Northerly trending dikes may be mid-Tertiary. **TKap**: Porphyritic andesite. Gray, coarsely porphyritic; 61% to 62% quartz, containing 15% to 25% phenocrysts of plagioclase and altered mafic minerals. May be an irregular laccolith. Intruded semi-conformably along the **TKvs**-**TKd** contact. Exposed on north slope of Twin Hills, south of park. **TKs**: Porphyritic silicic dikes. Light gray to tan porphyritic rhyolite, dacite, and fine-grained granite (68% to 73% quartz). Locally flow layered near margins. Individual dikes up to 20 m (66 ft) wide and traceable along strike for up to 6 km (4 mi). May include small mid-Tertiary dikes, especially with northerly trends. One K-Ar age is 72.3 ±1.7 million years old. Silver Lily dike swarm. **Kgp**: Porphyritic granodiorite. Tan to light-gray, fine-grained, 63%-70% quartz; dikes and irregular plugs. Phenocrysts (10% to 30%) include plagioclase, potassium feldspar, quartz, and biotite. Most intrusions in northern Tucson Mountains may be offshoots of Amole pluton; some may be feeders for **Kyap**. Discontinuous alteration and disseminated weak copper mineralization. Exposed south of park in Saginaw Hill area.	High.	**TKai** and **TKs** are linear features with limited extent. **Tkai** and **Kgp** are Not mapped in park.	None. **Tkai** and **TKs** have limited areal extent.	None.	Minimal. Few exposures in the park.	Precious and industrial metals occur where dikes are in contact with Amole Arkose.	Limited exposures.	Insignificant to recreation use.	**TKs**: East-west trends typical for dikes associated with Laramide Orogeny.
LOWER TERTIARY/ UPPER CRETACEOUS	Volcaniclastic sedimentary rocks (post-collapse) (TKvs)	Well-bedded gray, tan, and buff volcaniclastic sandstone, shale, and local conglomerate; limited thickness and areal extent, lateral lithologic variability, occurrence at many stratigraphic horizons; generally poor exposure. Contains abundant detritus from underlying Cat Mountain Tuff. Thickness 0 to 50 m (160 ft); maximum thickness on northeast slope of Twin Hills, southeast of the park.	Variable.	Limited to a few outcrops in the northern part of the park.	None documented.	None.	Minimal. Few exposures in the park.	None documented.	Limited exposures.	Insignificant to recreation use.	None.
LOWER TERTIARY/ UPPER CRETACEOUS	Southeastern post-collapse volcanics (TKb, TKbi, TKa, TKd, TKdl, Kab)	**TKb**: Tuff of Beehive Peak. Light gray to tan, massive dacite ash-flow tuff (69% to 70% quartz) containing 35% to 45% phenocrysts of plagioclase, sanidine, resorbed quartz, and biotite. Abundant small, angular fragments of Cretaceous sandstone and intermediate-composition volcanic rocks. Mostly non-welded to weakly welded; compaction foliation commonly obscure. Nearly vertical compaction-flowage foliation of pumice well developed within a few tens of meters of **TKbi**. Age relations with respect to nearby postcaldera lavas, such as dacite of Twin Hills, uncertain due to lack of exposed contacts, but probably younger and unconformable. Designated Lower Tertiary or Upper Cretaceous because K-Ar biotite age (60.2 ±1.8 million years old) may be only a minimum age. **TKbi**: Tuff of Beehive Peak. Vent intrusion. Funnel-shaped intrusion of flow-layered dacite; similar to TKb except for no rock fragments. Well-developed flow layering, especially near contact with cogenetic tuff. **TKa**: Andesite. Local flow of dark-gray, sparsely porphyritic andesite (57.5% quartz). Contains a few small plagioclase phenocrysts, mostly replaced by calcite and other alteration products. Maximum preserved thickness 15 m (49 ft). **TKd**: Dacite. Massive, light-gray dacite lava flows (65% to 69% quartz), containing 20% to 35% phenocrysts of plagioclase, biotite, and hornblende. Most exposures consist of a single flow as much as several 100 m thick. Flow layering locally well developed near base of flows. Weakly propylitically altered throughout, suggesting that K-Ar biotite date (58.3 ±1.7 million years old) is a minimum age. Maximum preserved thickness 350 m (1,150 ft). **TKdl**: Dacite. Lower flow. Locally occurs on northeast slope of Twin Hills; interlayered with **TKvs**. **Kab**: Andesite. Dark-gray flows of porphyritic andesite (62% quartz). Phenocrysts (10% to 15%) of plagioclase, augite, and serpentine pseudomorphs after olivine(?). Thickness up to 50 m (160 ft).	Relatively high, but less resistant than welded tuff.	Not mapped in park. Exposed south of the park.	Not mapped in park. Exposed south of the park.	None.	Not mapped in park.	Plagioclase, sanidine, quartz, and biotite.	Not mapped in park.	Not mapped in park.	**TKb**: Local extent (a few sq km). Includes the abandoned names"beehive rhyolite" and "biotite rhyolite." Previously interpreted as intrusive. **TKd**: formerly called "Shorts Ranch andesite", but this name and designation are inappropriate and abandoned.
CRETACEOUS (Upper)	Amole Pluton (Kaa, Kag, Kad)	**Kaa**: Aplite. Dikes, sheets, and irregular veins of fine-grained aplite (77% quartz), consisting mostly of quartz and alkali feldspar. K-Ar biotite age 77.0 ±2.2 million years old. **Kag**: Granite. Light-pinkish-gray, medium-grained two-feldspar biotite granite (70% to 77% quartz). Contacts with granodioritic border are commonly gradational, but locally sharp. K-Ar biotite age 73.3 ±3.3 million years old. Interior of pluton. **Kad**: Granodiorite. Dark-gray, medium-grained, equigranular granodiorite (58% to 63% quartz), with abundant biotite. K-Ar biotite age 75 to 77 ±2 million years old; Ar/Ar biotite-orthoclase age 73.0 million years old. Border zone exposed on Amole Peak and Signal Hill.	High.	Steep slopes and peaks in western part of park; granite and granodiorite provide firm foundations.	None documented; potential rockfall.	None.	Possible American Indian sites; petroglyphs?	Sulfides, copper oxides, carbonates, phosphates.	Vegetation limited to slope wash and fractures; saguaro cactus, ocotillo, and creosote bush.	Hiking and pack trails (Hugh Norris Trail); Sus Picnic Area.	Contact and magmatic metamorphic mineralization of lava flows and sedimentary rocks.

Map Unit Properties Table: Saguaro National Park-Tucson Mountain District (Saguaro West). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
CRETACEOUS (Upper)	Volcanics of Yuma Mine (post-collapse volcanic rocks) (Kyap, Kya, Kyr, Kyrb)	**Kyap**: Porphyritic andesite. Dark-gray, massive andesitic-dacitic lava flows (62% to 63% quartz), with 20% to 30% phenocrysts of altered plagioclase and pseudomorphs after augite or orthopyroxene(?). Individual flows up to 100 m (300 ft) thick. **Kya**: Aphanitic andesite. Dark-gray, fine-grained andesitic lava flows (54% to 62% quartz), with 20% to 40% small phenocrysts of plagioclase, augite, and serpentine pseudomorphs after olivine or orthopyroxene. Individual flows as much as 100 m (300 ft) thick. **Kyr, Kyrb**: Aphanitic rhyolite and dacite. Tan to light-gray lava flows (69% to 73% quartz), with a few small phenocrysts of sanidine, plagioclase, and recrystallized biotite(?). Individual flows as much as 150 m (490 ft) thick. **Kyrb** is a flow breccia that surrounds a massive flow interior; only locally sufficiently large to map separately.	High.	Both steep and gentle slopes; currently has old mine workings and unpaved roads.	None documented; potential rockfall along steep slopes and ridges.	None.	Possible American Indian sites.	Plagioclase, augite, biotite, sanidine, serpentine; mineralized by magma forming the Amole Pluton.	Lowland communities of desert scrub and desert grasslands.	Remains of Old Yuma Mine; hiking trails.	**Kyr**: At least 5 flows present locally (**Kyr1** to **Kyr5**, oldest to youngest).
	Cat Mountain Tuff (caldera-forming rocks) (Kci, Kcw, Kcp, Kcn)	**Kci**: Intrusive rhyolitic tuff. Elongate dike-like mass of indurated (but little welded) light-greenish gray, massive tuff. Amole Arkose is locally deflected to nearly vertical attitudes near tuff dike, suggesting emplacement of dike from below. On trend with the Museum fault zone, possible caldera ring fault system; may represent ash-flow feeder dike or could represent fill or fracture in caldera floor. Truncates **Kb** 1.5 km (0.9 mi) northeast of Red Hills Visitor Center. **Kcw**: Densely welded rhyolite. Gray-brown to red-brown, massive, densely welded tuff, with dark lenses of flattened pumice, mostly 5cm to 10 cm (2 to 4 in) long but in places as much as 1 m (3 ft). Variable orientations of compaction foliation adjacent to megabreccia lenses. Flattened pumice lenses locally elongate in the plane of foliation and define a north-trending flowage lineation. Main cliff forming unit in the Tucson Mountains. **Kcp**: Partly welded rhyolite. Gray to light-brown tuff, containing weakly developed compaction foliation that occurs along cooling breaks within **Kcw**. Mapped separately from **Kcn** only locally (mainly between Cat Mountain and Gates Pass), where welding zonation is broad and well preserved; many cooling breaks are present. Grades into **Kcw**. Primarily exposed south of the Park. **Kcn**: Nonwelded to partly welded rhyolite. Light gray to tan tuff, lacking well developed compaction foliation. Conspicuously developed at the top of the Cat Mountain Tuff, where such less welded tuff is commonly 50 to 100 m (160 to 300 ft) thick, and also within and adjacent to megabreccia lenses and irregular masses. Many small areas of tuff within the megabreccia units are too small to show on the reference map scale. In the weakly welded tuff at the top of the Cat Mountain Tuff, multiple flow units are locally separated by thin horizons of bedded surge or airfall tuff.	Welded tuff is more resistant than partly or non-welded tuff.	Welded tuff should provide firm foundations; both steep and gentle slopes; currently contains trails and roads.	None documented; potential rockfall.	None.	Possible American Indian sites.	Specular hematite and magnetite at Wasson Peak.	Cliffs with high fracture content provide nesting habitat; slopes have abundant saguaro cactus, staghorn cholla cactus and creosote bush.	Hiking, pack trails; roads for sight-seeing.	First volcanic activity in Tucson Mountains. Bodies of tuffaceous matrix around megablocks deep within the Cat Mountain Tuff have previously been misinterpreted as irregular intrusions called “Amole latite”, That interpretation is now abandoned.
	Cat Mountain Tuff, Megabreccia Member (caldera-forming rocks) (Kcm, Kcmt, Kcma, Kcms, Kcmg, Kcmr, Kcmb, Kcmp)	**Kcm**: Undivided. Megabreccias that are lithologically diverse, poorly exposed, or limited in extent. In addition to the predominant clast types listed below, locally contains rare fragments of unit **Xp**. **Kcmt**: Mainly clasts of Cretaceous tuff. Gray clasts of tuff with large quartz and abundant biotite phenocrysts. Compaction foliation shows chaotic orientations. Can be difficult to distinguish from **Kad**. Exposed tuff of Confidence Peak and along the base of the western mountain front near Gates Pass could be slightly disrupted caldera wall rocks, rather than far-traveled landslide blocks. Some Confidence Peak clasts were likely included with the Cat Mountain Tuff. **Kcma**: Mainly clasts of Cretaceous(?) andesite and dacite. Dark-brown to gray blocks of lava, some porphyritic with phenocrysts of plagioclase and biotite (59% to 68% quartz$_2$). Clasts of “turkey-track” andesite with coarse tabular plagioclase phenocrysts are locally distinctive, especially in the West 32nd Street area and between the heads of Sweetwater Drive and Camino del Cerro. Likely southern parts of an assemblage now preserved farther north as the Silver Bell Volcanics that accumulated within and near the Silver Bell caldera after its collapse. Could also be an older Jurassic or Early Cretaceous andesitic-dacitic volcanic sequence, perhaps related to source of **KJvct**. **Kcms**: Mainly clasts of Cretaceous sedimentary rocks. Blocks of light-brown to greenish-gray, well-bedded arkosic sandstone, shale, and conglomerate. Most recognizable blocks are derived from the Lower Cretaceous(?) **Ka**, but large masses of volcanic conglomerate at the head of Kings Canyon may be correlative with the Upper Cretaceous Fort Crittenden Formation or with **KJvc** exposed locally on Brown Mountain. Bedding attitudes, shown for some large blocks, tend to vary irregularly in short distances. Some structurally coherent slab-like blocks as much as 500 m (1,600 ft) long have accumulated pseudo-conformably with respect to compaction foliation of enclosing ash-flow tuff, presumably because the slabs could raft into place “hover-craft” style, perhaps cushioned and lubricated by tuff erupting concurrently within the caldera. **Kcmg**: Mainly clasts of Jurassic-Cretaceous Glance Conglomerate. Blocks of conglomerate dominated by limestone cobbles derived from Paleozoic sedimentary rocks, in a gray to reddish-brown, sandy matrix. Clasts up to several meters in diameter are sparsely but widely distributed. **Kcmr**: Abundant clasts of Jurassic(?) flow-layered rhyolite. Blocks of phenocryst-poor, light gray to yellow, massive rhyolitic lava (76%-77% quartz), locally spherulitic and flow layered. Resembles Jurassic lava flows in Santa Rita Mountains. Most exposures are south of park. Forms resistant knobs around Gould Mine. Previously interpreted as intrusive into the Cat Mountain Tuff. **Kcmb**: Abundant clasts of Jurassic or Triassic Recreation Red Beds. Areas containing blocks of red-brown sandstone and siltstone as much as 50 m (160 ft) long, juxtaposed with diverse other Mesozoic and Paleozoic rock types. Smaller blocks of Recreation Red Beds distributed widely, but are weakly resistant to weathering and are commonly poorly exposed. Minor exposures. **Kcmp**: Abundant clasts of Paleozoic sedimentary rocks. Formations thus far identified include **Pcn**, **Pc**, **Prv**, **Ps**, **Pe**, **PPNh**, **Me**, **Dm**, **Cb**. Exposures limited to southern part of the park.	High.	Currently contains roads and trails.	None documented.	Hadrosaur fossils found in block of **Ka** megabreccia.	Possible American Indian sites.	None documented.	Rocky ground cover with ocotillo, creosote bush, and prickly pear cactus.	Jeep trails, pack trails, hiking trails.	**Kcma**: not confined to the mid-Tertiary, as once believed. In-place pre-caldera andesite-dacite lavas are not exposed in the Tucson Mountains but must have been present on the now-eroded and concealed walls of the Tucson Mountains Caldera.

Map Unit Properties Table: Saguaro National Park-Tucson Mountain District (Saguaro West). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
PRE-CALDERA ROCKS											
CRETACEOUS (Upper)	Sandstone and shale (Kss)	Unnamed arkosic gray sandstone, shale, and minor laminated limestone. Similar to the underlying **Kb**. Represents continuation of similar depositional processes after emplacement of the Confidence Peak tuff. Could be an upper unit of **Kb**. General absence of volcanic detritus is notable because volcanism was in process in the Silver Bell caldera area 30 km (19 mi) to the northwest during this time. Most of the unit has been metamorphosed to hornfels due to proximity to the Amole pluton; red-brown garnets up to 1 cm (0.4 in) across in limy sediments. Unconformably overlain by caldera-filling tuff and megabreccia. Overlies **Ktc** along ridge crest west of Amole Peak.	Variable.	Outcrops are northwest of the Sensitive Resource Area.	None documented; potential rockfall.	None.	Unknown.	None documented.	Lowland communities of desert scrub and desert grasslands.	Hugh Norris Trail.	Only non-volcanic Cretaceous sedimentary rocks that overlie Laramide-age silicic volcanic rocks in southern AZ.
	Tuff of Confidence Peak (Ktc)	Crystal-rich, gray, welded rhyolitic tuff with 25% to 40% quartz, feldspar, and biotite phenocrysts; erupted from the Silver Bell caldera 30 km (19 mi) northwest of the Tucson Mountains caldera about 73 million years ago. Distinguished from Cat Mountain Tuff by more biotite and larger quartz phenocrysts. Occurs widely in the Megabreccia Member of the Cat Mountain Tuff. Other in-place **Ktc** may be parts of megablock along west escarpment north of Gates Pass (south of Park).	High (welded tuff).	Limited exposures northwest of the Sensitive Resource Area.	None documented; potential rockfall.	None.	Unknown.	None documented.	Lowland communities of desert scrub and desert grasslands.	Crossed by Hugh Norris Trail.	Outcrops in sec. 25 are the only clearly in-place **Ktc**.
CRETACEOUS (Upper or Lower)	Amole Arkose (Ka)	Gray to brown siltstone, arkosic sandstone, and sparse conglomerate and finely laminated limestone. Unconformably overlies the Recreation Red Beds (**JTRr**). Considered correlative with the Lower Cretaceous Bisbee Group, but lithologic continuity with Upper Cretaceous sedimentary rocks that overlie **Ktc** suggests a partly or entirely Upper Cretaceous age. Complexly folded around gently plunging, northwest-trending axes. Detailed structural interpretations impeded by lack of marker beds. Structures shown on cross sections are greatly generalized and simplified. Deposited in lake-floodplain, lakeshore, delta, and alluvial fan environments. Thickness greater than 1,000 m (300 ft).	Sandstone and conglomerate more resistant than shale.	Forms King Canyon bottom, slopes, and ridge crest. Current developments include trails.	Rockfall? Potential flash flooding in canyon.	Freshwater gastropods and pelecypods; *Holestean* fish skeletons; algal mats; Hadrosaur remains found in megabreccia.	Potential American Indian sites, (exposures along ephemeral stream?).	Precious and industrial metals occur in contact with Silver Lily dike swarm.	Forms benches and rocky slopes with abundant creosote bush, prickly pear cactus, and saguaro cactus.	Hiking and jeep trails; Mam-A-Gah picnic area.	Fluvial and lake deposits.
CRETACEOUS/ JURASSIC	Volcanic conglomerate (KJvc)	Red-brown conglomerate and volcanic sandstone; abundant cobbles of dark-gray to purple andesite and dacite. The intermediate-composition volcanic clasts contrast with the bimodal basalt-silicic rhyolite assemblage lower in the section and regionally in the Jurassic rocks of southern Arizona. Exposed in fault slices on the crest and flanks of Brown Mountain, south of park, and isolated outcrops northwest of Red Hills Visitor Center.	Variable.	Limited to minor exposures along Kinney Road.	Minor rockfall potential?	None.	None documented; limited exposure.	None documented.	Lowland communities of desert scrub and desert grasslands.	Minor exposure on bedrock knobs along Kinney Road.	May indicate start of Cretaceous-continental arc volcanism.
JURASSIC	Andesite porphyry (Jai)	Dikes and irregular bodies of porphyritic andesite (56% quartz) containing 10% to 30% phenocrysts of plagioclase in "turkey track" texture. K-Ar (plagioclase) date at 159 ±5 million years ago. Exposed south of Arizona-Sonora Desert Museum.	High.	Only exposed south of park.	Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	
	Rhyolite and ash-flow tuff (Jt)	Nonwelded to partly welded, pinkish-tan rhyolitic ash-flow sheet. Small and sparse pumice lapilli so compaction foliation is commonly obscure. Welding zonation is well developed; becomes less welded upward. Some quartz and altered feldspar phenocrysts; lithic fragments rare. Up to 50 m (160 ft) thick. Underlies **KJvc** on Brown Mountain. Bedrock knobs northwest of Red Hills Visitor Center.	High, but less than welded tuff.	Limited exposure.	Minor rockfall potential?	None.	None documented; limited exposure.	None documented.	Lowland communities of desert scrub and desert grasslands.	Isolated exposure on bedrock knobs.	
	Sandstone (Js)	Reddish sandstone and siltstone. Stratigraphic relations with the **Jt** and **Jlt** ash-flow sheets, and also with inferred higher and lower sedimentary units (**KJvc**, **JTRr**) remain uncertain due to limited outcrop area, lack of diagnostic marker horizons, and probable bounding faults. Minor exposures. Bedrock knobs northwest of Red Hills Visitor Center.	Less resistant than welded tuff.	Limited exposures.	Limited exposure.	None.	None documented; limited exposure.	Limited exposure.	Lowland communities of desert scrub and desert grasslands.	Isolated exposure on bedrock knobs.	Jurassic volcanic activity.
	Lithophysal ash-flow tuff (Jlt)	Densely welded ash-flow sheet with silica-filled lithophysal cavities a few cm in diameter in lower part and well-developed pumice compaction foliation near top. Altered outlines of phenocrysts increase upward. About 25 m (82 ft) thick. Exposed southwest of Arizona Sonora Desert Museum.	High.	Only exposed south of the park.	Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	
	Basaltic ash-flow tuff (Jb)	Vesicular, dark-gray olivine basalt (50% quartz). Locally greenish due to abundant alteration of epidote. Thickness 10 to 20 m (33 to 66 ft). Exposed southwest of Arizona Sonora Desert Museum.	High.	Only exposed south of park.	Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	
TRIASSIC/ JURASSIC	Recreation Red Beds (JTRr)	Red-brown mudstone, siltstone, and some interlayered sandstone. Includes tuff member and volcanic conglomerate member. Exposed at Red Hills and Brown Mountain.	Low.	Southeast of Sensitive Resource Area (no access).	Rockfall?	Potential trace fossils.	Potential American Indian sites.	Piedmontite in tuff.	Reddish soil with saguaro cactus, staghorn, barrel, teddybear cholla, and creosote bush.	Hiking near Red Hills Visitor Center and in Red Hills.	Records volcanic activity and fluvial/alluvial deposition.

Map Unit Properties Table: Saguaro National Park-Tucson Mountain District (Saguaro West). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
PERMIAN	Rainvalley Formation (Prv)	Thin-bedded limestone, dolomite, and sandstone; more than 30 m (100 ft) thick. Crops out at Snyder Hill, south of Park.	High.	Not mapped in park.	Not mapped in park.	Unknown.	Not mapped in park.	None documented.	Not mapped in park.	Not mapped in park.	
	Concha Limestone (Pcn)	Dark-gray, cherty, fossiliferous limestone. A common clast type in the Megabreccia Member of the Cat Mountain Tuff. More than 20 m (66 ft) thick. Crops out at Snyder Hill, south of park. Neither base nor top exposed.	High.	Not mapped in park.	Not mapped in park.	Marine invertebrates?	Not mapped in park.	None documented.	Not mapped in park.	Not mapped in park.	Part of carbonate shelf developed in SE Arizona.
	Scherrer Formation (Ps)	Light-brownish-gray, fine grained quartzite. Exposed near Sus Picnic area.	High.	Limited exposure.	None.	Potential marine invertebrates and burrows.	Very limited exposure.	None documented.	Minor exposures. Not applicable.	Minor exposures. Not applicable.	
PENNSYLVANIAN	Horquilla Limestone (PPNh)	Light-gray, fine-grained, thin-bedded cherty limestone and intercalated siltstone and dolomitic limestone. Forms ridge crest near Sus Picnic Area. Exposed at Twin Peaks, northwest of park.	Relatively high.	Limited exposure.	Minor rockfall potential?	Potential foraminifera, marine invertebrates, conodonts, and fish.	None documented; very limited exposure. Chert may have been used by American Indians.	Chert.	Minor exposures. Not applicable.	Outcrops adjacent to Kinney Road; roadside geology.	Permian and Pennsylvanian units are transitional between open marine and subaerial environments.
MISSISSIPPIAN (Lower-Middle)	Escabrosa Limestone (Me)	Light-gray, coarse, cherty limestone, crinoidal limestone. In park, exposed in fault block near Sus Picnic area and along Kinney Road. Minor slope deposits in isolated knobs of bedrock exposed at Twin Peaks, northwest of park. Thickness 35 m (115 ft) at Twin Peaks.	High.	Limited exposure.	None.	Potential crinoids and other marine invertebrates. Fossil coral in park collections may have come from **Me**.	None documented; very limited exposure.	Mined for cement.	Minor exposures. Not applicable.	Minor exposures. Not applicable.	Records maximum transgression from Antler Orogeny.
DEVONIAN (Upper)	Martin Formation (Dm)	Brown dolomite. Clasts in the Megabreccia Member of the Cat Mountain Tuff are metamorphosed to dark green and black hornfels near the Amole Pluton. In-place exposures only at Twin Peaks.	High.	Not mapped in park.	None.	None.	Not mapped in park.	Mined for cement.	Not mapped in park.	Not mapped in park.	Platform dolomite from marine transgression.
CAMBRIAN	Abrigo Formation (Ca)	Shale and sandstone, exposed only at Twin Peaks. Mapped in Rincon Mountain District.	Variable.	No outcrops in Tucson Mtn. District.	None.	Rare trilobites, brachiopods and trace fossils.	No outcrops in Tucson Mtn. District.	None documented.	No outcrops in Tucson Mtn. District.	No outcrops in Tucson Mtn. District.	Subtidal and intertidal units.
	Bolsa Quartzite (Cb)	Massive, vitreous, tan quartzite; occurs as clasts in the Megabreccia Member of the Cat Mountain Tuff. In-place exposures only at Twin Peaks. Mapped in Rincon Mountain District.	High.	No outcrops in Tucson Mtn. District.	None.	Potential trace fossils (*Skolithos*) and rare brachiopods.	No outcrops in Tucson Mtn. District.	None documented.	No outcrops in Tucson Mtn. District.	No outcrops in Tucson Mtn. District.	Transition from broad plain to tidally influenced river sediments.
PRE-CAMBRIAN (Proterozoic)	Porphyritic granite (Yg)	Light-tan, medium-grained muscovite-bearing granite, containing phenocrysts of potassium feldspar. Exposed on southern slopes of Twin Peaks.	High.	Not mapped in park.	None.	None.	Not mapped in park.	Potassium feldspar; muscovite.	Not mapped in park.	Not mapped in park.	Precambrian history.
PRE-CAMBRIAN (Archean)	Pinal Schist (Xp)	Fine-grained, gray-green quartz sericite schist exposed in place on the west side of Twin Peaks; forms sparse clasts in the Megabreccia Member of the Cat Mountain Tuff. Mapped in Rincon Mountain District.	Less resistant than granite.	No outcrops in Tucson Mtn. District.	None.	None.	No outcrops in Tucson Mtn. District.	Unknown.	No outcrops in Tucson Mtn. District.	No outcrops in Tucson Mtn. District.	Oldest rock exposed in southeastern Arizona.
AGE UN-CERTAIN	Quartz vein (qtz)	Quartz vein.	High.	Linear feature; limited extent for infrastructure.	None.	None.	Quartz may have been utilized by American Indians.	Quartz.	Not applicable.	Not applicable.	None.

Map Unit Properties Table: Saguaro National Park-Rincon Mountain District (Saguaro East)

Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY (Holocene)	Alluvium (Qay, Qas, Qa, Qag)	**Qay**: Gravel and minor sand. Poorly sorted and bedded, unconsolidated. Not mapped in park. **Qas**: Silt and sand, with minor gravel. Generally humus-rich and gray, locally contains efflorescence of carbonate and is white; poorly sorted and bedded; unconsolidated to slightly indurated. Surface capped by immature reddish-brown soil. Commonly 0.6 to 6 m (2 to 20 ft) thick. **Qa**: Sand, gravel, and silt. Grayish-brown, poorly sorted and bedded; unconsolidated to slightly indurated. Thickness commonly 0.6 m to 6 (2 to 20 ft). **Qag**: Gravel and sand. Grayish-brown, poorly sorted and bedded; unconsolidated. Not mapped in park.	Low.	**Qa** and **Qas** are minor linear features in the northwestern part of the park; stream channel deposits	**Qa**: floodplain; potential flash flooding.	Potential animal remains.	Possible American Indian artifacts buried in alluvium?	Placer deposits? Sand and gravel.	Ephemeral streams; Sonoran Paloverde mixed cacti/semidesert grassland- and mixed scrub.	Crossed by hiking trail and road; near picnic area.	**Qay**: youngest deposits along San Pedro River and lower reaches of its tributaries.
QUATERNARY (Pleistocene)	Terrace gravel deposits (Qt, Qts, Qtl)	**Qt**: Brownish-gray gravel and intercalated sand; generally coarser than underlying deposits; moderately well-sorted; poorly bedded; subrounded clasts; locally indurated by caliche. Unconformable on older gravels (**QTg** and **QTgy**). Thickness commonly 0.6 to 3 m (2 to 10 ft). **Qts**: Brownish-gray gravel; generally coarser than underlying deposits; well sorted; poorly bedded; unconsolidated; mostly subrounded clasts, including rhyolitic to trachytic volcanic rocks, most derived from up the San Pedro River but some of which are from the upper reaches of Tres Alamos Wash. Thickness commonly 0.6 to 6 m (2 to 20 ft). Not mapped in park. **Qtl**: Locally derived. Not mapped in park.	Low, except where locally indurated by caliche.	**Qt**: foundation for houses and roads in subdivisions.	None documented.	Potential animal remains.	Possible American Indian sites.	Sand and gravel.	Sonoran Paloverde mixed cacti/semidesert grassland-mixed scrub.	Picnic areas; Loma Verde Mine.	None.
	Pediment and alluvial deposits (Qp, Qpa, Qpf)	**Qp**: Pediment deposits. Brownish-gray gravel; moderately coarse-grained; poorly bedded; locally indurated by caliche, which is particularly abundant near Cornfield Canyon. Unconformable on older alluvial deposits. Thickness commonly 0.6 to 15 m (2 to 50 ft). **Qpa**: Alluvial deposits. Gray to pinkish-gray gravel; mostly poorly sorted; poorly to moderately well-bedded; weakly indurated. Includes some boulder fan deposits and debris-flow deposits near the Rincon Mountains. Thickness 15 to 122 m (50 to 400 ft). Exposed along margin of San Pedro Valley; not separable from **Qp** south of Ash Creek Canyon or from **QTs** in the San Pedro Valley. **Qpf**: To west, thick deposit of gravel with subrounded clasts; to east, gravel deposits with subrounded clasts thin or are absent.	Low except where locally indurated by caliche.	Roads and ranch buildings. Not mapped in park.	Not mapped in park.	Potential animal remains.	Not mapped in park.	None documented.	Not mapped in park.	Not mapped in park.	None.
QUATERNARY / TERTIARY (Pleistocene and Pliocene)	Gravel, grus and sand (QTgy)	Pediment, terrace, and basin deposits; beveled by a lower and more dissected surface than is the underlying gravel (QTg). Rincon Valley Quadrangle. Exposed in far southwestern corner of the park (sections 4 and 5, T15S, R16E).	Low.	Abundant roads outside of park.	None.	Potential animal remains.	Minor exposure; limited potential.	Sand and gravel.	Lowland desert scrub and grasses.	Minor exposures. Not applicable.	None.
	Facies border (QTgf)	Gradational and interfingering facies contact (2-dimensional feature) marking the contact between round pebble gravel derived mainly from far upstream and subangular-pebble gravel derived locally. Mapped on the Rincon Valley Quadrangle. Contact lies southwest of the park and on the west side of the Vail Fault. Significant as a contact between 2 facies.									
	Gravel, grus, and sand (QTg)	Clasts mostly of angular to subangular cobbles that consist largely of gneissic rocks from the core of the Rincon Mountains. Limited to area south of park Headquarters building, along western border.	Low.	Headquarters building; roads.	None documented.	Potential animal remains.	Minor exposure; limited potential.	Sand and gravel.	Mixed cacti-mixed scrub.	Roads; hiking trails.	None.
	Rubble deposits (QTgl)	Coarse blocks in jumbled disorder. Older deposits locally capped by reddish-brown soil; younger deposits have typical hummocky surfaces. Those shown with slump scarp symbol may still be active intermittently. Rincon Valley Quadrangle. Isolated deposits in central and eastern part of park.	Low. Landslide or slump masses if disturbed.	Slump deposits may reactivate; remote exposures.	Landslides may reactivate.	Potential animal remains.	Potential American Indian sites near springs.	None.	Landslide ecosystem.	Hiking and pack trails; Spud Rock campsite.	None.
QUATERNARY/ TERTIARY (Lower Pleistocene and Pliocene)	Formation of St. David Area (QTss, QTsmh, QTsm, QTst, QTsl)	**QTss**: Center facies. Silt, clay, and some intercalated sand and fine-grained gravel; poorly bedded; poorly to slightly indurated; locally has gypsiferous efflorescence. Some clay may be from volcanic ash. Thickness at least 30 m (100 ft). Weathers to badland topography. **QTsmh**: Base of pale-orange-gray conglomeratic sand. **QTsm**: Margin facies. Fine-grained gravel and conglomerate, some silt and sand; moderately well sorted and bedded; grades from pink gravelly silt near center facies (**QTss**) to grayish-pink sandy gravel near the mountains; may include some younger alluvial deposits (such as **Qpa**) in Happy Valley. Marker horizon near mouth of Redrock Creek. **QTst**: Rhyolitic tuff. Very light gray crystal-poor tuff. Exposed along lower reaches of Paige Canyon. Thickness 0.3 to 1 m (1 to 3 ft). **QTsl**: Largely very coarse blocky landslide deposits. Age uncertain.	Low for poorly indurated fine-grained sediments; higher for gravel and conglomerate.	Not mapped in park.	None documented.	Potential animal remains.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Deposits in San Pedro Valley on gentle sloping topography.
TERTIARY (Pliocene?)	Gravel and conglomerate (Tg)	Gray to pinkish-gray generally coarse-grained moderately indurated gravel and conglomerate. Contact relation to next older rock unknown. Local exposures in northeastern Happy Valley Quadrangle.	Moderately indurated.	Not mapped in park.	None.	Potential animal remains.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	None.

Map Unit Properties Table: Saguaro National Park-Rincon Mountain District (Saguaro East). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
TERTIARY (Miocene)	Nogales Formation (Tn)	Gravel and sand, semi-indurated; locally derived thick fan deposit in southeastern Rincon Valley Quadrangle; thin channel deposit 3 km (2 mi) northeast of Mountain View. Minor area mapped along east boundary of park.	Semi-indurated.	Not mapped in park.	None.	None.	Not mapped in park.	Not mapped in park.	Not exposed in Park	Not mapped in park.	None.
TERTIARY (Miocene and Oligocene)	Pantano Formation (Tp) (Members: Tpcg, Tpa, Tpuf, Tpc, Tpu, Tplf, Tpl)	**Tp**: Clastic sedimentary rocks ranging in coarseness from megabreccia to claystone, mostly moderately well sorted and indurated. Clasts mainly subrounded pebbles and some cobbles of Mesozoic and Paleozoic sedimentary rocks and Precambrian granodiorites; locally derived from Tertiary volcanic rocks. May be 3,500 m (11,500 ft) thick in the subsurface near the southwestern corner of the quadrangle. **Tp** is mapped within the park. The members below are only differentiated in the southern part of Rincon Valley Quadrangle. They are not exposed in the park: **Tpcg**: Reddish-gray pebble conglomerate and some siltstone and sandstone; moderately well sorted and indurated. Unconformable on underlying rocks. **Tpa**: Dark-gray andesite that contains large plagioclase phenocrysts. Also informally referred to as turkey-track porphyry. **Tpuf**: Upper fanglomerate and conglomerate. Mainly boulder and cobble conglomerate; some thin beds of sandstone. May contain masses of monolithologic sedimentary breccia – blocks rarely more than 1 m (3 ft) across, unsorted and mostly unbedded; clasts derived from **Yr**; probably of fanglomerate and landslide origin. Grades laterally to fine-grained deposits. **Tpc**: Claystone, mudstone, shale, and some sedimentary breccia; very locally contains bedded chert, limy siltstone, and tuffaceous sandstone. Indurated to very weakly indurated. Gypsum veinlets in places. Grades laterally into coarser grained rocks. Megabreccia: blocks commonly 1 to 5 m (3 to 16 ft) across derived from: **Tra, Trl, Trt, Tri, Dm, Ca, Cb, Yr**. **Tpu**: Undivided deposits of Tpuf and Tpc. **Tplf**: Lower fanglomerate and conglomerate. Mainly coarse fluvial deposits; some intercalated sandstone and siltstone. **Tpl**: Alternating thin beds of gray oolitic limestone, sandstone, and siltstone.	Indurated to weakly indurated. Coarse sediments are more resistant than fine sediments.	Isolated exposures located primarily on lower slopes, forming relatively flat, lowland topography in northwestern part of the park.	None documented.	Potential for reworked fossils from older layers.	Limited areal extent; unknown potential for American Indian sites.	**Tpc**: Quarried for brick making.	Sonoran Paloverde mixed cacti/semidesert grassland- and mixed scrub.	Limited areal extent; near picnic area west of Loma Verde Mine.	**Tpcg**: Probably correlative with the Mineta Formation 3 to 8 km (2 to 5 mi) north of the Happy Valley Quadrangle and with the Threelinks Conglomerate 3 to 6 km (2 to 4 mi) northeast of the quadrangle.
TERTIARY (Oligocene and younger)	Carbonate dike or vein (Tca)	Thick sheet of carbonate containing fragments of carbonate rocks probably derived from Paleozoic formations. Inferred to be derived from a thrust plate beneath the Rincon Valley Granodiorite and emplaced as a clastic dike during gravity gliding or low-angle normal faulting. Mapped as a linear feature in the Rincon Valley Quadrangle.	Relatively high.	Not mapped in park.	None.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Unknown.
TERTIARY (Oligocene)	Rhyolite and rhydodacite (Trd)	Includes finely porphyritic dikes near Ash Creek Canyon and coarsely porphyritic dikes north of Redrock Creek, Happy Valley Quadrangle. Linear features.	Relatively high.	Not mapped in park.	None.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Unknown.
	Rhyolitic agglomerate (Tra)	Clasts of rhyolitic welded tuff, commonly 5 to 20 cm (2 to 8 in) across, in a tuffaceous or siltstone matrix. May include some volcanic conglomerate. Minor outcrops in the northwestern part of the Rincon Valley Quadrangle.	Matrix variable.	Too limited to be applicable	None.	None.	Limited areal extent.	None.	Mixed cacti/ semidesert vegetation.	Crossed by Cactus Forest Drive.	One outcrop near park Headquarters.
	Rhyolitic lava flow (Trl)	Grayish-red lava flow at Twin Hills, just west of the western border of the park, probably near a vent that was a source of the tuff breccia and agglomerate of the northwestern corner of the Rincon Valley Quadrangle.	High.	Not mapped in park.	None.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not a unit on Drewes' map.
	Rhyolitic tuff breccia (Trt)	Very light gray to very pale orange crystal lithic tuff; in places contains small fragments of andesite. May be as old as tuff from a site 1 km (0.6 mi) south of the map and 4 km (2.5 mi) southeast of Mountain View, which is dated at 33 and 37 million years old. Exposures limited to south of Loma Verde Mine, Rincon Valley Quadrangle.	Relatively high.	Too limited to be applicable.	None.	None.	Limited areal extent.	None.	Mixed Sonoran Paloverde cacti and semidesert grassland- scrub.	Minor exposures next to Cactus Forest Drive.	Unknown.
	Porphyritic andesite (Tat)	Lava flows and some pyroclastic rocks with abundant large plagioclase phenocrysts. In places contains intercalated conglomerate similar to **Tplf**. Limited exposures south and east of Loma Verde Mine. Forms relatively flat topography.	High.	Too limited to be applicable.	None.	None.	Limited areal extent.	None.	Similar to **Tra** and **Trt**.	Poor exposures; crossed by roads.	Turkey-track porphyry.
	Intrusive rhyolite (Tri)	Three small necks of rhyolitic porphyry in the southern part of the Rincon Valley Quadrangle; few small dikes. Minor exposures near Loop Road, and east of Mica Mountain.	High.	Too limited to be applicable.	None.	None.	Very limited areal extent.	None.	Surrounded by Douglas fir-mixed conifer.	Not applicable.	Probable vents for **Tp** tuffs.
	Happy Valley Granodiorite (Th, Tha)	**Th**: Moderately coarse-grained massive biotite granodiorite. Locally contains faint flow-aligned crystals. Exposed as an intrusion south of Watkins Ranch, Happy Valley Quadrangle. **Tha**: Aplite (same description as **Th**).	High.	Steep terrane; not exposed in park.	Rockfall? Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Post-thrust intrusion.

Map Unit Properties Table: Saguaro National Park-Rincon Mountain District (Saguaro East). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
TERTIARY (Oligocene to Paleocene)	Diorite (Td)	Small dikes of unmetamorphosed nongneissic dioritic rocks near Joaquin Canyon along the northern edge of the Rincon Valley Quadrangle, north of the park boundary, and other scattered localities. Mapped as linear features.	Relatively high.	Not mapped in park.	None.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.
ROCKS OF THE LARAMIDE ALLOCHTHON (Units that have been moved from their original depositional site and now lie above the surface of the Santa Catalina fault in Saguaro National Park. "Upper Plate" rock units.)											
CRETACEOUS (Lower)	Bisbee Group (Kb): Schellenberger Canyon Formation (Ks)	**Kb**: The Bisbee Group consists of Upper Plate rock units mostly exposed west of Sentinel Butte and east of Camino Loma Alta Road. Minor exposures in sections 32 and 33, T14S, R16E. **Ks**: Gray to red shale, sandstone, and some fine-grained light-gray laminated limestone. Estimated preserved thickness less than 100 m (300 ft). Limited exposures.	Shale is less resistant than sandstone.	Unimproved roads.	None documented.	Potential algal laminations? *Trigonia* (marine clam) and vertebrates.	Unknown.	None documented.	**Kb**: semidesert mixed grass-mesquite vegetation types.	Unimproved roads leading to Deer Camp; Hope Camp Trail.	**Kb**: Type section is near Bisbee, AZ. East of the park, **Kb** is not part of the allochthon. **Ks**: Tidal flat and fan delta units signify a Late Cretaceous transgression. **Kw** and **Kbg** are proximal alluvial fan systems.
CRETACEOUS (Lower)	Bisbee Group (Kb): Willow Canyon Formation (Kw)	Gray to red sandstone, conglomerate, and siltstone. Conglomerate clasts mainly of Paleozoic limestone and chert; some sandstone is from the lower part of **Kb**. Estimated preserved thickness more than 800 m (2,600 ft). Southern Rincon Valley Quadrangle.	Variable.	Not mapped in park.	Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	
CRETACEOUS (Lower)	Bisbee Group (Kb): Glance Conglomerate (Kbg)	Basal cobble and pebble conglomerate; probably lenticular. Clasts of Paleozoic rocks and locally of Precambrian rocks. Estimated maximum thickness 150 m (490 ft). In the Canelo Hills, **Kbg** interfingers with radiometrically dated Jurassic volcanic rocks. One minor exposure mapped in the park near the Freeman Homestead Trail (map symbol **Kg** on Map I-997).	Relatively high. Minor exposure.	Limited exposure; not applicable.	None.	May include fossils from older units, such as **Pcn** brachiopods.	Very limited exposure; probably not applicable.	None.	Semidesert mixed grass-mesquite vegetation.	Too minor to be applicable; near Freeman Homestead Trail	
CRETACEOUS (Lower)	Bisbee Group (Kb): Limestone block (Kls)	Probably a landslide mass derived from Paleozoic rocks.	High, unless disturbed.	Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	
TRIASSIC	Walnut Gap Formation (JTRw)	Includes volcanic conglomerate, arkose, quartzitic sandstone, and some vesicular andesite. Lies with probable angular unconformity on underlying formations. Estimated preserved thickness is at least 300 m (1,000 ft). Exposed only on eastern edge of the Happy Valley Quadrangle.	Relatively high.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not part of Laramide allochthon; correlative with **JTRr**.
PALEOZOIC (Undivided)	Sedimentary rocks, undivided. (PZs)	Metamorphosed sequence of marble, hornfels, and metaquartzite, and an unmetamorphosed sequence of limestone, dolomite, shale, and sandstone. Exposed in normal faulted blocks of Upper Plate rocks. May include some Bisbee Fm and Apache Group.	High.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.
PERMIAN	Concha Limestone (Pcn)	Medium-gray fine-grained medium- to thick-bedded cherty limestone. Estimated preserved thickness about 70 m (230 ft). Found in normal faulted blocks of Upper Plate rocks. Minor outcrop in Rincon Mountains about 1.6 km (1 mi) east of the park.	High.	Not mapped in park.	Not mapped in park.	Some large productid brachiopods.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Permian strata is transitional between open marine and subaerial environments.
PERMIAN	Scherrer Formation (Ps)	Very light brownish gray fine-grained quartzite and sandstone; some light-gray dolomite. Estimated preserved thickness about 120 m (390 ft). Found in normal faulted blocks of Upper Plate rocks. Minor exposures of limited areal extent within Cactus Forest Drive.	High.	Limited extent; not applicable.	Minor rockfall?	Potential marine invertebrates and burrows.	Very limited areal extent; none documented.	Unknown.	Very limited areal extent.	Too limited to be applicable.	
PERMIAN	Epitaph Dolomite (Pe)	Dark-gray moderately thick-bedded slightly cherty dolomite; includes a lower unit, commonly faulted out, of dolomite marlstone and some intercalated limestone. Estimated preserved thickness less than 200 m (660 ft). Found in normal faulted blocks of Upper Plate rocks. Minor exposures of limited areal extent within Cactus Forest Drive.	High.	Limited extent; not applicable.	Minor rockfall?	Potential for few marine invertebrates.	Very limited areal extent; none documented	Unknown.	Very limited areal extent.	Too limited to be applicable.	
PERMIAN	Colina Limestone (Pc)	Medium-dark-gray moderately thick-bedded slightly cherty limestone. Some beds contain small white blebs of dolomite. Estimated preserved thickness less than 100 m (300 ft). Found in normal faulted blocks of Upper Plate rocks.	Relatively high.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	

Map Unit Properties Table: Saguaro National Park-Rincon Mountain District (Saguaro East). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
PENNSYLVANIAN	Earp Formation (PPNe)	Reddish-gray marlstone, siltstone, and shale, some intercalated pale-brownish-gray fine-grained limestone, and a thin bed of reddish-gray rounded chert-pebble conglomerate. Estimated thickness less than 200 m (660 ft). Found in normal faulted blocks of Upper Plate rocks within Cactus Forest Drive and southwest of the Javelina picnic area.	Variable.	Sparse outcrops. Development not recommended.	Minor rockfall?	Potential marine invertebrates and burrows.	Unknown. Limited areal extent.	Unknown.	Semidesert mixed grass-mesquite vegetation.	No access to exposures within Cactus Forest Drive.	In contact with Lower Plate rocks.
PENNSYLVANIAN	Horquilla Limestone (PPNh, PPNhm)	**PPNh**: Light-pinkish-gray fine-grained thin-to thick-bedded sparsely cherty limestone. Upper half contains much intercalated reddish-gray siltstone in units commonly 0.3 to 3 m (1 to 10 ft) thick. Unconformably overlies **Me**. Estimated thickness 500 m (1,600 ft). Mostly found in normal faulted blocks of Upper Plate rocks within Cactus Forest Drive and southwest of the Javelina picnic area. One small outcrop along the eastern border in Happy Valley Quadrangle. **PPNhm**: Metamorphosed facies in lower major thrust plate. Nearly white fine-grained slightly cherty marble. Estimated preserved thickness 150 m (490 ft). Exposure near Hope Camp Trail and along road leading to Madrona Ranger Station.	High.	Sparse outcrops. Development not recommended.	Minor rockfall?	Some beds contain fusulinids. Marine invertebrates, conodonts, and fish also possible.	Unknown. Limited areal extent.	Unknown.	Semidesert mixed grass-mesquite vegetation types.	No access to exposures within Cactus Forest Drive.	One local exposure mapped in contact with Lower Plate rocks.
MISSISSIPPIAN (Lower-Middle)	Escabrosa Limestone (Me)	Medium-gray thick-to thin-bedded medium- to coarse-grained bioclastic (in part crinoidal) cherty limestone. Limestone and shale beds at top may be the Black Prince Limestone of Early Pennsylvanian(?) or Late Mississippian age. Estimated thickness 190 m (620 ft). One isolated, minor outcrop mapped in the normal faulted blocks of Upper Plate rocks within Cactus Forest Drive. Surrounded by **PPNe**.	High.	Limited extent; fault blocks.	Minor rockfall?	Potential crinoids and other marine invertebrates. Fossil coral in park collections may have come from **Me**.	Unknown. Limited areal extent.	Unknown. Limited areal extent.	Semidesert mixed grass-mesquite vegetation types.	Geologic interest.	Maximum transgression from Antler Orogeny.
DEVONIAN (Upper)	Martin Formation (Dm)	Interbedded brown cherty dolomite, gray dolomitic fossiliferous limestone, and some sandstone. Estimated thickness less than 100 m (300 ft). Unconformably overlies **Ca**.	High.	Limited extent; fault blocks outside of the park.	Minor rockfall?	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Records the onset of the Antler Orogeny.
CAMBRIAN	Abrigo Formation (Ca)	Brownish-gray to brown shale, sandstone, and quartzite, and light-gray thin-bedded partly bioclastic limestone and intraformational conglomerate. Estimated thickness 210 m (690 ft). Minor exposure in normal faulted blocks of Upper Plate rocks in section 11, T15S, R17E, western border of the park.	Variable.	Limited extent; remote exposures.	None.	Rare trilobites, brachiopods and trace fossils.	Unknown; limited areal extent.	Unknown; limited areal extent	Semidesert mixed grass-mesquite vegetation types.	Limited exposure; geologic interest.	Cambrian units are in contact with Lower Plate rocks and record deposition along the southwestern margin of North America.
CAMBRIAN	Bolsa Quartzite (Cb, Cbm)	**Cb**: Light- to dark-gray, purplish gray, or brownish gray coarse-grained thick-bedded quartzite and some basal conglomerate. Unconformably overlies the Apache Group. Estimated thickness 150m (490 ft). **Cbm**: Mostly light-gray to light-brownish-gray metaquartzite. Estimated preserved thickness less than 150 m (490 ft). Both units exposed in fault blocks with **Ca**.	High.	Limited extent; remote exposures.	Minor rockfall?	Potential trace fossils (*Skolithos*) and rare brachiopods.	Unknown; limited areal extent.	Unknown; limited areal extent.	Semidesert mixed grass-mesquite vegetation types.	Limited exposure; geologic interest.	
PRECAMBRIAN (Proterozoic)	Diabase (Yd)	Metadiabase and possibly some diorite; dark greenish gray; fine to coarse grained, mainly in sills. One minor exposure mapped at Sentinel Butte.	High.	Too limited to be applicable.	None.	None.	None documented.	Limited extent.	Unknown; very limited exposure.	Geologic interest.	Exposed in Upper Plate.
PRECAMBRIAN (Proterozoic)	Apache Group: Dripping Spring Formation (Yds)	Banded light-colored and reddish-brown arkose, siltstone, and quartzite. Includes thin Barnes Conglomerate Member at base. Estimated preserved thickness 100 m (300 ft). Minor exposures mapped on Sentinel Butte and Rincon Creek Syncline.	Variable.	Local, limited exposures.	None.	Potential acritarchs.	None documented.	None documented.	Unknown; very limited exposure.	Geologic interest.	Exposed in Upper Plate.
PRECAMBRIAN (Proterozoic)	Apache Group: Pioneer Shale (Yp)	Reddish-brown shale, siltstone, and argillite. Includes very thin basal angular-pebble Scanlan Conglomerate Member. Probably unconformably overlies Pinal Schist. Estimated preserved thickness 100 m (300 ft). Minor exposures mapped on Sentinel Butte.	Variable.	Local, limited exposures.	None.	None.	None documented.	None documented.	Unknown; very limited exposure.	Geologic interest.	Exposed in Upper Plate.
PRECAMBRIAN (Proterozoic)	Rincon Valley Granodiorite (Yr)	Massive medium-grained biotite granodiorite or locally biotite-hornblende granodiorite; some quartz monzonite. K-Ar age on hornblende 1,560±100 million years old and on biotite from same specimen 1,450±50 million years old. Age relations to other Precambrian rocks uncertain. Isolated outcrops west of Santa Catalina Fault near Loma Verde Mine. Massive exposures south of Sentinel Butte. Considered part of the "Catalina Gneiss" by Bezy (2005).	High.	Currently contains campsites (Hope Camp) and unimproved roads.	None documented.	None.	Possible American Indian sites associated with Rincon Creek and tributaries.	Biotite.	Not certain; possibly in the Sonoran Paloverde mixed cacti/Sonoran creosote-bursage vegetation type.	Unimproved roads; camping (Hope Camp).	Correlative with Johnny Lyon Granodiorite? In contact with Lower Plate rocks.

Map Unit Properties Table: Saguaro National Park-Rincon Mountain District (Saguaro East). *Gray-shaded rows indicate map units in the accompanying GIS data but not mapped within the park.*

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Paleontological Resources	Cultural Resources	Mineral Occurrence	Habitat	Recreation	Geologic Significance
ROCKS OF THE LARAMIDE AUTOCHTHON (Units that have not been moved from their original depositional site and lie below the surface of the Santa Catalina fault in Saguaro National Park. "Lower Plate" rock units.)											
PRECAMBRIAN (Proterozoic)	Johnny Lyon Granodiorite (Yj, Yja)	**Yj**: Massive medium to coarse-grained biotite-hornblende granodiorite and quartz monzonite. Forms western half of a small batholith that intrudes Continental Granodiorite. Uranium-lead (U-Pb) age on zircon from Johnny Lyon Hills is 1,600±30 million years old. Intruded **Yc**. **Yja**: Small bodies, only some of which are mapped, and border phase of granodiorite.	High.	Not mapped in park.	None documented; Not mapped in park.	None.	Not mapped in park.	Biotite, hornblende, quartz.	Not mapped in park.	Not mapped in park.	**Yr** and **Yj** may represent fore-arc basin above subduction zone.
	Wrong Mountain Quartz Monzonite (Yw, Ywm, Ywa)	**Yw**: Large intrusive complex of stocks and layered sheets of moderately coarse grained to fine-grained biotite muscovite gneissic quartz monzonite. Typically contains garnet but few other accessory minerals. Locally grades into hybridized (partly assimilated?) **Ych**. Weakly to moderately foliated and lineated; generally more massive near core of gneiss dome. K-Ar ages of 23.5±0.9 and 24.8±0.9 million years old may record a Tertiary thermal event. Forms the main unit of the Rincon Gneiss Dome. Cores Tanque Verde and Rincon Peak anticlines. **Ywm**: Stock of nearly massive rock. Composition similar to gneissic quartz monzonite, but foliation weak and lineation absent to the unaided eye. Weathers to bold crags. **Ywa**: Aplite, alaskite, and pegmatite in pods and sheets. Many too small to map. Units are considered part of the "Catalina Gneiss" by Bezy (2005).	High.	Remote, rugged part of park; pack trails and campsites.	Remote rockfall potential.	None.	Possible American Indian sites and petroglyphs.	Garnet.	Crags and fractured cliffs in higher elevations provide nesting sites; includes many vegetation types: lowland mixed cacti-scrub to highland Ponderosa pine.	Pack trails; camping; hiking.	Part of metamorphic core complex. **Ywm**: May be last body of heated rock to be recrystallized during late Oligocene time.
	Metadiorite (Ydi)	Dark-greenish-gray amphibolite-rich small dikes, sills, and irregular masses. Relation to diabase unit (**Yd**) unknown. Mapped linear features.	High.	Limited extent; in rugged terrain.	None.	None.	Limited areal extent.	None.	Fractures and erosion provide sites for animals.	Irregular, linear exposures in backcountry.	May have economic interest. Precious and industrial metals often along margins.
	Dikes (Yri)	Light-brownish-gray to medium-gray rhyolitic to andesitic dikes, probably metamorphosed; some foliated. Limited areal extent.	High.	Limited extent; not in park.	Not mapped in park.	None.	Not mapped in park.	Not mapped in park.	Not mapped in park.	Not mapped in park.	
	Continental Granodiorite (Yc, Yca, Ych)	**Yc**: Dark-gray, coarsely porphyritic generally very coarse grained moderately to strongly foliated and lineated metagranodiorite. Locally large feldspar phenocrysts grade into augen. Dark minerals, chiefly biotite and chlorite, form pervasive meshwork throughout rock. Accessory sphene and titaniferous magnetite are usually abundant and apatite and zircon are common. In places intruded by unmapped thin layered sheets of **Yw**. Exposed on crest and flanks of Tanque Verde anticline. **Yca**: Granodiorite with many small intrusive bodies of aplite commonly as layered intrusives. Aplite probably largely of **Yja** and of quartz monzonite of **Ywa**. **Ych**: Gneissic granodiorite and quartz monzonite having textures and compositions between those of **Yc** and **Yw**. Typically contains highly elongated pods of recrystallized biotite and muscovite, is coarse grained, and in places contains small augen or phenocrysts. Units considered part of the "Catalina Gneiss" by Bezy (2005).	High.	Outcrops in park's backcountry; pack trails and camp sites.	None documented; rockfall potential for backcountry hikers.	None.	Possible American Indian sites.	Feldspar, biotite, chlorite, sphene, titaniferous magnetite, apatite, zircon.	Rocky terrain; fractures; dotted with ocotillo, creosote bush, occasional prickly pear and barrel cactus, and saguaro cactus.	Backcountry recreation; pack trails and camping; Tanque Verde Ridge Trail to Juniper Basin campsite.	Part of metamorphic core complex.
	Wrong Mountain Quartz Monzonite and Continental Granodiorite (Ywc)	Gneissic granodiorite (**Yc**), and abundant thin layered sheets of gneissic quartz monzonite (**Yw**) and of associated aplitic rocks (**Ywa**). Grades into mylonitic gneiss low on flanks of gneiss dome. Locally the layering is migmatitic. Exposed on flanks of Tanque Verde and Rincon Peak anticlines.	High.	Exposed in park's backcountry; pack trails and campsites.	None documented; rockfall potential?	None.	Possible American Indian sites.	Copper, lead; large feldspar crystals.	Rocky terrain; sparse vegetation and few springs.	Backcountry recreation; Tanque Verde Ridge Trail.	Part of metamorphic core complex.
PRECAMBRIAN (Archean)	Pinal Schist (Xp, Xpq, Xpc, Xpa, Xpqp, Xpr)	**Xp**: Mainly mica schist; includes muscovite schist, muscovite-biotite schist, some phyllite, metaquartzite, mylonitic and migmatitic gneiss, and aplite. Strongly and probably multiply deformed through dynamic and thermal events. **Xpq**: Light-gray fine- to medium-grained metaquartzite. Main exposure encircles Happy Valley Lookout Tower. **Xpc**: Thin beds of light-gray metaconglomerate. Not mapped in the park. **Xpa**: Schist containing abundant small aplite bodies, largely as layered intrusives. Aplite probably largely of quartz monzonite of **Ywa**. Not mapped in the park. **Xpqp**: Mixed metaquartzite, phyllite, and schist; may be in upper part of Pinal Schist like that found in the Happy Valley Quadrangle a few kilometers to the east. Not mapped in the park. **Xpr**: Laminated and locally schistose rock probably of volcanic origin. Local exposures near Catalina Fault Complex, sections 11 and 14, T15S, R17E.	Less resistant than granite or granodiorite.	Unimproved roads, pack trails, and campsites in park's backcountry.	None documented; rockfall potential for backcountry visitors.	None.	Possible American Indian sites.	Muscovite, quartz.	Lower elevations: prickly pear and saguaro cactus and abundant creosote bush. Higher elevations: ponderosa pine, oak, and Douglas fir.	Backcountry recreation; pack trails and camping.	Represents a marine environment that once received much sand, silt, and clay from a nearby continent. Part of metamorphic core complex. Oldest rocks in southern AZ.
AGE UNCERTAIN	Limestone and marble (ls)	Metamorphosed carbonate and calc-silicate rocks. May be as young as Permian or may possibly be an unrecognized facies of the Pinal Schist (**Xp**). Limited areal extent.	High.	Limited areal extent.	None.	None.	Limited areal extent.	Marble.	Limited areal extent.	Limited areal extent.	Unknown.
	Site of copper (Cu) mineralization	In Rincon Valley Quadrangle; in Wrong Mountain Quartzite (Yw)	Localized site	No mining.	Not applicable.	None.	Unknown.	Copper.	Not applicable.	Mineralogical interest.	Natural reactions to magmatic fluids and rock contacts.
	Site of lead (Pb) mineralization	In Rincon Valley Quadrangle; in Wrong Mountain Quartzite (Yw)	Localized site	No mining.	Not applicable.	None.	Unknown.	Lead.	Not applicable.	Mineralogical interest.	

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Saguaro National Park, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

Figure 17 summarizes the significant life forms, major extinctions, and tectonic events in North America from the Precambrian to the Quaternary. The geologic history exposed at Saguaro National Park begins in the Precambrian, approximately 1.6 billion years ago.

Precambrian (prior to 542 million years ago)

Although geologically distinct, the Rincon Mountain District and Tucson Mountain District share a complex geologic history extending as far back as the late Precambrian (fig. 17). About 1.65 billion years ago, crust in the southwestern United Sates was attached to the growing North American craton during mountain-building events called the Yavapai and Mazatzal orogenies (Hoffman 1989). The metamorphosed sand, silt, and clay of the 1.65-billion-year-old Pinal Schist may represent sediments deposited in a marine environment adjacent to the accreted terranes (Hoffman 1989; Bezy 2005).

The Johnny Lyon Granodiorite and the Rincon Valley Granodiorite were emplaced about 1.6 billion years ago. The granites formed from magma generated above a northwest-dipping subduction zone (Hoffman 1989). Sediments deposited the "forearc" basin, the area between the mainland and offshore volcanic islands, were accreted to the mainland in the process of plate subduction and subsequently metamorphosed.

Middle Proterozoic rocks of the Apache Group, which includes the dripping Spring Formation and the Pioneer Shale in the Rincon Mountain District, represent sediments deposited on a continental shelf. The little-deformed shale, siltstone, and quartzite of the Apache Group thicken to the north, in the Grand Canyon area, where it is intruded by 1.13-billion-year-old diabase sills (Hoffman 1989). Diabase sills also intrude the Apache Group sediments in the Rincon Mountain District; however, these sills have not been age-dated.

Paleozoic Era (542 to 251 million years ago)

The Paleozoic Era represents about 290 million years of Earth history, but only a few geologic remnants from this era are exposed in Saguaro National Park. The cratonic margins of North America were largely passive from the Late Proterozoic through the Early Ordovician. Most of the continent as we know it today was underwater in the Cambrian. A strip of land known as the Transcontinental Arch stretched southwestward from northern Minnesota across Nebraska and Colorado and into Arizona (fig. 18). Land plants had not evolved in the Cambrian so sediment was easily eroded from the exposed land mass.

The Bolsa Quartzite and Abrigo Formation represent deposition along the southwestern margin of the North American craton (Strickland and Middleton 2000). The gradational succession from Bolsa Quartzite to the Abrigo Formation represents a variety of fluvial to subtidal settings. The Bolsa records a transition from braided streams (streams choked with sediment) to tidally influenced fluvial sedimentation. The Abrigo sediments were deposited in subtidal and intertidal environments. Together, the sedimentary textures and structures suggest that a marine embayment, open to the southwest, punctuated the craton's margin during Middle-to-Late Cambrian time.

From the Ordovician through the Middle Devonian, the sea lay to the west and south of southeastern Arizona, and no rocks representing these geologic periods are found in Saguaro National Park. However, the effects of tectonic compression during the Antler Orogeny were felt in southeastern Arizona during the Late Devonian. The Martin Formation represents carbonate platform dolomite deposited in shallow near-shore marine environments as the sea advanced into the region (Johnson et al. 1991).

Maximum marine transgression resulting from the Antler Orogeny occurred during the Early and Middle Mississippian, and built a marine carbonate platform represented by the Escabrosa Limestone (fig. 19) (Armstrong et al. 1980; Poole and Sandberg 1991). In southern Arizona, lower Escabrosa strata record a major transgressive event wherein the shallow sea flooded much of southern and central Arizona. By the end of the Early Mississippian, marine regression, regional uplift, and erosion had removed some of the Escabrosa Limestone. Upper Escabrosa rocks record another transgression in the Middle Mississippian. Late Mississippian rocks are missing in southern Arizona, as this was a time of regional marine regression along the western margin of the United States.

The Pennsylvanian and Permian periods were times of great tectonic instability in the western interior United States. On the western margin of the continent, in the vicinity of central Nevada, continental shelf and slope rocks were being compressed against the continental margin as the Sonoma Orogeny advanced eastward (fig. 17). Southeast of Arizona, the South American tectonic plate collided with the North American plate and the proto-Gulf of Mexico closed, causing the uplift of the northwest-southeast trending Ancestral Rocky Mountains in Colorado, the northeast-southwest trending Sedona Arch in central Arizona, and the Mogollon Rim (an uplift in east-central Arizona). South of the Mogollon Rim, a carbonate shelf developed in southeastern Arizona (Blakey 1980; Peterson 1980). The Pedregosa Basin formed in southeasternmost Arizona and southwestern New Mexico. The Permian climate of the west-central United States was arid and dry, resulting in marine evaporitic conditions (fig. 20). The sediments that formed the Pennsylvanian and Permian strata in Saguaro National Park were deposited in transitional environments between the open marine carbonate shelf and the uplands of the Mogollon Rim.

Mesozoic Era (251 to 65.5 million years ago)

Triassic Period (251 to 200 million years ago)

By the beginning of the Mesozoic, all the continents had come together to form a single land mass (supercontinent) called Pangaea that was located symmetrically about the equator (Dubiel 1994). During the Triassic Period, Pangaea reached its greatest size and then began to split apart. A series of volcanoes ("volcanic arc") formed above an active subduction zone along the west side of the continent (Oldow et al. 1989; Christiansen et al. 1994; Dubiel 1994; Lawton 1994; Peterson 1994).

The volcanic arc developed in the Triassic and reached its maximum development in the Cretaceous. The thick sequence of Late Triassic and Jurassic continental volcanic rocks in southeastern Arizona represents a major change from the shallow marine shelf conditions that persisted in the region during most of Paleozoic time (Kluth 1983; Dubiel 1994; Peterson 1994).

In the Triassic, a northwest-flowing fluvial system, which included north-flowing tributaries in southern Arizona, developed in the southwestern United States (Dubiel 1994). The Late Triassic was an unusually wet episode for the Western Interior, and principal depositional environments included fluvial, floodplain, marsh, and lacustrine settings with minor eolian and playa environments forming at the close of the Triassic.

Jurassic Period (200 to145 million years ago)

Dramatic modifications to the western margin of North America occur in the Jurassic (fig. 21). During the Early and Middle Jurassic, Saguaro National Park was located along the Mogollon slope, a northwest-to-southeast trending highland that supplied clastic debris to the Colorado Plateau throughout much of the Jurassic (Busby-Spera 1988; Peterson 1994). Wrangellia, a foreign terrane located in the Pacific, collided with North America, causing volcanic activity along the west coast from Mexico to Canada, including on the Mogollon slope. The collision caused west-to-east directed thrust faulting in Nevada. A basin formed landward of the thrusting (foreland basin), which allowed a shallow sea to encroach into Utah from the north.

The Jurassic and Triassic Recreation Red Beds and units of volcanic tuff exposed in the Red Hills (Tucson Mountain District) and the isolated exposures of the Jurassic and Triassic Walnut Gap Formation mapped in the western part of the Happy Valley Quadrangle (Rincon Mountain area) record the volcanic activity in the region as well as fluvial and alluvial deposits associated with the Mogollon slope. To the north, extensive dune fields developed in the Four Corners area of Arizona, Utah, Colorado, and New Mexico during the late Triassic and early Jurassic (Peterson 1994).

In latest Jurassic time, southeastern Arizona began to be disrupted by large-scale, high-angle, primarily northwest-trending faults. A large transform fault zone (megashear), called the Mojave-Sonora megashear, truncated the southwestern continental margin of North America (Kluth 1983; Stevens et al. 2005; Anderson and Silver 2005). During this time, the North American lithospheric plate was rotating counterclockwise, causing the Gulf of Mexico to begin to open. The northwest-southeast trending megashear was a principal structure that accommodated approximately 800 to 1,000 km (500 to 600 mi) of displacement related to the rotation of the North American plate (Anderson and Silver 2005; Haenggi and Muehlberger 2005).

Cretaceous Period (145 to 65.5 million years ago)

Accelerated lithospheric plate collision during the Cretaceous caused thrust-faulted mountains to form along the western margin of North America as a result of the Sevier Orogeny. In southern Arizona during the Early Cretaceous, rifting occurred in the northwest-southeast trending Bisbee Basin and adjacent Chihuahua trough to the southeast (Elder and Kirkland 1994; Dickinson and Lawton 2001; Haenggi and Muehlberger 2005). Rifting in the southern interior tilted the Mogollon slope towards the northeast and opened a series of local pull-apart basins in response to transtension associated with the Mojave-Sonora megashear (Elder and Kirkland 1994; Anderson and Nourse 2005).

The Glance Conglomerate and the Willow Canyon Formation, basal units of the Lower Cretaceous Bisbee Group, represent proximal deposits of alluvial fan systems that rimmed local fault-block mountain ranges and basins. Northwest or west-northwest-trending normal faults bounded the basins on at least one side (Bilodeau and Lindberg 1983).

Marine fossils, including the clam *Trigonia*, have been found in the Shellenberger Canyon Formation. Much of the upper Shellenberger Canyon Formation in the Whetstone and Santa Rita Mountains has been interpreted as shallow marine tidal flat and fan delta deposits that signify a late Early Cretaceous transgressive event (Bilodeau and Lindberg 1983).

By the early Late Cretaceous, the Bisbee Basin had been either filled with eroded material from surrounding highlands, or thrusting and uplift to the south had caused deposition to cease (Dickinson et al. 1989; Elder and Kirkland 1994; Kring 2002). The few exposures of Bisbee Group siliciclastics in the Rincon Mountain District are only part of the 3,000 to 4,000 m (9,800 to 13,100 ft) of Bisbee Group sediments (Dickinson et al. 1989; Kring 2002).

In the Tucson Mountains, the lower part of the Amole Arkose Formation may correlate to the Bisbee Group in the Rincon Mountain District. In the Upper Cretaceous, the Amole Basin remained an extension of the northwest-southeast Chihuahua Trough, with uplifted highlands forming its northeast and southwest borders. Water drained these highlands and carried rock fragments into the basin, producing large alluvial fans that spilled out of local canyons. While boulders and cobbles were deposited near the mountain front, finer-grained sand, silt, and mud were transported farther downstream to form a series of migrating streams that flowed across a relatively flat and very broad valley floor (Kring 2002). Stream channels were often up to 30 m (100 ft) wide from bank to bank, and they were often turbulent, scouring the underlying sediments (Risley 1987; Kring 2002). Coarse sand settled in the bottom of the streambeds and was also deposited in sandbars or as overbank deposits. These sands became the lithified arkosic sandstones that dominate the Amole Arkose Formation in the Tucson Mountains.

The streams eventually emptied into Amole Lake, a large lake up to 80 m (260 ft) deep that possibly spanned a distance of several tens of miles (Risley 1987; Kring 2002). Deltas of sand, silt, and mud formed at the mouth of the rivers. Anoxic (oxygen-depleted) conditions and possibly aphotic (little or no sunlight) conditions existed in sections of the lake that were too deep or that contained too much silt and clay. Over broad, relatively flat areas near the shore of Amole Lake and in shallow water, particularly near parts of the shore that were not disturbed by incoming river currents, algal colonies grew, forming algal mats that spread out over distances of at least tens of feet. Gastropods and pelecypods lived in shallow areas of the lake, and fish (similar to modern American gar pike) swam above the oxygen-depleted layers of the lake.

Amole Lake was similar to modern lakes, with turtles, fish, and clams. Algal mats may have been the most unusual feature of the lake, but these, too, can be found in modern environments (e.g., Walker Lake in Nevada). At least 1,000 m (3,000 ft) of sediment accumulated in and around the lake, which suggests that Amole Lake may have existed for at least several hundred thousand years (Risley 1987; Kring 2002).

Few fossils have been preserved in the Amole Arkose Formation in the Tucson Mountains. However, fossil wood chips, twigs, and much larger logs up to 0.6 m (2 ft) in diameter have been discovered in stream deltas near the shore of Amole Lake, suggesting that the surrounding highlands supported a forest of coniferous trees (Kring 2002). Tree rings in the fossil logs indicate that they grew in a temperate climate with distinct seasons.

In the Saguaro National Park region during the Late Cretaceous, dinosaurs roamed across the valley floor and possibly on the wooded slopes of the surrounding mountains. Hadrosaur remains found in a megabreccia block of Amole Arkose in the Tucson Mountains correlate to fragments of hadrosaur, sauropod, carnosaur, and ceratopsian dinosaurs that have been found in the nearby Santa Rita Mountains and Whetstone Mountains.

The volcanic highlands of southeastern Arizona formed part of the western border of the most extensive interior seaway ever recorded in North America (fig. 22). As mountains rose in the west and the Gulf of Mexico continued to rift open in the south, seawater encroached into an elongate depression called the Western Interior Basin (or the Western Interior Seaway). Seawater advanced and retreated many times during the Cretaceous until the Western Interior Seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 5,000 km (3,000 mi) (Kauffman 1977).

With the advent of the Laramide Orogeny, the Western Interior Seaway began to disappear. As the land rose, Amole Lake eventually drained. In the Saguaro National Park region, Laramide deformation occurred just a few million years before the Tucson Mountains Caldera erupted. These folded rocks of the Amole Arkose Formation became the floor of the Tucson Mountains Caldera (Lipman 1993; Kring 2002).

The Laramide Orogeny began in the Late Cretaceous and continued into the mid-Tertiary (about 50 million years ago). The orogeny marked a return of northeast-southwest compression in southeastern Arizona. Like the Sevier Orogeny, the Laramide Orogeny was the result of subduction of an oceanic lithospheric plate beneath the western margin of the North American continent. However, the Laramide Orogeny differed from the Sevier Orogeny in two significant respects. First, whereas the subducting slab associated with the Sevier Orogeny formed a relatively steep angle, subduction during the Laramide Orogeny was relatively flat (fig. 23). Secondly, the Sevier Orogeny deformed near-surface Paleozoic and Mesozoic strata, but because flat-slab subduction transferred the compressive stress farther inland, the Laramide Orogeny involved deep-seated basement blocks of Precambrian rocks.

As the Laramide Orogeny developed, stratovolcanoes erupted in southeastern Arizona (Elder and Kirkland 1994; Kring 2002; Bezy 2005). At least seven areally extensive volcanoes were active in southeastern Arizona in the Late Cretaceous, about 70 to 75 million years ago (Bezy 2005).

About 1 million years prior to the Tucson Mountains Caldera, the Silver Bell Caldera formed in the Silver Bell Mountains, about 30 km (18 mi) northwest from the Tucson Mountains and on the other side of Avra Valley. When the Silver Bell stratovolcano erupted, it covered the Tucson Mountain region with more than 100 m (330 ft) of tuff. Following this eruption, some sandstones and shales were deposited before the volcanic activity in the Tucson Mountains began.

A sequence of rhyolitic extrusions marks the initiation of the Tucson Mountains volcanic activity. The ash-flow tuffs, formally recognized as the Cat Mountain Tuff, now form most of the red cliffs in the Tucson Mountains. Erupted and emplaced during several violent volcanic eruptions, the Cat Mountain Tuff contains dense mixtures of cinders, ash, and gas that compacted and fused into weather resistant welded tuff.

The Tucson Mountains' ash flow eruptions may have lofted plumes of gas and ash as high as 20 to 40 km (12 to 24 mi) into the stratosphere, depositing ash over distances greater than 1,000 km (600 mi) (Kring 2002). The ash may have traveled as far east as the Mississippi River valley and covered Chihuahua, New Mexico and the Texas panhandle. Eruptions may have affected Earth's climate. Over 400 cu km (96 cu mi) was erupted from the volcanic activity that produced the Tucson Mountains Caldera, which is 2,000 times more magma than erupted in the 1980 Mount St. Helens event in Washington (Lipman 1984).

After the eruptions drained enough of the magma chamber, the chamber's roof and overlying volcanic debris collapsed to form the Tucson Mountains Caldera. The floor of the caldera sank unevenly, and large blocks of welded tuff and slabs of older rock, some up to 600 m (2,000 ft) across, slid into the caldera, forming the megabreccia member of the Cat Mountain Tuff.

After the floor of the caldera collapsed and the megabreccia and tuffs were emplaced, lava erupted from volcanic vents and began to fill the caldera (Kring 2002). The volcanics of Yuma Mine are examples of these lava flows.

A large body of magma, the Amole granite, intruded, uplifted, and tilted the caldera fill and lava flows. Hot, mineral-rich solutions accompanied the intrusion of the Amole granite and associated dikes; silver, gold, copper, and other metals crystallized in cracks. Silica-rich dikes (Silver Lily dike swarm) crosscut the entire volcanic complex following the intrusion of the Amole pluton.

The Tucson Mountains caldera cycle likely occurred within a period of about 1 million years (Kring 2002). Following the volcanic activity, southeastern Arizona became relatively quiet, and erosion became the dominant geologic process to affect the landscape.

Cenozoic Era (the past 65.5 million years)

Tertiary (65.5 to 2.6 million years ago)

Multiple igneous intrusions and mylonitization began in the Late Cretaceous or early Tertiary and ended in the early Miocene. The Santa Catalina Mountains of southern Arizona contain at least 12 plutons that can be divided into three intrusive episodes: 1) 60 to 75 million years ago (Latest Cretaceous to Paleocene), 2) 44 to 50 million years ago (Eocene), and 3) 25 to 29 million years ago (Oligocene) (Anderson 1988). Mylonitic fabric associated with the 60 to 75 million year old episode is compressional in origin, but the mylonitic fabric associated with the 25 to 29 million year old episode formed in an extensional setting. Volcanic activity returned to southeastern Arizona 40 to 45 million years ago (during the second intrusive episode) after the Tucson Mountains Caldera cycle ended.

Lavas and low-volume tuffs erupted from a series of volcanic vents during the mid-Tertiary (Dickinson 1979; Nations et al. 1985; Kring 2002). In the Tucson Mountains, mid-Tertiary volcanic eruptions concentrated in three areas: 1) a dacitic lava field in the northern part of the range; 2) a series of basaltic lavas and rhyolitic tuffs on the east side of the range; and 3) several dacitic to rhyolitic lava domes exposed at the very southern end of the range (Lipman 1993; Kring 2002).

The dacitic lava field likely erupted 25 to 30 million years ago (Oligocene) from at least three volcanic vents (Lipman 1993). From West Sunset Road, the southernmost exposure of the dacite lava flows, lavas are found through Contzen Pass (Picture Rocks Road) all the way to the end of the range, well past Pima Farm Road, in the vicinity of Rattlesnake Pass. Four flows are found at Safford Peak, and Panther Peak also is composed of dacite lava flows. Basaltic lava flows and associated rhyolitic ash flow tuff and volcaniclastic sedimentary rocks exposed in Tumamoc Hill and Sentinel Peak (also called A-Mountain) were deposited about 20 to 30 million years ago (Lipman 1993; Kring 2002). The dacite domes on the south side of the range are not as extensive as the dacitic lava field. They are exposed at the very southern end of the range, south of Valencia Road (Kring 2002).

A large number of ash flow calderas were being produced elsewhere in southern Arizona and New Mexico at about the same time as lavas were erupting in the Tucson Mountains. The Turkey Creek Caldera, responsible for most of the volcanic rocks in Chiricahua National Monument (Graham 2009), is perhaps the best known of these mid-Tertiary calderas. The Turkey Creek caldera formed about 25 to 30 million years ago and like the Tucson Mountains Caldera, is about 20 km (12 mi) in diameter (Drewes 1982; Kring 2002).

Volcanic activity returned to the Tucson area because the angle of the subducting sea floor (the Farallon Plate) was increasing in the mid-Tertiary. As the angle of subduction increased along the western margin, the amount of compressive force being applied to the North American Plate decreased and the Laramide Orogeny came to a close. As the compressive forces decreased, the crust was no longer constrained and it began to relax. As it relaxed, extensional faults (normal faults) developed.

Some of these normal faults dipped gently beneath Earth's surface, forming detachment faults. Regions initially close together can be transported 10 to 25 km (6 to 15 mi) apart along these detachment (décollement) surfaces. During fault movement, the part of Earth's crust that is being uncovered (unroofed) begins to rise because the mass of the overlying rock is removed. The rocks that slowly rise to the surface are composed primarily of metamorphic mineral assemblages that formed under unusually high temperatures and pressures.

As these deep-seated rocks rise to the surface, mylonitization gives way to brittle deformation that is associated with detachment faulting (Anderson 1988)). At the surface, these metamorphic rocks form domed-shaped mountain ranges called metamorphic core complexes (fig. 4). More than 25 of these distinctive, isolated, domed terranes extend in a narrow sinuous belt from southern Canada to northwestern Mexico (Coney 1979; Nations et al. 1985; Davis 1987; Dickinson 1991; Kring 2002; Bezy 2005).

The Rincon Mountain District is part of a metamorphic core complex that includes the Tortilita Mountains, Santa Catalina Mountains, and Rincon Mountains. At the southern end of the Rincon Mountains, lateral displacement was at least 27 km (16.2 mi), and possibly 35 km (21 mi) (Dickinson 1991; Kring 2002). The detachment fault (Santa Catalina Fault) separated material in a northeast-southwest direction; thus, material above the fault plane moved to the southwest relative to the material below the fault. When restored to its original position, the Tucson Mountains Caldera would be near and possibly directly over what is now the southwestern Santa Catalina Mountains (Dickinson 1991; Kring 2002).

Fanglomerates (Pantano Formation) form fan-shaped deposits adjacent to the metamorphic core complexes. These deposits and the presence of low-angle detachment faults suggest that erosion and gravity gliding “unroofed” the metamorphic core complex (Nations et al. 1985). The region contained local basins with internal drainage systems, high basin-margin relief, and landslide deposits adjacent to lake and playa sediments.

Tilting is also associated with detachment faulting. As the Tucson Mountains block was transported westward, it tilted, so the Paleozoic and Mesozoic strata now dip to the east and the older strata lie west of the younger strata (Lipman 1993; Kiver and Harris 1999; Bezy 2005).

Continued extension about 15 to 10 million years ago moved the Tucson Mountains even farther to the west as the current Basin-and-Range topography began to develop (fig. 2). The crust broke into blocks separated by new, more steeply dipping faults. Some blocks were displaced by as much as 1.4 km (2.4 mi) relative to other blocks to form deep grabens, such as the Tucson Basin and Avra Valley. For example, the Santa Catalina Mountains are 2,073 m (6,800 ft) higher than the surface of the Tucson Basin, and the top of the Tucson Basin block lies below sea level buried by 2,100 m (7,000 ft) of Miocene-Pleistocene debris. This caused nearly 4,300 m (14,000 ft) of vertical change to occur (Kiver and Harris 1999). The Nogales Formation mapped in the Rincon Mountain District formed in the Miocene as sediments filled these basins (Nations et al. 1985).

Quaternary Period (the past 2.6 million years)

Downward-cutting streams, faulting, and erosion have exposed the rocks in the Rincon Mountain and Tucson Mountain Districts as uplift of the southeastern Arizona region continued into the Quaternary. Sediments flushed from the canyons during flash floods have formed beveled rock platforms (pediments) and alluvial fans along the mountain fronts, and they continue to fill the basins adjacent to the mountain ranges.

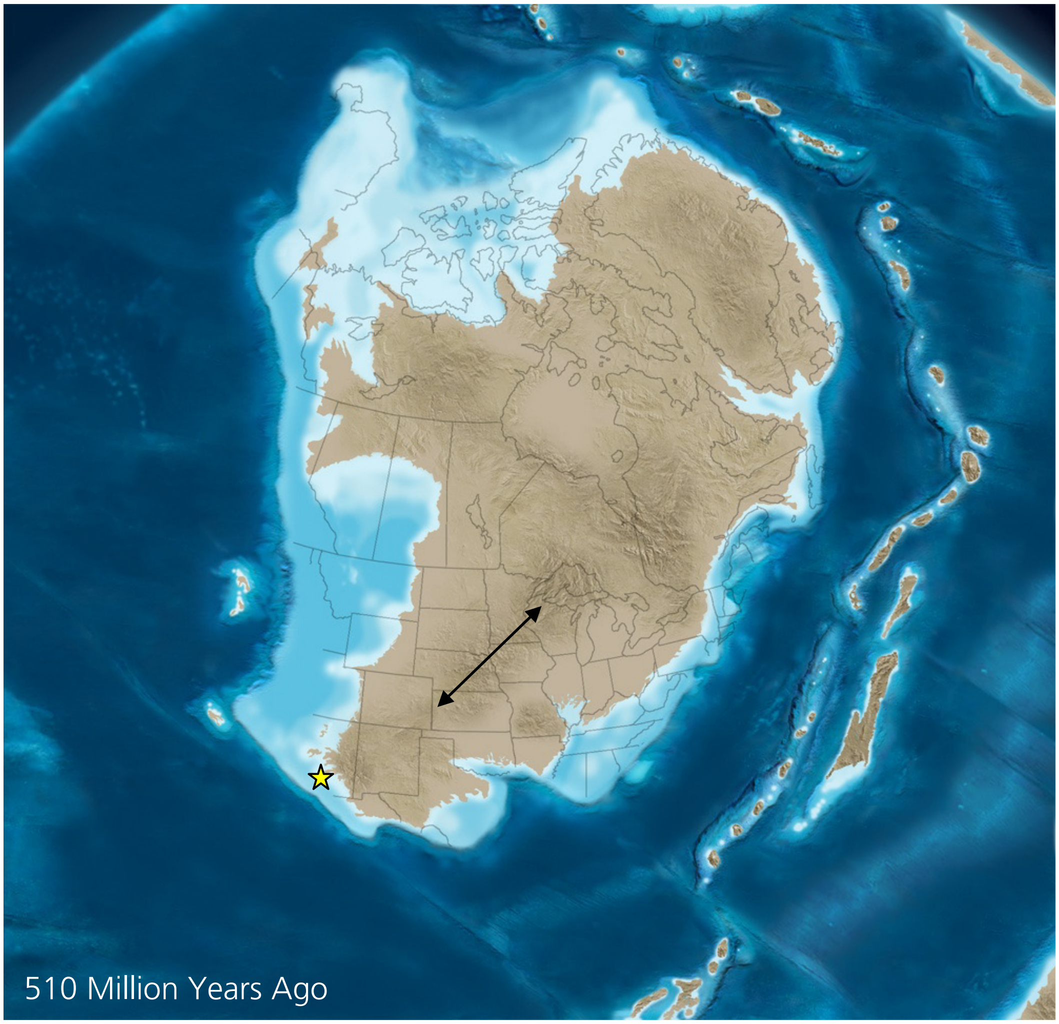


Figure 18. Cambrian paleogeographic map of North America during deposition of the Bolsa Quartzite and Abrigo Formation. Approximately 510 million years ago, the land mass of the proto-North American continent was much smaller then it is today. The arrows mark the spine of the Transcontinental Arch, which formed a northeast-to-southwest trending highland from northeastern Minnesota to southeastern Arizona. The yellow star is the approximate location of today's Saguaro National Park. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Map courtesy of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/~rcb7/namC510.jpg (access February 9, 2010).

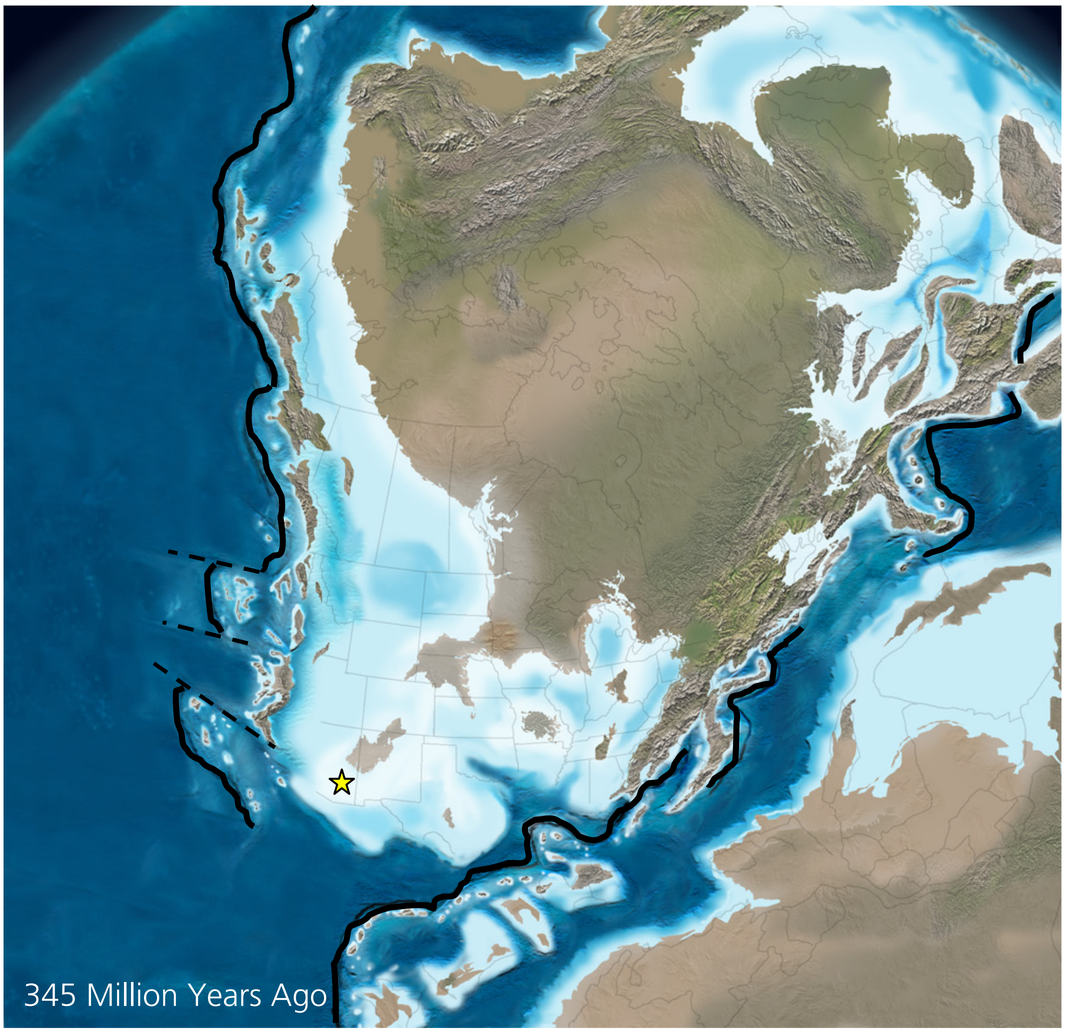


Figure 19. Early Mississippian (345 million years ago) paleogeographic map of North America. Beginning in the Devonian, the Antler Orogeny had initiated a major marine transgression that inundated the western United States. A shallow sea covered southeastern Arizona. The thick black lines indicate subduction zones that had formed along the margins of the proto-North American continent as the global land masses began to come together. Dashed black lines indicate potential transform (strike-slip) faults. The yellow star is the approximate location of today's Saguaro National Park. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Map modified from the Early Mississippian map of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/rcb7/namM345.jpg (accessed February 9, 2010).

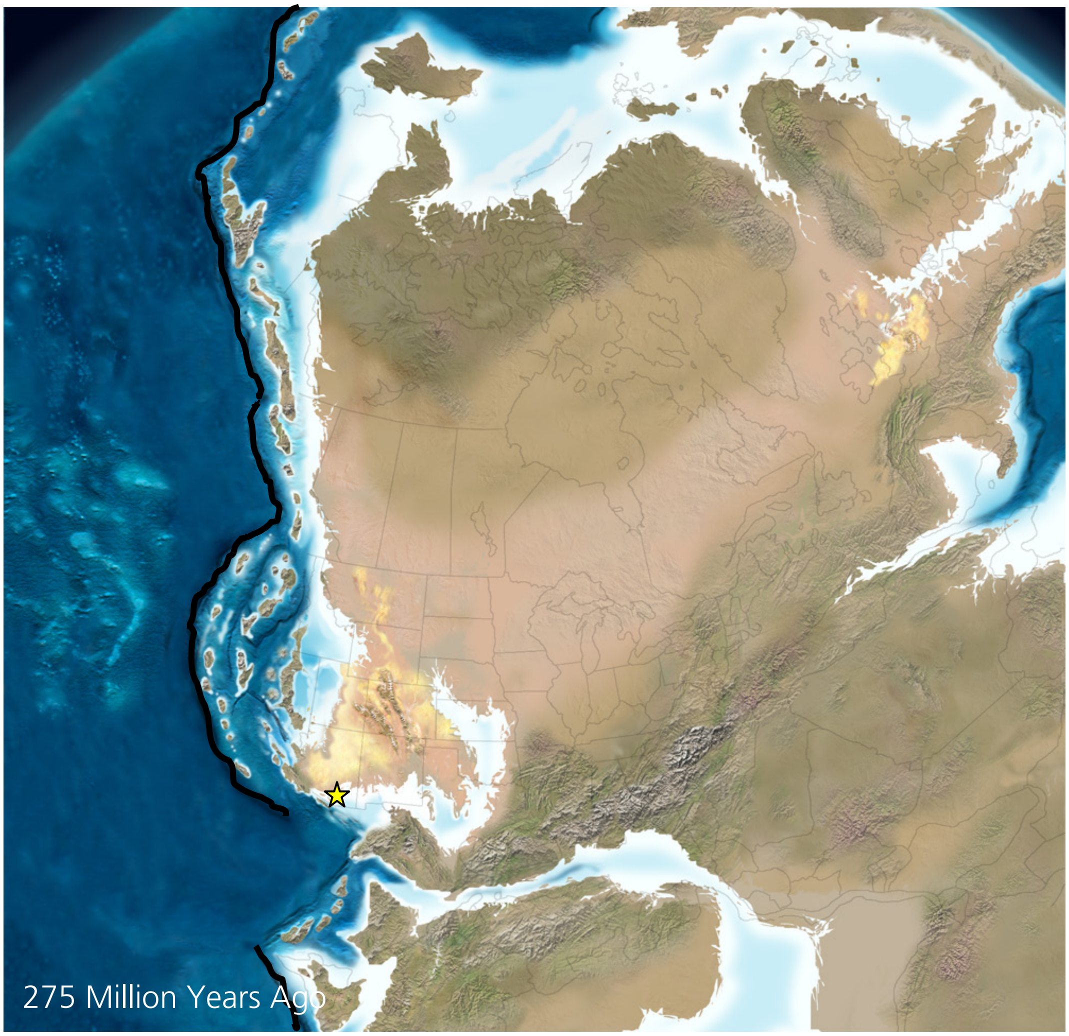


Figure 20. Middle Permian (275 million years ago) paleogeographic map of North America. Remnants of the northwest-southeast trending Ancestral Rocky Mountains can still be seen in Colorado. The light brown color in northeastern and central Arizona represents sand deposited in an arid dune environment. The Pedregosa Basin in southeastern Arizona and southwestern New Mexico is closing as South America collides with North America. The thick black lines mark the location of the subduction zone off the western margin of the land mass that will soon become the supercontinent, Pangaea. The yellow star represents the approximate location of today's Saguaro National Park. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Modified from the Middle Permian paleogeographic map of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/rcb7/namP275.jpg (accessed February 9, 2010).

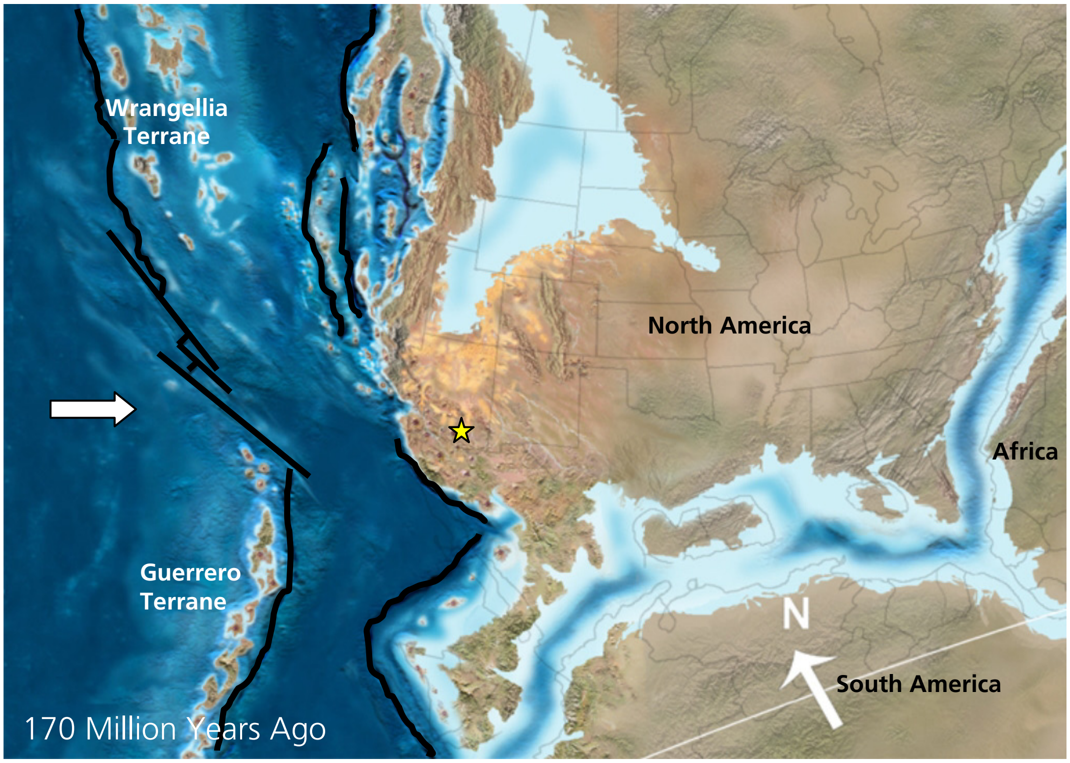


Figure 21. Middle Jurassic paleogeographic map of the southern half of the North American continent. Approximately 170 million years ago, the Greater Wrangellia Terrane collided with North America, forming a string of active volcanoes along the western margin from Mexico to Canada and causing thrust faulting in Nevada. The volcanic arc in the Wrangellia Terrane included today's Wrangell Mountains, the Queen Charlotte Islands, and Vancouver Island. The Guerrero Terrane closed to the south. Saguaro National Park (yellow star) lies along the Mogollon Slope. The basin forming landward of the thrusting in Nevada (foreland basin) allows an epicontinental sea to encroach from the north. Black lines indicate subduction zones. The supercontinent, Pangaea, is beginning to break apart and South America and Africa are drifting away from North America. The North American continent lies closer to the equator (white line and North arrow) than it does today. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Modified from the Middle Jurassic paleogeographic map of Dr. Ron Blakey, Northern Arizona University http://jan.ucc.nau.edu/rcb7/namJ170.jpg (accessed February 9, 2010).

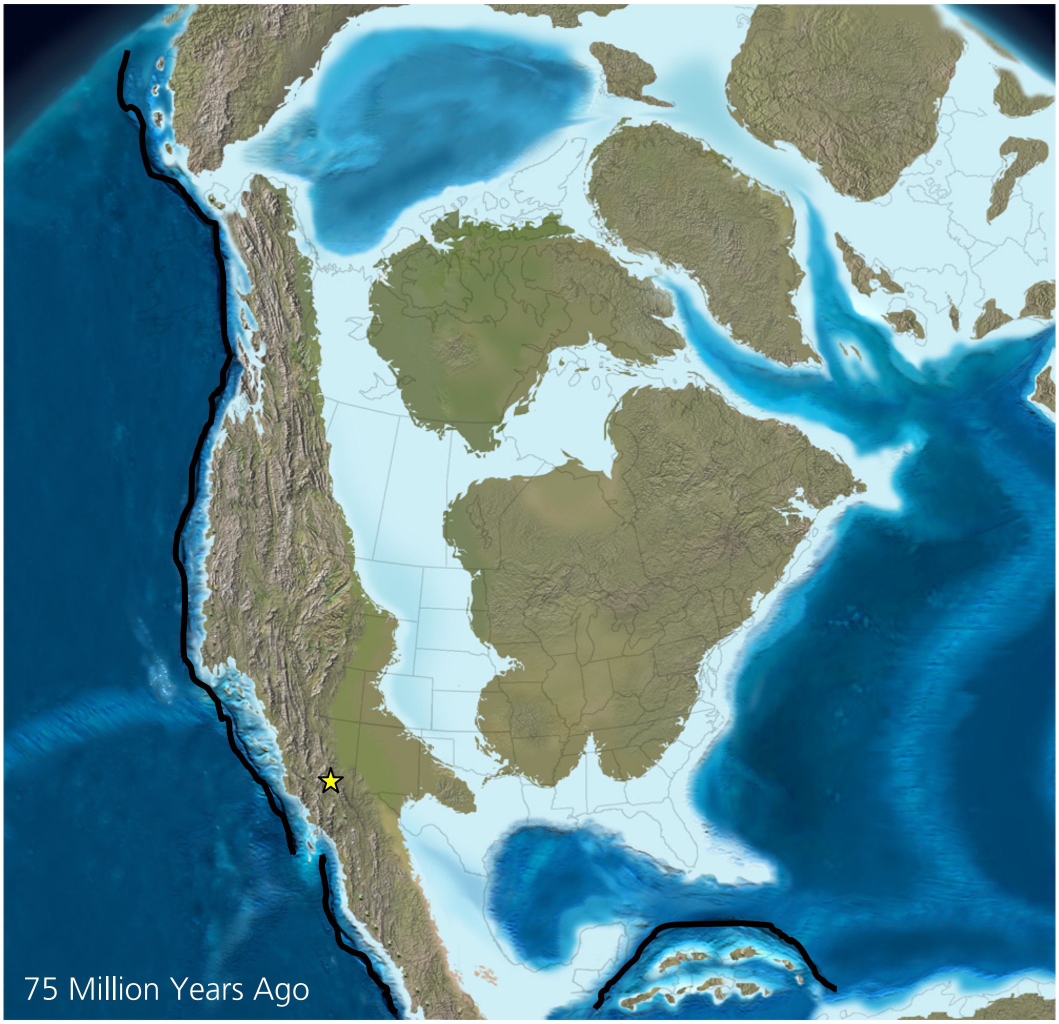


Figure 22. Late Cretaceous paleogeographic map of North America. Approximately 75 million years ago, the Western Interior Seaway slowly retreated to the northeast, leaving vast alluvial plains to mark its past locations. Along the western continental margin, the Sevier Orogeny was at its climax. Regional metamorphism affected western Arizona and eastern California. Paleozoic and Mesozoic sandstone, mudstone, and limestone were metamorphosed to quartzite, schist, and marble. The yellow star marks the approximate location of today's Saguaro National Park. Thick, black lines identify subduction zones. Brown color is land surface. Relative depths of marine water are divided into shallow (light blue) and deep (dark blue). Modified from the Late Cretaceous paleogeographic map of Dr. Ron Blakey, Northern Arizona University, http://jan.ucc.nau.edu/rcb7/namK75.jpg (accessed February 10, 2010).

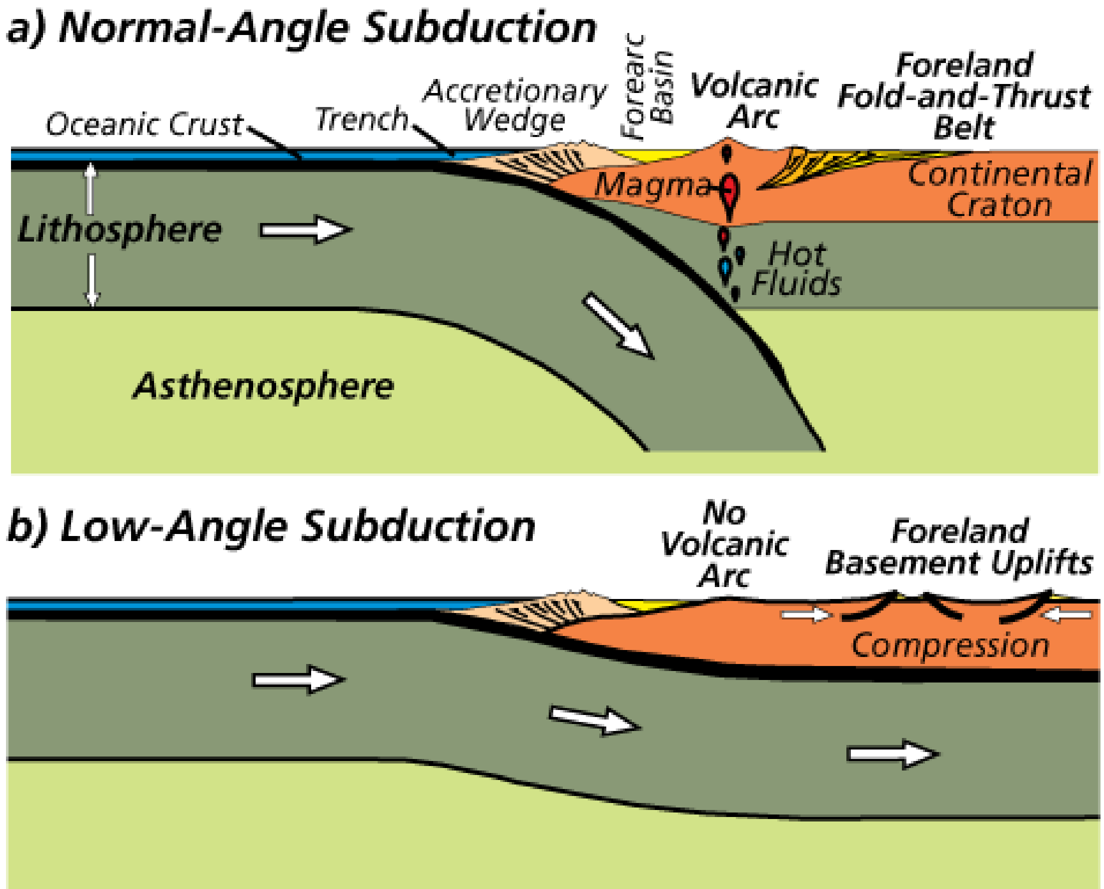


Figure 23. Subduction during the Laramide Orogeny. Normally, the subduction angle at an active continental margin is relatively steep (A), as it was in the early Mesozoic and off the present coast of North America and South America. Under these conditions, sedimentary strata are folded and thrust into mountain ranges that border the continental margin. During the Late Cretaceous to Eocene Laramide Orogeny, the subducting slab flattened out and deformation occurred farther inland (B). The down-going slab in low-angle subduction does not extend deep enough to heat up and produce magma so volcanism ceases or migrates toward the craton. The subducting slab transmits stress farther inland, causing hard rock in the crust to compress and break along reverse faults, forming basement uplifts such as those in today's Rocky Mountains. Diagram courtesy of Dr. Robert J. Lillie, Oregon State University.

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: http://geomaps.wr.usgs.gov/parks/misc/glossarya.html. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."

allochthon. A mass of rock or fault block that has been moved from its place of origin by tectonic processes; commonly underlain by décollements.

allochthonous. Describes rocks or materials formed elsewhere and subsequently transported to their present location. Accreted terranes are one example.

alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

andesite. Fine-grained volcanic rock commonly associated with subduction zone volcanoes. Named for the subduction zone volcanoes of the Andes Mountains.

angular unconformity. An unconformity where the rock layers above and below are oriented differently. Also see "unconformity."

aplite. A light-colored intrusive igneous rock characterized by a fine-grained texture. Emplaced at a relatively shallow depth beneath Earth's surface.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

ash (volcanic). Fine material ejected from a volcano (also see "tuff").

augen. Describes large lenticular mineral grains or mineral aggregates that have the shape of an eye in cross-section. Found in metamorphic rocks such as schists and gneisses.

autochthon. A body of rocks in the footwall (underlying side) of a fault that has not moved substantially from its site of origin. Although not moved, the rocks may be mildly to considerably deformed.

authochthonous. Formed or produced in the place where now found. Similar to "authigenic," which refers to constituents rather than whole formations.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie rocks exposed at the surface.

basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.

basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.

batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.

block (fault). A crustal unit bounded by faults, either completely or in part.

braided stream. A sediment-clogged stream that forms multiple channels which divide and rejoin.

breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

cataclasite. A fine-grained rock formed by pervasive fracturing, milling, crushing, and grinding by brittle deformation, typically under high pressure.

cataclastic. Describes structures in a rock such as bending, breaking, or crushing of minerals that result from extreme stresses during metamorphism.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clastic dike. A tabular mass of sedimentary material that cuts across the structure or bedding of pre-existing rock in a manner of an igneous dike; formed by filling cracks or fissures from below, above, or laterally.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

contact metamorphism. Changes in rock as a result of contact with an igneous body.

continental rise. Gently sloping region from the foot of the continental slope to the deep ocean abyssal plain; it generally has smooth topography but may have submarine canyons.

continental shelf. The shallowly submerged part of a continental margin extending from the shoreline to the continental slope with water depths less than 200 m (660 ft).

continental slope. The relatively steep slope from the outer edge of the continental shelf down to the more gently sloping ocean depths of the continental rise or abyssal plain.

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

dacite. A fine-grained extrusive igneous rock similar to andesite but with less calcium-plagioclase minerals and more quartz.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

décollement. A large-displacement (kilometers to tens of kilometers), shallowly-dipping to sub-horizontal fault or shear zone.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

delta. A sediment wedge deposited where a stream flows into a lake or sea.

detachment fault. Synonym for décollement. Widely used for a regionally extensive, gently dipping normal fault that is commonly associated with extension in a metamorphic core complex.

detritus. A collective term for lose rock and mineral material that is worn off or removed by mechanical means.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

diorite. A type of plutonic igneous rock. It is the approximate intrusive equivalent of andesite.

dip. The angle between a bed or other geologic surface and horizontal.

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.

discordant. Describes contacts between strata that cut across or are set at an angle to the orientation of adjacent rocks.

dune. A low mound or ridge of sediment, usually sand, deposited by wind.

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

facies (metamorphic). The pressure and temperature conditions that result in a particular, distinctive suite of metamorphic minerals.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fan delta. An alluvial fan that builds into a standing body of water. This landform differs from a delta in that a fan delta is next to a highland and typically forms at an active margin.

fanglomerate. A sedimentary rock of heterogeneous materials that were originally deposited in an alluvial fan and have since been cemented into solid rock.

fault. A break in rock along which relative movement has occurred between the two sides.

felsic. Describes an igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic."

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

granodiorite. A group of intrusive igneous (plutonic) rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.

hanging wall. The mass of rock above a fault surface (also see "footwall").

hornfels. A fine-grained rock composed of a mosaic of grains that are the same size in each dimension without preferred orientation. Typically formed by contact metamorphism, which occurs near the contact with an intrusion of molten material.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin-and-Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

intercalated. Layered material that exists or is introduced between layers of a different type.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

joint. A break in rock without relative movement of rocks on either side of the fracture surface.

laccolith. A mushroom- or arcuate-shaped pluton that has intruded sedimentary strata and domed up the overlying sedimentary layers. Common on the Colorado Plateau.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.
lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.
lentil. A minor rock-stratigraphic unit of limited geographic extent and thinning out in all directions.
lithofacies. A lateral, mappable subdivision of a designated stratigraphic unit, distinguished from adjacent subdivisions on the basis of rock characteristics (lithology).
lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.
lithophysa. A hollow, bubble-like structure composed of concentric shells of finely crystalline potassium-rich feldspar, quartz, and other minerals.
lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.
mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."
magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.
marl. An unconsolidated deposit commonly with shell fragments and sometimes glauconite consisting chiefly of clay and calcium carbonate that formed under marine or freshwater conditions.
marlstone. An indurated rock of about the same composition as marl, called an earthy or impure argillaceous limestone.
matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.
megabreccia. A term for a coarse breccia containing individual blocks as much as 400 m (1,300 ft) long.
member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.
meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.
metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.
metamorphic core complex. A generally domal or arch-like uplift of deformed metamorphic and plutonic rocks overlain by tectonically detached and distended relatively unmetamorphosed cover rocks.
metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.
metasomatism. A metamorphic process in which the original chemical composition of a rock is changed by reaction with an external source; commonly thought to occur in the presence of a fluid medium flowing through the rock.
mylonite. A fine-grained, foliated rock typically found in localized zones of ductile deformation, often formed at great depths under high temperature and pressure.
mylonite structure. A flow-like appearance, characteristic of mylonites, that is produced by intense small-scale crushing, breaking, and shearing of the rock.
normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.
nuée ardente. A swiftly-flowing, turbulent gaseous cloud, sometimes incandescent, erupted from a volcano and containing ash and other pyroclastic materials in its lower part.
orogeny. A mountain-building event.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.
overbank deposit. Alluvium deposited outside a stream channel during flooding.
paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.
Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.
passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").
pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.
permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.
phreatophyte. A deeply-rooted plant that obtains its water supply from the water table or through the capillary fringe.
plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.
pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.
porphyroclast. A partly-crushed, non-metamorphosed rock fragment within a finer-grained matrix in a metamorphic rock.
propylitization. Describes low-pressure- and low-temperature alteration around many ore bodies.
pseudomorph. A mineral whose outward crystal form takes after that of another mineral; described as being "after" the mineral whose outward form it has (e.g., quartz after fluorite).
quartzite. Metamorphosed quartz sandstone.
recharge. Infiltration processes that replenish groundwater.
red beds. Sedimentary strata composed largely of sandstone, siltstone, and shale that are predominantly red due to the presence of ferric iron oxide (hematite) coating individual grains.
regression. A long-term seaward retreat of the shoreline or relative fall of sea level.
reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").
rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

sill. An igneous intrusion that is of the same orientation as the surrounding rock.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

stock. An igneous intrusion exposed at the surface; less than 100 km^2 (40 mi^2) in size. Compare to "pluton."

stope. An underground excavation formed by the extraction of ore.

strata. Tabular or sheet-like masses or distinct layers of rock.

stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

tectonic. Relating to large-scale movement and deformation of Earth's crust.

terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").

terrane. A large region or group of rocks with similar geology, age, or structural style.

thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.

transgression. Landward migration of the sea as a result of a relative rise in sea level.

trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

vent. An opening at Earth's surface where volcanic materials emerge.

volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).

volcaniclastic. Describes clastic volcanic materials formed by any process of fragmentation, dispersed by any kind of transporting agent, deposited in any environment.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and web sites that may be of use to resource managers. Web addresses are current as of August 2010

Geology of National Park Service Areas

National Park Service Geologic Resources Division (Lakewood, Colorado). http://nature.nps.gov/geology/

NPS Geologic Resources Inventory. http://www.nature.nps.gov/geology/inventory/gre_publications.cfm

U.S. Geological Survey Geology of National Parks (includes 3D photographs). http://3dparks.wr.usgs.gov/

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NPS Geoscientist-in-the-parks (GIP) internship and guest scientist program. http://www.nature.nps.gov/geology/gip/index.cfm

Resource Management/Legislation Documents

NPS 2006 Management Policies (Chapter 4; Natural Resource Management): http://www.nps.gov/policy/mp/policies.html#_Toc157232681

NPS-75: Natural Resource Inventory and Monitoring Guideline: http://www.nature.nps.gov/nps75/nps75.pdf.

NPS Natural Resource Management Reference Manual #77: http://www.nature.nps.gov/Rm77/

Geologic Monitoring Manual
R. Young and L. Norby, editors. Geological Monitoring. Geological Society of America, Boulder, Colorado.

Website under development. Contact the Geologic Resources Division to obtain a copy.

NPS Technical Information Center (Denver, repository for technical (TIC) documents): http://etic.nps.gov/

Geological Survey Websites

Arizona Geological Survey: http://www.azgs.state.az.us/

U.S. Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geological Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

Climate Change Information

Global change impacts in the United States (report): http://www.globalchange.gov/publications/reports/scientific-assessments/us-impacts

NPS Climate Change Response Program: http://www.nature.nps.gov/climatechange/index.cfm

Other Geology/Resource Management Tools

Bates, R. L. and J. A. Jackson, editors. American Geological Institute dictionary of geological terms (3rd Edition). Bantam Doubleday Dell Publishing Group, New York.

U.S. Geological Survey National Geologic Map Database (NGMDB): http://ngmdb.usgs.gov/

U.S. Geological Survey Geologic Names Lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

U.S. Geological Survey Geographic Names Information System (GNIS; search for place names and geographic features, and plot them on topographic maps or aerial photos): http://gnis.usgs.gov/

U.S. Geological Survey GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”).

U.S. Geological Survey Publications Warehouse (many USGS publications are available online): http://pubs.usgs.gov

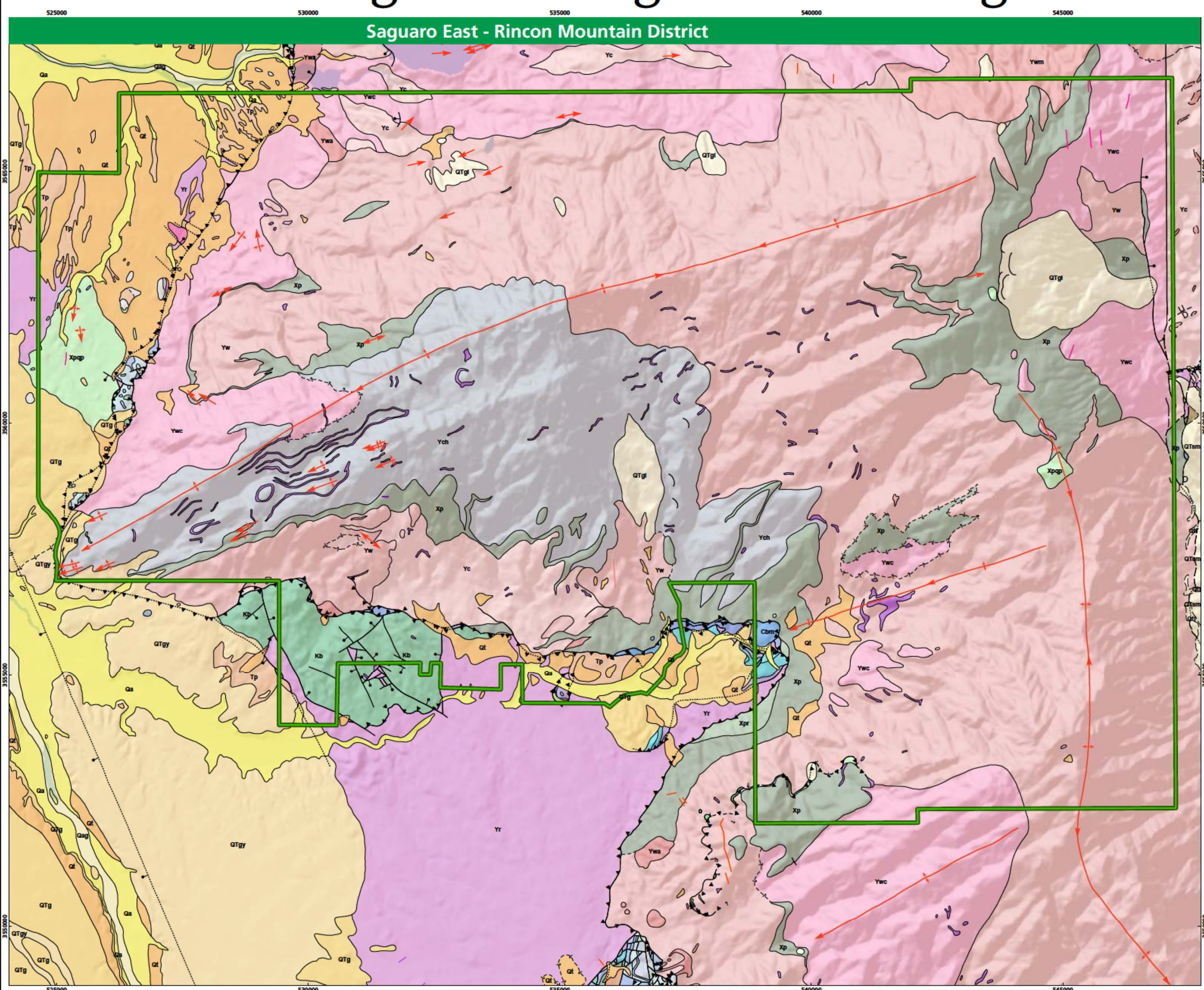
U.S. Geological Survey, description of physiographic provinces: http://tapestry.usgs.gov/Default.html

Appendix A: Overviews of Digital Geologic Data

The following pages are an overview of the digital geologic data for Saguaro National Park. For a poster-size PDF of these overviews and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

Overview of Digital Geologic Data for Saguaro NP

Saguaro East - Rincon Mountain District



0 1 2 3 4 Kilometers

0 1 2 3 4 Miles

UTM Zone 12N NAD 83

scale greater than source data

Geologic Contacts
- known or certain
- approximate
- queried
- map boundary

Linear Dikes
- Tca - Carbonate dike or vein
- Td - Diorite
- Tai - Andesite
- Tri - Intrusive rhyolite
- Ywm - Wrong Mountain Quartz Monzonite, massive phase

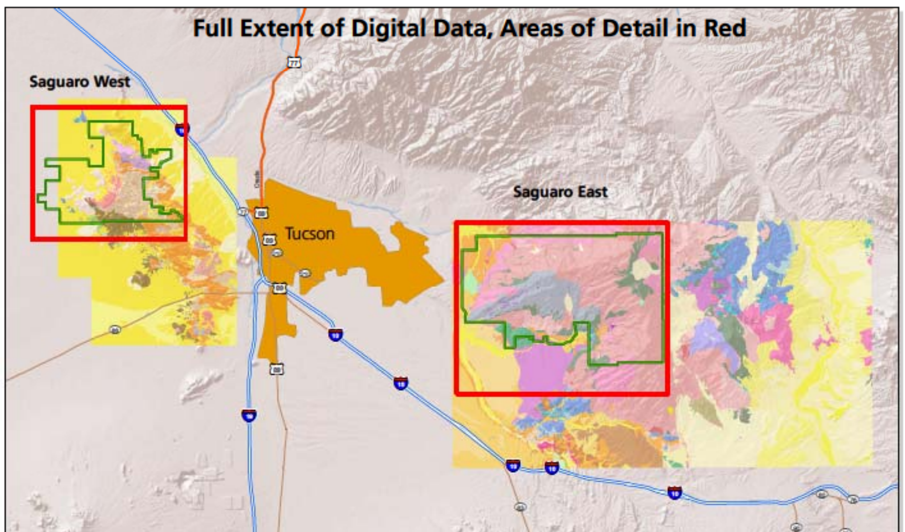
Faults
- high-angle fault, known or certain
- unknown offset/displacement, known or certain
- unknown offset/displacement, approximate
- unknown offset/displacement, concealed
- thrust fault, known or certain
- thrust fault, approximate
- thrust fault, concealed
- thrust fault, queried

Folds
- anticline, known or certain
- syncline, known or certain
- hinge line, known or certain

NPS Boundary

Geologic Units
- Qa - Sand, gravel, and silt
- Qag - Gravel and sand
- Qt - Terrace gravel deposits
- Qtl - Terrace gravel deposits, locally derived
- QTgy - Gravel, grus, and sand
- QTg - Gravel, grus, and sand (basin deposits)
- QTgl - Rubble deposits
- QTsm - Formation of St. David Area, margin facies
- Tg - Gravel and conglomerate
- Tn - Nogales Formation
- Tp - Pantano Formation
- Tpc - Pantano Formation, claystone member
- Tra - Rhyolitic agglomerate
- Trt - Rhyolitic tuff breccia
- Tat - Porphyritic andesite
- Tai - Andesite
- Tri - Intrusive rhyolite
- Kb - Bisbee Group
- Kbg - Glance Conglomerate
- Ps - Scherrer Formation
- Pe - Epitaph Formation
- Pc - Colina Limestone
- PPNe - Earp Formation
- PPNh - Horquilla Limestone
- PPNhm - Horquilla Limestone, metamorphosed facies
- Me - Escabrosa Limestone
- Dm - Martin Formation
- Ca - Abrigo Formation
- Cb - Bolsa Quartzite
- Cbm - Bolsa Quartzite, metamorphosed facies
- Yd - Diabase
- Yds - Dripping Spring Formation
- Yp - Pioneer Shale
- Yr - Granodiorite of Rincon Valley
- Yw - Wrong Mountain Quartz Monzonite
- Ywm - Wrong Mountain Qartz Monzonite, massive phase
- Ywa - Wrong Mountain Quartz Monzonite, aplite
- Ydi - Metadiorite
- Yc - Continental Granodiorite
- Ych - Continental Granodiorite and other rocks (hybridized)
- Ywc - Wrong Mountain Quartz Monzonite and Continental Granodiorite
- Xp - Pinal Schist
- Xpqp - Pinal Schist, quartzite and phyllite
- Xpr - Pinal Schist, metarhyolite
- ls - Limestone and marble

Full Extent of Digital Data, Areas of Detail in Red



This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

Drewes, H. 1974. Geologic Map and Sections of the Happy Valley Quadrangle, Conchise County, Arizona. Scale 1:48,000. Miscellaneous Investigations Map I-832. U.S. Geological Survey.

Drewes, H. 1977. Geologic Map and Sections of the Rincon Valley Quadrangle, Pima County, Arizona. Scale 1:48,000. Miscellaneous Investigations Map I-997. U.S. Geological Survey.

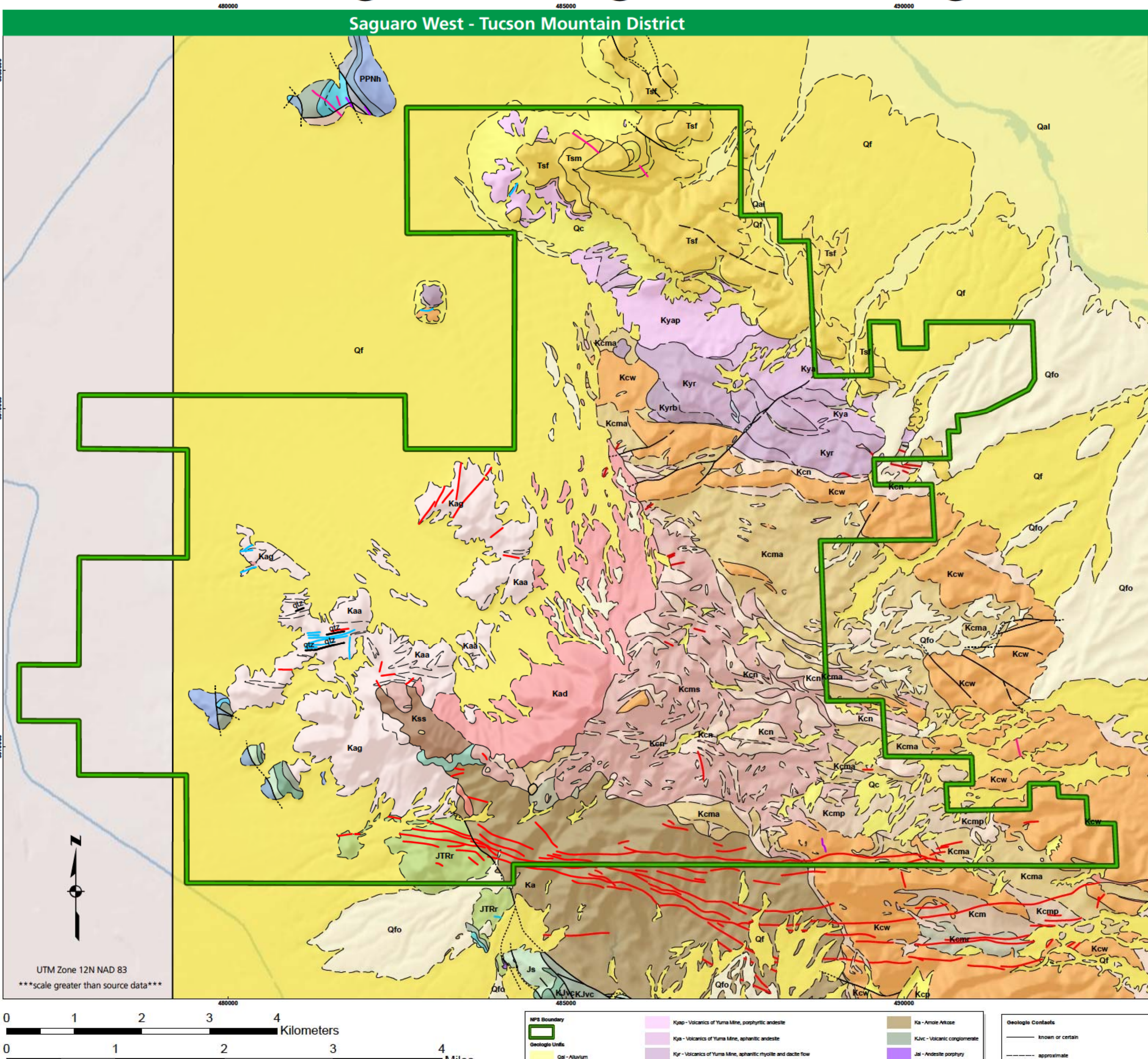
Lipman, P.W. 1993. Geologic Map of the Tucson Mountains Caldera, Southern Arizona. Scale 1:24,000. Miscellaneous Investigations Map I-2205. U.S. Geological Survey.

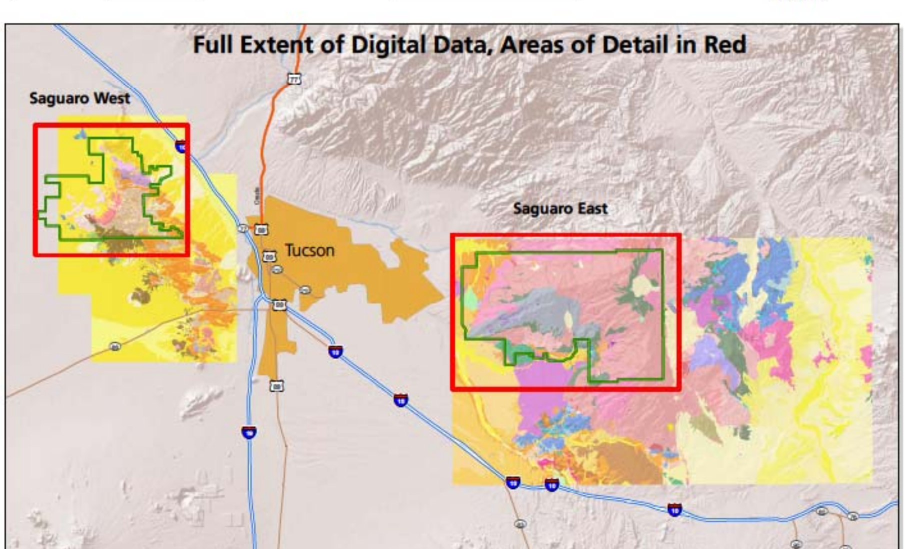
Digital geologic data and cross sections for Saguaro National Park, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

Produced by the Geologic Resources Inventory

August 2010

Overview of Digital Geologic Data for Saguaro NP





NPS Boundary

Geologic Units

- Qal - Alluvium
- Qc - Colluvium
- Qf - Alluvial-fan deposits
- Qfo - Older alluvial-fan deposits
- Tsf - Safford Dacite, lava flows
- Tsv - Safford Dacite, vent intrusions
- Tss - Safford Dacite, vent splatter
- Tst - Safford Dacite, tuffaceous rocks
- Tsm - Safford Dacite, mudflow deposits
- Tc - Tertiary colluvium
- TKal - Andesite
- TKs - Porphyritic silicic dikes
- Kgp - Porphyritic granodiorite
- Kaa - Amole Pluton, aplite
- Kag - Amole Pluton, granite
- Kad - Granodiorite
- Kyap - Volcanics of Yuma Mine, porphyritic andesite
- Kya - Volcanics of Yuma Mine, aphanitic andesite
- Kyr - Volcanics of Yuma Mine, aphanitic rhyolite and dacite flow
- Kyrb - Volcanics of Yuma Mine, aphanitic rhyolite and dacite flow breccia
- TKvs - Volcaniclastic sedimentary rocks
- Kci - Cat Mountain Tuff, intrusive rhyolitic tuff
- Kcw - Cat Mountain Tuff, densely welded rhyolite
- Kcp - Cat Mountain Tuff, partly welded rhyolite
- Kcn - Cat Mountain Tuff, nonwelded to partly welded rhyolite
- Kcm - Cat Mountain Tuff, Megabreccia member, undivided
- Kcmt - Cat Mountain Tuff, Megabreccia member, mainly clasts of tuff of Confidence Peak
- Kcma - Cat Mountain Tuff, Megabreccia member, mainly clasts of andesite and dacite
- Kcms - Cat Mountain Tuff, Megabreccia member, mainly clasts of Cretaceous sedimentary rocks
- Kcmr - Cat Mountain Tuff, Megabreccia member, abundant clasts of flow-layered rhyolite
- Kcmb - Cat Mountain Tuff, Megabreccia member, abundant clasts of Recreation Red Beds
- Kcmp - Cat Mountain Tuff, Megabreccia member, abundant clasts of Paleozoic sedimentary rocks
- Kss - Sandstone and shale
- Ktc - Tuff of Confidence Peak
- Ka - Amole Arkose
- KJvc - Volcanic conglomerate
- Jal - Andesite porphyry
- Jt - Rhyolite and ash-flow tuff
- Js - Sandstone
- Jlt - Lithophysal ash-flow tuff
- Jb - Basaltic ash-flow tuff
- JTRr - Recreation Red Beds
- Ps - Scherrer Formation
- PPNh - Horquilla Limestone
- Me - Escabrosa Limestone
- Dm - Martin Formation
- Ca - Abrigo Formation
- Cb - Bolsa Quartzite
- Yg - Porphyritic granite
- Xp - Pinal Schist

Geologic Contacts

- known or certain
- approximate
- quadrangle boundary

Faults

- high-angle fault, known or certain
- unknown offset/displacement, known or certain
- unknown offset/displacement, approximate
- unknown offset/displacement, concealed

Linear Dikes

- Tal - Andesite
- Tri - Intrusive rhyolite
- TKal - Andesite
- TKs - Porphyritic silicic dikes
- Kgp - Porphyritic granodiorite
- Kaa - Amole Pluton, aplite
- qtz - Quartz vein

This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source maps used in creation of the digital geologic data product were:

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Lipman, P.W. 1993. *Geologic Map of the Tucson Mountains Caldera, Southern Arizona.* Scale 1:24,000. Miscellaneous Investigations Map I-2205. U.S. Geological Survey.

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August 2010

Appendix B: Scoping Meeting Participants

The following is a list of participants from the GRI scoping session for Saguaro National Park, held on April 6, 2006. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI publications web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

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