Island Mountains of Southeastern Arizona
geology, vegetation & wildlife

John V. Bezy & F.M. Conway

Down-to-Earth #24

ISLAND MOUNTAINS OF SOUTHEASTERN ARIZONA
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&

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East face of the Chiricahua Mountains near Portal, Arizona.

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INTRODUCTION

Eleven island-like mountain ranges tower thousands of feet above adjacent basins in southeastern Arizona. In the order that they are presented in this book, these island ranges are: Santa Catalina, Rincón, Tortolita, Santa Rita, Tucson, Galiuro, Pinaleño, Chiricahua, Mule, Huachuca, and Whetstone Mountains (Figure 1). These island mountains, together with over a dozen other ranges, that are either lower in elevation or more difficult to access, make up the Basin and Range geologic province of southeastern Arizona.

Most of these ranges and intervening basins trend northwest-southeast and are part of the huge geologic Basin and Range Province that extends from southern Oregon to central Mexico. This mountain-vally topography results from a period of extension from about 15 to 5 million years ago that broke the crustal rocks of western North America into blocks, separated by steeply dipping faults. Some of these crustal blocks were uplifted to form ranges; other blocks subsided as much as 2.4 mi (4 km) to form deep basins. Streams cut deep canyons into the rising ranges and transported eroded boulders, cobbles, gravel, sand and clay to aprons of sediment - alluvial fans and bajadas - in nearby subsiding basins. Many of these sediment-filled basins had no drainage outlets to the sea and held shallow lakes (playas) that fluctuated in size with changes in climate. As the Santa Cruz and San Pedro Rivers and other streams integrated the drainage of southeastern Arizona with that of the Gila and Colorado Rivers, their tributaries eroded headward into the alluvial fill of these formerly closed basins. Today, ephemeral or seasonal drainages continue to deeply erode alluvial fans and bajadas on all sides of the ranges (Figure 2).

Although these ranges share a common geologic origin, each has its own assemblage of large and small landforms that makes it unique. These landforms are the products of a host of geologic processes. Erosion by flash flooding is the most important, cutting deep canyons that expose the structure and variety of rocks in each range. Massive landslides, debris flows and rock falls actively sculpt mountain slopes and feed loose rock debris to streams for transport to the adjacent basins. Chemical and mechanical weathering, although less dynamic, are important processes that place their stamp on these island mountains.

Geologic processes have not been uniformly active throughout the life of the ranges. Erosion by running water, for example, has sculpted the mountains since their bedrock was first exposed to the atmosphere and continues to be the dominant process shaping the modern landscape. Debris flows, deep chemical weathering, and freeze-thaw shattering of the bedrock wear down mountain slopes today but were far more active during wetter climatic cycles. Faulting gave rise to the original uplift of the ranges and shaped today's basin and range topography of southeastern Arizona, yet has been mostly inactive over the past 5 million years.

The biological diversity of the ranges of southeastern Arizona is as remarkable as the geology. These ranges comprise cool, humid islands supporting highland vegetation of the Sonoran and Chihuahuan Deserts above broad basins As one ascends from 2500 ft (762 m) along the basin floors to over 10,720 ft (3270 m) at Mt. Graham - the highest elevation in southeastern Arizona - in the Pinaleño Mountains, temperature decreases and precipitation increases,. This elevation increase, slope aspect (the direction a slope faces), topography, rock type, cold air drainage, climatic fluctuations during and since the last Ice Age, and a host of other factors are responsible for the rich mosaic of life zones found here.

Many plant species common to the Sierra Madre Occidental of western Mexico reach their most northerly point in the Santa Catalina, Pinaleño, Chiricahua and other high ranges of southeastern Arizona. For this reason, these ranges are often referred to as Madrean Sky Islands. Chihuahua pine (Pinus leiophylla var. chihuahuana), Apache pine (Pinus engelmannii), Chihuahua white pine (Pinus strobiformis), Mexican blue oak (Quercus oblongifolia), Arizona cypress (Cupressus arizonica), and Arizona mountain ash (Sorbus dumosa) are a few of the Madrean tree species of SE Arizona. Vegetation ranges from Palo Verde and Saguaro in the foothills to stands of pine, fir, and spruce at the crest of the highest ranges. Numerous plant and animal species inhabit the ranges. Many are emigrant species from the Rocky Mountains, the Sierra Madre Occidental, and the subtropical lowlands of Sonora and Sinaloa, that migrated to southeastern Arizona during and since the last Ice Age. Wildlife includes both migratory species and permanent residents, and is as diverse as any part of the Southwest. Many species inhabit more than one of these plant communities; others migrate with the seasons. This rich biologic mosaic produces one of the most spectacular ecologic regions of the southwestern North America.

Part 1 presents the geologic evolution of mountains of southeastern Arizona. Part 2 examines the biological diversity, focusing on the vertical zonation of plants, from palo verde and saguaro to pine-fir-spruce forest, encountered as one ascends from dry foothills to mountain crests. Major plant and animal species commonly found in each life zone are introduced and their role in the larger ecosystem is discussed. Part 3 is an in-depth exploration of the distinctive geologic landscapes of these eleven mountain ranges, focusing on areas that are especially scenic, accessible, and important from a natural history perspective. Roads and public lands that provide the best access are listed for each mountain range. The final pages contain recommendations for further reading.

The guidebook is intended to provide the reader with an understanding of the dynamic processes that have shaped the mountains of southeastern Arizona. You will encounter many of the geologic features and plant communities presented in the text again and again as you continue to explore the Southwest. I hope that this volume will enhance the pleasure of those explorations.

A word of caution: The roads recommended for use can be driven with most vehicles of moderate clearance under normal conditions by experienced drivers. Unpaved roads or segments of roads that are not paved are identified. Drainages are subject to flash flooding during periods of heavy rainfall and should be crossed with caution. Restaurants, gasoline, information on road conditions, and emergency services are available in the larger communities of the region. Consult detailed regional maps to visit places described in this volume.

Figure 1 - previous page. Southeastern Arizona's Basin and Range Province of consists of fault-bounded mountain ranges that rise thousands of feet above adjacent basins. Vegetation, soil, and rock varnish mask the true color of the many types of rock that form the ranges. The tributaries of major streams are eroding the alluvial fans and bajadas along the margins of the ranges. The ranges discussed in this publication are: 1. Santa Catalina, 2. Rincón, 3. Tortolita, 4. Santa Rita, 5.Tucson, 6. Galiuro, 7. Pinaleño, 8. Chiricahua, 9. Mule, 10. Huachuca, and 11. Whetstone Mountains (Courtesy of Google Earth).

GENERAL GEOLOGY OF THE MOUNTAINS OF SOUTHEASTERN ARIZONA

Proterozoic to Cenozoic

A broad variety of igneous, sedimentary, and metamorphic rocks core the mountains of southeastern Arizona and span more than 1650 million years of geologic time. Geologists divide this grand expanse of time into the: Cenozoic Era (65 million years ago to the present), Mesozoic Era (252 to 65 million years ago), Paleozoic Era (541 to 252 million years ago), and the Proterozoic Eon (4000 million to 541 million years ago). The Pinal Schist, at 1650 million years, is the oldest rock exposed in the mountains of southeastern Arizona.

Middle Proterozoic rocks formed as arcs of volcanic islands, granitic intrusions, deep to shallow marine sediments and coastal plain sediments on the southern margin of the ancestral North American continent. Over hundreds of millions of years these volcanic tuffs, lava and ash flows, granites, shales, limestones, dolomites, sandstones, and conglomerates were rafted to and collided with North America as denser oceanic plates sank beneath the less-dense North American plate. During the accretion of these island arcs and associated basins, many of these rocks were deformed by compression and altered by heat and pressure to form metamorphic rocks. The Pinal Schist, for example, was originally deposited as sediments - sands, silts, and clays – to form sedimentary sandstones, siltstones, and shales. Over time these sedimentary rocks were buried at depth and subjected to intense heat and pressure, transforming them into new metamorphic rocks—schists and phyllites. Igneous intrusions, such as the 1400 million-year-old Oracle Granite, invaded these older rocks in multiple places. These Proterozoic rocks are the foundations upon which younger sedimentary rocks were deposited and upon which volcanic and intrusive igneous rocks accumulated and intruded.

During later Proterozoic time, rivers, vast desert dune fields, and shallow seas deposited the sandstones, conglomerates, shales, limestones, and dolostones of the Apache Group (Pioneer Shale, Dripping Spring Quartzite, Mescal Limestone), and the overlying Troy Quartzite. In places, igneous rocks, ranging from granites and rhyolites to diabases, have intruded these ancient strata. Regional uplift was accompanied by erosion that beveled off some of the Proterozoic rocks. Following deposition of the Troy Quartzite 1080 to 1260 million years ago, there is a time gap representing at least 600 million years of geologic history that is not represented by sedimentary rock in this part of Arizona. Either no rocks were deposited during this missing interval or sediment was deposited but was later removed by erosion.

For most of the Paleozoic Era shallow seas repeatedly advanced and retreated across Arizona, depositing hundreds of feet of limestones, dolomites, sandstones, and shales over the eroded Proterozoic rocks. These include the Cambrian Bolsa Quartzite (510-520 million years ago) and Abrigo Formation (495-505 million years ago), the Devonian Martin Formation (365 to 418 million years ago), the Mississippian Escabrosa Limestone (340 million years ago), and Permian-Pennsylvanian Naco Group (Horquilla Limestone, Earp Formation, Colina Limestone, Epitaph Dolomite, Sherrer Formation, Concha Limestone, and Rainvalley Formation)(316-280 million years ago). These sedimentary rocks were deposited in shallow seas, river floodplains, and wind-blown sand flats along arid coastlines.

During early Mesozoic time the movement of the Pacific Oceanic Plate beneath the North American Plate, a process called subduction, triggered the emplacement of shallow granitic intrusions, scattered volcanic

eruptions, and mountain building across southeastern Arizona. The igneous intrusions of the Mule, Dragoon, Patagonia, and Sierrita Mountains, and the Rice Peak Porphyry, Leatherwood Granodiorite, and Alamo Canyon Granite exposed in the Santa Catalina Mountains were emplaced during this time. Compression of crustal rocks gave rise to the Mogollon Highlands in southern Arizona. Streams draining these mountains deposited sediment as far north as present-day northwestern Colorado.

Regional subsidence, beginning about 155 million years ago, allowed the sea to again advance across southeastern Arizona. Marine sediment deposited in a shallow arm of the sea and gravel, sand, silt, and clay eroded from the Mogollon Highlands and other mountains accumulated in basins. These sediments form the rocks of the Bisbee Group (the Glance Conglomerate, Morita Formation, Mural Limestone, and the Cintura Formation) and the Fort Crittenden Formation.

The Laramide Orogeny, that great episode of mountain building that gave rise to the Rocky Mountains and uplifted the Colorado Plateau 80 to 50 million years ago, was marked by regional faulting and extensive volcanic activity in southeastern Arizona. Proterozoic faults were re-activated and new faults fractured Mesozoic rocks. Large masses of magma cooled to form granites that are now exposed in many of the ranges in southeastern Arizona. In scattered volcanic centers the magma reached the surface as outpourings of andesite, rhyolite, and latite.

The 66 million years of the Cenozoic Era also witnessed great tectonic activity in southeastern Arizona. Magma continued to invade crustal rocks to within a few miles of the surface, where they cooled to form granitic rocks, such as the Catalina and Wilderness Suites Granites of the Santa Catalina Mountains. But the greatest tectonic event was the northeast-southwest extension of the southwestern part of North America, which caused crustal rocks to be stretched and thinned. As stretching and thinning continued, crustal rocks in southern Arizona and other parts of the western continent pulled apart and broke along low angle fractures called detachment faults. The Catalina Fault, the detachment fault associated with the uplift of the Santa Catalina, Rincón, and Tortolita Mountains, began to form at depths of up to 6 to 8 mi (10 to 13 km). Continued extension moved rocks below the fault 16 to 19 mi (25 to 30 km) toward the east-northeast and closer to the surface as rocks above the fault slid toward the southwest. Heat, friction and pressure altered granites to gneiss, and eventually produced rising domes of metamorphic rock called metamorphic core complexes. The Santa Catalina, Rincón, Tortolita, and Pinaleño Mountains, are four of more than two dozen such structures that extend from northern Mexico to southern Canada.

A second period of extension began about 15 million years ago that broke the rocks of western North America into blocks, separated by new, more steeply dipping faults. In southeastern Arizona, some of these crustal blocks were further uplifted to form most of the mountain ranges discussed in this volume. Other blocks subsided as much as 2.4 mi (4 km) to form deep basins between these various ranges. Movement continued along these high angle faults until about 5 million years ago, forming the Basin and Range topography and geologic province that extends from Oregon into central Mexico, including southeastern Arizona.

Streams cut deep canyons into the rising mountains and deposited aprons of boulders, gravel, sand and silt, called alluvial fans and bajadas, that filled the adjacent subsiding, closed basins. Shallow lakes pooled and evaporated, leaving behind layers of mineral salts. Finally, the Santa Cruz, San Pedro and other streams integrated the drainage of most of these basins with that of the Gila-Colorado river system. Today, wet-weather drainages are eroding the alluvial fans and bajadas.

VEGETATION AND WILDLIFE OF THE ISLAND MOUNTAINS

The vegetation and wildlife of the mountains of southeastern Arizona are amazingly diverse. From this diversity ecologists have identified a series of life zones, each with a distinctive association of plants, which occurs with increased elevation (Figure 3). These life zones and their approximate limits of elevation are:

- Sonoran Desert scrub (up to 4000 ft; 1219 m)
- desert grassland (3500 to 5400 ft; 1067-1646 m)
-

- open oak woodland (3700 to 6400 ft; 1128-1951 m)
- pine-oak woodland (4800 to 7400 ft; 1463-2256 m)
- pine-oak forest (5600 to 8600 ft; 1701-2621 m)
- pine forest (6000 to 9600 ft; 1829-2926 m)
- montane fir forest (6700 to 9100 ft; 2042-2774 m
- subalpine forest (8000 to 10,720 ft; 2438-3270 m)
- canyon woodland (up to 6500 ft; 1981m)

Rainfall, soil moisture, air temperature, evaporation, slope aspect (north vs. south facing), and humidity are major factors controlling this vertical zonation. Soil chemistry and the parent rock from which soil is derived are also important. Ocotillo and mountain mahogany, for example, are more abundant on carbonate-rich soils derived from limestone and dolomite. Cold air drainage down canyons limits how high temperature sensitive plants from lower elevations can grow and, conversely, permits high elevation plants to extend their range to lower levels. The availability of water along streams makes it possible for species from higher life zones to become established within lower zones. The plants of each zone reach their upper limits on south-facing slopes and their lower limits on north-facing slopes. South-facing slopes receive more intense energy from the sun which causes increased soil temperature and evaporation. The reverse is true on shady, north-facing slopes where lower temperatures and evaporation rates mean more moisture for plant growth. Low temperature, particularly frost, controls the upper range of many plants, especially those of the Sonoran Desert. The boundaries of these life zones are transitional, with gradual change occurring over distance. Species characteristic of adjoining life zones intermingle along these transitional boundaries.

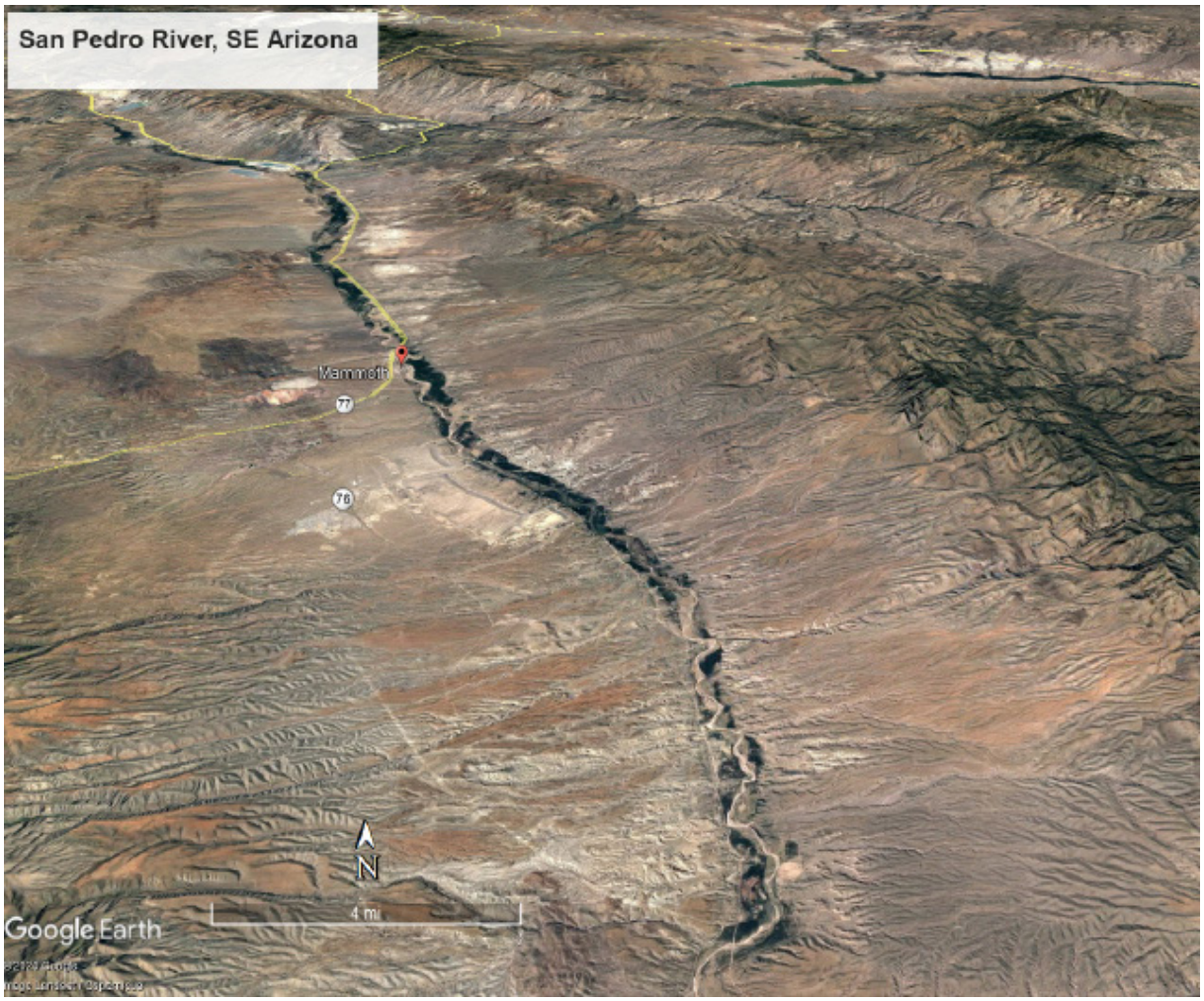


Figure 2. The San Pedro River valley east of the Rincon and Santa Catalina Mountains.

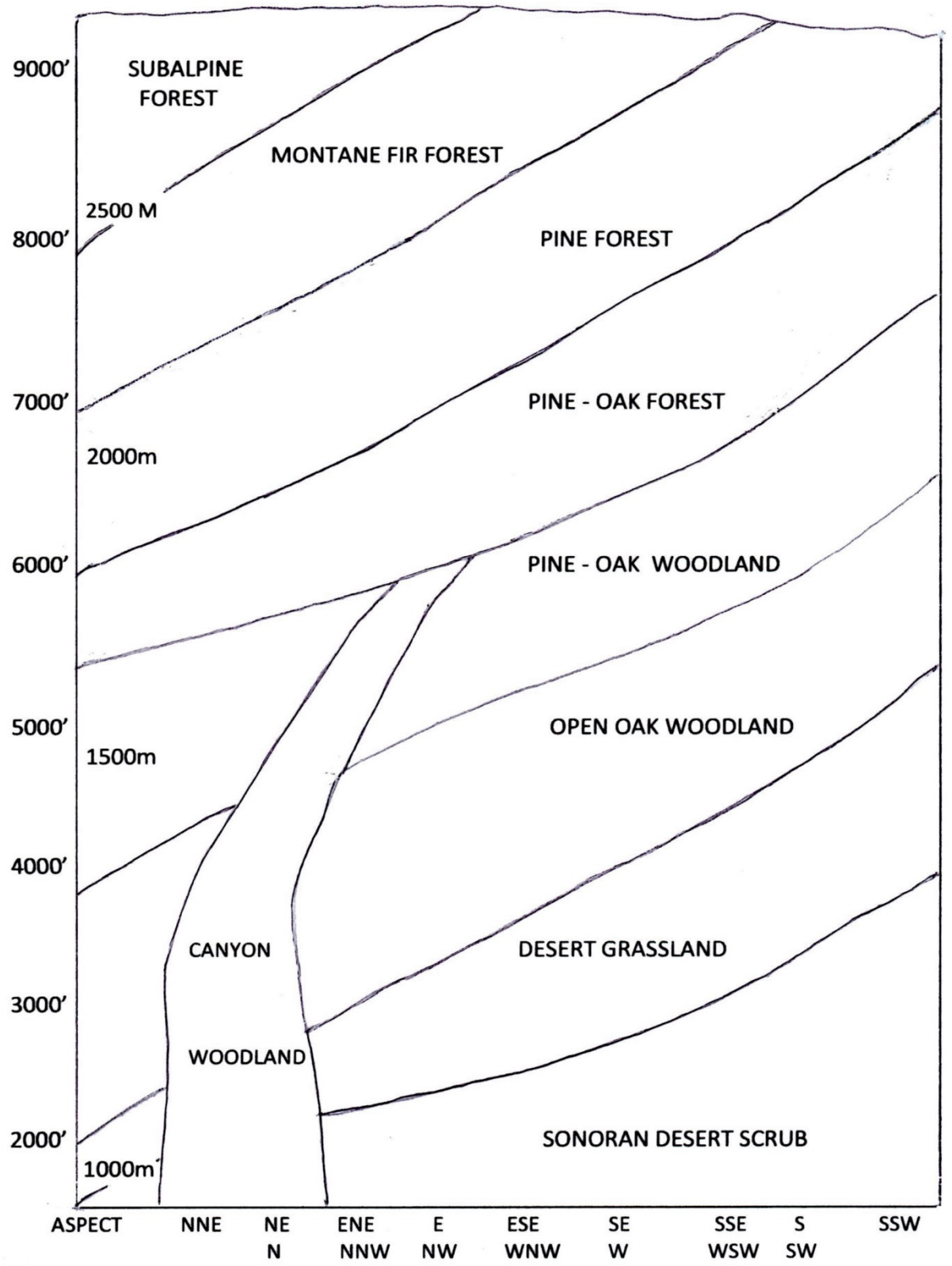


Figure 3. Life zones of the mountains of southeastern Arizona, showing major plant species, elevation, and slope aspect (after Whittaker, 1975).

Recent insect infestations and wildfires have destroyed the vast tracts of conifer forests in the Santa Catalina, Pinaleño, and Chiricahua Mountains and other ranges in southeastern Arizona. The suppression of small fires in these ranges during the period 1935-1980 led to the build-up of fuel that fed the huge conflagrations within these forests. Insect outbreaks killed extensive areas of the forest which also contributed to this fuel load.

Vegetation

Sonoran Desert scrub (up to 4000 ft; 1291 m**) (**Figure 4)

The hallmark plants of this part of the Sonoran Desert are saguaro (*Carnegiea gigantea*), foothills palo verde (*Cercidium microphyllum*), and ocotillo (*Fouquieria splendens*). These plants prefer rocky, well drained soils and are particularly abundant on the south-facing slopes. There are various species of cholla (*Cylindopuntia spp.*), prickly pear (*Opuntia spp*), and barrel cactus (*Ferrocactus spp*). The principal tree species include mesquite (*Prosopis velutina*), acacia (*Vachellia constricta* and *Senegalia greggii*), ironwood (*Olneya tesota*), and foothills and blue palo Verde (*Cercidium floridum*). These trees produce large quantities of seeds in pods that are an important source of food for animals and birds. Creosote bush (*Larrea tridentata*) and bursage (*Ambrosia deltoidea*), jojoba (*Simmondsia chinensis*), desert hackberry (*Celtis pallida*), fairy feather duster (*Calliandra eriophylla*), and shrubby buckwheat (*Eriogonum fasciculatum*) are common shrubs. Most of these plants have spines or terpenes that protect them from browsing animals.

The Sonoran Desert is a recently evolved biome, thought to have developed in the last 9,000 to 10,000 years since the end of the last Ice Age. Many trees and cacti, including palo verde, mesquite, acacia, mimosa, and saguaro, originated in the subtropics of southern Sonora and Sinaloa and adapted to climatic conditions that became progressively dryer and warmer.

Figure 4. Sonoran Desert scrub, northern Tortolita Mountains.

desert grassland (3500 to 5400 ft; 1067-1646 m) (Figure 5)

Above 3500 to 4000 feet elevation temperatures are too low for many Sonoran Desert plants and mountain slopes support a variety of grasses that include sideoats grama (*Bouteloua curtipendula*), spider grass (*Aristida ternipes*), slender grama (*Bouteloua filiformis*), and the exotic tanglehead (*Heteropogon contortus*). Scattered ocotillo (*Fouquieria splendens*) and mesquite (*Prosopis juliflora*), Arizona rosewood (*Vauguelinia californica*), and catclaw (*Senegalia greggii*) and whitethorn (*Vachellia constricta*) acacias are conspicuous tree forms. Many grassland sites in southeastern Arizona have been severely degraded by more than a century of overgrazing and invasion by exotic grass species, particularly buffel grass (*Pennisetum cilare*) from Africa. This and human suppression of wildfires have allowed mesquite to populate large grassland areas. Grass species from the Chihuahua Desert and from the warmer and generally wetter eastern Sonoran Desert populate this grassland.

Figure 5. Desert grassland, degraded by over a century of overgrazing, northwest of the Santa Catalina Mountains.

open oak woodland (3700 to 6400 ft; 1128-1951 m)(Figure 6)

Numerous species of evergreen oaks dominate this zone: Mexican blue oak *(Quercus. oblongifolia)*, Emory oak *(Q. emoryi)*, netleaf oak *(Q. rugosa),* Arizona white oak *(Q. arizonica),* Mexican gray oak *(Q. grisea)*, and silverleaf oak *(Q. hypoleucoides).* These trees grow in widely spaced, park-like distributions. Grasses, shrubs, herbs, and succulents like agave and cactus dominate the more open interspaces between the oaks. The Spanish term *encinal*—the place of the oaks—is commonly used to describe this woodland. At the upper limits of the open

oak woodland and on north-facing slopes, alligator juniper (*Juniperus deppeana*), Mexican piñon (*P. cembriodes*), and border piñon *(P. discolor)* are mixed with Chihuahua pine *(Pinus leiophylla* var. *chihuahuana)* and Apache pine *(P. engelmannii).*

On higher, wetter slopes the trees grow more closely together and the dominant species are Mexican piñon, alligator bark juniper , and silverleaf oak. Shrubs, such as manzanita (*Arctostaphylos spp*), agave, and bear grass are common ground cover in this zone. As in all life zones, the density of the vegetation depends on many factors, including soil conditions, slope aspect, human use, and frequency of wild fires.

Figure 6. Open oak woodland on a north-facing slope, east of Santa Catalina Mountains.

Mining decimated the oak woodlands. Large numbers of trees were cut to make charcoal for smelters and for construction. Acorns, pine nuts, and juniper berries are an important food source for many species of birds and animals, including humans.

pine-oak woodland (4800 to 7400 ft; 1463-2256 m) (Figure 7)

With increased precipitation and lower average temperature the trees of this zone are taller but their crowns do not form a continuous, closed canopy. Chihuahua pine (*Pinus chihuahuana*) and Apache pine (*Pinus engelmannii*) and some ponderosa pine (*Pinus ponderosa*) grow in the higher parts of this woodland, but in places are mixed with Arizona oak (*Quercus arizonica*) and silverleaf oak (*Quercus hypoleucoides*), netleaf oak (*Quercus rugosa*), Mexican piñon (*Pinus cembroides*) and alligator juniper (*Juniperus deppeana*). Schott's yucca (*Yucca schottii*), Palmer's agave (*Agave palmeri*), prickly pear cactus (*Opuntia spp*), and beargrass (*Nolina microcarpa*) are reminders that water is still a major factor in plant growth in this life zone.

Figure 7. Pine-oak woodland, Pinaleño Mountains.

Figure 8. Pine-oak forest, Pinaleño Mountains.

pine-oak forest (5600 to 8600 ft; 1701-2621 m) (Figure 8)

Increased precipitation and cooler temperatures at this elevation result in a forest dominated by Ponderosa Pine (*Pinus ponderosa*) and Silverleaf Oak (*Quercus hypoleucoides*). Oaks form a lower tree layer beneath the pines. Individual trees grow closer together with crowns forming a closed canopy in more moist locations. Fendler buckbrush (*Ceanothus fendleri*) and California coffeeberry (*Frangula californica*) are common shrubs.

pine forest (6000 to 9600 ft; 1829-2926 m) (Figure 9)

At this elevation, ponderosa pine, Arizona pine (*Pinus arizonica*), southwestern white pine (*Pinus strobiformis*), Douglas-fir (*Pseudotsuga menziesii*), and white fir (*Abies concolor*) commonly form thick forests. Aspen (*Populus tremuloides*), New Mexico locust (*Robinia neomexicana*), Rocky Mountain maple (*Acer glabrum*) and big tooth maple (*Acer grandidentotum*) are decidious trees that are more common where fire, wind, and insect infestations have opened up the forest floor to sunlight. Gambel oak (*Quercus gambelii*), the only deciduous oak in southeastern Arizona, is also present in this zone.

montane fir forest (6700 to 9100 ft; 2042-2774 m)(Figure 10)

Douglas-fir and white fir are the signature trees of this cool, moist, high-elevation forest. Corkbark fir (*Abies lasiocarpa*) occurs at the lower part of this life zone. Maple, aspen, and other deciduous trees add a palette of red, yellow, and gold to the high country during the fall.

subalpine forest (8000 to 9157 ft; 2438-2791 m)(Figure 11)

Corkbark fir, Douglas-fir, white fir, thin leaf alder *(Alnus tenuifolia*) are the trees most identified with the subalpine forest (Figure 12), which is found on crest of the Pinaleño Mountains and on north-facing slopes below Mount Lemmon in the Santa Catalina Mountains. Most of the deciduous trees found in the montane fir forest extend to the highest part of these ranges as well. Spruce (*Picea spp*) occurs in the subalpine zone on the Pinaleño Mountains, but not in the Santa Catalina Mountains.

Figure 9. Pine forest in the Santa Catalina Mountains.

Figure 10. Montane fir forest of the Pinaleño Mountains.

Three wildfires, the Bullock Fire in 2002, the Aspen Fire in 2003, and the Bighorn Fire in 2020 destroyed over 203,000 acres, much of it in the pine, montane fir, and subalpine forests of the Santa Catalina Mountains. Wildfires burned large tracts of high elevation forests in the Chiricahua Mountains in 2011 and the Pinaleño Mountains in 2004. Many of the indigenous tree species evolved with low, rapidly moving wildfires that clear the forest of undergrowth and dead trees. Ponderosa pine depends upon these periodic "cool fires" for seed germination. But years of wildfire suppression led to a buildup of fuels that caused destructive conflagrations damaging native flora.

Figure 11. Subalpine forest below Mt. Lemmon, Santa Catalina Mountains.

Figure 12. Destruction by the 2003 Aspen Fire, Santa Catalina Mountains.

It is thought that many of the tree species of the montane fir and subalpine forests are relicts from earlier Ice Age climates. Cooler and perhaps wetter conditions permitted these Rocky Mountains species to extend their range into the mountains of southeastern Arizona. Warmer and dryer climates since the last Ice Age have isolated these tree populations from those of the Rocky Mountains.

canyon woodland (up to 6500 ft; 1981 m) (Figure 13)

Many mountain drainages, such as the Cañada del Oro and Sabino Canyon in the Santa Catalina Mountains, that have sufficient surface or subsurface flow support verdant riparian forests. Principal tree species in the lower reaches of these canyons include: fremont cottonwood (*Populus fremontii*), Arizona sycamore (*Platanus wrightii*), Goodding willow (*Salix gooddingii*), Arizona walnut (*Juglans major*), western soapberry (*Sapindus drummandii*), and velvet ash (*Fraxinus velutina*). Arizona alder (*Alnus oblongifolia*), boxelder, Rocky Mountain maple, and bigtooth maple dominate in the higher parts of canyons. Air in the canyons is scented with the pungent fragrances of these trees and canyon ragweed (*Ambrosia ambrosioides*). Canyon grape (*Vitis arizonica*) and virgin's bower (*Clematis drummondii*) are common vines and add splashes of crimson and gold to the brown and yellow of canyon deciduous trees during the fall.

Scouring by flash floods can destroy large swaths of canyon woodlands. As such, these riparian environments are more ephemeral than woodlands beyond the reach of flood events. In places, extraction of groundwater has lowered water table beyond the reach of roots, resulting in the death of many trees. Human settlement has further reduced the extent of canyon woodlands.

Figure 13. Canyon woodland of Peppersauce Canyon, Santa Catalina Mountains.

Wildlife

The diverse life zones of the mountains of southeastern Arizona support an equally diverse population of mammals, birds, reptiles, and amphibians. Some large mammals, such as cougar (*Felis concolor*), black bear (*Ursus americanus*), coyote (*Canis latrans)*, mule deer (*Odocoileus hemionus*), and Coues white-tailed deer (*O. virginianus couesi*), range through several life zones.

Bobcat (*Felis rufus*), Gray Fox (*Urocyon cinereoargenteus*), kit fox (*Vulpes macrotis*), ringtail (*Bassariscus astutus*), badgers (*Taxidea taxus*), coati (*Nasua nasua*), long-tailed weasel (*Mustela frenata*), raccoon (*Procyon lotor*), striped skunk (*Mephitis mephitis*), and spotted skunk (*Spilogale gracilis*) feed upon insects, seeds, rodents, birds, eggs, nuts, lizards, carrion, and fruits within a more restricted area.

Herbivores include Abert's squirrel (*Sciurus aberti*), Arizona gray squirrel (*Sciurus arizonensis*), rock squirrel (*Spermophilus variegatus*), black-tailed jackrabbit (*Lepus californicus*), desert cottontail rabbit (*Sylvilagus audubonii*), Packrat (*Neotoma albigula*), Round-tailed Ground Squirrel (*Spermophilus tereticaudus*), Harris' antelope squirrel (*Ammospermophilus harrisii*) and numerous other rodent species. They are preyed upon by a wide range of mammals and raptors. Javelina (*Tayassu tajacu*), porcupine (*Erethizon dorsatum*), and desert bighorn sheep (*Ovis canadensis*) are more difficult prey, but they and their young are taken by larger predators. Predation by humans and disease introduced by domestic livestock have greatly reduced the desert bighorn sheep population. Jaguar (*Felis onca*), grizzly bear (*Ursus arctos horribilis*), and Mexican wolf (*Canis lupus baileyi*) once inhabited the mountains of southeastern Arizona but have been removed by hunting and predator control programs.

Raptors are at the top of the avian food chain. Cooper's hawk (*Accipiter cooperii*), the common black hawk (*Buteogallus anthracinus*), the gray hawk (*Asturina nitida*), Harris hawk (*Parabuteo unicinctus*), the northern goshawk (*Accipiter gentilis*), the red-tailed hawk (*Buteo jamaicensis*), and the peregrine falcon (*Falco peregrinus*) are some of the birds of prey that feed on rodents, reptiles, and smaller birds during the day. Great horned owls (*Bubo virginianus*), Mexican spotted owls (*Strix occidentalis lucida*), the western screech-owl (*Otus kennicottii*), and the northern pygmy owl (*Glaucidium gentilis*) are mostly nocturnal hunters of rodents, insects, and small birds. The greater roadrunner (*Geococcyx californianus*) hunts during the day, mainly by running down small birds, rodents, insects, lizards, and snakes--including rattlesnakes. Turkey vultures (*Cathartes aura*) and common ravens (*Corvus corax*) are valuable carrion-eaters.

Gambel's quail (*Callipepla gambelii*), Mearns quail (*Cyrtonyx contezumce mearns*), white-winged dove (*Zenaida asiatica*), and mourning doves (*Zenaida macroura*) eat seeds and some insects and fruit. In wet years when these foods are abundant these birds provide a particularly important source of protein for many bird and mammal predators higher in the food chain. The desert, grassland, woodlands, and forests of the mountains of southeastern Arizona support numerous species of birds that depend upon seeds, fruit, nuts, nectar, pollen and insects as well. These include: wrens, sparrows, swallows, jays, nuthatches, swifts, warblers, thrushes, woodpeckers, flycatchers, gnatcatchers, hummingbirds, warblers and many other avian species that make this part of Arizona an international destination for birders.

Before the establishment of farms, ranches, and urban zones such as Tucson and Sierra Vista, many mammals could winter in and cross the basins to reach nearby ranges. Continued urban expansion in the basins, and recreational and residential development within the mountains have led to reduced habitat and smaller wildlife populations. Habitat loss continues to be the greatest threat to wildlife in southeastern Arizona and the rest of the Earth.

Island Mountains of Southeastern Arizona: An In-depth Look

The Santa Catalina Mountains

Rising as a great mountain island to over 9000 feet (2743 m) at Mount Lemmon, the Santa Catalina Mountains are the greatest expanse of high country within the Sonoran Desert. An unusual dome-like profile (Figures 14, 15) sets it apart from the numerous, steep, sharp-crested ranges in the region. This distinctive profile is a legacy of the range's remarkable geologic history and the structure of its bedrock.

The basement rocks in this area are the 1650 million-year-old Pinal Schist, intruded by molten rock or magma that cooled to form the 1450 million-year-old Oracle Granite. Later intrusions of magma formed the Rice Peak Porphyry 71 million years ago, the Leatherwood Granodiorite 69 million years ago, the Alamo Canyon Granite 67 million years ago, the Wilderness Suite Granite between 43 and 57 million years ago, and the Catalina Granite 26 million years ago. These rocks resided miles below the surface before mountain building began (Figures 16, 17, 18, 19).

The formation of the Santa Catalina Mountains from these deeply buried rocks began about 35 million years ago. At that time, northeast-southwest extension of the southwestern part of North America caused crustal rocks to be stretched and thinned,causing rocks in southern Arizona and other parts of the western continent to be pulled apart and broken along low angle fracture systems called detachment faults (Figure 20). The Catalina Fault, the detachment fault associated with the uplift of the Santa Catalina Mountains, began to form at depths of up to 6 to 8 mi (10 to 13 km). Continued extension moved rocks below the fault 16 to 19 mi (25 to 30 km) toward the east-northeast and closer to the surface as rocks above the fault slid toward the southwest. As rocks below the detachment fault moved slowly toward the surface, they began to arch upward in response to the removal of the weight of overlying rocks.

The intense friction, heat, and pressure caused by this movement deforms rocks above and below the fault. The Wilderness Suite and Oracle Granite below the fault were so hot that they flowed like putty. Constituent minerals of these granites, especially quartz, smeared plastically. Feldspars broke into pieces or had their corners broken off to produce lenticular crystals. This deformation transformed the granites into a metamorphic rock called gneiss (Figure 21). Rocks above the fault deformed in a brittle manner and shattered into angular

fragments called breccia. This dome of gneiss and breccia, separated by a low angle detachment fault is a metamorphic core complex. The nearby Rincón and Tortolita Mountains are a part of the same structure and were formed at the same time as the Santa Catalina Mountains.

A second period of extension began about 15 million years ago segmenting the crustal rocks of western North America into mountain-sized blocks, separated by new, steeply dipping faults. In southeastern Arizona, some of the crustal blocks were further uplifted to form mountain ranges, such as the Santa Catalina, Tortolita, Rincón, Tucson Mountains and many other ranges. Other blocks subsided as much as 2.4 mi (4 km) to form deep basins, such as the Tucson and Oro Valley Basins and the San Pedro Valley. These fault-bound mountains and basins are a part of the Basin and Range geologic province that extends from Oregon to central Mexico.

These episodes of igneous intrusions, uplift, and faulting deformed the Pinal Schist, the Apache Group, the Campo Bonito Formation, the Martin Formation, the Escabrosa Limestone, the Naco Group and the Bisbee Group along the margins of the Santa Catalina Mountains. The Leatherwood

Granodiorite, the Rice Peak Porphyry and older sedimentary, igneous and metamorphic rocks were elevated to form the crest of the range. Massive quantities of mineral-bearing solutions accompanied injections of magma and flowed along faults and joints, depositing copper, gold, silver, lead, zinc and other metals. Although these were not the equivalent of great mineral bonanzas found in other parts of the American West, mining supported the first settlements in the Santa Catalina Mountains contributing to the local and regional economies.

Channeled by joints and faults, streams cut deeper and deeper into the Catalinas, (Figure 16), exposing a broad suite of igneous, sedimentary, and metamorphic rocks. The true colors of these rocks are masked by rock varnish—a patina of iron and manganese oxide that gives desert ranges and basins their nearly uniform tan coloration (Figure 22).

Rock fragments flushed down mountain canyons during flash floods planed off bedrock platforms, called pediments, along the margins of the range (Figure 23). Boulders, cobbles, sand, silt, and clay accumulated as fan-shaped aprons of sediment at the mouths of canyons. As erosion progressed, these alluvial fans (Figure 16) expanded into the adjacent basins and merged to form bajadas. Bajadas are alluvial plains (Figure24) that slope for miles from the foot of the ranges to the center of neighboring basins and commonly cover pediments. Bajada-pediment slopes are graceful hallmark landforms of the Basin and Range geologic province and are even a design element on some Arizona license plates (Figure 24, inset).

Figure 14 (previous page). The Santa Catalina Mountains have a dome-like profile that sets them apart from sharp-crested ranges in southeastern Arizona (Photo courtesy of Dr. Anthony Lux).

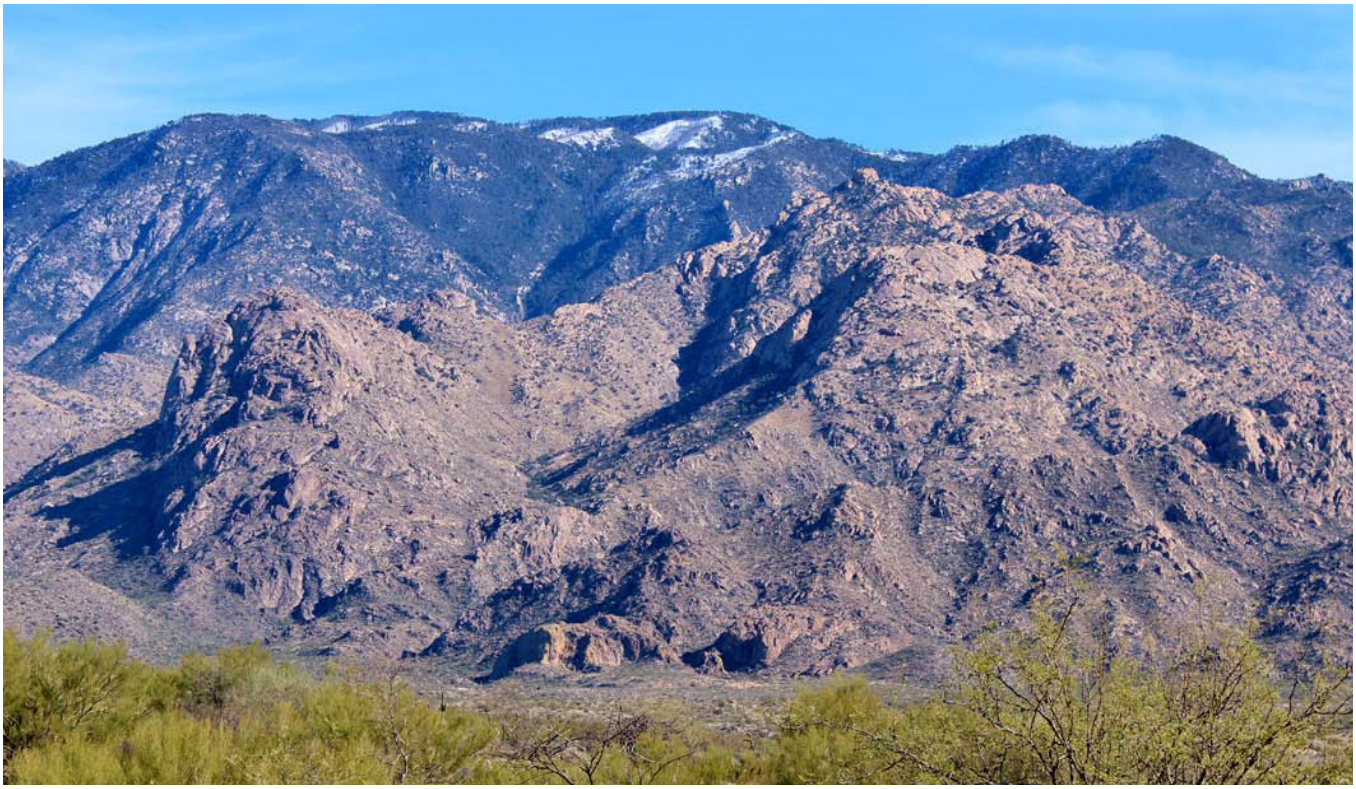
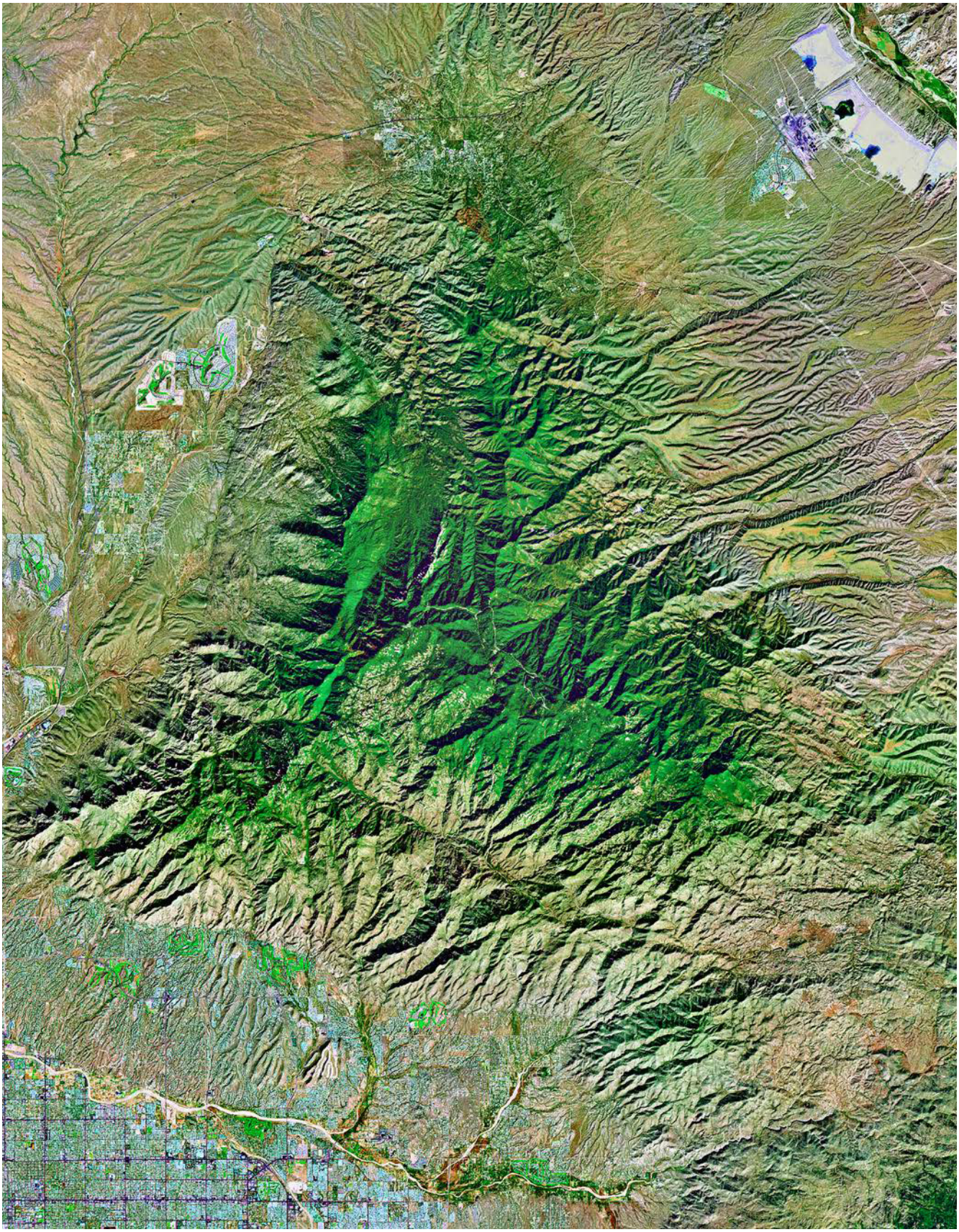


Figure 15. The dome-like form of the Santa Catalina Mountains is due to their geologic structure as a metamorphic core complex.

Figure 16 (following page). Satellite image of the Santa Catalina Mountains (Courtesy of John Dohrenwend). Faults bound the range and control the courses of major drainages. Highly eroded bajadas and alluvial fans border all but the southeast side of the range.



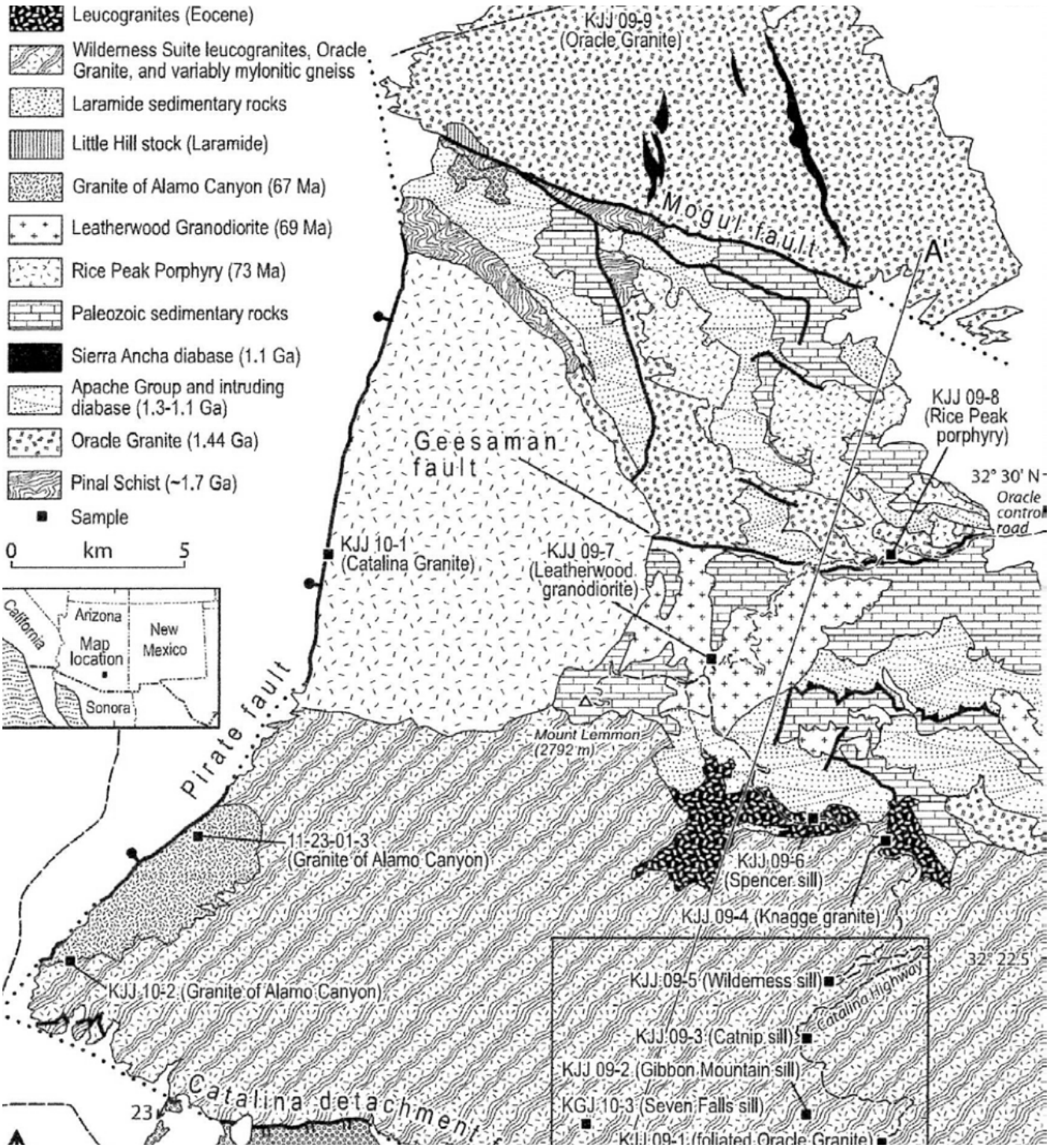


Figure 17. Geology of the western, northern, and eastern Santa Catalina Mountains (Fornash, 2013).

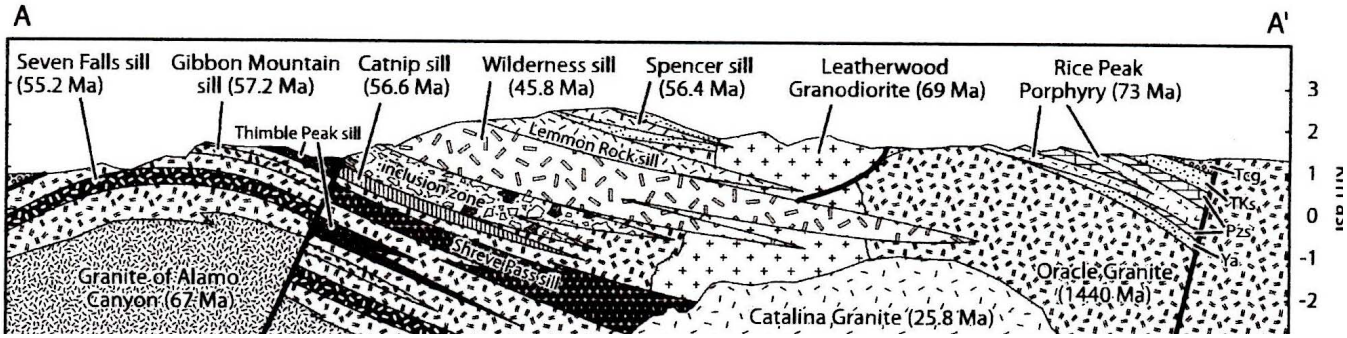


Figure 18. Cross-section A-A', Figure 17, central Santa Catalina Mountains (Fornash, 2013).

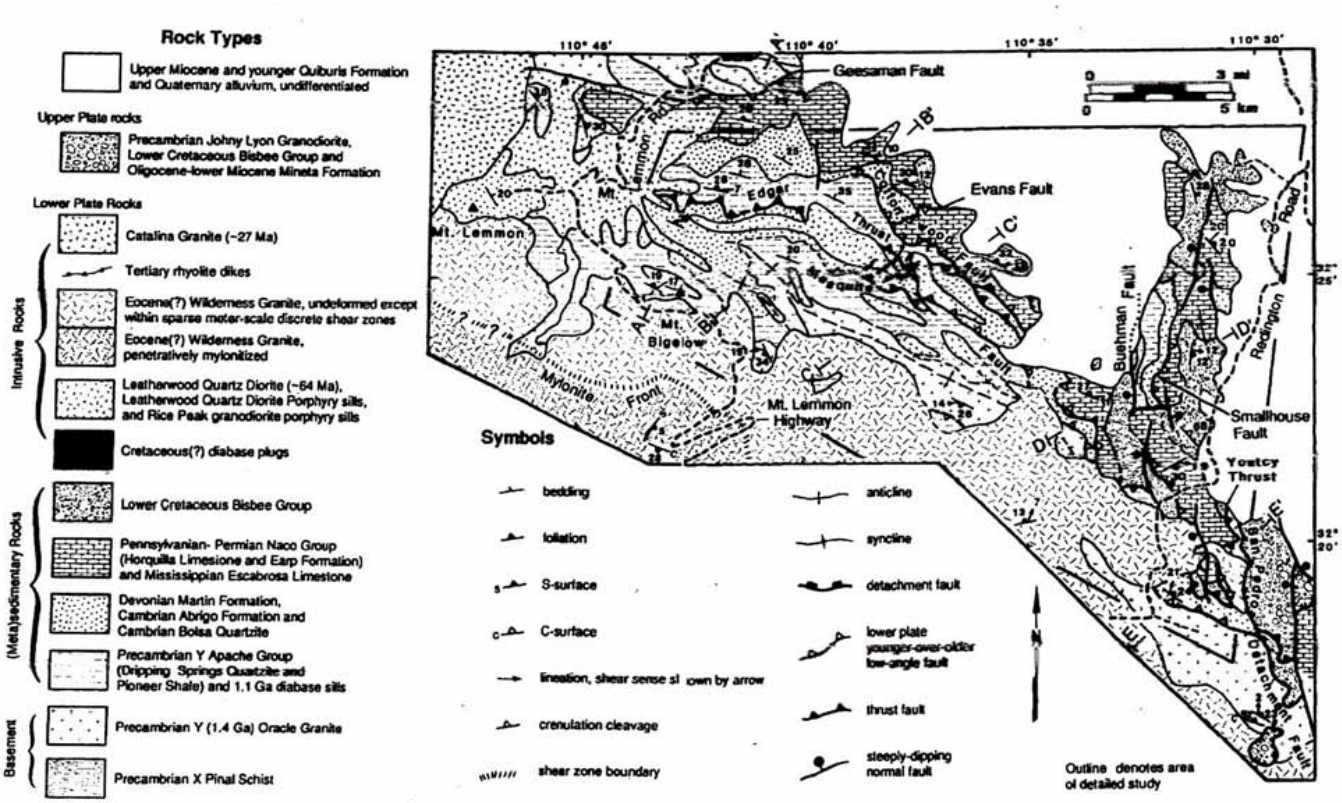


Figure 19. Geologic map of the southeastern Santa Catalina Mountains (Bykerk-Kauffman, 1990).

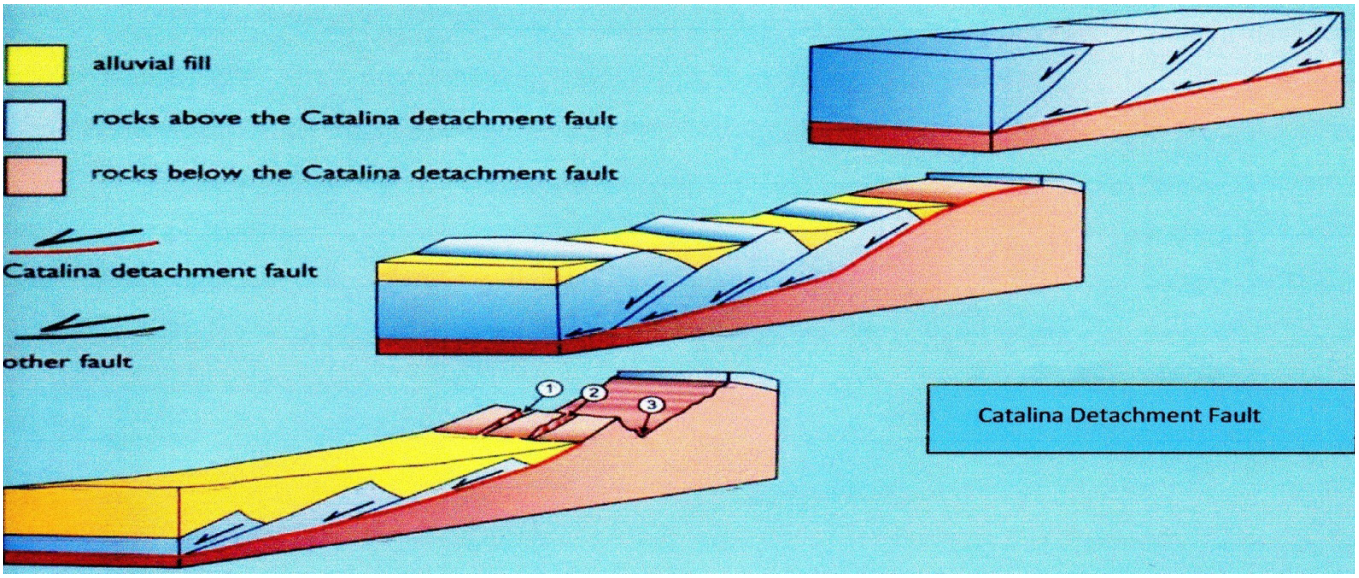


Figure 20. Block diagram illustrating the formation of the Santa Catalina metamorphic core complex: 1. Sabino canyon, 2. Bear Canyon, 3. Molino Canyon.

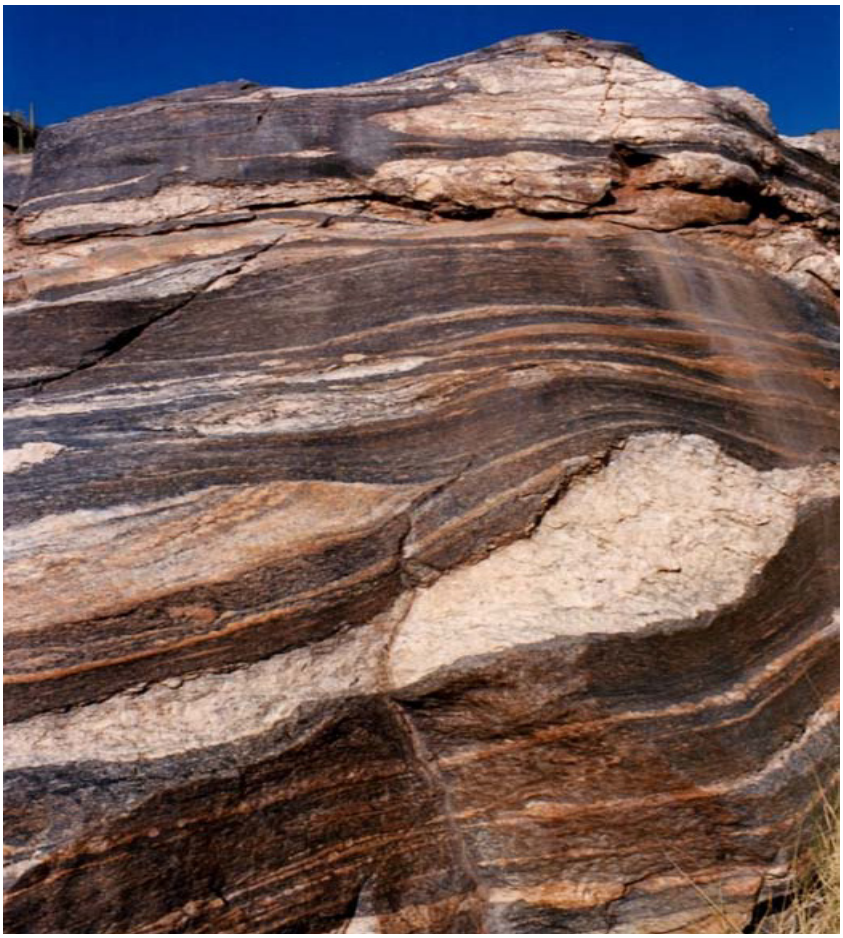


Figure 21. Gneiss near Molino Canyon with contortions produced when the rock was in a plastic state (courtesy of Dr. Larry Fellows).

Figure 22. Rock varnished boulder of Catalina Granite. Fresher surfaces are lightly varnished and contrast with dark highly varnished surfaces. Rock varnish masks the true color of most rocks in southeastern Arizona mountains, giving them a dull tan to reddish brown patina. Petroglyphs (inset), carved into rock varnish, are common in southeastern Arizona.

Figure 23. Pediment (the flat surface in the middle ground) cut into Catalina Granite.

Figure 24. Highly dissected and oxidized bajajda-pediment slope along the eastern margins of the Santa Catalina Mountains. Some Arizona license plates contain a bajada-pediment slope as a design element (inset).

The Western and Northern Santa Catalina Mountains

The bedrock of the western Santa Catalina Mountains is truncated by the Pirate Fault (Figures 17, 26). Movement along this steep (50-55 fault was mainly vertical. The fault block to the west dropped an estimated 10,000 to 13,000 ft (about 3,000 to 4,000 m) relative to the Santa Catalinas and is deeply buried by the alluvial fill of the Oro Valley Basin. Headward stream erosion along this fault intercepted the ancestral northwesterly flow of the Cañada del Oro diverting it to its current south-flowing course.

Slippage along the Pirate Fault and erosion by the Cañada del Oro and its tributaries have produced stunning landscapes in the Wilderness Suite, Catalina, and Oracle Granites along the western and northern sides of the Santa Catalina Mountains. Vertical cliffs and pinnacles have been weathered and eroded from the Wilderness Suite Granite, from Pusch Ridge to Catalina State Park. Here the granite and gneiss are broken by widely spaced, vertical joints that serve as avenues along which chemical and physical weathering and erosion penetrate the bedrock. Rock shattering, caused by ice expansion and wedging by plant roots, and chemical decomposition, enlarge the joints. Water from rain and snowmelt is channeled into joints, cutting them into ravines and canyons. This concentrated action of weathering and erosion eventually widens and deepens the ravines and canyons, leaving the massive granite and gneiss in between standing as towering pinnacles, which are best developed in Catalina State Park (Figure 27).

The light-colored rock exposed in the western Santa Catalina Mountains north of Catalina State Park is the Catalina Granite (Figure 25). Tributaries of the Cañada del Oro have carved huge amphitheater-shaped embayments into the granite. Erosion has stripped away the bajada from this margin of the range, exposing the

sloping bedrock surfaces (the pediments) that floor each embayment (Figure 28). These are the most extensive exhumed pediments in southeastern Arizona.

The hundreds of dome-shaped hills on these Catalina Granite pediments and the ridges that separate the embayments are domed inselbergs (Figure 29). Weathering and erosion, guided by two sets of natural cracks in the bedrock (joints), have sculpted these graceful and distinctive landforms. The sets of vertical joints have a rhomboidal (that of a deformed rectangle) pattern when viewed from above (Figure 30). Each joint-bound dome is a resistant block of granite that is under compressional stress. This internal stress, produced as the granite cooled miles below the Earth's surface and perhaps by later movements within the crust, is gradually being released as erosion exposes more of the bedrock.

Sets of curvilinear joints (Figures 31) parallel to the ground service are produced within each rhomboid by this slow release of internal stress. These curvilinear joints divide the expanding granite into curved sheets that eventually arch up to form the crests of the domed inselbergs.

The magma that cooled to form the Catalina Granite invaded and deformed older rocks deep within the Earth's crust. These older, deformed rocks have been exposed by faulting and erosion. North of the Catalina Granite is a landscape of ridges and valleys developed on the ancient (Proterozoic) Pinal Schist, the Abrigo Formation, the Bolsa Quartzite, the Campo Bonito Formation, and the Apache Group (Figure 32). South of the Catalina Granite intrusion are folded and faulted expanses of Wilderness Suite Granite (Figure 33).

At the northern end of the Santa Catalina the Oracle Granite has weathered to a landscape dominated by rounded boulder hills, called boulder inselbergs (Figure 34). This 1400 million-year-old rock has been weakened by numerous tectonic events, making it less resistant to erosion than the younger granites to the south. It is broken by sets of vertical and horizontal joints that divide the bedrock into individual rectangular blocks—joint block. Weathering widens and deepens the joints and rounds the corners and edges of the joint blocks, producing rounded boulders. Wet weather streams wash away loose rock debris and lower the ground surface, leaving the inselbergs as high standing erosional remnants. Stream beds are streaked with black magnetite sand eroded from the granite (Figure 35).

Figure 25. Catalina Granite with large feldspar crystals and an aplite dike.

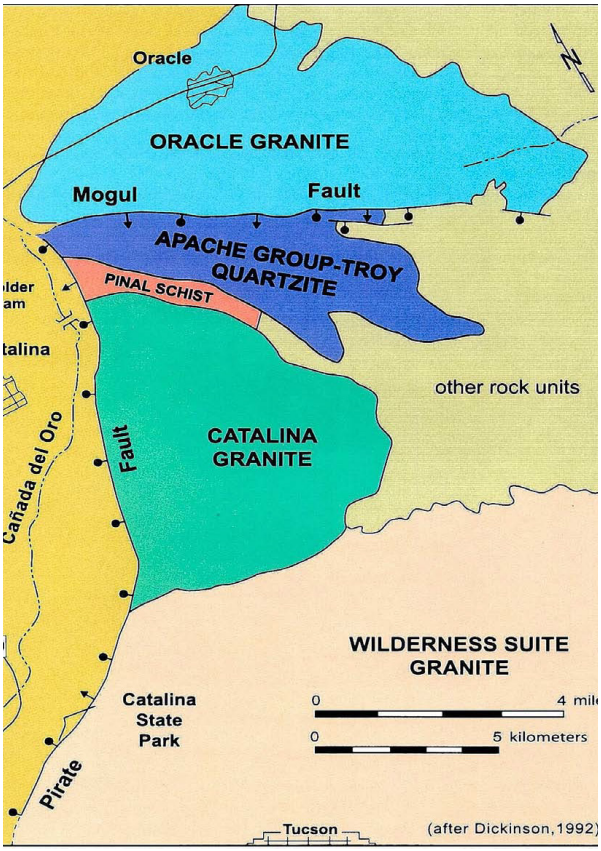


Figure 26. Geologic sketch map of the western and northern Santa Catalina Mountains. The Bolsa Quartzite, not delineated on the map, is also present.

Figure 27. Pinnacles at Catalina State Park (Courtesy of Dr. Anthony Lux).

Figure 28. Embayments cut into the Catalina Granite on the western face of the Santa Catalina Mountains.

Figure 29. Domed inselberg in Catalina Granite.

Figure 30. Joint-bound domed inselberg in Catalina Granite (courtesy of Google Earth).

Figure 31. Curvilinear (exfoliation) joints along the crest of a domed inselberg in Catalina Granite.

Figure 32. Ridge and valley topography north of the Catalina Granite. The ridge in the middle ground is composed of Pinal Schist.

Figure 33. Fold in Wilderness Suite Granite, south of Catalina Granite (Courtesy of Dr. Larry Fellows).

Figure 34. Boulder inselberg in Oracle Granite near the town of Oracle.

Figure 35. Black magnetite sands derived from weathering and erosion of the Oracle granite.

The Eastern Santa Catalina Mountains

The high eastern face of the Santa Catalina Mountains is cut by deep canyons and bordered by highly-dissected bajadas that slope gracefully to the floodplain of the San Pedro River. Upended layers of sedimentary rocks form asymmetrical ridges (Figures 36, 37). Between the Mogul and Geesaman Faults is a pile of igneous, sedimentary, and metamorphosed sedimentary rocks that include the Apache Group, the Bolsa Quartzite, the Rice Peak Porphyry, the American Flag Formation, the Campo Bonito Formation, the Martin Formation, the Escabrosa Limestone, the Naco Group , and the Pinal Schist.

Zones of fault-shattered rock, particularly along the Mogul and Geesaman Faults, acted as conduits for mineral-bearing solutions from depth to penetrate host rocks at the surface. These fluids circulated along faults and joints, filling many voids with quartz veins and ores containing silver, copper, lead, vanadium, molybdenum, and tungsten. Mines opened and closed due to fluctuating market prices for metals, exhaustion of mineral veins, flooding, and poor management. Some investors, such as William "Buffalo Bill" Cody, were swindled out of fortunes by dishonest partners or employees.

Farther south, inclined sedimentary rocks of the Bisbee Group form a rugged landscape of steep ridges and valleys.

The high bajada surfaces that slope from the eastern margin of the Santa Catalina Mountains to the San Pedro River floodplain may be over 1 million years old. Weathering has developed a soil that contains clay and is stained red by the oxidation of iron.

The Southern Santa Catalina Mountains

The original dome shape of the Santa Catalina Mountains is evident in the southern third of the range, known as the forerange. Here the most common rocks are gneiss and granites. Gneiss has a laminated texture, like that of innumerable, thin layers. Sculpting of this texture by weathering and erosion produces an angular, ledgy landscape (Figure 38) found nowhere else in the range. The gneiss, sometimes referred to as the Catalina Gneiss, is a metamorphic rock that had two parent rocks: the Proterozoic 1400 million-year-old Oracle Granite and the Eocene-age, 50 million-year-old Wilderness Suite Granite. These granites formed from great molten masses of rock that slowly cooled miles below Earth's surface.

Between 35 and 20 million years ago, when these granites were at a depth of 7 to 10 miles (10 to 50 km), the Earth's crust in this region was stretched and sheared in a southwest-northeast direction. Intense pressure and heat accompanying this stretching deformed part of the deeply buried Oracle and Wilderness Suites Granites into a new rock--gneiss. Dark-colored bands in the gneiss are interpreted to be deformed Oracle Granite; those of lighter colors once may have been Wilderness Suite Granite (Figure 39).

The landscape of the forerange is in large part controlled by faults and joints and the lineation of the gneiss. Innumerable faults, (a fracture along which movement has occurred) and sets of cracks called joints, caused by movement and pressure, permeate the bedrock and control the course of most drainages in this and other parts of the range. The expansion of water freezing to ice, plant root wedging, and slightly acidic groundwater widen and deepen these fractures, forming small ravines. Over time, ravines become canyons. Pima, Sabino, Bear, and Molino Canyons and most other drainages are aligned along faults and joints (Figure 40).

The relatively straight southern face of the mountain front is the result of slippage along the Catalina Detachment Fault. South of the fault the bedrock is deeply buried by the alluvial fill of the Tucson Basin.

Figure 36. Upturned layers of sedimentary rock along the eastern margins of the Santa Catalina Mountains, south of Peppersauce Canyon.

Figure 37. Inclined layers of rock in the Apache and Bisbee Groups along the southeastern margin of the Santa Catalina Mountains.

Figure 38. Aligned streaks of deformed minerals give the gneiss of the southern part of the Santa Catalina Mountains a ledgy texture (Courtesy of Dr. Larry Fellows).

Figure 39. Banded gneiss in Molino Basin.

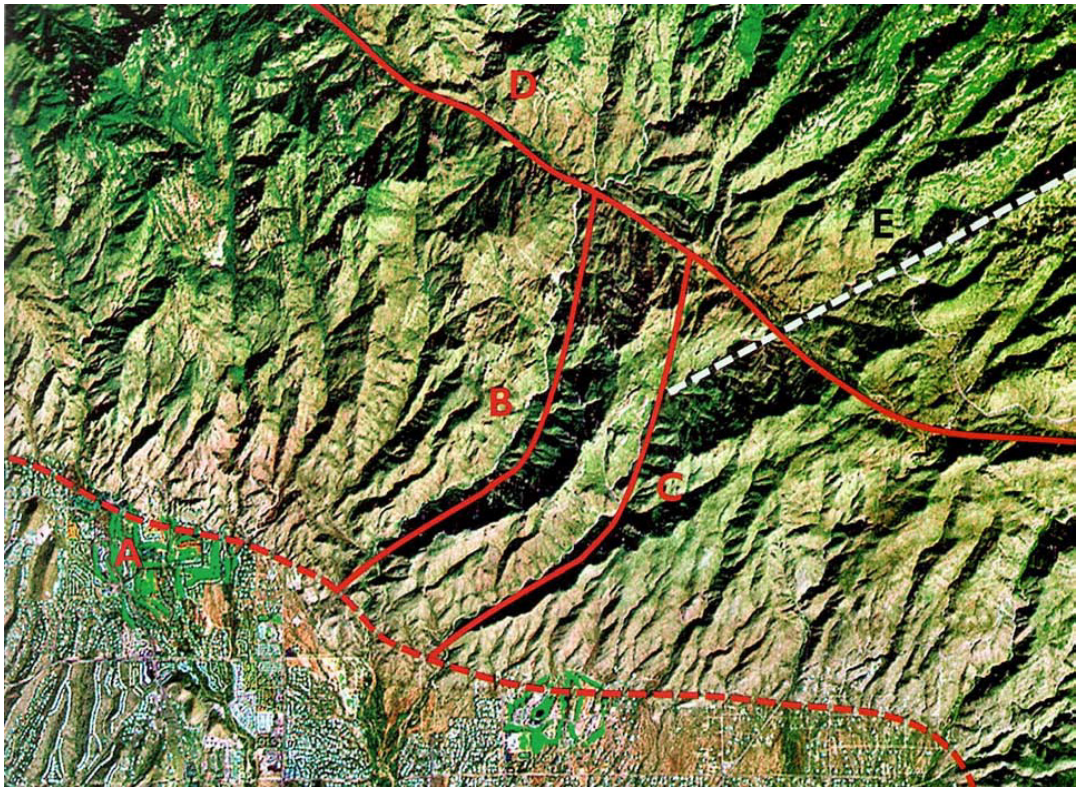


Figure 40. Satellite image of the Santa Catalina forerange illustrating the alignment of major canyons along faults: A=buried trace of the Catalina Detachment Fault; B=Sabino Canyon Fault; C= Bear Canyon Fault; D=Romero Pass Fault; E=Upper Bear Canyon Fault.

Figure 41. Thimble Peak sill above Sabino Canyon (Courtesy of Dr. Larry Fellows).

Intrusive sills are a major structural component of the Wilderness Suite Granite and form the bold cliffs of the southern Santa Catalina Mountains. These sills are tabular injections of magma that invaded older crustal rock and cooled at depth, and were then uplifted and exposed by erosion. They vary in thickness from a few feet to thousands of feet and are miles in length. The Thimble Peak sill is 2600 ft (800 m) thick (Figure 41). Harder and more erosion resistant than the surrounding host rock, sills form the imposing cliffs exposed in the walls of Sabino and other forerange canyons.

Rock falls, landslides, and debris flows are important processes that sculp mountain slopes and feed rock debris to streams where they are swept away by flash floods. Chemical decomposition and mechanical wedging by ice and plant roots weaken and break down solid rock. Great slabs and blocks of weakened bedrock frequently separate from cliff faces along joints and fall to lower slopes where they accumulate as talus. After heavy rains whole sections of this loose slope material, as well as bedrock, can give way as landslides cascade to the valley below. Rock debris from rock falls and landslides blanket canyon slopes in the mountains of southeastern Arizona. Slope failure that occurs when rock mantle is saturated after torrential precipitation from hurricanes or heavy rains or snow melt can result in dangerous debris-flows. These surges of rock debris change form with time and distance as they move down pre-existing channels. A snout of boulders and cobbles is trailed by a coarse slurry, and then by a more liquefied tail of finer material. Rock debris is deposited along the course of the flow, often in the form of confining lateral levees. Lobes and levees of boulders and cobbles deposited by ancient and modern debris-flows extend for hundreds of yards beyond the mouths of forerange canyons (Figures 42). The monsoon rains of late July 2006 generated hundreds of flow chutes, some of which are still evident in the Santa Catalina Mountains (Figure 43).

The Crest of the Santa Catalina Mountains

Hidden beneath the forest cover of the high Santa Catalina Mountains is some of the most complex geology of the range. Capping the massive granites and gneiss f bedrock is a package of sedimentary rocks lifted to their location on the roof of the range by the rising dome and later faulting. Such remnants of once extensive rocks perched on the roofs of igneous intrusions are called roof pendants.

The major sedimentary and metamorphic units in the Santa Catalina roof pendant include: the mostly carbonate rocks of the Earp, Martin, and Abrigo Formations and the Horquilla and Escabrosa Limestones; the Bolsa and Dripping Spring Quartzites; the Pinal Schist; and the Pioneer Formation. At Mount Lemmon, the highest peak in the range, the Bolsa Quartzite, the Dripping Spring Quartzite, and a local sandstone and conglomerate have been intruded by a diabase dike of the Apache Group. In some locations thrust faulting has shoved older rocks above younger rocks. As in other parts of the range, faults served as plumbing for hot, mineral bearing solutions to deposit metals.

About 69 million years ago magma that cooled to form the Leatherwood Granodiorite invaded the Dripping Springs Quartzite and the Escabrosa Limestone and Martin Formation in the Marble Peak area. The hot, mineral-bearing solutions that accompanied the magma reacted with the limestones and dolomites to produce an ore called skarn that contains copper, zinc, gold, lead, silver, and magnetite. The Marble Peak mines have produced metals intermittently since the late 1930s.

The injection of the circular Catalina Granite pluton shaped the topography in the headwaters of the Cañada del Oro in the crest of the range. The rising pluton forced host rocks to conform to its curved margin. The curved pattern of these deformed rocks has been etched into the modern landscape by weathering and erosion, giving the upper Cañada del Oro its curved course (Figures 44).

Figure 42. Late Pleistocene or Holocene debris-flow levees, southern Santa Catalina Mountains (courtesy of A. Youberg, 2006).

Figure 43. Debris flow scar in Sabino Canyon (Courtesy Dr. Larry Fellows).

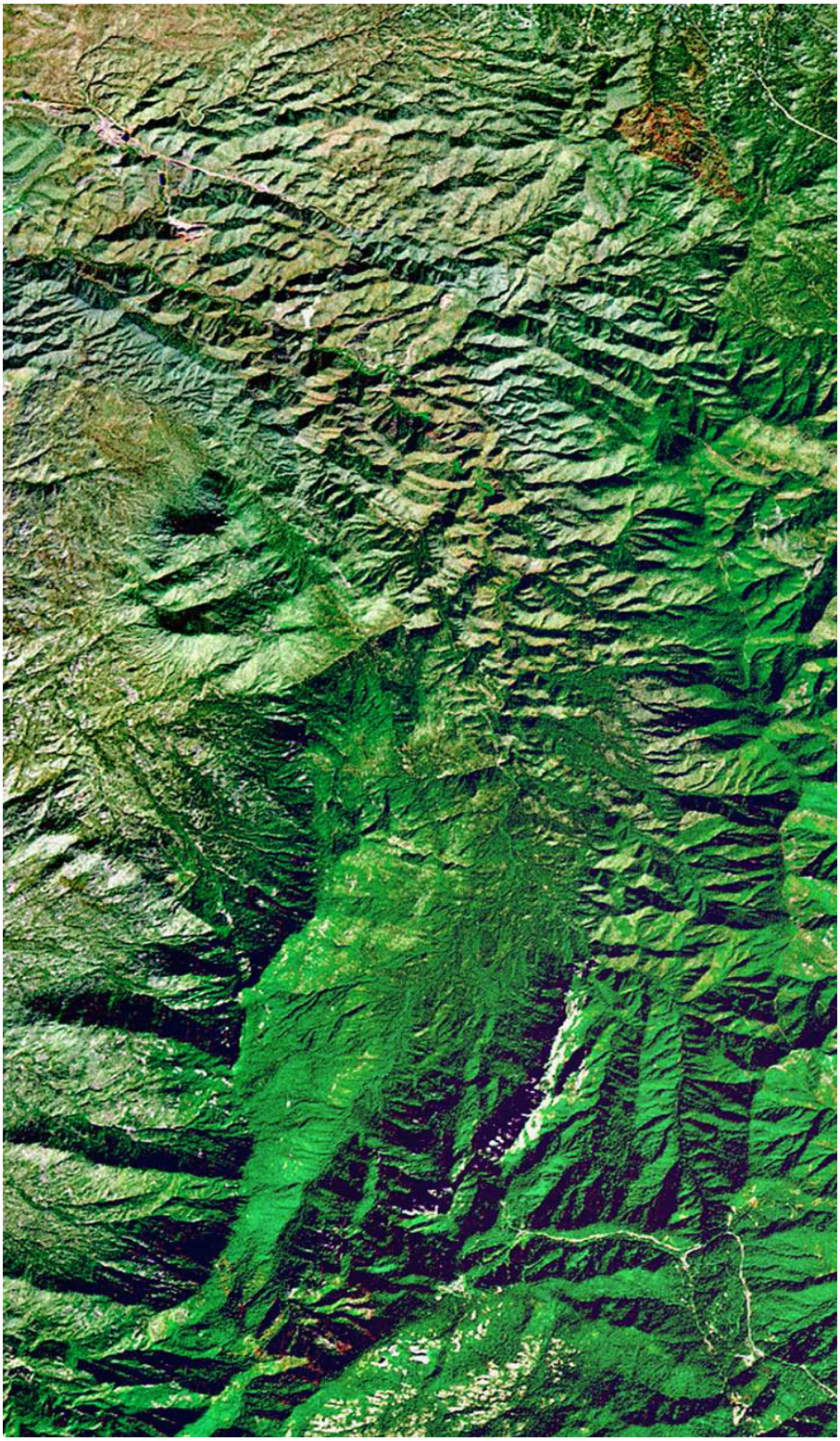


Figure 44. The course of the Cañada del Oro follows the curved outcrops of host rocks deformed by the intrusion of the Catalina Granite.

Rincón Mountains

Recommended access. Saguaro National Park (East). Much of the high Rincón Mountains are a wilderness area accessible only by trails. The Cactus Forest Drive at Saguaro National Park (East) offers the most scenic view of the range and access to geologic features related to the evolution of the range. Follow Old Spanish Trail in eastern-most Tucson to the park entrance.

The Rincón Mountains, like the Santa Catalina and Tortolita Mountains, are a metamorphic core complex. The range formed as a result of stretching and thinning of the Earth's crust in western North America beginning about 35 to 30 million years ago. The Catalina Fault, the detachment fault associated with the uplift of all three ranges, parallels the western margin of the Rincón Mountains (Figures 45,46,47, 48), but is covered by sediment for most of its length. Heat and pressure from slippage along this fault altered the Wilderness Suite and Oracle Granites to gneiss, the principal rock type of the range. As movement along the Catalina Fault continued, the gneiss formed a dome. Older rocks, such as the Pinal Schist, the Horquilla Limestone, the Earp Formation, the Epitaph Dolomite, and the Bisbee Group, were uplifted along the margins of the rising dome. Remnants of the Pinal Schist cap parts of the crest of the Rincon Mountains.

During Oligocene time large slabs of these older formations slid down the flanks of the rising dome by the pull of gravity along glide faults. The faulted and folded outcrops of Epitaph Dolomite and Horquilla Limestone near the park visitor center may have slid into their position below the much older Pinal Schist along a glide fault, disrupting the normal vertical sequence of bedrock. Thrust faulting that occurred before the development of the Catalina fault may also be responsible for the placement of the dolomite and limestone below the schist. Slumping and landslides along faults and weaker foliation planes in the gneiss are active processes on the high, steep slopes of the range.

Basin and Range faulting between 15 and 5 million years ago uplifted the Rincón Mountains and down-dropped the adjacent Tucson Basin and San Pedro Valley. Streams cut fault- and joint-aligned canyons into the rising Rincón Mountains. Streams wore back the margins of the range, leaving beveled rock platforms (pediments) covered with aprons of boulders, gravel, sand, and silt (alluvial fans and bajadas) that filled the adjacent basins. Today, wet-weather drainages are cutting into the alluvial fans and bajadas and the underlying pediments.

Arroyos along the first few miles of the Cactus Forest Drive provide good exposures of the Pinal Schist, at 1,650 million years, the oldest rock in southeastern Arizona. The schist was originally deposited as layers of sandstone, siltstone, and shale in shallow seas by streams eroding a nearby continent. Heat and pressure metamorphosed these rocks into schist and phyllite that are chemically and structurally dissimilar to their parent rocks.

The top of the Pinal Schist in this area is part of a beveled platform of bedrock that slopes from the Rincón Mountains towards the Tucson. Here the pediment is covered by a thin veneer of sand and pebbles, worn from the mountains. In other locations where erosion has exposed the pediment surface, it is incised by shallow stream channels, covered by patches of sediment, and dotted with low bedrock hills. Downslope from this location the pediment is buried by increasing thicknesses of sediment. In many basins the deeply buried pediments are terminated by high-angle faults.

Buried pediments are a factor for hydrologists searching for water for cities expanding onto the margins of desert basins. Many well drillers, hoping to find sediment saturated by groundwater, have been disappointed by encountering shallowly buried pediments which yield little water.

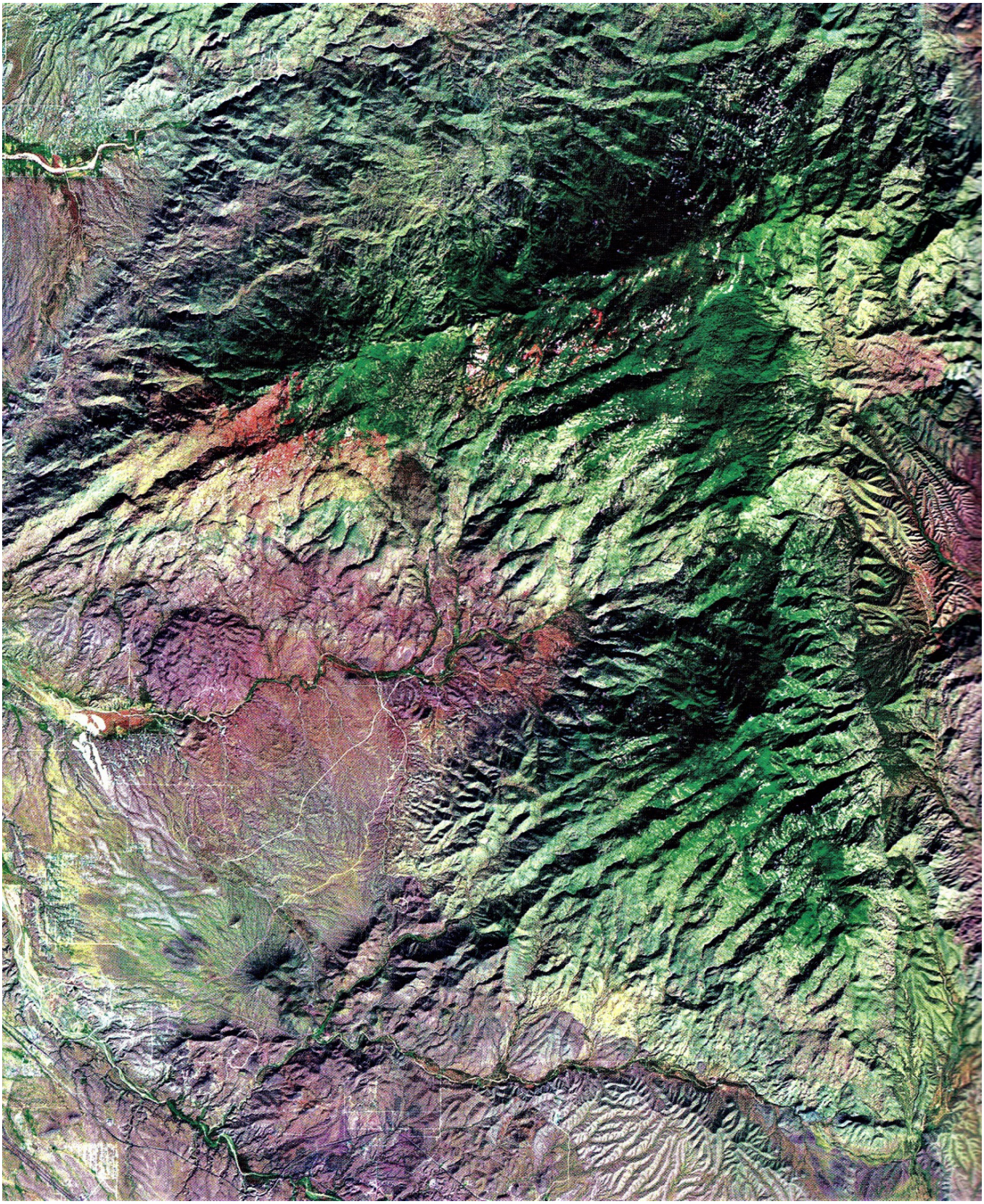


Figure 45. False-color satellite image of the Rincón Mountains (courtesy of Dr. John Dohrenwend).

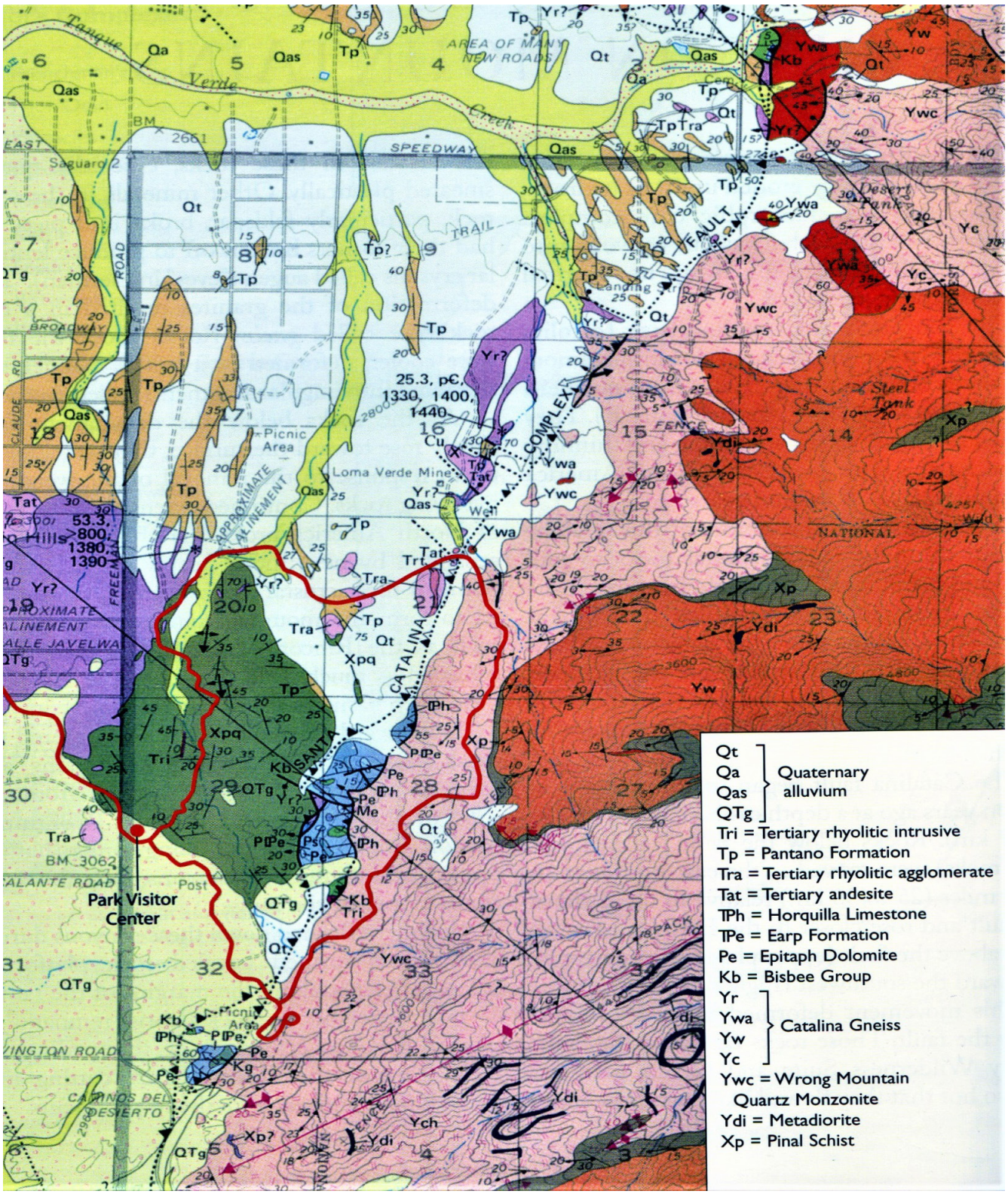


Figure 46. Geologic map of the Cactus Forest Drive area, Saguaro National Park-East (Drewes, 1977).

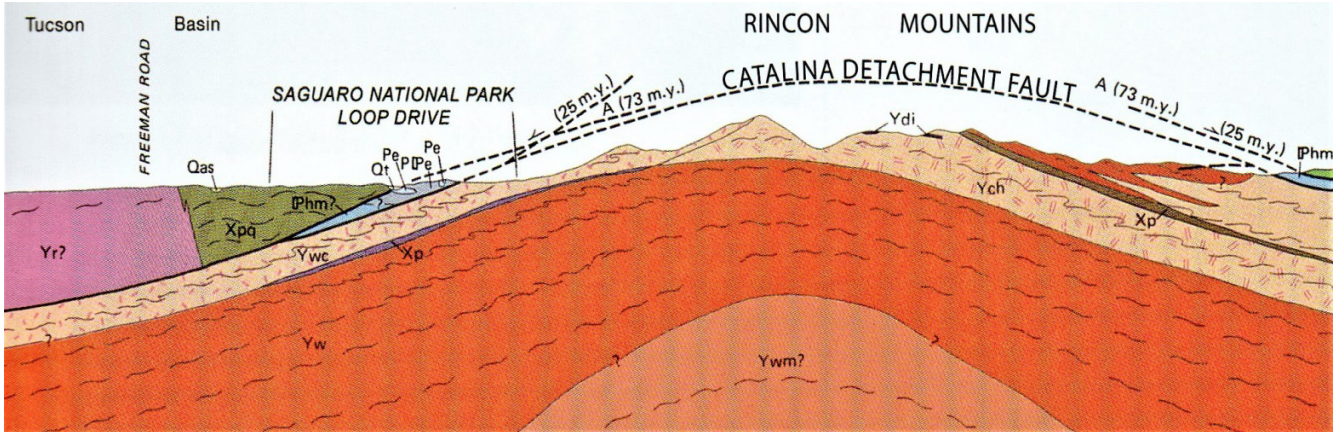


Figure 47. Geologic cross-section of the western Rincón Mountains, illustrating the position of upper and lower plate rocks in relation to the Catalina detachment fault. Qt, Qas=alluvium; Tr=rhyolite; Tat=andesite; Pe=Epitaph Dolomite; Phm=Horquilla Limestone; Ywc, Yr, Yw, YWm=Catalina Gneiss; Ydi=diorite; Xp, Xpq=Pinal Schist. Note that the much older Pinal Schist has been thrust faulted over the younger Epitaph Dolomite and Horquilla Limestone. (modified from Drewes, 1977)

Figure 48. The Catalina Detachment Fault (C) separates folded limestone (A) and gneiss (B), Loop Drive, Saguaro National Park (East).

Tortolita Mountains

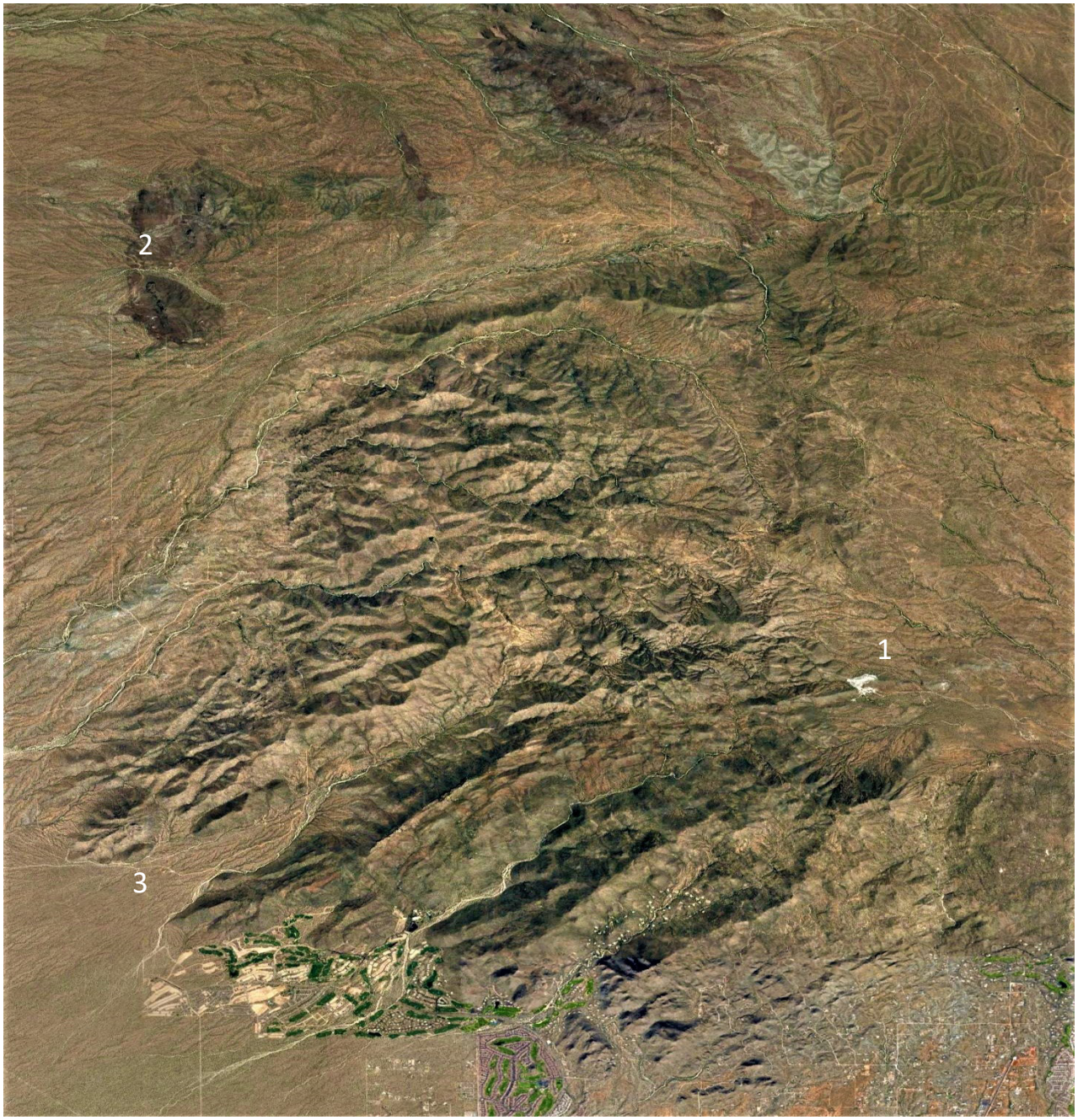


Figure 49. Satellite image of the Tortolita Mountains, 1=White Rock Mine area; 2=Owl Head Buttes area; 3=Cochise Canyon area (Courtesy of Google Earth).

The Tortolita Mountains (Figure 49) are the northwestern part of the Santa Catalina-Rincón metamorphic core complex that is detached from the Santa Catalina Mountains by the slippage on the Pirate Fault (Figure 50). The bedrock between the Tortolita and Santa Catalina Mountains is buried by thousands of feet of sediment in the Oro Valley Basin.

The Pinal Schist and intrusions of Oracle Granite are the basement rocks for much of the Tortolita Mountains. Many other granitic rocks, such as the Wilderness Suite and Catalina Granites, were emplaced later by repeated invasions of magma. Heat and stress associated with slippage along the Catalina Detachment Fault

metamorphosed zones of Oracle and Wilderness Suites Granites into gneiss, as it did in the Santa Catalina and Rincón Mountains. This fault is thought to be along the southwestern margin of the range, but buried by sediment. Intrusions of magma coupled with faulting deformed and metamorphosed sedimentary rocks over broad areas of the range. Magma also exploded, flowed, or was injected onto the surface as lava flows, cinders and ash, and dikes and sills that cooled to form a variety of volcanic rocks, especially in the northern part of the range.

Three areas of the range are of particular geologic interest and can be reached by roads that can be driven with vehicles of moderate clearance: the eastern margin of the range near the White Rock Mine, the entrance to Cochise Canyon, and Owl Head Buttes (Figure 49).

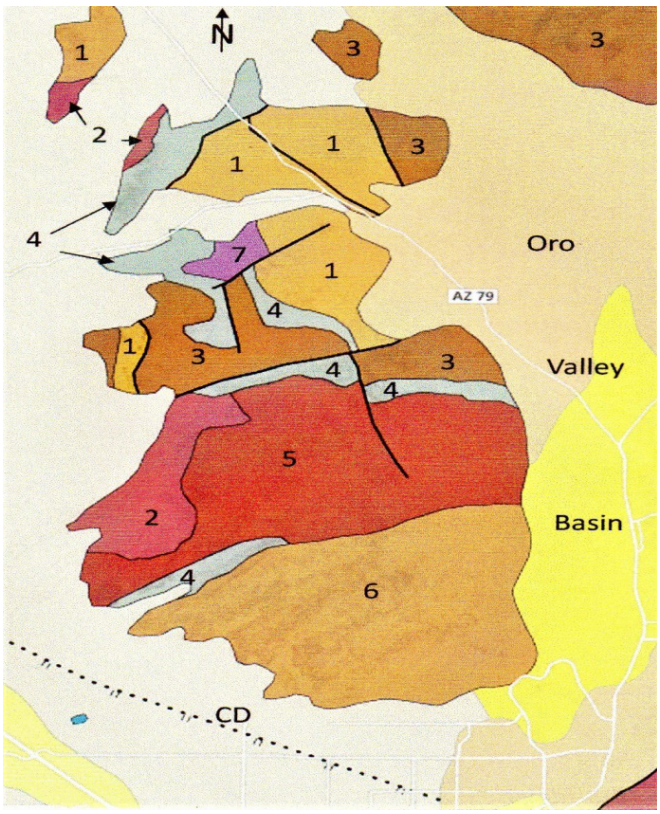


Figure 50. Highly generalized geologic map of the Tortolita Mountains. 1= Middle Miocene to Oligocene volcanic rocks (11-38 million years ago); 2 = Early Tertiary to Late Cretaceous muscovite-bearing granite (50-80 million years ago); 3 = Middle Proterozoic granitic rocks (Oracle Granite)(1400-1450 million years ago); 4 = Early Proterozoic metasedimentary rocks (includes Pinal Schist)(1600-1800 million years ago); 5 = Early Tertiary to Late Cretaceous Granite (50-82 million years ago); 6 = Middle Miocene to Oligocene granitic rocks (Catalina Granite (26 million years ago); 7 = Middle Proterozoic diabase in Apache Group (1050-1150 million years ago); CD = Catalina Detachment Fault covered with sediment; solid black lines are major faults (modified from Arizona Geological Survey, 2000).

The White Rock Mine area

Recommeded Access. From Tucson, follow highway 77 north to the town of Catalina. Drive west for 6 mi (9.65 km) on the Rail X Ranch Road to the White Rock Mine area. Note that the mine is private property.

The eastern face of the Tortolita Mountains in Figure 51 is composed mainly of Tertiary-age granites that have engulfed an extensive exposure of highly deformed Concha Limestone. The heat, pressure, and acidic fluids that accompanied the intrusions of magma that cooled to form these granites altered the Concha Limestone. Limestone was metamorphosed to marble (Figure 52) and sandstone was transformed to quartzite. These metasedimentary rocks are resistant to weathering and erosion and form ridges. Less resistant rock form valleys and slopes. The White Rock Mine, a marble quarry, began production in 1958 and is now closed.

Streams have cut back this face of the range, filling the Oro Valley Basin with rock debris. Extending out from the foot of the range, and partially buried by a veneer of sediment, is an extensive bedrock platform , i.e., pediment. In places, the pediment is exposed as low hills and in stream channels.

Figure 51. East face of the Tortolita Mountains, west of the town of Catalina, is mostly composed of Tertiary-age granites (A). These granites enveloped the older late Permian-age Concha Limestone, metamorphosing it to marble and sandstone to quartzite. The middle of the image is the sediment-filled Oro Valley Basin. The hills in the foreground are the western margin of a bajada sloping from the Santa Catalina Mountains. The white scar on the mountain face is the White Rock Mine, an abandoned marble quarry (B).

Figure 52. Oblique image of White Rock Mine quarry and tilted beds of Permian Concha Limestone. In this area the Concha Limestone was metamorphosed to marble, which was quarried here beginning in 1958 (courtesy of Google Earth).

Owl Head Buttes

Recommended Access. Follow Highway 79 north from Oracle Junction for 9 mi (14.5 km), turn west on Park Links Road and follow it 6.6 mi (10.6 km) to Owl Head Buttes Road, turn south and drive for about 3 mi (4.8 km) to Owl Head Buttes.

Owl Head Buttes (Figure 53) and the nearby area of Chief Butte attracted silver and copper prospectors in the 1880s. The most famous of these was Tom Jeffords, who led U.S. General Oliver Howard to the Dragoon Mountains for peace talks with Cochise, and who later became Indian agent to the Chiricahua Apache. Jeffords operated a small ranch near Owl Head Buttes from 1892-1914.

Owl Head Buttes are the erosional remnants of an extensive sequence of lava, ash and cinders that blanketed this area 21 to 27 million years ago (Oligocene time). Mineral-laden groundwater deposited copper and silver in the zone of crushed rock (breccia) along the Owl Head Buttes Fault to the west of the buttes (Figures 54). Most of the mineralization occurred in highly fractured quartz diorite and Pinal Schist below the dacite and rhyolitic volcanic rocks.

Figure 53. The dacite and rhyolite of the Owl Head Buttes are erosional remnants of ash flows and tuffs that blanketed this area between 21 and 27 million years ago. Copper and silver were deposited by hydrothermal fluids in fault-shattered quartz diorite and Pinal Schist below the dacite and rhyolite volcanic rocks.

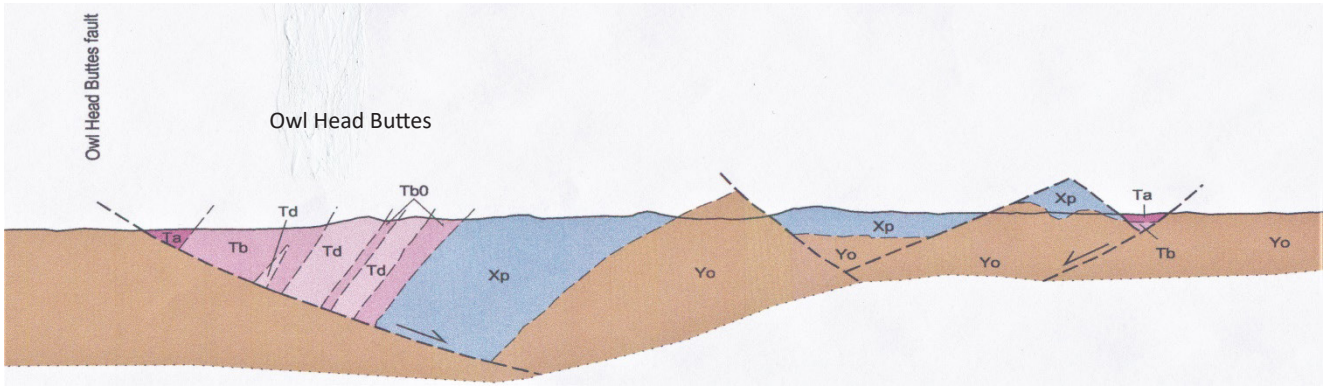


Figure 54. Southwest-northeast geologic cross-section, Owl Head Buttes and adjacent area. Ta=andesitic lava, Tb=basaltic andesite lava, Td=dacitic lava, TbO=aphyric basaltic andesite; Yo=Oracle Granite, Xp=Pinal Schist (modified from Ferguson, 2003).

Cochise Canyon

Recommended Access. From exit 236 on Interstate Highway 10, follow Cochise Canyon Drive to the mouth of Cochise Canyon.

The Cochise Canyon area of the Tortolita Mountains is geologically complex. The Pinal Schist basement rock and metamorphosed sedimentary units have been highly deformed by multiple granitic intrusions and fractured by slippage along faults. The Catalina Detachment Fault, which led to the formation of the metamorphic core complex structure of the Tortolita Mountains, is buried under basin fill only a few miles southwest of the canyon.

There is a good example of deformed bedrock at the entrance to Cochise Canyon (Figure 55). The Pinal Schist (A) was originally deposited 1.65 billion years ago as layers of sandstone, siltstone, and shale. The rocks probably represent a marine environment that received sand, silt, and clay eroded from a nearby continent. Over time these sedimentary rocks were buried at depth and subjected to intense heat and pressure, transforming them into new rocks—called schists and phyllites. These highly altered rocks bear little resemblance to the original sedimentary layers. The schist is silver-gray in color and has thinly bedded layers of quartz and mica; the phyllite has a satiny appearance with fine, wavy planes of aligned very fine grained minerals, such as mica. The schists and phyllites have been highly fractured by episodes of faulting.

The granite (B), a quartz monzonite to quartz syenite, cooled from a body of molten rock (magma) that invaded and engulfed older igneous and metamorphosed rocks in this part of Earth's crust during Miocene time, 23 to 28 million years ago. The magma was injected in phases and cooled miles below the surface. The granite has been fractured by faulting and exposed by faulting and erosion.

Figure 55. Highly deformed Pinal Schist (A) and granite (B) at the entrance to Cochise Canyon.

Santa Rita Mountains

Rising to 9,453 ft (2,881 m) at Mount Wrightson, the Santa Rita Mountains are the second highest range in southeastern Arizona, after Mount Graham (10,720 ft; 3267 m) in the Pinaleño Mountains. Although the range is 25 mi (40 km) long, its high country area is less than that of the Santa Catalina and Pinaleño Mountains because of steep slopes and a sharp, narrow crest.

The Santa Rita Mountains are of particular geological importance because they contain the most complete sequence of rocks, from Proterozoic time to the present--1,650 million years, in southeastern Arizona. This nearly unbroken sequence of rocks, from every major period of geologic time, has allowed geologists to reconstruct the geologic evolution of southeastern Arizona. The geology of the range is very complex and bedrock is covered by forest at higher elevations. The sedimentary, igneous, and metamorphic rocks that form the range have been repeatedly folded, fractured by faulting, and intruded by masses of magma (molten rock). Copper, silver, lead, and zinc deposited by hydrothermal solutions accompanying some of the magmatic intrusions continue to attract mining companies to the range.

The Sawmill Canyon and Salero Faults divide the Santa Rita Mountains into the northeastern, central, and southwestern sectors, each with a distinct geological structure, tectonic history, and combination of rock types (Figure 56). The active Basin and Range Santa Rita Fault borders the range on the west.

The Northeastern Sector. Proterozoic granite and Pinal Schist are the basement rocks for this sector and for the entire range, as they are for all of southeastern Arizona (Figure 57). Fault-bordered packages of Paleozoic and Mesozoic sedimentary rocks are common in this part of the range. Dikes (Figures 58, 59), plugs, and stocks of magma intruded these rocks during Triassic, Jurassic, and Tertiary time. The hot, acidic, mineral-bearing solutions that accompanied the magma circulated along faults, depositing copper, gold, and other metals. Beginning in the 1870s, mining camps were established on the east and west sides of the northern Santa Rita Mountains and copper smelters were built at Helvetia and Rosemont. Placer gold mining, including hydraulic mining, centered

on Greaterville. The white scar on the range at Helvetia is a marble quarry.

The numerous faults comprising the Sawmill Fault zone bordering the northeastern sector of the range on the south originated during the Proterozoic and have been repeatedly reactivated during the Mesozoic and Cenozoic. Movement along the Sawmill Fault zone has displaced thousands of feet of rock. The Santa Rita Fault borders the Santa Rita Mountains on the west and may have been active as early as Mesozoic time (70-250 million years ago). The fault was re-activated between 25 and 5 million years ago during the period of crustal extension that formed the Basin and Range geologic province. Vertical movement on the fault, which may in aggregate be up to 6,000 ft (1829 m), resulted in the subsidence of the Santa Cruz basin to the west.

About 56 million years ago quartz latite and quartz monzonite stocks intruded and mineralized the Horquilla Limestone and other sedimentary rocks in this area. A Canadian mining company plans to excavate an open pit copper mine in the Rosemont mining district on the northeast side of the range. There is opposition to the mine over environmental and social issues by the 'Save the Scenic Santa Ritas' activist group.

The Central Sector. Much of this part of the range is formed from Late Cretaceous stocks (igneous intrusions less than 40 sq. mi (100 sq. km)). The majestic Madera Canyon is cut into the Madera Canyon Granodiorite; Mount Wrightson consists of a tilted stack of rocks that include the andesite, rhyolite, latite flows, and sedimentary rocks of the Triassic Mount Wrightson Formation, the Permian-Pennsylvanian Naco Group, the Pennsylvanian Escabrosa Limestone, the Cambrian Abrigo Formaton, and Proterozoic granite (Figures 60, 61).

The Madera Canyon alluvial fan (Figure 62) is a major landform, constructed of sediment eroded from Madera Canyon. Studies of fault scarps (Figure 62, A) on the fan indicate that the last slippage along the fault occurred in the Upper Pleistocene.

Madera Canyon and Mount Wrightson are popular destinations for visitors to the Santa Rita Mountains. Elephant Head, the prominent butte west-southwest of Madera Canyon, is a faulted stock of Late Cretaceous Elephant Head Quartz Monzonite (Figure 63).

Southwest Sector. Southwest of the Solero Fault are the San Cayetano Mountains and Grosvenor Hills in the southwest sector of the Santa Rita Mountains (Figure 64). Tertiary, Triassic, and Jurassic volcanic and sedimentary rocks, intruded by Tertiary and Jurassic granitic intrusions form these two highlands. Mineralization by solutions that accompanied dacite, rhyolite, and quartz monzonite intrusions deposited lead, zinc, and silver in this part of the range. The Wrightson, Salero, Cave Creek, and Tyndall mining districts were established as miners staked claims. Between 1911 and 1917 in the latter district the Glove Mine produced lead, zinc, silver, gold, and molybdenum from a quartz monzonite intrusion into Horquilla Limestone.

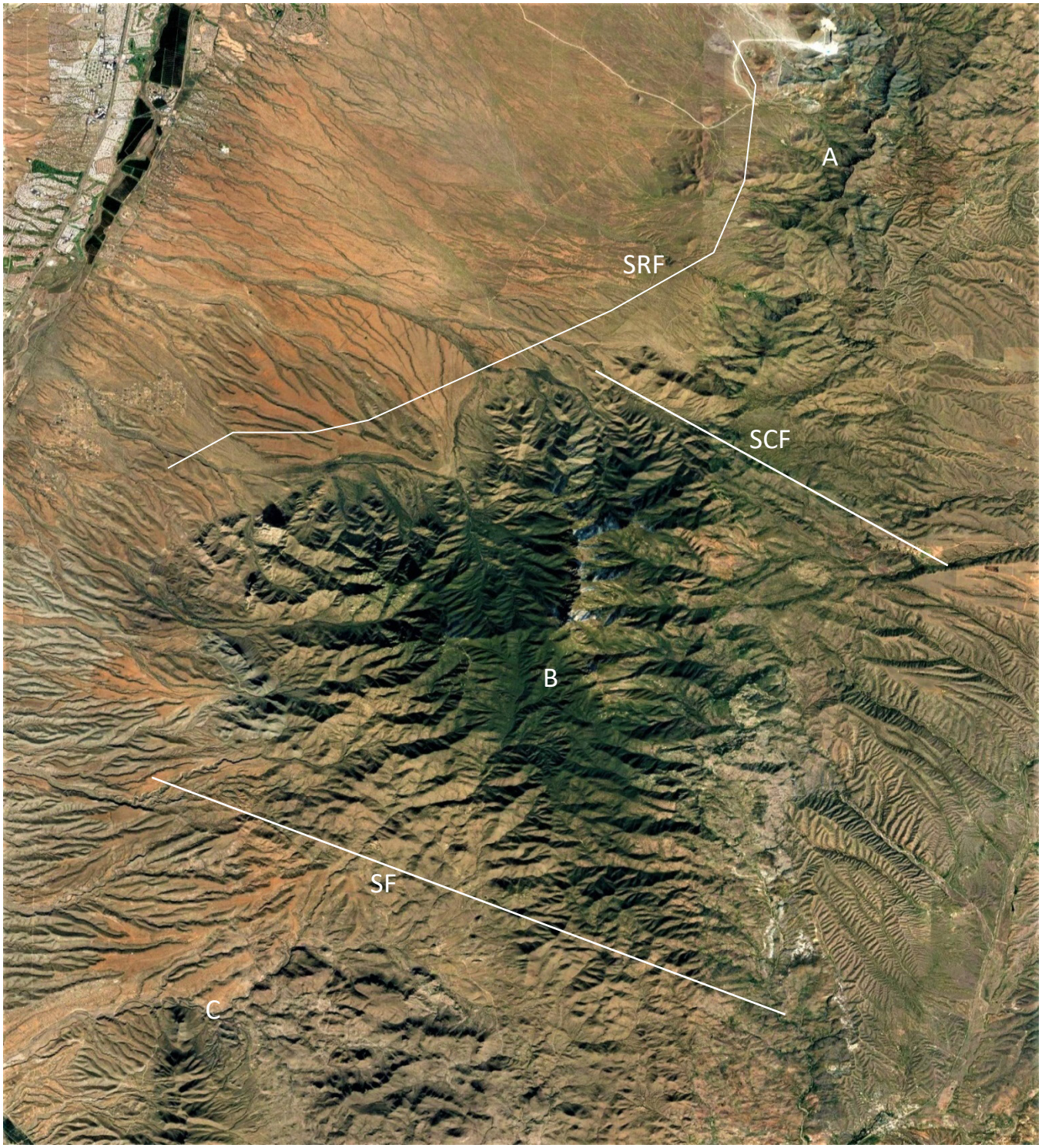


Figure 56. High-altitude image of the Santa Rita Mountains; northeastern (A), central (B), and southwestern (C) geologic sectors and the approximate locations of the Sawmill Canyon (SCF), Salero (SF) and Santa Rita (SRF) Faults (courtesy of Google Earth).

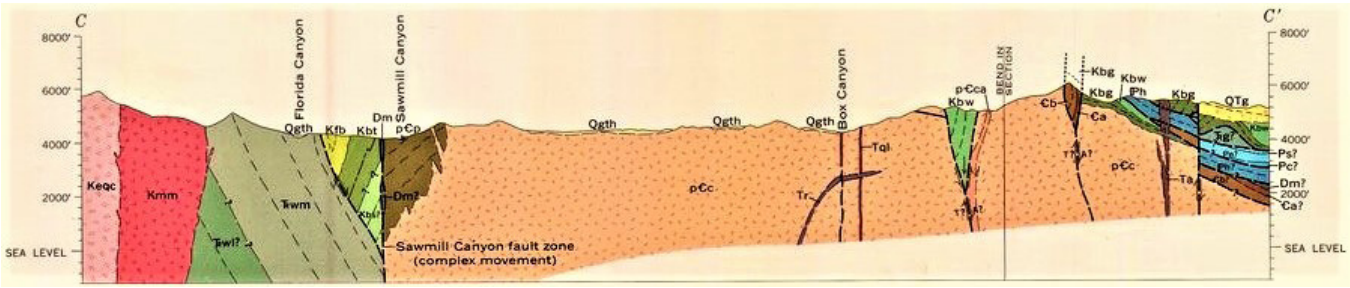


Figure 57. Northeast-southwest geologic cross-section of part of the northeastern sector, Santa Rita Mountains. C=southwest, C'=northeast; p€p=Pinal Schist, €c=Proterozoic granite, €a=Abrigo Formation, €b=Bolsa Quartzite, Trg=Gardner Canyon Formation, Pe=Epitaph Dolorite, Ph=Horquilla Limestone, Kfb=Fort Crittenden Formation, Kbt, Kbs, Kbg, Kbw=Bisbee Group, Tr=rhyolite porphyry dikes of Box Canyon, Tql=quartz latite stocks and dikes (Drewes, 1971).

Figure 58. Rhyolite dike, Box Canyon Road, Melendez Pass.

Figure 59. Volcanic dikes of Tertiary rhyolite porphyry along the Box Canyon Road near Melendez Pass, northern Santa Rita Mountains (Courtesy of Google Earth).

Figure 60. Mount Wrightson and neighboring peaks of volcanic and sedimentary rocks of the Mount Wrightson Formation.

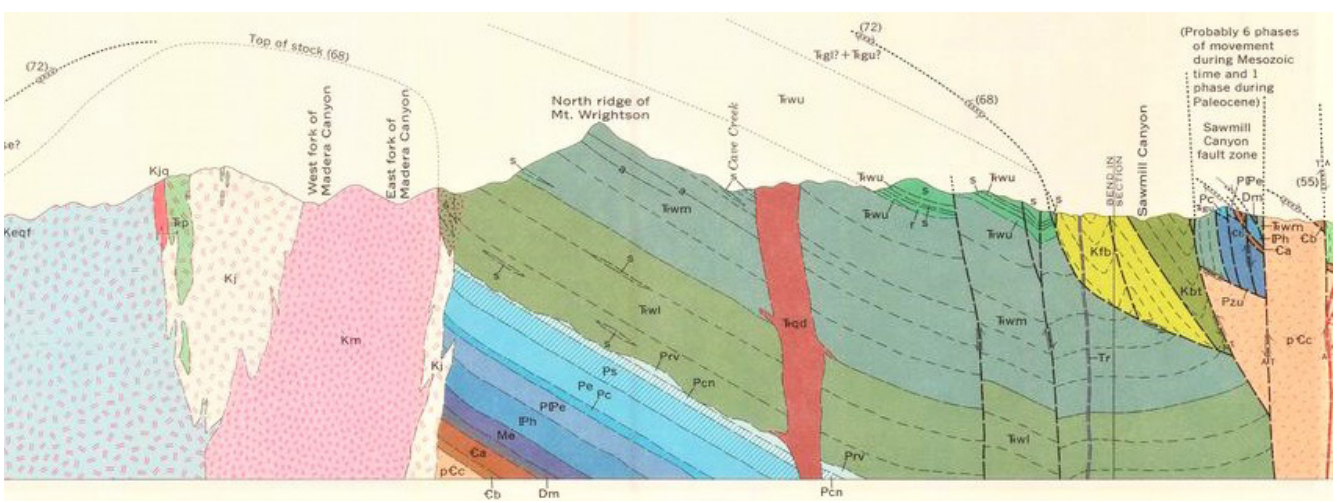


Figure 61. Northeast-southwest geologic cross-section of part of central sector of the Santa Rita Mountains: Keqc, Kj=Elephant Head Quartz Monzonite, Km=Madera Canyon Granodiorite, Trwl, Trwm, Trwu=andesite, rhyolite, latite and sedimentary rocks of the Mt. Wrightson Formation, Trqd=quartz monzonite, Ps, Pe, Pc, PPe, Ph=Naco Group, Me=Escabrosa Limestone, Є̄a=Abrigo Formation, pЄc=Proterozoic granite (Drewes, 1971).

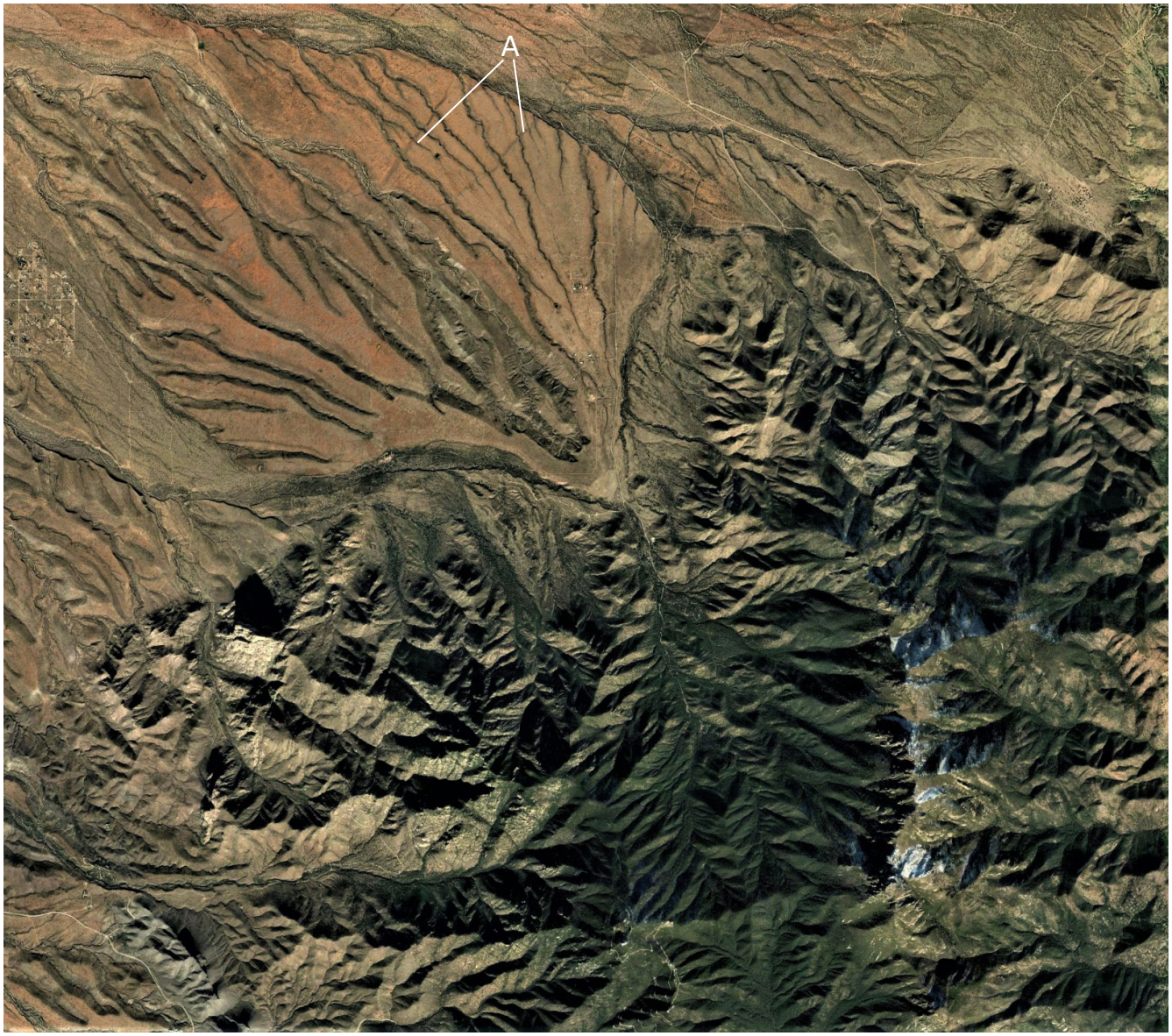


Figure 62. Aerial image of the Madera Canyon drainage basin and alluvial fan. Sediment eroded from the basin has been deposited in this fan shaped alluvial deposit. The surface of the fan is ruptured by active(?) faults (A) that ruptured in the Upper Pleistocene or early Holocene. (courtesy of Google Earth).

Figure 63. Elephant Head is a faulted, quartz monzonite stock that intruded older rocks during the Cretaceous.

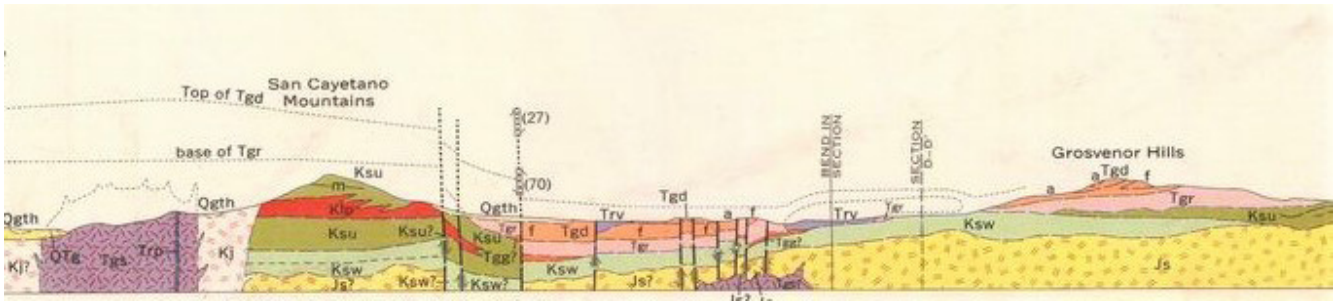


Figure 64. Northeast-southwest geologic cross-section of part of the southwest sector, Santa Rita Mountains: Ksu,Ksw=Cretaceous volcanic and sedimentary rocks, Tgd, Tgr,=Oligocene volcanic rocks, Trp=Oligocene Piper Gulch Monzonite, Js= Jurassic Squaw Gulch Granite(Drewes, 1971).

Tucson Mountains

Recommended Access. Gates Pass and Saguaro National Park (West) Saguaro National Park (West) offers excellent access tothe best scenery and important geologic features in the Tucson Mountains. From Tucson, follow Speedway Boulevard west to Gates Pass. After this stop, follow Gates Pass and Kinney Road to the Park entrance.

The Tucson Mountains are the eroded remnants of one of several huge volcanoes that were active in this part of southeastern Arizona about 70-75 million years ago (Figures 65, 66, 67 This volcanism was fed by massive intrusions of molten rock (magma) that formed miles below the surface and rose buoyantly through overlying rocks. When rising magma neared the surface, pressure fell, dissolved gases came out of solution to form froth, and clouds of ash and cinders exploded from surface vents. Most of the particles fell to the ground and built volcanoes around the vents (Figure 68,1) or accumulated as nearly horizontal layers called tuff.

Denser mixtures of cinders, ash, and gas formed red-hot clouds that flowed down the slopes of the volcanoes. Particles deposited by these “fire clouds” were compacted and fused into a rock called welded tuff, the Cat Mountain Tuff in the Tucson Mountains (Figures 69,70). Pieces of older rock, ripped from strata below the volcano by the rising magma, are present in the tuff.

After large-volume eruptions drained the magma chamber beneath the Tucson Mountains volcano, its roof collapsed to form a large depression (caldera) that was 12 miles (20 km) across (Figure 68, 2 and 3). The caldera floor sank unevenly like a trap door—about 300 feet (100 m) on the south side and as much as 15,000 feet (4600 m) beneath Wasson Peak on the north. As the floor subsided, huge blocks of welded tuff and slabs of older rock, some up to 2,000 feet (600 m) across, slid into the caldera. Deposits of this megabreccia (Figure 69, inset) are interlayered with the Cat Mountain Tuff in the Tucson Mountains. Later, lava flowed into the caldera. Then a large body of magma intruded, uplifted, and tilted the caldera fill and overlying hardened lavas. The magma, which cooled, crystallized, and solidified beneath the debris-filled caldera, formed the Amole granite. Hot, mineral-rich solutions that accompanied the intrusion of the granite circulated through the fractured rocks in the caldera. Silver, gold, copper, and other metals in the hot fluids crystallized in fractures in the adjacent rocks. Mineralization also occurred where injections of molten rock, called dikes (such as the Silver Lily Dikes,) penetrated the caldera fill and overlying volcanic rocks.

Beginning about 30-35 million years ago the Earth’s crust deep beneath these rocks was broken along a low-angle fracture, called the Catalina Detachment Fault (Figures 17,20,46). From beneath what are now the Tucson Mountains, granite in the “lower plate” (below the detachment fault) moved northeastward 16-22 mi (25-35 km) relative to rocks in the “upper plate” (above the detachment fault). This granite was then domed upward and eventually eroded to form the Santa Catalina and Rincón Mountains. Thus granite and gneissic rocks comprising the core of the Santa Catalina and Rincón Mountains originally resided deep beneath what are now the Tucson Mountains and Tucson Basin.

Extensive lava flows were emplaced from 30 to 15 million years ago. Remnants of the basaltic lava flows are preserved in the northern part of the range and at Tumamoc Hill and A Mountain.

Basin and Range extension between 15 to 5 million years ago resulted in high-angle faults that down-dropped the Tucson Basin and Avra Valley and uplifted the Tucson Mountains. Stream erosion has exposed the internal structure and plumbing system of the ancient volcano and caldera. The walls of the caldera and most of the lava that flowed from the caldera have been worn away and deposited in adjacent basins by flash floods and debris flows.

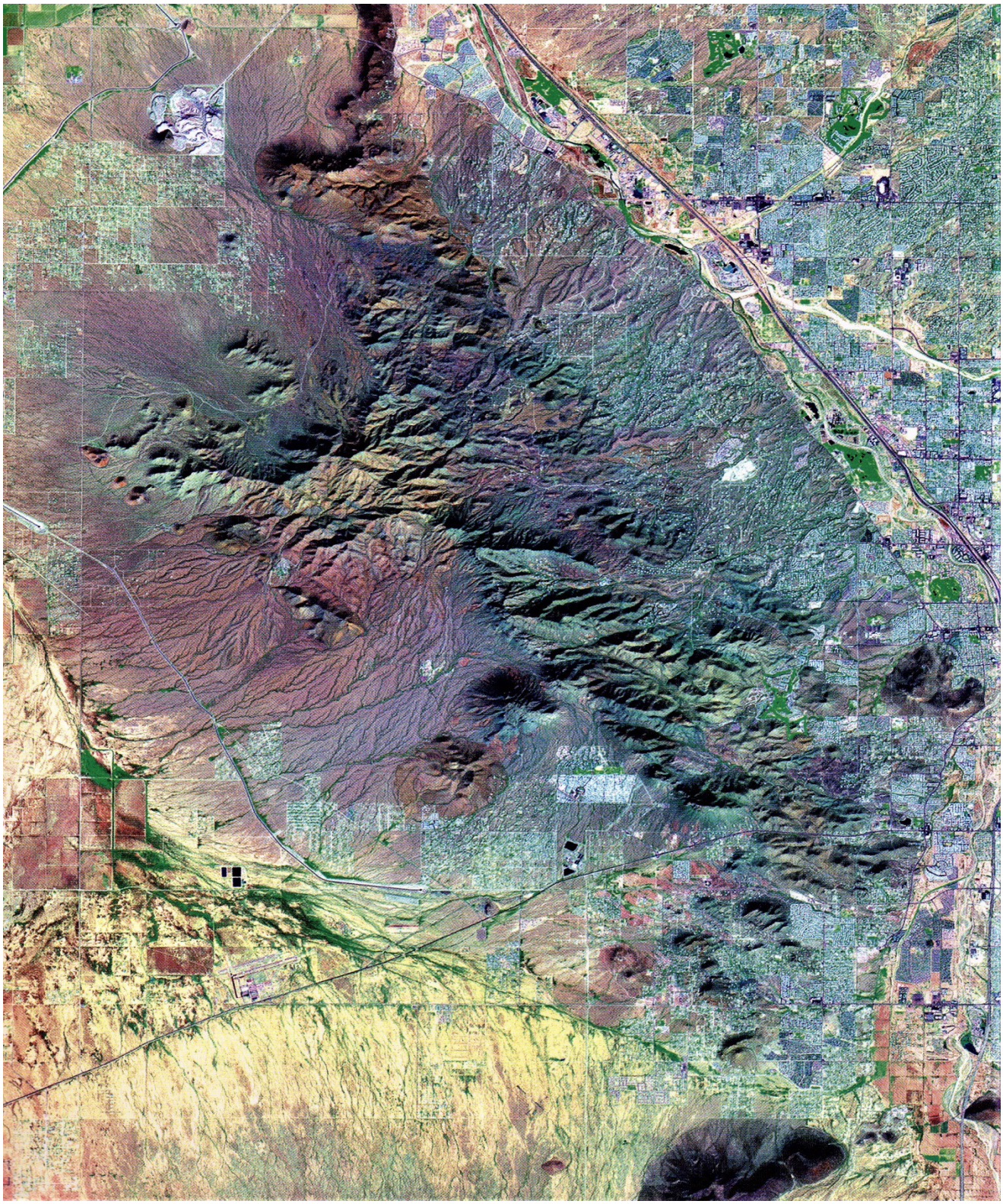


Figure 65. False color Landsat image of the Tucson Mountains. Colors reflect vegetation, urban zones, and oxidation of various types of rock(Courtesy of Dr. John Dohrenwend).

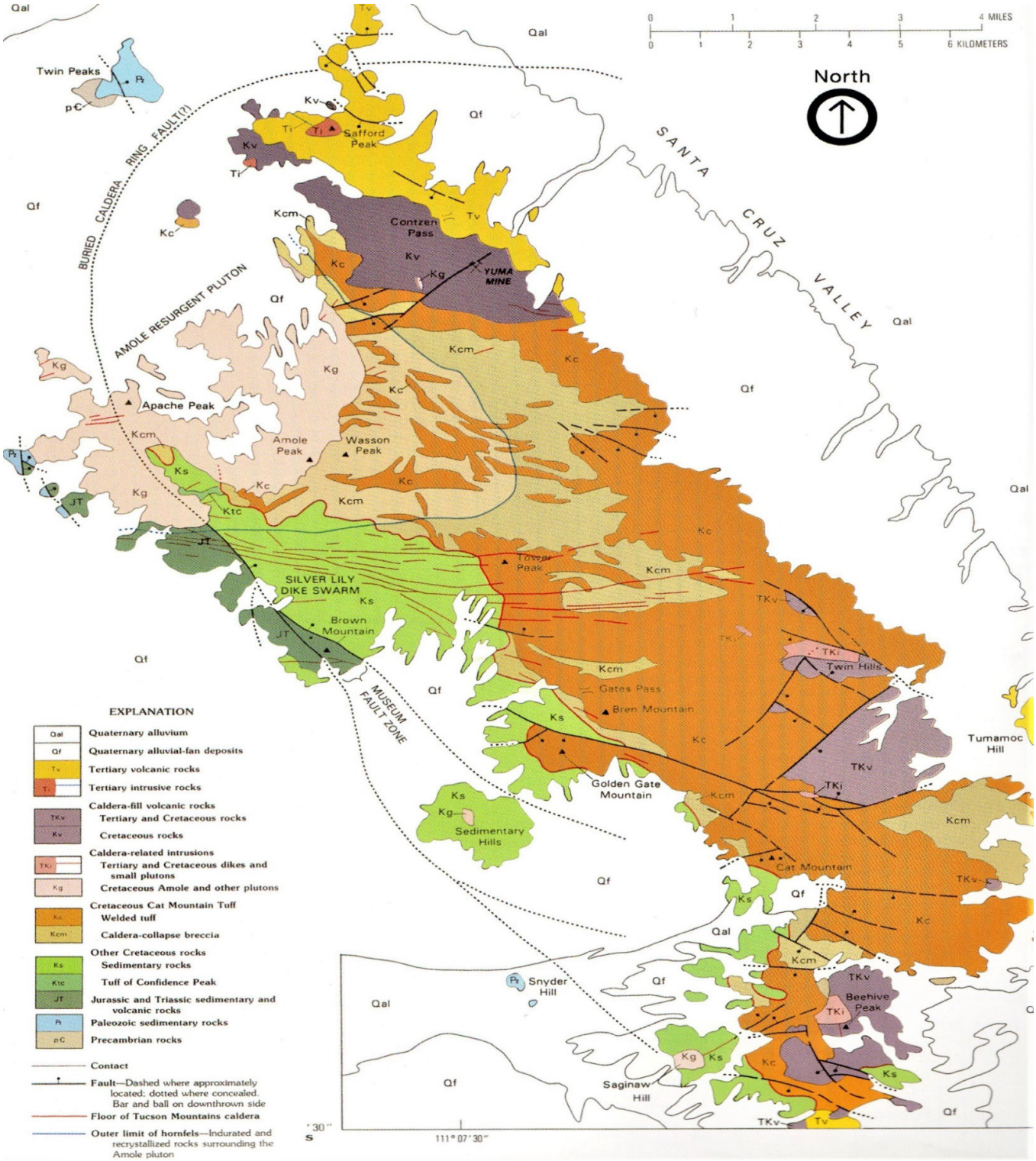


Figure 66. Geologic map of the Tucson Mountains (Lipman, 1993).

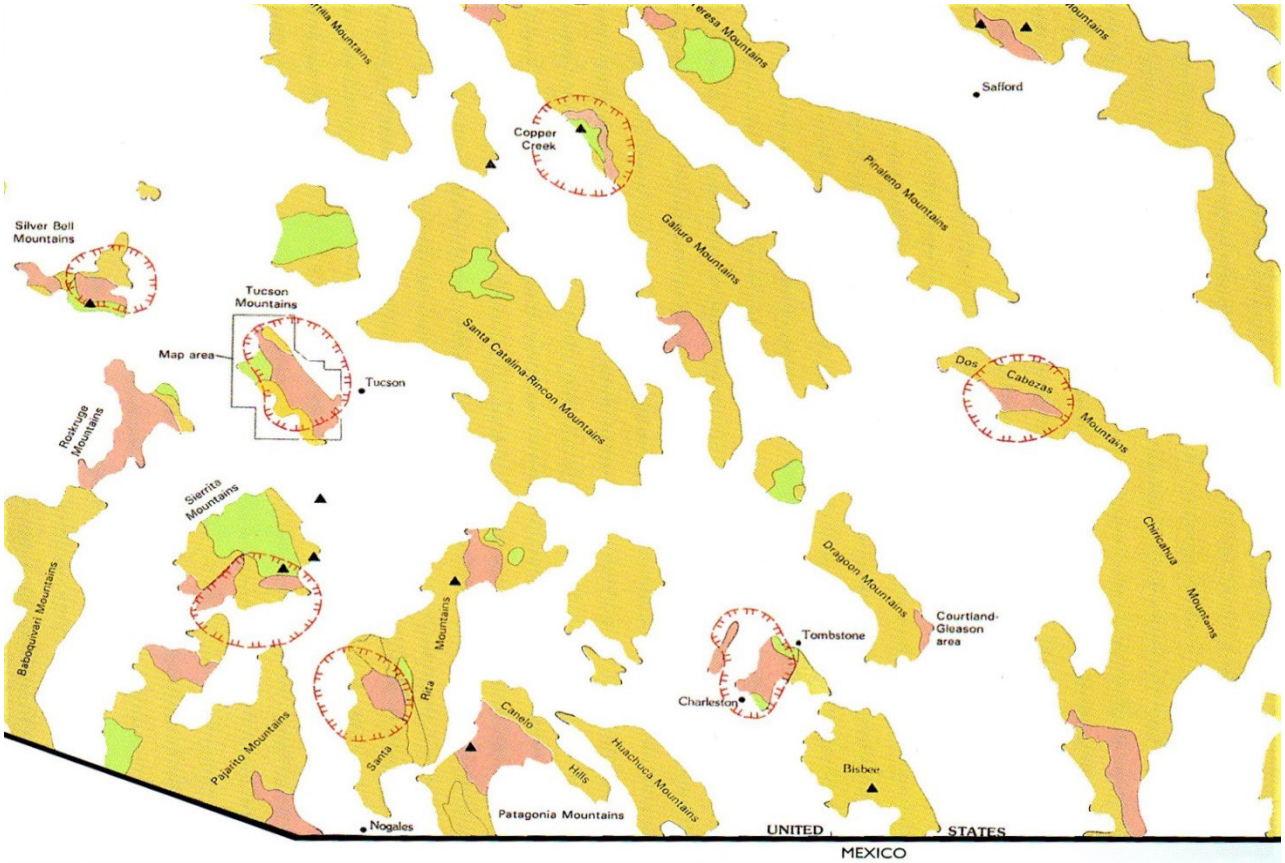


Figure 67. Late Cretaceous (70-75 mya) silicic volcanic centers in central southeastern Arizona (Lipman, 1993).

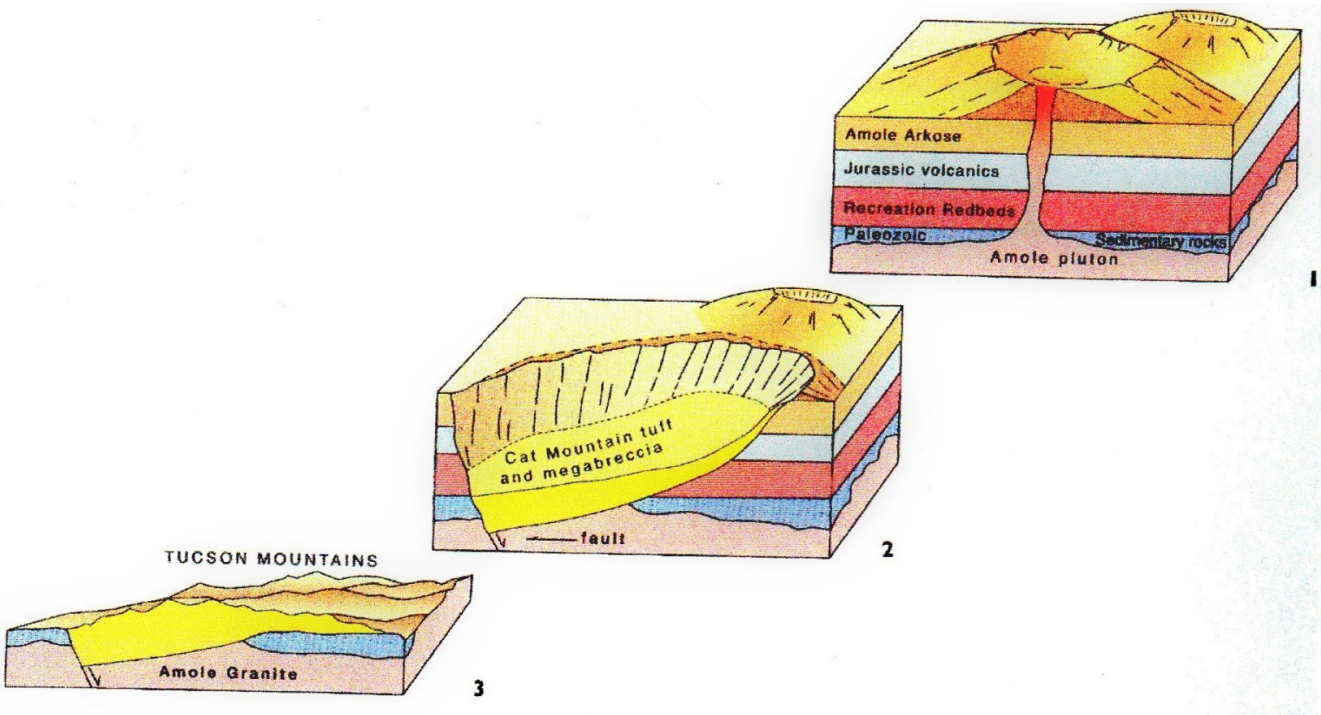


Figure 68. Block diagram illustrating the evolution of the Tucson Mountains: 1) invasions of magma builds volcanoes at the surface, the last invasion cools to form the Amole pluton, 2) collapse of magma chamber along a fault forms a caldera, 3) continued faulting and erosion shape the Tucson Mountains.

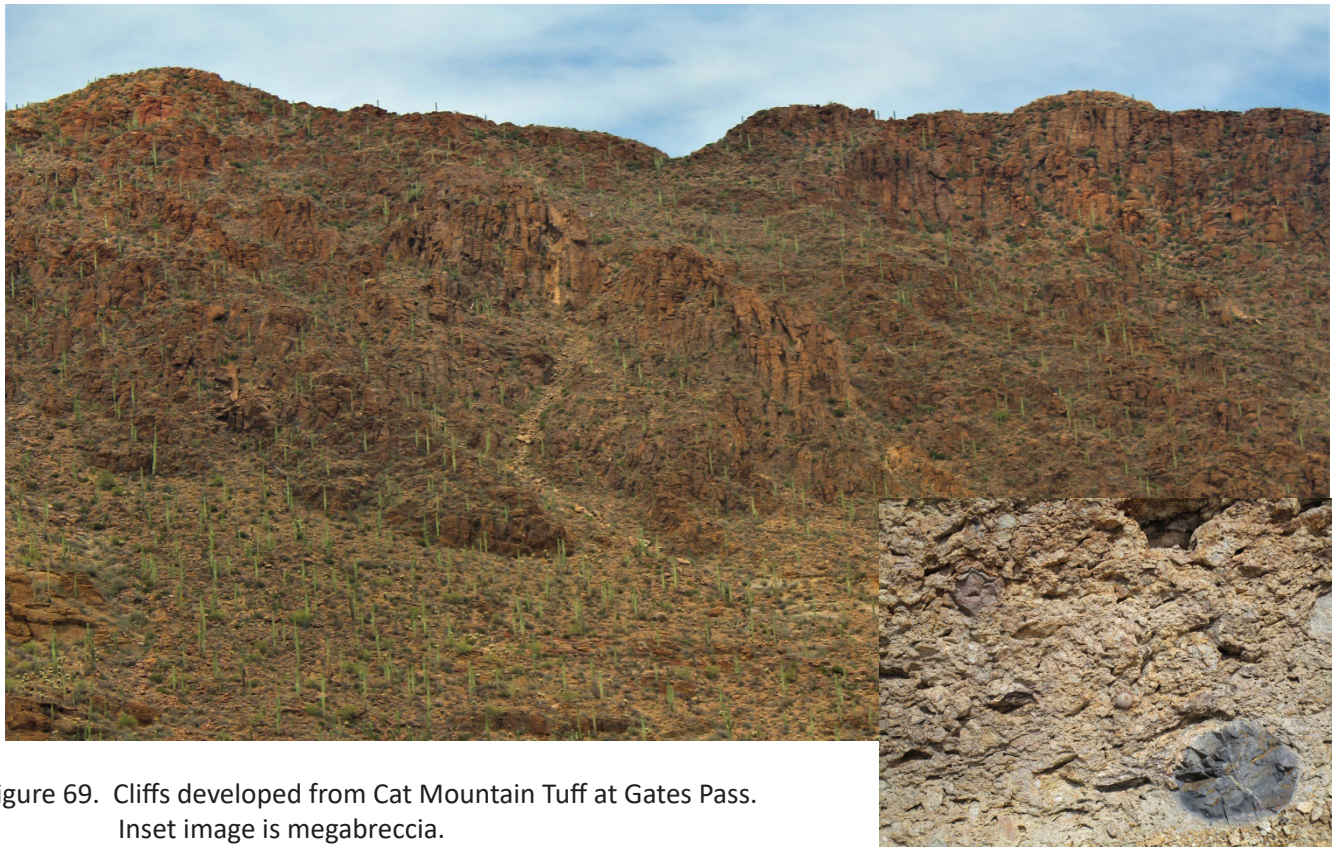


Figure 69. Cliffs developed from Cat Mountain Tuff at Gates Pass. Inset image is megabreccia.

Figure 70. Cat Mountain Tuff west of Gates Pass.

Galiuro Mountains

Recommended Access. The Galiuro Mountains are the most remote and difficult range to access in southeastern Arizona. Much of the high country is Galiuro Wilderness managed by the Coronado National Forest. Travel by motor vehicle is prohibited in the Wilderness and access to trailheads is by unpaved road. Avavaipa Canyon, cut through the northern margin of the range, is the Aravaipa Canyon Wilderness and is managed by the Nature Conservancy and the Bureau of Land Management (BLM). A permit from the BLM is required to enter this Wilderness. The Muleshoe Ranch Cooperative Management Area at the south end of the range is owned and managed by The Nature Conservancy, the Forest Service, and the Bureau of Land Management, and includes the BLM's Redfield Canyon Wilderness, part of the Galiuro Wilderness, and The Nature Conservancy's Muleshoe Preserve. Contact these agencies regarding access.

The Galiuro Mountains are capped by rhyolite and andesite ash flows (Figures 71,72) from the explosive eruption of a volcano between 24 and 29 million years ago. The collapse of the volcano into its underlying magma chamber formed a huge caldera near the present-day Santa Teresa Mountains. Faulting and erosion has destroyed the circular form of the caldera and it is not a recognizable landform. The deposition of these ash flows, called the Galiuro Volcanics, occurred during a widespread, 10 million-year-long volcanic flare-up that produced dozens of calderas across much of southwestern North America. Volcanic rocks from these eruptions are found in the Chiricahua Mountains and other ranges in the Southwest and built a vast plateau, the Sierra Madre Occidental, in northwestern Mexico.

Basin and range faulting between 15 and 5 million years ago elevated the Galiuro Mountains. The range is bordered on the west by a high-angle fault with at least 5000 ft (1524 m) of vertical displacement. A second, parallel fault to the east has been carved into a deep canyon by the head-ward erosion of Rattlesnake and Redfield Creeks. This canyon bisects the range along its entire length. Along the northwestern and southwestern margins of the range, faulting and erosion have exposed the older Proterozoic- to Tertiary-age rocks beneath the 2100 ft-thick (650 m-thick) cap of Galiuro Volcanics.

The rugged range is only 7,663 ft (2336 m) high at Bassett Peak. The Galiuro Volcanics were welded (fused) from incandescent clouds of gas and ash (nuées ardentes) and the residual heat of the thick ash blanket. Because of this they are resistant to weathering and erosion and form imposing cliffs that rim the crest of the range. Access to the interior of the range is primarily where major drainages have breached this volcanic rimrock.

Some mines in the Galiuro Mountains have produced substantial quantities of metals. Mineralization by acidic hydrothermal fluids along Laramide-age (50-70 million years) stocks and dikes and in adjacent host rock deposited copper, gold, silver, and lead. The U.S. Geological Survey (Creasey and Jinks, 1981) reports that the Copper Creek mining district (Figure 73) has produced the 1354 oz (38.4 kg) of gold, 194,851 oz (5,523.9 kg) of silver, over 11 million pounds (5 million kg) of copper, and over 3 million pounds (1,361,000 kg) of lead. Hydrothermal fluids migrating along the fault plane adjacent to Rattlesnake and Redfield Creeks during the Miocene (24-29 million years ago) deposited small quantities of copper and molybdenum in the Galiuro Volcanics.

Figure 71. Geologic map of the Galiuro Mountains (Arizona Geological Survey, 2000). Map key continued on following page.

Map key for Figure 71 (my=millions of years ago)

Tv=Miocene to Oligocene (11=38 my) volcanic rocks; Tsm= Miocene to Oligocene (11=38 my) sedimentary rocks; Tsy=Pliocene to middle Miocene (2-16 my)sedimentary rocks; Tkg=early Tertiary to late Cretaceous(50-82 my) granitic rocks; Kv= early Tertiary to late Cretaceous(50-82 my) volcanic rocks; KJs=Cretaceous to upper Jurassic sedimentary rocks, including the Bisbee Group (80 to 160 my); Pz=Paleozoic (270-280 my) sedimentary rocks; PP=Permian to Pennsylvanian (280-310 my) sedimentary rocks; M€=Mississippian, Devonian, Cambrian (330-540 my) sedimentary rocks; Yd=middle Proterozoic 1050-1150 my) diabase; Ys= middle Proterozoic (700-1300 my) sedimentary rocks, including the Apache Group and Troy Quartzite; Xg=early Proterozoic (1600-1800 my) granitic rocks; Xm= early Proterozoic (1600-1800 my) metamorphic rocks; Xms= early Proterozoic (1600-1800 my) metasedimentary rocks, including the Pinal Schist. Solid black lines are major faults (Arizona Geological Survey, 2000).

Figure 72. Oblique aerial photograph of the west face of the Galiuro Mountains. The range is riddled with faults now eroded by streams. The fault that bounds the west side of the range is buried by an apron of alluvial rock debris deposited by running water . Aravaipa Creek, along the left side of the image, cut Araviapa Canyon. The stream is thought to have existed before Basin and Range faulting and down-cut its canyon through the rising Galiuro Mountains (courtesy of Google Earth).

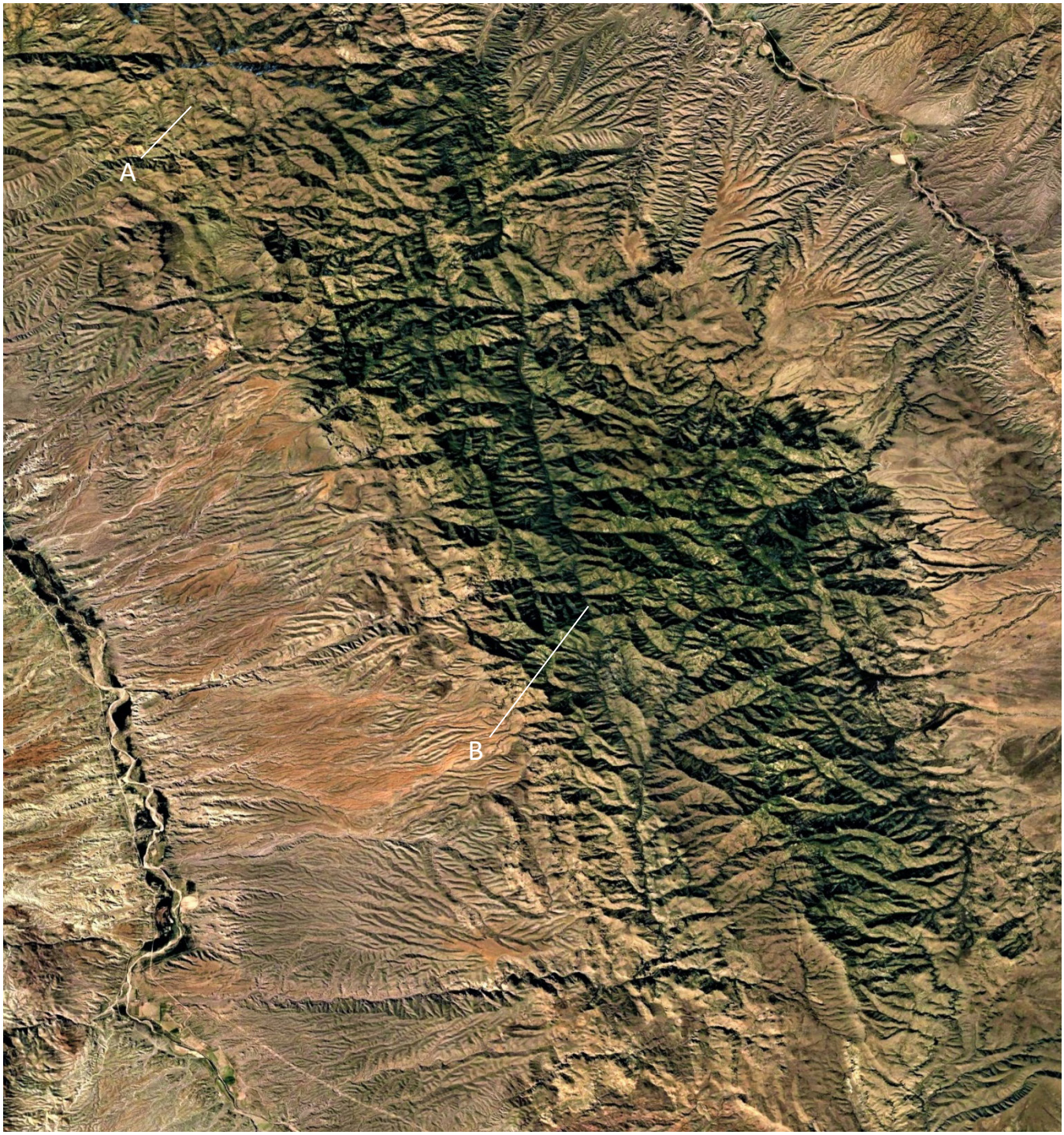


Figure 73. Satellite image of the Galiuro Mountains. A=Copper Creek, B=Powers Mine (Courtesy of Google Earth).

Pinaleño Mountains

Recommended access. From Safford, follow Highway 191 south to Highway 366, which follows the crest of the Pinaleño Mountains.

The Pinaleño Mountains (Figure 74) are a metamorphic core complex, similar in geologic structure to the Rincón, Santa Catalina, and Tortolita Mountains. The northeast-southwest stretching of the southwestern part of North America that began about 35 million years ago caused crustal rocks to be stretched and thinned. As stretching and thinning continued, crustal rocks in southeastern Arizona pulled apart and broke along low angle fractures, called detachment faults. The detachment fault associated with the uplift of the Pinaleño Mountains is the Safford Fault (Figure 76, 77, 78). Movement along this fault began about 15 million years ago (middle Miocene Epoch) and slid rocks above the fault more than 4 mi (7 km) to the northeast. The removal of the weight of these rocks permitted deeply buried Proterozoic (1400 to 1800 million years ago) granite and schist below the fault to move slowly toward the surface and form a dome.

Extreme pressure and friction generated by movement along the detachment fault pulverized and re-crystallized adjacent zones of the Proterozoic granite and gneiss into a new, fine grained, dense rock called mylonite. Mylonite is common along the northeast margin of the range.

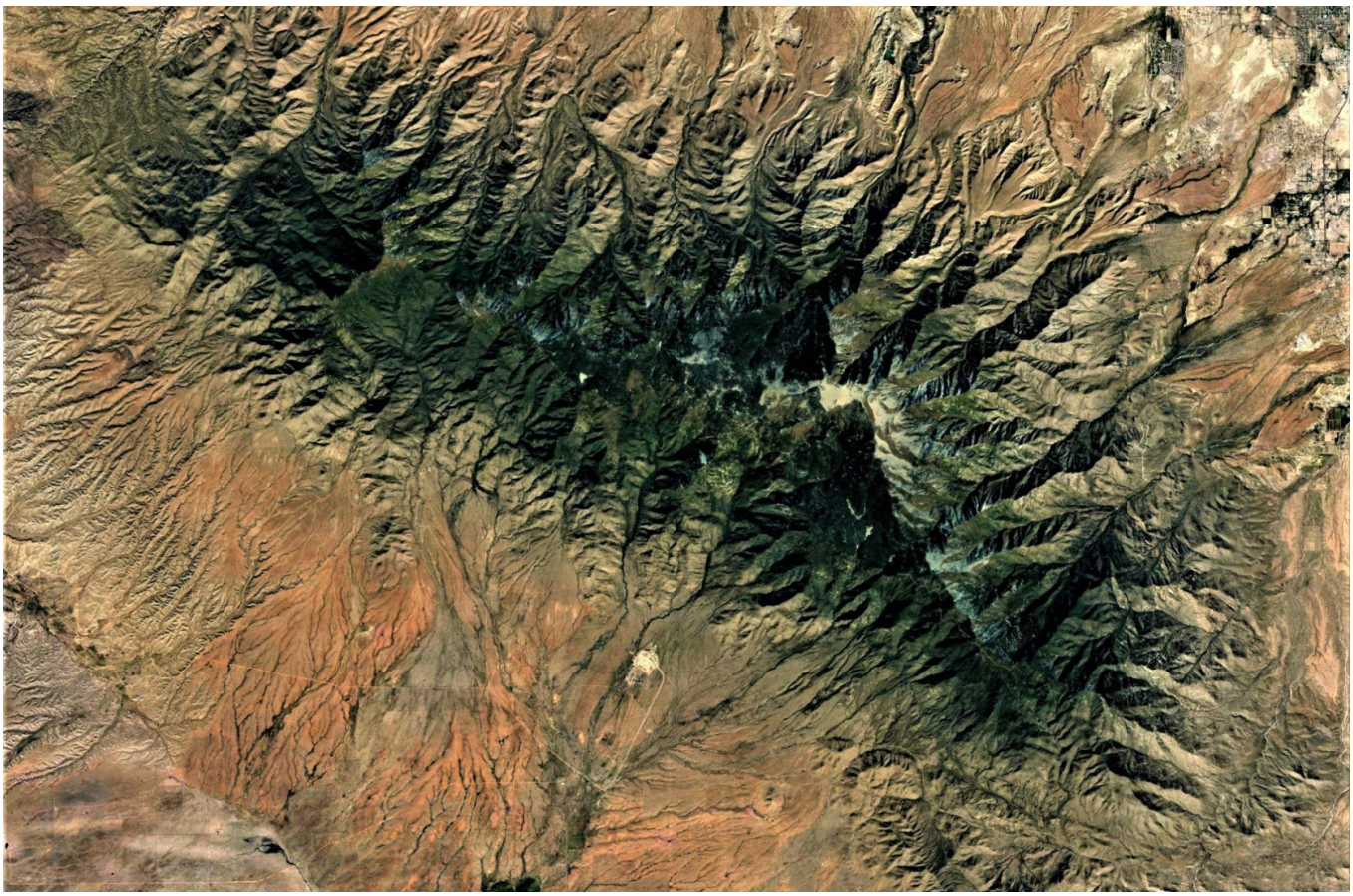


Figure 74. Satellite image of the Pinaleño Mountains (courtesy of Google Earth).

Continued movement along the detachment fault and doming of the Pinaleño Mountains led to the subsidence of the 2.8-mi (4.5 km-) deep Safford Basin northeast of the range. Streams eroded deep canyons into the Pinaleño Mountains and adjacent highlands and filled the basin with sediment. The early Safford Basin had no drainage outlet and shallow lakes pooled on the basin floor. Lake and stream sediments interfinger in the basin fill, reflecting cycles of sediment deposition caused by climatic changes and uplift due to faulting. Flash floods built fan shaped deposits, called alluvial fans, at the mouths of canyons along the margin of the range. Over the

last several million years, as the Gila River integrated the drainage of the Safford Basin with that of the Salt and Colorado Rivers, its tributaries eroded headward into these alluvial fans. The streams that built these alluvial fans down-cut their courses below the original fan surfaces, producing spectacular examples of “abandoned” alluvial fans along the northeast margin of the range (Figure 75).

High-angle faults that have had repeated slippage during the last 5 million years are present along the northeast margin of the range. Movement along these faults, which may merge at depth with the low-angle, middle Miocene Safford detachment fault, could have played a role in the deep erosion and abandonment of the alluvial fans.

No economic deposits of precious or industrial metals have been found in the Pinaleño Mountains.

Figure 75. Oblique satellite image of the highly eroded and” abandoned” alluvial fans along the northeastern flank of the Pinaleño Mountains (Courtesy of Google Earth).

Figure 76. The northeast face of the Pinaleño Mountains. Most of the range is composed of Proterozoic granite, gneiss, and schist and Miocene-age mylonite.

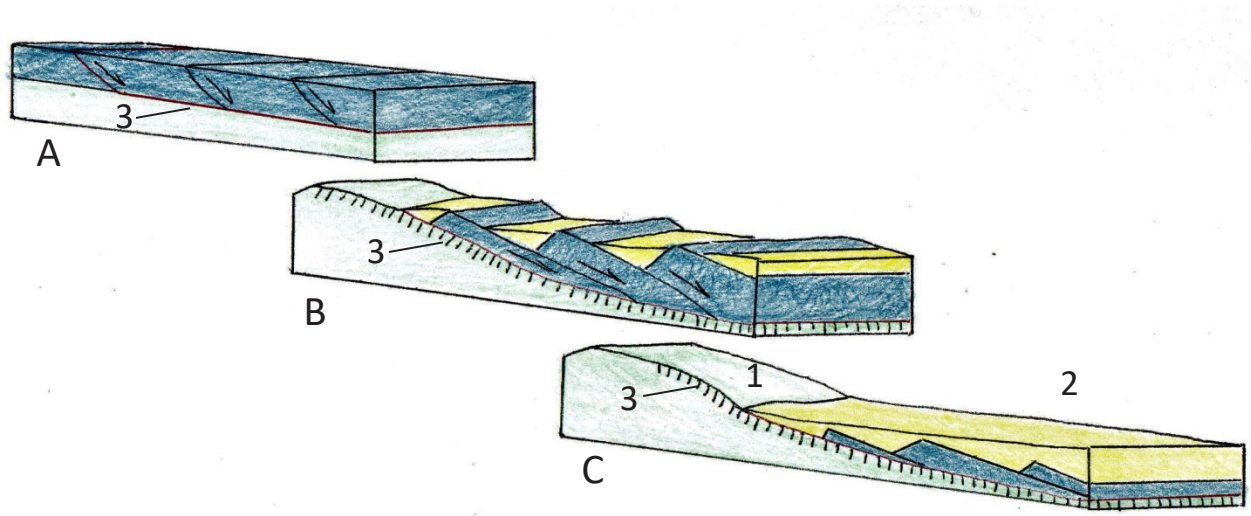


Figure 77. Block diagram illustrating the formation of the Pinaleño Mountains. A=early Miocene (20 my); B=late Miocene (8 my); C=present; 1=Pinaleño Mountains; 2=Safford Basin; 3=Safford Fault; yellow=alluvial sediments; blue=Oligocene to early Miocene sedimentary and volcanic rocks; light blue Proterozoic granite and gneiss; hatching=milonite; arrows indicate the direction of fault movement.

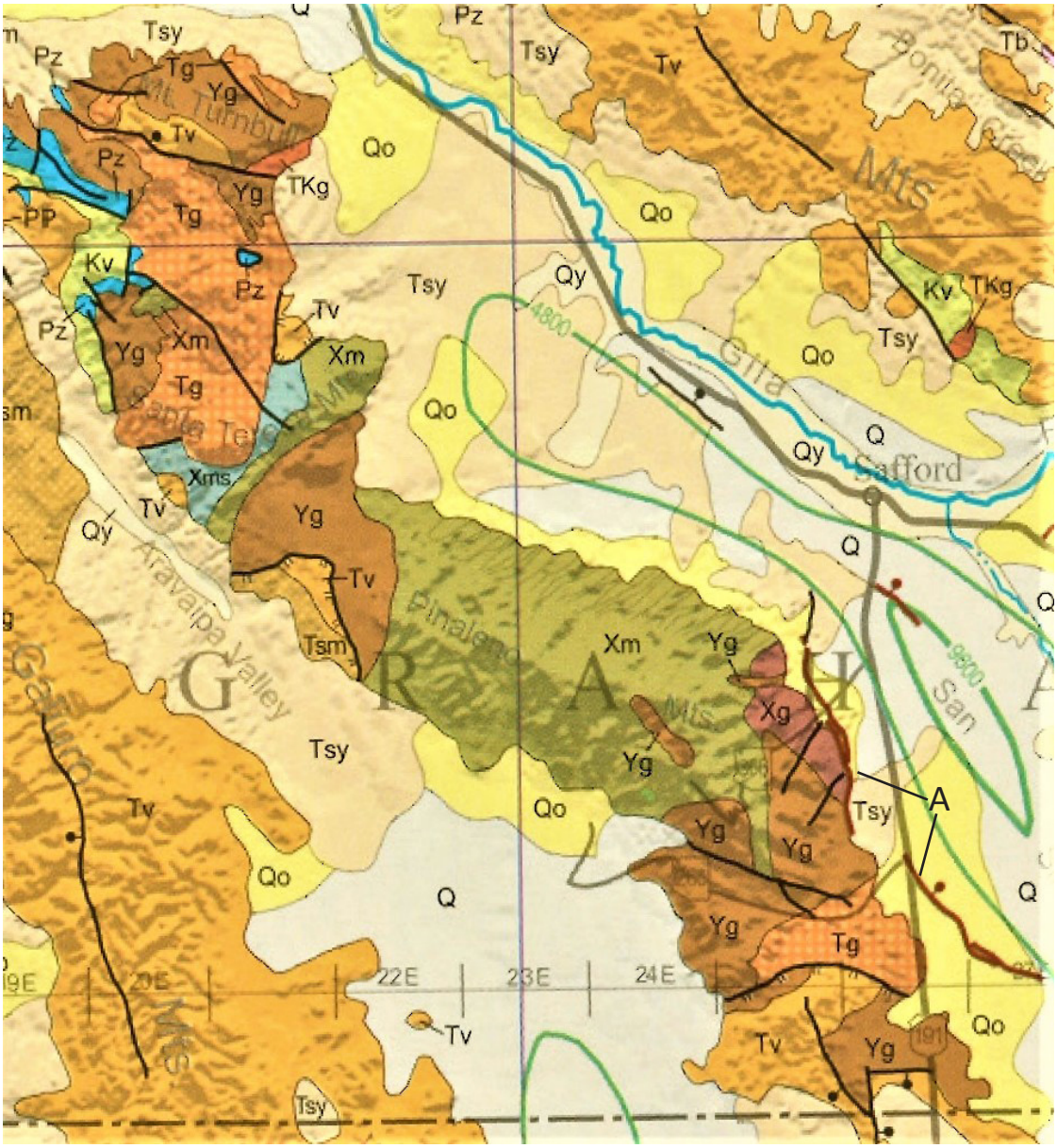


Figure 78. Geologic map of the Pinaleño Mountains. A=the Safford Fault; Xm=early Proterozoic metamorphic rocks, 1600-1800 my; Xg=early Proterozoic granitic rocks 1600-1800 my; Xms=early Proterozoic metasedimentary rocks, 1600-1800 my; Yg=middle Proterozoic granitic rocks, 1400-1450 my; Pz=Paleozoic sedimentary rocks, 248-544 my; PP=Permian to Pennsylvanian sedimentary rocks, 280-310 my; Kv=early Tertiary to Late Cretaceous volcanic rocks, 50-82 my; Tv=middle Miocene to Oligocene volcanic rocks, 11-38 my; Tg=middle Miocene to Oligocene granitic rocks, 14-26 my; Tsm=middle Miocene to Oligocene sedimentary rocks, 11-32 my; Tsy=Pliocene to middle Miocene deposits, 2-16 my; Qo=early Pleistocene to late Pliocene surficial deposits, 0.75 to 3 my; Q=Quaternary surficial deposits, 0-2 my (Arizona Geological Survey, 2000).

Chiricahua Mountains

Recommended Access. Chiricahua National Monument. From Willcox, follow Highways 186 and 181 to the Monument. Portal-Paradise area. From Interstate Highway 10, follow Highway 80 south to the Portal turnoff. Fort Bowie National Historic Site. From Willcox, follow Highway 186 and Apache Pass Road to the Site.

About 27 million years ago (Oligocene Epoch), compressed water vapor, carbon dioxide, and molten rock violently erupted from a magma chamber and built a volcano just south of what is now Chiricahua National Monument. Steam and gas blew the magma into massive clouds (nuées ardentes) of red-hot gas, pumice and ash which cascaded down the slopes of the volcano (Figure 79). The eruptions blanketed more than 1,200 sq. mi (3,100 sq. km) with volcanic ash and cinders. These deposits slowly compressed, fused together, and cooled to form the Rhyolite Canyon Tuff, the most extensive rock in this part of the Chiricahua Mountains (Figures 80, 81).

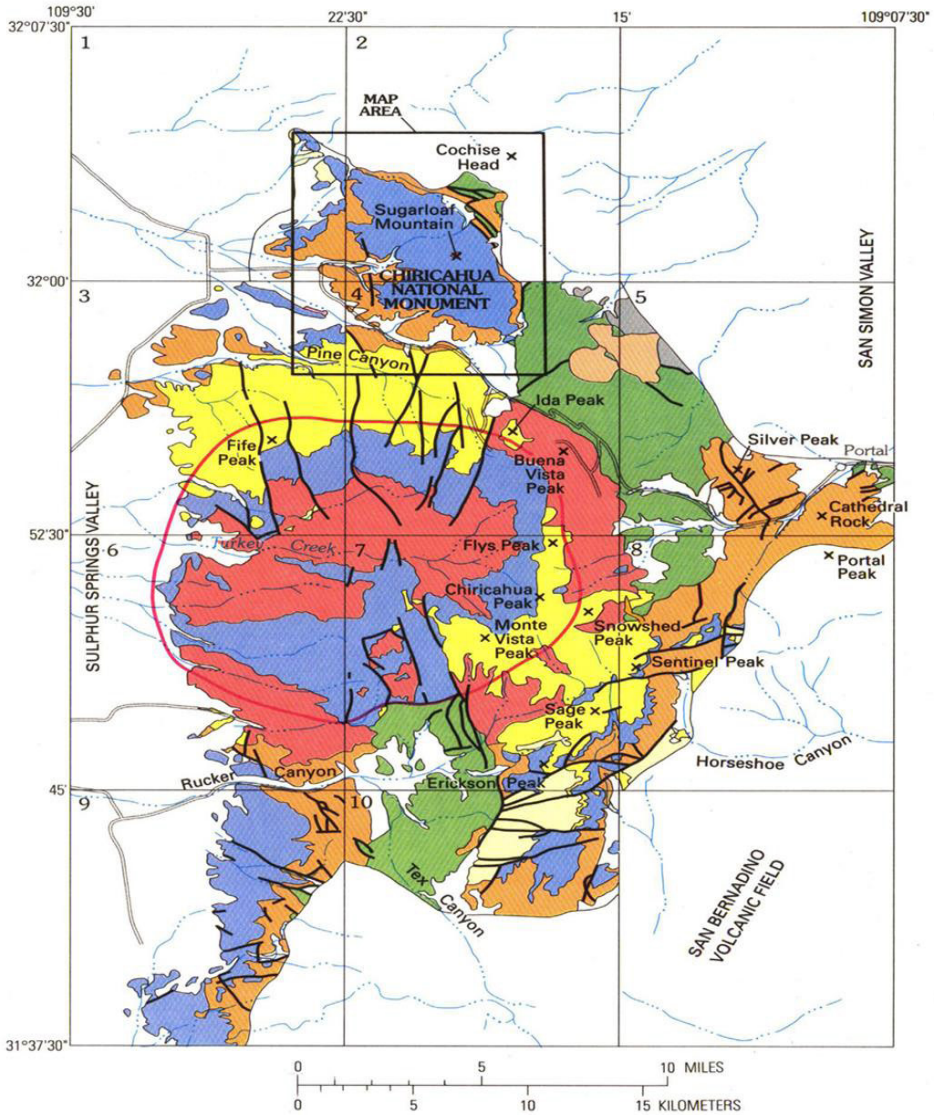
Figure 79. Nuée ardentes, clouds of hot gas, ash, and pumice that can race down volcanoes at speeds up to 100 mi (160 km) per hour, are common during explosive eruptions (courtesy of U.S. Geological Survey).

As the magma was ejected, the ground above the magma chamber collapsed and formed a caldera, a huge depression about 12 mi (19 km) across and 5,000 ft (1,524 m) deep. The caldera, buried by pumice and ash and altered by erosion and faulting, is no longer a recognizable landform. Dozens of other calderas also formed during this 10 million-year-long volcanic flare upin Arizona, New Mexico, Colorado, and the vast Sierra Madre Occidental of northwestern Mexico.

Between 15 and 5 million years ago Basin and Range extension broke the Earth's upper crust into northwest-southeast trending blocks separated by steeply dipping faults. Some blocks were uplifted to form ranges, such as the Chiricahua, Dos Cabezas, Mule, and Dragoon Mountains.Other fault-bound blocks subsided to form basins, such as the Sulphur Springs and San Simon Valleys.

As the ash deposits cooled and contracted, a series of horizontal and vertical cracks, called joints, developed. Over millions of years, especially during the last Ice Age (2 million to 10,000 years ago) these joints were widened and deepened by weathering and erosion to form slot canyons separated by towering pinnacles of Rhyolite Canyon Tuff (Figures 82, 92, and outside back cover).

Figure 80. Satellite image of the Chiricahua Mountains (courtesy of Google Earth).



GEOLOGIC INDEX MAP OF THE CHIRICAHUA MOUNTAINS

[(Simplified from *Geologic map of the Turkey Creek caldera* (du Bray and others, in press)]

EXPLANATION

Quaternary surficial deposits

ROCKS THAT POSTDATE THE TURKEY CREEK CALDERA

Rhyolite lavas, pyroclastic rocks, and conglomerate

OLIGOCENE ROCKS OF THE TURKEY CREEK CALDERA

Moat deposits—Mainly rhyolite lavas and pyroclastic rocks

Resurgent intrusion and extrusive equivalents—Dacite and monzonite porphyry

Rhyolite Canyon Tuff

ROCKS THAT PREDATE THE TURKEY CREEK CALDERA

Tertiary volcanic rocks—Mainly Oligocene rhyolite ash-flow tuff and lava and andesite lava

Tertiary intrusive rocks—Granite and granodiorite

Mesozoic and Paleozoic rocks—Mainly sedimentary rocks; also includes mafic lava flows, dikes, and sills

Precambrian granite

Contact

Structural margin of Turkey Creek caldera—Mostly buried by moat deposits; position approximate

Fault

Road

Stream

Figure 81. Geologic map of the northern and central Chiricahua Mountains (Pallister and DuBray, 1994).

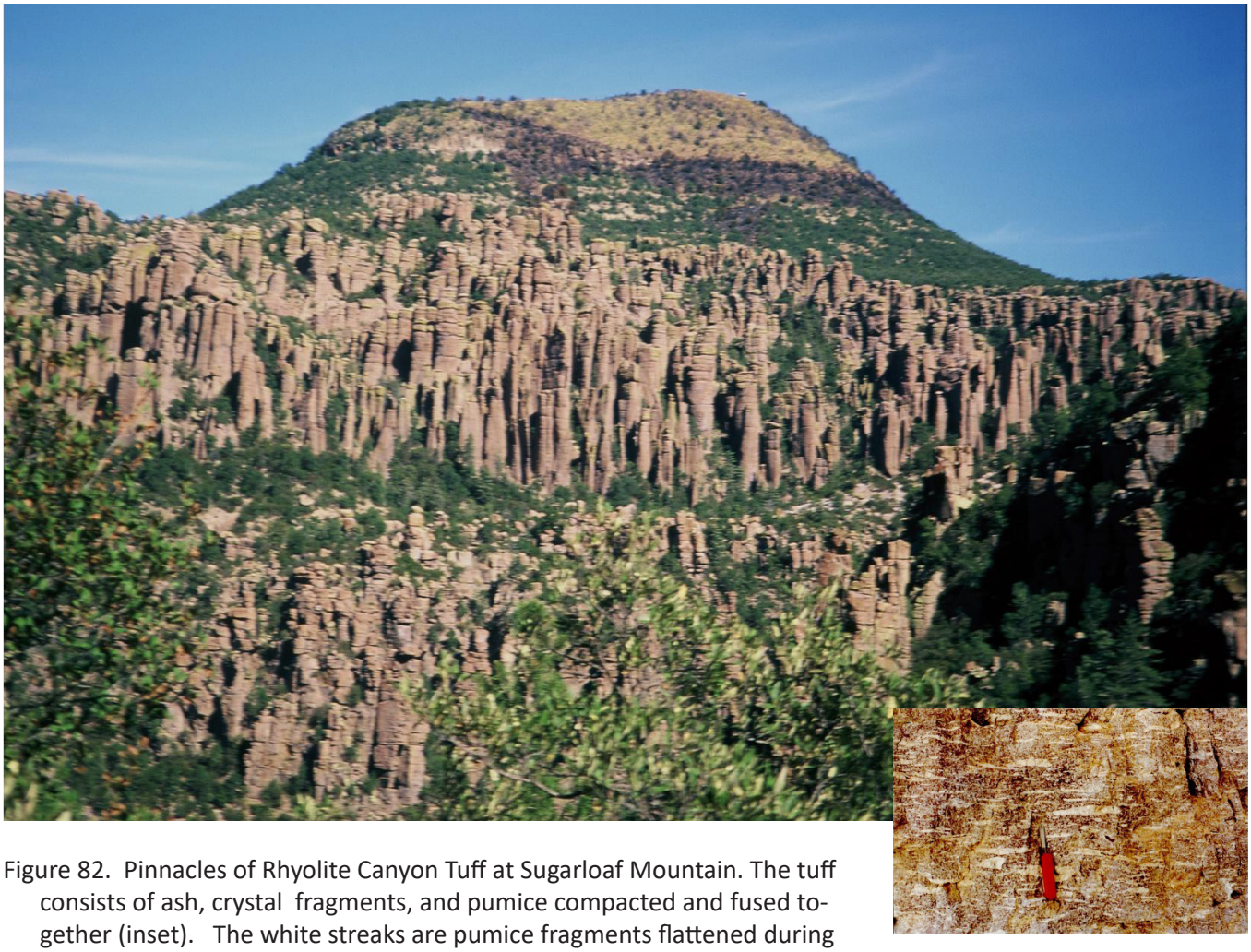


Figure 82. Pinnacles of Rhyolite Canyon Tuff at Sugarloaf Mountain. The tuff consists of ash, crystal fragments, and pumice compacted and fused together (inset). The white streaks are pumice fragments flattened during compaction. The dark-colored rock in the mesa is a remnant of a dacite flow.

The eastern escarpment of the Chiricahua Mountains in the Portal and Cave Creek Canyon area is geologically interesting and offers spectacular scenery. The canyons on this side of the range are deeper than those on the western side. This is because the San Simon Valley has been down-faulted about 1000 ft (300 m) lower than the Sulphur Springs Valley and streams down-cut their canyons to the elevations where they empty into their respective basins.

Rhyolite lavas, pyroclastic flow deposits from nuées ardentes , dacite lavas and other volcanic rocks exposed along this side of the range (Figure 83) are from the Portal caldera, which pre-dates the Turkey Creek Caldera of Chiricahua National Monument area. Cave Creek Canyon is named for the numerous alcoves weathered into the relatively soft volcanic rocks in the cliffs along the canyon (Figure 84).

Ten mi (16 km) north of Portal along this side of the range, faulting has exposed a thick sequence of Paleozoic sedimentary rocks, which can be easily accessed at Harris Mountain (Figure 85, 86). These sedimentary rocks and Proterozoic granodiorite are some of the rocks that underlie the great pile of volcanic rocks produced during the Tertiary eruptions of the Turkey Creek and Portal Calderas. Faulting has thrust these rocks from where they were deposited and juxtaposed some with much older Proterozoic granodiorite.

A similar sequence of sedimentary and igneous rocks along the northern margin of the range have been tilted and broken into elongated slices by movement along the Apache Pass Fault (Figures 87-91). Stream erosion of softer layers has etched a landscape of narrow ridges and valleys that follow the course of the fault. Movement along this and other faults has juxtaposed rocks of vastly different ages. There are similar exposures of faulted

sedimentary and igneous rocks in the southern part of the Chiricahua Mountains. Fort Bowie was situated to guard Apache Spring and Apache Pass, a strategic corridor connecting the Sulphur Springs and San Simon Valleys.

Figure 83. Silver Peak area, near Portal, is composed of volcanic rocks erupted from the Portal caldera: 1=rhyolite lava, 2=pyroclastic flow deposit, 3=dacite lava. The yellow line is a fault; arrows indicate direction of bedrock movement along the fault (after Pallister, 1989).

Figure 84. Cave Creek Canyon is named for the numerous alcoves weathered into volcanic tuff.

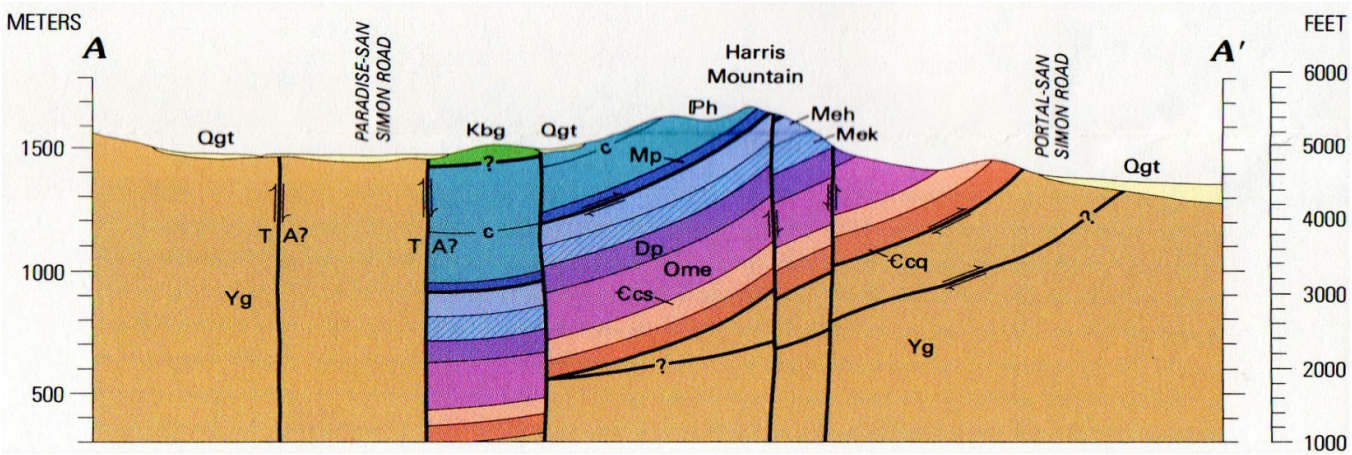
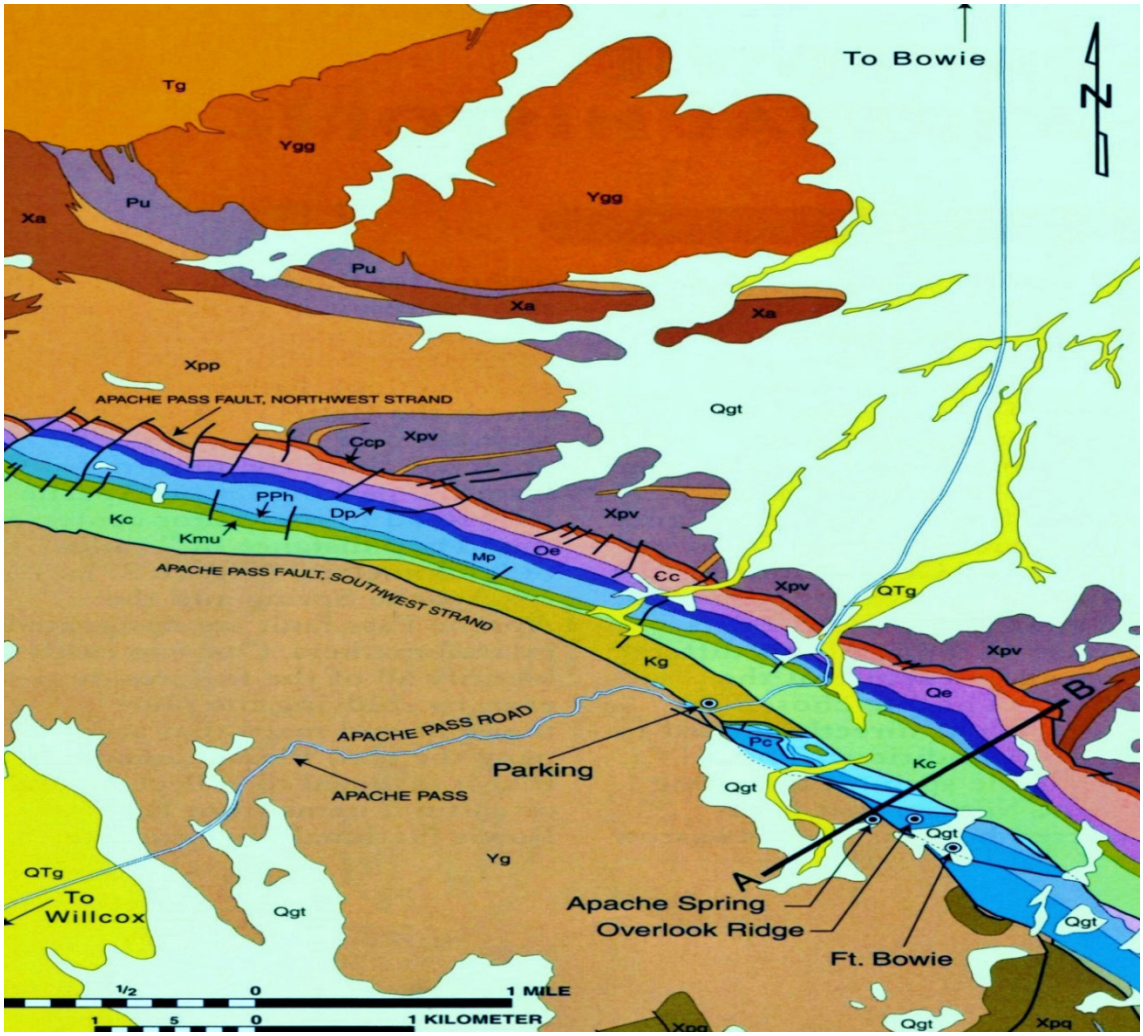


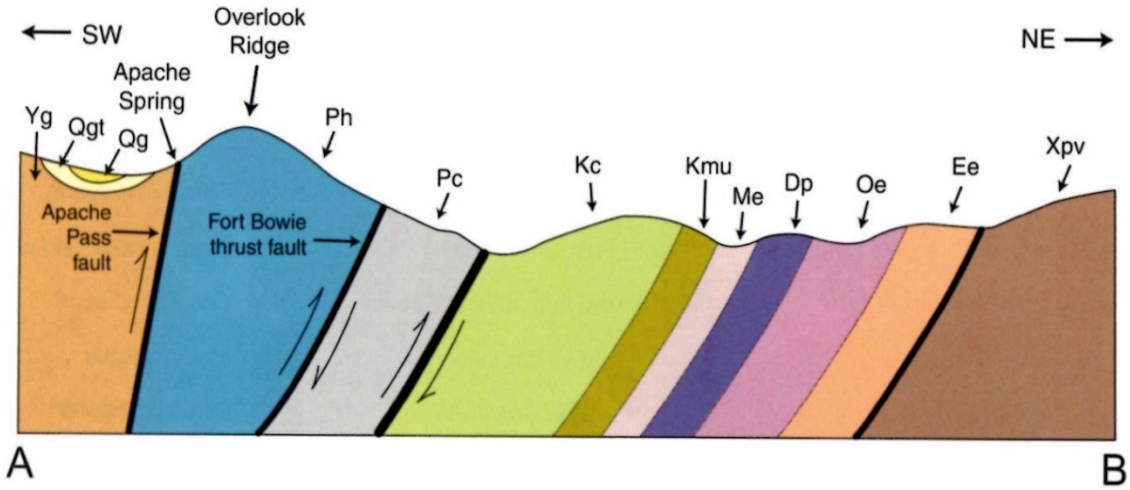
Figure 85. Geologic cross-section of the Harris Mountain area, about 10 mi (16 km) north of Portal. Yg=Proterozoic granodiorite, Ph=Horquilla Limestone (Permian and Pennsylvanian), ꞒEcq=Coronado Sandstone (quartzite)(Cambrian), Ꞓcs=Coronado Sandstone (sandstone-siltstone)(Cambrian), Ome=Montoya Group and El Paso Formation (Ordovician), Dp=Portal Formation (Devonian), Mek=Escabrosa Limestone, lower member (Mississippian), Meh= Escabrosa Limestone, upper member (Mississippian), Mp=Paradise Formation (Mississippian), Kbg=Glance Conglomerate of the Bisbee Formation (Cretaceous), Qgt= Pleistocene gravel and sand. Solid lines with arrows are faults (modified from Drewes, 1982).

Figure 86. Oblique satellite image of Harris Mountain (Courtesy of Google Earth).

Figure 87. Satellite image of upturned sedimentary and igneous rocks along the Apache Pass Fault. A-B is the geologic cross-section in Figures 89 and 90. Fort Bowie is at the arrow. (courtesy of Google Earth).

Figure 88. Hogbacks of limestone along the Apache Pass Fault, Apache Pass Road.

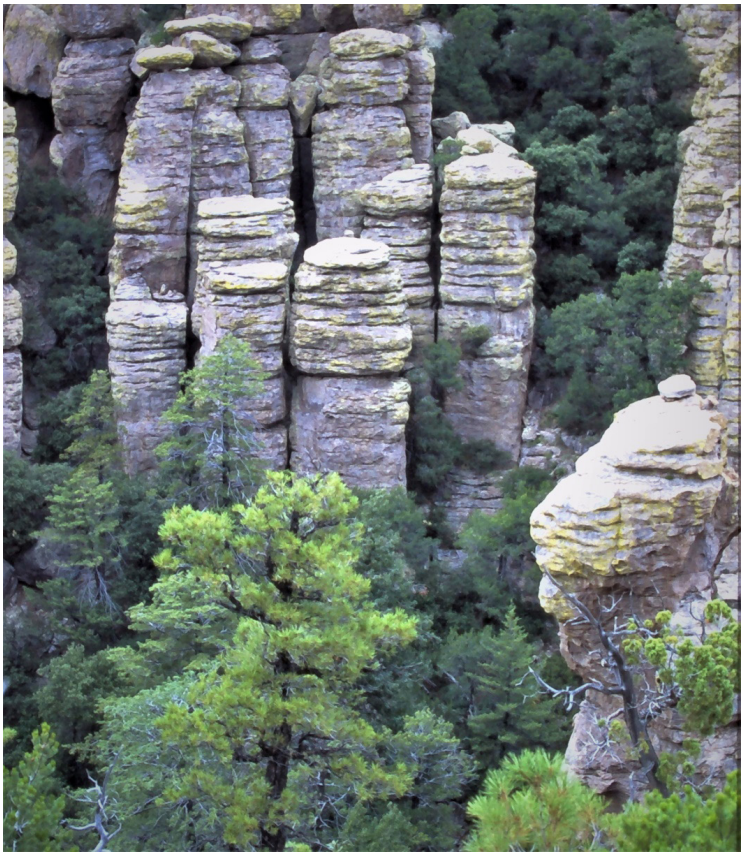




Fgures 89 & 90. Geologic map and A-B cross-section of the Apache Pass Fault near Fort Bowie. Rocks exposed along cross-section A-B are: Yg=Rattlesnake Point Granite, Ph=Horquilla Limestone, Pc=Colima Limestone, Kc=Cintura Formation, Kmu=Mural Limestone, Me=Escabrosa Limestone, Dp=Portal Formation, Oe=El Paso Formation, Ee=Coronado Sandstone, Xpv=metavolcanic rocks (modified from Drewes, 1984.)

Figure 91. Deformed layers of sedimentary rocks along the Apache Pass Fault north of Fort Bowie.

Figure 92. Left and following three images illustrate, slot canyons developed along joints, Chiricahua National Monument: upper left in Heart of Rocks; upper right and lower left, deep shade and vertical walls impedes the establishment of plants; lower right, joints and horizontal ribs.



Mule Mountains

Recommended access. Highway 80 crosses the Mule Mountains and offers the best access to the most significant geologic features in the range.

The Mule Mountains (Figure 93) are a comparatively small range (7370 ft [2246 m] in elevation and about 6 mi [9.65 km] wide and 20 mi [32 km] long) but have yielded considerable copper, lead, zinc, gold, and silver. The metal ores were extracted by open pit and underground mining between 1874 and 1975. Tourism now centers on the attractive mining town of Bisbe; the principal economic activity locally.

The Proterozoic (1650 million years) Pinal Schist is the basement rock for the Mule Mountains, as it is for most of southeastern Arizona. There is a time gap of over 1000 million years that is not represented by rock between the Pinal Schist and the overlying 5000 ft (1524 m) of Paleozoic-age sedimentary rocks. These sedimentary rocks include the Cambrian Bolsa Quartzite and Abrigo Limestone, the Devonian Martin Limestone, the Cretaceous Mural Limestones, the Mississippian Escabrosa Limestone, and the lower Pennsylvanian Naco Group (Figure 94).

About 180 million years ago these Paleozoic sedimentary rocks were intruded by magma that cooled to form the Juniper Flat Granite north and west of the present town of Bisbee. About the same time a second intrusion of magma cooled to form the Sacramento Stock south of Bisbee. This intrusion invaded and shattered the Paleozoic quartzite and limestone. The shattered rock is called breccia. Episodes of mineralization by hot, acidic, mineral-bearing solutions accompanied this intrusion and deposited lead, zinc, copper, gold, silver, and iron in this breccia and the limestones adjacent to the stock (Figure 95). Most of the mineral wealth of the Mule Mountains came from the mines of Sacramento Hill and the Lavender Pit (Figures 96, 97, 98) that were developed in breccia and altered limestone associated with the emplacement of the Sacramento Stock.

Uplift of the area re-activated the Dividend Fault, which was mineralized by a later intrusion. Rocks southwest of the fault were dropped several thousand feet and cut with canyons that became filled with sediment worn from rocks northeast of the fault. These sediments are the early Cretaceous Glance Conglomerate, which were then covered by the Cretaceous sediments of the Bisbee Group. Basin and Range faulting between 15 and 5 million years ago fractured these Cretaceous sediments, which have been stripped by erosion from the western half of the Sacramento Stock mineralized zone.

The removal of these Cretaceous sediments permitted downward percolating groundwater to increase the metal content of subsurface ore by a process called supergene enrichment. Circulating groundwater oxidizes and leaches metals from surface ores and deposits them in and enriching deeper ores at the base of the oxidized zone. Some supergene ores in the Sacramento Hill area were enriched to 23% copper. Most of the ore in this area averages between 0.4 and 0.7% copper. Valuable deposits of metals also occur where acidic hydrothermal fluids dissolved limestone and replaced it with skarn, a calcium-silica ore containing a wide variety of minerals.

Mule Gulch and other streams have cut canyons into the zone of shattered rock along the Dividend Fault. These canyons divide the range into a northeastern section of Cretaceous rocks and a southwestern section of Paleozoic and Proterozoic rocks. The latter rocks were mineralized by metal-bearing solutions that accompanied the intrusion of the Juniper Flat Granite and the Sacramento Stock. Sediment eroded from the Mule Mountains has accumulated as alluvial fans and bajadas in the San Pedro Valley to the west and the Sulphur Springs Valley to the east. The Escabrosa Limestone and other erosion resistant limestones form high cliffs in many parts of the Mule Mountains (Figure 99).

Figure 93. Satellite image of the Mule Mountains (courtesy of Google Earth).

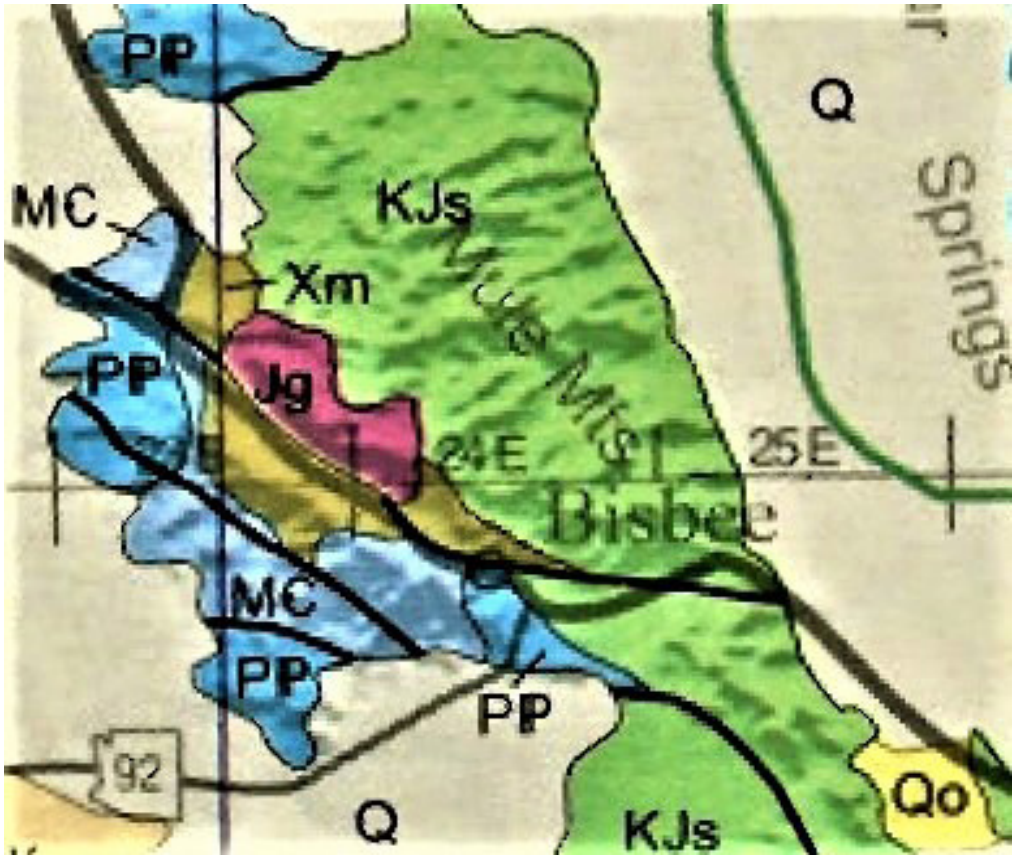


Figure 94. Geologic map of the Mule Mountains: my=millions of years ago; Xm=early Proterozoic metamorphic rocks, 1600-1800 my; M€=Mississippian, Devonian, and Cambrian sedimentary rocks, 330-540 my; PP=Permian to Pennsylvanian sedimentary rocks, 280-310 my; Jurassic granitic rocks, 160-200 my); KJs=Cretaceous to upper Jurassic sedimentary rocks, 80-160 my; Qo=early Pleistocene to late Pliocene surficial deposits, 0.75-3 my; Q=Quaternary surficial deposits, 0-2 my; heavy black lines are faults (Arizona Geological Survey, 2000).

Figure 95. Chemical alteration along fractures by hydrothermal solutions (Courtesy of Roger N. Weller).

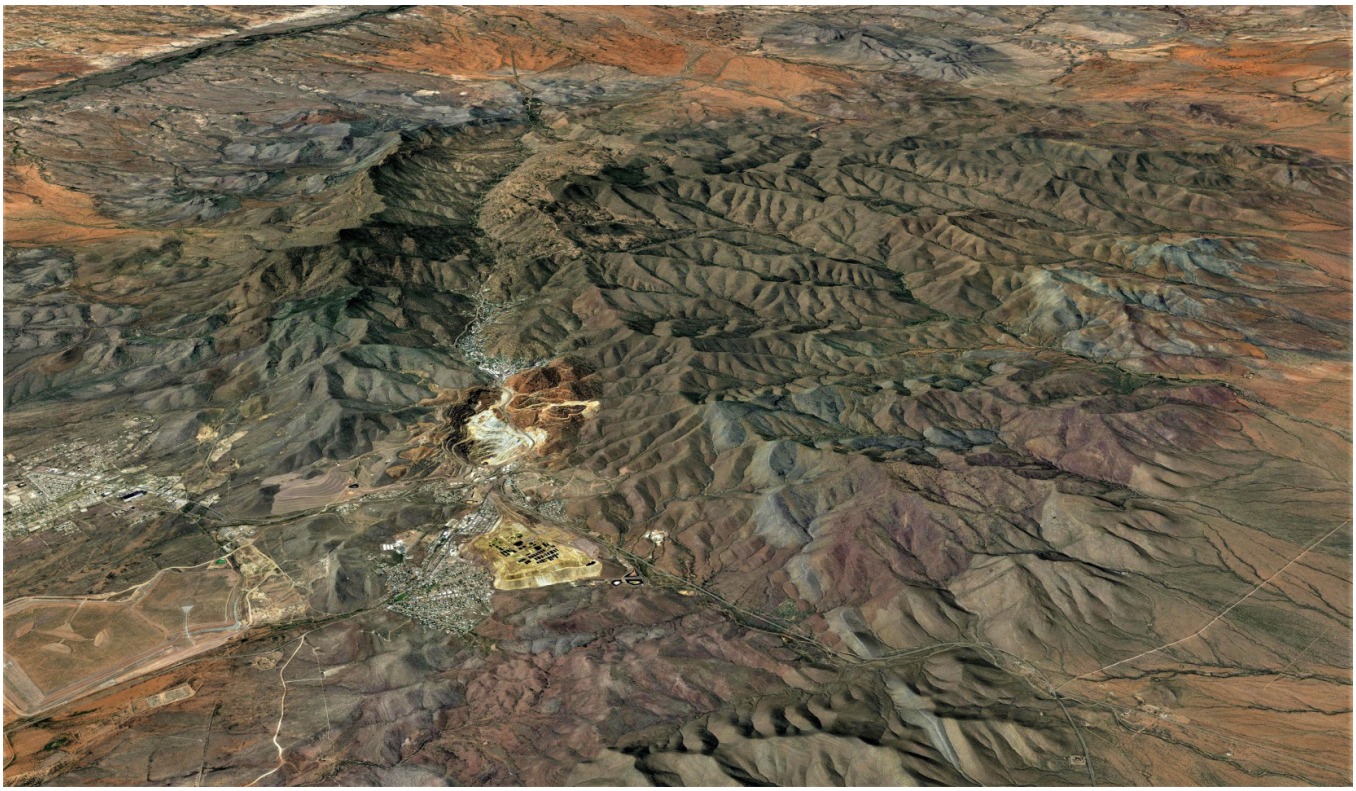


Figure 96. Oblique image of the Mule Mountains: red line=Dividend Fault; A=Sacramento Hill and the Lavender Pit. Rocks to the southwest of the Dividend Fault are mineralized Paleozoic and Proterozic rocks. Those to the northeast are Cretaceous sedimentary rocks overlying much older Proterozoic granites and schist (courtesy of Google Earth).

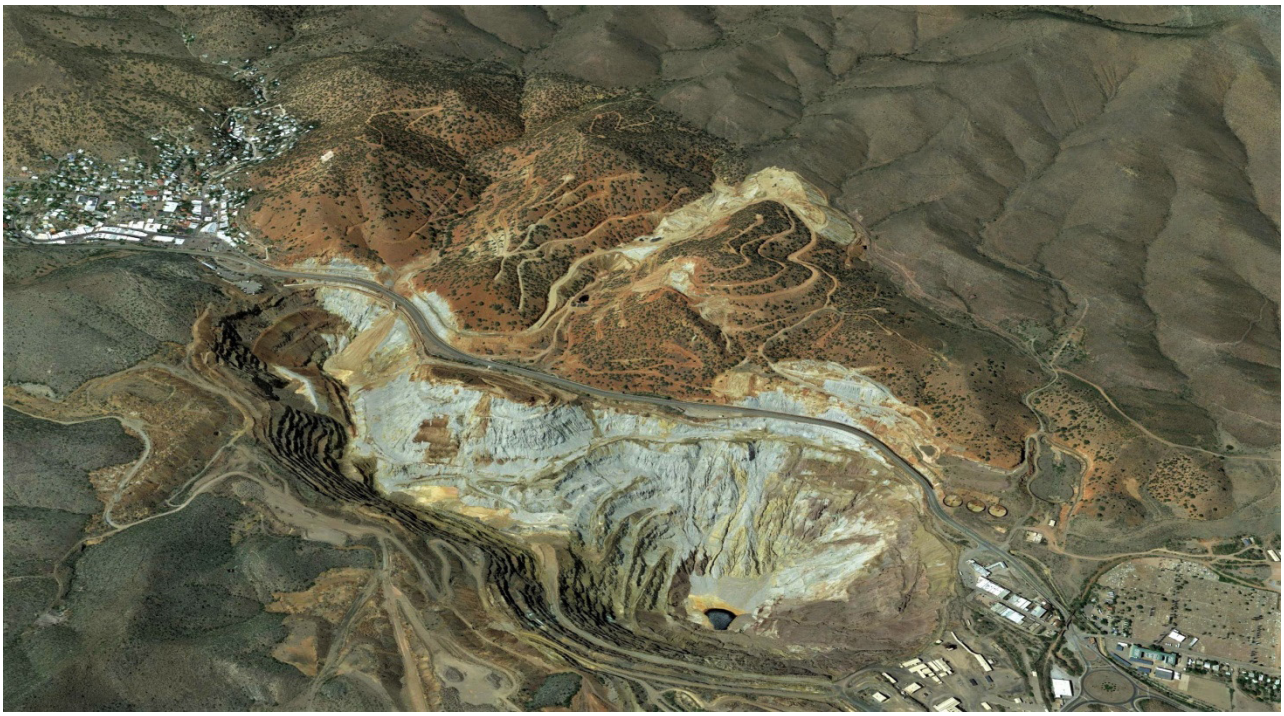


Figure 97. Oblique satellite image of the Lavender Pit, Sacramento Hill, and Bisbee. The orange-colored rock, called “iron hat” by prospectors, is due to oxidized iron (courtesy of Google Earth).

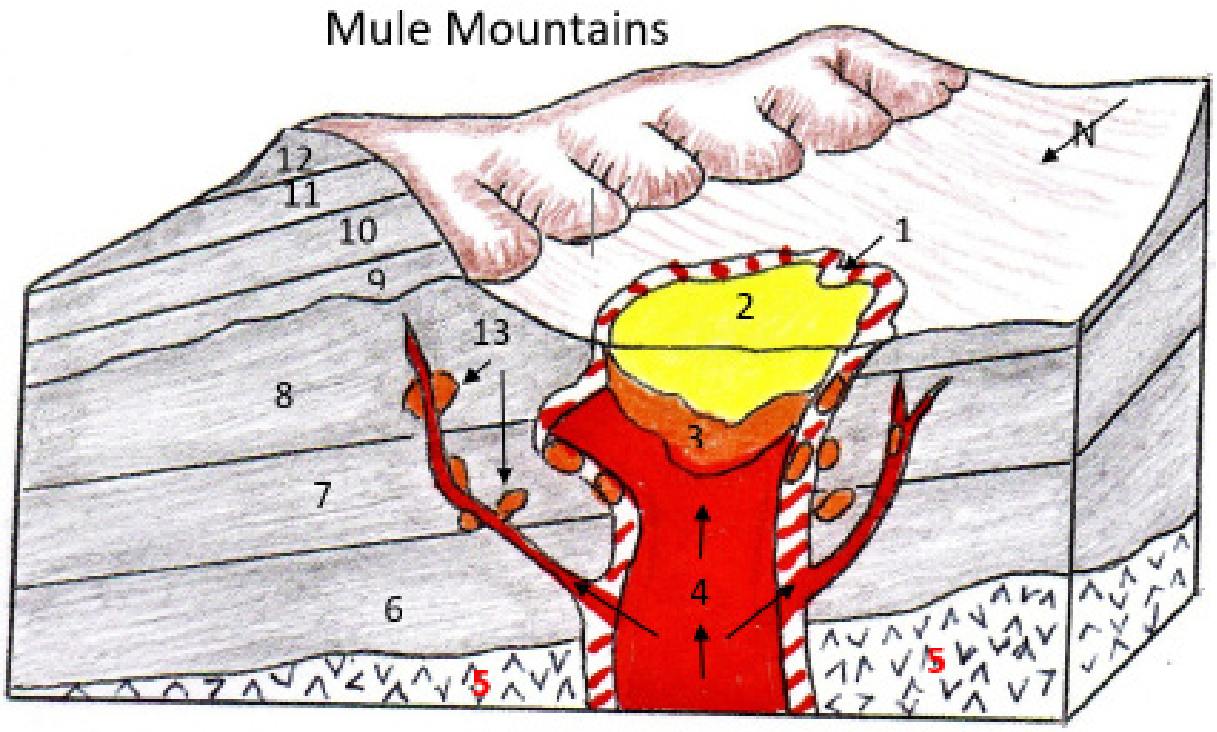


Figure 98. Block diagram of the Sacramento Hill and Lavender Pit area, Mule Mountains. 1=breccia from emplacement of pre-Cretaceous granitic intrusion (4); 2=granitic intrusion leached of metals; 3=secondary enriched ore; 4=pre-Cretaceous granitic intrusion; 5=Proterozoic granite; 6=Bolsa Quartzite, Abrigo Limestone, and Martin Limestone; 7=Escabrosa Limestone; 8=Naco Limestone; 9=Glance Conglomerate; 10=Morita Formation; 11=Mural Limestone; 12=Cintura Formation; 13=ore bodies associated with dikes (based on information from Bisbee Mining and Minerals).

Figure 99. The erosion resistant Escabrosa Limestone forms high cliffs (Courtesy of Roger N. Weller).

Huachuca Mountains

Recommended Access. From Sierra Vista, follow Highway 90 east and Highway 92 south 6 mi (9.66 km) to Ramsey Canyon Road, which leads to the Nature Conservancy's Ramsey Canyon Preserve. There is a fee to enter the Preserve. Brown Canyon, a second option, can be reached by following Ramsey Canyon Road from Highway 92 for 2.1 mi (3.38 km) to a wire gate on the right (north) side of the road. Park here (adds another 0.4 mile to the hike) and follow the two-track road north and west into Brown Canyon where it becomes the Brown Canyon Trail. There is no marker or sign here. A third option is to follow Highway 92 past the turn-off for Ramsey Canyon to Coronado National Memorial.

Reaching an elevation of 9446 ft (2879 m) at Miller Peak, the Huachuca Mountains (Figure 100) offer cool conifer forests along the crest of the range and beautiful riparian forests in Ramsey, Brown, and other deep canyons cut into the steep slopes of the range. The Fort Huachuca Military Reservation limits civilian access to much of the northern Huachuca Mountains, but most of the southern part of the range is public land managed by the U.S. Forest Service and the National Park Service.

The Huachuca Mountains are geologically complex (Figure 101). Repeated folding and faulting between 150 million (late Jurassic time) and 5 million years ago have deformed most of the rocks in the range. In the late Jurassic, extension of the crustal rocks of southeastern Arizona created basins in which sedimentary rocks were formed. In what is now the southeastern Huachuca Mountains magma (molten rock) cooled below the surface to form granite or exploded onto the surface forming a large caldera. Hot, acidic solutions that accompanied the magma deposited copper, gold, lead, silver and other metals in the host rocks, especially limestones.

About 80 million years ago, at the start of the Laramide period of mountain building in the American West, the continental crust in southeastern Arizona was compressed. In many places this compression shoved older rocks over younger rocks along thrust faults. Sedimentary rocks were extruded out of the basins in which they were deposited and deformed into highlands. Many rocks were broken into slivers and slid miles from where they formed (Figures 102, 103). The Glance Conglomerate, for example, was overturned by intense folding. Pebbles within the conglomerate were stretched by stress. A thick slice of this 145 million year-old conglomerate was thrust into the 1400 to 1600 year-old Proterozoic granite. The Jurassic-age granite and volcanic caldera in the southern part of the range were highly fractured by faults. Renewed continental extension beginning about 25 million years ago moved rocks along low-angle detachment faults. Continued stretching broke the rocks along high-angle Basin and Range faults, uplifting the Huachuca Mountains and down-dropping the San Pedro basin to the east. Episodic movement continued along the Foothills Fault along the eastern margin of the range until about 2 million years ago. Between 3 and 5 million years ago, shallow lakes pooled in the closed San Pedro basin. As the San Pedro River integrated the drainage of the basin with the Gila and Colorado Rivers, its tributaries and those of other major streams cut deeply into alluvial fans and bajadas along the margins of the Huachuca Mountains. The most impressive of these deeply eroded alluvial fans are along the southwestern margin of the range (Figure 104). The soils of the alluvial fan surfaces are reddish-orange from oxidized iron and may be as much as 1 million years old.

The rocks that make up the Huachuca Mountains are presented in Figure 101. Proterozoic granite is the oldest exposed rock and forms most of the eastern part of the range. This granite and most of the Cambrian, Paleozoic, and Mesozoic rocks have been deformed by folding and faulting during the above periods of extension and compression. The major rock units are separated by northwest-southeast trending Laramide faults that have been re-activated a number of times by regional stress. Many streams in the Huachuca Mountains are aligned along these faults (Figure 105).

As was the case with many mountain ranges of southeastern Arizona that contain rocks mineralized by Jurassic-age hydrothermal solutions, the lure of bonanzas attracted prospectors and miners to the Huachuca Mountains during the late 1800s. Mines have produced large amounts of silver, tungsten, copper, gold, and lead.

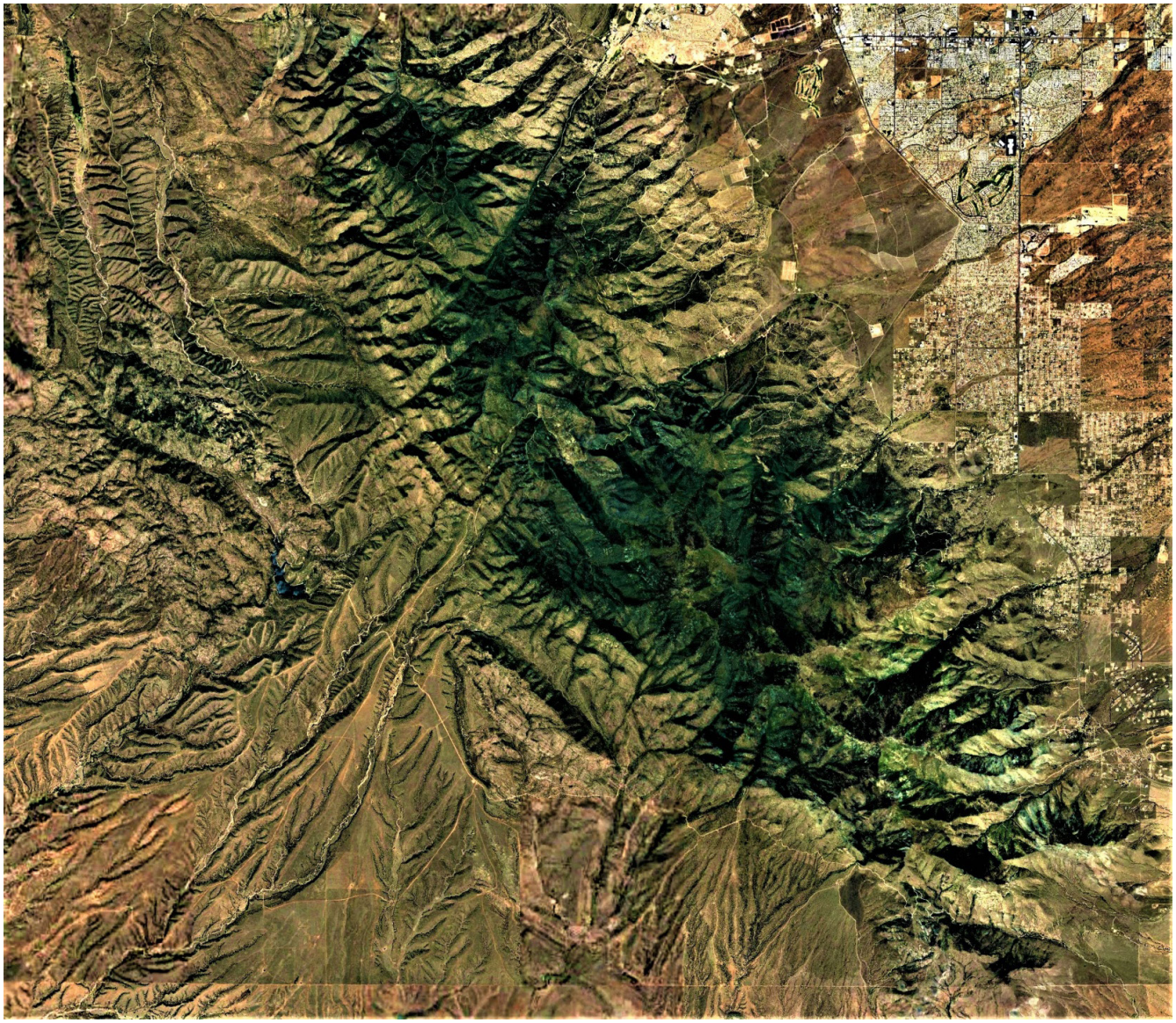


Figure 100. Satellite image of the Huachuca Mountains (Courtesy of Google Earth).

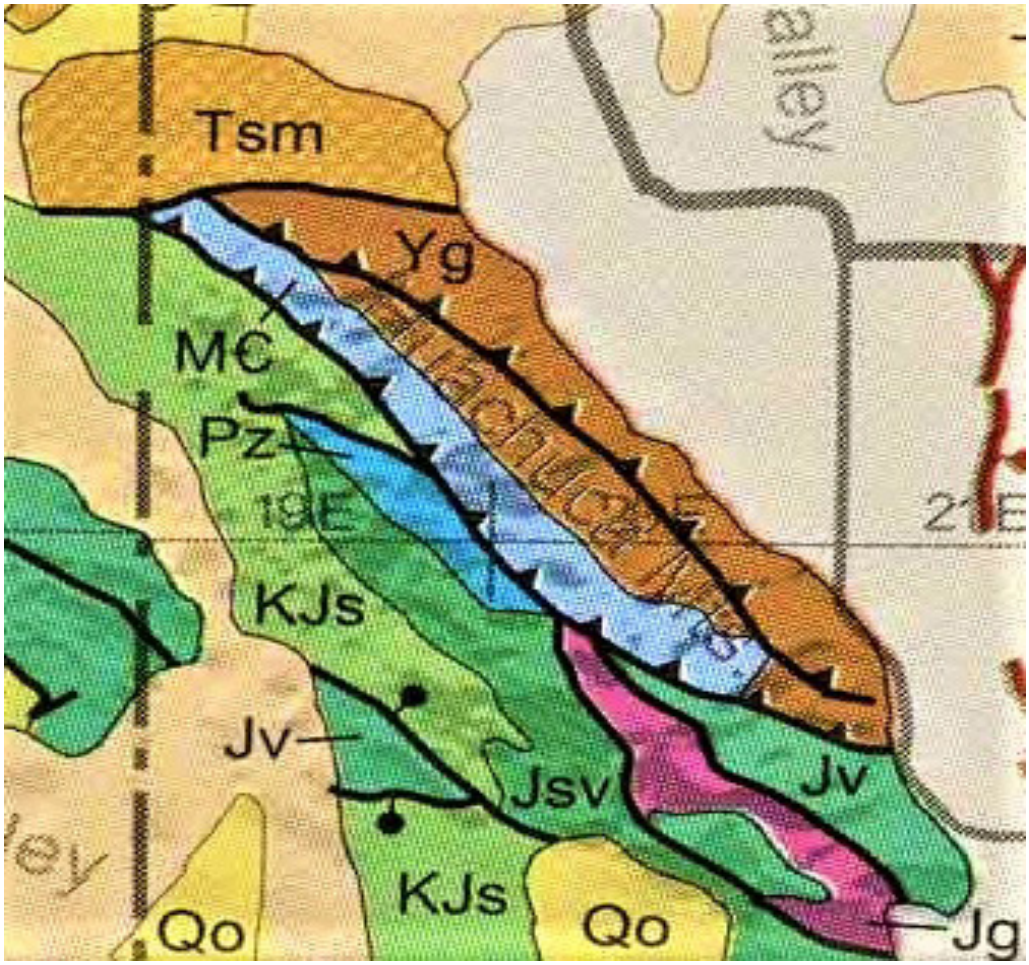


Figure 101. Geologic map of the Huachuca Mountains; Q=Quaternary alluvium (0-2 ma); Qo=early Pleistocene surface deposits (0.75-3 ma); Tvy=Pliocene to middle Miocene volcanic rocks (2-12 ma); Tsy=Pliocene to middle Miocene sedimentary rockss (2-16 ma); Tsm=middle Miocene to Oligocene sedimentary rocks (11-32 ma); KJs=Cretaceous to upper Jurassic sedimentary rocks, including the Bisbee Group (80-160 ma); Jsv=Jurassic sedimentary and volcanic rocks (150-170 ma); Jv=Jurassic volcanic rocks (160-200 ma); Jg=Jurassic granitic rocks (160-200 ma); Pz=Paleozoic sedimentary rocks (248-544 ma); MЄ=Mississippian, Devonian, and Cambrian sedimentary rocks, including the Bolsa Quartzite, the Abrigo Formation, the Martin Formation, and the Escabrosa Limestone (330-540 ma); Yg=middle Proterozoic granitic rocks (1400-1450 ma); ma=millions of years ago). Heavy black lines are faults (Arizona Geological Survey, 2000).

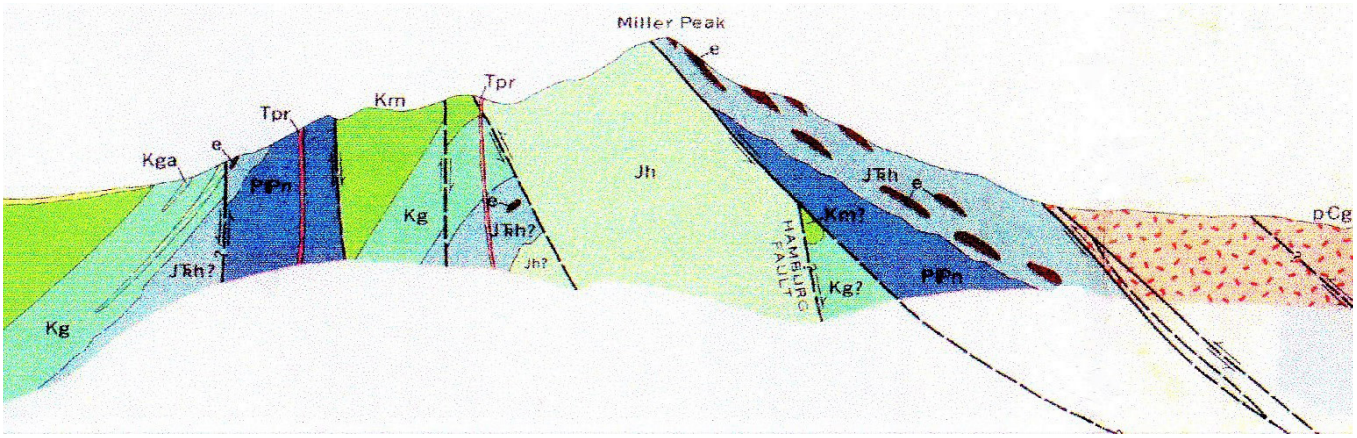


Figure 102 Northeast-southwest geologic cross-section of the Miller Peak area, north of Coronado National Memorial, southern Huachuca Mountain: =Tertiary rhyolite(Tpr); =Cretaceous Glance Conglomerate (Kg, Kga), Morita Formation (Km); Permian Naco Group (PPn); Jurassic Huachuca Quartz Monzonite (Jh) and siliceous volcanic rocks (JTrh) with exotic blocks of Paleozoic sedimentary rocks (e); Proterozoic granite (p€g) (modified from Hayes and Raup, 1968).

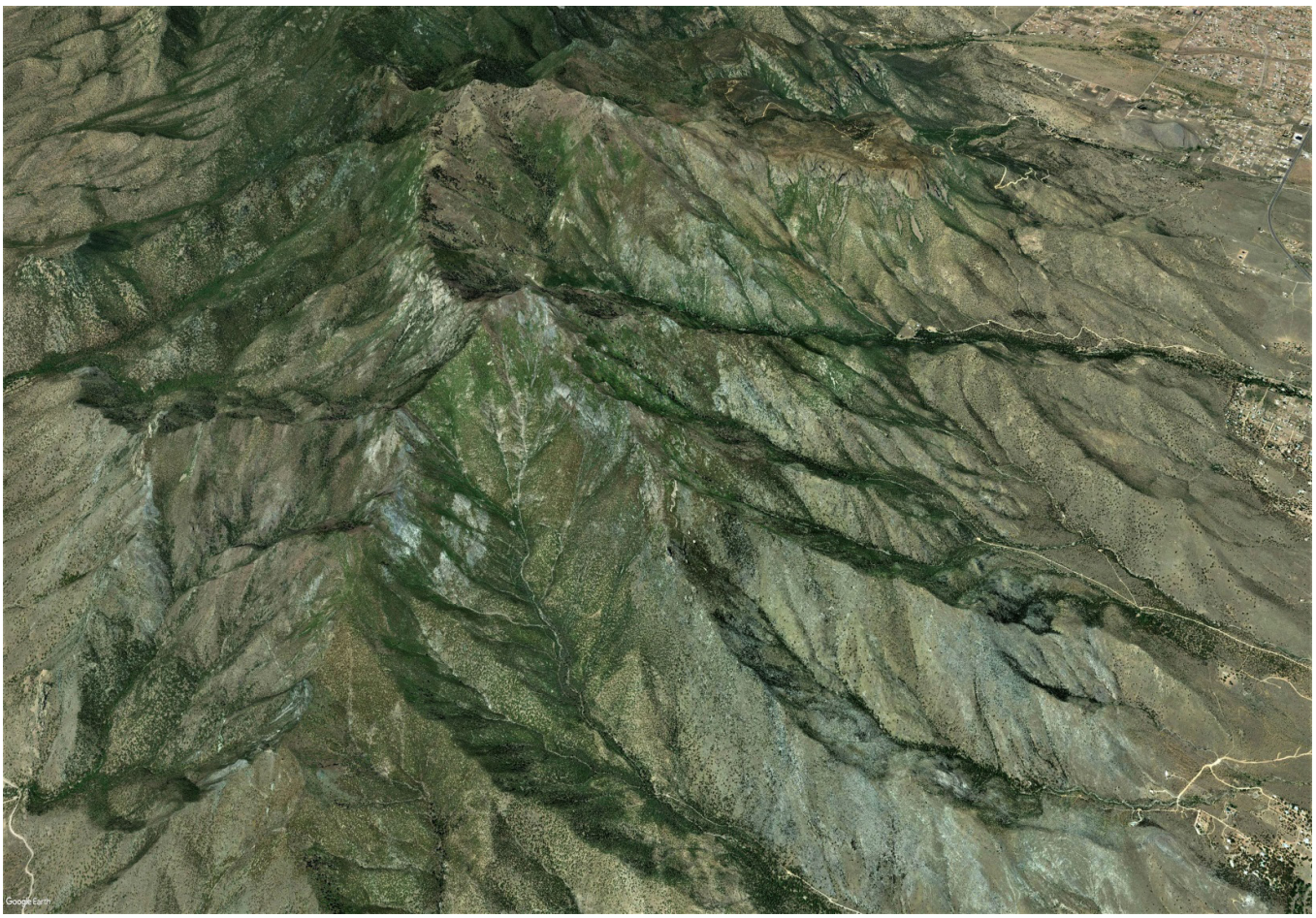


Figure 103. Oblique satellite image of the Miller Peak area, southern Huachuca Mountains (Courtesy of Google Earth).

Figure 104. Oblique satellite image of highly eroded alluvial fans, southwestern Huachuca Mountains (courtesy of Google Earth).

Figure 105. Oblique image of fault aligned stream valley, Huachuca Mountains (Courtesy of Google Earth).

Whetstone Mountains

Recommended Access. Kartchner Caverns State Park offers the best access road to the base of the Whetstone Mountains. From Interstate Highway 10, follow State Highway south for 9 mi (14.5 km) the Park access road. There is an admission fee at the Park.

The Whetstone Mountains are a southwest-tilted fault block range (Figures 106, 107), a geologic structure similar to a number of other Basin and Range mountains in southeastern Arizona. The range is unique in that it contains the most complete stratigraphic section of Pennsylvanian and Permian rocks in the region and an impressive system of limestone caves protected at Kartchner Caverns State Park.

The Proterozoic basement rocks for the range are Pinal Schist intruded by alaskite and quartz monzonite. In the northern part of the Whetstone Mountains the quartz monzonite is faulted into contact with Cretaceous sandstones, conglomerates and shales of the Bisbee Group. The middle part of the range comprises tilted layers of Cambrian Bolsa Quartzite and Abrigo Limestone, Devonian Martin Formation, Mississippian Escabrosa Limestone, Pennsylvanian Black Prince and Horquilla Limestones , and Permian Earp Formation, Colina Limestone, Epitaph and Scherrer Formations, Concha Limestone, and Rainvalley Formation (Figure 108, 109, 110, 112). The erosion resistant limestones and the Bolsa Quartzite form high cliffs in the Whetstone Mountains (Figures 110, 113).

These sedimentary rocks have been invaded by Cretaceous, Tertiary, and Jurassic intrusions of granite. Hydrothermal solutions accompanying these intrusions mineralized the host rocks. Ore containing uranium, tungsten, and fluorite are associated with the quartz monzonite intrusion in the northern part of the range and copper, lead, silver, and gold with the Cretaceous granodiorite in the southern Whetstone Mountains. Rhyolite flows and tuffs were deposited were magma exploded onto the surface.

These rocks represent a diverse succession of depositional environments. The Pinal Schist formed from sand, silt, and clay deposited in the sea by streams eroding a nearby continent. Heat and pressure have metamorphosed these sediments to the extent that they bear little resemblance to the original sedimentary layers. Cambrian quartzite and sandstone record the advance of the sea on a continental margin. The Pennsylvanian and Permian limestones and dolostones were deposited in the shallow sea along continental shelves, and in deep ocean and tidal environments along the edge of a continent. Cretaceous sandstones, shales, conglomerates, and limestones were deposited on stream deltas and in the adjacent shallow sea.

Continental extension of this part of North America, between 12 and 5 million years ago, caused the crustal rocks of southeastern Arizona to break into blocks, separated by new and re-activated, high-angle faults. Some of these crustal blocks subsided as much as 2.4 mi (1.4 km) to form deep basins, such as the San Pedro Valley. High-standing blocks between these basins eroded to form mountains, such as the Whetstone Mountains, which were tilted to the southwest. Streams have cut deep canyons into the range and filled the adjacent basins with thousands of feet of sediment. Fan-shaped deposits of rock debris, called alluvial fans, accumulated where canyons exited the Whetstone Mountains.

Kartchner Caverns, the major tourist attraction in the Whetstone Mountains, are located in a block of Paleozoic rocks separated from the east face of the range by a fault (Figures 108, 111). The caverns developed in the highly faulted Mississippian Escabrosa Limestone. Slightly acidic ground water penetrated the limestone along faults and organic-rich bedding planes and dissolved the adjacent limestone. Over time fault-bound passages and caves caverns enlarged to caverns by solution of the limestone and the collapse of cave and cavern ceilings. David Jagnow's detailed study of Kartchner Caverns revealed that the cavern system first formed at the lower levels of the Escabrosa Limestone and expanded upward along faults by solution and ceiling collapse until it encountered beds strong enough to maintain cavern ceilings. The study of dated bat guano deposits indicates that cavern ceilings have been stable for 50,000 years.

Figure 106. Satellite image of the Whetstone Mountains (courtesy of Google Earth).

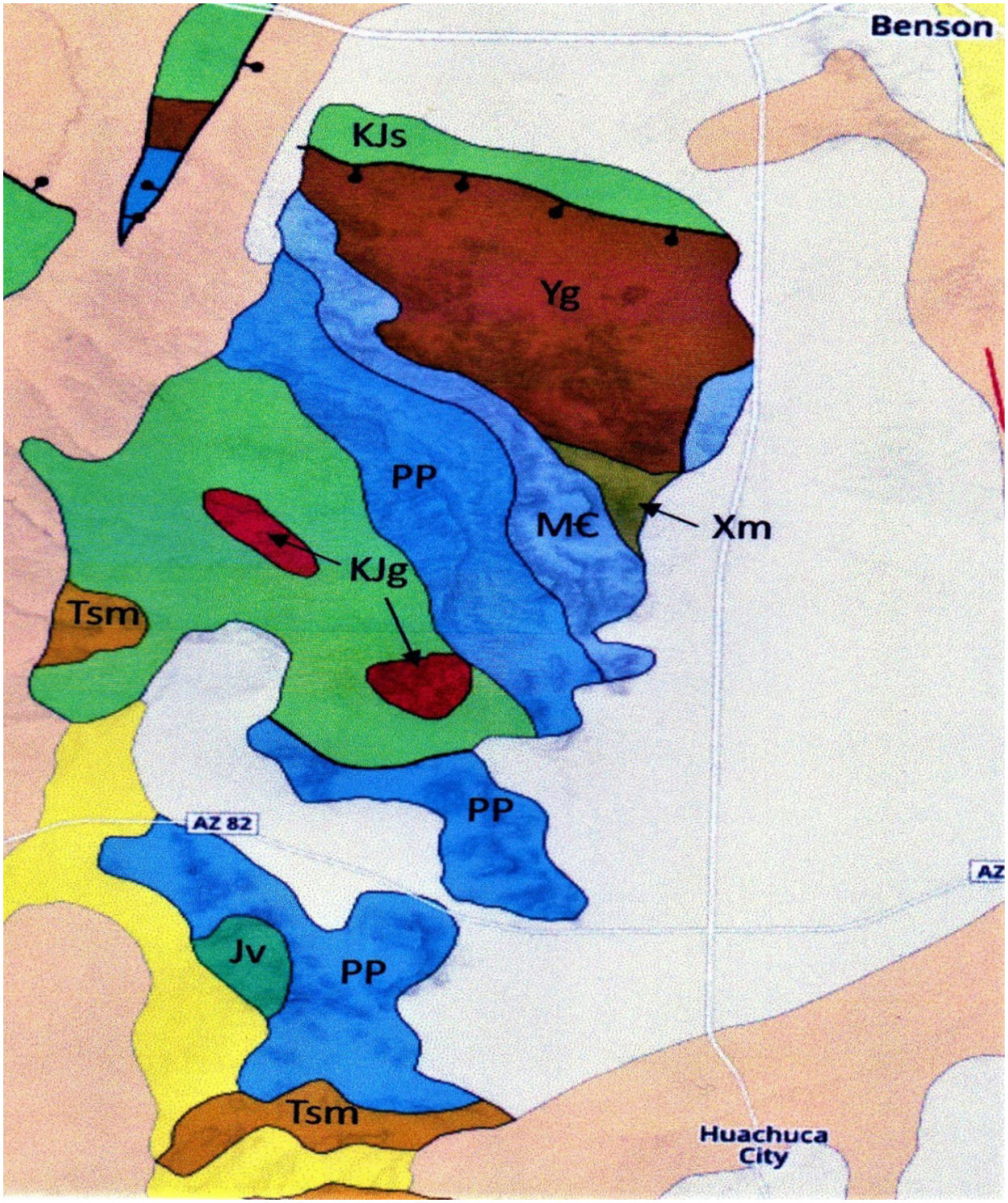


Figure 107 Geologic map of the Whetstone Mountains: KJs=Cretaceous to upper Jurassic sedimentary rocks, including the Bisbee Group, 80-160 m.y.; Yg=middle Proterozoic granitic rocks, 1400-1450 m.y.; M€=Mississippian, Devonian, and Cambrian sedimentary rocks, includes the Bolsa Quartzite, the Abrigo and Martin Formations, and the Escabrosa Limestone, 330-540 m.y.; PP=Permian to Pennsylvanian sedimentary rocks, including the Naco Group, 280-310 m.y.; Tkg=early Tertiary to late Cretaceous granitic rocks, 50-82 m.y ; Tsm=Tertiary sedimentary rocks, 11-32 m.y.; Jv=Jurassic volcanic rocks, 160-200 m.y.; Xm=early Proterozoic metamorphic rocks, 1600-1800 m.y.; m.y.=million years ago (modified from Arizona Geological Survey, 2000).

Figure 108. Oblique aerial image of the Whetstone Mountains. Kartchner Caverns is developed in a block of Escabrosa Limestone, separated from the mountains front by a fault (courtesy of Google Earth).

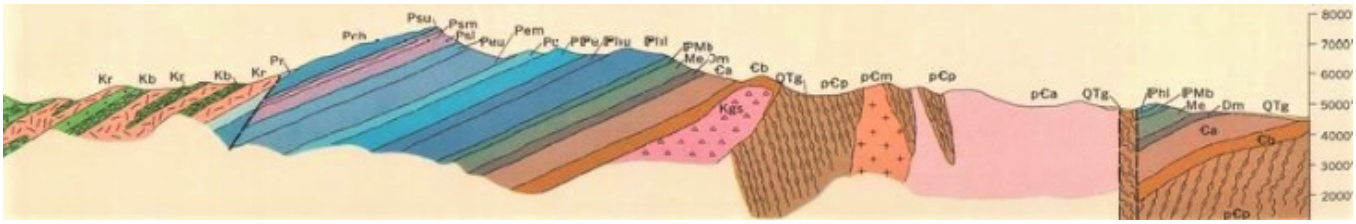


Figure 109. Northeast-southwest geologic cross-section of the Whetstone Mountains. A great block of Cretaceous (Kb), Pennsylvanian-Permian (Prh thru Pmb), Mississippian (Me), Devonian (Dm), Cambrian (€a,€b) sedimentary rocks and Proterozoic metamorphic rocks (p€p) have been tilted and invaded by Proterozoic (p€m, p€a) and Creatceous (Kgs,Kr) igneous intrusions (Creasey, 1967).

Figure 110. Tilted limestones along the eastern Whetstone Mountains (Courtesy of Gary N. Weller).

Figure 111. Big Room, Kartchner Caverns (Courtesy of Mike Lewis, https://commons.wikimedia.org/wiki/File:Kartchner_Big_Room.jpg/filelinks).

Figure 112. Oblique satellite image of highly deformed, once-horizontal limestone beds, central Whetstone Mountains (Courtesy of Google Earth).

Figure 113. The Bolsa Quartzite is very resistant to erosion and forms high cliffs in the Whetstone, Huachuca, and other ranges of southeastern Arizona (Courtesy of Roger N. Weller).

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Inside back cover: Cat Mountain Tuff and Saguaros, Gates Pass, Tucson Mountains.

Outside back cover: Pinnacles of Rhyolite Canon Tuff, Chiricahua National Monument.