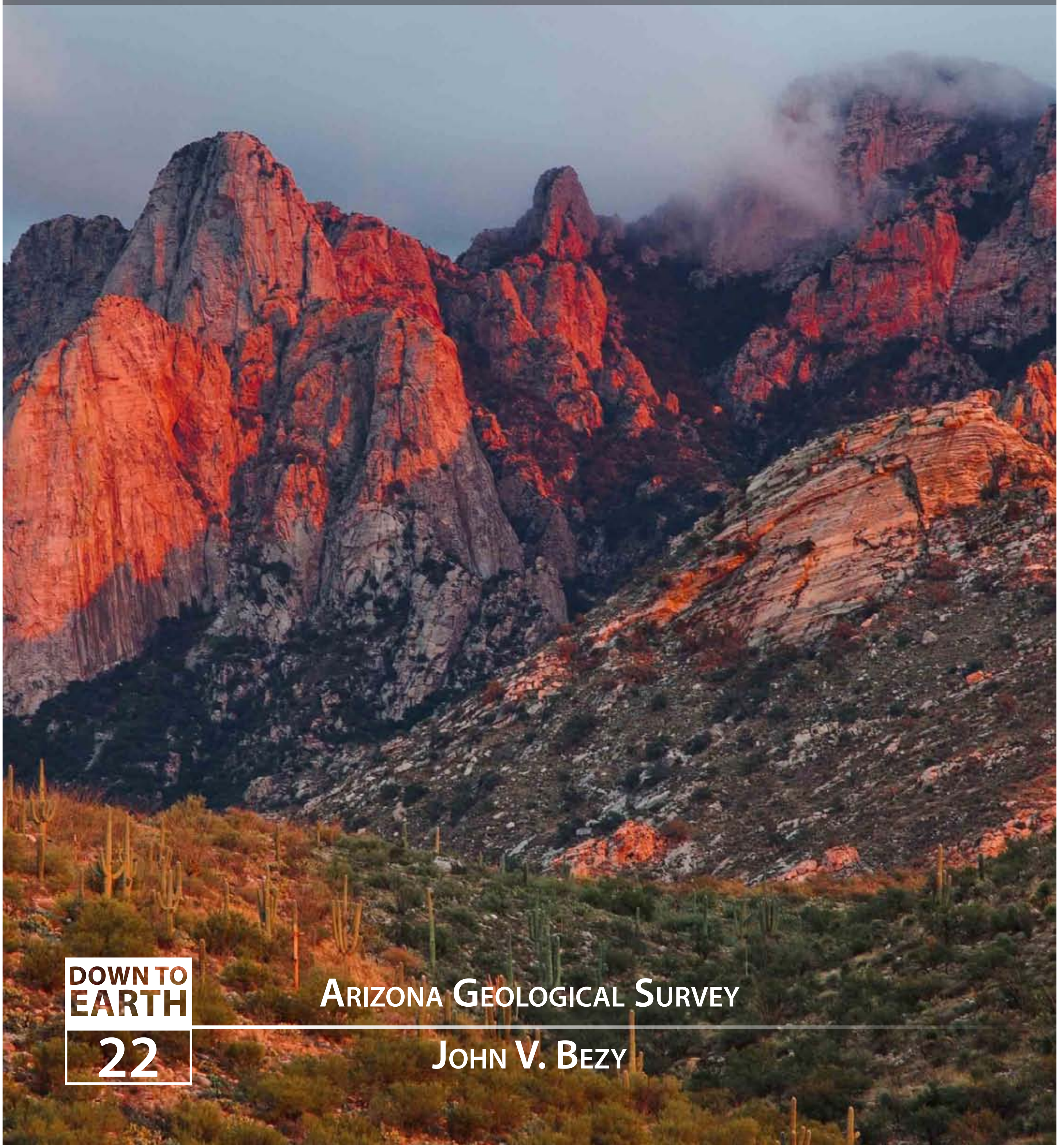
A GUIDE TO THE GEOLOGY OF THE

SANTA CATALINA MOUNTAINS, ARIZONA:

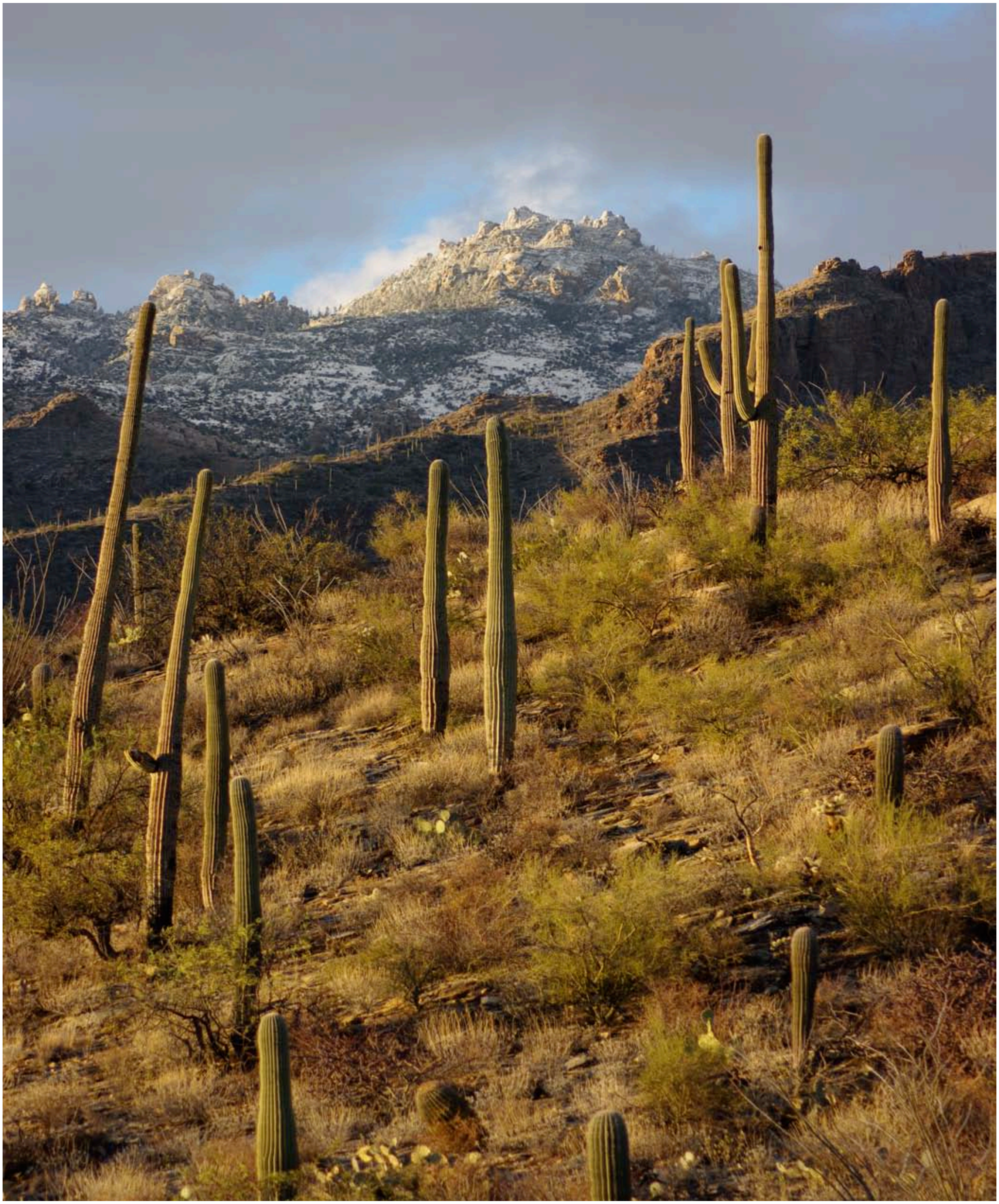
THE GEOLOGY AND LIFE ZONES OF A MADREAN SKY ISLAND



DOWN TO EARTH
22

ARIZONA GEOLOGICAL SURVEY

JOHN V. BEZY



Inside front cover. Sabino Canyon, 30 December 2010. (Megan McCormick, flickr.com (CC BY 2.0).

A Guide to the Geology of the Santa Catalina Mountains, Arizona:
The Geology and Life Zones of a Madrean Sky Island

John V. Bezy

Arizona Geological Survey
Down-to-Earth 22

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Table of Contents

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This publication would not have been possible without the professional support of Dr. M. Lee Allison, Director, Arizona Geological Survey and State Geologist.

We dedicate this volume to the many geologists, biologists, botanists, and ecologists whose combined efforts have given us a greater understanding of our beautiful Santa Catalina Mountains

INTRODUCTION

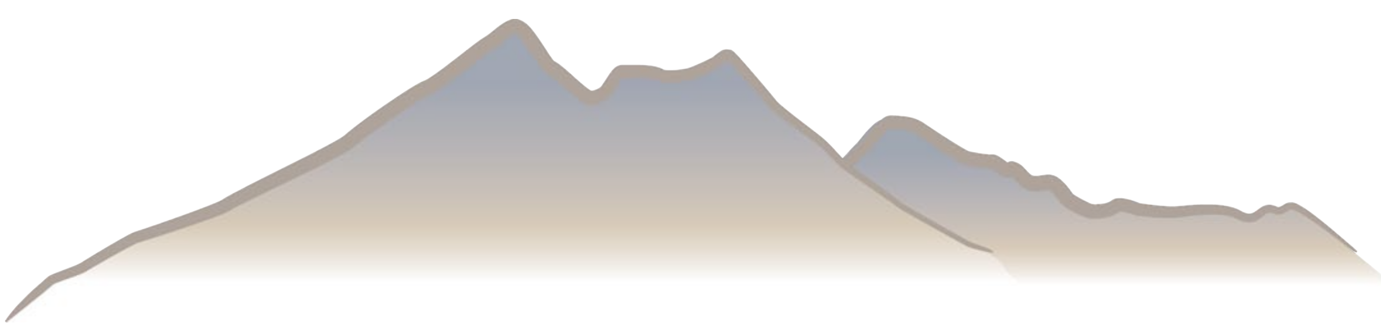
Natural landscapes have distinctive personalities. Each is the product of the interplay of geology, climate, vegetation, time, and often, human activities. The landscapes that form the Santa Catalina Mountains of southeastern Arizona give that range a unique personality like no other in the American Southwest.

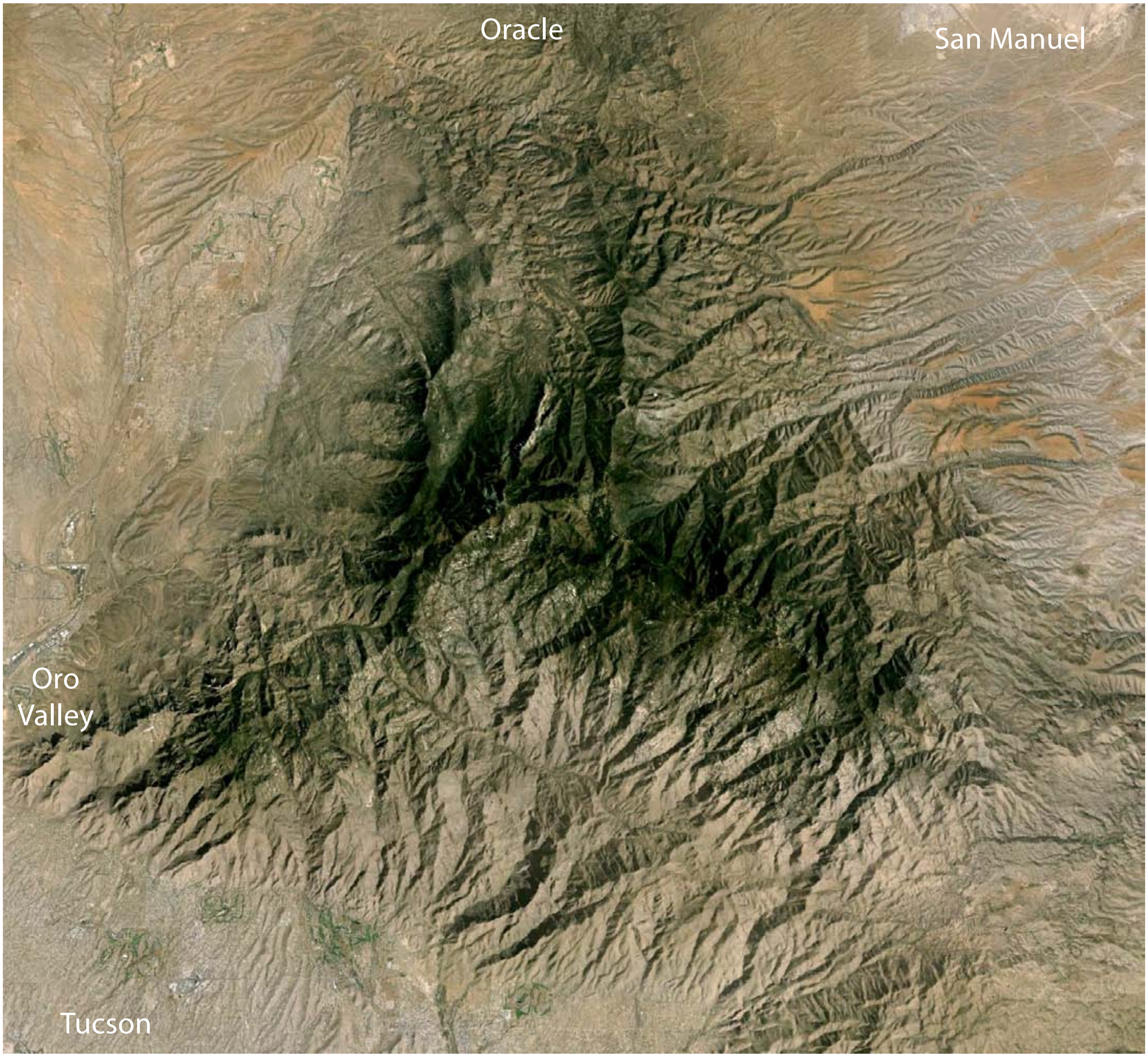
Rising as a great mountain island to over 9000 feet in elevation at their summit, Mount Lemmon, the Santa Catalina Mountains are the greatest expanse of high country within the Sonoran Desert (Map A). An unusual dome-like profile (Figure 1) sets it apart from the numerous, steep, sharp-crested mountain ranges in the region. This distinctive profile is a legacy of the range's remarkable geologic history and the structure of its bedrock. Formed miles deep within Earth's crust before being exhumed, this ancient structure has guided surface weathering and erosion for millions of years. The result is a mosaic of mountain landscapes of singular beauty and complexity.

An extraordinary assemblage of large and small landforms, uncommon in most other Southwestern ranges, makes up the landscapes of the Santa Catalina Mountains. These landforms are the products of a host of geologic processes. Erosion by flash flooding is the most important, cutting deep canyons that provide access to the heart of the range (Figure 2). Massive landslides, debris flows and rock falls also actively sculpt mountain slopes and feed loose rock material to streams for transport to the adjacent basins. Chemical and mechanical weathering, although less dynamic, are important processes that place their stamp on every part of the range.

These processes have not been uniformly active throughout the geologic life of the range. Erosion by running water, for example, has sculpted the Santa Catalina Mountains since its bedrock was first exposed to the atmosphere and continues to be the dominant process shaping the modern landscape. Mud slides, deep chemical weathering, and freeze-thaw shattering of the bedrock wear down mountain slopes today but were far more active during wetter climatic cycles of the geologic past. Faulting gave rise to the original uplift of the range and shaped today's basin and range topography of southern Arizona, yet has not been active over the past 5 million years. Acting alone and in concert, these processes have sculpted a magnificent landscape montage from the bedrock of the Santa Catalina Mountains.

The biological diversity of the range is as complex as the geology. The Santa Catalina Mountains rise as a great mountain island from the vast, sea-like expanse of the surrounding Sonoran Desert. Temperature decreases and precipitation increases as one ascends from 2,500 to 9157 feet in elevation. This elevation increase, slope aspect, 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 in the Santa Catalina Mountains.





Map A. Satellite image of the Santa Catalina Mountains (Courtesy Google Earth).

Life zones range from palo verde and saguaro desert scrub in the foothills (from approximately 2,500 feet) to stands of pine and fir at the crest of the range. Numerous plant and animal species inhabit the range. Many are immigrant species that originated in the Rocky Mountains, the Sierra Madre Occidental, and the subtropical lowlands of Sonora and Sinaloa during and since the last Ice Age. The wildlife of the range, both migratory species and permanent residents, is as diverse as any mountain range in the Southwest. Many species inhabit more than one of these life zones; others migrate up and down the range with the seasons. This rich biologic mosaic, overlain on a rugged geologic fabric, produces one of the most spectacular ecologies in the Southwest.

Part 1 of this volume presents the geologic evolution of the Santa Catalina Mountains. Parts 2 thru 5 are an in-depth exploration of each of the distinctive geologic landscapes that make up the range: the southern Santa Catalina Mountains containing bold cliffs and canyons of gneiss; the western and northern Santa Catalina Mountains, dominated by a wide range of landforms developed on granites and deformed sedimentary and metamorphic rocks; the eastern Santa Catalina Mountains with its great ridges of upturned sedimentary strata and graceful bajada remnants; and the crest of the Santa Catalina Mountains, capped by a complex package of rocks lifted and intruded into the roof of the range.

Part 6 is an overview of the biological diversity of the range. The focus is on the vertical zonation of plants, from saguaro and palo verde to pine-fir forest, encountered as one ascends the range. Major plant and animal species commonly found in each life zone are introduced and their role in the larger ecosystem is discussed. Roads and public lands that provide the best access to the features discussed in the text are listed at the beginning of Parts 2-6 as Roads and Places. The final pages contain recommendations for further reading for those who wish to discover more about this remarkable range.

Figure 1. The Santa Catalina Mountains has a dome-like profile that sets it apart from sharp-crested ranges in southeastern Arizona (Photo courtesy of Dr. Anthony Lux).

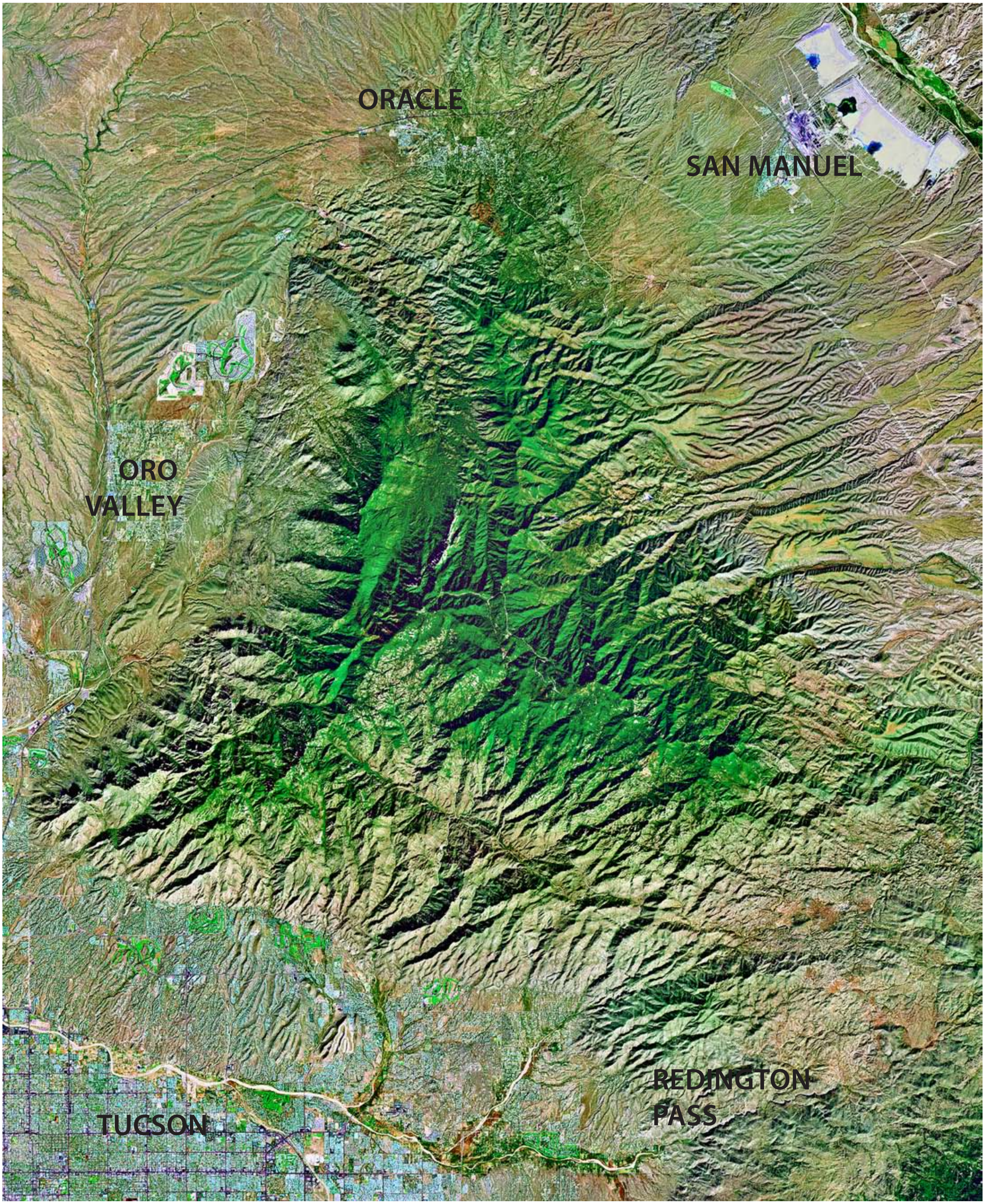


Figure 2. Satellite image of the Santa Catalina Mountains and adjacent basins. Flash floods are cutting numerous fault- and joint-aligned canyons into the bedrock of the range and eroding away the surrounding aprons of rock debris (Image courtesy of Dr. John Dohrenwend).

PART 1. Geologic History: The Formation of the Santa Catalina Mountains

The Santa Catalina Mountains are a complex mix of rocks spanning 1.65 billion years of geologic time. The ages and geologic time periods of the principal rock units of the range are:

Cenozoic

Quaternary alluvium 0.01- 2.6 million years
Oligocene-Miocene sedimentary rocks 12-38 million years
Catalina Granite (Oligocene) 26 million years
Leucogranites (Eocene) 40-50 million years
Wilderness Suites Granite and Gneiss (early Eocene) 46-57 million years

Mesozoic

Laramide sedimentary rocks
Little Hills Stock (Laramide) 63.8 million years
Alamo Canyon Granite (Cretaceous) 67 million years
Leatherwood Granodiorite (Cretaceous) 69 million years
Rick Peak Porphyry (Cretaceous) 71 million years
American Flag Formation (Cretaceous) 72-75 million years
Bisbee Group (lower Cretaceous and upper Jurrasic) 80-155 million years
- Glance Conglomerate
- Mural Limestone
- Morita Formation
- Cincture Formation

Paleozoic

Naco Group (Permian-Pennsylvanian) 280-310 million years
- Earp Formation
- Horquilla Limestone

Escabrosa Limestone (upper and lower Mississipian) 325-355 million years
Martin Formation (Devonian) 365-418 million years
Abrigo Formation (upper and middle Cambrian) 495-505 million years
Bolsa Quartzite (middle Cambrian) 510-520 million years

Proterozoic

Campo Bonito Formation (late Proterozoic) 700-800 million years
Sierra Ancha Diabase (late-middle Proterozoic) 1.1 billion years
Apache Group and diabase (late-middle Proterozoic) 1.1-1.3 billion year
- Mescal Limestone
- Dripping Springs Quartzite (includes Barnes Conglomerate member)
- Pioneer Formation (includes Scanlan Conglomerate member)

Oracle Granite (middle Proterozoic) 1.40 billion years
Pinal Schist (early Proterozoic) 1.65 billion years

The basement rocks in this part of Arizona are the 1.65 billion-year-old Pinal Schist, intruded by molten rock or magma that cooled to form the 1.4 billion-year-old Oracle Granite. This granite makes up most of the basement rocks exposed in the range. Above these are over 3600 feet (1100 m) of discontinuous layers of sedimentary and metamorphosed rocks. In ascending order these are: the Apache Group; the Campo Bonito Formation; sea-deposited sequences of limestone and dolomite that include the Martin Formation, the Escabrosa Limestone, and the Naco Group; and the Bisbee Group. About 71 million years ago molten rock invaded these layers and cooled to form the Rice Peak Porphyry. More intrusions of molten rock formed the 69 million-year-old Leatherwood Granodiorite and the 67 million-year-old Alamo Canyon Granite. Between 43 and 57 million years ago, seven massive, layer-shaped intrusions of magma, called sills, were injected into the older bedrock to form the Wilderness Suite Granite. The final major intrusion of magma emplaced the Catalina Granite 26 million years ago (Map B). These rocks were buried miles below the surface before mountain building began.

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. 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, began to form at depths of up to 6 to 8 miles (10 to 13 km). Continued extension moved rocks below the fault 16 to 19 miles (25 to 30 km) toward the east-northeast and closer to the surface as rocks above the fault slid toward the southwest.

The intense friction, heat, and pressure caused by this movement deformed rocks above and below the Catalina Fault. Rocks far below the fault, mainly Wilderness Suite and Oracle Granites, were so hot that they flowed like putty. The constituent minerals of these granites, especially quartz, smeared plastically. Other minerals, particularly feldspar, broke into pieces or had their corners broken off to produce lenticular crystals called *augen* ("eyes" in German). This deformation transformed the granites into a new rock type, called gneiss (Figure 4). Rocks above the fault were cooler and under less pressure and, unlike the plastically--altered rocks below the fault, deformed in a brittle manner and shattered into angular fragments called breccia.

As the rocks below the Catalina detachment fault moved slowly toward the surface, they began to dome up in response to the removal of the weight of overlying rocks. This rising dome of gneiss and highly shattered bedrock separated by a low angle detachment fault, later to be exposed at Earth's surface, is a metamorphic core complex.

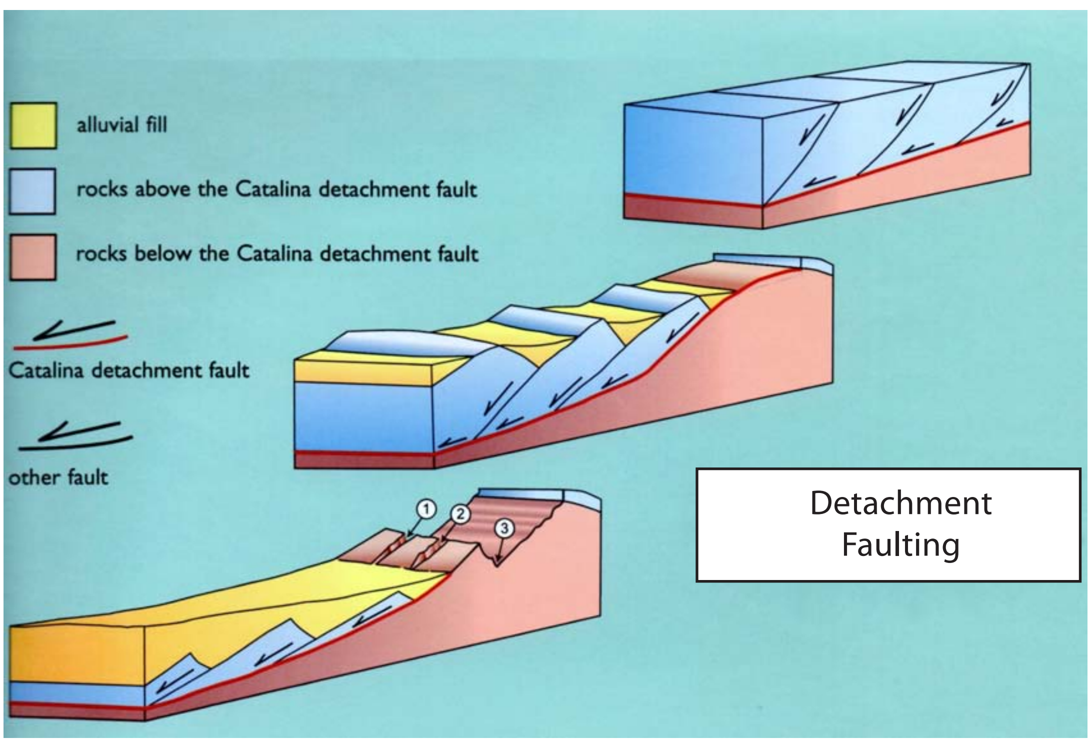
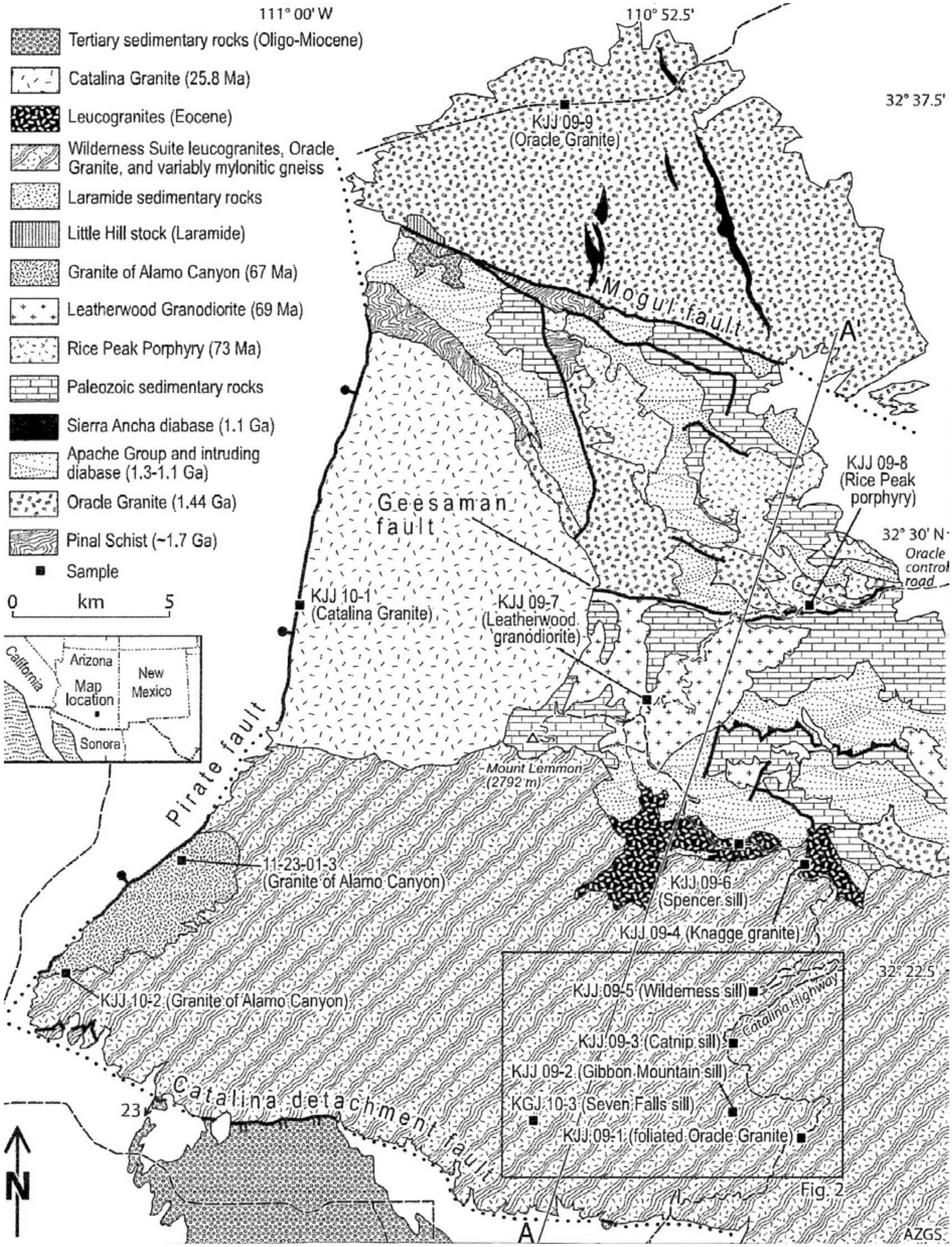
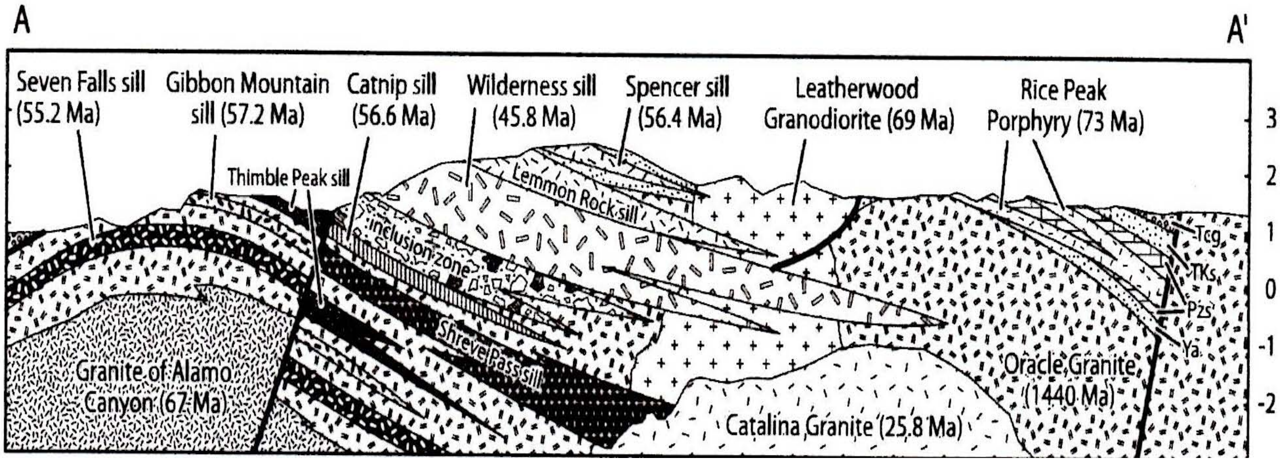


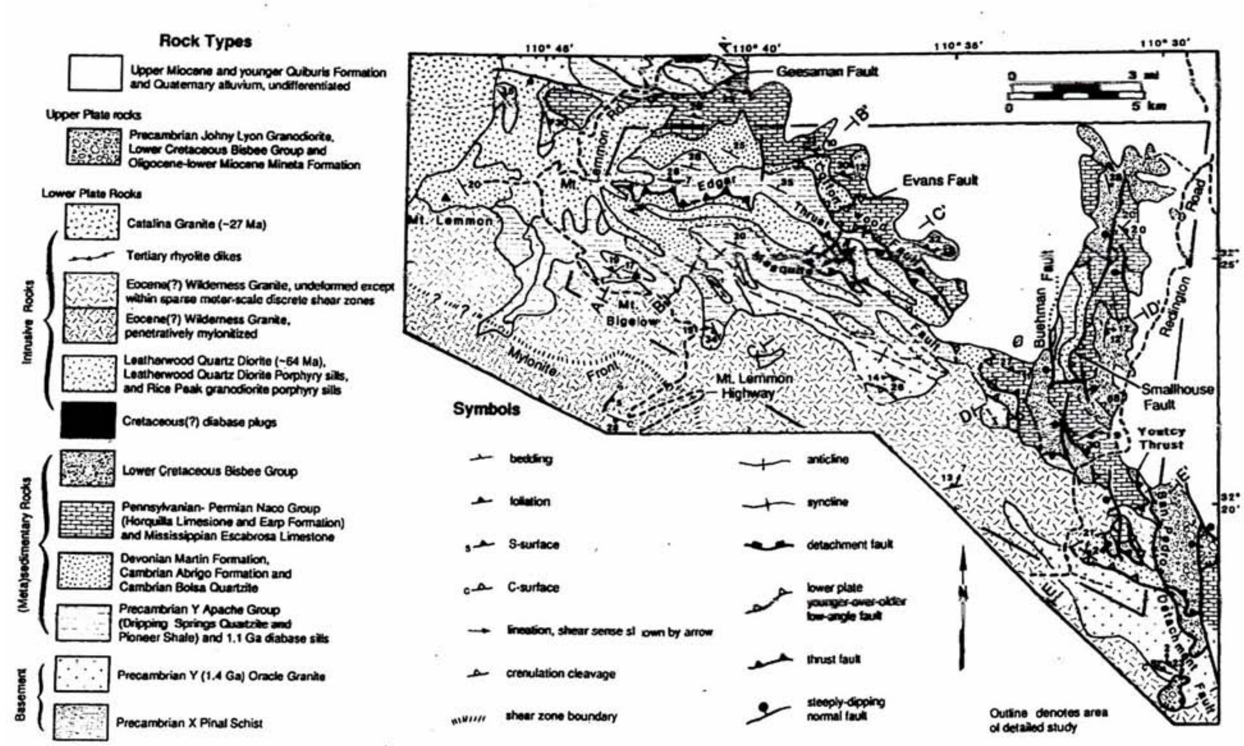
Figure 3. Block diagram illustrating the formation of the Santa Catalina Mountains metamorphic core complex: 1. Sabino Canyon, 2. Bear Canyon, 3. Molino Canyon.



Map B. Geology of the southern, western, northern and eastern Santa Catalina Mountains (Fornash, 2013).



Map B Cross-section A-Á, central Santa Catalina Mountains (Fornash, 2013).



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

The Santa Catalina Mountains is one of more than two dozen such structures that extend from northern Mexico into southern Canada, including the nearby Rincon and Tortolita Mountains. Twenty six million years ago, molten masses of rock (magma) rose from the deep crust and penetrated and pushed aside older bedrock of the emerging Santa Catalina Mountains. The magma cooled over millions of years to form the Catalina Granite (Figure 5). This granite, and the older Pinal Schist and Apache Group it deformed are the bedrock of much of the western flank of the range (Figures 6, 7 and 8).

A second period of extension began about 15 million years ago and broke the crustal rocks of western North America into blocks, separated by new, more steeply dipping faults. In southern Arizona, some of these crustal blocks were further uplifted to form mountain ranges such as the Santa Catalina, Galiuro, Rincon, Tortolita, and Tucson Mountains. Other blocks subsided as much as 2.4 miles (4 km) to form deep basins such as the Tucson Basin, the Oro Valley basin, and the San Pedro Valley (Figure 9). 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 northern Mexico.

Intense pressure accompanying 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

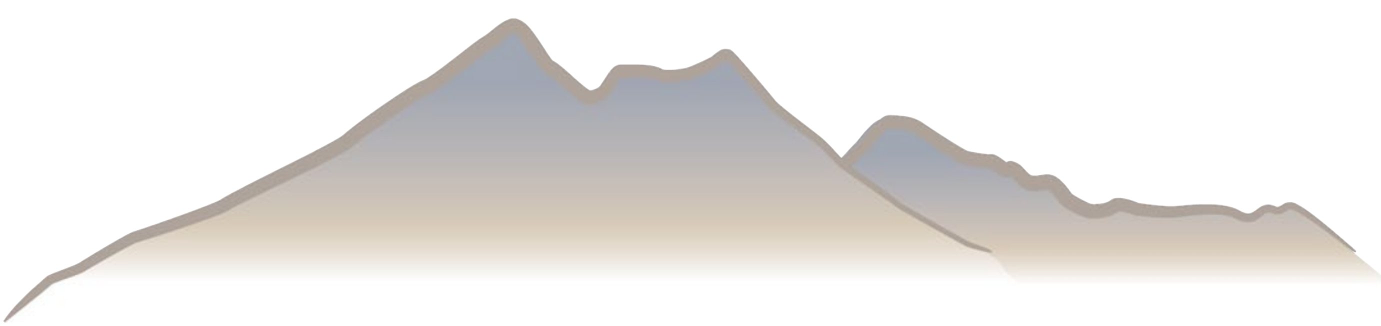
Rice Peak Porphyry and older sedimentary, igneous and metamorphic rocks were elevated to form the crest of the range. Massive quantities of mineral-bearing solutions that accompanied repeated injections of magma flowed along faults and joints, depositing copper, gold, silver, lead, zinc and other metals. Although these were not the great mineral bonanzas found in other parts of the American West, mining supported the first settlements in the Santa Catalina Mountains and continues to contribute to the regional economy (Figure 10).

Downward-cutting streams encountered the rocks of the rising metamorphic core complex that eventually became the Santa Catalina Mountains. Running water stripped away much of the more easily eroded breccia from the crest of the once-buried dome, leaving the more erosion-resistant gneiss as the principal rock of the southern part of the range. Continued erosion by streams cut the Cañada del Oro, Sabino, Bear, Molino, and other deep canyons into the hard gneiss and granite.

Running water, aided by weathering and debris flows, cut deeper and deeper into the rising dome, laying bare its unique structure and exposing an increasing variety of igneous, sedimentary, and metamorphic rocks The true colors of these various rock units are masked by rock varnish--a patina of iron and manganese oxide that gives desert ranges and basins their nearly uniform tan coloration (Figure 11).

Rock fragments flushed down mountains canyons during flash floods were reduced in size as they collided with each other and bedrock. Boulders and cobbles, tumbled by torrential flows, cut canyon floors progressively deeper. This coarse sediment, along with sand, gravel, silt, and clay, filled the adjacent deep basins and accumulated along the margins of the range as deposits called alluvial fans and bajadas. As the Cañada del Oro and the San Pedro River integrated the drainage of the closed basins surrounding the range with that of the Gila and Colorado Rivers, their tributaries eroded headward into these alluvial fans and bajadas. Today, these wet-weather drainages continue to strip away deposits on all sides of the range (Figure 12).

Removal of this alluvial debris is exposing a fascinating array of smaller-scale geologic features in the granites and gneiss along the margins of the range. Rounded domes, extensive sloping shelves of bedrock, faults, great folds of deformed rock, injections of once-molten rock, hills of rounded granite boulders, and towering pinnacles are just a few of the hallmark landforms of these granitic-gneissic landscapes that give the Santa Catalina Mountains its unique geologic character.



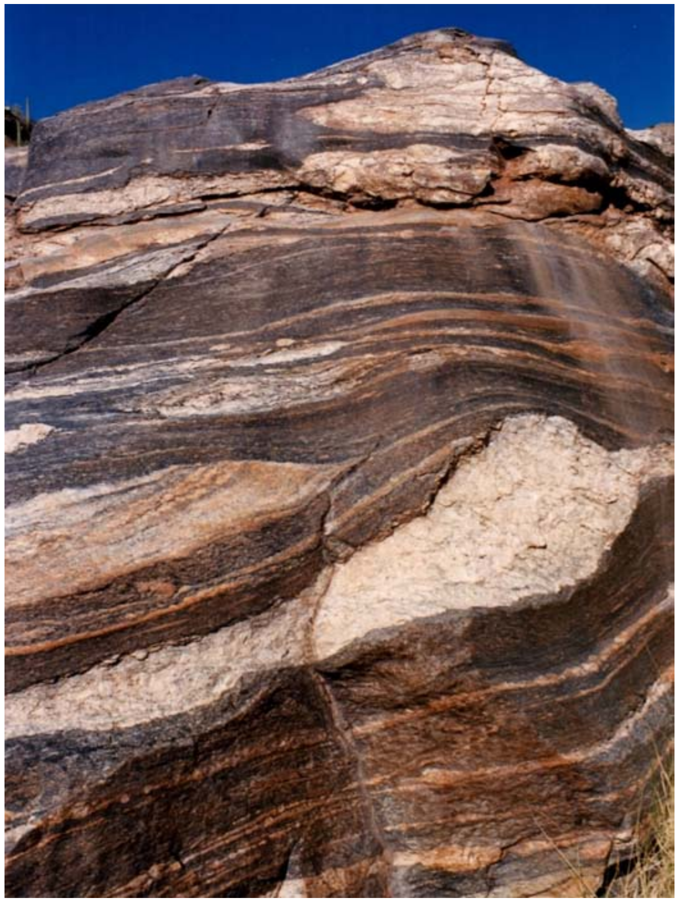


Figure 4. Gneiss near Molino Canyon with contortions produced when the rock was in a plastic state (Dr. Larry Fellows).

Figure 5. The Catalina Granite dominates much of the western face of the Santa Catalina Mountains. It originated 26 million years ago as a rising mass of molten magma that deformed older overlying rocks and cooled miles below the surface.

Figure 6. The 1.64 billion-year-old Pinal Schist, along the Canada del Oro, is the oldest rock in southeastern Arizona and is the basement rock for much of the Santa Catalina Mountains.

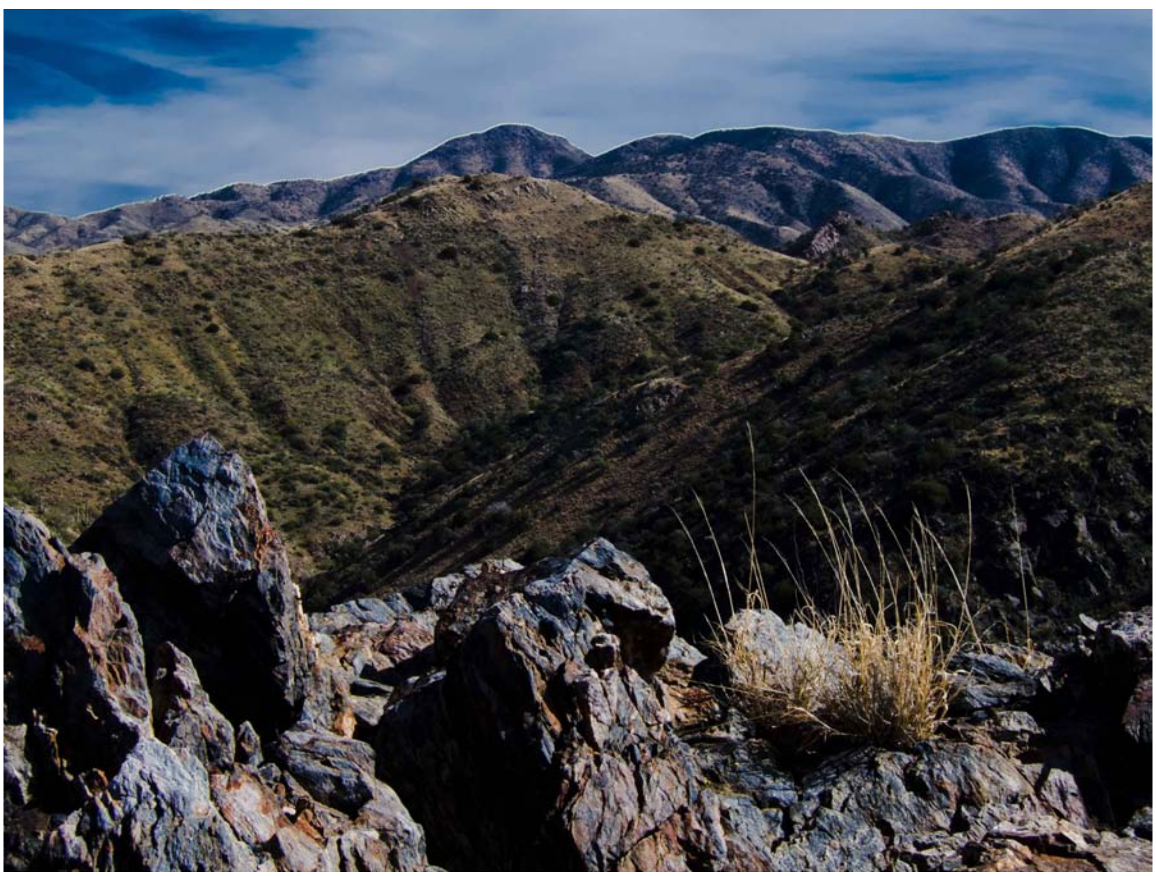


Figure 7. Ridge and valley topography along the Canada del Oro, developed on outcrops of Pinal Schist and Apache Group deformed by the intrusion of the Catalina Granite (Photo courtesy of Dr. Anthony Lux).

Figure 8. Wilderness Suite Granite deformed by the emplacement of the Catalina Granite, north of Catalina State Park.

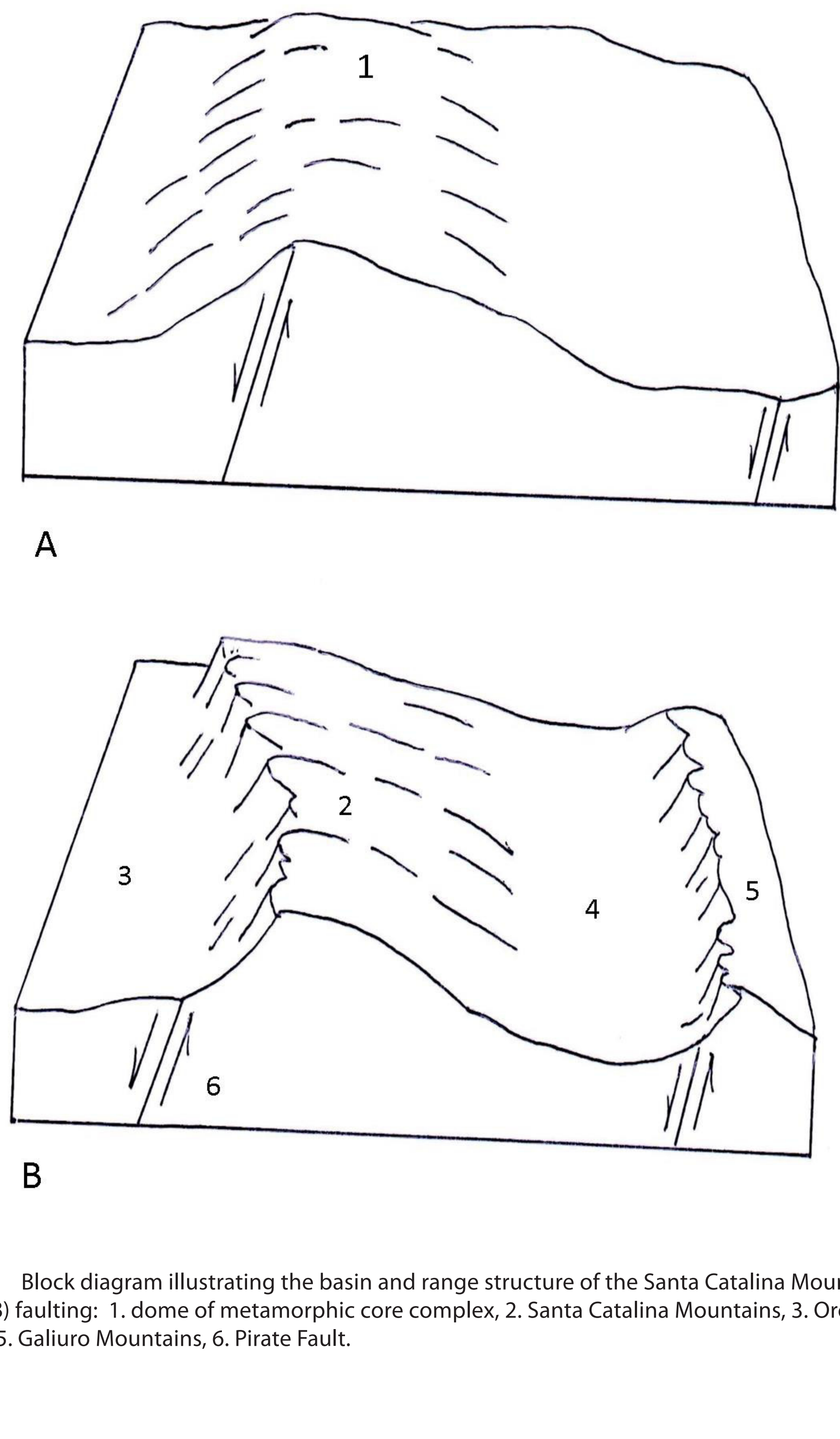


Figure 9. Block diagram illustrating the basin and range structure of the Santa Catalina Mountains region before (A) and after (B) faulting: 1. dome of metamorphic core complex, 2. Santa Catalina Mountains, 3. Oro Valley basin, 4. San Pedro basin, 5. Galiuro Mountains, 6. Pirate Fault.

Figure 10. Little Hills Mine area, near the Cañada del Oro, north of Biosphere 2.

Figure 11. Rock varnished boulder of Catalina Granite. Fresher surfaces are lightly varnished and contrast with dark, highly varnished surfaces. Rock varnish masks the true colors of most rocks that form the Santa Catalina Mountains, giving the range a dull tan to reddish brown patina.

Figure 12. Canyon cut into a bajada on the east side of the Santa Catalina Mountains.

PART 2. The Southern Santa Catalina Mountains

Roads and Places: Pima Canyon, Sabino Canyon, the Catalina Highway

The Santa Catalina Mountains are a domed, uplifted, and highly eroded block of sedimentary, igneous, and metamorphic rocks. Much of the original dome shape is preserved in the southern third of the range, known as the forerange. .Here, as in much of the southern part of the range, the most common rocks are granite and gneiss. 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 13) like no other part of the range. This texture is a reflection of the high temperature and pressure origin of the rock.

Figure 13. Aligned streaks of deformed minerals give the gneiss of the southern part of the range a ledgy texture (Photo courtesy of Dr. Larry Fellows).

The rocks of the forerange are separated from those of the main range by the Romero Pass fault. Vertical slippage crushed and weakened rocks along the fault. Streams eroded the fault-shattered zone into a succession of saddles and Sabino and Molino Basins that border the forerange on the north.

Gneiss is a metamorphic rock. Intense heat and pressure caused minerals in the parent rocks to recrystallize (metamorphose) to form the gneiss. Gneiss of the Santa Catalina Mountains had two parent rocks: the Precambrian-age (1.4 billion years old) Oracle Granite and the Eocene-age (50 million years old) Wilderness Suites Granite. These granites formed from great molten masses of rock that slowly cooled miles below Earth's surface.

The minerals feldspar, quartz, and mica crystallized as the granite slowly cooled. The Wilderness Suite Granite is unusual in that it also contains crystals of red garnet.

Between 35 and 20 million years ago, when these granites were at a depth of 7 to 10 mi (10 to 15 km), the Earth's crust in this region was stretched and sheared in a southwest-northeast direction. Intense pressure and heat that accompanied this stretching deformed part of the deeply buried Oracle and Wilderness Suite 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 4).

This southwest-northeast stretching is preserved as lineation in the gneiss. At temperatures of 600°F (350°C), the quartz crystals in the granites behaved like hot, soft plastic and smeared in long ribbons parallel to the direction of crustal stretching. The feldspar crystals, which are more brittle at this temperature, were rolled, crushed, and smeared—also in the direction of extension. These long, aligned streaks of deformed minerals give the gneiss its unique texture which imparts an angularity to the cliffs and canyon walls of the southern Santa Catalina Mountains.

Structures, faults and joints, coupled with the geometry (i.e., lineation) of the gneiss contributed to the landform evolution of the range. Innumerable faults (a fracture along which movement has occurred) and sets of cracks called joints, caused by movement and pressure, permeate the bedrock and are responsible for many of this area's grand landforms. Faults and joints can be traced for miles across the landscape. Both are pathways along which water from rain and snow melt can penetrate the bedrock. The water freezes during winter nights and the resulting expansion of the ice shatters mineral grains and widens fracture walls. Plant roots wedge open the fractures further. Accumulated soil acts as a sponge that keeps slightly acidic groundwater in contact with fracture walls, hastening chemical weathering and decomposition of the rock. In time, these fractures widen and deepen forming small ravines and pinnacles. Over thousands of years ravines become canyons. Pima, Sabino, Bear, and Molino Canyons and most other drainages in the range are aligned along faults and joints (Figures 14 and 15).

Faulting has shaped this part of the range in other ways as well. It is responsible for the straight southern face of the mountain front. Non-faulted mountains commonly have ridges or spurs that extend into the adjacent valley. Here the mountain front is truncated by the Catalina detachment fault. Slippage along faults produces zones of powdered (fault gouge) and crushed (breccia) rock that can be traced for miles. This grinding action left parallel scratches and polished surfaces, called slickensides, on numerous faulted rock (Figure 16). Groundwater containing dissolved iron circulated through the breccia and cemented the crushed rock fragments. The oxidation (rusting) of these minute quantities of iron stained red many fault zones exposed in canyons draining the southern part of the range.

Sills, an intrusive structural component, form much of the Wilderness Suite granite and many of the high, bold cliffs of the southern Santa Catalina Mountains. 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 17). Sills were injected into surrounding rock and cooled at depth, and were then uplifted and exposed by erosion. They make up much of the rock in the southern Santa Catalina Mountains. 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.

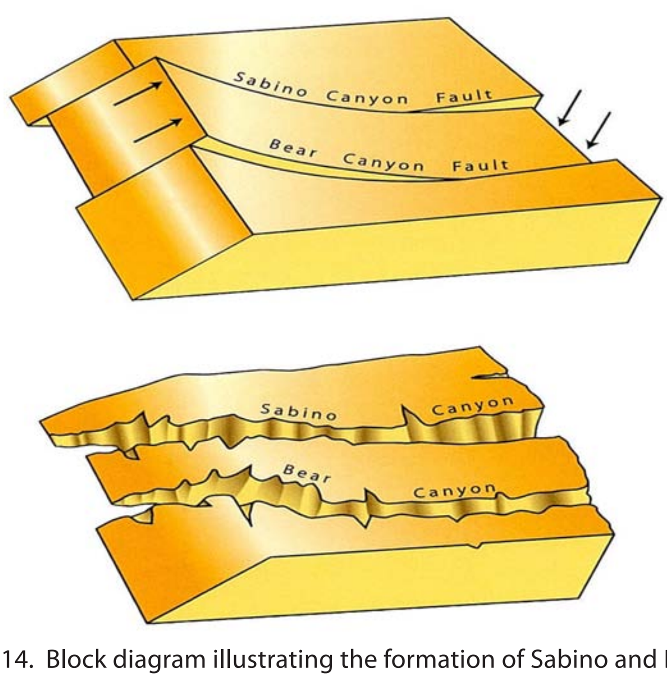


Figure 14. Block diagram illustrating the formation of Sabino and Bear Canyons along faults.

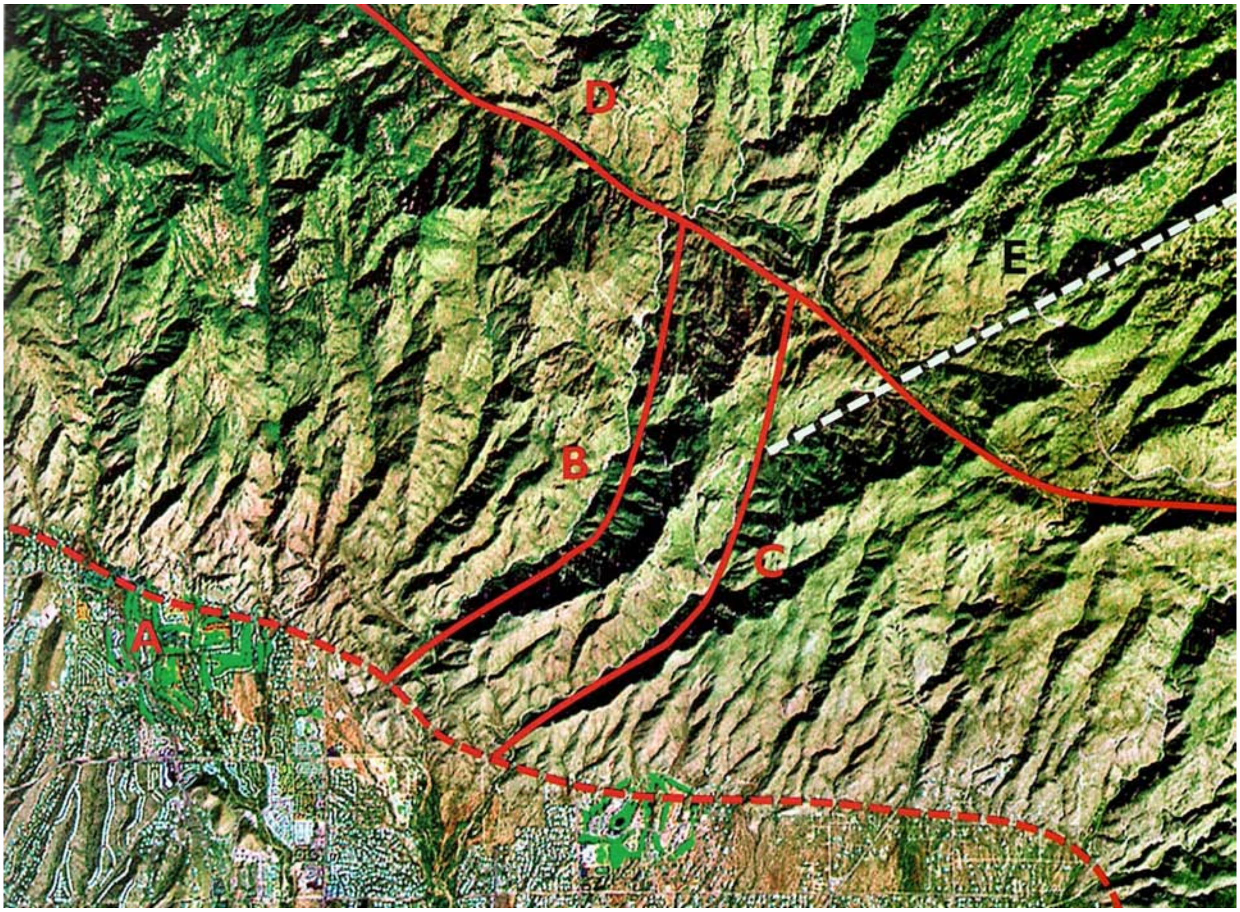


Figure 15. Satellite image of the Santa Catalina forerange illustrating the alignment of major canyons along faults: A=buried trace of the Catalina detachment fault, B=Sabino Canyon fault, C=Bear Canyon fault, D=Romero Pass fault, E=Upper Bear Canyon.

The forces uplifting the Santa Catalinas are in competition with those that wear them down. Weathering and erosion attacked the domed bedrock as soon as it was exposed to the atmosphere, imprinting the forerange with their own suite of distinctive landforms. Triangular dome facets are a major element of the southern front of the range (Figure 18). These triangular-shaped convex rock faces retain the original arched form of the bedrock. Streams flowing down the surface of the newly exposed dome quickly cut into the more easily eroded rock at its crest and incised deep canyons into the underlying, erosion-resistant granite and gneiss. The resulting series of triangular-shaped rock faces between the mouths of Sabino, Bear, and other canyons are hallmark features of metamorphic core complex mountains.

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 in boulder fields. These rockfalls expose areas of light-colored, less weathered rock that contrast with the dark mineral oxide staining on the rest of the cliff surfaces in Sabino, Bear, and other forerange canyons. Small rock fragment are constantly shed from cliffs falling to slopes below, where they break into pieces and accumulate as cones and aprons of rock debris called talus.

After heavy rains whole sections of this loose slope material, as well as bedrock, can give way as landslides and cascade to the valley below. Landslide scars are common features on steep slopes in the Santa Catalina Mountains Wildfires contribute to landslides by destroying vegetative cove that stabilizes loose rock debris on steep slopes. Rock debris from rockfalls and landslides mantles the slopes of all canyons (Figure 19). The monsoon rains of late July 2006 generated hundreds of debris flow chutes, some of which are still evident in the Santa Catalina Mountains.

Slope failure that occurs when rock mantle is saturated after torrential precipitation from hurricanes or heavy rains on snow can result in debris flows. These surges of rock debris change form with time and distance as they move down pre-existing channels. A front of boulders and cobbles is followed by a coarse slurry, and then by a more liquefied tail of finer material. Rock debris is deposited all 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 20 a, b, c).

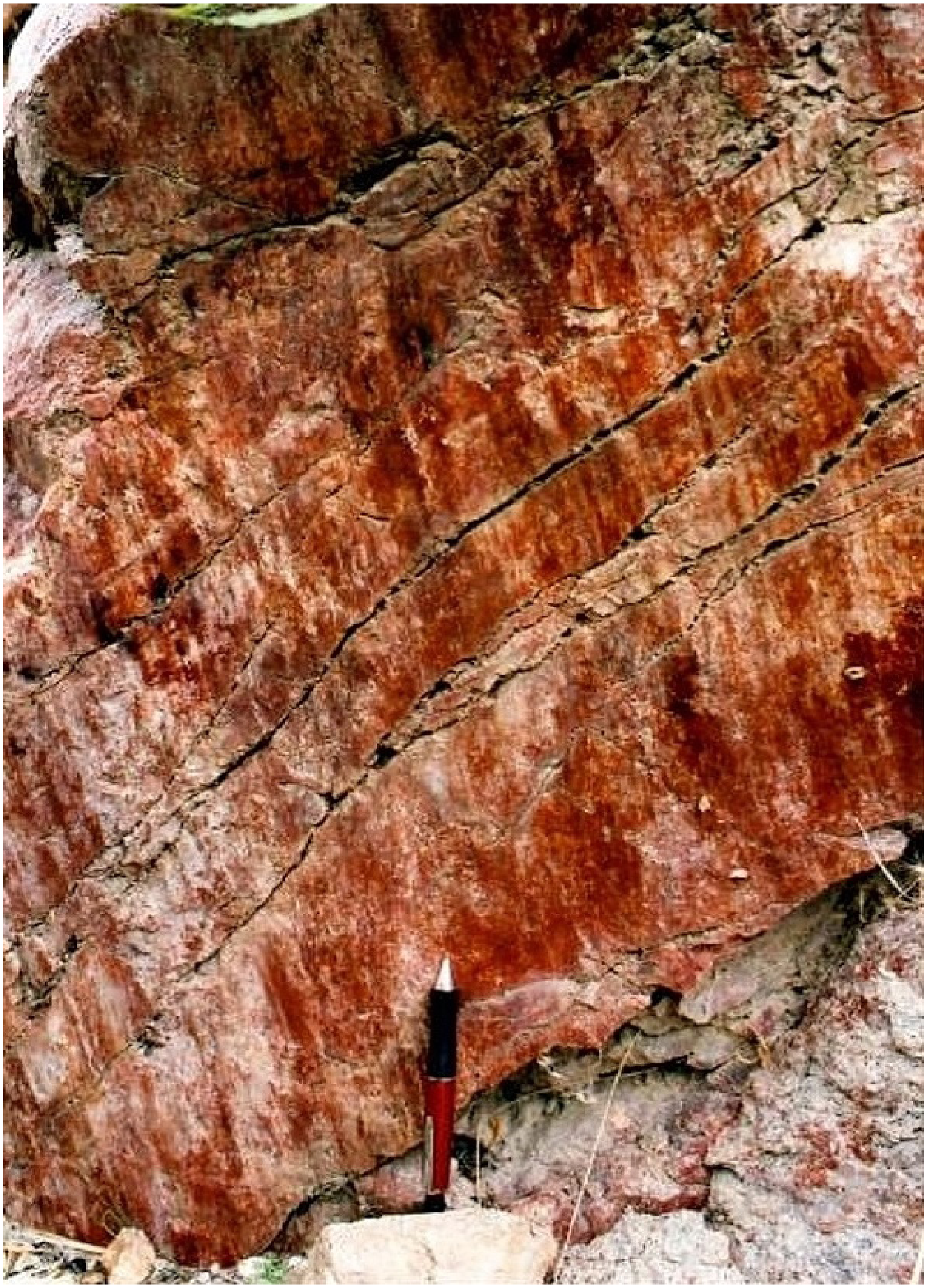


Figure 16. Slickensides, finely etched lineation parallel to the pen, along a fault in Sabino Canyon (Photo courtesy of Dr. Larry Fellows).

Figure 17. Thimble Peak sill above Sabino Canyon (Photo courtesy of Dr. Larry Fellows).

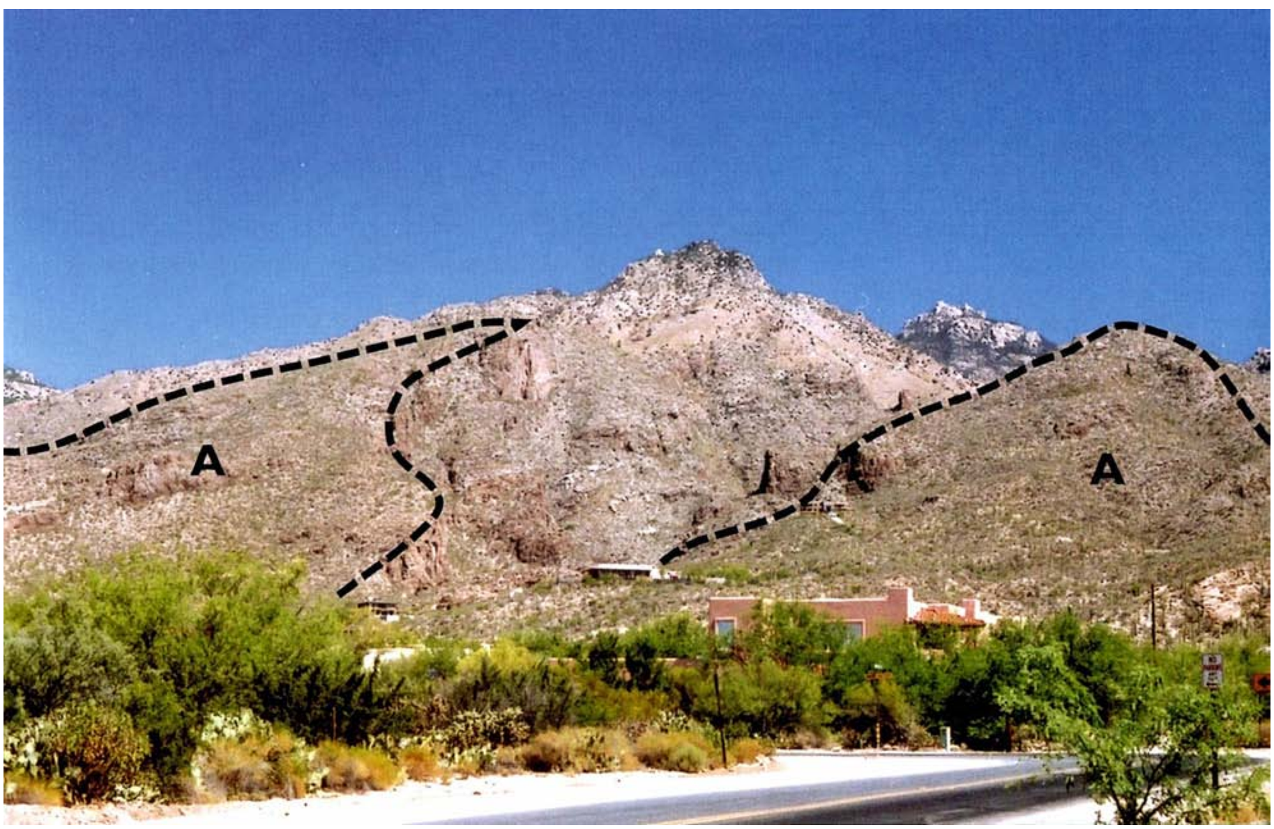


Figure 18. Triangular dome facets along the southern Santa Catalina Mountains.

Figure 19. Boulders from a landslide or rockfall in Sabino Canyon (Photo courtesy of Dr. Larry Fellows).

Figure 20a. Debris flow-rafted boulders near the southern base of the forerange (Photo courtesy of Dr. Larry Fellows).

Figure 20b. Debris flow scar, Sabino Canyon (Photo courtesy of Dr. Larry Fellows). This scar formed during the July 2006 monsoon rains that initiated over 300 small volume debris flow events in the Santa Catalina Mountains.

Figure 20c. Late Pleistocene or Holocene debris flow levees along the southern foot of the range (Photo Youberg, 2006).

Rockfalls, landslides, and debis flows play a major role in canyon widening. The rock debris from these events eventually reaches the streambed where, overtime, it is broken into smaller fragments and flushed from the canyon by flash floods. Although these processes are currently very active, much of this rock material may also have accumulated during the wetter climatic cycles of the last Ice Age.

Running water is the principal agent responsible for wearing down the Santa Catalina Mountains. The drainages along which this water flows act as geological conveyor belts, moving rock fragments from the floors of canyons to the adjacent basins. Most of this rock material is flushed from the canyons by torrential flash floods during the summer thunderstorm season.

The stream beds in which these floods erode and deposit display their own interesting suite of features. Rock fragments in the stream channel are boulders, cobbles, pebbles, and sand that have been rounded by tumbling during floods. In the high upstream portions of the channels the fragments are larger and more angular because they have not been subjected to as many shattering collisions with other rocks that occur during transport by flash floods. Beyond the mouths of Sabino, Bear, and other canyons are jumbles of boulders that have been rafted and flushed along by debris flows. Subsequent flows of lesser volume have washed away the small rock fragments, leaving the boulder deposits as testimony to the power of flowing mud.

By the time most rock fragments are transported beyond the mountain front into the Tucson Basin, collisions and tumbling have reduced them to rounded pebbles and sand-sized particles. Also, because of more gentle slopes in the basin, streams do not have the power to transport large rock fragments. In the lowest part of the basin, sand and clay are the most common deposits.

Streaks of black sand are common in the steam beds that drain the southern part of the range (Figure 21). The sand is composed of heavy minerals eroded from the granite and gneiss bedrock. About 40 percent of the dark-colored mineral grains in this area are magnetite, a common ferrous and ferric iron oxide. Ilmenite, an iron titanium oxide, and garnet, a silicate mineral, are other common heavy minerals in this area.. Magnetite, which is magnetic, can be separated from the other heavy minerals by a magnet. Red garnets, pyrope, are panned from some of the local stream beds and are referred to as desert sand rubies.

These dark minerals streaks are the result of sorting by running water. As physical and chemical weathering processes cause the granite and gneiss to disintegrate, the major rock-forming minerals (feldspar, quartz, and biotite), together with smaller quantities of magnetite, ilmenite, and garnet are flushed into drainages. Flowing water separates these minerals by weight and concentrates the heavier, dark-colored sand-sized particles in long streaks. This process is called hydraulic sorting. Flakes and nuggets of placer gold are deposited in stream gravel in the same manner.

Figure 21. Magnetite or black sands forming long streaks in a stream bed in the Catalina forerange. (Photo courtesy of Dr. Larry Fellows.)

Tinajas, Gnammas, Tafoni, Rock Varnish and Case-hardened Surfaces

Depressions and basins that hold water are common where stream beds are cut into bedrock (Figure 22). Called tinajas, from the Spanish word for a large earthen water jar, these rock tanks are cut by boulders, cobbles, and pebbles tumbled by swiftly flowing water during flash floods. The upstream sides of these depressions, which bear the full impact of the moving rock debris, are consequently deeper than the downstream sides, which are breached by outlet channels. Because of this asymmetrical shape, tinajas are flushed clear of organic and rock debris by flash floods and filled with water by the slower flows that follow. Tinajas are critical sources of water for humans and wildlife that inhabit and travel through deserts. Some are more than 20 ft (6 m) deep and hold thousands of gallons (liters) of water months after the last rain.

Many relatively level granite and gneiss surfaces contain flat-bottomed, circular to irregularly shaped, shallow depressions that commonly have overhanging rims (Figure 23). These solution pans, or gnammas, which are up to 3 ft (1 m), deep, can hold rain and snowmelt for days. Solution pans form at points of rock weakness (joints, or lichen disintegration, or flaked surfaces) and expand by chemical and lichen-induced weathering. Periodic pooling of water results in the chemical alteration of the minerals in the rock. Some minerals dissolve, some oxidize, and others are changed to clay minerals. Lichens and algae flourish in the more humid environments of the pans and decompose the rock grain by grain. The rock disintegrates slowly and the resulting debris is swept and flushed from the enlarging solution pan by wind and heavy rains.

Cavities, called tafoni, are weathered into many granite and gneiss cliffs (Figure 24). These openings, which can measure several yards (m) in diameter, are commonly aligned along joints, bedding planes, or other zones of weakness in bedrock. Tafoni, the product of several processes acting in concert, are particularly common where rock faces have developed a hardened crust of mineral salts that were drawn from the interior of the rock. This"case-hardened"outer surface (Figure 25) is resistant to weathering and erosion. Small breaks in this resistant surface, however, enlarge relatively rapidly and, in time, penetrate the softer interior of the rock. Within these shaded cavities, higher humidity and lower temperatures cause rock to disintegrate more rapidly than outside surfaces. Cavity walls are usually crumbling and flaking due to expansion of clay minerals that swell when wet, the growth of ice crystals, and the dissolving of mineral cement that binds rock grains together. Tafoni weathering, one of the numerous processes that reduce solid rock to fragments that are then swept away by erosion, adds texture to the rocks of the range.

Figure 22. Tinaja in Sabino Canyon (Photo courtesy of Dr. Larry Fellows).

Figure 23. Solution pans or gnammas weathered into granite, Windy Point (Photo courtesy of Dr. Larry Fellows).

Figure 24. Tafoni in granite, Windy Point area.

Rock varnish, a tan to brown mineral patina (Figure 25a) found on most exposed rock in the range, masks the true colors of the gneiss—which are black and white. This patina consists of thin layers (typically less than one hundredth of an in (0.25 mm thick) of clay minerals (illite, smectite, and kaolinite) stained by high concentrations of iron and manganese oxides. The clay minerals settle as dust from the atmosphere. Manganese, also derived from windborne dust and rain, produces a black to dark-brown coloration on surfaces exposed to air.

Micro-colonies of lichens and bacteria inhabit the varnish and gain energy by oxidizing the manganese. They anchor themselves to rock surfaces with the clay particles, which provide protection against extremes in temperature and humidity. In the process, the manganese becomes attached firmly to and darkens the clay. Each time the rock surface is wetted by rain, more manganese and clay are added to sustain the slowly growing colony. Such colonies thrive where the rock acidity is neutral and the surface is so nutrient poor that competing colonies of lichens and mosses cannot survive. Rock varnish develops best on rocks that have moderately rough surfaces. Basalt, sandstone, and many metamorphic rocks, such as gneiss, are commonly well varnished. Siltstone and shale disintegrate too rapidly to retain such a coating.

All of Earth's deserts have varnished rocks, giving the landscape its warm tones of brown and ebony. In the American Southwest, these surfaces provoke great interest because of their archaeological importance. In innumerable locations prehistoric Indians pecked petroglyphs (rock writings) through the mineral skin to the fresh rock below (Figure 25b).

Even though older surfaces tend to be more heavily varnished and darker than younger surfaces, scientists are unable to use rock varnish as a tool for determining the exact age of exposure of rocks. The rate at which rock varnish forms is not constant because it is affected by many variables, such as climatic change, wind abrasion, biological competition, and abundance of manganese. Some researchers believe that the clay and manganese content of rock varnish reflects past climatic conditions. Because some varnished surfaces may be many thousands of years old, they could reveal information about climatic change that took place repeatedly during the Ice Age and in the past 10,000 years.

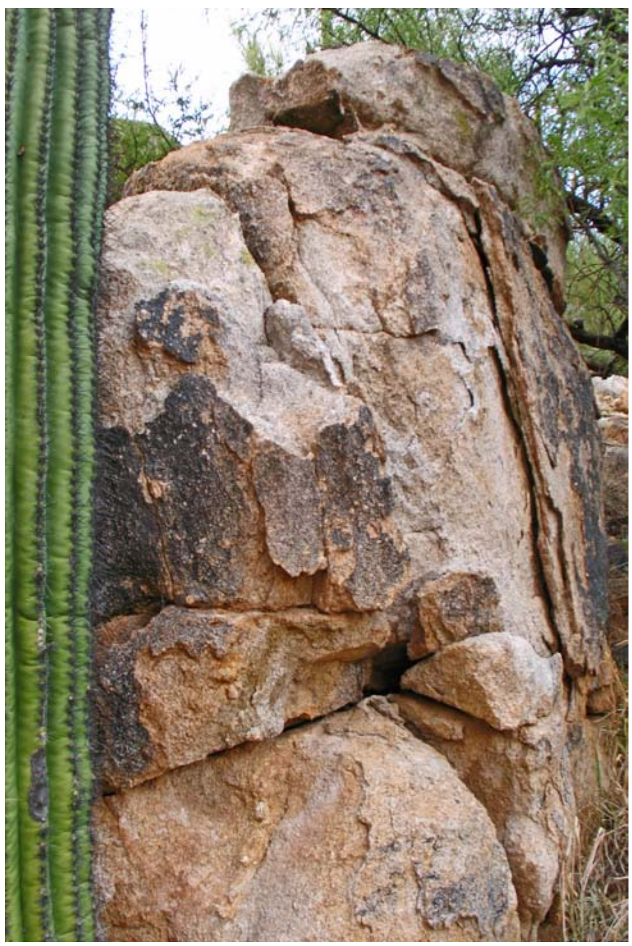


Figure 25a. Case hardened layer on granite bluff; black patina on the case-hardened layer is rock varnish (Dr. Larry Fellows).

Figure 25b. Petroglyph in rock varnish on Wilderness Suites Granite, Catalina State Park (Photo courtesy of Ian Jarosak, Catalina State Park).

Pinnacles grace the Wilderness Suite granite cliffs in the area of Windy Point along the Catalina Highway (Figure 26). These slender spires are the products of surface weathering and erosion by running water guided by deep joints (cracks) in the granite. Joints serve as avenues along which water and tree roots can penetrate the granite. Rock fracturing, caused by expansion that occurs when water freezes, and wedging by plant roots, enlarges the joints. Along the joints chemical decomposition from slightly acidic rain and snowmelt causes the mineral biotite to weather to clay. This greatly weakens the interlocking mineral grains in the granite, causing it to break down into its major component minerals—quartz and feldspar.

Running water then flushes the weathered products from the joints, cutting them deeper and wider. The rock between the joints is left standing as pinnacles. The pinnacles appear to be leaning toward the cliff because the joints are at an angle from the vertical. These pinnacles are impressive testimony to the important role that rock structure—in this case joints—plays in the development of the landscape.

Figure 26. Pinnacles in Wilderness Suite granite, Windy Point (Photo courtesy of Dr. Larry Fellows).

PART 3. The Western and Northern Catalina Mountains

Roads and Places: Catalina State Park, Charouleau Gap Road, Biosphere 2, Oracle State Park, and Cody Loop Drive in Oracle, Arizona

The western and northern Santa Catalina Mountains are dominated by three massive intrusions of granite and a wedge of metamorphic rocks. The granites were injected as masses of molten rock that slowly cooled deep within the Earth's crust. The metamorphic rocks were formed by heat and pressure, also miles below the surface. The granites were emplaced at different times: the Oracle Granite 1.45 billion years ago, the Wilderness Suite Granite 45-50 million years ago, and the Catalina Granite 26 million years ago (Figure 27).

The magma that formed the Catalina Granite invaded the older host rock as a circular mass. The eastern half of this pluton is preserved in the western Santa Catalina Mountains; the central portion is buried below at least 6,000 feet of alluvial fill in the Oro Valley Basin; the western portion forms part of the Tortolita Mountains. The metamorphic rocks are the 1.65 billion-year-old Pinal Schist (the oldest rock in southern Arizona), altered from sandstone, siltstone and shale, the 1.1 to 1.3 billion-year-old Apache Group, and the 540 million-year-old Bolsa Quartzite, also metamorphosed from sedimentary rocks. Regional uplift has beautifully exposed these rocks in the western and northern flanks of the range. Weathering and erosion have sculpted each of these rock types into very different landscapes.

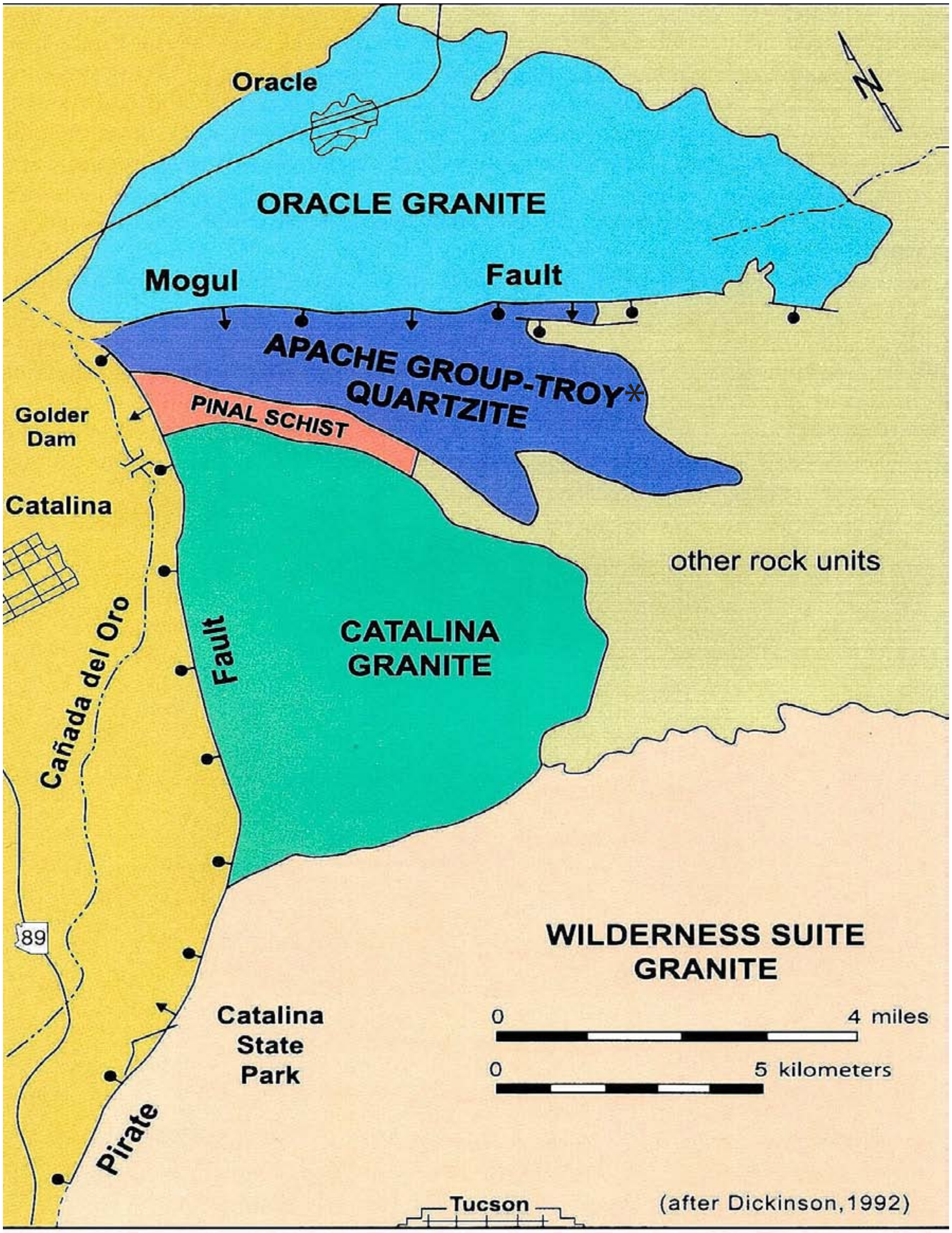


Figure 27. Geologic sketch map of the central western Santa Catalina Mountains. * Should read Bolsa Quartzite.

Each landscape is a unique combination of landforms, which have developed in many cases because of differences in hardness and fracture (joint) patterns of the bedrock. Most of the geologic features here are granitic landforms, some massive and others small-scale. Together they make up four distinctive landscapes not found in other parts of the Santa Catalina Mountains.

Between 25 and 5 million years ago, as southern Arizona's basins and ranges began to form, the western side of the Santa Catalina Mountains was truncated by the Pirate Fault (Figure 28). Movement along this steep (50-55° from the horizontal) fault was mainly vertical. Rocks west of the fault dropped an estimated 10,000 to 13,000 feet (about 3,000 to 4,000 m) relative to those in the Santa Catalinas east of the fault.

Erosion began wearing back the face of the range even as it was being uplifted. Between 2 and 6 million years ago the headwaters of streams carved embayments or reentrants (Figure 29) into the western mountain front and planed off bedrock platforms, called pediments, that sloped toward the Cañada del Oro. These pediments were buried by alluvial fans—great, fan-shaped aprons of rock debris that were deposited by streams draining the retreating mountain front. By one million years ago these fans merged with fans built out from the eastern slopes of the Tortolita Mountains and filled the Cañada del Oro Basin with sediment.

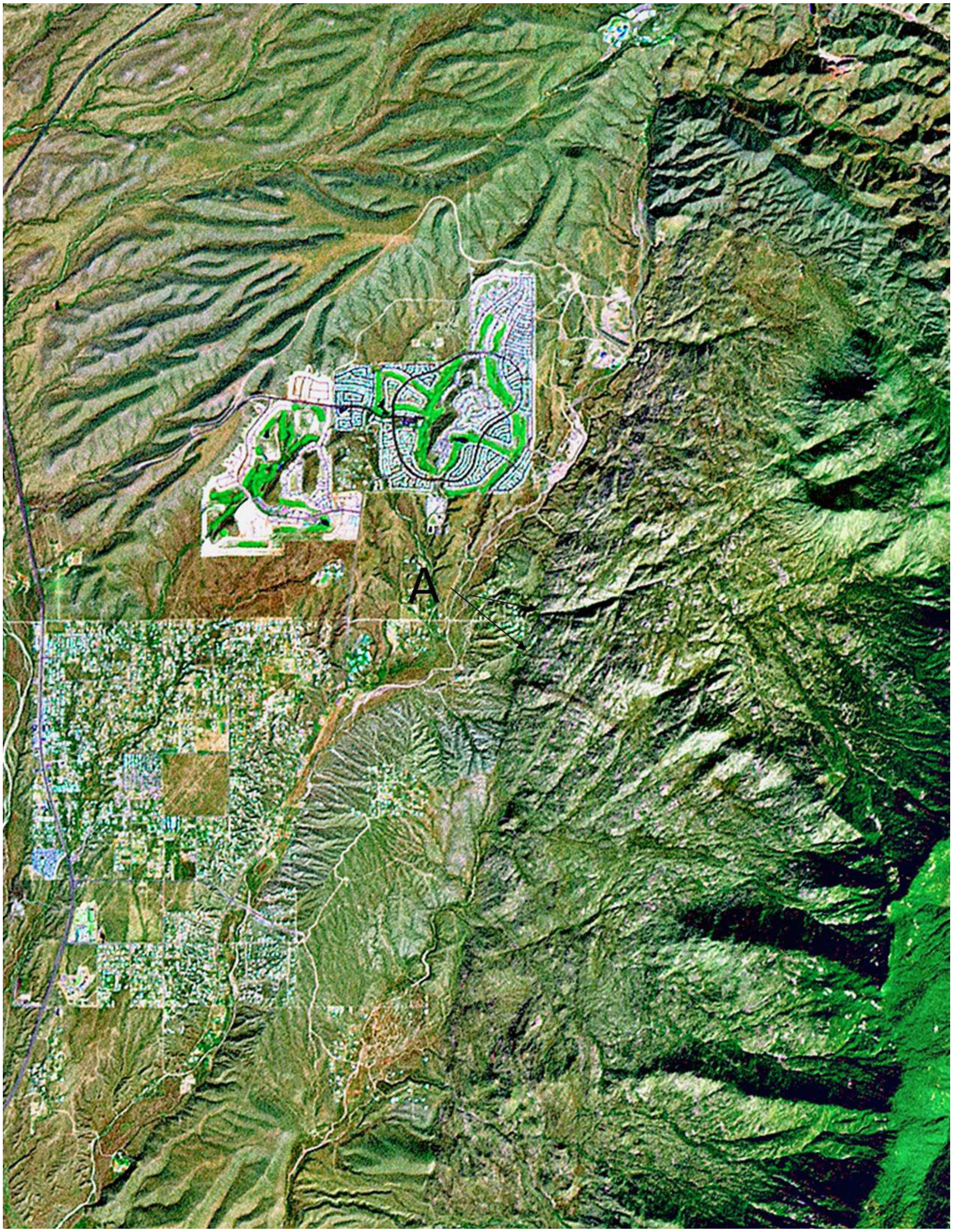


Figure 28. The Pirate Fault, the northeast-southwest lineation at letter A, truncates the rocks of the western Santa Catalina Mountains.

Figure 29. Embayments cut into the Catalina Granite on the western face of the Santa Catalina Mountains.

Over the past several million years, today's landscape began to take its present form. Throughout much of southern Arizona rivers were extending their headwaters into higher basins that previously had no outlet to the sea. These expanding streams removed much of the sedimentary fill and altered and integrated the drainage basins they invaded.

These processes produced particularly dramatic changes along the western face of the range. Prior to this time the Cañada del Oro exited the heart of the Santa Catalina Mountains near the present town of Oracle and drained to the northwest. A more rapidly expanding drainage, eroding along the shattered rock zone of the Pirate Fault, began to extend its headwaters northward from the Tucson Basin. This new stream cut a valley through the alluvial fan sediments that filled this part of the basin and exposed the older pediments along the western margin of the Santa Catalina Mountains. In time, this stream intercepted the ancestral Cañada del Oro and caused it to flow south.

The newly captured Cañada del Oro underwent at least four major episodes of down-cutting and left remnants of its former floodplains as part of today's landscape. Called stream terraces, these stepped surfaces range in age from 500,000 to 4,000 years. Hohokam farmers built Romero Pueblo on one of these terraces overlooking the Cañada del Oro and Sutherland Wash (Figure 30).

The present landscape in the western and northern Santa Catalinas is a mosaic of exhumed pediments, stream terraces, remnants of alluvial fans, and the embayed mountain front—all produced over a span of at least 5 million years. Adding to the complexity of this landscape is the array of smaller, landforms developed on the surfaces of pediments cut into the Wilderness Suite, Catalina, and Oracle Granites.

Figure 30. Stream terraces along Sutherland Wash. Romero Ruin is situated on the terrace in the middle ground (Photo courtesy of Dr. Larry Fellows).

The Wilderness Suite Granite Landscape: Pinnacles and Cliffs

Vertical cliffs and pinnacles dominate the southwestern face of the Catalinas from Pusch Ridge to Catalina State Park. Hard, erosion-resistant Wilderness Suite Granite and Gneiss comprise the bedrock.

The Wilderness Suite Granite is broken by widely spaced, vertical joints. These fractures 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 the joints, cutting them into ravines and canyons. Joints actually control the location of most streams crossing bedrock. This concentrated action of weathering and erosion eventually widens and deepens the ravines and canyons, leaving the massive granite in between standing as towering pinnacles which are best developed in Catalina State Park (Figure 31).

Figure 31. Pinnacles at Catalina State Park (Photo courtesy of Dr. Anthony Lux).

Intense compressional stress has deformed the Wilderness Suite Granite, which is granitic gneiss, in this part of the range. One clearly deformed feature is an arch-shaped fold exposed in the north wall of Alamo Canyon at Catalina State Park (Figure 32). This structure, which extends for 4 miles (6-7 km) in a northeast-southwest direction, has been cut off by the Pirate Fault. The fold's western portion has dropped down several thousand feet and is buried in the sedimentary fill of the Tucson and Oro Valley Basins. The crest of the fold has been eroded away, but its eastern portion forms the towering cliffs of Pusch Ridge. This deformation could have occurred 45 to 50 million years ago when the Wilderness Suite granite intruded the local crust or 26 million years ago when the Catalina granite pushed aside the Wilderness Suite granite.

Triangular faceted spurs give the cliffs of Pusch Ridge a particularly abrupt character (Figure 33). The shape of these spurs is controlled by movement along the Pirate Fault. Unlike those spurs found on the southern face of the forerange, they do not reflect the domal structure of the range. Over millions of years the granite and gneiss east of the Pirate Fault rose about 10,000 to 13,000 ft (3000 to 4000 m) relative to the same rocks beneath the Oro Valley basin west of the fault. This movement created a high escarpment along the western face of the range. Concurrent down-cutting by streams during uplift carved deep canyons into the escarpment, segmenting it into this series of aligned, triangular-shaped spurs. Continued weathering and erosion wore the mountain front back several hundred yards (meters) eastward from the fault along which it formed.

Triangular faceted spurs occur along the margins of many of the faulted mountain ranges in the Basin and Range Province in the western United States and northwestern Mexico. They provide bold evidence that faulting has played an active role in shaping the landscape.

Remnants of alluvial fans form gentle, westward sloping surfaces that once extended to the base of Pusch Ridge and the high cliffs of Catalina State Park. Large boulders, 6 to 30 feet (2 to 9 m) in diameter and weighing 50 to 1000 tons, make up the surface of these old fan remnants (Figure 34). The boulders are blocks of granite and gneiss derived from the west face of the range, one-half mile (about 800 m) to the east.

Figure 32. Fold in Wilderness Suite Granite, north of Catalina State Park (Photo courtesy of Dr. Larry Fellows).

Figure 33. Triangular faceted spur, north of Pusch Ridge (Photo courtesy of Dr. Larry Fellows).

The huge boulders were rafted to their present location at the heads of alluvial fans by debris flows, or fell from the cliff face (perhaps during earthquakes) onto the fans which then extended to the base of the mountains. Subsequent erosion by running water has washed away much of the alluvial fan material, separating these remnants from the cliff face that was the source of the boulders. Boulder levees deposited by more recent debris flows extend from the mouths of canyons in this part of the range.

Rock basins, or tinajas, that hold water, such as those at Romero Pools, are evidence to the cutting power of flash floods along these drainages.

Figure 34. Boulder of Wilderness Suite Granite deposited on alluvial fan surface by a debris flow.

Figure 35. Case hardened Wilderness Suite boulder (Photo courtesy of Dr. Larry Fellows).

Most of the granite and gneiss boulders in these old fan remnants have a patina of rock varnish and a protective mineral rind (Figure 35), the latter from a process called case hardening. This rind consists of a durable film of amorphous (lacking an orderly crystal form) silica that has been drawn from the interior of the rock and re-precipitated on its surface. Although silica is not very soluble in water, small quantities are leached from the rock each time it is wetted by rain or dew. When the moisture evaporates, the silica is deposited on the surface of the rock. While the surface is hardened by the buildup of silica, the interior is progressively weakened by the removal of that mineral.

Case hardening protects rock surfaces from chemical weathering and low energy erosion. Once this protective rind is broken, however, the softer, weathered zone beneath is exposed to the elements and disintegrates quickly.

Although there has been no movement on the Pirate Fault in 5 million years, it has had an enormous impact on the today's topography. The course of the Cañada del Oro is extraordinarily straight along this western margin of the range because the stream is following the more easily eroded zone of shattered rock along the fault. The position of the Cañada del Oro in this part of the basin is also a result of stream piracy controlled by this fault zone.

Tremendous friction is generated as fault surfaces slide together. This grinding action produces a zone of powdered rock (fault gouge) and highly broken rock (fault breccia) that can be observed at Breccia Hill (Figure 36), and at other locations where the Cañada del Oro has exposed the fault surface. These features demonstrate how an ancient geologic structure, in this case a fault, can control modern landscapes.

Steam terraces, step-like surfaces, along the margins of the Cañada del Oro and Sutherland Wash record changes in the history of erosion and deposition in this part of the basin (Figure 37). Standing high above the streams that cut them, these benches are remnants of former floodplains.

Figure 36. The fault breccia at Breccia Hill (left side of the photo), hard and resistant to erosion, projects above non-brecciated granite (Photo courtesy of Dr. Larry Fellows).

Figure 37. Stream terraces along the west bank of the Cañada del Oro, north of Saddlebrooke.

The geologic history of the Cañada del Oro and Sutherland Wash includes episodes of valley filling followed by episodes of down-cutting during which the streams removed this fill. Sediment accumulated in these valleys when great quantities of rock debris were being eroded from the slopes of the Santa Catalina Mountains. During periods of reduced slope erosion the streams cut their channels through this sediment, leaving remnants of the former valley floors as high-standing stream terraces. The streams shifted laterally and progressively widened the new valley floors by undercutting the slopes of the adjacent stream terraces.

These stream terraces represent at least four major periods of down-cutting and channel backfilling. Alternating wet and dry climatic conditions caused variations in the quantity of water and rock debris that moved down the drainages during the last 500,000 years. These graceful, stepped landforms resulted.

Stream terraces stand above the flash flood zones of valleys and have long been preferred locations for human settlements, agricultural fields, roads, and railroads. Romero Ruin, a 12th century Hohokam village, for example, was built on one of these terraces.

The Catalina Granite Landscape: Exhumed pediments and domed inselbergs

Pediments

The light-colored rock exposed in the western Santa Catalina Mountains north of Catalina State Park is the Catalina Granite. It is softer and more easily eroded than the Wilderness Suite Granite to the south or the Apache Group and Bolsa Quartzite to the north. This relative softness permitted tributaries of the Cañada del Oro to carve huge amphitheater-shaped reentrants into this western face of the range. Each reentrant is floored by sloping bedrock surfaces, called pediments, that were planed off by mountains streams (Figure 38). These embayments and pediments give a unique character to this part of the range, and host a fascinating array of classic granitic landforms.

Pediment size is influenced by the hardness and structure of the bedrock. The pediments developed on the moderately hard Catalina Granite are of moderate width, averaging 2.9 miles (4 km). Those cut into in the highly weathered and weaker Oracle Granite to the north are about 5 miles (8 km) wide, while the much more resistant Wilderness Suite Granite near Catalina State Park has pediments only 400 to 1200 yards (about 350 to 1100 m) in width. Most pediments in southern Arizona are buried by alluvium. Here they have been exhumed by erosion and exhibit an interesting suite of minor features that add texture to the landscape.

Figure 38. A pediment (the flat surface in the middle ground) cut into Catalina Granite.

Domed inselbergs

The hundreds of dome-shaped hills on the Catalina Granite pediments and the ridges that separate the embayments are domed inselbergs (Figure 39). Weathering and erosion, guided by two sets of natural cracks in the bedrock (joints), have sculpted these graceful and distinctive landforms. Sets of vertical joints have a rhomboidal (that of a deformed rectangle) pattern when viewed from above (Figure 40). Each joint-bound rhomboid 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 (Figure 41) parallel to the ground service are produced within each rhomboid by this slow release of internal stress. These joints terminate against the vertical joints that bound the rhomboids. These curvilinear joints divide the expanding granite into curved sheets that eventually arch up to form the crests of the domed inselbergs. Each of the rhomboids of bedrock is then a domed inselberg in varying states of development or decay.

Figure 39. Domed inselberg in Catalina Granite.

Figure 40. Satellite image of joint-bound domed inselberg in Catalina Granite (Courtesy of Google Earth).

Figure 41. Curvilinear joints along the crest of a domed inselberg in Catalina Granite.

The relatively fracture-free sheeting of the domed inselbergs contributes to their growth and longevity. Rain and snowmelt drain quickly from the steepening inselberg slopes and pool in the adjacent vertical joints along their margins. These margins slowly deepen into lowlands by weathering and erosion. The removal of confining bedrock that accompanies the continuing growth of the lowlands, in turn, results in expansion and increased slope angle of the domes. Steeper slopes result in more rapid drainage of moisture and increased resistance to erosion. Some high domed inselbergs in this area may be several million years old.

Domed inselbergs are common elements of the landscape, particularly in eastern and southern Africa and the granite terrain of Brazil. Some, such as Stone Mountain in Georgia, Half Dome at Yosemite National Park in California, and the Sugarloaf in the harbor of Rio de Janeiro, Brazil are magnificent landforms of international renown.

Rounded or spheroidal boulders are perched on the crests of many domed inselbergs (Figures 42). They are the remnants of curved sheets of granite that once formed the outer layers of the domes. Weathering and erosion reduced the sheets to individual, angular slabs of rock scattered along the sides and tops of the domes (Figure 43).

Because of the mineral composition of granite, these angular slabs become rounded by prolonged exposure to the atmosphere. The Catalina Granite is a homogeneous, non-layered rock composed mainly of tightly interlocking crystals of quartz, feldspar, and biotite mica. The freeze-thaw action of moisture and the expansion of wetted salt particles cause quartz and feldspar grains to fracture along their boundaries with other crystals. Rainwater, which is mildly acidic because of the carbon dioxide gained from the atmosphere, alters the biotite to crumbly clay minerals. These processes weaken the rock, causing it to disintegrate crystal by crystal. Because weathering processes attack rock corners from three directions and edges from two directions, these parts of the slabs experience the greatest disintegration and rounding. In time, the slabs are rounded to boulders.

Figure 42. Perched boulder developed from curved sheet of Catalina Granite on a boulder inselberg.

Figure 43. Angular slabs of granite that are slowly sliding down the slope of a domed inselberg.

Granite disintegration leaves a ground surface composed of granular gravel, called grus (Figure 44). Unlike water deposited gravels, which tend to be rounded by tumbling in a stream, grus consists of sharp-edged feldspar and quartz crystals. Grus develops best where granite weathers under desert conditions. In humid climates feldspar is reduced to clay minerals. Here, where aridity prevails, physical fragmentation is more active than chemical decomposition. As a result, both feldspar and quartz remain as crystals that contribute to the granular nature of the surrounding ground.

Boulders that form on steep slopes eventually succumb to the pull of gravity and roll to the base of the domes. Those that weather to a rounded form on domal crests are more stable and will endure until atmospheric processes reduce them to crystal gravel.

Figure 44. Grus weathered from Catalina Granite. The large, light-colored grains are feldspar crystals.

Some boulders become rounded by separating (spalling) into thin layers that are concentric with their surfaces—much like those of an onion. This weathering process, called exfoliation, occurs when feldspar in the surface rock chemically combines with water and converts to kaolinite clay. The clay is greater in volume but weaker than the original feldspar. As a result, the outer layers of the granite boulders expand and crumble away.

The steep faces of many domed inselbergs are scarred by shallow bedrock drainages, called gutters (Figure 45). These channels appear to be the result of both subsurface and surface processes. Many can be followed upslope to source areas of decomposed rock beneath curved granite sheets. Gutters may begin with the subsurface decaying action of moisture held in contact with granite surfaces by a thin veneer of rock debris. Later, after erosion has washed away the rock debris, these decayed areas are deepened by the flow of surface water down the face of the domes.

Figure 45. Gutters channel water from the layer of grus capping this domed inselberg.

Features within the Granite

Some features within the Catalina Granite date from about 26 million years ago when this rock was magma, a huge mass of molten rock within the Earth's crust. Other features formed after the rock had cooled and solidified enough to develop cracks. Dark inclusions in the granite (Figure 46) are xenoliths. They are fragments of older rock, perhaps altered Pinal Schist that became incorporated into the rising magma when it was hot and plastic. Xenoliths range in size from 0.5 inches (1.25 cm) to more than 12 yards. Locally they make up 40 percent of the bedrock surface.

The white veins in the granite are dikes (Figure 47). They formed when cracks in the granite were filled with younger injections of molten rock, called aplite. Aplite is similar to the older granite host rock in that it consists mainly of the minerals quartz and feldspar. The size of aplite mineral crystals, however, is much smaller. This is because the dikes cooled too rapidly for large crystals to grow. Magma from which the Catalina Granite formed cooled at a slower rate, permitting large crystals to develop. The aplite dikes range from less than an inch (a few centimeters) to more than 20 feet (6 meters) in width, and up to 3 miles (5 kilometers) in length.

The Catalina Granite between Nicholas and Sutherland Washes exhibits a radial pattern of joints and mineral banding that is visible on satellite images (Figure 48). The pattern has topographic expression because major drainages in the area are aligned with and have eroded along the radial joints. Some of these joints are filled with 20-foot-wide (6-meter) granite dikes that contrast with the Catalina Granite. The mineral banding is quartz monzonite, a granitic-type rock that is rich in biotite mica, which gives it the dark color. It is not clear if this pattern dates from the emplacement of the granite some 26 million years ago or if it is a younger structure caused by later stress.

Figure 46. The dark inclusions are xenoliths within the Catalina Granite. The feldspar crystals are particularly coarse-grained.

Figure 47. Fine-grained aplite dike within the Catalina Granite.

Figure 48. Satellite image of mineral bands (A) and radial joints (B) in the Catalina Granite. (Courtesy of Google Earth).

Bajada and stream piracy

The gently sloping plain between the towns of Catalina and Oracle is a bajada (Figure 49). It consists of boulders, cobbles, gravel, sand, and silt transported from the Cañada del Oro and other canyons of the western Santa Catalina Mountains by flash floods and debris flows during the last several million years. Rock debris first accumulated as a fan-shaped deposit, called an alluvial fan, at the mouth of each canyon. These fans enlarged as erosion continued to wear back the mountain front. By about 1 million years ago, the fans had merged to form a continuous apron of alluvial material—a bajada—at the base of western Santa Catalina Mountains.

The reddish-orange color of the soil on the surface of the bajada indicates that the surface has been exposed to atmospheric weathering for a long time—in this case over 1 million years. During this period of extensive weathering, iron minerals in the sediment oxidized or rusted, giving a reddish hue to the ground.

Subsequent down-cutting and changes in the course of the Cañada del Oro have separated the bajada from the mountain front. This stream originally flowed northwestwardly out of the Santa Catalina Mountains towards the Gila River. About 1 million years ago the flow of this ancestral stream was intercepted by a southward flowing stream that had established itself along the western flank of the range. This stream, which had a steeper gradient than the ancestral Cañada del Oro and followed the more easily eroded zone of shattered rock along the Pirate fault, extended its drainage basin northward by head-ward erosion. In time, its headwaters cut into the drainage basin of the Cañada del Oro and eventually captured the flow of this older stream.

Figure 49. Bajada, in the foreground, deposited by the ancestral Cañada del Oro, northeast of Saddlebrooke, Arizona.

The "elbow" or point of capture occurred a short distance southeast of Biosphere 2, where the present Cañada del Oro makes its abrupt turn to the south. This process, called stream piracy, is common wherever differences in rock hardness or stream gradient allow one stream to erode more rapidly than its neighboring drainages.

The piracy of the ancestral Cañada del Oro changed the nature of the sedimentary fill in some parts of the Oro Valley basin. Before piracy, the basin fill west of the Catalina Granite was composed of rock fragments eroded from this granite. After the flow was diverted to the south along the stream's present course, the fill was composed of many rock types transported from the heart of the range (Figure 50). Wet weather streams are now cutting into and washing away the loose sediment of the bajada and other alluvial landforms in this part of the basin.

The graceful profiles of bajadas that sweep down from the Black and Tortolita Mountains can be seen on the northern and northwestern horizons. These distinctive landforms, produced where erosion is wearing back the face of desert mountains, are hallmarks of western America's Basin and Range country.

The Apache Group-Bolsa Quartzite Landscape: Parallel ridges and valleys

North of the pediment and domed inselberg landscape of the Catalina Granite is a wedge-shaped zone of rugged ridges and valleys (Figure 51) eroded into rocks of the Abrigo Formation, the Bolsa Quartzite, the Campo Bonito Formation, the Apache Group, the Pinal Schist, and a large slice of Oracle Granite (Figures 27 and 28). These formations have been deformed by faults and folds and intruded by volcanic rocks such as the Rice Peak Porphyry and the Little Hill Alaskite. Much of this deformation appears to have occurred 26 million years ago when the rising magma that would cool to form the Catalina Granite pushed into these older rock units.

Rock hardness and resistance to erosion has greatly influenced the evolution of the ridge and valley topography of this landscape. Some rocks such as well-cemented conglomerate, schist, quartzite, metamorphosed sedimentary rocks, and limestone are particularly resistant to erosion and tend to form high ridges.

Figure 50. The light-colored basin fill (A) is derived from the Catalina Granite before the piracy of the ancestral Cañada del Oro. The overlying, darker sediment(B) consists of many rock types transported from the heart of the range after piracy occurred.

Shale, siltstone and poorly cemented conglomerates are softer and erode to form valleys. Such complex geology results in equally complex topography. The Apache Group, for example, consists of the Mescal Limestone, the Dripping Spring Quartzite, the Barnes Conglomerate, and the Pioneer Shale and a number of other units. Each unit is harder or softer than that of neighboring rocks, which is reflected in the resulting rugged mosaic of ridges, cliffs, slopes, ravines, and valleys.

The Mogul Fault (Figure 28) separates the rocks of this ridge and valley zone from the main body of the Oracle Granite to the north. Movement was primarily vertical, with rocks south of the fault dropping down in relation to the Oracle Granite. This fault adds geologic complexity and mineralization to this part of the range. About 20-25 million years ago a small body of molten rock penetrated and chemically altered older rocks at the west end of the Mogul Fault. The magma cooled to form the Little Hill Alaskite. Hot, mineral-laden solutions accompanying the intrusion circulated through the shattered rocks along the Mogul Fault and other fractures. Metals, once dissolved in the hydrothermal solutions, crystallized and filled minute openings and veins in the surrounding rock. The Arizona Bureau of Geology and Mineral Technology reported that, between 1937 and 1981, 5.7 million lbs. of copper, 53,000 lbs. of lead, 15,000 oz. of silver, and 300 oz. of gold were mined from this zone. The Little Hill mine, located in the shattered rocks along the Mogul Fault, produced most of the copper, lead, and silver. Mineralization also lends color to the crushed landscaping rock that is quarried in this area. (Figure 52).

Figure 51. Ridge and valley topography north of the Catalina Granite. The ridge in middle-ground is composed of Pinal Schist.

Figure 52. Mineralization in the Little Hills Mine area lends color to rock that is crushed and used for landscaping in nearby communities.

The Oracle Granite Landscape: Boulder inselbergs

The Oracle Granite, unlike the younger and harder Catalina and Wilderness Suite Granites to the south, does not support bold cliffs and towering pinnacles. The tremendous stress that accompanied its emplacement into the Earth's crust, plus intense chemical alteration of its constituent minerals, have weakened crystal bonds and predisposed the rock to relatively rapid breakdown by granular disintegration. It is also much older than the other granites, 1.4 billion years, and has been subjected to numerous tectonic events. Individual quartz crystals are highly fractured, biotite has been recrystallized, and feldspars crystals lack crystal faces making it easier for moisture to penetrate and weaken the granite.

The Oracle Granite is also broken by a dense system of joints. Moisture has penetrated these joints and weakened the granite to a depth of 230 feet (70 m) in places. Quartz veins and dikes of the shallow intrusive rock diabase (Figure 53) are common and, where closely spaced, add sufficient strength to form ridges and low hills such as American Flag Hill. Gold and smaller deposits of lead, copper, and silver have been found where the dikes contact the Oracle Granite.

Most of the Oracle Granite, except for that making up Oracle Ridge, has been beveled to pediments that extend for as much as 5 miles (8 km.) from the mountains front. These pediments were formerly covered by a thin veneer of gravels. Today, tributaries of the San Pedro River, such as Flag and Smelter Washes and Bonito Creek, are stripping away this alluvial cover and exposing and cutting into the pediments below.

Figure 53. A diabase dike in Oracle Granite near the town of Oracle.

Boulder inselbergs

The dozens of isolated, rounded boulder hills that dominate the landscape near the village of Oracle are boulder inselbergs (Figure 54). They are resistant remnants of bedrock left on the pediments surfaces as erosion wears back the mountain front. Boulder inselbergs are the characteristic landforms of the Oracle Granite.

Boulder inselbergs form where surface and subsurface weathering and erosion have enlarged sets of vertical and horizontal joints in resistant sections of Oracle Granite. These joint sets divide the bedrock into individual rectangular blocks—joint blocks—with dimensions that range from 3 to 18 feet (1 to 6 meters).

Figure 54. Boulder inselberg near the town of Oracle.

Weathering widens and deepens the joints and rounds the corners and edges of the joint blocks, producing boulders. Wet weather streams lower the pediment surfaces by washing away loose rock debris, leaving the inselbergs as high standing erosional remnants. Boulders at the crests of the inselbergs have not shifted from their original position so the joint pattern of the bedrock is well displayed, giving clear evidence as to how these landforms evolved.

In time erosion will wear away the boulder inselbergs. They become progressively lower with increasing distance from the mountain front. Down slope from the pediments, on the bajada, the inselbergs project through the thin alluvial veneer as mere piles of boulders (Figure 55).

Small-scale features

Outcrops of Oracle Granite exhibit many of the characteristic small scale features found in the Catalina and Wilderness Suite granitic landscapes. Case hardened surfaces, rock varnish, tafoni, xenoliths, and dikes are common. Crystals of feldspar and quartz form grus soil over broad areas. Black streaks of magnetite sand darken many stream beds (Figure 56). Corestones, residual boulders developed in place by the subsurface weathering of joint blocks in pediments, are visible in road cuts (Figure 57).

Figure 55. Erosion has reduced many inselbergs to piles of boulders.

Figure 56. Black magnetite sand worn from the Oracle Granite.

Figure 57. Corestone in Oracle Granite in road cut near the village of Oracle.

PART 4: The Eastern Santa Catalina Mountains

Roads and Places: the Mt. Lemmon Road, Peppersauce Canyon

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. Erosion by the headwaters of tributaries flowing into the San Pedro River has exposed a vast array of igneous, metamorphic, and sedimentary rocks. Many of these rocks are highly fractured and displaced vertically and horizontally by faults. Unlike the western face of the range, this eastern margin is not truncated by a steep normal fault similar to the Pirate Fault. Nor are there exhumed pediments or domed or boulder inselbergs. The San Pedro basin that borders this side of the range is much lower in elevation than the Oro Valley basin. In addition, the San Pedro River is miles from the mountain front and has not eroded its course along a fault shatter zone at the foot of the range, as is the case with the Cañada del Oro.

The Mogul and Geesaman Faults Zone

The geology here is extremely complex. Between the Mogul (Figure 58) and the Geesaman Faults, a pile of igneous, sedimentary and metamorphosed sedimentary rocks that includes 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, the Pinal Schist, and the Oracle Granite have been displaced by faulting. Upended layers of sedimentary rocks form asymmetrical ridges along this part of the eastern face of the range (Figure 59). Along the southeastern margins of the range the pattern is repeated. Here movement along high-angle fractures has tilted and broken many of the once-horizontal formations named above and those of the Bisbee Group into elongated slices that dip steeply to the east (Figure 60). The Glance Conglomerate, the Mural Limestone and the sandstones, limestones, quartzites, and shales of the Morita and Cinture Formations form the Bisbee Group.

Horizontal slippage on both the Mogul and the Geesaman Faults has displaced miles of rock. Many units have been dragged into contact with rocks of vastly different ages. For example, horizontal and vertical movement along the Mogul Fault has juxtaposed the 1.4 billion-year-old Oracle Granite and the 72-75 million-year-old American Flag Formation. In other places severe compressional forces have broken and shoved the 330 million-year-old Escabrosa Limestone on top of the much younger American Flag Formation. This reverse faulting provides exception to one of the basic principles of geologic thought—superposition—that younger rocks are found above older ones in vertical sequence.

The hardness and composition of these various units determine their topographic expression. The American Flag Formation consists of conglomerates and green-colored, poorly sorted, hard, rock-fragment bearing sandstones. The formation is mainly ancient alluvial fan deposits. It is hard, erosion resistant, and caps ridges and inclined layers that dip to the northeast, north and south of Peppersauce Canyon. The Rice Peak Porphyry invaded this unit but did not produce mineralization.

Figure 58. Movement along the Mogul Fault has placed the 72-75 million-year-old American Flag Formation and the 330 million-year-old Escabrosa Limestone, in Oracle Ridge, in contact with the 1.4 billion-year-old OracleGranite, in the foreground. The fault is located at the base of the escarpment.

The limestones in this part of the range are also erosion resistant and form gray cliffs in canyons and along the mountain front. The Escabrosa Limestone (Figure 61) and its dolomite unit are carbonate rocks composed of calcium carbonate and calcium-magnesium carbonate, respectively. Heat from intrusions of Leatherwood Granodiorite has altered these rocks and the dolomites of the older Martin Formation to white marble. Originally precipitated from sea water and deposited in shallow seas and along coastal plains, these units contain fossil crinoids, corals, brachiopods, fish teeth, and bryozoa. Circulating groundwater has dissolved the limestone and dolomite, enlarging fractures into caves, such as Peppersauce Cave. Mildly acidic rain water and snowmelt have dissolved solution pits on most limestone outcrops (Figure 62).

Figure 59. Upturned layers of sedimentary rock along the eastern margins of the range, south of Peppersauce Canyon.

Figure 60. Inclined layers of rock in the Apache and Bisbee Groups along the southeastern margin of the Santa Catalina Mountains.

Figure 61. Ridge of Escabrosa Limestone. Ocotillo and agave have an affinity for carbonate rocks.

Well-cemented and metamorphosed layers of Dripping Springs Quartzite and Barnes Conglomerate of the Apache Group, the Scanlan Conglomerate of the Pioneer Formation, and the Bolsa Quartzite also form cliffs and ridges. All of these units were originally deposited by streams, in shallow seas, or as sand dunes. The Dripping Springs Quartzite (Figures 63) and the Barnes Conglomerate (Figure 64) are beautifully exposed in Peppersauce Canyon. Boulders of the latter, with quartz, quartzite, and jasper pebbles stretched by the heat and pressure of metamorphism and cemented with a maroon sand matrix, are popular landscaping rock in nearby communities.

Figure 62. Solution pits dissolved into the Escabrosa Limestone by mildly acidic rain water and snowmelt.

Figure 63. Dripping Springs Quartzite, Peppersauce Canyon.

Figure 64. Barnes Conglomerate, Peppersauce Canyon.

The Campo Bonito Formation is a comparatively thin deposit of sandstone, siltstone and conglomerate exposed along slopes in Peppersauce Canyon. It is thought to have been deposited by glaciers in a shallow sea, perhaps 700-800 million years ago.

About 73 million years ago the rocks in this part of the range were invaded by dikes, sills, and other bodies of molten rock that cooled to form the Rice Peak Porphyry. Faulting has dislocated the intrusion, the largest section being Rice Peak. The gray-green porphyry is darker than related granitic rocks and contains more plagioclase than potassium feldspar and is richer in iron and magnesium minerals. The intrusion lacked sufficient heat to produce minerals by contact metamorphism with host rocks. Nor was the intrusion accompanied by large quantities of mineral-bearing hydrothermal solutions. As a result, no deposits of precious or industrial metals have been found within or around the margins of the porphyry. It is relatively hard and resistant to erosion and, together with large expanses of folded and faulted Pinal Schist and Oracle Granite, forms high peaks and ridges in this part of the range.

Over the past 15 million years weathering and erosion by streams wore back this eastern face of the range. Flash floods and debris flows built great sloping aprons of rock debris, called bajadas, which filled the adjacent San Pedro Basin. Faulting and integration of drainage in the basin with that of the Gila and Colorado Rivers caused streams flowing across bajadas to down cut their courses to accommodate their gradients to that of the San Pedro River. In time, these streams carved canyons hundreds of feet below the original bajada surfaces. These bajada remnants (Figures 65 and 66) are a major and graceful component of the landscape.

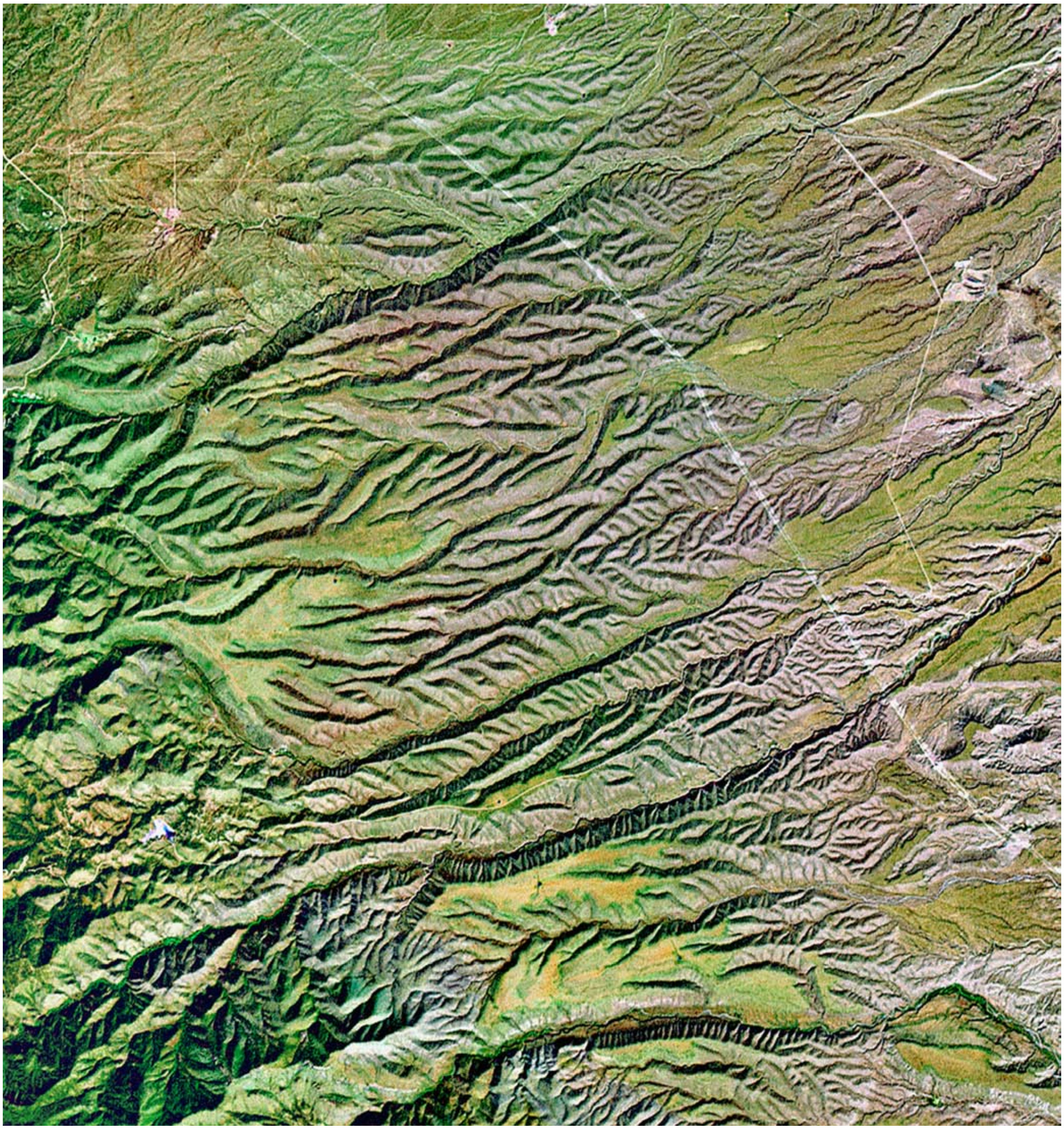


Figure 65. Satellite image of the highly dissected bajada along the eastern margins of the Santa Catalina Mountains.

Figure 66. Highly dissected and oxidized bajada remnants along the eastern margins of the Santa Catalina Mountains.

Mining

Prospectors and miners probably scoured the range between the Mogul and Geesaman Faults since the Spanish and Mexican periods. Formal claims were staked and small mines established beginning in the late 1870s. Many early prospectors lacked the capital to purchase the machinery and stamp mills needed to develop deep mines and process the ore. Many claims were sold to Tucson merchants and groups of wealthy investors from the East. Mines opened and closed as market prices for metals rose and fell. Flooding caused some shafts to be abandoned; others closed as mineral veins were exhausted or the metal content of the ore became too low to extract economically. Some investors, such as William “Buffalo Bill” Cody, lost fortunes because of dishonest partners or employees.

Most metal ores in this part of the range occur along the Mogul and Geesaman Faults. Zones of fault-shattered rock acted as conduits for mineral-bearing solutions from depth to penetrate host rocks at the surface (Figures 67 and 68). These fluids circulated along faults and joints, filling many voids with quartz veins and ores containing the metals. Groundwater emerging as springs along faults provided miners with water needed to work their claims (Figure 69).

Gold and tungsten are the most important metals in this part of the range, followed by silver, copper, lead, vanadium, and molybdenum. Tungsten, vanadium, and molybdenum are important in making steel alloys and have a wide range of other industrial uses.

Figure 67. Mine tailings from mine developed along a fault in the Escabrosa Limestone.

Figure 68. Mine developed along a fault in Peppersauce Canyon. Fault zones are frequently conduits for percolating, mineral-rich waters.

Figure 69. Spring emerging from a fault in the Escabrosa Limestone.

PART 5: The Crest of the Santa Catalina Mountains

Roads and Places: the Catalina Highway and the Mt. Lemmon Road

The highest portion of the Santa Catalina Mountains is bounded by the Geesaman Fault on the north and the Wilderness Suite Granite on the South. Hidden beneath the forest cover is some of the most complex geology of the range. Capping the massive granites and gneiss that form most of the 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 roof of igneous intrusions are called "roof pendants". And, indeed, the brilliant cliffs of limestones and dolomite in Marble Peak (Figure 70) and other outcrops must have seemed to many an alluring adornment offering hopes of riches.

Major sedimentary and metamorphic units in the roof pendant include: the mostly carbonate rocks of the Earp, Martin, and Abrigo Formations, 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 Apace Group. Smaller outcrops of other units occur throughout this highest portion of the range. Intense folding and faulting has added to the complexity of the rocks along the crest of the range. In the Mount Bigelow area the folds are so tight that they are in a nearly horizontal position (called recumbent folds). Thrusting along the Edgar Fault and other fractures has shoved older rocks above younger rocks, disrupting the normal vertical sequence of the bedrock (Figure 71). As in other parts of the range, these faults served as plumbing for hot, mineral bearing solutions to deposits metals.

Figure 70. Tilted layers of limestone and dolomite are the bedrock in Marble Peak.

Figure 71. Older Dripping Springs Quartzite at the top of the road cut has been thrust-faulted over the younger Mescal Limestone below (Photo courtesy of Dr. Larry Fellows).

About 69 million years ago a massive body of molten rock (magma) intruded many of the above mentioned rocks, particularly the carbonate rocks and the Dripping Springs Quartzite. This magma, which cooled to form the Leatherwood Granodiorite (Figure 72), was accompanied by tremendous heat and huge quantities of hydrothermal solutions that altered and produced mineralization in the host rocks—particularly the limestones and dolomites. The Leatherwood Granodiorite in composition locally from s granite to diorite, and is rich in biotite. Many smaller dikes and sills penetrated other, older rock units as well.

Figure 72. Leatherwood Granodiorite intruded by pegmatite dikes (Photo courtesy of Dr. Larry Fellows).

Mining

The richest mineral zone is where the Leatherwood Granodiorite invaded the Escabrosa Limestone and the Martin Formation in the Marble Peak area. Hot fluids accompanying the granodiorite contained aluminum, magnesium, and iron in solution. As these fluids reacted with the limestones and dolomites, these minerals combined with those from the carbonate rocks to produce an ore call called skarn. Copper, zinc, gold, lead, silver and other metals have been produced from skarn ores of Marble Peak since the 1880s. Copper is particularly abundant along the bedding planes in the Escabrosa Limestone. Iron in the form of magnetite is present but has not been commercially produced. Mineral bearing solutions also flowed along the shattered rock of faults, depositing metals in voids of rocks along Red Ridge and other locations. Heat and pressure from the intrusion altered the limestones and dolomites of the Martin and Earp Formations and the Escabrosa and Horquilla Limestones to white marble at Marble Peak. Mineralization in this part of the range may also have been produced by hydrothermal solutions from the Catalina Granite 26 million years ago.

The injection of the circular Catalina Granite pluton shaped the topography in the headwaters of the Cañada del Oro. 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 canyon of the Cañada del Oro its curved course (Figures 73 and 74).

The Marble Peak mines have produced metals intermittently since the late 1930s. Various companies, including Phelps-Dodge Copper Company, the Continental Materials Corporation, and Union Mines, Inc., have owned these properties. Due to low copper prices and operational problems, profits have not met expectations.

Figure 73. The course of the upper Cañada del Oro is controlled by the curved outcrops of host rocks deformed by the Catalina Granite pluton (Photo courtesy of Dr. Anthony Lux).

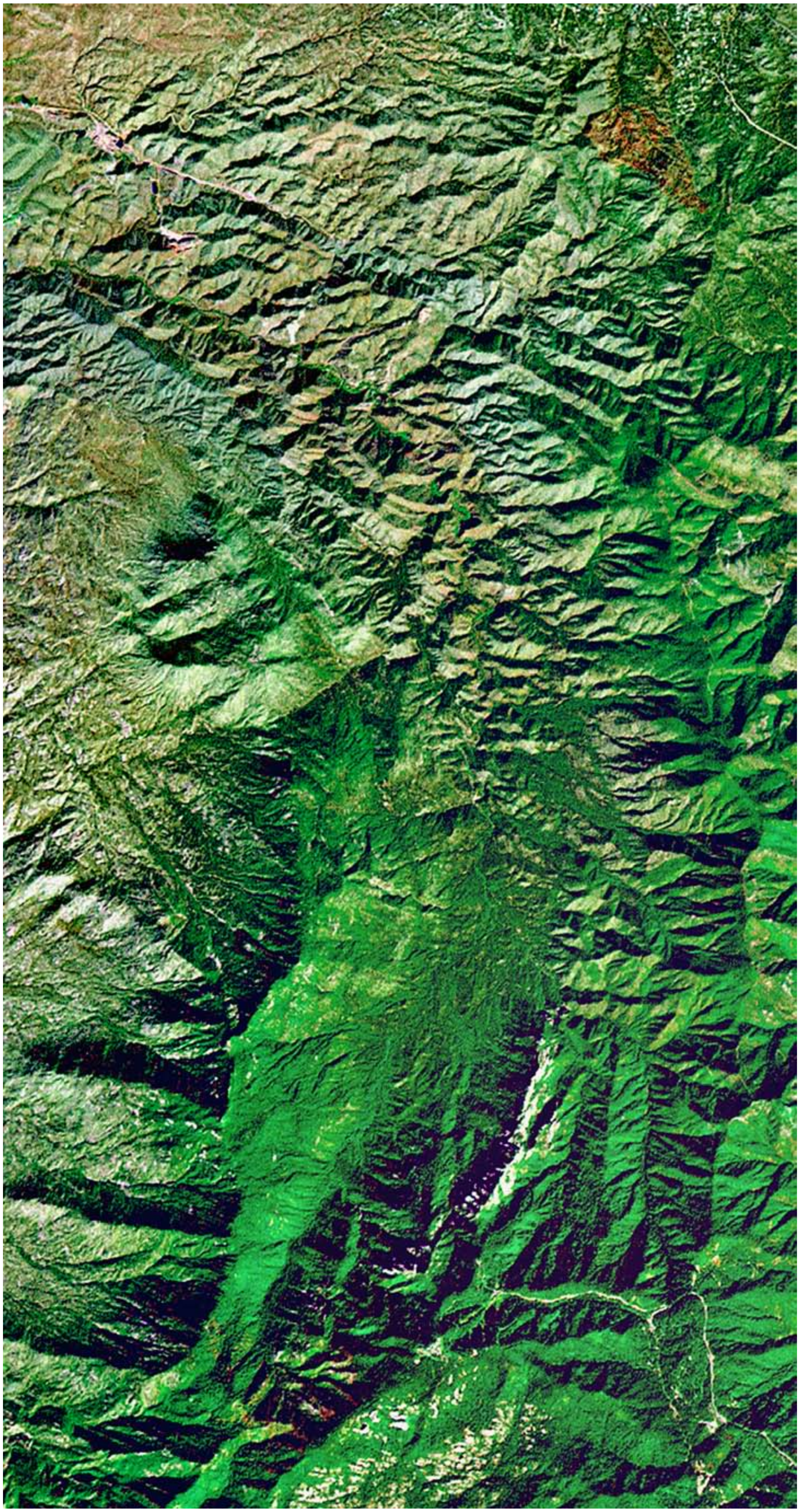


Figure 74. The course of the Cañada del Oro follows the curved outcrops of host rocks deformed by the Catalina Granite pluton.

PART 6: Life Zones of the Santa Catalina Mountains

Roads and Places: the Catalina Highway, the Mt. Lemmon Road, Sabino Canyon, Catalina State Park

The vegetation and wildlife of the Santa Catalina Mountains is as diverse as the geology. Ecologists have identified a series of life zones, associated primarily with elevation and are characterized by a distinctive associationof plants (Figure 75). These life zones and their approximate 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 9157 ft; 2438-2791m)
Canyon woodland (up to 6500 ft; 1981m)

Precipitation, soil moisture, air temperature, and topography, especially slope aspect (compass direction a slope faces), are major factors controlling this vertical zonation. Soil chemistry and the parent rock from which it 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 where 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 within drainages makes it possible for species from higher life zones to become established within lower zones. The plants of each zone generally reach their upper elevational limits on south-facing slopes and their lower limits on north-facing slopes. South-facing slopes receive more intense energy from the sun that 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 Sonoran Desert plants

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.

Vegetation

Sonoran Desert scrub (up to 4000 ft; 1291 m) (Figure 76)

The hallmark plants of this part of the Sonoran Desert are saguaro (*Carnegiea gigantea*), Foothill palo verde (*Cercidium microphyllum*), and ocotillo *(Fouquieria splendens*).. These plants prefer rocky, well drained soils and are particularly abundant on the south-facing slopes of the forerange. There are various species of cholla (*Cylindropuntia spp.*), prickly pear (*Opuntia spp.*), and barrel cactus (*Ferocactus spp*). Other trees include mesquite (*Prosopis velutina*), acacia (*Vachellia constricta* and *Senegalia greggii*), ironwood (*Olneya tesota*), 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. Some of these plants have spines, which help them conserve water and 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, acacias, mimosa, and saguaro, originated in the subtropics of what is now southern Sonora and Sinaloa and are adapted to the climatic conditions that became progressively dryer and warmer.

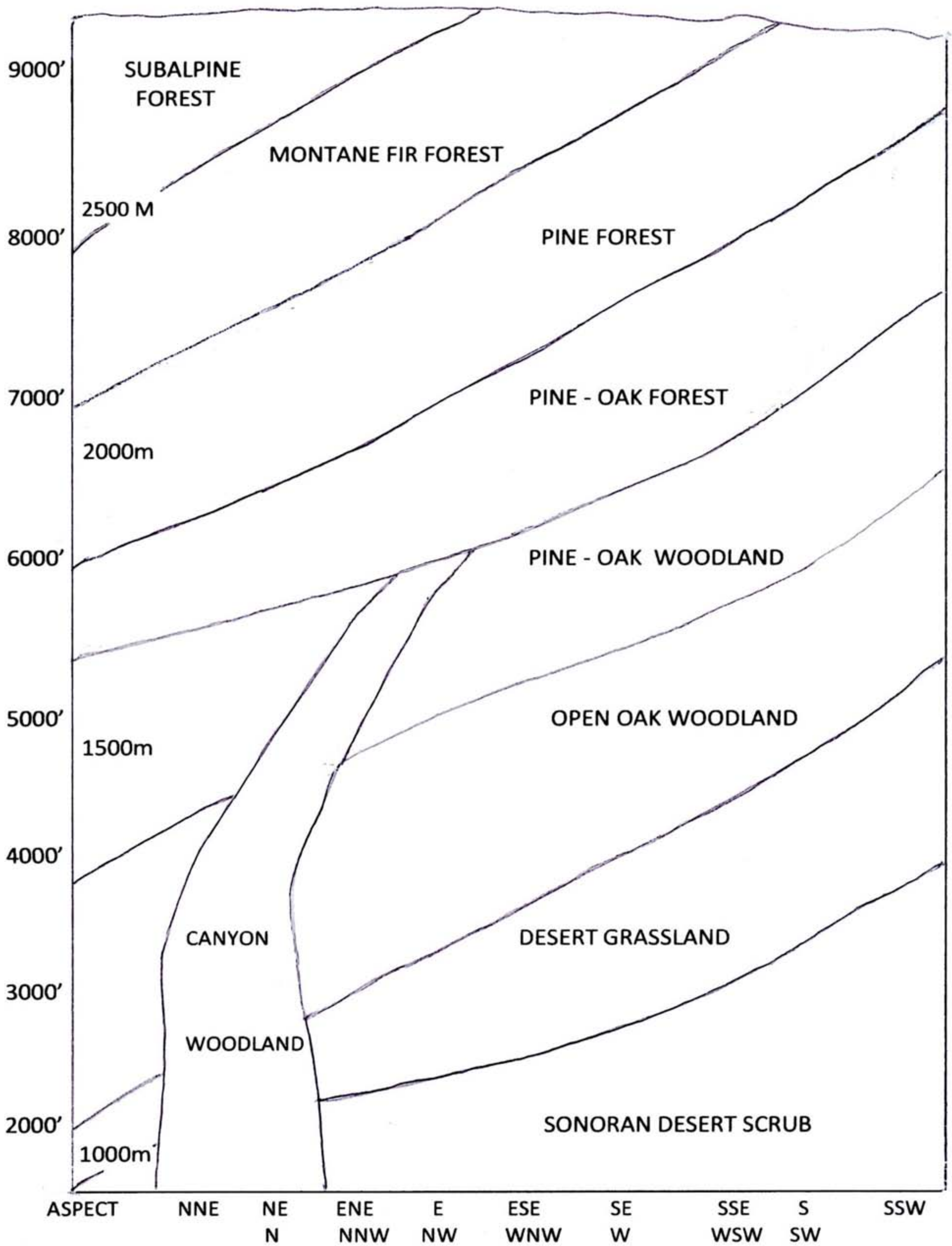


Figure 75. Life zones of the Santa Catalina Mountains showing elevation and slope aspect (After Whittaker, 1975).

Figure 76. Sonoran Desert scrub, best developed on dry, well-drained, south-facing slopes, Babad Do'Ag Vista, Catalina Highway.

Desert grassland (3500 to 5400 ft; 1067-1646 m) (Figure 77)

Above 3500 to 4000 feet elevation temperatures are too low for many Sonoran Desert scrub plants and mountain slopes support a variety of grasses that include sideoats grama (*Bouteloua curtipendula*), spider grass (*Aristida ternipes*), slender grama (*Bouteloua filiformis*), and tanglehead (*Heteropo-gon contortus*). Scattered ocotillo (*Fouquieria splendens*), mesquite (*Prosopis veutina*), and catclaw (*Senegalia greggii*) and whitethorn (*Vachellia constricta*) acacias are conspicuous tree forms. Many desert grassland sites 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 has 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.

Open oak woodland (3700 to 6400 ft; 1128-1951 m) (Figure 78)

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 often grow in widely spaced, park-like distributions. Grasses, shrubs, herbs, succulents like agave and cacti grow in the more open interspaces. The Spanish term *enciñal*—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 *(P. leiophylla* var. *chihuahuana)* and Apache pine *(P. engelmannii).* Shrubs such as manzanita (*Arctostaphylos spp.*) may also occur within 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 wildfires.

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

Figure 77. Desert grassland, degraded by over a century of overgrazing, Molino Canyon, Catalina Highway.

Figure 78. Open oak woodland, near Bug Springs Campground, Catalina Highway.

Pine-oak woodland (4800 to 7400 ft; 1463-2256 m) (Figure 79)

With the increased moisture and lower average temperature of this life zone the trees 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 (*Q. hypoleucoides*), netleaf oak (Q. 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 79. Pine-oak woodland, near General Hitchcock campground, Catalina Highway.

Pine-Oak Forest (5600 to 8600 ft; 1701-2621 m) (Figure 80)

Increased moisture and cooler temperatures at this elevation result in a forest dominated by Ponderosa pine (*Pinus ponderosa*) 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.

Figure 80. Pine-oak forest life zone, near San Pedro Vista, Catalina Highway.

Pine forest (6000 to 9600 ft; 1829-2926 m) (Figure 81)

At this elevation, ponderosa pine, Arizona pine (*Pinus arizonica*), southwestern white pine (*P. 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 the range, is also present in this zone.

Figure 81. Pine forest life zone, near Box Elder picnic area, Catalina Highway.

Montane fir forest (6700 to 9100 ft; 2042-2774 m)(Figure 82)

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.

Figure 82. Montane fir forest, near Mt. Lemmon, Catalina Highway.

Subalpine forest (8000 to 9157 ft; 2438-2791 m)(Figure 83)

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

Two wildfires, the Bullock Fire in 2002 and the Aspen Fire in 2003, affected nearly 114,000 acres of pine, montane fir, and subalpine forests–most of the high country forests (Figure 84). Many of these tree species evolved with low, rapidly moving wildfires that clear the forest of undergrowth and dead trees. But years of wildfire suppression by humans led to a buildup of fuels that caused these destructive conflagrations.

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 have since isolated these populations from those of the Rocky Mountains.

Figure 83. Subalpine forest below Mt. Lemmon.

Figure 84. Destruction by the 2003 Aspen Fire, near junction of Mt. Lemmon Road and Catalina Highway. The photo was taken in 2012.

Canyon woodland (up to 6500 ft; 1981 m)(Figure 85)

Cañada de Oro, Sabino Canyon, Peppersauce Canyon, and other drainages that have sufficient surface or subsurface water flow may 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 drummondii*), 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 85. Canyon woodland, Peppersauce Canyon.

Wildlife

The diverse life zones of the Santa Catalina Mountains 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*), woodrats (*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. Disease introduced by domestic livestock has greatly reduced the desert bighorn sheep population. Jaguar (Felis onca), grizzly bear (*Ursus arctos horribilis*), and Mexican wolf (*Canis lupus baileyi*) once inhabited the Santa Catalina Mountains 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*), common black hawk (*Buteogallus anthracinus*), gray hawk (*Asturina nitida*), Harris hawk (*Parabuteo unicinctus*), northern goshawk (*Accipiter gentilis*), red-tailed hawk ((*Buteo jamaicensis*), and 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*), western screech-owl (*Otus kennicottii*), and 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, 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), 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 Santa Catalina Mountains 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, Saddlebrooke, Oro Valley, and Oracle, many mammals could winter in and cross the basins bordering the Santa Catalina Mountains to reach nearby ranges. Continued urban expansion in the basins, and recreational and residential development within the mountains at Summerhaven have led to reduced habitat and smaller wildlife populations. Habitat loss continues to be the greatest threat to wildlife in the Santa Catalina Mountains region.

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Inside back cover. The summer monsoon brings life-giving rains and wildfires to the Santa Catalina Mountains. (Photo courtesy of Dr. Anthony Luz).

Poppies after spring rain (Photo courtesy of Dr. Anthony Lux).

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