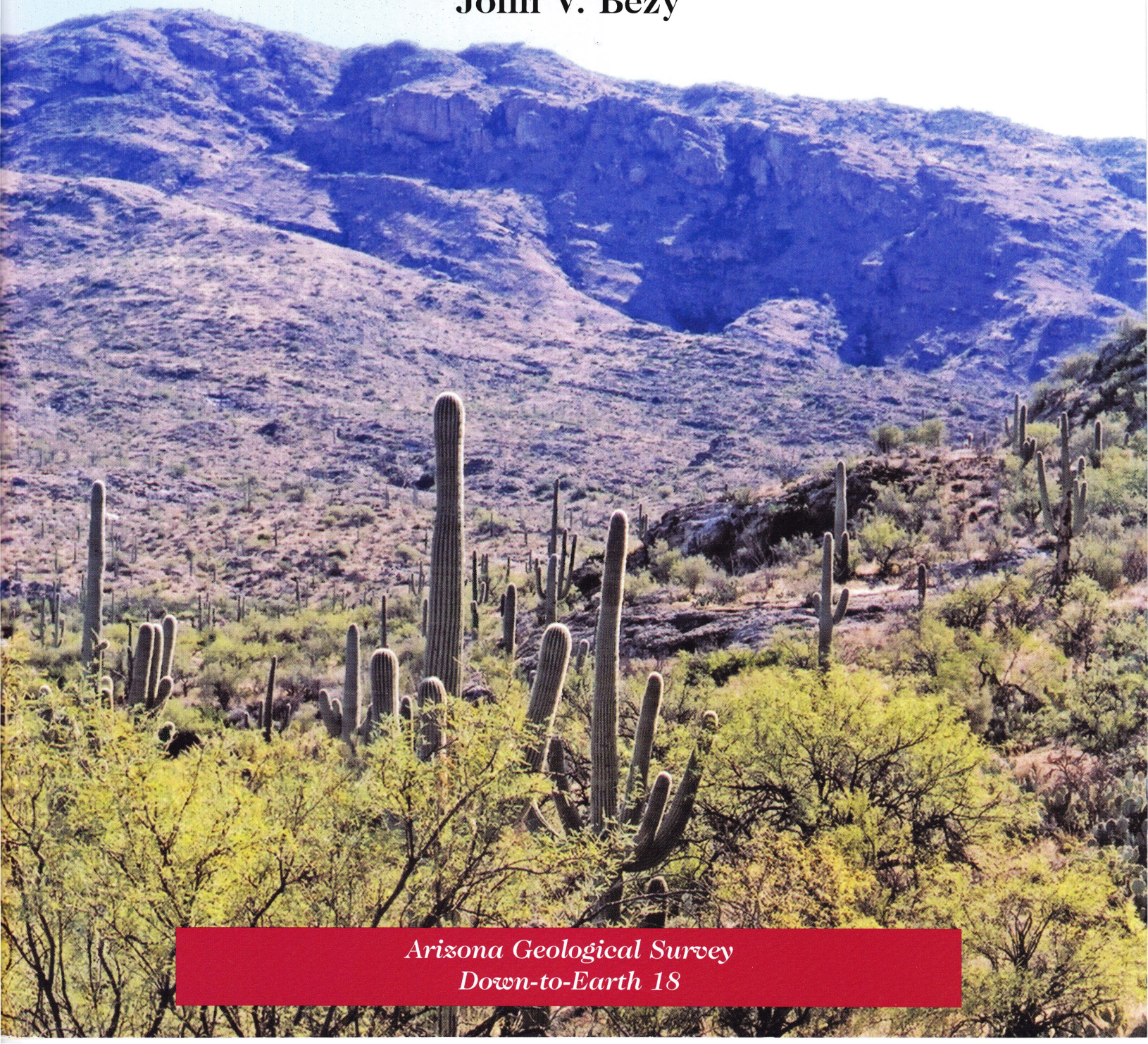


A GUIDE TO THE GEOLOGY OF

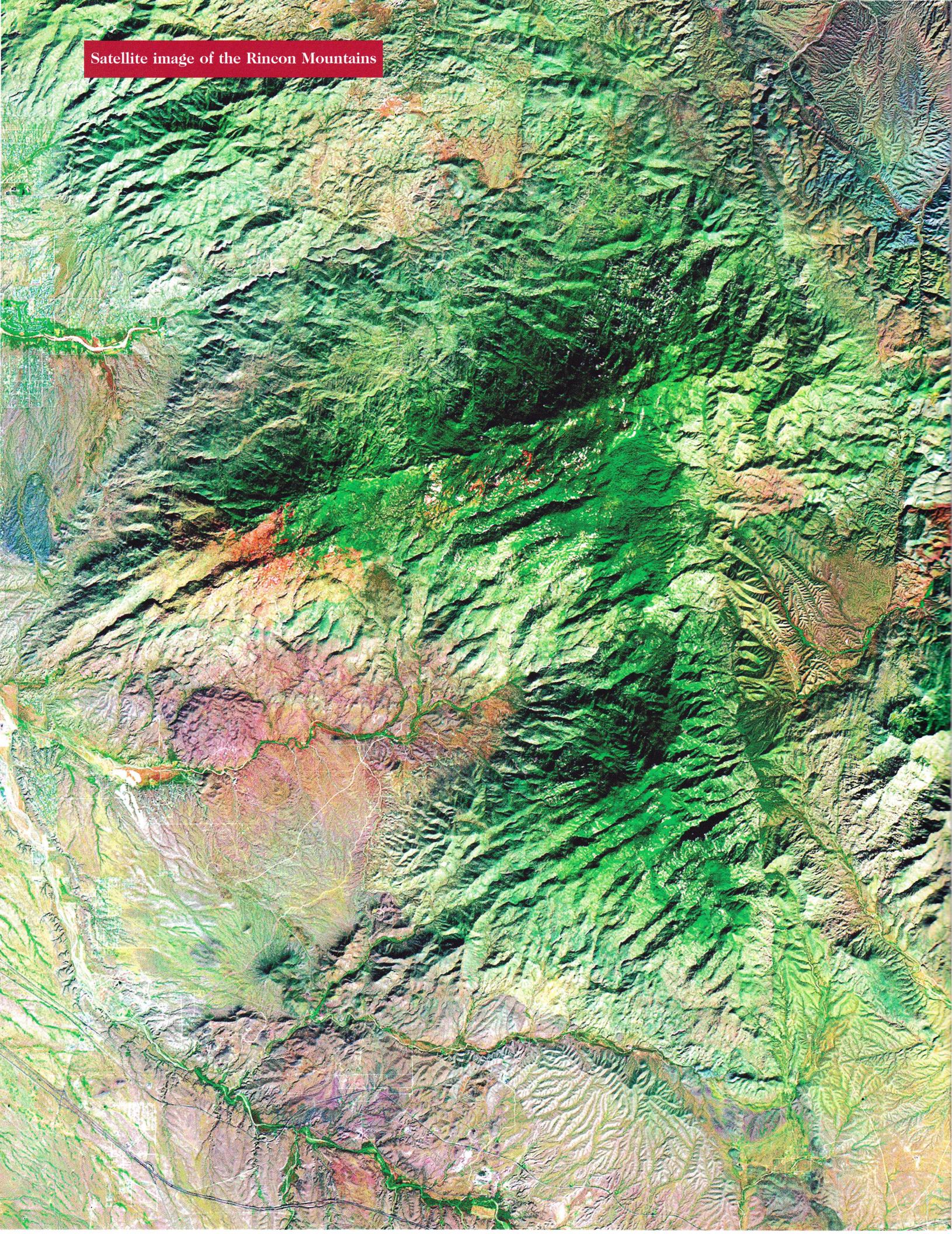
SAGUARO NATIONAL PARK

John V. Bezy



*Arizona Geological Survey
Down-to-Earth 18*

Satellite image of the Rincon Mountains



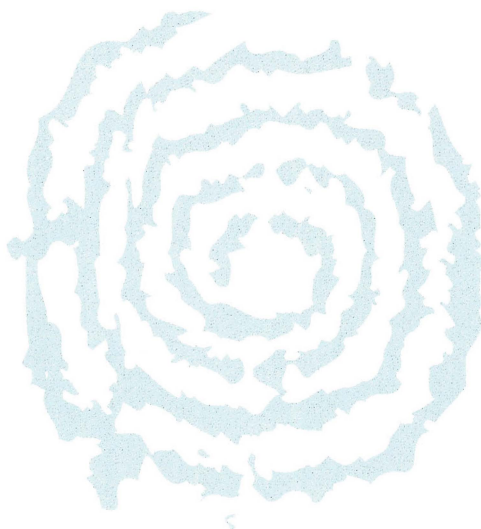
A GUIDE TO THE GEOLOGY OF

SAGUARO NATIONAL PARK

John V. Bezy

Photographs by

Larry D. Fellows
Director and State Geologist
Arizona Geological Survey



Arizona Geological Survey
Down to Earth 18

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Dr. John Dohrenwend graciously granted permission to use his satellite images in this publication. Poster-sized satellite image maps (1:100,000 scale) of the Tucson Basin, the Santa Catalina Mountains, and the Rincon Mountains may be ordered from John Dohrenwend; P.O. Box 1467, Moab, UT 84532-1467; Phone ((866) 230-8941; E-mail; Dohrenwend@rkymtnhi.com.

This publication would not have been possible without the professional support of Dr. Larry D. Fellows, Director of the Arizona Geological Survey (retired).

INTRODUCTION

Saguaro National Park (Figures A and B) offers a variety of spectacular geologic features. Because of the relatively sparse vegetation in the lower elevations of the park, most of these features are easy to recognize and photograph.

Some of these features are common throughout the Southwest. Others occur only in regions that have similar geology.

This booklet is your field guide to the geology of this magnificent desert and mountain landscape. Most of the geologic features described in the text can be reached by short hikes from the tour roads of the park. This book is written for the visitor who has an interest in geology, but who may not have had formal training in the subject. It may also help ensure that the visiting geologist does not overlook some of the features described.

To set the stage, I have briefly described the geologic setting and history of the Tucson Basin. More detailed discussions of the general geology precede the Tucson and Rincon Mountains sections of the guidebook.

In the following pages, emphasis is given to geologic features that are common in the landscape. Precise directions to each feature are provided in the text. The locations of the geologic features and the access roads and trails that should be used are shown on Figures A and B. All roads are used by hikers and bicyclists and should be driven with care.

Another purpose of the field guide is to provide the reader with an understanding of the dynamic processes that have shaped this exceptional landscape. Many of the features discussed in the text will be encountered again and again as you continue to explore the Southwest. We hope that your experience in Saguaro National Park will enhance the pleasure of those explorations.

Please help preserve the features in the park for future generations by not collecting samples. All natural and cultural resources in Saguaro National Park are protected by law. Off-road vehicle travel is not permitted in Saguaro National Park. Much of the Rincon Mountains section of the park below 4,500 ft (about 1500 m) is closed to off-trail hiking or equestrian use. Mine shafts can be death traps and should not be entered.



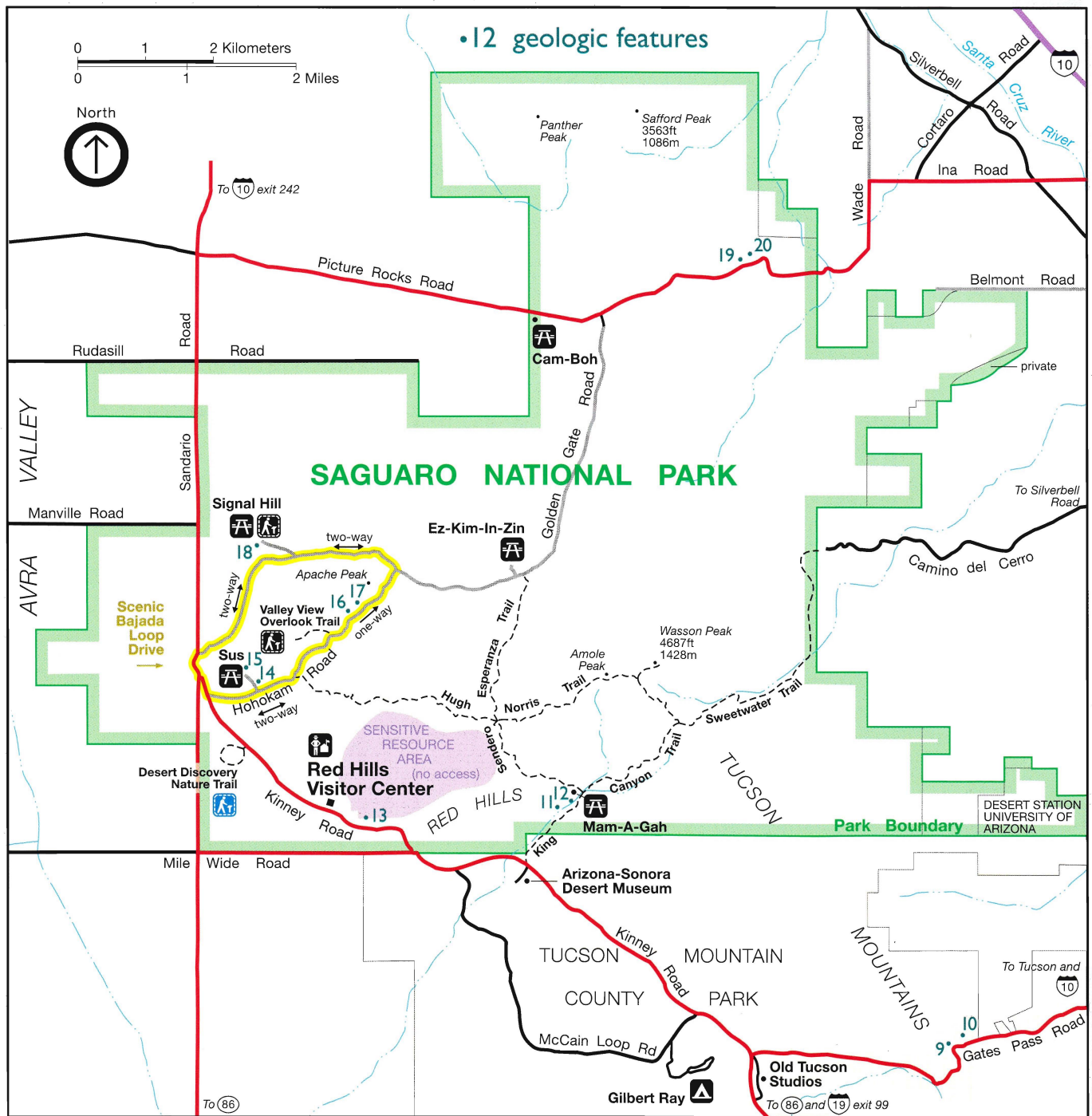


Figure B. Geologic features in the Tucson Mountains District, Saguaro National Park.



Scenes along the Tucson Mountains Tour Road.



GENERAL GEOLOGY OF THE TUCSON BASIN

The Earth's brittle surface, the *crust*, is broken into plates that are in motion (Figure C). In some areas the plates are colliding; in others they are sliding past or overriding each other. In the ocean basins plates are moving apart and new crust is forming. Saguaro National Park's present landscape is ultimately related to such plate movements.

About 80 million years ago, the westward-moving North American plate was overriding a plate beneath the Pacific Ocean to the west. The heavier ocean-basin rock was forced beneath the lighter continental rock of the North American plate. Friction between these converging plates compressed and thickened the crustal rocks of western North America, producing a period of mountain building known as the *Laramide Orogeny* that lasted until about 50 million years ago.

The temperature of the subsiding oceanic rock that was being depressed increased with depth, causing the rocks to melt. Water in the ocean rock accelerated melting as it mixed with hot rocks in the Earth's mantle. The overly thickened, deep roots of the compressed mountain belts of western North America also experienced partial melting. This melted rock, called *magma*, rose buoyantly through and assimilated the overlying crustal rocks. In places where the magma reached the land surface volcanoes formed and molten rock spread out on the ground as lava. The 70-million-year-old volcanic rocks of the Tucson Mountains are products of these explosive volcanic eruptions. Granite in the same range formed from molten rock that cooled and crystallized far below the surface.

Between 35 and 15 million years ago changes in plate motion caused the crust

beneath western North America to stretch, thin, and break along low-angle fractures called *detachment faults*. Heat and pressure accompanying movement along these faults produced uplifts of highly sheared and metamorphosed rock called *metamorphic core complexes*. The Catalina fault, the detachment fault associated with the Rincon and Santa Catalina Mountains metamorphic core complex, parallels the western and southern margins of those ranges respectively. This fault, covered by sediment for most of its length, is exposed near the tour road in the Rincon Mountains section of Saguaro National Park.

Continued extension of this part of North America, between 12 and 5 million years ago, caused the crust to break into blocks separated by new, more steeply dipping faults. Some of these crustal blocks subsided as much as 2.4 miles (1.4 km) relative to the other blocks to form deep basins, such as the Tucson basin and Avra Valley. The high-standing blocks between these basins were eroded to form mountains. This period of crustal deformation formed the Basin and Range geologic province that extends from southern Oregon to northern Mexico (Figure E).

Downward-cutting streams exposed the rocks of the rising Rincon Mountains. In the Tucson Mountains, faulting, and erosion by running water, obliterated the original circular-shape of the volcanic caldera. Canyon-cutting flash floods have worn down both ranges and filled the adjacent basins with thousands of feet of sediment. Fan-shaped deposits of rock debris, called *alluvial fans*, accumulated where canyons exit the mountains. These fans also have been highly eroded by running water.

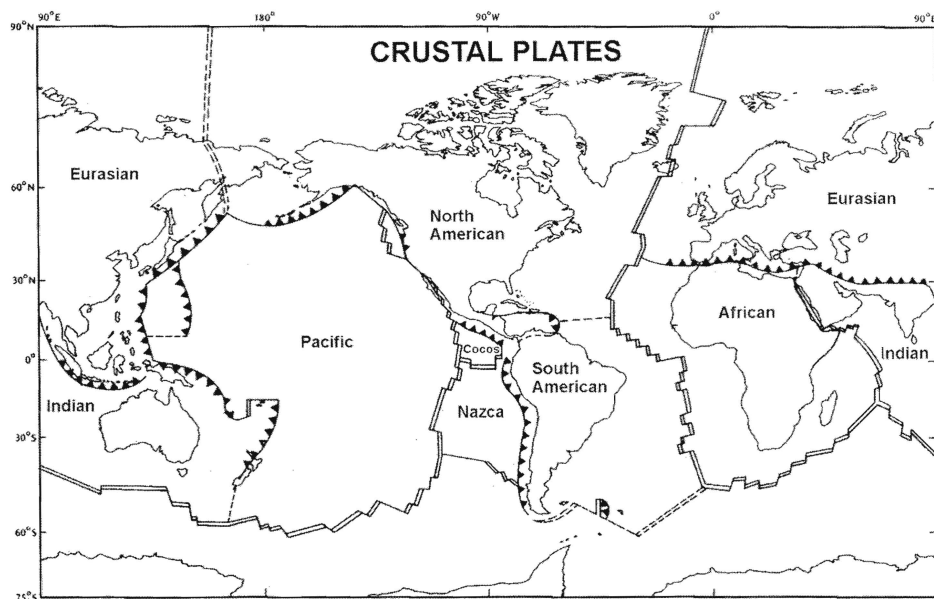


Figure C. Earth's crustal plates. Movement of these plates is responsible for earthquakes, volcanic eruptions, and tectonic features such as metamorphic core complexes.

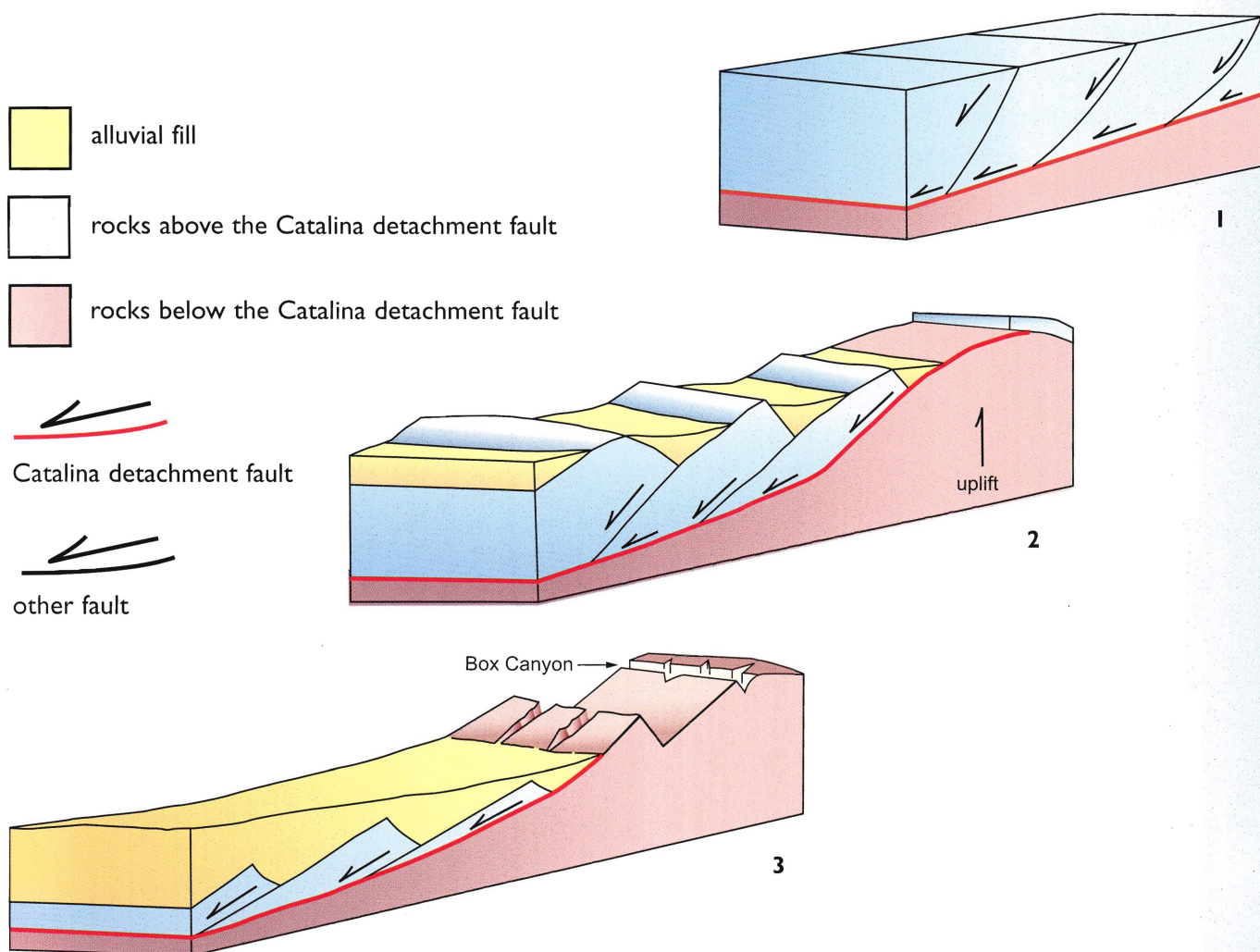


Figure D. Block diagram illustrating the formation of the Rincon Mountains metamorphic core complex.

Metamorphic Core Complexes

1. Frenchman's Cap
2. Thor-Odin
3. Pinnacles
4. Valhalla
5. Okanogan
6. Kettle
7. Selkirk
8. Bitterroot
9. Pioneer
10. Albion-Raft River-Grouse Creek
11. Ruby
12. Snake Range
13. Whipple
14. Buckskin-Rawhide
15. Harquahala-Harcuvar
16. White Tank-South Mountain
17. Picacho
18. Tortolita
19. Catalina-Rincon (red)
20. Santa Teresa-Pinaleno
21. Comobabi-Coyote
22. Pozo Verde
23. Magdalena
24. Madera
25. Mazatan
26. Death Valley turtle backs

--- Basin and Range geologic province

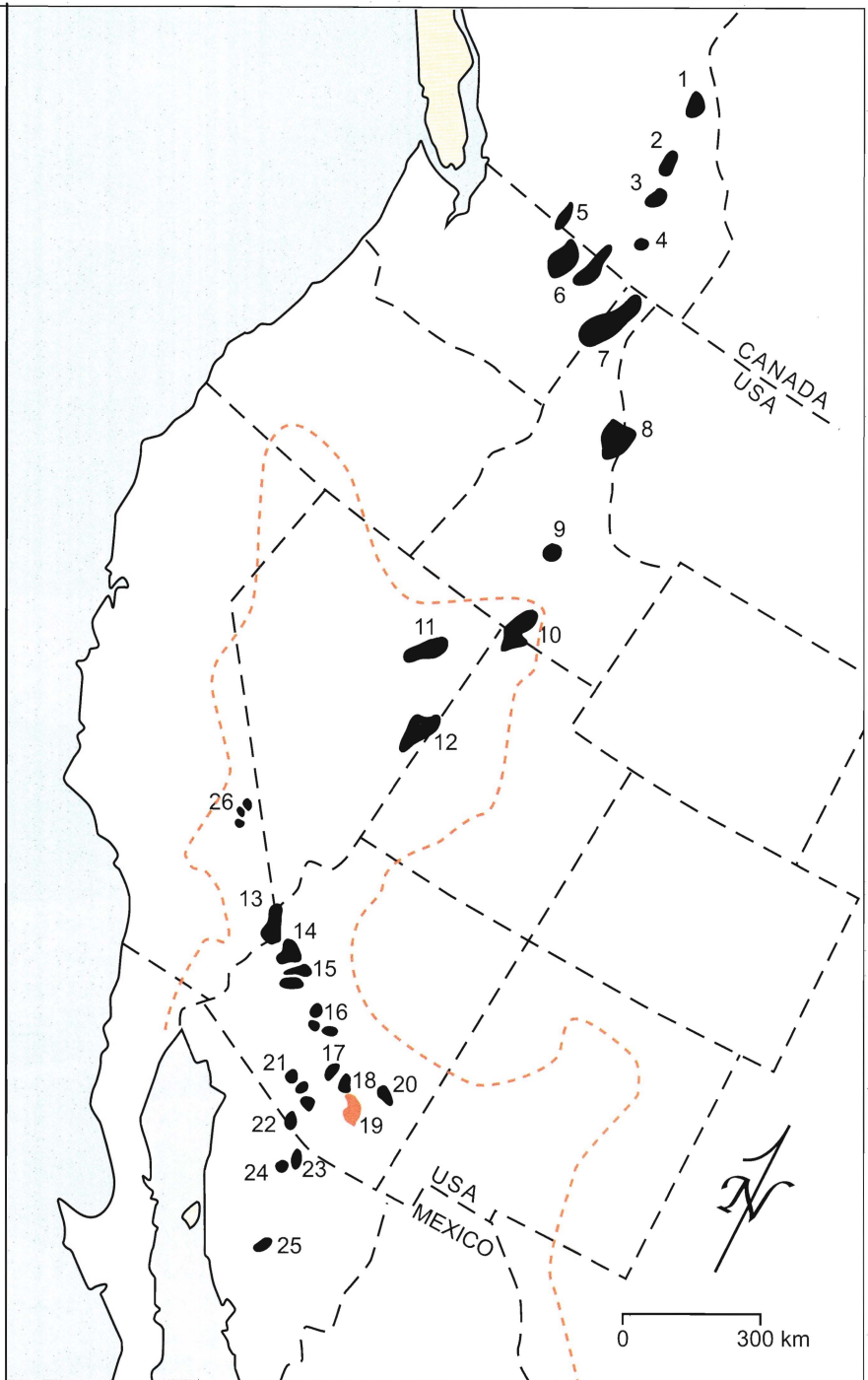


Figure E. Distribution of metamorphic core complexes in western North America (modified from Crittenden Jr., Coney, and Davis, 1980).

GENERAL GEOLOGY OF THE RINCON MOUNTAINS

The Rincon Mountains are, in large part, a highly eroded uplift of bedrock, called a metamorphic core complex. Although running water has cut canyons into the mountain range, much of its original arched shape is preserved.

The Rincon, Santa Catalina, and Tortolita Mountains are among several dozen metamorphic core complexes that extend from northern Mexico into southern Canada (Figure E). They formed as a result of the stretching and thinning of the Earth's crust in western North America beginning 35 to 30 million years ago.

In some parts of the continent this stretching and thinning caused crustal rocks to pull apart and break along low-angle fractures (usually less than 30 degrees) called detachment faults. The Catalina fault, the detachment fault associated with the uplift of the Rincon Mountains, parallels the western margin of the range but is covered by sediment for most of its length (Figure F).

The Catalina fault began to form about 30 million years ago at a depth of about 6 to 8 mi (10 to 13 km). Rocks below the fault (called lower plate rocks) were moved to the east-northeast 16 to 19 miles (25 to 30 km) relative to those above the fault and rose closer to the Earth's surface as rocks above the fault (upper plate rocks) descended toward the southwest (Figure D).

This movement deformed rocks above and below the fault. Those rocks far below the fault, mainly Wilderness Suite and Oracle granites, were so hot that they flowed like putty. The min-

eral crystals in these rocks, especially quartz, smeared plastically. Other minerals in the same rock, particularly feldspar, broke into pieces or had their corners broken off to produce lenticular crystals called *augen* ("eyes" in German). This deformation of the granites resulted in a new rock type called *gneiss*. Rocks above the fault were cooler, deformed in a brittle manner, and shattered into angular fragments called *breccia*.

As the rocks below the detachment fault slowly rose toward the surface, they were domed up in response to the removal of the weight of overlying rocks. Continued extension of this part of North America broke the crust into blocks separated by new, more steeply dipping faults. Some of these crustal blocks were further uplifted to form the mountain ranges of the region, such as the Rincon Mountains. Other blocks subsided as much as 2.4 miles (about 4 km) to form deep basins, such as the Tucson Basin.

Downward cutting streams encountered the rocks of the rising Rincon Mountains and stripped away much of the breccia from the crest of the once-buried complex. Continued erosion by running water along joints (natural cracks) and faults cut canyons into the hard gneiss slopes of the range.

Sediment flushed down these canyons during flash floods formed beveled rock platforms, called *pediments*, along the margins of the range. A thin veneer of this rock debris, remnants of alluvial fans, covers most of the pediments. Today, wet-weather drainages are cutting into the sediment and the underlying pediments.

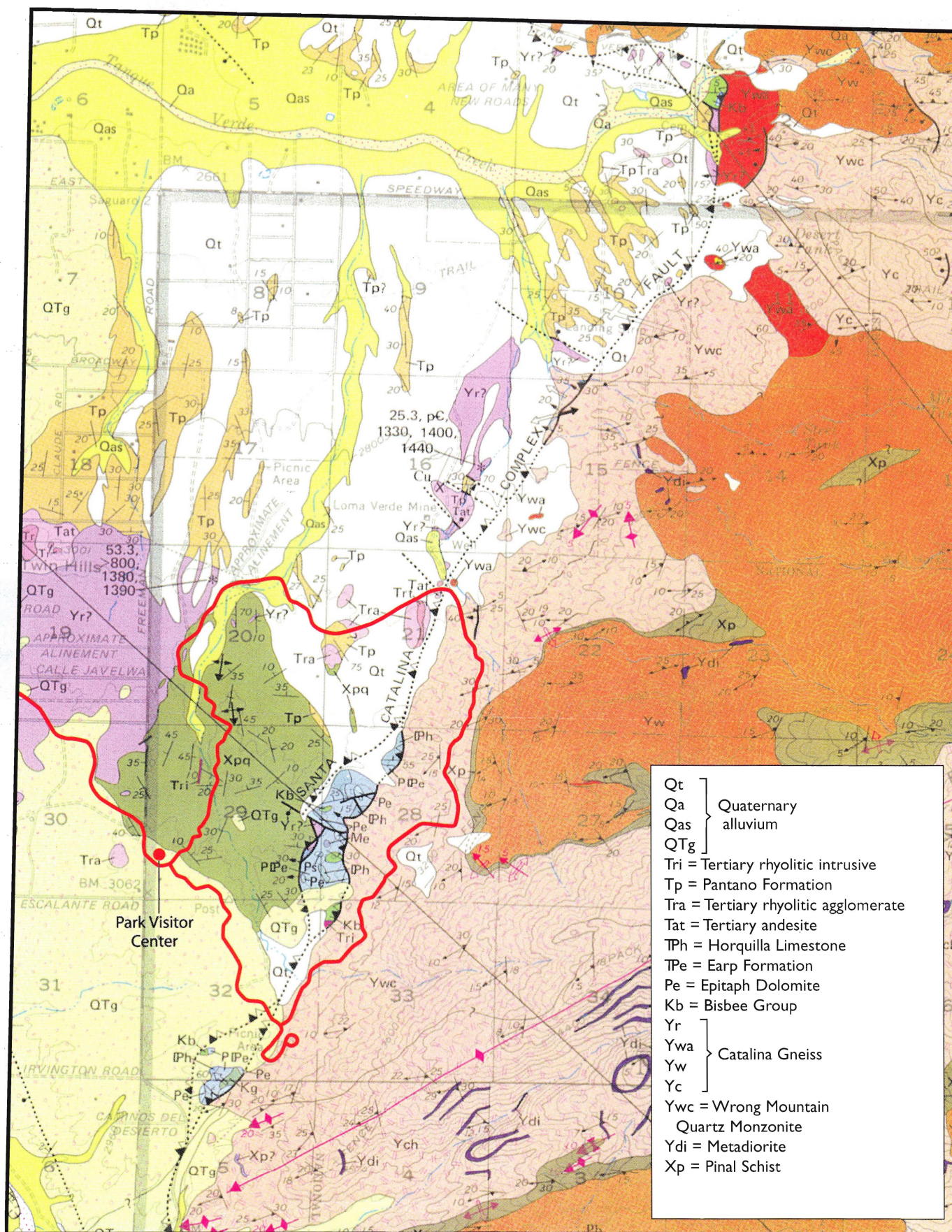


Figure F. Geology of the tour road area, Rincon Mountains District, Saguaro National Park. Geologic map from Drewes (1977).

GEOLOGIC FEATURES IN THE RINCON MOUNTAINS DISTRICT

Locations of geologic features in the Rincon Mountains District of Saguaro National Park are provided in relation to mileage on the tour road, beginning at the Entrance Station. For example, to visit

Feature 1 drive 0.5 mi past the Entrance Station and then hike 35 yd (about 35 m) to a rock face. Please note the reading on your car's odometer at the Entrance Station and use it to keep track of mileage as you drive the tour road.



Feature 1

SCHIST (PINAL SCHIST)

LOCATION

Tour road, mile 0.5. Park along the right side of the road just before crossing the dry wash. Walk this drainage upstream (right) for about 35 yd (about 35 m) to a stream bank of dark-colored rock.

“Over time sedimentary rocks were buried at depth and subjected to intense heat and pressure”



Figure 1.1 Pinal Schist.

The dark gray rock exposed along the east side of this dry wash is the *Pinal Schist* (Figure 1.1). At about 1.65 billion years old, it is the most ancient rock in southern Arizona. The Pinal Schist was originally deposited as layers of sandstone, siltstone, and shale. These rocks probably represent a marine environment that received much sand, silt and clay from a nearby continent.

Over time these sedimentary rocks were buried at depth and subjected to intense heat and pressure, transforming them into new rocks — called schists and phyllites. These highly altered rocks bear little resemblance to the original sedimentary layers. The schist is silver-gray in color and has thinly bedded layers of quartz and mica; the phyllite has a satiny appearance with fine, wavy planes of aligned very fine grained minerals such as mica. The schists and phyllites have been highly fractured by faulting.

All rocks are divided into three great categories. Sedimentary rocks are composed of rock fragments or precipitated minerals that were deposited by standing or running water, ice, or wind. Igneous rocks were once so hot they were molten. The Pinal Schist is an example of the third category — metamorphic rocks. These were once sedimentary, igneous, or metamorphic rocks that have been chemically and structurally transformed by intense heat and pressure into new material. Sometimes the change is so great that it is not possible to identify the parent rock.

Feature 2

PEDIMENT

LOCATION

Tour road, mile 0.6. Park and look toward the southeast.



Figure 2.1. Pediment surface (dashed line) cut on Pinal Schist.

The top of the Pinal Schist at this location (Figure 2.1, A) is a surface that gently slopes from the Rincon Mountains (B) toward the Tucson Basin. This surface is part of a more extensive beveled platform of bedrock, called a *pediment*. Here, the pediment is covered by a thin veneer of sand and pebbles, worn from the Rincon Mountains and deposited by running water. In other locations, erosion has exposed the pediment surface. Most exposed pediment surfaces are uneven, incised by shallow stream channels, covered by patches of sediment, and dotted with low bedrock hills.

Many geologists believe that small streams draining from the face of the range planed off the pediment surface. Other geologists are convinced that these features were formed by the deep weathering of the bedrock, perhaps when the climate of southern Arizona was warmer and wetter. Study and debate continues on the origin of these landforms.

Downslope from the mountain front, pediments are buried by increasing thicknesses of sediment. In many basins the deeply buried pediments are terminated by high-angle faults.

Exposed pediments, together with bajadas (Feature 17), are hallmark landforms of the Basin and Range geologic province. They form the long, smooth slopes that extend from mountain fronts to the centers of adjacent basins.

Buried pediments are a consideration in the search for water as cities expand onto the margins of desert basins. Many well drillers, hoping to find sediment saturated by groundwater, have been disappointed by encountering shallowly buried bedrock pediments which yield little water.

“Buried pediments are a consideration in the search for water”

Feature 3

TRIANGULAR DOME FACETS

LOCATION

Tour road, mile 1. Park and look toward the Rincon Mountains to the east and southeast.

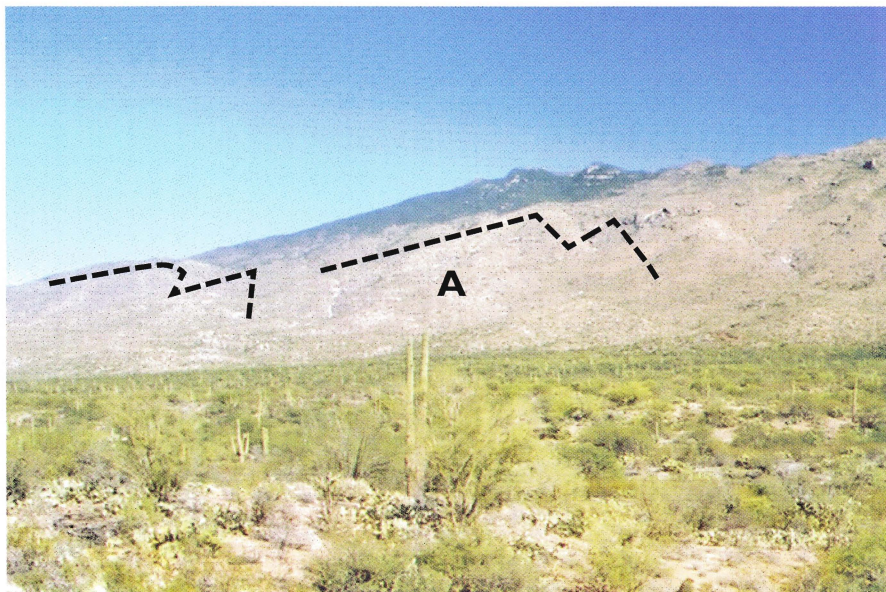


Figure 3.1. Triangular dome facets along the western margin of the Rincon Mountains.

Triangular-shaped, convex rock faces (Figure 3.1, A) separated by V-shaped canyon mouths form the western margin of the Rincon Mountains. These landforms, called *triangular dome facets*, retain the original arched form of the bedrock when it was first being exposed to weathering and erosion at the Earth's surface. They are hallmark features of metamorphic core complexes.

About 20 to 30 million years ago, the crust in this part of the continent was stretched, thinned, and broken along low angle fractures, called detachment faults. This movement allowed masses of rock to dome up as metamorphic core complexes, which mountains with this structure are called.

Streams that flowed down the slope of the newly exposed dome toward the detachment fault were quickly established. These drainages cut down through more easily eroded rock on the crest of the dome and incised deep canyons in the underlying, erosion-resistant gneiss (Feature 7). The resulting series of aligned triangular-shaped rock faces between the mouths of canyons produce a bold and distinctive western front for the Rincon Mountains.

*“Triangular dome facets
are hallmark features of
metamorphic core
complex mountains”*

The Pinal Schist, limestones, and other rocks in Figure 4.1 located above the Catalina detachment fault, and are referred to as upper plate rocks. Movement along the detachment fault displaced the rocks beneath the fault miles to the northeast of their original location and uplifted them from great depth. Today, most upper plate rocks lie beneath the Tucson Basin. As you follow the tour road about 0.2 mi (about .33 km) past the Loma Verde trailhead which is on upper plate rocks, you will cross the buried trace of the Catalina detachment fault and move to a landscape developed on the Catalina gneiss that forms the lower plate rocks of the Rincon Mountains metamorphic core complex. The gneiss slowly rose to form the Rincon Mountains.

Feature 4

UPPER PLATE ROCKS

LOCATION

Tour road, mile 3.5, Loma Verde trailhead. Park and refer to the text and diagram.

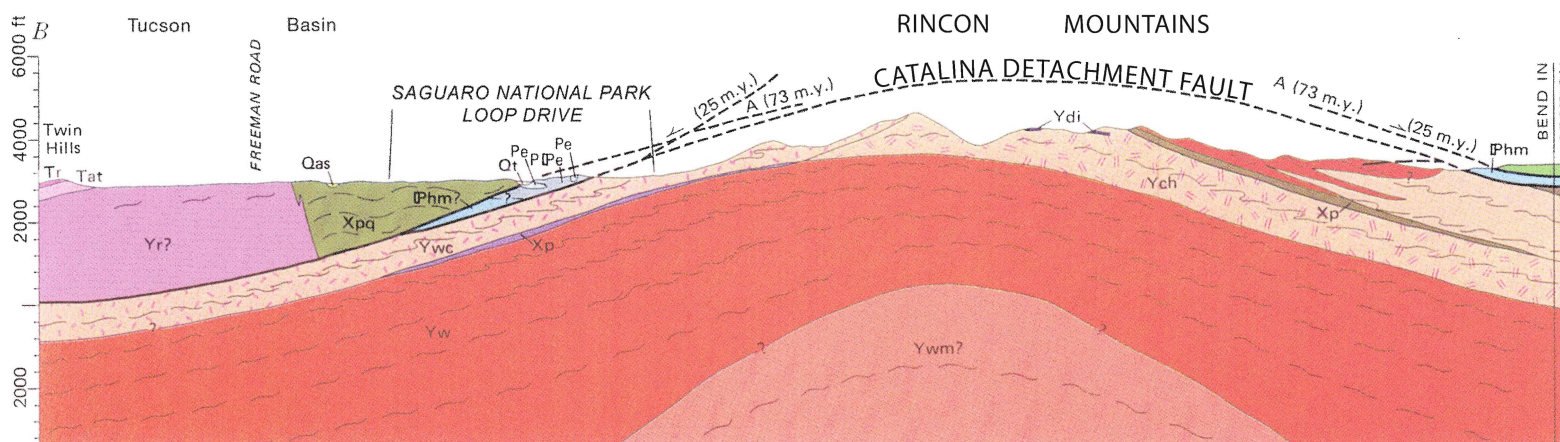


Figure 4.1. Cross-sectional view of the western Rincon Mountains, illustrating the position of the upper and lower plate rocks in relation to the Catalina detachment fault. (Qt, Qas = alluvium; Tr = rhyolite; Tat = andesite; Pe = Epitaph Dolomite; Ywc, Yr, Yw, Ywm = Catalina Gneiss; Ydi = diorite; Xp, Xpq = Pinal Schist) (modified from Drewes, 1977).

"Most upper plate rocks lie beneath the Tucson Basin"

Feature 5

DIKE

LOCATION

Tour road, mile 3.8. Park along the right side of the road opposite the first rock retaining wall. Walk up the road for 25 yd (about 25 m); the dike is on the right side of the road.



Figure 5.1 Dike (A) intruded into gneiss (B).

The vein of dark-colored rock in this exposure of lower-plate rock is a *dike* (Figure 5.1, A). A dike is an intrusion of molten rock that cuts across the layers or fabric of the rock that is invaded. The molten rock, called *magma*, originated miles below the Earth's surface. About 20 to 30 million years ago (during Tertiary time), the magma migrated under great pressure and wedged open and filled cracks in the older lighter-colored gneiss (B) (see Feature 7). The magma then cooled to form the dark dike rock exposed in the road cut.

Dikes are of economic interest because precious and industrial metals have been found in the recrystallized zones that commonly occur along their margins.

These lower-plate rocks have been extensively fractured by faults.

"A dike is a sheet-like intrusion of molten rock"

Feature 6

CATALINA DETACHMENT FAULT

LOCATION

Tour road, mile 6.1. The low bluff to the north (Figure 6.1, A) marks the trace of the Catalina Detachment Fault. The National Park Service does not permit visitors to walk to the fault.



Figure 6.1. The Catalina detachment fault (C) separates folded limestone (A) and gneiss (B).

The gray, Paleozoic-aged (542 to 251 million years old) limestones (Figure 6.1, A) at this location are separated from the underlying, dark-colored gneiss (B) by the *Catalina detachment fault* (C). The detachment fault is a low-angle fracture in these rocks, along which movement has occurred. The detachment fault is named for the nearby Santa Catalina Mountains, where this fault was first described in the geologic literature.

About 35 million years ago the gneiss was located as much as 8 mi (13 km) below the Earth's surface. East-west stretching of western North America thinned and broke the crustal rocks along low angle fractures — detachment faults (Figures D and 4.1). In this area the gneiss and granite beneath the detachment fault were displaced at least 15 to 22 mi (25 to 35 km) toward the northeast. The limestones above the Catalina detachment fault are fault bounded slivers within the detachment fault zone. The limestones were originally deposited as horizontal layers, but have been deformed into intricate folds by the fault movement. Note that the limestone contains numerous veins of the mineral calcite (calcium carbonate). The limestone became intensely fractured during periods of active faulting. The calcite was dissolved from the limestone by warm fluids and re-deposited in the fractures. This process of fracturing and calcite deposition occurred repeatedly during the period of faulting.

The granite that once existed below the Catalina detachment fault was fractured, ground and cemented, producing a very fine-grained type of metamorphic rock, called cataclasite. The removal of the weight of the great thickness of crustal rocks that were displaced to the southwest permitted the underlying rocks to arch up, producing the dome shape of the Rincon Mountains. As a result, the Catalina detachment fault dips to the west on the west side of the range and to the east on the east side of the range.

Detachment faults are a distinctive type of fault associated with the extension of the Earth's crust. In western North America, movement along these detachment faults led to the formation of highly deformed uplifts called metamorphic core complexes.

“The detachment fault is a low-angle fracture in these rocks, along which movement has occurred”

Feature 7

LOWER PLATE ROCKS (THE CATALINA GNEISS)

LOCATION

Tour road, mile 6.6. Walk to the small hills near the road called the Javelina Rocks.



Figure 7.2. Detail of the Catalina gneiss (coin for scale).

“Gneiss is a metamorphic rock that has a layered texture layered and may consist largely of granite rocks”

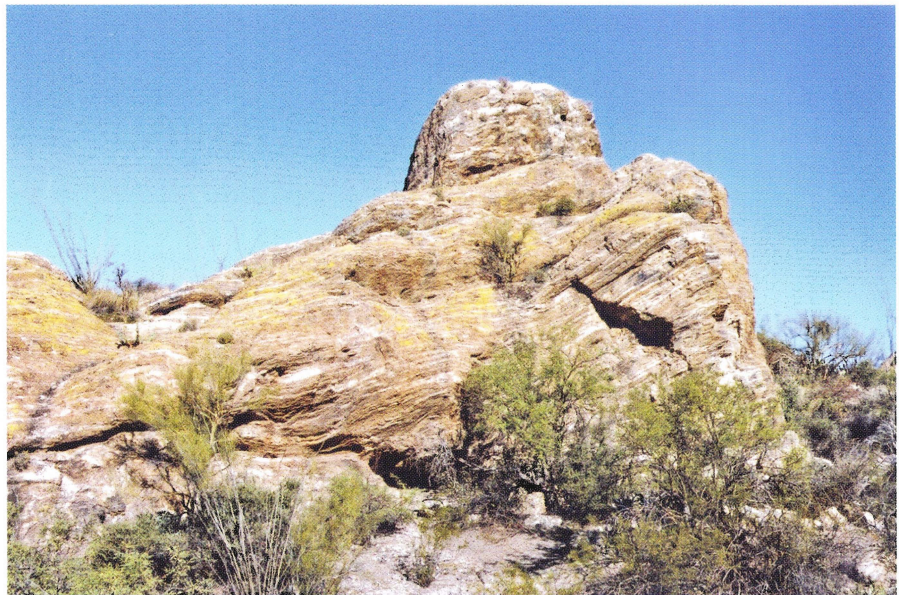


Figure 7.1. Catalina gneiss (lower plate rocks) at the Javelina Rocks.

The color-banded rock in Figure 7.1 is *gneiss*, the most common rock type in the Rincon Mountains. The gneiss is below the Catalina detachment fault and forms the lower-plate rocks of the Rincon Mountain metamorphic core complex. Because gneiss has a laminated texture, like that of innumerable, small-scale layers, the landscape has an angular, ledgy character.

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

The minerals feldspar, quartz, and mica crystallized as the granite slowly cooled. The Wilderness Suite granite is somewhat unusual in that it also contains crystals of red garnet. About 35 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. The intense pressure and heat that accompanied this stretching deformed part of the deeply buried Oracle and Wilderness Suite granites into the gneiss exposed in this part of the Rincon Mountains.

At temperatures of 600 °F (350 °C), the quartz crystals in the granites behaved like hot, soft putty and smeared in long ribbons parallel to the direction of crustal stretching (Figure 7.2). The feldspar crystals, which are more brittle at these temperatures, were rolled, crushed, and smeared also in the direction of extension. These long, aligned streaks of deformed minerals give gneiss its unique texture. The dark-colored bands are interpreted to be deformed Oracle granite; those of lighter colors once may have been Wilderness Suite granite.

Locally the gneiss is stained red and yellow by iron oxides. This is particularly common along fractures, where hot fluids chemically altered the rock and deposited minute quantities of hematite and limonite.

Feature 8

FRACTURE-CONTROLLED DRAINAGE, BOX CANYON

LOCATION

Tour road, mile 6.8. Turn left at the stop sign and drive to the Javelina Picnic Area. Hike the Tanque Verde Ridge Trail for about 1 mi (about 1.6 km) to view this feature. Box Canyon is closed to visitors.

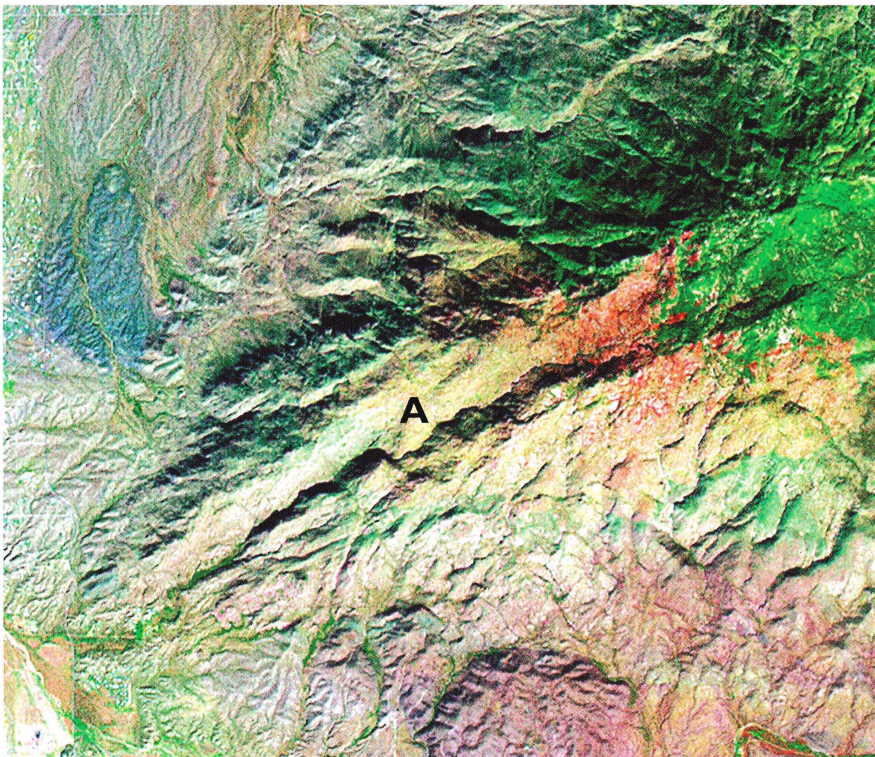


Figure 8.1. Satellite image of the Box Canyon area (A) of the Rincon Mountains.

Box Canyon and many of the other canyons in this part of the Rincon Mountains have unusually straight courses. Tributary canyons also tend to join these major canyons at high angles (Figure 8.1). A major reason is that canyons have developed along *fractures*.

Fractures are natural cracks found throughout the bedrock of the Rincon Mountains. Most fractures are the result of stress associated with faulting, arching and other movements in the Earth's crust that occurred during the conversion of granite to gneiss. Some of these cracks are major features that can be traced for miles across the mountain range.

Fractures are deepened and widened by chemical and physical weathering and erosion. Water seeps into these cracks, freezes and expands, and shatters the adjacent rock. Plant roots also wedge open joints and fault-fractured rock. Slightly acidic groundwater converts some minerals to clay, causing the gneiss to disintegrate. Running water from rain and snowmelt seeks out these weathered zones along fractures, eroding them into the deep, rectangular system of canyons that is cut into the slopes of the Rincon Mountains.

Geologists have not found a fracture system parallel to box canyon, and some think that it could have formed from a groove in the detachment fault.

“Fractures are deepened and widened by chemical and physical weathering and erosion”

GENERAL GEOLOGY OF THE TUCSON MOUNTAINS

About 70-75 million years ago at least seven huge volcanoes were active in southeastern Arizona (Figure G). The Tucson Mountains are the eroded remnant of one of them. The volcanism was fed by massive intrusions of molten rock (magma) that formed miles below and rose buoyantly through overlying rocks (Figure H, 1). When rising magma neared the surface, pressure fell, dissolved gases came out of solution to form froth, and clouds of ash and cinders exploded from vents. Most of the particles fell to the ground and accumulated as nearly horizontal layers called tuff.

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

After large-volume eruptions drained the magma chamber, the chamber's roof and overlying volcanic debris collapsed to form a large hole (caldera) that was 12 mi (20 km) across. (Crater Lake in Oregon, a caldera of similar origin, is 6 mi [10 km] across.) The caldera floor sank unevenly like a trap door (Figure H, 2) - about 300 ft (100 m) on the south side and as much as 15,000 ft (4600 m) beneath Wasson Peak on the north. As its floor subsided, huge blocks of welded tuff and slabs of older rock, some up to 2,000 ft (600 m) across, slid into the caldera. Deposits of this megabreccia are interlayered with Cat Mountain tuff in the Tucson Mountains. Later, lava flowed into the caldera. Then a large body of magma intruded, uplifted, and tilted the caldera fill and overlying hardened lavas. The magma, which cooled, crystallized, and solidified beneath the

debris-filled caldera, formed the Amole granite. Hot mineral-rich solutions that accompanied the intrusion of the granite circulated through the fractured rocks in the caldera. Silver, gold, copper, and other metals in the hot fluids crystallized in cracks in the adjacent rock. Mineralization also occurred where injections of molten rock called dikes (Silver Lily Dikes) penetrated the caldera fill and overlying volcanic rocks.

Beginning 30 - 35 million years ago the Earth's crust deep beneath these rocks was broken along a low-angle fracture called a detachment fault (Figure D). From beneath what are now the Tucson Mountains, granite in the "lower plate" (below the detachment fault) moved northeastward 16-22 mi (25-35 km) relative to rocks in the "upper plate" (above the fault), were domed upward, and were eventually eroded to form the Santa Catalina and Rincon mountains. In other words, rocks that crop out in the Santa Catalina and Rincon mountains today were originally in place deep beneath what are now the Tucson Mountains and Tucson basin.

Extensive lava flows took place from 30 - 15 million years ago. Remnants of them are preserved in the northern part of the range and at Tumamoc Hill and A Mountain.

More stretching from 15 - 5 million years ago (see General Geology of the Tucson Basin) resulted in high-angle faults that further deformed the volcanic and older rocks. Downcutting streams have exposed the complex internal structures and plumbing system of the ancient volcano and caldera (Figure H, 3). Walls of the caldera and most of the lava that flowed from the caldera and solidified have been removed by erosion. Flash floods and mudflows have flushed this rock debris from the mountains into the adjacent basins.

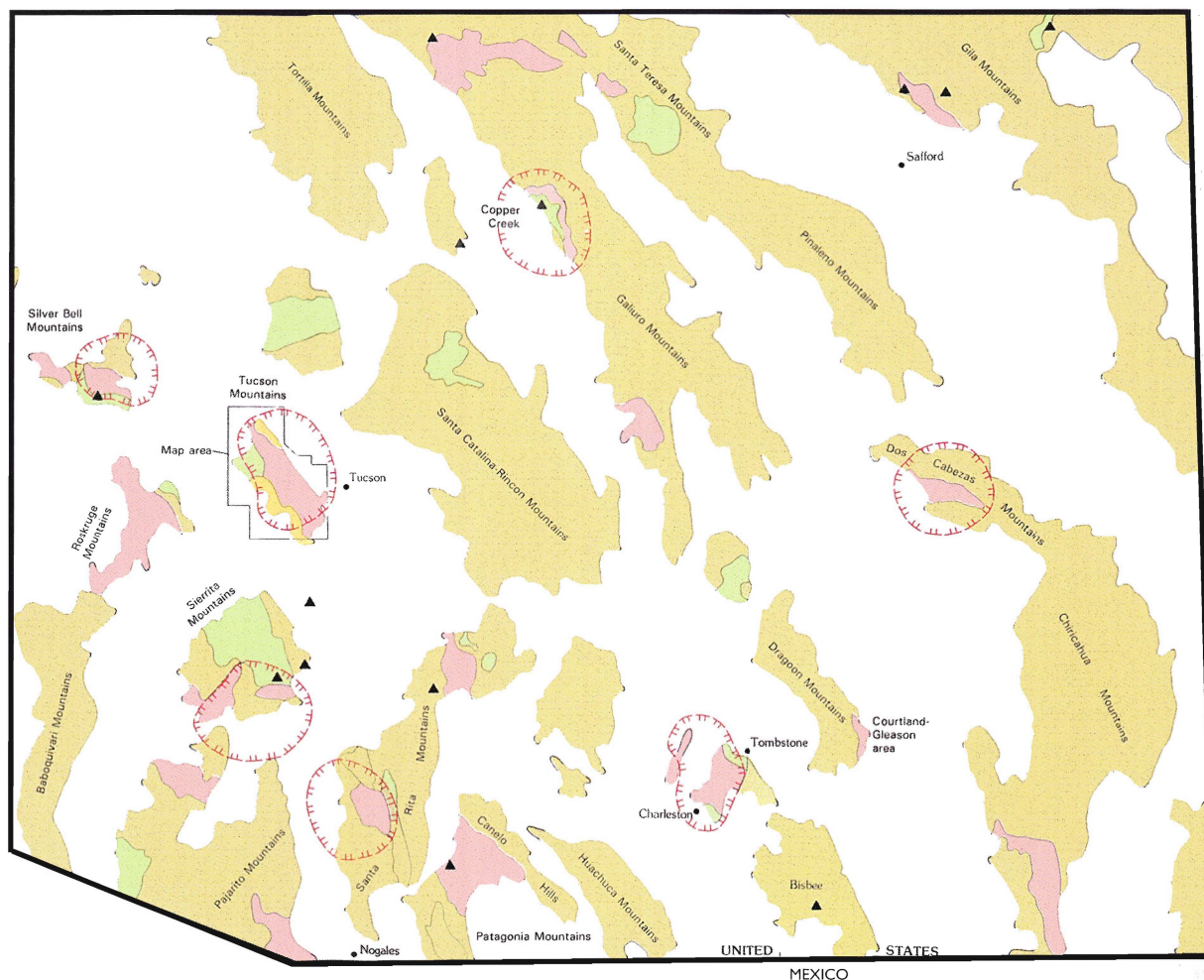
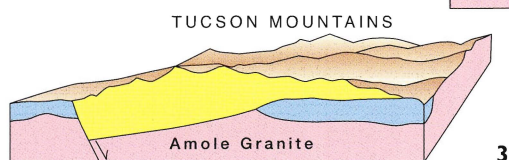
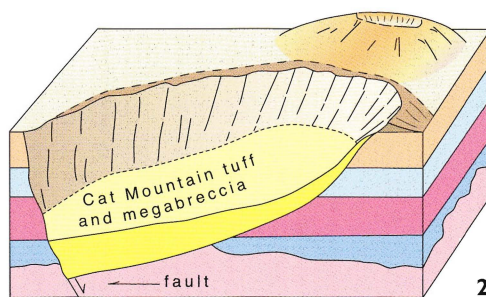
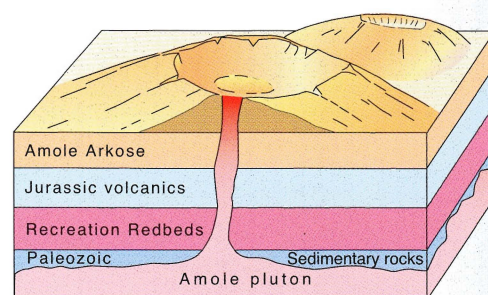


Figure G. Map of the late Cretaceous-age volcanoes in the Tucson Mountains area, southern Arizona (Lipman, 1993)

Figure H. Block diagram illustrating the evolution of the Tucson Mountains: 1) magma from the Amole pluton intrudes older rocks and builds volcanoes at the surface; 2) the Tucson Mountains caldera collapses along a fault; 3) continued faulting and erosion shape the Tucson Mountains.



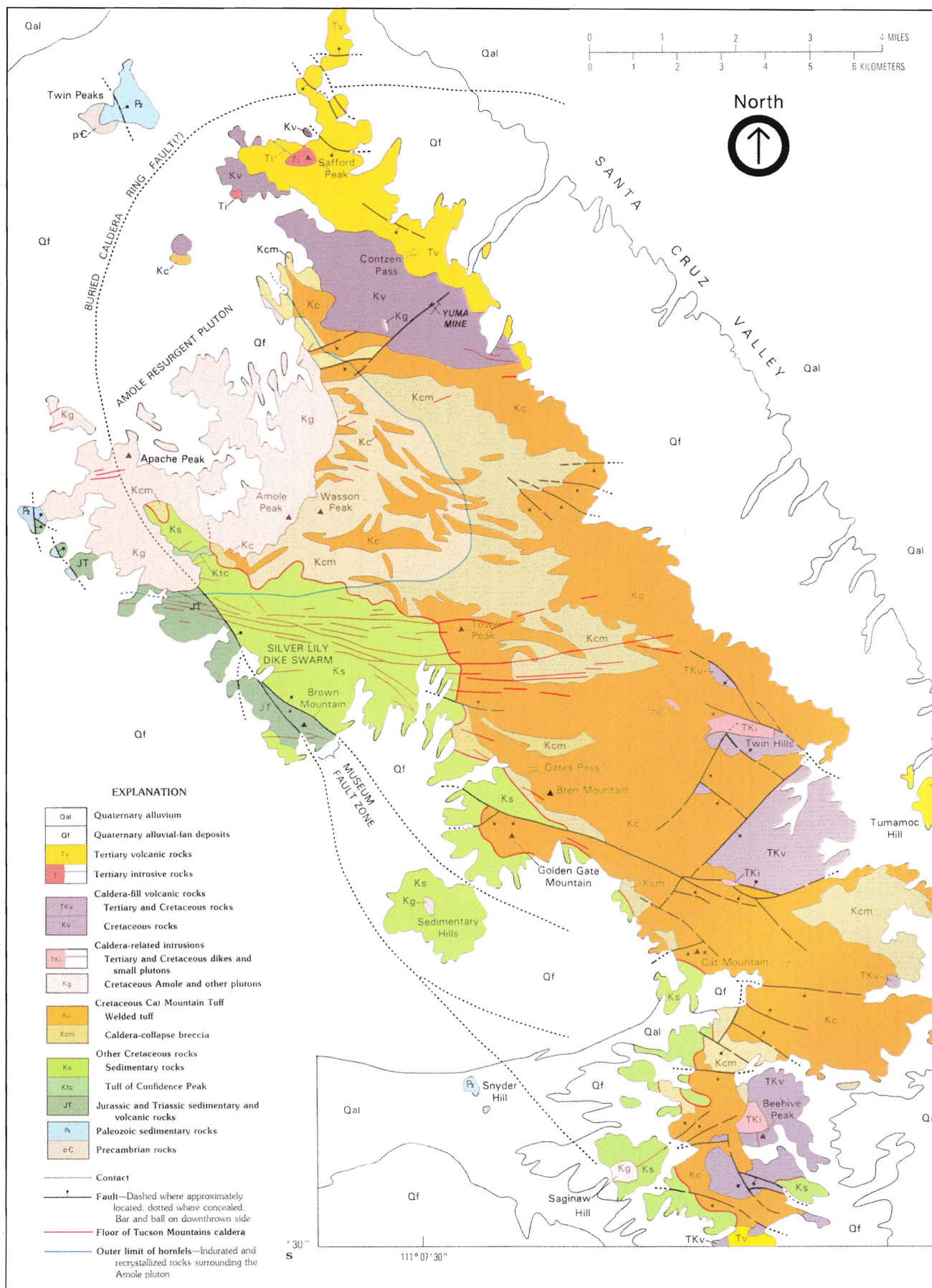
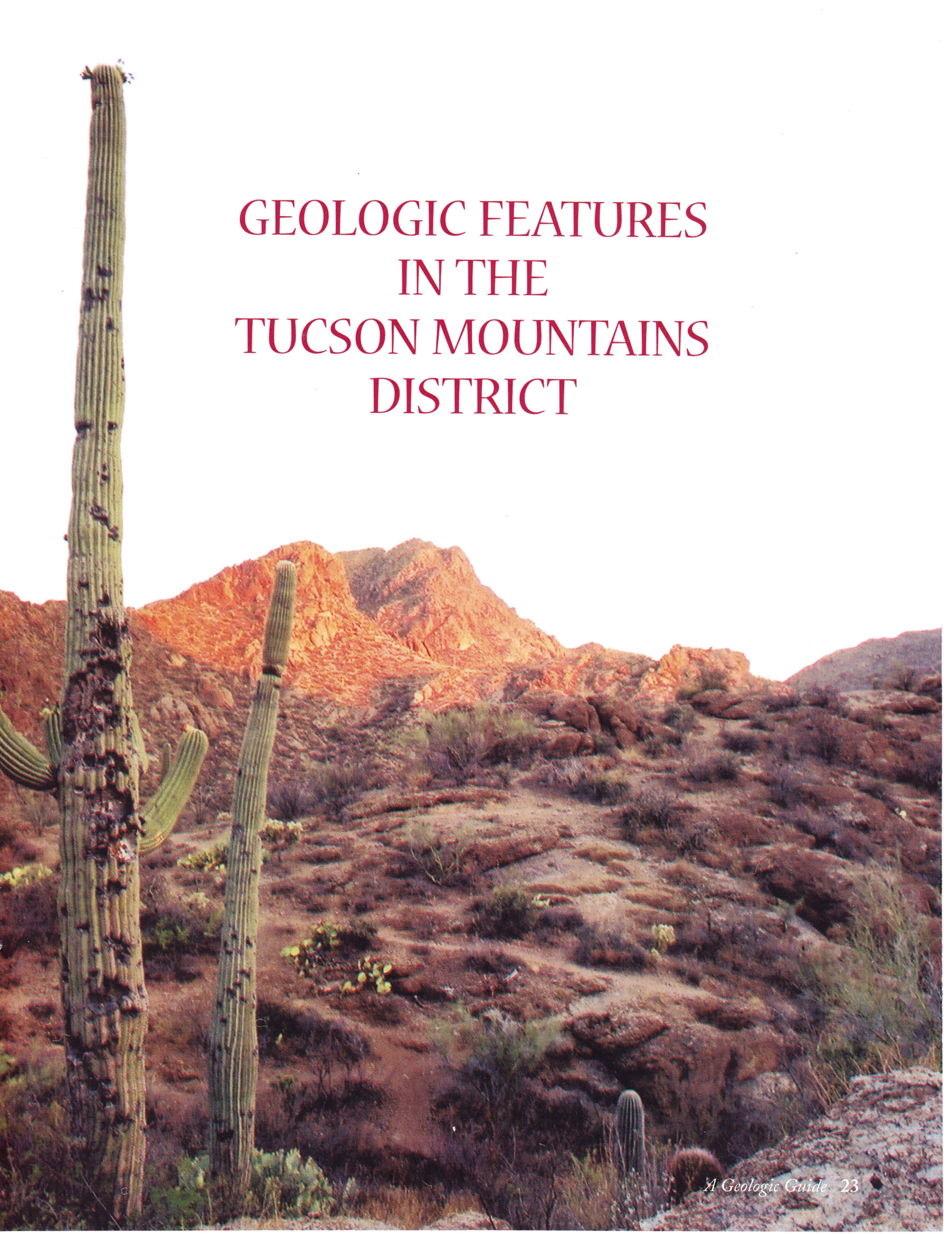


Figure I. Geology of the Tucson Mountains (Lipman, 1993).

A tall saguaro cactus stands prominently on the left side of the frame. In the background, a range of reddish-brown mountains rises against a clear sky. The foreground and middle ground are filled with desert scrub and smaller cacti.

GEOLOGIC FEATURES IN THE TUCSON MOUNTAINS DISTRICT

Feature 9

MEGABRECCIA

LOCATION

Drive Speedway Boulevard west to Gates Pass. Park in the parking lot and examine the bedrock about 50 yards (about 50 m) north and northwest of the parking lot.



Figure 9.2. Detail of the megabreccia. The black rock is a fragment within the megabreccia.

“Megabreccia is a chaotic mix of unsorted rock fragments”



Figure 9.1. Highway cuts through a large rock fragment (A) within the megabreccia at Gates Pass.

The jumble of large, unsorted rock fragments in Figures 9.1 and 9.2 is *megabreccia*. It formed as landslide deposits that accumulated during the collapse of the volcanic caldera that occurred in this area 73 million years ago. Huge volumes of ash, erupted from the floor of the crater, engulfed the rock debris that fell into the subsiding caldera during the eruption of the Cat Mountain Tuff (Feature 10). The result is a chaotic mix of welded tuff, Amole Arkose, Paleozoic limestone, and Recreation Red beds. The origin of the megabreccia puzzled geologists for decades until the volcanic history of the Tucson Mountains was finally unraveled.

Some of the individual blocks of rock such as the one shown in Figure 9.1 are hundreds of feet across. These large masses of relatively cooler rock served as a heat sink as the surrounding ash sheet cooled, commonly reducing the degree of welding that occurs where tuff encases megabreccia.

Feature 10

WELDED TUFF (CAT MOUNTAIN TUFF)

LOCATION

Drive Speedway Boulevard west to Gates Pass. Park in the parking lot. The welded tuff is exposed in the cliff that forms the skyline northeast of the parking lot.



Figure 10.1. Cliffs developed from Cat Mountain Tuff at Gates Pass.

The rock in Figure 10.1 is a 73-million-year-old deposit of compressed volcanic ash, pumice, rock fragments, and crystals of feldspar, quartz, and biotite known as the Cat Mountain Tuff.

Small-scale features in the tuff reflect its violent volcanic history. The white streaks in the rock are flattened pumice fragments, called *fiamme*. Pumice is volcanic glass that is permeated by gas bubbles. Pumice fragments were compressed and their bubbles deflated by the weight of the overlying volcanic material when the ash sheet was hot and soft. Most of the material between the *fiamme* is volcanic ash, which is composed of microscopic pieces of volcanic glass and crystal fragments that were produced by the explosive eruption. The eruption produced great billowing clouds of ash, pumice, rock fragments, and gas that glowed with intense heat (more than 1000°C; 1800°F). These hot glowing clouds rolled down the slopes of the erupting caldera at speeds of up to 100 mph (160 kph) and blanketed the landscape with thick layers of hot ash and pumice. The collapsed floor of the caldera filled with these ash sheets and great slabs of older rock. This fill reached a maximum thickness of 15,000 ft (4600 m) at the northern end of the caldera floor.

Intense heat fused the volcanic glass with the pumice, which cooled to form the Cat Mountain Tuff. Some ash sheets were intensely welded together, while others are unconsolidated ash and pumice. The more thoroughly welded zones, being more resistant to weathering and erosion, form cliffs; poorly fused deposits form slopes.

Welded tuff occurs widely on the Earth's surface. It is the principal bedrock of the Galiuro and Chiricahua Mountains of southeastern Arizona, and the Sierra Madre Occidental of western Mexico.

*"Intense heat fused
volcanic glass with
pumice"*

Feature 11

ARKOSE (AMOLE ARKOSE)

LOCATION

Drive Kinney Road to the King Canyon Trailhead. The trailhead is on the north side of the road, just past the entrance to the Arizona Sonora Desert Museum. Hike the King Canyon Trail for about 0.5 mi (0.8 km) to see this feature.

“Arkose is a type of water-deposited sandstone that contains high quantities of feldspar crystals”



Figure 11.1. Amole Arkose.

The sandstone (Figure 11.1) along this part of the trail is the *Amole Arkose*. Arkose is a type of water-deposited sandstone that contains high quantities of feldspar crystals. Feldspar grains generally break down into smaller fragments and are altered to clay close to the source rock, which is usually granite. The presence of numerous, large feldspar grains indicates that the sandstone was derived from the weathering and erosion of nearby outcrops of granite.

The arkose is part of a 3,300 ft-thick (1000 m-thick) unit of sedimentary rocks called the Amole Arkose Formation. These sedimentary layers reveal much about the depositional environment in this part of Arizona about 100 million years ago (early middle Cretaceous time). Conglomerates of cobbles, pebbles, and sand were deposited by streams that built alluvial fans at the base of a mountain range composed of granite, Paleozoic limestone, and Recreation Red Beds. Sandstones, siltstones, and mudstones accumulated along streams and deltas. Limestones and mudstone were deposited in an extensive lake that pooled in a basin adjacent to the mountain range.

The Amole Arkose Formation of the Tucson Mountains may correlate with a similar series of sedimentary rocks, called the Bisbee Group, that is present in many other mountain ranges of southern Arizona. If these rocks do correlate, the lake-, basin-, alluvial fan-, and mountain-range environment of late Cretaceous time was extensive.

Feature 12

DIKE

LOCATION

Drive Kinney Road to the King Canyon Trailhead. The trailhead is on the north side of the road, just past the entrance to the Arizona Sonora Desert Museum. Hike the King Canyon Trail for 0.5 mi (0.8 km). The dike is visible in the hillside to the west.



Figure 12.1. Dacite dike (A) intruded into Amole Arkose (B).

The vein of light gray - colored rock on this hillside is a dike (Figure 12.1, A). A dike is a sheet-shaped intrusion of once-molten rock that cuts across the layers or fabric of the rock it invaded. The molten rock, called *magma*, originated miles below the Earth's surface, possibly from the same magma body that cooled to form the Amole Granite (Feature 14). About 73 million years ago, the magma migrated under great pressure and wedged open and filled cracks in the older Amole Arkose (B) (Feature 11). Over time the magma cooled to form dacite, a type of igneous (once molten) rock. The arkose can easily be distinguished from the dacite by distinctive layering that dips to the south.

This dike is part of a swarm of similar intrusions called the Silver Lily dikes (Figure I), which trend easterly across this part of the Tucson Mountains. Some dikes are 3.7 mi (6 km) long and 66 feet (20 m) wide. They fill fractures that mark a hinge bounding the most down-dropped northern part of the Tucson Mountains caldera.

These dikes are of economic interest because precious and industrial metals have been found in some of the recrystallized zones that occur where the dacite is in contact with the arkose. Caution! Mine workings are dangerous and should not be entered.

"Over time the magma cooled to form dacite"

Feature 13

SANDSTONE, SHALE, AND CONGLOMERATE (RECREATION RED BEDS)

LOCATION

Drive Kinney Road past the King Canyon Trailhead to mile marker 6. Park in the paved turnout just west of the McCain Loop Road. Hike approximately 100 yds (100 m) to the Red Hills on the east side of Kinney Road.

"These rocks are mainly sandstone and shale that were deposited by running water"



Figure 13.1. The Recreation Red Beds in the Red Hills, Tucson Mountains.

The reddish rocks (Figure 13.1) that form these low hills are the Jurassic-age (about 150 million years old) Recreation Red Beds. They owe their color to a small amount of iron oxide derived from volcanic debris in the bedrock. These rocks are mainly sandstone and shale that were deposited by running water. There are also some beds of conglomerate, a sedimentary rock that contains sand, pebbles, and cobbles that were rounded by tumbling in a streambed. Some of the cobbles are volcanic rocks. The presence of rounded fragments of this size suggests that they were deposited in basins along the margin of a large volcanic field. These rocks are twice as old as the Tucson Mountain caldera.

Volcanic rocks of the same age are preserved in the Santa Rita and Huachuca Mountains south and southeast of Tucson, respectively. These scattered deposits of volcanic rock appear to be the remnants of three large ash-flow calderas that dominated this part of North America during Jurassic time.

Feature 14

GRANITE AND GRANODIORITE (AMOLE GRANITE)

LOCATION

Follow Kinney Road from the Red Hills Visitor Center north to Hohokam Road. Turn right (east) and continue to the Sus Picnic Area. Hike to the low hills on the right side of the road.

The tan rock in Figure 14.1 is the Amole Granite. The granite is the solidified remaining portion of the magma chamber into which the caldera collapsed. It was molten rock (magma) from this chamber that built the volcano that caved in to form the caldera. The granite is part of a much larger intrusion of molten rock, called a *pluton*. After the collapse of the caldera, about 73 million years ago magma again surged toward the surface. This resurgence uplifted and tilted to a nearly vertical position the overlying Cat Mountain Tuff (Feature 10) and caldera-fill lavas. Erosion by running water has exposed the granite and granodiorite of the pluton in this western part of the Tucson Mountains (Figure I).

Igneous rocks can be subdivided into two broad classes: volcanic and plutonic. Volcanic rocks form by the rapid cooling of molten rock (lava) that has poured or exploded onto the surface. Lavas that form basalt, for example, cool so quickly that the rock consists only of small and microscopic crystals. Plutonic rocks which crystallize slowly, from magma, miles below the Earth's surface, contain much larger irregularly shaped, interlocking crystals.

The Amole granite consists of approximately equal amounts of three minerals: quartz, alkali feldspar (rich in potassium and sodium), and plagioclase. The quartz is glassy-looking and clear gray; the alkali feldspar is blocky in shape with a red or orange tint; and the plagioclase is grayish or white and commonly has cleavage (parallel breakage) and distinctive striations on some crystals. The granite also contains small amounts of several other minerals, mainly flakes of black mica (biotite) and silver mica (muscovite).

Granodiorite, similar in origin to granite but darker in color, occurs along the margins of the granitic pluton. Granodiorite contains crystals of biotite, hornblende (greenish-black), plagioclase feldspar (white), and quartz (gray).

Magma that formed the Amole Granite cooled and, even as solid rock, contained a great deal of internal heat. This remnant heat drove the underground circulation of hot, mineral-rich fluids that flowed through cracks in the granite and adjacent rocks. As these migrating fluids reached the low-temperature and low-pressure environments of surface rocks, silver, gold, copper, lead, vanadinite, and wulfenite and other minerals crystallized and filled rock cracks. Before the establishment of Saguaro National Monument, prospectors dug small mines that followed some of these metal-bearing veins.

During later geologic periods, new injections of molten rock—called dikes (Figure 14.2; Features 5 and 12)—filled cracks in the granite and granodiorite. Precious and industrial metals form in the recrystallized zones along the margins of some dikes.

The exposure of plutons of erosion-resistant granite at the Earth's surface has formed majestic ranges, such as the Sierra Nevada in California and the Sawtooth Mountains in Idaho. Mineralization by hot fluids accompanying the magmas has produced bonanzas of gold and silver.

Rocks such as granite and granodiorite cooled and solidified deep below the Earth's surface. Because they are now exposed to the surface, substantial thicknesses of rocks that were once on top of them must have been removed by erosion.



Figure 14.1. Amole granite.

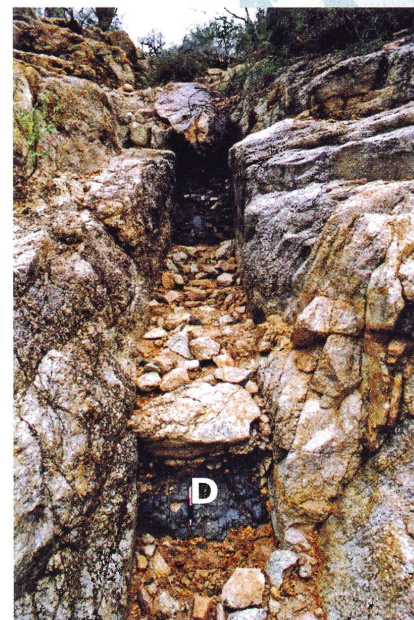


Figure 14.2. Dike (D) cutting Amole granite.

Feature 15

LIMESTONE (HORQUILLA AND ESCABROSA LIMESTONE)

LOCATION

Follow Kinney Road from the Red Hills Visitor Center North to Hohokam Road. Turn right (east) and continue to the Sus Picnic Area. Walk to the top of the hill to the west (left) of the parking lot.

"These limestones were deposited as fine calcium carbonate sediment"



Figure 15.1. The Horquilla and Escabrosa limestones (L), Tucson Mountains.

The gray rock (Figure 15.1) exposed on the west side of this hill is the Horquilla limestone (Permian and Pennsylvanian age [318 to 258 million years old]) and the Escabrosa limestone (Mississippian age [359 to 318 million years old]). These limestones were deposited as fine calcium carbonate sediment when this part of North America was covered by a shallow sea.

Originally deposited as horizontal layers, these limestones have been tilted and thrust into contact with sedimentary rocks of Jurassic or Cretaceous age (about 150-130 million years old) by fault movement. Limestone, resistant to erosion in arid and semi-arid climates, tends to form topographic high points. The Horquilla and Escabrosa limestones, together with other carbonate rocks of similar age, are exposed in hills and mountain ranges across southern Arizona. Kartchner Caverns was developed in the Escabrosa Limestone in the Whetstone Mountains near Benson, Arizona.

Carbonate rocks, such as limestone, dolomite, and marble, play a role in controlling the temperature of Earth's atmosphere. Rainwater absorbs carbon dioxide from the atmosphere, falls onto the land, and dissolves and transports calcium and bicarbonate from the rocks of the continents to the oceans. The calcium and bicarbonate ions form the shells of marine organisms, which eventually settle to the sea floor and form limestone and dolomite. Some of these carbonate rocks are uplifted and dissolved by rainwater. Other carbonate rocks are pulled deep into the Earth's crust, where they are metamorphosed and release carbon dioxide. The released carbon dioxide moves upward through faults and fractures and is discharged into the atmosphere. This recycling of carbon dioxide, one of the "greenhouse" gases, helps maintain the temperature of Earth's atmosphere in a range that allows life to flourish.

Limestone's chief commercial use is in the manufacture of cement.

Feature 16

GRABEN

LOCATION

Follow Kinney Road from the Red Hills Visitor Center to Hohokam Road. Turn right (east) and continue to the Valley View Overlook Trail. Hike this trail for 700 yd (about 700 m) to the top of the ridge for a view of the Avra Valley.

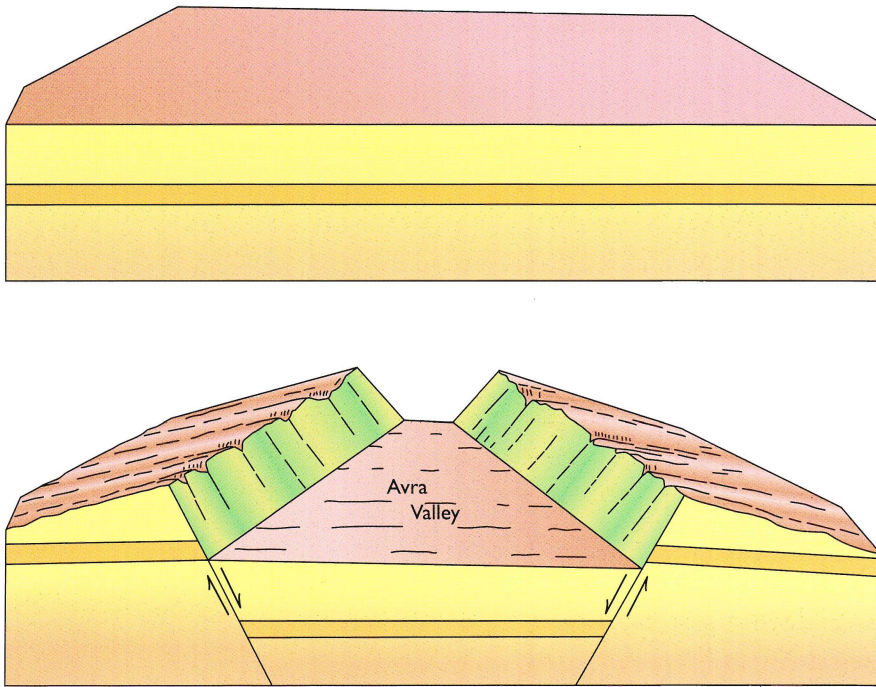


Figure 16.1. Block diagram illustrating the formation of the Avra Valley graben.

The Avra Valley, the sediment-filled basin between the Tucson and Silverbell Mountains, is a *graben* (the German word for “grave”) (Figure 16.1). This basin was not carved by running water, but is a block of bedrock that has been dropped down between two breaks in the Earth’s crust, called faults, along which movement has occurred.

These faults, and many others in southern Arizona, moved when crustal rocks of this western part of North America were stretched and pulled apart in a northeast-southwest direction beginning about 15 million years ago. As stretching continued the blocks of rock between the faults subsided due to gravity, forming the trench-like Avra Valley graben. Other crustal blocks were uplifted relative to other blocks to form the Tucson and Silverbell Mountains. This period of rock deformation produced a landscape of relatively short, narrow mountain ranges separated by broad basins — the Basin and Range geologic province that extends from southeastern Oregon to northern Mexico (Figure E).

The total vertical movement on some of these faults is more than 2 mi (3 km). The Avra Valley graben is filled with thousands of feet of gravel, sand, silt, and clay eroded from the adjacent Tucson and Silverbell Mountains. Water from rainfall and snowmelt accumulated with and saturated the basin’s sediment as groundwater. This “fossil” water is being extracted and pumped to the rapidly growing city of Tucson.

Some southern Arizona grabens extend for more than 50 mi (about 80 km). The rift valleys of East Africa, Death Valley, and the Rhine Graben are of even grander scale. Mid-oceanic rift valleys are graben structures that extend like a seam around the Earth for thousands of miles and are the birthplace of new igneous rock that floors the ocean basins.

“The graben is filled with thousands of feet of gravel, sand, silt, and clay”

Feature 17

BAJADA

LOCATION

Follow Kinney Road from the Red Hills Visitor Center to Hohokam Road. Turn right (east) on this road and continue to the Valley View Overlook Trail. Hike this trail for 700 yd. (about 700 m) to the top of the ridge for a view of this feature.

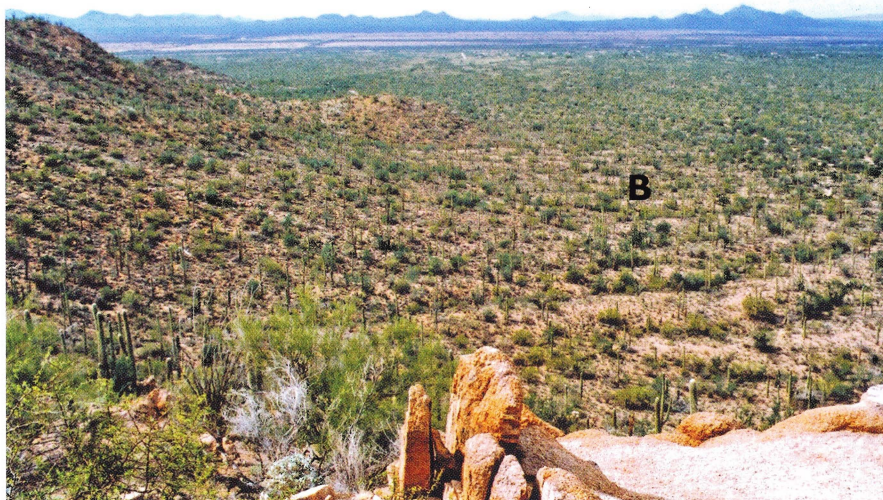


Figure 17.1. Bajada (B) built of rock debris worn from the western Tucson Mountains.

The plain before you that slopes gently toward the Avra Valley is a *bajada* (Figure 17.1). It consists of gravel, sand, and silt transported from the canyons of the Tucson Mountains by flash floods and mudflows during the last several million years. Rock debris first accumulated as fan-shaped deposits, called alluvial fans, at the mouth of each canyon. These fans enlarged as erosion continued to wear back the mountain front. In time, the fans merged to form the bajada — that continuous apron of alluvial material adjacent to the Tucson Mountains.

Note the darker color of the soil on the surface of this bajada. This color indicates that this surface has been exposed to atmospheric weathering for a long time. During this period of extensive weathering, iron minerals in the sediment oxidized or rusted, giving a reddish hue to the ground.

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

“Bajadas consist of gravel, sand, and silt”

Feature 18

ROCK VARNISH

LOCATION

Follow Kinney Road from the Red Hills Visitor Center to Hohokam Road. Turn right (east) and continue to Golden Gate Road. Turn left (west) and drive to the Signal Hill Picnic Area. Hike the Petroglyph Trail to the top of the hill to see this feature.



Figure 18.1. Rock-varnished granodiorite with petroglyphs.

The black-colored substance on the surface of the rock (granodiorite) in Figure 18.1 is *rock varnish*. This mineral patina masks the true color of the granodiorite, which is dark gray. Rock varnish develops best on rocks that are reasonably hard. Basalt, sandstone, and many metamorphic rocks are commonly well varnished, whereas siltstone and shale disintegrate too rapidly to retain such a coating.

Rock varnish consists of thin layers (typically less than one hundredth of an inch [0.25 mm] thick; Figure 18.2) of clay minerals 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 oxidize 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 the clay and darkens it. 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.

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 the rock. 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.

Well-varnished surfaces have a dull luster that causes entire hillsides to glisten in intense desert sunlight. This mineral coating gives the landscape its warm tones of brown and ebony, commonly masking colorful bedrock below. All of the Earth's deserts have varnished rocks, but in the Southwest these surfaces provoke even greater interest because of their archaeological importance. At innumerable locations prehistoric Indians etched petroglyphs (rock drawings) through the mineral skin to the fresh rock below. Today these symbols are being re-varnished as the process continues.

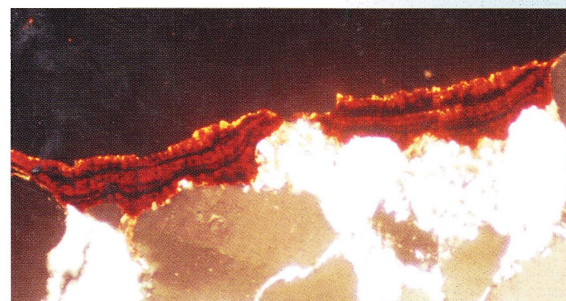


Figure 18.2. Transmitted light microscope photograph of layers of clay, manganese, and iron that form rock varnish. Photograph was provided by Dr. Ron Dorn, Arizona State University.



Magnetite sand (black) is derived from the weathering of the granodiorite.

Feature 19

DACITE

LOCATION

Follow Kinney Road from the Red Hills Visitor Center to Sandario Road. Turn right (north) and continue to Picture Rocks Road. Turn right (east) and drive to the Box Canyon parking area, which is located on the north side of the road.



Figure 19.1. Dacite cliffs at Box Canyon, Tucson Mountains

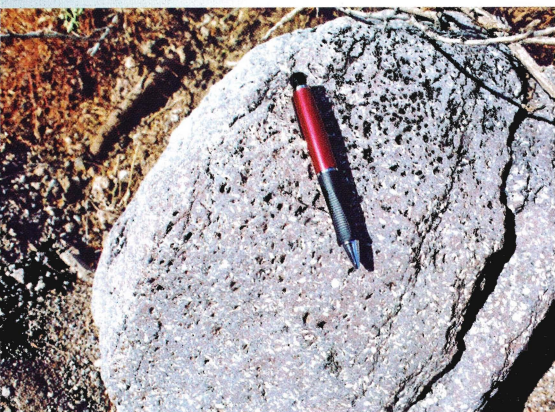


Figure 19.2. Gas cavities in dacite.

The dark rocks in this area (Figure 19.1) are the remnants of lava flows and volcanic vents that cooled about 25 to 30 million years ago to form dacite. Dacite is made up of interlocking, irregularly shaped crystals of the minerals feldspar (white) and mica (brownish-black). Because the lava cooled rapidly, the crystals did not have an opportunity to grow very large. The flow layers are preserved in the dacitic rock by aligned open lens-shaped cavities (Figure 19.2) that were gas bubbles stretched by flowage while the lava was hot.

These flows, which range from about 80 to more than 300 ft (25 to 100 m) in thickness, followed the valleys that existed at the time of the eruptions. Today these volcanic rocks form cliffs and peaks (Safford and Panther Peaks) because dacite is resistant to erosion. These volcanic rocks are an excellent example of the process of topographic reversal — the formation of highlands where a lowland once existed.

"Dacite is resistant to erosion"

Feature 20

COOLING JOINTS

LOCATION

Follow Kinney Road from the Red Hills Visitor Center to Sandario Road. Turn right (north) and continue to Picture Rocks Road. Turn right (east) and drive to the Box Canyon parking area, which is located on the north side of the road.



Figure 20.1. Columnar jointing in dacite.

The dacite at this location weathers into vertical columns approximately 2 to 3 ft (0.6 to 0.9 m) wide (Figure 20.1). This rock originated as flowing lava, at a temperature of about 2,000 ° F (1100 ° C), which cooled and solidified. Because the hot lava was in direct contact with cool rocks underneath and cool air above, it cooled and solidified very rapidly. As the temperature of the dacite dropped, the rock contracted, and a network of polygonal cracks formed (Figure 20.2). These cracks are typically perpendicular to the upper and lower cooling surfaces of the flow.

Columnar joints are common in basalt and other types of volcanic rocks, worldwide. Devil's Postpile in California, Giant's Causeway in Northern Ireland, and Devil's Tower in Wyoming provide dramatic examples of columnar jointing.

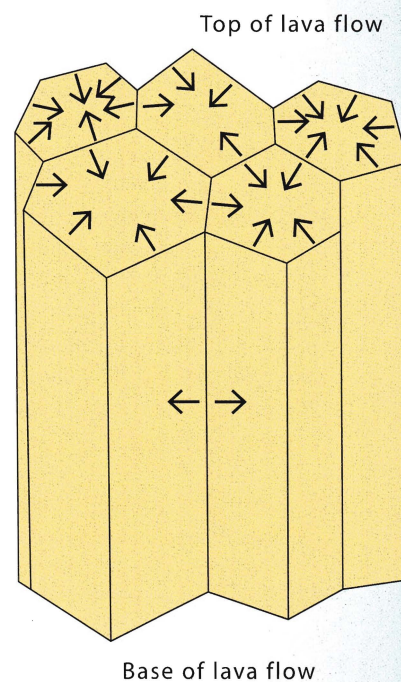


Figure 20.2. Diagram illustrating the formation of cooling cracks.

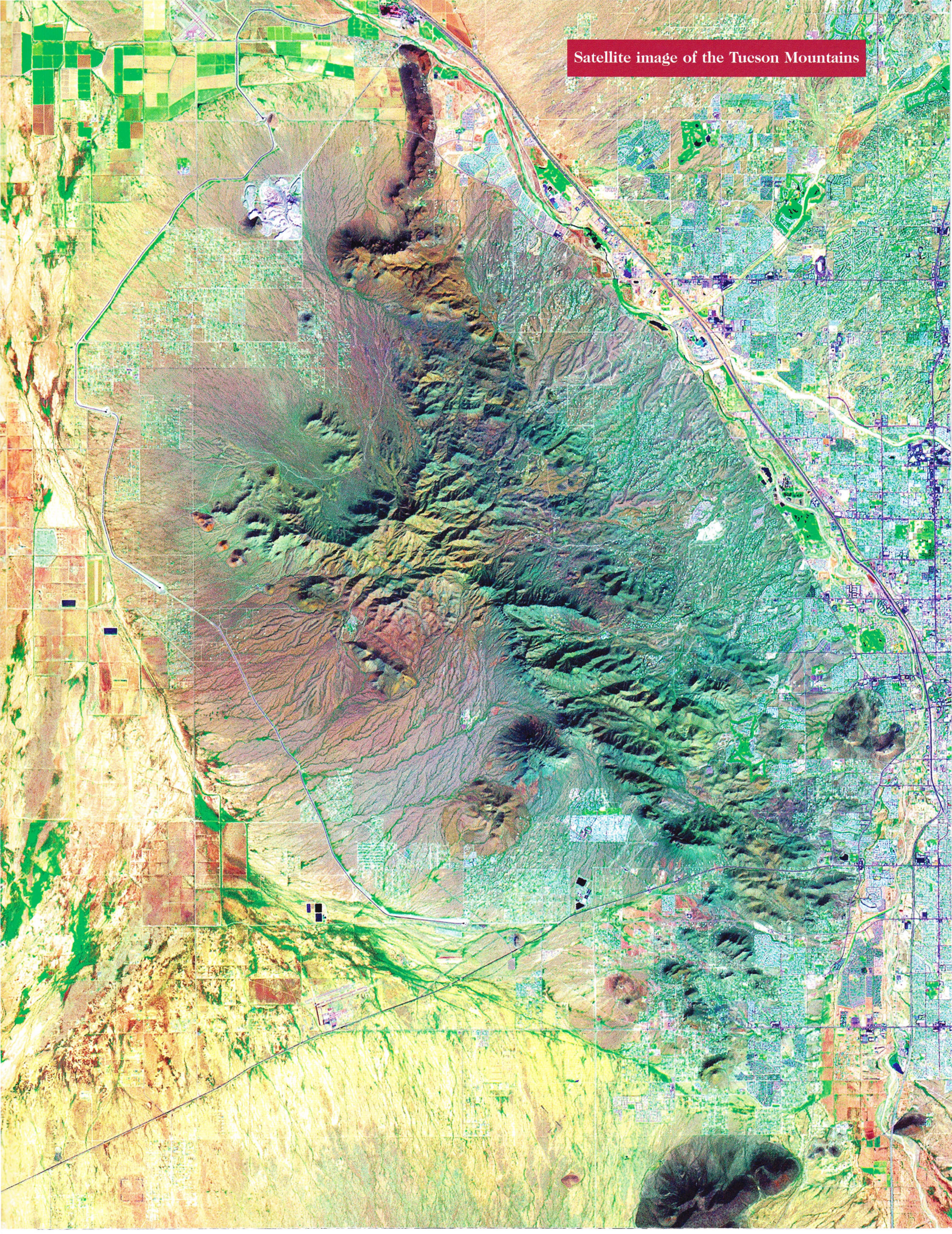
“As the temperature of the dacite dropped, the rock contracted, and a network of polygonal cracks formed”

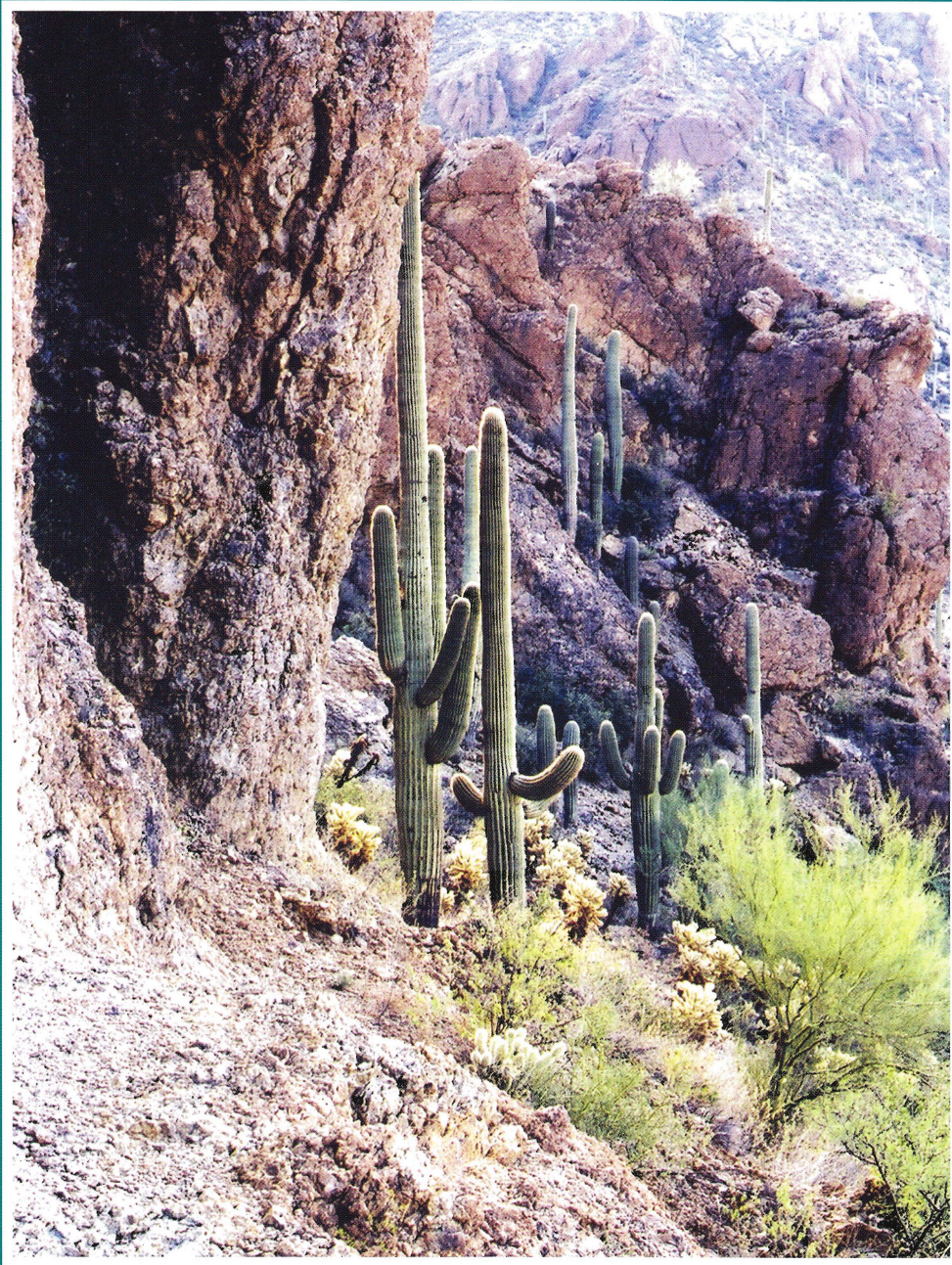
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Satellite image of the Tucson Mountains





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