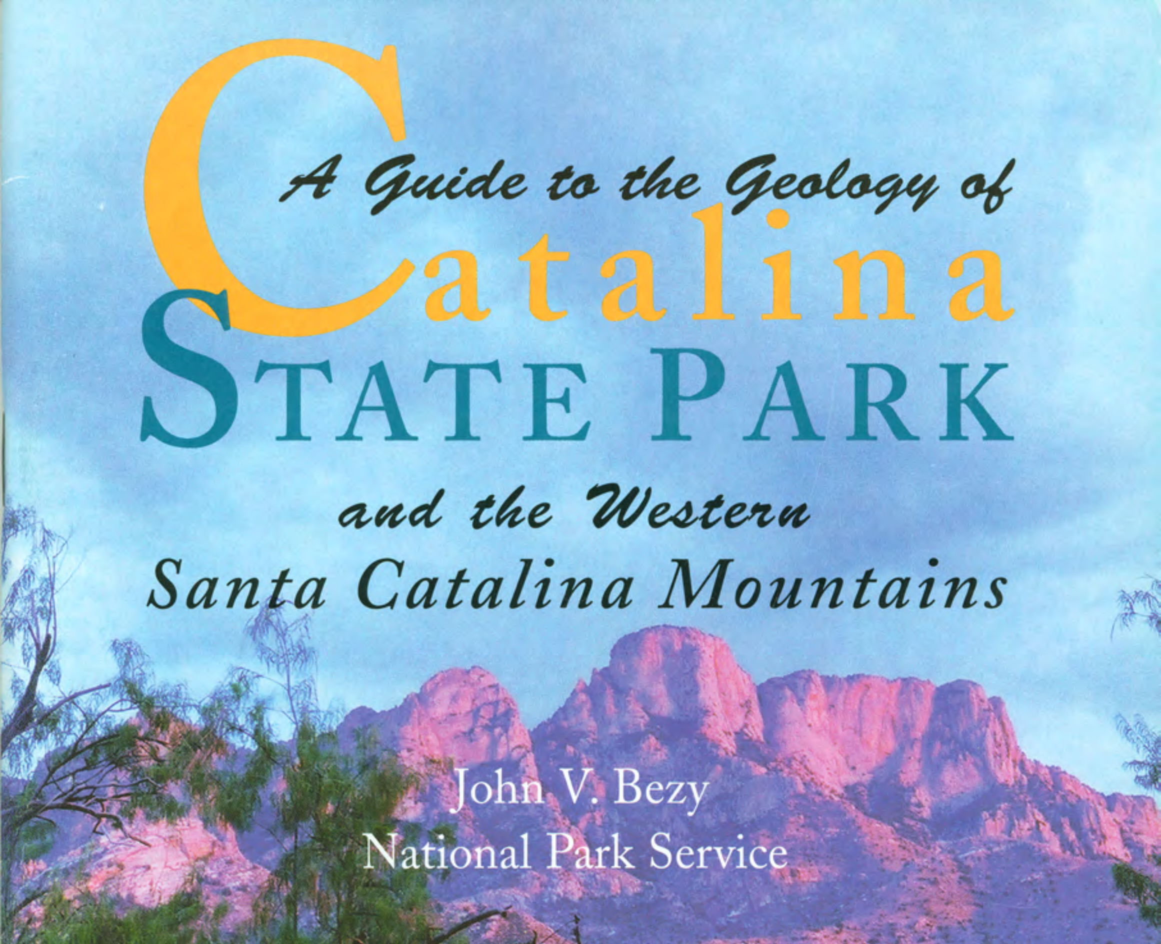
A Guide to the Geology of Catalina State Park and the Western Santa Catalina Mountains



John V. Bezy
National Park Service

Arizona Geological Survey
Down-to-Earth 12

National Park Service
Arizona Geological Survey — AZGS
Arizona State Parks

Satellite image of the western Santa Catalina Mountains

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This project was done cooperatively by the National Park Service, Arizona State Parks, and the Arizona Geological Survey.

Photographs by

Larry D. Fellows
Director and State Geologist

Arizona Geological Survey

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Down-to-Earth 12

Book design: John A. Birmingham

Photos: Larry D. Fellows
unless otherwise noted

Printed in the United States of America

Published by
the Arizona Geological Survey
416 W. Congress, #100, Tucson, AZ 85701
(520) 770-3500
www.azgs.az.gov
Published as an E-book in June 2011

in cooperation with

Arizona State Parks
1300 W. Washington
Phoenix, AZ 85007
Tel & TTY (602) 542.4174
(800) 285.3703 from (520) or (928)
www.pr.state.az.us

ISBN 1-892001-15-2

Acknowledgments

The author expresses sincere gratitude to Drs. Lester McFadden (University of New Mexico), Larry Fellows, Philip Pearthree and Jon Spencer (Arizona Geological Survey), and Mr. Robert Scarborough (Arizona-Sonora Desert Museum) for technical review of this publication. Special thanks are due to Dr. Fellows for his contribution to the organization of this publication and the many photographs that grace its pages. I also thank Drs. Arthur Trevena (Unocal Corporation), Richard Reeves and Victor Baker (University of Arizona) and Chiaki Oguchi (University of Tsukuba, Japan) for their insightful discussions in the field. Dr. Oguchi also provided valuable laboratory analysis of weathered granites. Appreciation is extended to Mr. William Andrew Amann, Jr., and Mr. William Roe for field assistance, to Mr. Craig Spillman for assistance with aerial photography, Ms. Rose Ellen McDonnell (Arizona Geological Survey) and Ms. Sarah Davis and Ms. Heidi Schewel (Coronado National Forest) for editorial review.

Mr. John Birmingham (Arizona Geological Survey) deserves a special thanks for the many hours he devoted to designing this publication.

Dr. John Dohrenwend graciously granted permission to use his satellite image in this publication. Poster-sized satellite image maps (1:100,000 scale) of the Tucson basin area can be ordered from John Dohrenwend, P.O. Box 141, Teasdale, UT 84773; Phone (435)425-3118; E-mail: Dohrenwend@rkymtnhi.com.

This publication would not have been possible without the professional support of Dr. Larry Fellows, Director of the Arizona Geological Survey, Mr. Neil Donkersley, Manager of Catalina State Park, and Ms. Julie Allbrooks, Merchandise Coordinator, Arizona State Parks.

I am particularly grateful to Ms. Gretchen Graham (Pima Community College) for editorial assistance, field support and encouragement through the completion of this project.

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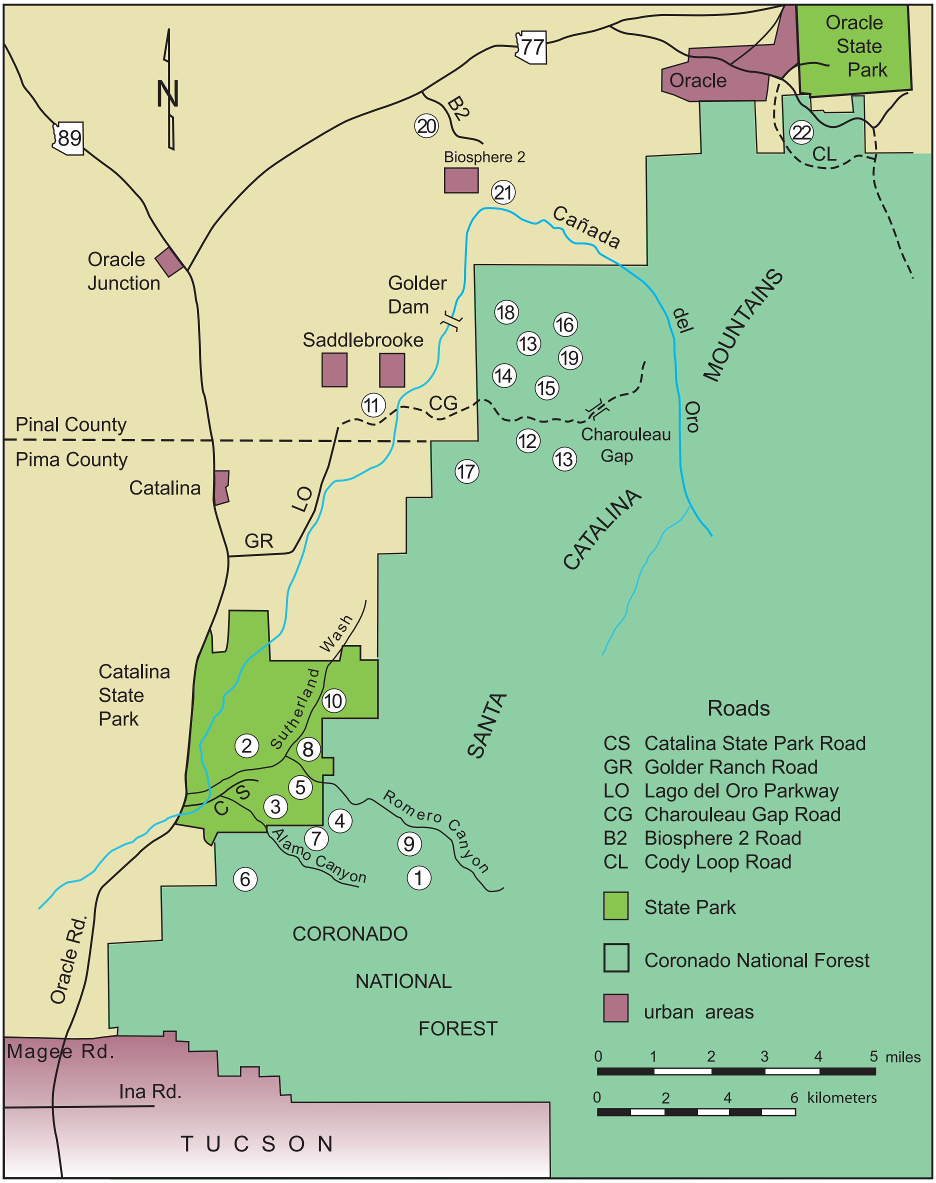


MAP A

Index map and location of geologic features (circled numbers)

Introduction

The northwestern margin of the Santa Catalina Mountains, located within Catalina State Park and the adjacent Coronado National Forest, contains a variety of spectacular geologic features (Map A). Because of the relatively sparse desert vegetation, all of them are easy to recognize and photograph.

Some of these features occur throughout much of the western United States. Others are unique to landscapes produced by the weathering and erosion of granite.

This booklet is your field guide to the geology of this splendid desert landscape. It is a hiker's guide; excursions on foot to the geologic features described in the text are encouraged. This book is written for the visitor who has an interest in geology, but 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 area's geologic setting and geologic history. In the following pages, emphasis is given to descriptions of geologic features that are common in this landscape. Precise locations are provided for those features that have more limited distribution.

The locations of the geologic features and the access roads and trails that should be used are shown on Map A. Most of the roads can be driven with any vehicle of moderate clearance. The Charouleau Gap Road is rough, rocky, and requires a 4-wheel-drive vehicle. One may prefer to hike along it. All dirt roads are slick when wet and should be driven with care. The Cañada del Oro is subject to flash flooding during periods of heavy rainfall and should be crossed with caution. Restaurants, gasoline, and emergency services are available in the towns of Catalina, Oracle, and Oro Valley, in addition to the City of Tucson. Emergency first aid is available at Catalina and Oracle State Parks.

The 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 at Catalina State Park and the Coronado National Forest will enhance the pleasure of those explorations.

General Geology

The Santa Catalina Mountains and the adjacent Oro Valley, Tucson, and San Pedro basins are typical of the topography that dominates much of western North America from central Mexico to Oregon. East-west stretching of this part of the continent between 25 and 5 million years ago caused the Earth's crust to thin and break along faults (cracks) into long, north-and northwest-trending blocks. Some of these blocks were uplifted to form mountain ranges, such as the Santa Catalinas; other blocks were down-dropped to produce the adjacent basins. Geologists, therefore, refer to this vast region as the **Basin and Range** geologic province.

The Santa Catalina Range is bordered by **normal faults**—deep, steeply sloping (30-70 degrees from the horizontal) cracks in the Earth's crust along which movement, primarily vertical, has occurred. This western side of the range is bounded by the Pirate Fault (Map B), which lies at the base of the mountain front and is inclined 50 to 55 degrees from the horizontal. Rocks west of this fault dropped an estimated 10,000 to 13,000 feet (about 3,000 to 4,000 meters) relative to those in the Santa Catalinas east of the fault. Geologic evidence indicates there has been no movement along the Pirate Fault in the last 5 million years.

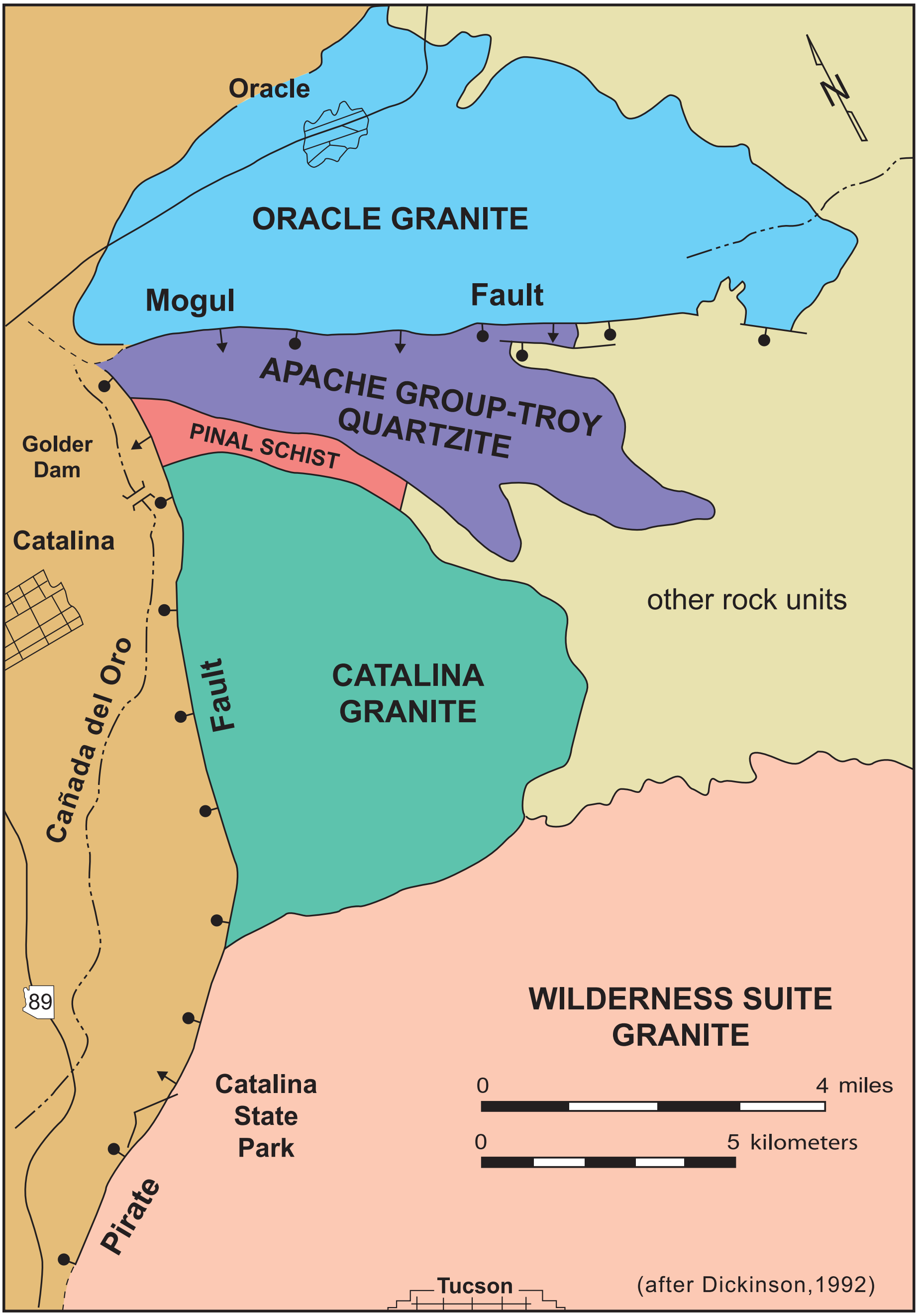
The bedrock of this part of the Santa Catalina Mountains is mainly the Oracle, Catalina, and Wilderness Suite granites. These granites were injected deep within the Earth's crust as great molten masses. They were emplaced at different times: the Oracle Granite 1.45 billion years ago, and the Wilderness Suite Granite 45-50 million years ago, and the Catalina Granite 26 million years ago. The molten rock, which cooled and solidified over millions of years and miles below the Earth's surface, has since been exposed by erosion.

These three granites have weathered and eroded into very different landscapes. Each landscape is a unique combination of landforms, which have developed in many cases because of differences in the hardness and fracture (joint) patterns of the bedrock. Many of the geologic features described in this guide are granitic landforms, some massive and others small-scale, that together make up these distinctive landscapes.

Erosion was wearing back the western face of the Santa Catalina Mountains even as the range was being uplifted. Between two and six million years ago the headwaters of streams carved embayments (drainage basins) into the mountain front and planed off bedrock platforms, called **pediments** (see Feature 12; Figure 12.1), that slope toward the Cañada del Oro. Later, 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 had merged with fans that built out from the eastern slopes of the Tortolita Mountains and filled the Cañada del Oro Basin with sediment.

About one million years ago 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 outlets to the sea. These expanding streams removed much of the sedimentary fill and altered and integrated the drainage of the basins they invaded.

These processes produced particularly dramatic results in the Cañada del Oro Basin. Prior to this time the Cañada del Oro exited the heart of the Santa Catalina



MAP B

Geology of the western Santa Catalina Mountains

Mountains near the present town of Oracle and drained to the northwest. A more rapidly expanding stream, eroding along the shattered rock zone of the Pirate Fault, began to extend its headwaters northward from the Tucson Basin. This new stream cut its valley through the alluvial fan sediment that filled this part of the basin and re-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 formed 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 500,000-4,000 years.

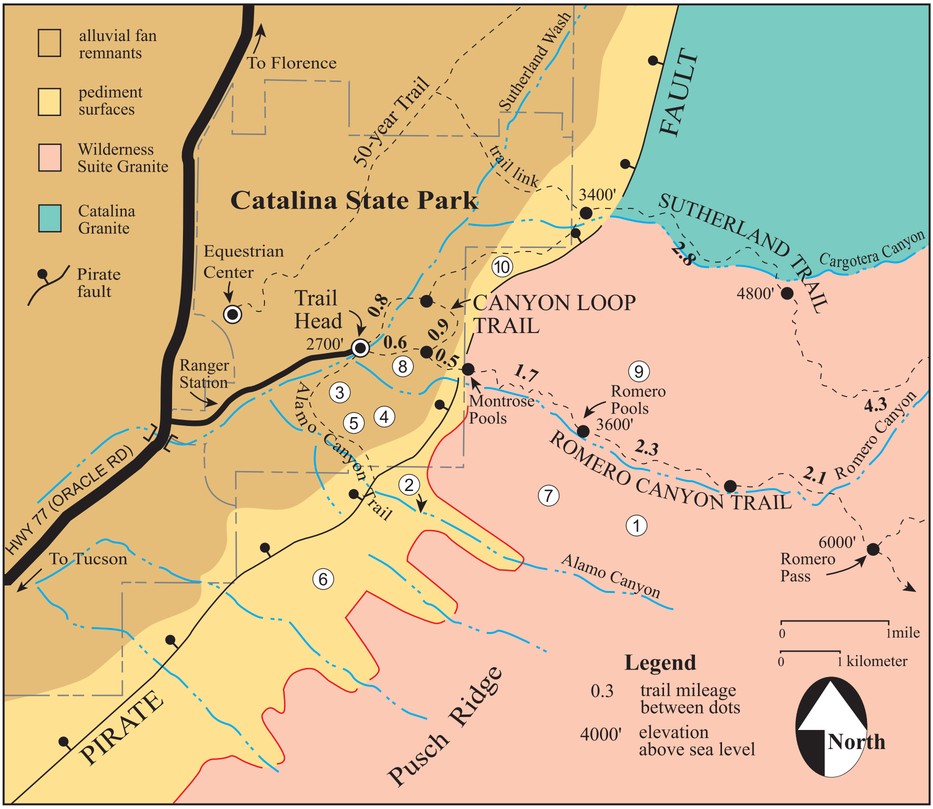
The present landscape is a mosaic of exhumed pediments, stream terraces, remnants of alluvial fans, and the embayed front of the range—all produced over a span of at least five million years. These are typical features of the Tucson Basin and the much larger Basin and Range province of the western United States. Adding to the complexity of this landscape is the array of smaller, less widespread landforms developed on the surfaces of pediments cut into the Wilderness Suite, Oracle, and Catalina granites.

Geologic Features in the Catalina State Park Area

Follow Oracle Road (Highway 77) north about 5 miles (8 kilometers) from the intersection with Magee Road to Catalina State Park. Pay entrance fee at the Ranger Station and drive straight ahead to the parking lot at the end of the road (Map C).

Features along the Alamo Canyon Trail

The Alamo Canyon Trail is not a signed park trail. To reach the Alamo Canyon Trail follow the Birding Trail for about 250 yards (250 meters) where the trail forks. Follow the left fork for about 450 yards (450 meters) to a bench at the top of a ridge. The Alamo Canyon Trail begins behind the bench and continues to the south for about 2 miles (3.2 kilometers).



MAP C

Geologic features (circled numbers) in the Catalina State Park area

Feature -1- Granite Pinnacles

Location: These features are best viewed along the Alamo Canyon Trail at Catalina State Park (Map C).

1.1

Catalina State Park is best known for the dramatic granite pinnacles (Figure 1.1) that have developed in the upper, cliff-forming unit of the Wilderness Suite granite in this part of the Santa Catalina Mountains. These towering spires are the products of surface weathering and erosion by running water guided by deep joints (cracks, see Feature 15) in the rock.

The Wilderness Suite granite differs from the Oracle and Catalina granites that make up the western face of the range in that it is dominated by widely spaced, vertical joints. These fractures serve as avenues along which chemical and physical weathering and erosion penetrate the granite. Rock shattering, caused by ice expansion, wedging by plant roots, and chemical decomposition, enlarges 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.

The pinnacles at Catalina State Park are impressive testimony to the important role that rock structure—in this case joints—plays in the development of the landscape.

Feature -2- Magnetite Sand

Location: Sandy streambeds throughout Catalina State Park.

2.1

The streaks of black sand (Figure 2.1) in these streambeds and dry washes are composed of heavy minerals that were eroded from the granite and gneiss bedrock in the Catalina Mountains. 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.

These dark minerals accumulate in streaks due to 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 by the same process.

Feature -3- Debris-flow-rafted Boulders

Location: These boulders are best viewed by hiking the Alamo Canyon trail to the tops of the alluvial fan remnants that tower above Alamo Canyon (Map C).

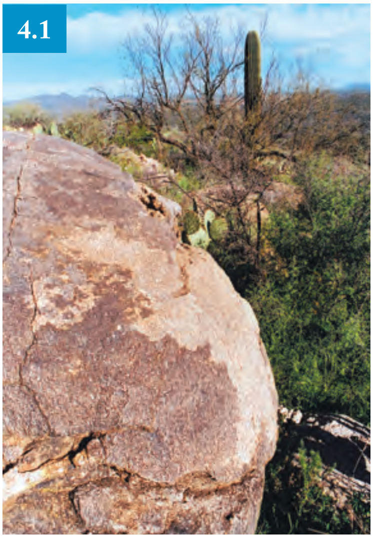
3.1

Large boulders (Figure 3.1, arrow), 6 to 30 feet (2 to 9 meters) in size and weighing 50 to 1000 tons, make up the surface of these old alluvial fan remnants. The boulders are blocks of granite and gneiss derived from the west face of Pusch Ridge, one-half mile (about 800 meters) to the east.

The alluvial fan surface on which you are standing once extended to the base of Pusch Ridge. These huge boulders fell from the cliff face (perhaps during earthquakes), accumulated in drainages at the heads of the old alluvial fans, and were rafted to their present location along the lower fan slopes by debris flows. Subsequent erosion by running water has washed away most of the old alluvial fan material, separating these remnants from the cliff face that was the source of the boulders.

Feature -4- Rock Varnish

Location: This feature is best viewed on boulders on the alluvial fan remnants that tower above Alamo Canyon (Map C).


4.1

The dark brown blotches (Figure 4.1) on the nearby granite boulders are **rock varnish**. This mineral patina gives the landscape a tan to dark-brown cast. Rock varnish develops best on weathering-and erosion-resistant rocks that have moderately rough surfaces. Sandstone, basalt, and many metamorphic rocks are commonly well varnished, whereas siltstone and shale disintegrate too rapidly to retain such a coating.

Rock varnish is a thin coating (typically less than one hundredth of an inch) of clay minerals (illite, montmorillonite, 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.

Scientists are unable to use desert varnish as a dating tool, even though older surfaces tend to be more heavily varnished and darker than younger surfaces. The rate at which desert 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 one million 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. In innumerable locations prehistoric Indians pecked petroglyphs (rock drawings) through the mineral skin to the fresh rock below. Today these symbols are being revarnished as the process continues.

Feature -5-

Case Hardening

Location: This feature is best viewed on boulders on the surfaces of the alluvial fan remnants that tower above Alamo Canyon (Map C).

5.1

The surfaces of most of the granite and gneiss boulders in this area have developed a protective mineral rind (Figure 5.1), 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 reprecipitated on its surface. Although silica is not very soluble in water, small quantities are leached from the rock each time the rock is wetted by rain and dew. When the moisture evaporates, the silica is deposited on the surface of the rock. While the surface of the rock 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 is exposed to the elements and disintegrates quickly.

Feature -6- Triangular Faceted Spurs

Location: These short, truncated ridges are best viewed from the Alamo Canyon Trail (Map C).

6.1

Ridges between canyons cut into the margins of high mountains normally slope gradually from the crest of the range toward adjacent valleys. The ridges that extend westward from Pusch Ridge, however, terminate in triangular cliff faces called facets (Figure 6.1). Such ridges, **called triangular faceted spurs**, are common indicators that the mountain range has been uplifted along a fault.

The triangular faceted spurs shown in Figure 6.1 are the result of uplift of the Catalina Mountains along the Pirate Fault and the simultaneous downcutting of canyons by streams that drain the western flank of this range. Over millions of years the granite and gneiss east of the Pirate Fault rose about 10,000 to 13,000 feet (3000 to 4000 meters) relative to the same rocks beneath the Oro Valley basin west of the fault (Figure 6.2). This movement created a high escarpment along the western face of the range. Concurrent downcutting by streams during uplift along the Pirate Fault carved deep canyons into the rising mountains east of the fault and segmented the escarpment into a series of aligned, triangular-shaped slopes. Continued weathering and erosion caused these escarpment remnants to retreat several hundred yards (meters) eastward from the fault along which they initially 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. In rugged, rapidly rising ranges such as the Chugach Mountains in Alaska, relatively unweathered triangular faces tower a thousand feet (300 meters) or more above the adjacent lowlands. Triangular faceted spurs provide bold evidence that faulting has played an active role in shaping the landscape.

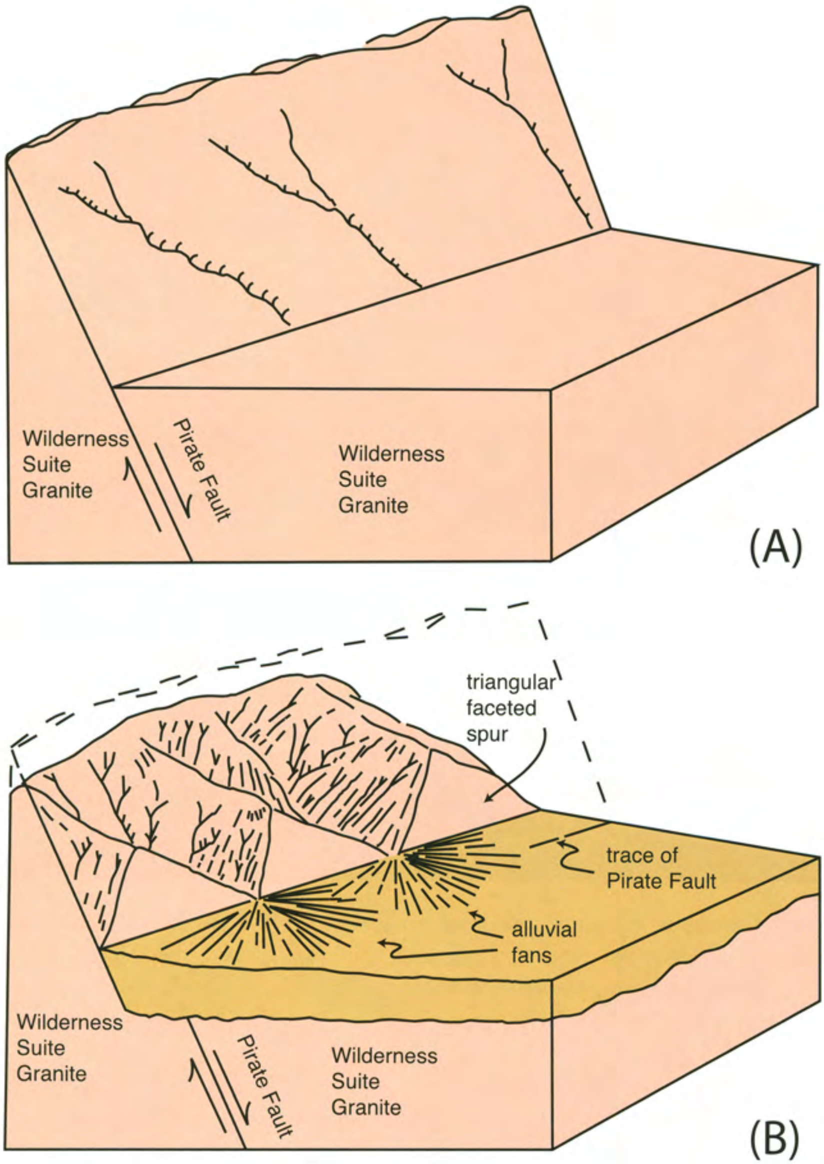


Figure 6.2 Uplift of the Catalina Mountains along the Pirate Fault created a high escarpment along the western face of the range (A). Downcutting by streams segmented the escarpment into a series of aligned, triangular-shaped spurs (B).

Feature -7- Fold

Location: This feature is exposed in the north wall of Alamo Canyon. Although it is visible from the Ranger Station, the best view of it is from the Alamo Canyon trail. Hike the trail for 2 miles (about 3.2 kilometers) from the trailhead just south of the parking area. (Map C).

7.1

The layers in the gneiss bedrock in the north wall of Alamo Canyon (Figure 7.1, F) have been deformed into an arch-shaped **fold**. This fold, which extends for approximately 4 miles (6-7 kilometers) in a northeast-southwest direction (Figure 7.2), has influenced the topography of this Pusch Ridge section of the mountain range.

The fold has been cut off by the Pirate Fault (see Feature 10). The western portion of the fold south of Alamo Canyon has dropped down several thousand feet and is buried by sand, gravel, and boulders eroded from the retreating mountain front. The crest of the fold has been eroded away. The rocks of the eastern portion of the fold form the towering cliffs of Pusch Ridge. The northeastern end of the fold plunges and disappears in the gneiss bedrock of the range; the southwestern end of the structure is buried in the sedimentary fill of the Tucson and Oro Valley Basins. Folds such as this, thought to be caused by compressional stress in the Earth's crust, occur elsewhere in the Catalina, Tanque Verde, and Rincon Mountains. The age of this structure is unknown. It is older than the Pirate Fault and may have formed 45 to 50 million years ago when the Wilderness Suite granite intruded the local crust.

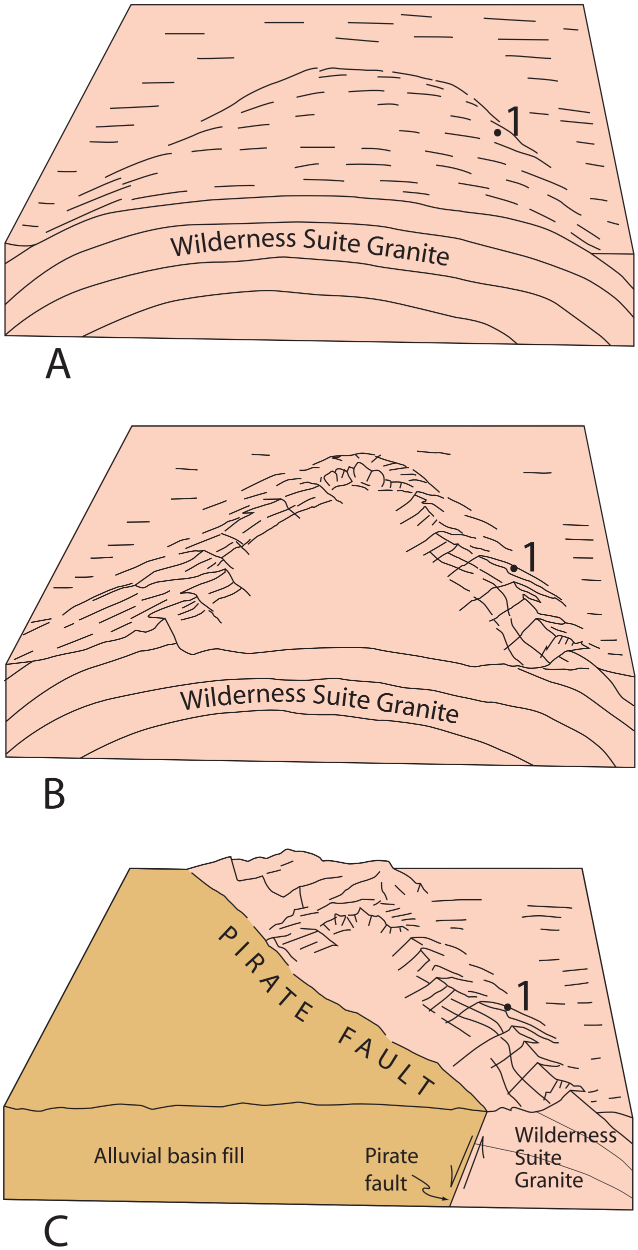


Figure 7.2 Lateral pressure possibly caused the Wilderness Suite Granite to be folded (A). Erosion removed highly fractured rock from the crest of the fold (B). Movement along the Pirate Fault down-dropped the western part of the fold, which is buried by thousands of feet of alluvial basin fill worn from the Santa Catalina Mountains (C).

Geologic Features along the Romero Canyon Trail

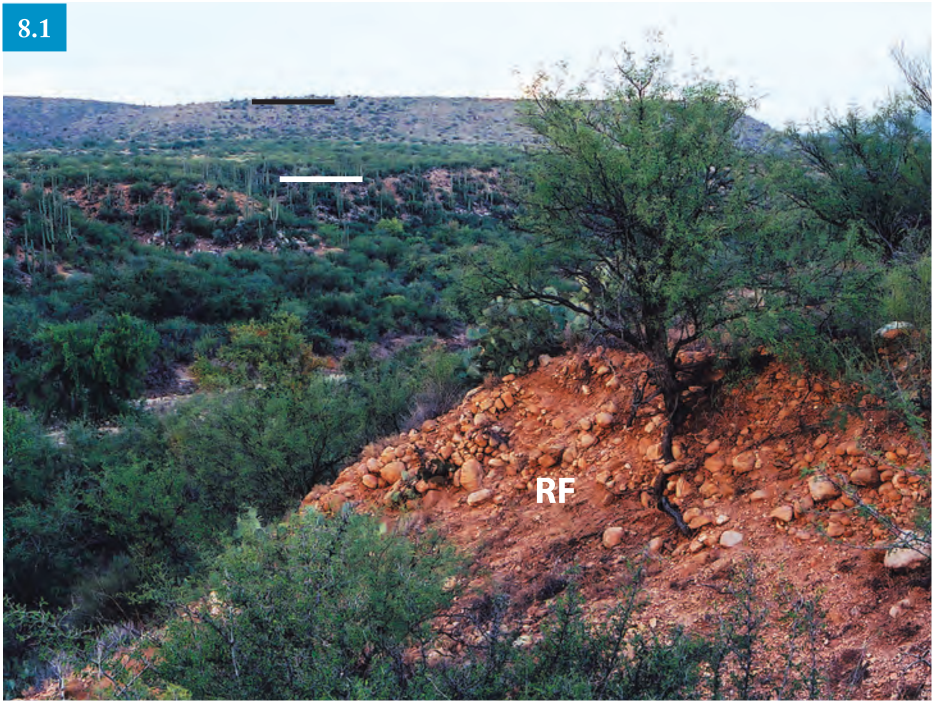
Drive to the parking lot at the end of the park road and hike to the trailhead (Map C).

Feature -8-

Stream Terraces

Location: Follow the Romero Canyon Trail for about 350 yards (320 meters) to a bench on the edge of a flat, step-like surface overlooking Sutherland Wash Valley.

8.1



These flat, step-like surfaces are **stream terraces** (Figure 8.1, dashed lines). They consists of silt, sand, gravel, cobbles and boulders deposited by running water. Note that tumbling in a stream during flash floods rounds the gravel-, cobble-, and boulder-sized rock fragments (RF).

Stream sediment was once much thicker in this area. Over the last several hundred thousand years, however, Sutherland Wash cut its valley into this sedimentary fill (Figure 8.2, A). Lateral erosion and deposition by the wash built a floodplain in the floor of the valley. Later, the wash cut its channel down into the floodplain (B), leaving remnants of the former valley floor as high standing stream terraces. Repeated episodes of sediment deposition and downcutting have produced a flight of terraces along Sutherland Wash (C) that are visible from this vantage point.

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. For more information on the development of stream terraces see Feature 11.

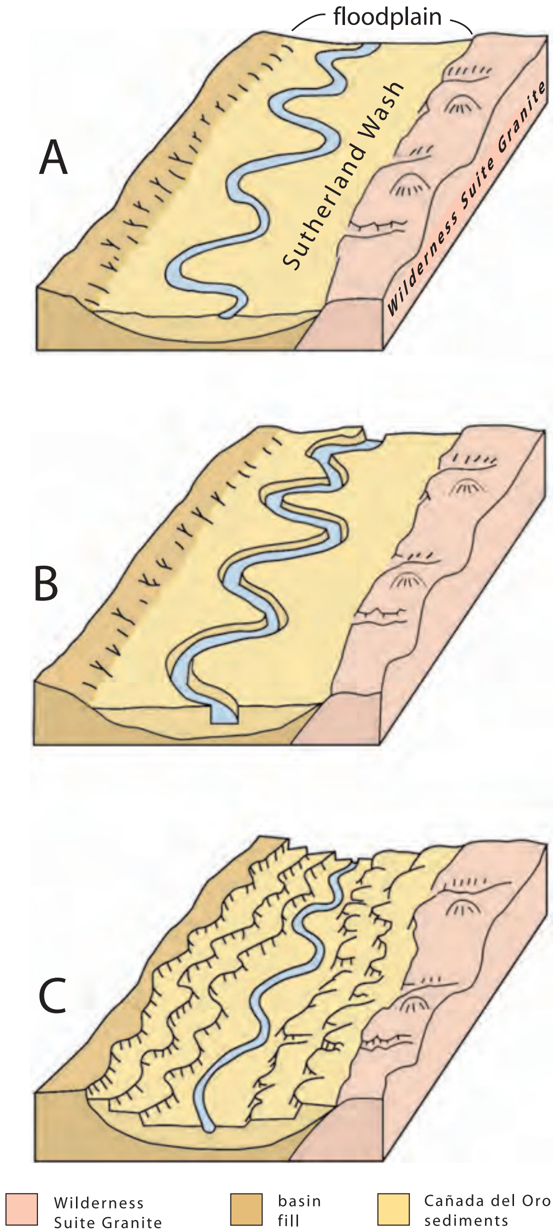


Figure 8.2 Sutherland Wash cut a floodplain in the basin fill west of the Pirate Fault (A). Sutherland Wash cut its bed into the sediment previously deposited along its floodplain (B). Repeated cycles of cutting and filling by Sutherland Wash produced step-like terraces along the margins of the valley (C).

Feature -9- Tinajas

Location: The Romero Pools are along the Romero Canyon Trail 2.8 miles (4.5 kilometers) from the trailhead.

9.1

Rock basins that hold water in the Romero Pools (Figure 9.1) are called **tinajas**, the Spanish word for large earthen water jars fired so that water will seep to the vessel's surface and keep its contents cool by evaporation. These tinajas or rock tanks, as they are called in English, are best formed in the bedrock channels of steep canyons cut into desert mountain ranges.

Boulders, cobbles, and gravel tumbled along by swiftly flowing water during flash floods act as cutting tools that gouge out weak zones in the underlying bedrock. The upstream sides of these enlarging 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 feet (6 meters) deep and hold thousands of gallons (liters) of water months after the last rain. Please do not pollute or camp near these precious water resources.

Geologic Features along the Canyon Loop Trail

The Canyon Loop Trail, which starts at the park trailhead, continues for 2.3 miles (3.6 kilometers).

Feature -10- Fault

Location: This feature is best viewed by hiking the Canyon Loop Trail .8 mile (about 1300 meters) to Breccia Hill (Map C).

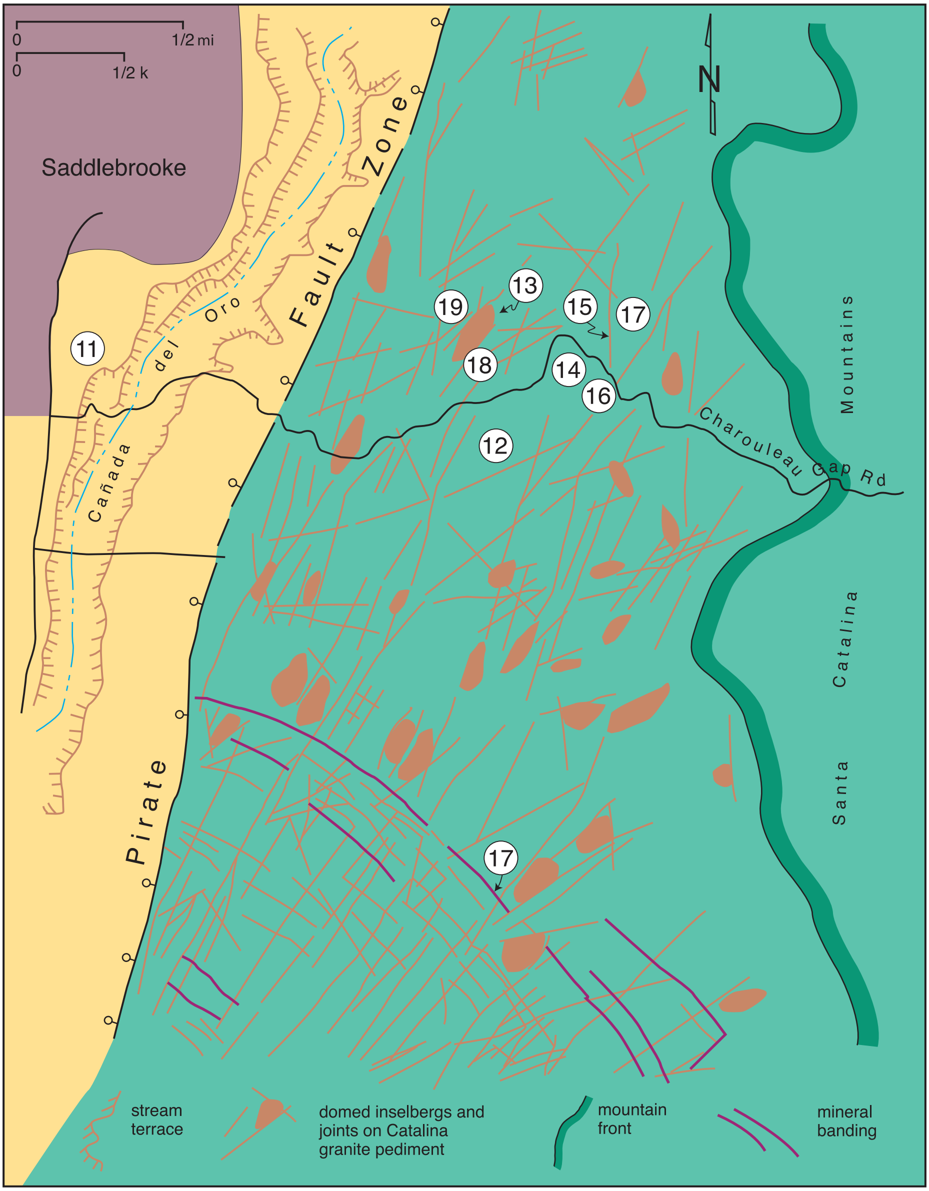
10.1

Faulting, movement along a fracture in the brittle rocks of the Earth's surface, can have an enormous impact on a region's topography. Vertical movement along the Pirate Fault, for example, formed the steep western face of the Santa Catalina Mountains, the sediment-filled Cañada del Oro basin to the west, and a host of minor features that make up the local landscape (Map B). Total vertical movement along this fault is estimated to be 1.8 to 2.5 miles (3 to 4 kilometers). Bedrock to the west of the fault has dropped down to form the Cañada del Oro basin, which is filled with thousands of feet of sediment. Bedrock to the east of the fault has been uplifted and forms the impressive western side of the Santa Catalina Mountains. Erosion has worn back the face of the range as much as 2.9 miles (4 kilometers) from the fault that produced it. 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 Pirate fault. The position of the Cañada del Oro in this part of the basin is also a result of stream piracy (see Feature 21) controlled by this fault zone.

Tremendous friction is generated as fault surfaces slide together. This grinding action produced a zone of powdered rock **(fault gouge)** and highly broken rock **(fault breccia)** that can be observed here at Breccia Hill and at other locations where the Cañada del Oro has exposed the fault surface (Figure 10.1, arrow). Movement on the Pirate Fault is thought to have occurred six to twelve million years ago. This demonstrates how an ancient geologic structure, in this case a fault, can control modern landscapes.

Features along the Charouleau Gap Road (Four-Wheel Drive)

Follow Oracle Road (Highway 77) for 10.5 miles (16.9 kilometers) north of the intersection with Magee Road to Golder Ranch Road, turn right (east) and proceed 1.2 miles (1.9 kilometers) to Lago del Oro Parkway. Turn left (north) and follow Lago del Oro Parkway for 3 miles (4.8 kilometers) to the Charouleau Gap four-wheel-drive road. Follow this road across the Cañada del Oro (Map D).



MAP D

Geologic features (circled numbers) in the Charouleau Gap Road area

Feature -11- Stream Terraces

Location: The stream terraces are developed best on alluvial fill on the west side of the Cañada del Oro (Map D).

The step-like surfaces in Figure 11.1 (white lines) are stream terraces. Standing high above the stream that cut them, these benches are remnants of former floodplains.

The geologic history of the Cañada del Oro includes episodes of valley filling followed by episodes of down-cutting during which the stream removed this fill. Sediment accumulated in the valley of the Cañada del Oro when great quantities of rock debris were being eroded from the slopes of the Santa Catalina Mountains. During periods of reduced slope erosion the stream cut its channel through this sediment, leaving remnants of the former valley floor as high-standing stream terraces. The stream shifted laterally across its floodplain and progressively widened the new valley floor by undercutting the slopes of the adjacent stream terraces (Figure 11.2).

Stream terraces record changes in the geologic history of a river valley. Here they represent at least four major periods of downcutting and channel backfilling. Alternating wet and dry climatic conditions caused variations in the quantity of water and rock debris that moved down the Cañada del Oro during the last 500,000 years. These graceful, stepped landforms resulted.

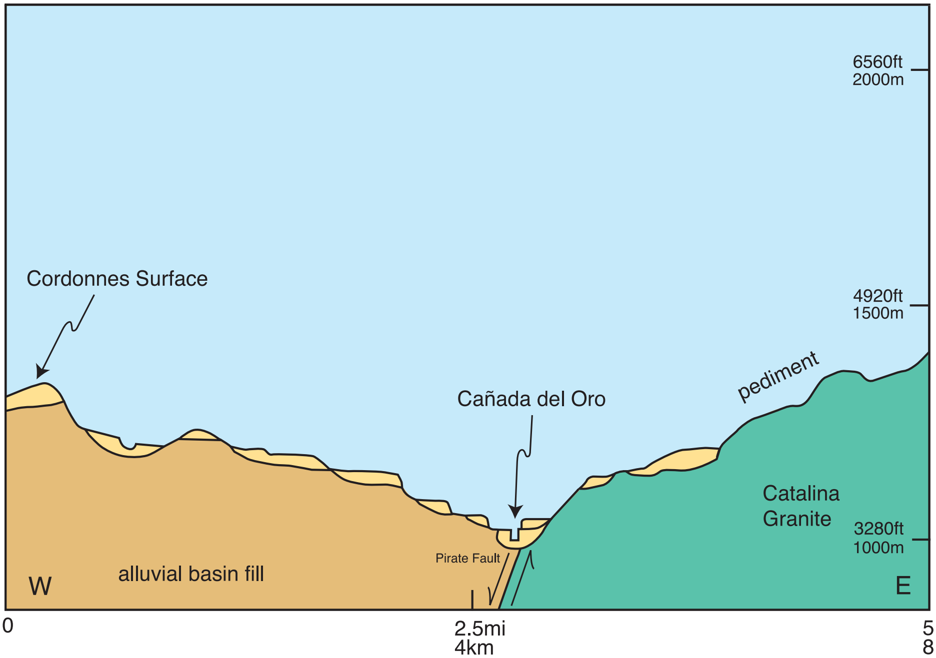


Figure 11.2 Cross-section of stream terraces along the Canada del Oro (after McFadden, 1981). The Cordonnes Surface is the surface of a bajada (Feature 20) that pre-dates development of the stream terraces (after McFadden, 1981).

Feature -12- Pediments

Location: Follow the Charouleau Gap 4-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to reach this feature (Map D).

12.1

The sloping bedrock surfaces that floor the embayments cut into this side of the Santa Catalina Mountains are called pediments (Figure 12.1). These surfaces extend from the base of the mountain to the Cañada del Oro valley. Small streams that drained this face of the range planed off the pediments between six and two million years ago.

The width of the pediments is the distance the mountain front has been eroded back from its original location along the Pirate Fault. The hardness and structure of the bedrock controlled the development of the pediments. Here, in the moderately hard Catalina granite, the pediment is about 2.9 miles (4 kilometers) wide. To the north, in the highly weathered and weaker Oracle granite, pediments average 5 miles (8 kilometers) in width. Near Catalina State Park, the Wilderness Suite granite is the bedrock. This granite has been altered to gneiss, a harder rock, over broad areas. In addition, most small joints (cracks; see Feature 15) have been filled by injections of once-molten rock, welding the bedrock into a highly resistant unit that offers few avenues for penetration by weathering and erosion processes. As a result, pediments cut into the Wilderness Suite granite are only 400 to 1200 yards (about 350 to 1100 meters) wide.

These pediment surfaces were subsequently buried deeply by sediment worn from the Santa Catalina Mountains. Since then, the Cañada del Oro and its tributaries have exhumed (exposed) them.

After the initial uplift of the Santa Catalina Mountains, movement of the local crustal rocks slowed or ceased five million years ago. Since then, desert streams have had sufficient time to bevel off these gently sloping pediments.

Feature -13- Domed Inselbergs

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to view this feature (Map D).

13.1

The dozens of domed-shaped granite hills here are domed inselbergs (also called exfoliation domes and bornhardts)(Figure 13.1, arrow). Weathering and erosion, guided by two major sets of natural cracks in the bedrock, called joints, have sculpted these graceful and distinctive landforms from the Catalina granite.

Sets of vertical joints that fracture the granite in this area have a rhomboidal (that of a deformed rectangle) pattern that is clearly visible when viewed from above (Figure 13.2, J). Each joint-bounded 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 Earth's crust, is gradually being released as erosion exposes more of the bedrock.

Sets of curvilinear joints (Figure 13.3, A) parallel to the ground surface are produced within each rhomboid by this slow release of internal stress. These joints terminate against the vertical joints that bound the rhomboids. These curved joints divide the expanding granite into curved sheets that eventually arch up to form the curved crests of the domed inselbergs. Each rhomboid of bedrock is then a domed inselberg in varying stages of development or decay (Figure 13.4).

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 the rhomboid margins. These

Figure 13.2 Aerial photo of domed inselberg and bounding vertical joints (J). Photo by John V. Bezy

marginal zones 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. The high domed inselbergs in this area are very resistant landforms that 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.

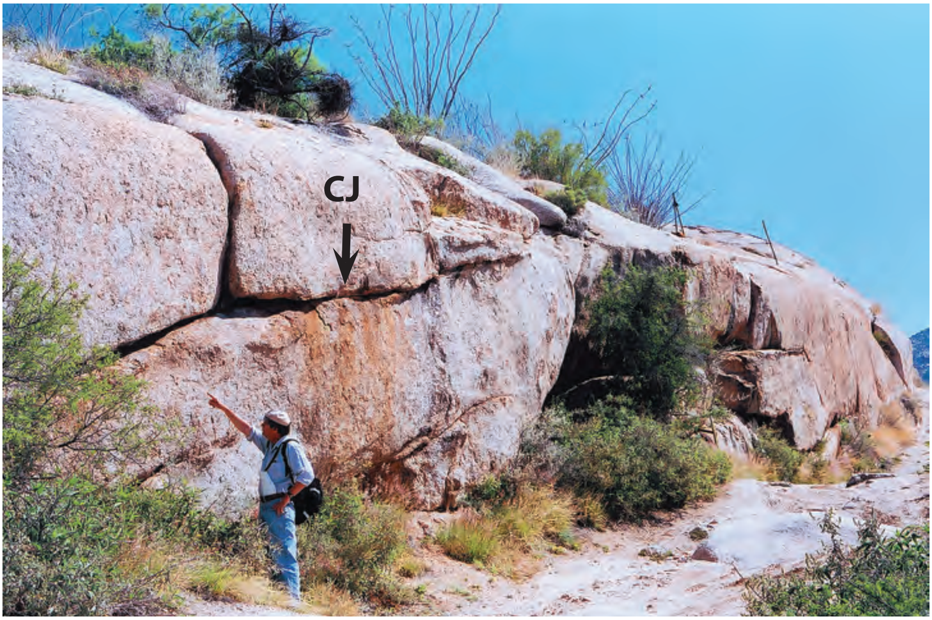


Figure 13.3 (Above) Curved joints

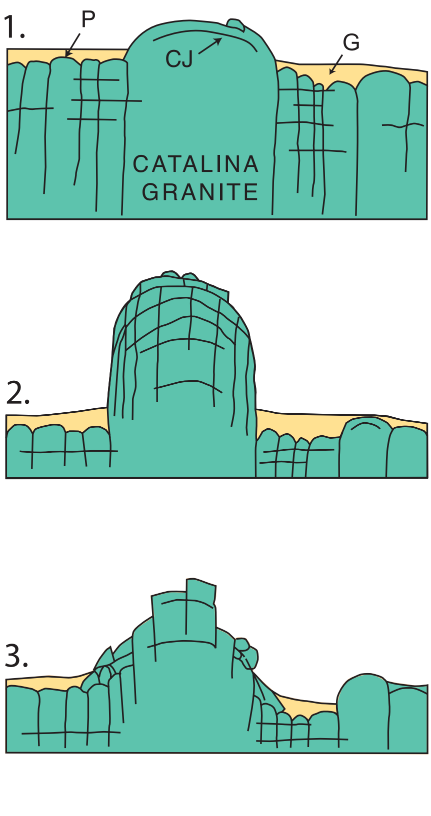


Figure 13.4 (Left) Stages in the development of a domed inselberg. Curved joints (1,CJ) develop by the release of internal stress in the Catalina Granite as the domed inselberg begins to form. The inselberg increases in height as the curved sheets continue to arch up and the pediment surface (1, P) is lowered by weathering and erosion (2). In time, the domed inselberg wears down (3). A thin mantle of **grus** (G) (Feature 14) covers portions of the pediment surface. Diagrams modified after Thomas, 1974.

Feature -14- Grus

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to reach this feature (Map D).

14.1

The ground surface here is composed of granular gravel, called **grus** (Figure 14.1, G), derived from the disintegration of the surrounding Catalina granite. Unlike water-deposited gravels, which tend to be rounded by tumbling in a stream, grus consists of sharp-edged feldspar and quartz crystals.

In the desert, granite breaks down into its major component mineral crystals: quartz, feldspar, and biotite. Freezing of moisture and expansion of wetted salt particles within the rock causes quartz and feldspar grains to fracture along their boundaries with other crystals. Also, the mineral biotite converts easily to clay minerals when weathered, causing microcracks that further weaken the rock. Prolonged exposure to the elements causes these mineral crystals to separate grain by grain until the rock crumbles to grus. Feel the nearby granite outcrops—many are decomposed to the point that crystals can easily be rubbed from the surface.

Grus develops best where granite mountains are weathered under desert conditions. In more 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.

Feature -15- Joints

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to reach this feature (Map D).

15.1

The cracks present throughout the surrounding Catalina granite are **joints** (Figure 15.1). Some joints formed as the once-molten granite cooled and contracted. Others are the result of stress caused by faulting, folding and other movements in the Earth's crust long after the emplacement of the granite. Many joints, particularly the graceful, curvilinear joints (Figure 13.3) present in the numerous domed inselbergs (Feature 13) of the Catalina granite are still widening.

Sets of joints intersect other joints at various angles and divide the bedrock into compartments. Some of these joints, called master joints, are extensive and can be traced for miles across the landscape (Figure 15.2, J). Spacing between joints varies from a few inches (several centimeters) to 50 yards (about 50 meters).

Joints are pathways along which destructive chemical and physical weathering processes can penetrate the bedrock. Water from rain and snowmelt seeps into joints and freezes during winter nights. The resulting expansion of the ice exerts sufficient pressure to shatter mineral grains and widen joint walls. Plant roots also enter and wedge open the joints. Accumulated soil acts as a sponge that keeps slightly acidic groundwater in contact with joint walls, which enables chemical weathering to decompose the rock.

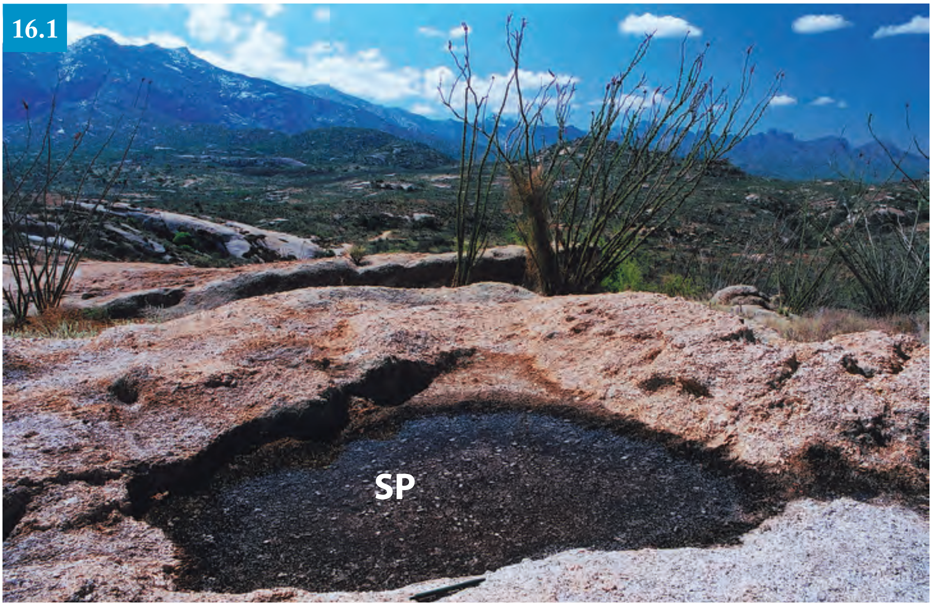
Over hundreds of thousands of years, weathering and erosion by running water have widened and deepened intersecting joint sets to form the intricate, rectangular pattern of drainage channels that are cut into the granites of the Santa Catalina Mountains.

Figure 15.2 Aerial photo of master joints in Catalina granite.
Photo by John V. Bezy

Feature -16- Solution Pans (Gnammas)

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to reach this feature (Map D).

16.1



Many relatively level granite surfaces in this area contain flat-bottomed, circular depressions that commonly have overhanging sidewalls (Figure 16.1, SP). These solution pans or gnammas, which are up to 3 feet (1 meter) across and 4 inches (10 centimeters) deep, can hold water for days after rain and snowmelt.

Pans form at points of rock weakness (joints, areas of 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 nearby 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 granite grain by grain. The rock disintegrates slowly and the resulting debris is swept and flushed from the enlarging solution pans by wind and heavy rains.

Feature -17- Features in the Granite

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (about 2.4 kilometers) to reach this feature (Map D).

17.1

Some features in 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.

The dark inclusion in the granite pictured in Figure 17.1 (arrow) is a xenolith (pen for scale). **Xenoliths** are fragments of older rock, perhaps altered Pinal Schist that became incorporated into the rising magma when it was hot and plastic. They range in size from 0.5 inch (1.25 centimeters) to more than a dozen square yards (meters). Locally xenoliths make up 40 percent of the bedrock surface.

The white veins in the granite are **dikes** (Figure 17.2). They formed when cracks in the Catalina 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 these mineral crystals, however, is much smaller in the aplite than in the granite. This indicates that the molten rock from which the aplite formed cooled too rapidly for large crystal to grow. Magma from which the Catalina granite formed cooled at a slower rate that permitted 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 granite bedrock between Nicholas and Sutherland Washes exhibits a **radial pattern of joints** (J) and **mineral banding** (MB) that is visible on aerial photographs (Figure 17.3). 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 (fissure fillings; see the preceding paragraph) that contrast with the Catalina granite. The band 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 stress. More study is needed.

Figure 17.2 Aplite dikes in Catalina Granite (Pen for scale)

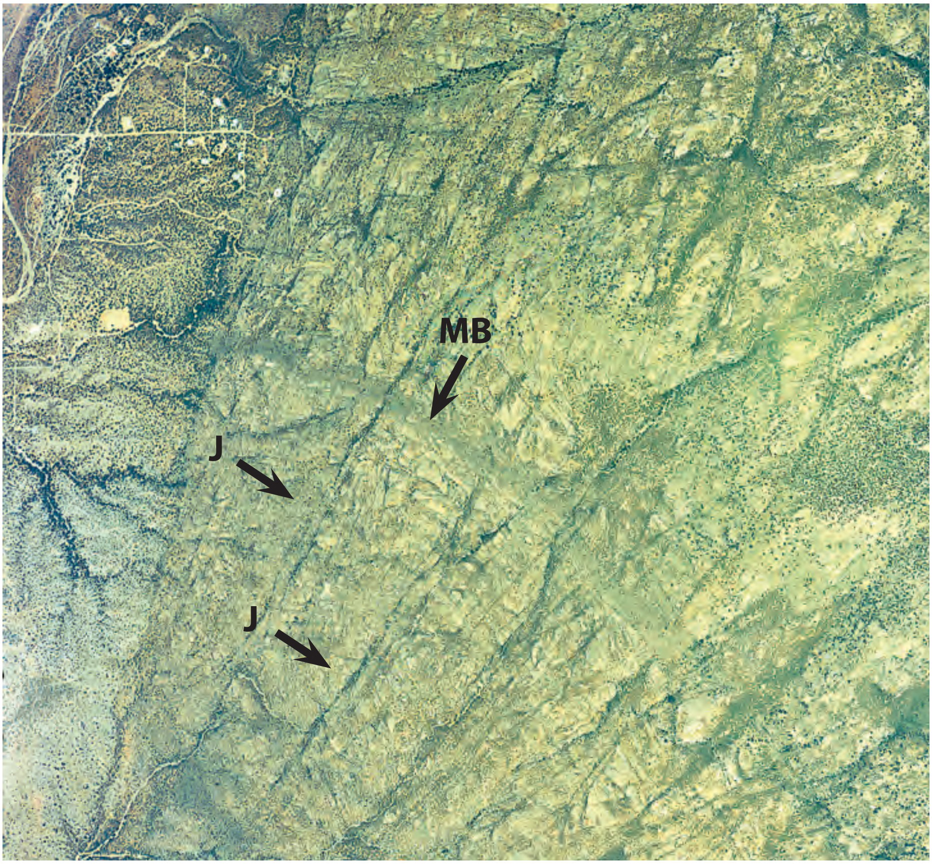
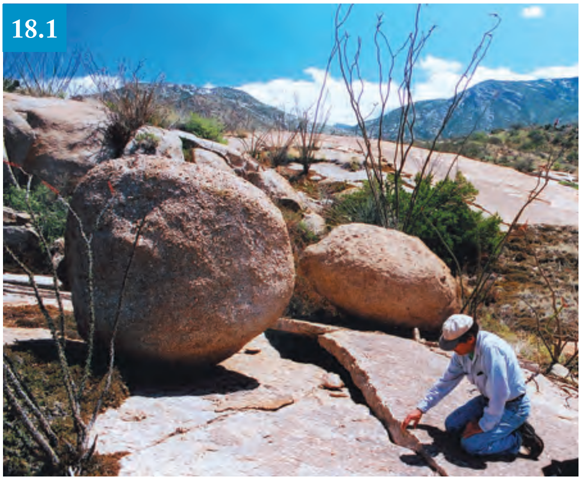


Figure 17.3 Aerial phote of radial pattern of joints (J) and mineral banding (MB).

Feature -18- Spheroidal Boulders

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to reach this feature (Map D).



18.1

The rounded or spheroidal boulders (Figure 18.1) perched on the crests of domed inselbergs (exfoliation domes; see Feature 13) in this area are characteristic of many granite landscapes. 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 (Figure 18.2) scattered along the sides and tops of the domes.

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.

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.

Some boulders become rounded by separating (spalling) into thin layers that are concentric with their surfaces—much like those of an onion (Figure 18.3). 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.

Figure 18.2 Remnant of curved sheet of granite on domed inselberg slope.

Figure 18.3 Boulder spalling into concentric layers.
Photo by John V. Bezy

Feature -19- Gutters

Location: Follow the Charouleau Gap four-wheel-drive road across the Cañada del Oro for about 1.5 miles (2.4 kilometers) to reach this feature (Map D).

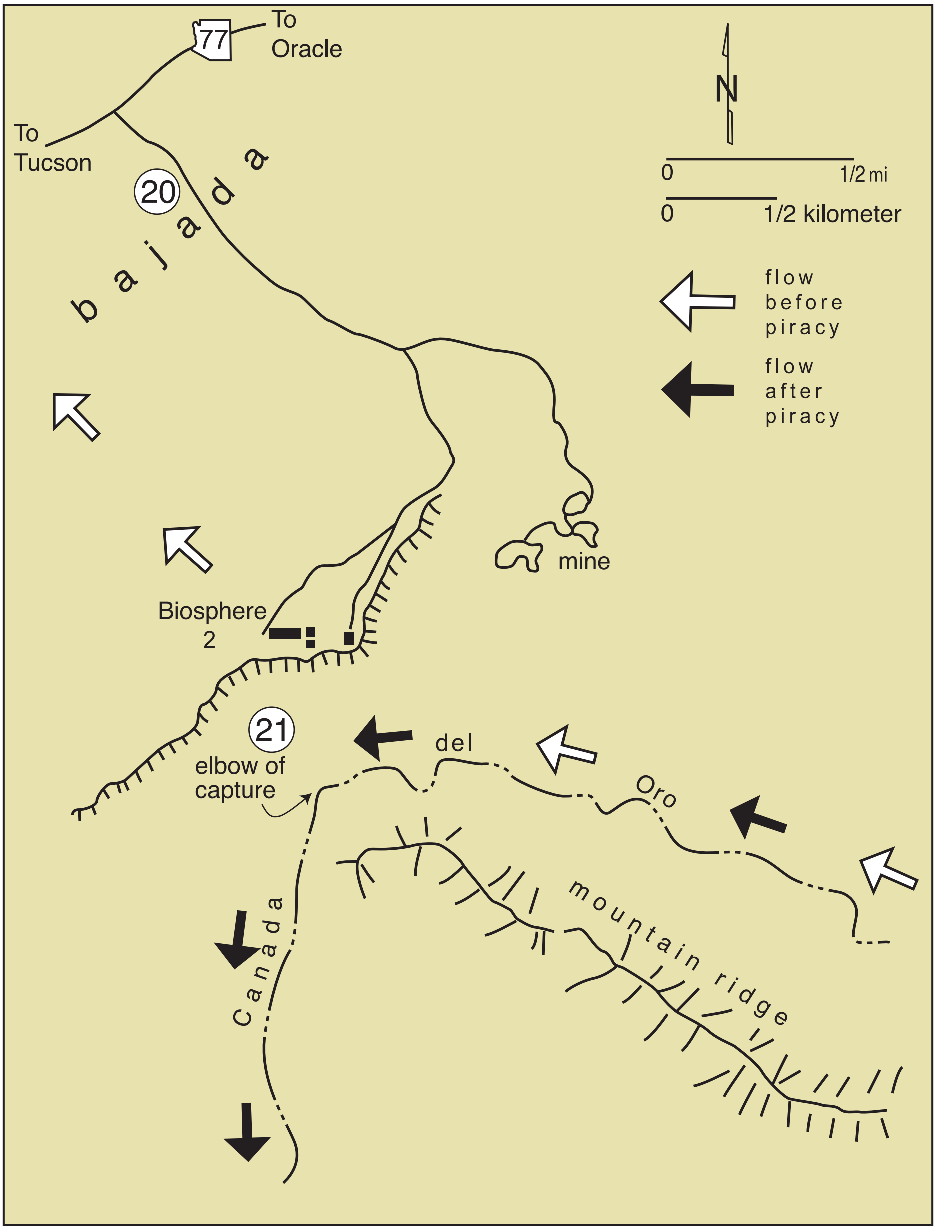
19.1

The steep faces of many of the domed inselbergs are scarred by shallow bedrock drainages called gutters (Figure 19.1, G). 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.

Gutters are common, small-scale features found wherever exfoliation domes have developed in granite.

Geologic Features near Biosphere 2

Follow Highway 77 20.3 miles (32.7 kilometers) north from the intersection with Magee Road and turn right (southeast) on the Biosphere 2 access road.



MAP E

Geologic features (circled numbers) in the Biosphere 2 area

Feature -20- Bajada

Location: Follow the Biosphere 2 access road for about .5 mile (800 meters) and hike to a high point that provides a view of the area (Map E).

20.1

The gently sloping plain on which you have been driving for the last 15-20 minutes is a bajada (Figure 20.1, arrow). It consists of gravel, sand, and silt transported from the canyons of the Santa Catalina Mountains by flash floods 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. By about 1 million years ago, they had merged to form the bajada—that continuous apron of alluvial material adjacent to the Santa Catalina Mountains.

Note the reddish-orange color of the soil on the surface (called the Cordonnes Surface by geologists) of this bajada. This color indicates that this surface has been exposed to atmospheric weathering for a long time—in this case over one million years. During this period of extensive weathering, iron minerals in the sediment oxidized or rusted, giving a reddish hue to the ground.

Subsequent downcutting and changes in the course of the Cañada del Oro have separated the bajada from the mountain front. Wet weather desert streams are now cutting into and washing away the loose sediment that makes up the bajada.

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.

Feature -21- Stream Piracy

Location: This feature is best viewed from the lawn immediately south of the Biosphere 2 restaurant. There is a fee to enter Biosphere 2.

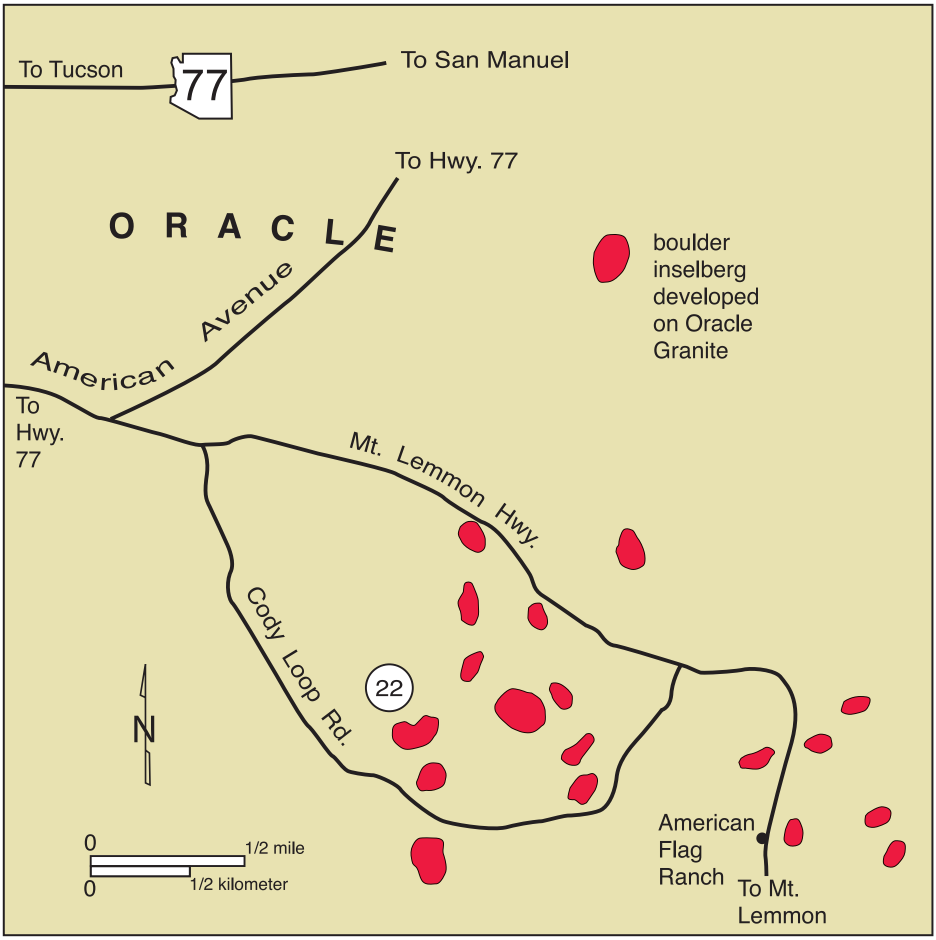
21.1

The Cañada del Oro originally flowed northwestwardly out of the Santa Catalina Mountains near the town of Oracle. (see Figure 21.1 and Map E). About a 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 Santa Catalina Mountains. This stream, which had a steeper gradient than the Cañada del Oro and followed the more easily eroded zone of shattered rock along the Pirate Fault, extended its drainage basin northward by headward erosion. In time, its headwaters cut into the drainage basin of the Cañada del Oro, and eventually captured the flow of the Cañada del Oro. The "elbow" or point of capture (arrow) occurred a short distance southeast of Biosphere 2, where the Cañada del Oro makes its abrupt turn to the south.

Stream piracy is common wherever differences in rock hardness or stream gradient allow one stream to erode more rapidly than its neighboring drainages. In some regions, the diversion of watercourses by stream piracy has produced valleys and gorges abandoned by rivers that carved them.

Geologic features near the Town of Oracle.

Follow Highway 77 north for 23.9 miles (38.5 kilometers) from the intersection with Magee Road to the town of Oracle. Continue on American Avenue for 2.3 miles (3.7 kilometers) and turn right on the Mount Lemmon road. Proceed for .3 mile (about 500 meters) to Cody Loop Road; follow this road for 1.6 miles (2.6 kilometers) to the first boulder inselbergs. More boulder inselbergs can be seen further along this road and along the Mt. Lemmon Road in the vicinity of American Flag Ranch (Map F).



MAP F

Boulder inselbergs (Feature 22) near the town of Oracle

Feature -22- Boulder Inselbergs

Location: This feature is best viewed along the Cody Loop Road.

22.1

The surrounding boulder-clad hills (Figure 22.1) are called **boulder inselbergs**. They are the characteristic landform of pediments (see Feature 12) cut into the 1.45 billion-year-old Oracle granite that forms this northern portion of the Santa Catalina Mountains.

Closer examination of the bedrock will reveal that it is fractured by sets of vertical and horizontal cracks, called joints (see Feature 15). Joints divide the bedrock into individual rectangular blocks—joint blocks—with dimensions that range from 3 to 18 feet (1 to 6 meters).

Weathering has widened the joints and rounded the corners and edges of the joint blocks, producing boulders. The blocks that make up inselbergs near Oracle Ridge have not shifted from their original position, so the joint pattern of the bedrock is well displayed. Even farther to the north and east, where the inselbergs have been reduced by erosion, the structural integrity of the bedrock is still preserved—clear evidence that these landforms are the products of surface weathering and erosion guided by a dense pattern of vertical and horizontal joints.

Boulder inselbergs have developed on the sloping surfaces of pediment remnants along the northern and northeastern flanks of the Santa Catalina Mountains. Consequently, the inselbergs become progressively older and lower with increasing distance from the mountain front. Northeast of the Mount Lemmon Road the inselberg remnants are buried by the gravel, sand, and silt of the modern bajada (see Feature 20).

Boulder inselbergs are common landforms that develop wherever granite bedrock is divided into blocks by a dense network of vertical and horizontal joints.

Suggested Readings

Banks, N.G., 1976, Reconnaissance geologic map of the Mount Lemmon quadrangle, Arizona: U.S. Geological Survey Miscellaneous Field Studies Map MF 747, scale 1:62,000.

Banerjee, A.K., 1957, Structure and petrology of the Oracle Granite, Pinal County, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 112 p.

Budden, R.T., 1975, The Tortolita-Santa Catalina Mountain Complex: Tucson, University of Arizona, M.S. thesis, 133 p., 5 sheets, scale 1:62,500.

Bull, W.B., McCullough, E.F., Jr., Kresan, P.L., Woodward, J.A., and Chase, C.G., 1990: Quaternary geology and geologic hazards near Canada del Oro, Tucson, Arizona, in Gehrels, G.E. and Spencer, J.E., eds., Geologic excursions through the Sonoran Desert Region, Arizona and Sonora: Arizona Geological Survey Special Paper 7, p. 1-8.

Childs, Craig, 2000, The Secret Knowledge of Water: Seattle, Sasquatch Books, 288 p.

Creasey, S.C., Banks, N.G., Ashley, R.P. and Theodore, T.G. 1977, Middle Tertiary plutonism in the Santa Catalina and Tortolita Mountains, Arizona: U.S. Geological Survey Journal of Research, v. 5, no. 6, p. 705-717.

Davis, G.H., Bedford, J.M., Constenius, K.N., Johnson, J.A., Kong, F., Ornelas, R., Pecha, M., and Rodriguez, E.P., 1994, Deep cataclastic counterparts of neotectonic fault-rock architecture in the granite footwall of the Basin and Range Pirate fault, southern Arizona: Geological Society of America Abstracts with Programs, v. 26, no. 7, p. A267-A268.

Dickinson, W.R., 1991, Tectonic setting of faulted Tertiary strata associated with the Catalina core complex in southern Arizona: Geological Society of America Special Paper 264, 106 p., scale 1:125,000.

_____, 1992, Geologic map of the Catalina Core Complex and San Pedro trough, Pima, Pinal, Graham, and Cochise Counties, Arizona: Arizona Geological Survey Contributed Map 92-C, scale 1:125,000 scale.

_____, 1994, Trace of main displacement surface (bedrock/basin fill contact) of Pirate fault zone, west flank of Santa Catalina Mountains, Pima and Pinal Counties, Arizona: Arizona Geological Survey Contributed Map 94-G, 9 p., scale 1:24,000.

Hoelle, J.L., 1976, Structural and geochemical analysis of the Catalina granite, Santa Catalina Mountains, Arizona: Tucson, University of Arizona, M.S. thesis, 79 p.

Keith, S.B., Reynolds, S.J., Damon P.E., Shafiqullah, M., Livingston, D.E. and Pushkar, P.D., 1980, Evidence for multiple intrusion and deformation within the Santa Catalina-Rincon-Tortolita crystalline complex, southeastern Arizona, in Crittenden, M.D., Jr., Coney, P.J. and Davis, G.H., eds., Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, p. 217-267.

McCullough, E.J., Jr., 1963, A structural study of the Pusch Ridge-Romero Canyon area, Santa Catalina Mountains, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 67 p.

McFadden, L.D., 1978, Soils of the northern Canada del Oro Valley, southern Arizona: Tucson, University of Arizona, M.S. thesis, 116 p.

_____, 1981, Quaternary evolution of the Canada del Oro Valley, southeastern Arizona: Arizona Geological Society Digest, v. 13, p. 13-19.

Pashley, E.F., Jr., 1963, A reinterpretation of the anticlinal structure exposed in the northwest face of Pusch Ridge, Santa Catalina Mountains, Arizona: Arizona Geological Society Digest, v. 6, p. 49-53.

_____, 1966, Structure and stratigraphy of the central, northern, and eastern parts of the Tucson basin, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 273 p., 5 sheets, scales 1:65,000, 1:170,000, 1:250,000.

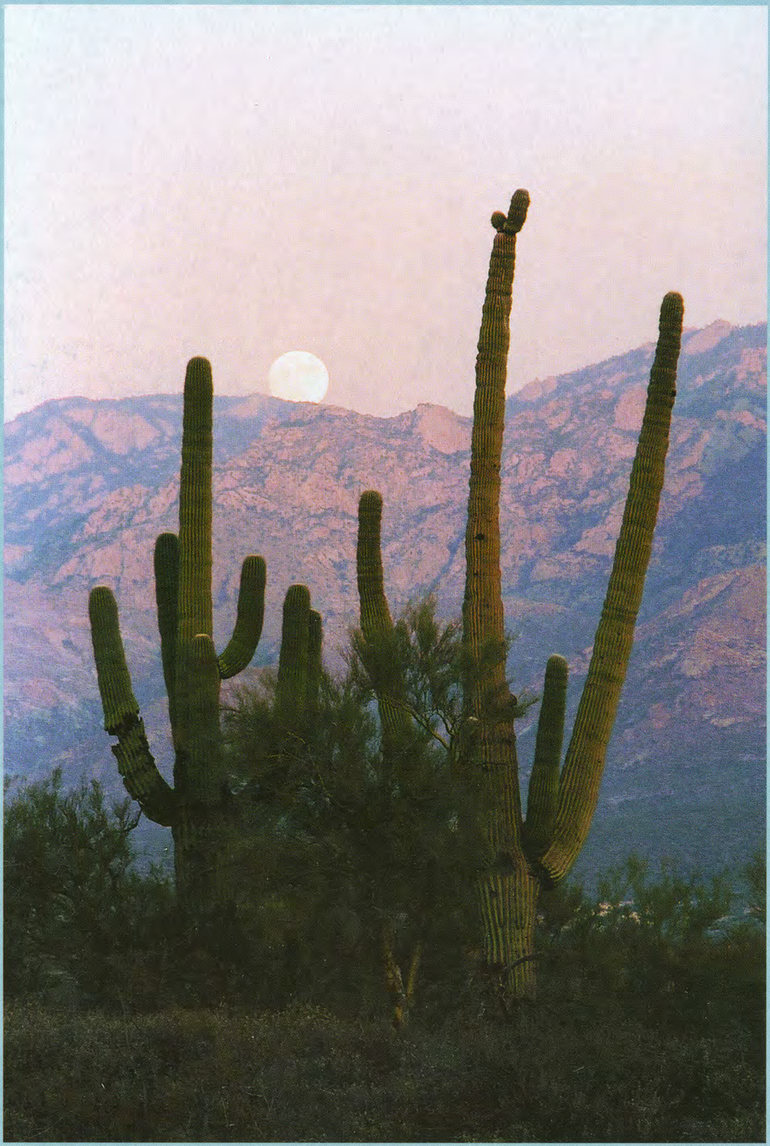
Skotnicki, S.J., 2000, Geologic map of the Oracle Junction 7.5' Quadrangle and the eastern third of the Tortolita Mountains 7.5' Quadrangle, Pima and Pinal counties, Arizona: Arizona Geological Survey Open-File Report 00-04, 19 p., scale 1:24,000.

Spencer, J.E., Richard, S.M., and Ferguson, C.A., 2000, Compilation geologic map of the Oracle 7.5' Quadrangle, Pinal and Pima counties, Arizona: Arizona Geological Survey Open-File Report 00-05, 30 p., scale 1:24,000.

Thomas, M.F, 1974, Tropical geomorphology: London, Macmillan, 332p.

Wallace, R.M., 1955, Structures at the northern end of the Santa Catalina Mountains, Arizona: Tucson, University of Arizona, Ph.D. dissertation, 45 p.

Woodward, J.A., 1990, The role of lithology and non-tectonic base-level change on the development of three pediment levels, southwestern Santa Catalina Mountains, Arizona: Tucson, University of Arizona, M.S. prepublication manuscript, 27 p.



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