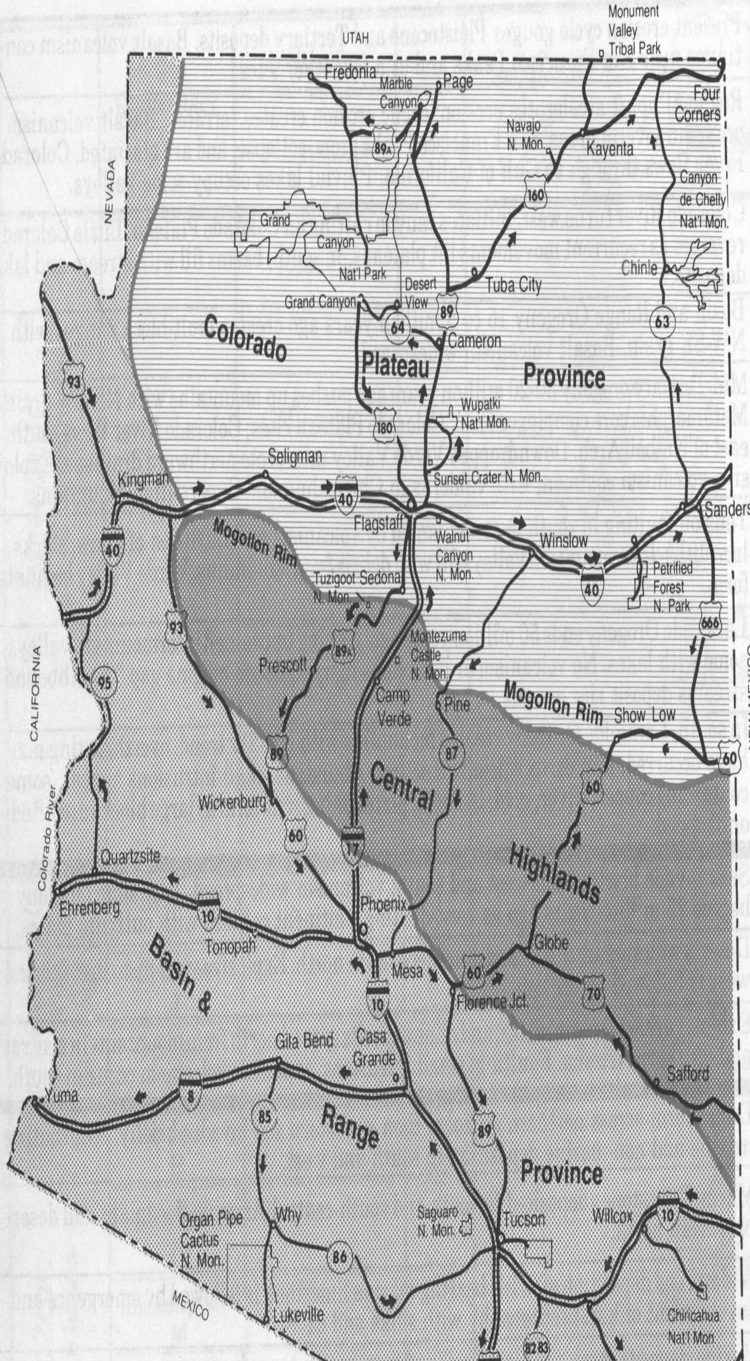


I
Some Geology Basics

Arizona's dry climate and varied topography make it a geologic wonderland, an open textbook of geology. From desert lowland to barren mountaintop, from bent and broken rocks of the southern ranges to the layer-cake strata of the stable northern plateau, about 2 billion years of geologic "happenings" have left their traces for us to piece together into a coherent, albeit patchwork, history.

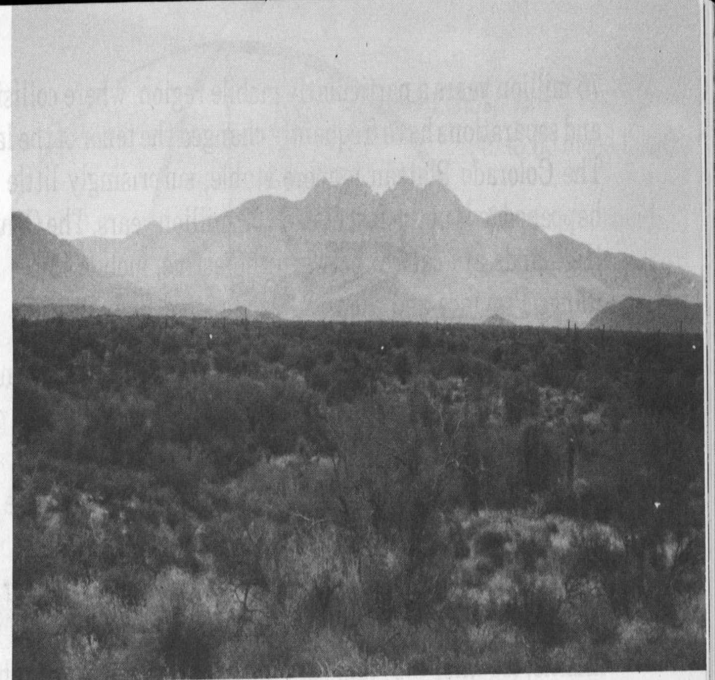
THREE PROVINCES

In this book, as in many other discussions of Arizona's geology, the state is divided into three regions or provinces: the Basin and Range deserts of southern and western Arizona (Chapter II), the mountainous Central Highlands (Chapter III), and in the north the Colorado Plateau (Chapter IV), named for the river which has so boldly and beautifully carved a canyon through it. In each province, geology plays the major role in governing the spacing and character of hills and mountains, canyons and valleys, cliffs and plains. By governing their habitats, geology has ruled over plant and animal life as well, and much more recently over the ways of man.

In the Basin and Range deserts each rocky mountain range at first seems different, out of character with its neighbor, the transitions between them buried deep beneath debris-filled desert valleys. Yet certain patterns emerge. Many of the ranges — particularly those with smoothly domed summits — are recognized now as having a common basic structural pattern. Many others display certain rocks in common, suggesting a single ancient mountain-building episode that created long-gone mountains to match today's Sierras. In yet others, older and much distorted rock exhibits a definite "fabric," a northeast-southwest (NE-SW) trend of cracking and jointing and mineral alignment, as well as of rock types, telling us of even earlier, even greater ranges of folded rock, mountains of Himalayan magnitude, crushed and forced upward by collision between continents.

Some of the rock types and trends of the Basin and Range Province continue into the Central Highlands, where we can learn from their continuity how these trends behave. The Central Highlands manifest also many features characteristic of the Colorado Plateau to the north, and therefore may be considered transitional between the Basin and Range Province

Mountain Ranges alternate with desert basins in the Basin and Range Province.



The Four Peaks form a well recognized landmark in the mountainous Central Highlands. Their rock is Precambrian quartzite.

and the Plateau. But in their tight-clustered ranges and narrower, shallower, and less numerous basins, the Highlands are distinct and deserve a chapter of their own.

The Colorado Plateau, on the other hand, bears little resemblance to the southern deserts. Ranging 4000 to 9000 feet above sea level, the Plateau is in reality a step-by-step series of flat-topped units separated from each other by cliffs or steep slopes — an unconventional landscape made more beautiful by the many and varied hues of bare rock. Seeming grotesque to some, this vast and lonely land is to many others imbued with haunting magic and singular charm.

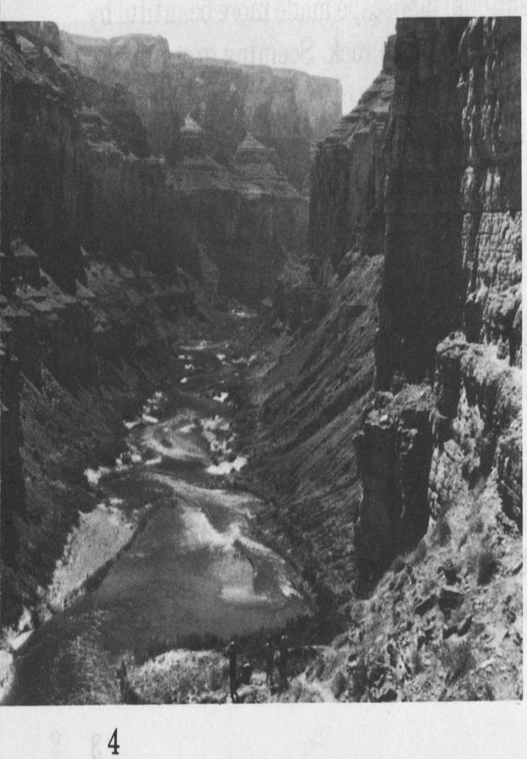
PUSH-PULL GEOLOGY

Why the difference between Arizona's three provinces? Newest geologic thinking places them at the doorstep of **Plate Tectonics** — a now well-documented theory stating that portions of the earth's crust have drifted around on the surface of the earth throughout geologic time, breaking apart here, crunching together there, sliding past one another somewhere else. Arizona's southern deserts lie in what has been for the last

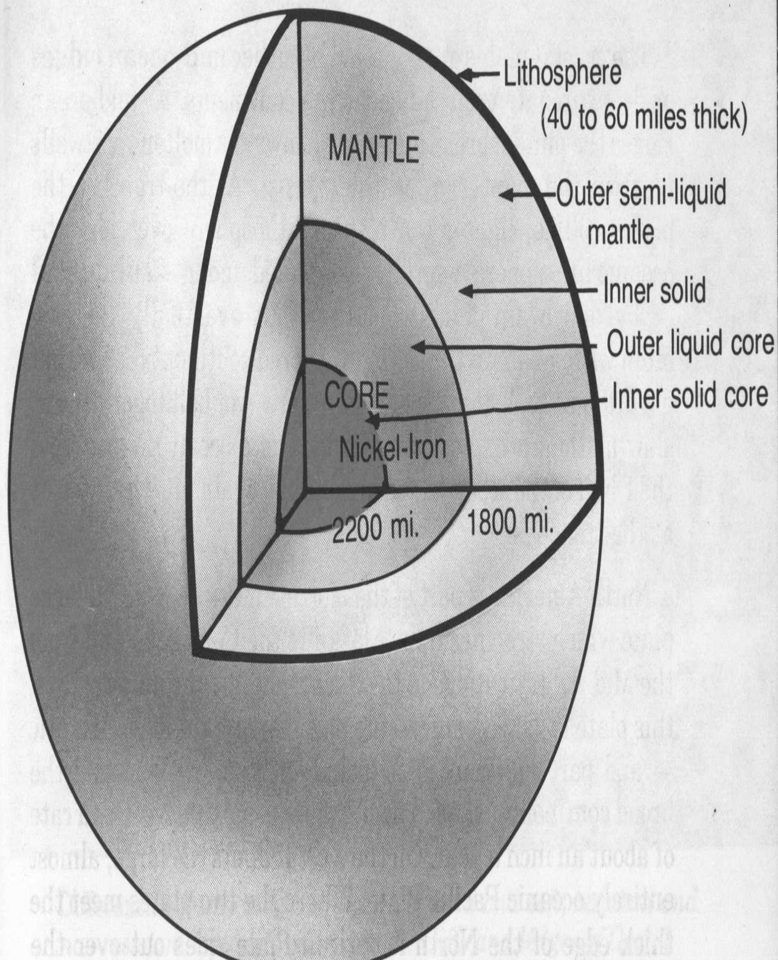
75 million years a particularly mobile region, where collisions and separations have frequently changed the tenor of the land. The Colorado Plateau is more stable; surprisingly little has happened to it in the last 600 to 700 million years. The Central Highlands are caught between the active, mobile Basin and Range Province and the firm, deep-rooted Plateau.

Let's look for a moment at the earth as a whole. At its center, we now know, is a large, spherical **core**, extremely hot, part liquid and part solid. Around the core is the thick **mantle**, also partly liquid (or at least plastic) and partly solid. Outside the mantle, floating on it, if you wish, is the earth's crust, a feeble 3 miles thick under the oceans and 20 to 25 miles thick under the continents. It is attached to the upper or outer part of the mantle; together they make up the **lithosphere**, a layer about 40 miles thick under the ocean, about 60 miles thick under the continents. Relative to the size of the earth the lithosphere is merely a thin film, one that varies in thickness and that, like a film of cooled fat on a bowl of chicken broth, can be rumpled and moved about by stirrings in the "liquid" below.

And stirrings there are: broad, strong, rolling, boiling convection currents as the mantle is heated by the great stove of the earth's interior. Because of the large size of the earth and the thickness and stickiness of the semi-molten mantle, the currents move agonizingly slowly by human standards — an inch a year or less. But with them they carry the film on the surface — the lithosphere — shifting it about, tearing it apart



In the Colorado Plateau Province, flat-lying rock layers are deeply dissected by streams and rivers.



into separate plates, at times shoving the parts together. So the currents constantly, though gradually, reshape the face of the earth; they are responsible for the rising and falling, the folding and bending of rock layers in the earth's crust, as well as for cataclysmic geologic processes like earthquakes and volcanic eruptions.

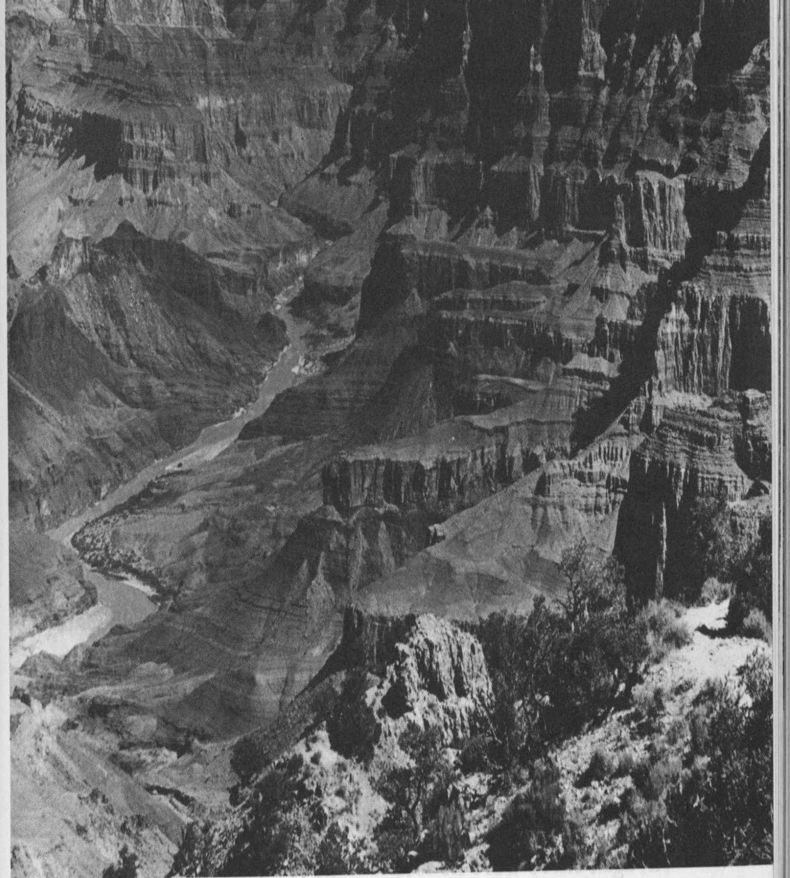
As a result of all this motion the earth's lithosphere consists of a dozen large, relatively rigid **plates** and an as yet undetermined number of smaller ones. We've seen that under the oceans the crust is thin; there it consists of dark, heavy **basalt**, rich in iron and magnesium. Continental crust is more varied. It contains all the other kinds of rock, most of them lighter in color and weight than basalt because they contain much smaller amounts of iron and magnesium minerals. The continental lithosphere, with its thicker, lighter crust, floats high on the mantle, so that like an iceberg its upper surface rises above the level of the sea.

The crustal plates are bordered by either **mid-ocean ridges** or deep, arcuate **trenches** near the continents. At mid-ocean ridges the plates spread apart very slowly as molten rock wells up from the mantle to form new crust. At the trenches the plates collide; lighter continental lithosphere overrides the oceanic lithosphere, which is then pulled under — **subducted** — by downward-plunging currents. It eventually remelts, often with an admixture of light-colored continental rock that got dragged under too. So like giant conveyor belts operating in slow motion, oceanic plates form at mid-ocean ridges, cross their half of the ocean basin, and plunge again into the interior at the trenches.

North America is part of the North American Plate, a large plate which stretches from Alaska to the Caribbean and from the Mid-Atlantic Ridge to the Pacific shore. Like many others, this plate is part oceanic — the part beneath the deep Atlantic — and part continental — including both dry land and the broad continental shelf. The big plate is moving west at a rate of about an inch a year. On the west it abuts the large, almost entirely oceanic Pacific Plate. Where the two plates meet the thick edge of the North American Plate rides out over the Pacific Plate, which is drawn down under the continent in a typical oceanic-continental plate collision. Sometimes two continental plates collide, and neither goes under; their edges bend and crumple into magnificent mountains, as India and Asia have done, creating the Himalayas. There is evidence in Arizona that continental collisions of both these types — continental plate *vs* oceanic plate, and continental plate *vs* continental plate — have happened here in the past.

There is also evidence in Arizona that the crust was at times pulled apart rather than pushed together, giving us tensional as well as collisional **tectonics**. The word **tectonic** comes from the Greek *tekton* — carpenter or builder — and carries implications of how the earth, or any part of it, is put together.

What's the result of all this pushing and pulling, squeezing and stretching? Mountains, yes, and intermountain basins. But the present mountains and basins — the present landforms — are shaped as much by erosion and deposition as by tectonic events. The higher the uplift, the steeper the slope, the stronger the stream. And the stronger the stream (or river or



Differential weathering *and erosion of hard and soft, resistant and non-resistant layers of rock create the cliffs and ledges of Grand Canyon. Sandstone and limestone are normally more resistant than shale and mudstone.*

rivulet), the greater its ability to cut into the land. So uplift breeds downcutting — a strong geologic tenet. And what of basins? Down-dropping invites deposition — another geologic tenet — so the basins are gradually filled in. Some rocks are harder, stronger, more resistant to erosion than others, and wear into cliffs and ledges or into high-standing mountain peaks. Other rocks are weaker and end up as slopes or erode away altogether.

THREE DIVISIONS OF TIME

Arizona's pull-apart and push-together story can only be related in respect to time. Geologic time begins, of course, with the birth of *geos*, the earth, about 4.5 billion years ago. That's 4,500,000,000 years — a long, long, long time by any measure. Geologists divide that immensity of time into **eras, periods**, and **epochs**, somewhat as calendars divide a human lifetime into years, months, and days. But the geologic units are not as uniform as calendar units. The first era, the **Precambrian Era**, for instance, is longer than the other three put together. It lasted about 3.9 billion years, from 4.5 billion years ago when the earth formed until only about 600 million years ago. The oldest rocks in North America are 4 billion years old, the oldest in Arizona around 2 billion years old.

The next era, the **Paleozoic Era** (its name means "old life"), was a great deal shorter: about 330 million years. The third or **Mesozoic Era** ("middle life") lasted 180 million years, and the fourth or **Cenozoic Era** ("recent life") only about 60 million years. These figures, by the way, become more and more refined as techniques are perfected for measuring the age of rocks. More exact figures are given in the table at the beginning of this chapter.

Another way to think of the last three eras — the Paleozoic, Mesozoic, and Cenozoic Eras — is as the Age of Fishes, the Age of Reptiles, and the Age of Mammals. For a long time geologists thought there were no fossils in Precambrian rocks, and that no life existed in Precambrian time. However we know better now: Life did exist in younger parts of that great era, but shells and skeletons didn't, and it is shells and skeletons that are most likely to be preserved. A few fossils are now known from Precambrian rocks — cabbagelike mounds built by algae, imprints of jellyfish, and bacteria. Some of these occur in Arizona's Precambrian rocks.

Eras are divided into **periods**, which also vary in length, and periods are divided into **epochs**. I should say that the divisions of geologic time are not just haphazard, but represent significant and commonly worldwide breaks in the continuity of rock layers or in the fossil record, the earth's great diary of life. Eras begin and end at quite significant breaks, with major mountain-building and erosion and in some cases extinctions of whole groups of animal and plant life. Periods are separated by shorter and less significant breaks; epoch breaks are still less significant. Most of the time units were first recognized in Europe, and since they were defined research in other parts of the world has narrowed the gaps between units or even filled them in completely. Nevertheless the units stand us in good stead, enabling geologists around the world to speak the same language in regard to geologic time.

Names of the Paleozoic periods derive from specific locations where rocks of certain ages accumulated: Cambria (the Roman name for Wales), Perm (a province in Russia), and so forth. Mesozoic names vary: Triassic is three-layered (in Germany anyway), Jurassic is from the Jura Mountains in France, Cretaceous refers to the Chalk, the white limestone of England.

Cenozoic period names are relics of an early nomenclature that divided up rocks by how hard they were. Primary and Secondary are no longer used; we are left with Tertiary for poorly consolidated rocks and Quaternary for unconsolidated gravel, sand and clay. But let me warn you: These definitions do not always apply. Cenozoic epoch names, which all very nicely end in *-cene*, refer again to the development of life, particularly mammals. The Paleozoic and Mesozoic periods are divided into epochs, too, but I won't be using them in this book.

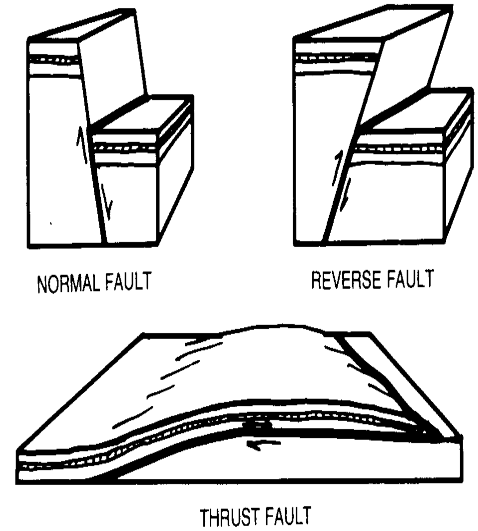
Though the Precambrian is longer than all the other eras put together, as we've seen, there is an opposite side to the coin: We know much more about the shorter, later eras than we do about the long Precambrian. This is partly because the older the rocks, the more often they have been eroded and bent into mountains and broken and squashed into more mountains and then eroded again, repeatedly; each time their story becomes harder to read. It's also partly because fossils — useful indicators of the age of rocks — are so few and far between in Precambrian rocks. And, too, it's because the older rocks have been covered over by younger rocks. So as we go back in time there are fewer and fewer pages in the earth's diary, and what pages there are are more and more faded and splotched and torn with age. The most recent rocks — those of the Recent or Holocene Epoch, lie right on the surface as sand and silt and gravel and soil, and as lava flows and new volcanic ash.

Rocks are dated by a variety of methods. For a long time only sedimentary rocks which contained recognizable fossils could be given a place in the time sequence; all other rocks had to be dated in terms of "older than" or "younger than" these sedimentary units. Today we can date volcanic rocks, including sedimentary rocks with a component of volcanic ash, by **radiometric** methods — by determining the relative amounts of certain radioactive elements and the daughter products of their gradual but very regular decay. Several isotopes of uranium and thorium, for instance, decay at invariable rates into isotopes of lead, so by measuring the quantities of isotopes of uranium, thorium, and lead in a rock we can determine the date at which the uranium decay began — the age of the rock. This method is most useful for Precambrian igneous and metamorphic rocks. The potassium-argon dating method, which works well for igneous rocks more than a million years old, works the same way, with measurements of radioactive potassium-40 and its daughter product argon-40. Carbon-14 decays quite rapidly and so is useful for sedimentary rocks laid down in the last 50,000 years or so, or for archeological remains — bone fragments and charcoal from early campfires — within the same range. A relatively new method of dating has developed since we have learned that the earth's magnetic field occasionally reverses, with the north and south magnetic poles switching their positive and negative polarities. Because the switches are irregular it has been possible to work out a yardstick of sorts, recognizable in both sedimentary and igneous rocks containing iron minerals that lined up with the earth's magnetic field as the rock formed.

Geologically the exact age of the rocks is in most cases not nearly as important as knowing their relative positions: which unit is above and therefore younger than another unit, or which is below and therefore older. It is a basic geologic "law" that layered rocks — including both sedimentary and volcanic layers — become younger upward. Geologic history therefore begins at the bottom, and one must read from the bottom of the page, or the end of the book, upward and forward. Look for a moment at the chart that precedes this chapter. If you want to know what happened in Arizona through geologic time, in the proper order, begin at the beginning with events of the Precambrian Era, and read upward toward Cambrian and Orovician and so forth, all the way up to the Recent Epoch. The rocks are arranged the same way except where they have been severely bent and broken by mountain-building processes.

MORE TERMS AND CONCEPTS

To handle time, as we've seen, we need names. To handle rocks and the landforms in which we see them, we need more names. Fortunately, many geologic terms are already in common use: silt, clay, sand, pebble, boulder, river, mountain, canyon, and so forth. But some terms are specific to geology or

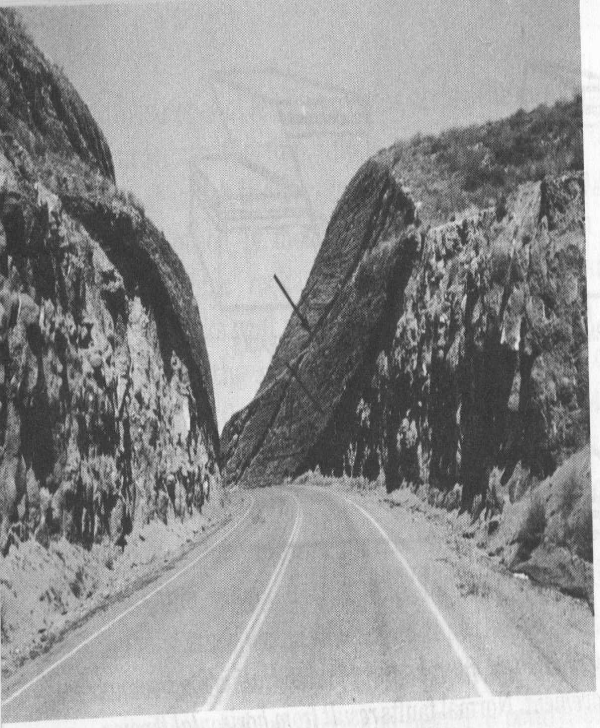


Geologists recognize three main kinds of faults. Half-arrows connote direction of movement. Normal faults *result from horizontal tension, while* reverse faults *and* thrust faults *are caused by horizontal compression.*

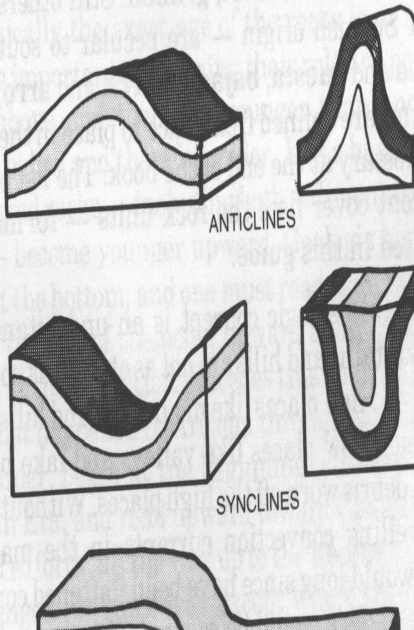
have specific geologic meanings: **formation**, **anticline**, **alluvial fan**, **pediment**, **fault**, **graben**. Still others — words commonly of Spanish origin — are pecular to southwestern geology: **mesa** and **cuesta**, **bajada**, **playa**, and **arroyo**. These and other terms are defined from place to place in the text, and also in the Glossary at the end of the book. The list of symbols inside the front cover lists the rock units — **formations** or **groups** — used in this guide.

Another useful geologic concept is an understanding that rocks and mountains and hills are *not* as eternal as poets would have us believe. High places like mountains and hills are worn down by erosion; low places like valleys and lake basins are filled up with debris worn off the high places. Without the work of those upwelling convection currents in the mantle, the earth's crust would long since have been flattened completely, and its entire surface would be covered with a sea of uniform depth.

But upwelling in the mantle *does* occur, and causes continents to drift and collide and crumple into mountains or rise into flat-topped plateaus. Geologists use the word **orogeny** for mountain-building, and give names to the various mountain-building episodes, orogenies, that have occurred through geologic time.



A highway cut exposes a two-layered thrust fault (arrows) where darker, somewhat more resistant older rocks have pushed up and over less well consolidated younger rocks.



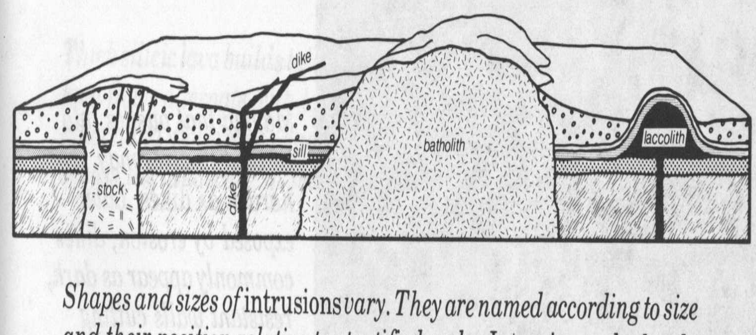
Three kinds of folds are easily recognized when they occur in layered (stratified) sedimentary or volcanic rocks.

This brings us to another basic geologic concept: Rocks can be broken, smoothly or jaggedly, or folded in a variety of ways. Some breaking takes place deep below the surface, where pressures and temperatures are tremendous. But both folds and breaks commonly show up on the surface, either because they extend through to the surface in the first place, as does the San Andreas Fault in California, or because erosion has cleaned off rocks that used to hide them. **Faults** are breaks along which displacement of the two sides has occurred. Breaks or cracks without relative displacement are called **joints**, and they are much more common than faults. There is hardly a place in Arizona where you can't see joints and faults and folds, or their surface expression in the form of mountains and cliffs and shattered rock.

THREE CLASSES OF ROCKS

By now you must be sure that geologists think in threes. They do. There are also three basic classes of rock, classed by their origin: igneous, sedimentary, and metamorphic rock.

- **Igneous rocks** originate from molten rock material or **magma** that comes from a source fairly well down in or below the earth's solid crust. Some magma pushes through to the surface and cools rapidly as **volcanic** or **extrusive igneous rock**. Extrusive rocks solidify so rapidly that crystals have little or no time to form, so these rocks are very fine-grained, with grains that are invisible to the naked eye. Common volcanic rocks are **lave, tuff** or **welded tuff** formed from volcanic ash, and **breccia**, a broken and recemented mixture of lava and tuff.



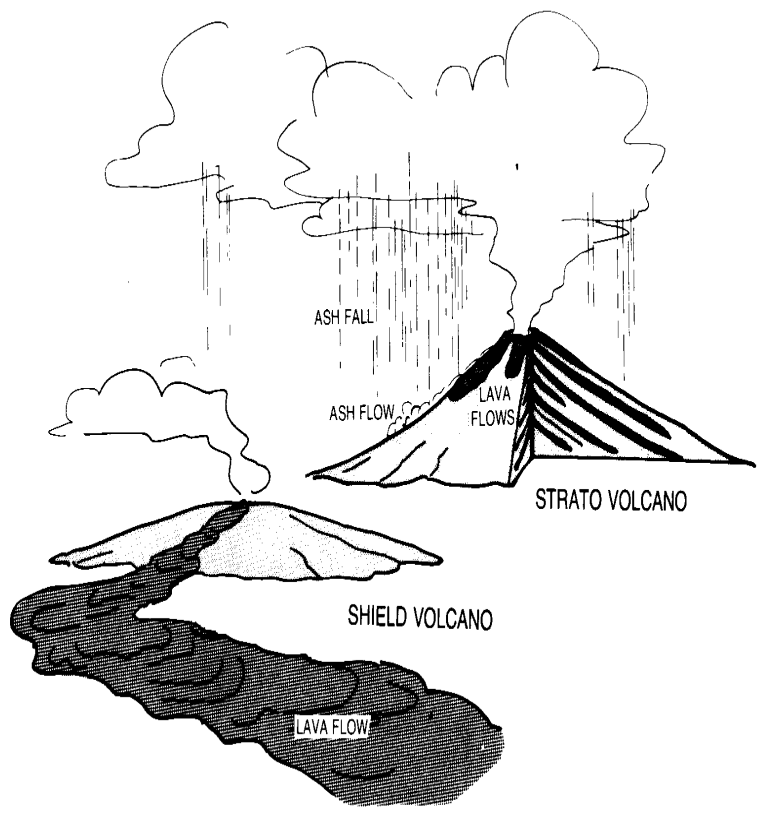
Shapes and sizes of intrusions *vary. They are named according to size and their position relative to stratified rocks.* Intrusive rocks *harden below the surface; those shown at the surface here have been bared by erosion.*

Some magma never makes it to the surface. Instead, it cools and hardens within the crust, becoming **intrusive igneous rock**. Intrusive rock crystallizes slowly and its individual crystals, forming over a long period of time, grow large enough to be visible to the naked eye. **Granite** is the most common intrusive igneous rock.

In Arizona a common and economically important intrusive rock falls between these two extremes. It cools in shallow intrusions, some of them probably just under former volcanoes where some of the same magma reached the surface and became volcanic rock. Some of the magma minerals had time to grow into large crystals, but others with different crystallization temperatures didn't. This kind of rock is called **porphyry**, and it is characterized by having large crystals, **phenocrysts**, scattered through a finer matrix.

Another thing about igneous rocks: Chemically and in terms of their mineral makeup they fall into two groups: dark ones of basic or **basaltic** composition, containing a high proportion of iron and magnesium, and light-colored, more acid, **silicic** ones with a high proportion of silica and a low proportion of dark iron and magnesium minerals. The dark rocks are thought to derive from the earth's mantle; light ones come from a shallower source where continental-type rocks have melted, as they do where plates collide. When magma appears at the surface as volcanic outpourings, the dark basaltic lava is fairly runny; it flows easily and relatively quietly from volcanic vents; the light-colored silicic magma, thick and sticky, erupts as short, stubby flows or, plugging the volcano for a time, bursts out explosively, scattering volcanic ash far and wide. There are many examples of both basaltic and silicic volcanism along the highways of Arizona. Throughout the state most Tertiary volcanic rocks are silicic and most Quaternary ones are basaltic.

Magma that pushes into vertical fissures may harden as dikes. *Later exposed by erosion, dikes commonly appear as dark, resistant walls cutting cross-country like this one near Tuba City.*



Thick silicic lava builds tall, graceful stratovolcanoes *in which stubby lava flows alternate with layers of volcanic ash. Basaltic lava, on the other hand, flows easily and forms low* shield volcanoes *or spreads out across the landscape in flat sheets.*

COMMON ROCKS OF ARIZONA

Class	Rock	Description
Sedimentary	Sandstone	Grains of sand cemented together
	Shale	Grains of silt and clay cemented together, usually breaking into flat slabs. When massive, called mudstone or siltstone.
	Conglomerate	Sand and pebbles deposited as gravel and then cemented together.
	Limestone	Composed mostly of calcite deposited as a limy mud. Usually white or gray, often containing fossils.
	Caliche	Impure limestone deposited close to the surface by groundwater evaporation.
Igneous Extrusive	Rhyolite	Light-colored, very fine-grained rock formed as lava or volcanic ash, the extrusive equivalent of granite.
	Dacite	Like rhyolite but with more alkali feldspar
	Andesite	Dark, fine-grained rock with abundant crystals of plagioclase feldspar.
	Basalt	Very fine-grained black or gray volcanic rock, often with visible gas-bubble holes or vesicles.
Igneous Intrusive	Granite	Common light-colored coarse-grained rock with visible quartz and feldspar crystals, usually peppered with black mica or hornblende.
	Monzonite	Medium-grained rock, often porphyritic, with feldspar predominating, some hornblende or quartz.
Metamorphic	Marble	Recrystalized limestone, commonly with visible calcite crystals.
	Quartzite	Sandstone and/or conglomerate so tightly cemented or welded that it breaks through individual sand grains and pebbles.
	Greenstone	Dark gray or green rock resulting from metamorphism of basalt or other dark igneous rock.
	Gneiss	Banded or streaky crystalline rock formed from older granite or sandstone.
	Schist	Medium-grained rock with mica grains lined up so that rock has streaky appearance and tends to split along parallel planes.

• **Sedimentary rocks** originate, as their name implies, from sediment—remains of other rocks broken up by weathering and erosion or dissolved by running water. They are deposited by water in river valleys, lakes, or seas, or by wind as dunes. Glacial ice also deposits sedimentary rocks, but Ice Age glaciers hardly touched Arizona so glacial deposits are of only minor impotance here. Common sedimentary rocks are **limestone, shale, sandstone,** and **conglomerate**, the last full of pebbles or boulders. When not yet completely solidified or cemented, sedimentary deposits are called **sand** and **clay** and **gravel**.

Sedimentary rocks are characteristically **stratified**, arranged in **strata** or layers, so that even when they are later bent or broken they can be readily recognized. The sedimentary layers may be thick or thin; always their thickness is measured perpendicular to the layering or stratification. With rare exception sedimentary layers, or strata, were deposited in horizontal position.

• **Metamorphic rocks** also have their beginnings in other rocks, but are altered by long-term application of heat and pressure, usually deep below the surface. They may be only a little altered, as with **metasedimentary** or **metavolcanic** rocks, both of whose origins are clear, or they may be altered so severely that geologists are hard put to pin down their origins, as with **gneiss** and **schist**.

MINERALS

Rocks are made of minerals, natural substances with definite chemical makeup and very often with definite color and characteristic ways of crystallizing. Arizona has some particularly beautiful minerals, most notably ores of copper such as bright blue **azurite** and equally bright green **malachite**. Specimens of these and many other minerals are exhibited in the Geology Museum at the University of Arizona in Tucson, in museums in many old mining towns, and in rock shops and jewelry shops throughout the state. Common rock-forming minerals are listed below.

• **Quartz**: a clear glassy or milky white mineral so hard that it can't be scratched with a knife. Quartz comes in white, which is most common, pink (rose quartz), lavender (amethyst), or other pastel colors, tinted with minute amounts of other minerals. It is common as gray glassy grains in granite and in sandstone derived from granite.

• **Feldspar**: a family of translucent pinkish, grayish, or whitish minerals that *can* be scratched with a knife, and that normally break along flat cleavage faces that reflect sunlight. Feldspar crystals are the most abundant components of granite and many other intrusive and metamorphic rocks.

Gneiss may be highly contorted, as if it had been heated to a taffylike consistency. J. Gilluly photo, courtesy of USGS.

Desert varnish *and carbonaceous material streak the cliffs of Canyon de Chelly.*

• **Mica**: a group of black or silver minerals that separate into shiny, flat, paper-thin flakes. Mica can be scratched easily with a knife or even with a fingernail. Black mica is **biotite**, white mica is **muscovite** — the two most common varieties. Mica is common in granite and other intrusive rocks as well as in schist, a metamorphic rock.

• **Calcite**: a white or light gray mineral that makes up limestone. Sometimes transparent but in some varieties opaque, it can't be scratched with a fingermail but can be with a knife. When dilute acid is dropped on it, it fizzes.

• **Hematite**: an iron oxide easily recognized by its rust-red color. Adhering to quartz grains it lends its color, in all degrees from pale pink to deep purple-red, to sandstone, siltstone, and other rock types.

• **Limonite**: a dull, rusty yellow iron oxide that gives a mustard yellow or tan color to rocks in which it occurs.

• **Hornblende**: a black mineral that appears as rod-like crystals in dark igneous and metamorphic rocks.

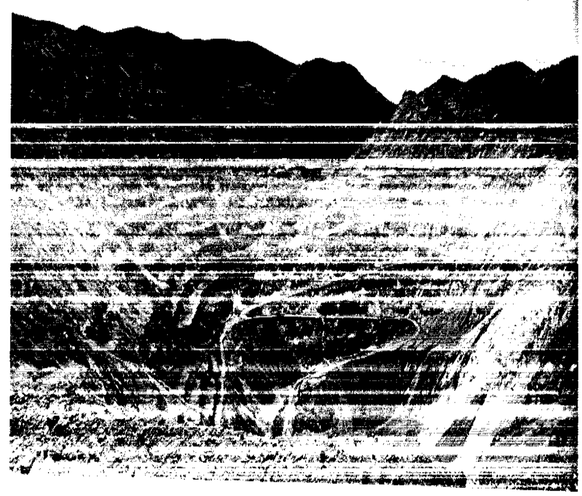
• **Gypsum**: a translucent, fairly soft white or light gray mineral formed as an **evaporite** when sea water or salty ponds dry up. In red sedimentary rocks gypsum commonly appears as **veins** and **veinlets**.

Certain rocks can be recognized just by their color and texture. But the weathered surface of a rock may conceal its interior color, so we often give both colors: "Light gray limestone that weathers tan," for example. **Weathering** is just what it says: surface and near-surface changes due to sun and air and rain and, in some cases, plant and animal products. In Arizona dust may play a major role in weathering; recent research indicates that **desert varnish**, the dark, shiny coating common in rocks of the desert, may in part derive from ever-present desert dust.

TWO TOPICS OF INTEREST

Geologic topics of special interest in Arizona are water and copper. Here, water is in short supply, at least as far as man is concerned. Ways of increasing the water available to man revolve around geology. Ways to find more of it entail wells and geologic studies of water-bearing rock layers. Ways to transfer it from place to place entail knowledge of geologic features, including the **permeability** of rock over which, or through which, it must pass. And ways to keep it from misbehaving periodically, from damaging the works of man, entail dams and other flood control devices. You will see both dams and canals from some of Arizona's highways. A recent project to supplement Arizona's water supplies is the Central Arizona Project, a very large and intricate diversion system — dams, pumping systems, and canals — that will bring Colorado River water to the metropolitan and agricultural areas of the state.

Copper is of special interest because copper ores are abundant here; Arizona produces more than half the copper produced in United States, with the economic benefits and environmental detriments that go with mining of almost any kind. Southern Arizona is the great copper producer; towns like Ajo and Tombstone, Bisbee and Douglas, Clifton and Morenci, Globe and Miami are dependent on copper mining and smelting. Rich ores used to lure miners underground; most mines now are big open-pit affairs that move thousands of tons per day of **overburden** and low-grade ore. You are an invited guest at some mines, either at established viewpoints or with guided tours.

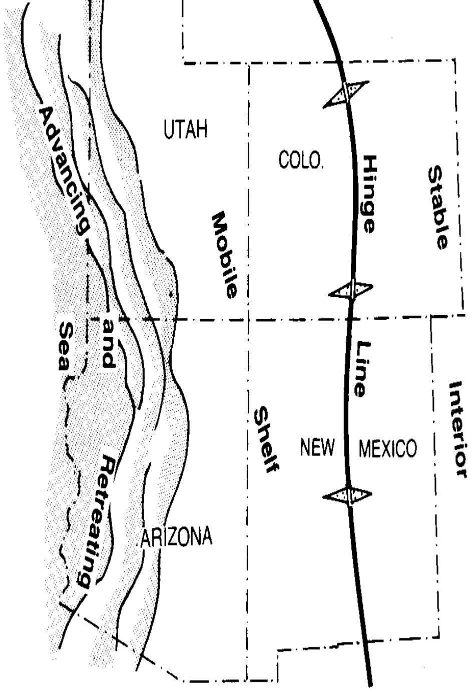


Between 1950 and 1974, the Lavender Pit was a major Bisbee copper producer.
Richard Byrd photo.

ARIZONA THROUGH TIME

With this groundwork, let's take a very quick look at Arizona's place in the geologic history of North America. The record is fragmentary, as much of the evidence is deep down and hidden from view, or has been partly obscured by **metamorphism** or completely destroyed by erosion. Our earliest record comes from Precambrian gneiss and schist now exposed at the bottom of Grand Canyon, in the mountains of central Arizona, and in some of the desert ranges. It shows that around 2 billion years ago Arizona was placed much as it is now, along the southwest edge of a large continent having more or less the outline of the present North America. Layered sedimentary and volcanic rocks accumulated in offshore basins and along the edge of the continent, layers of sandstone and limestone and shale interspersed with lava flows and ash deposits. About 1.7 billion years ago these rocks were lifted into a great mountain range. Granitic magma pushed upward, in some cases following rock joints, and hardened into **batholiths** (large intrusive masses) and coarsely crystalline veins. The resulting ranges stretched up and down the edge of the continent much as the Andes of South America do today.

After many more cycles of deposition, emergence, mountain-building, and wearing down, over much of the world an unusually long period of erosion brought the Precambrian Era to a close. Except for a few scattered islands, Arizona and the rest of the proto-North America were beveled to a broad, flat, sea-level **peneplain**.



In Paleozoic time Arizona was part of a hinged shelf that flexed downward periodically, allowing the sea to advance across an almost flat land. As a result, Paleozoic strata thicken westward.

In Paleozoic time — the Age of Fishes — the nearly featureless continent was once more alternately elevated and submerged tilting this way and that so that the sea periodically flooded across its margins. Especially along its mobile southwestern edge, which seemed hinged to the firmer, more stable central part of the continent, marine sedimentary rocks alternated with continental deposits that accumulated on river floodplains and deltas or as dunes on broad, sandy shores. At times widespread erosion removed previous deposits, or prevented their deposition, so the Paleozoic record is not by any means complete. It's clear, though, that Paleozoic seas came from the west, lapping and then overlapping the west edge of the continent. At times rivers flowing from uplifts to the east and northeast swept silt and sand out over earlier marine sediments.

The Mesozoic Era — the Age of Reptiles — saw a good deal of **uplift**, with mountains in the central and eastern parts of the state. Erosional debris from the mountains spread northwestward and westward. And for a long time as the Sierra Nevada rose farther west, this area, cut off from sources of moisture, was a vast desert, with dunes blowing endlessly across an almost featureless landscape. Toward the end of the era, late in Cretaceous time, seas rolled one last time across the land, coming from the northeast. But incursion of the sea was short, and most Mesozoic deposits were of continental nature: sandstone and shale layers of dune and delta and floodplain, together indicating an environment not unlike that of northern Africa today, with its desert dunes and the great floodplain and delta of the Nile.

At the end of Mesozoic time North America broke away from Europe and began a westward and northwestward odyssey. As it collided with the Pacific Plate and overrode it, the bruised crust buckled and broke, mountains rose, and volcanoes spewed vast quantities of ash and lava. The newborn Rocky Mountains shed quantities of debris in the direction of Utah and Arizona; the Sierra Nevada was still contributing debris from the west. Collison and union with several offshore islands or microcontinents complicated the picture in southwestern Arizona. But through all the activity the Colorado Plateau area remained relatively stable and unaltered, with Paleozoic and Mesozoic sedimentary rocks still keeping their original horizontal positions.

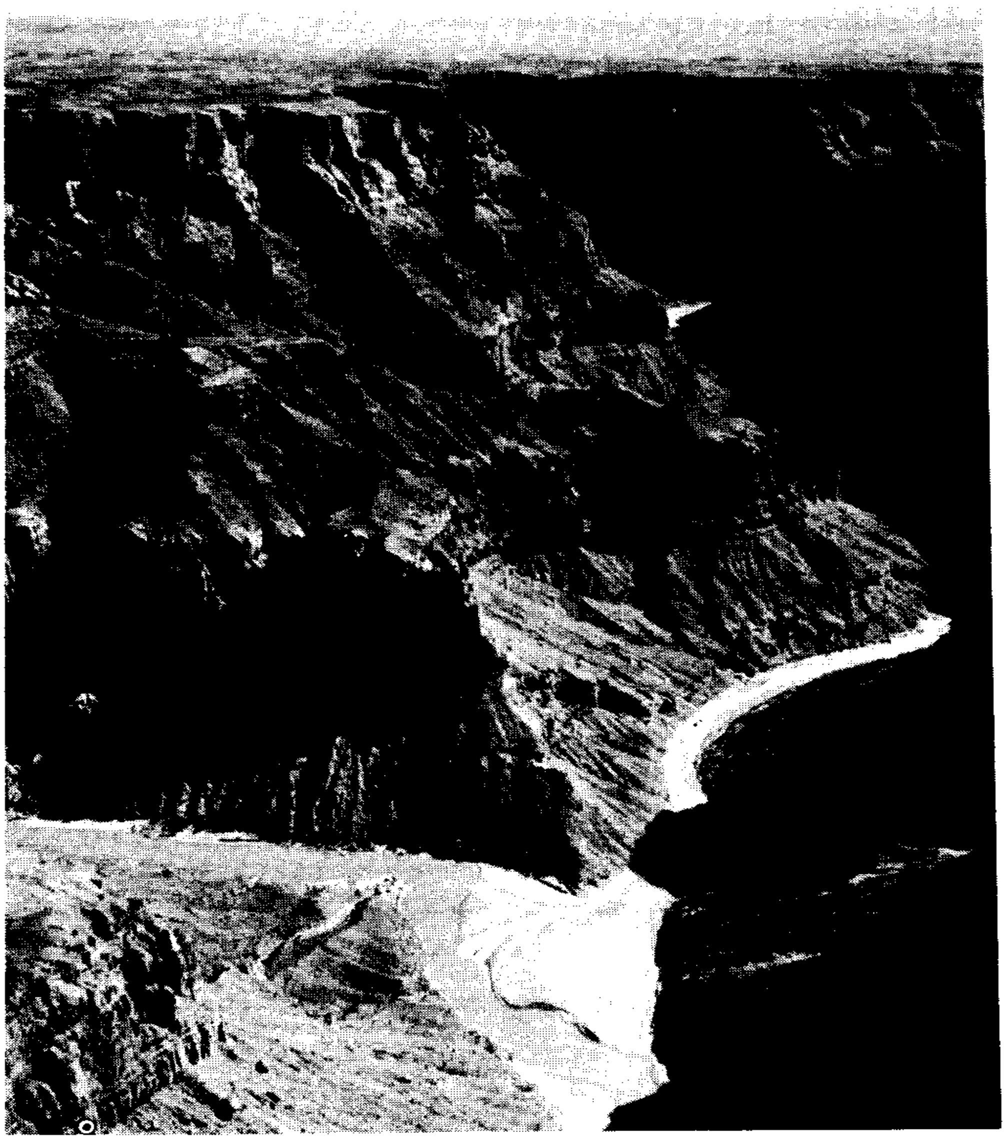
Cenozoic time — the Age of Mammals — brought continued restlessness and uplift to all of western United States. Plateaus rose in northern Arizona and adjacent states, and in southern and western Arizona deep basins formed by faulting and downdropping between mountain blocks. Major rivers and streams cut downward through uplifted areas. The Colorado River shifted its course and brought about another period of increased erosion over all of its drainage area. And by late Quaternary time the landscape looked much as we know it

The sandy floor of a desert wash descends in a succession of steps separated by cobbles and boulders. Streamside vegetation forms a narrow, luxuriant border.

today, with deeply filled basins, some of them dissected anew by streams rejuvenated by uplift and boosted by meltwater during the Ice Ages.

* * *

With this glimpse of geologic processes let's go to Arizona's highways. The following logs are not strictly logs, but annotations of some of the things that can be seen as you drive along. Before starting off down the highway, read the introduction to the chapter covering the area you'll be travelling in — southern deserts, central mountains, or northern plateau. Beyond that introduction, each roadlog stands alone. Town names are used to locate specific stretches; highway mileposts serve to refine specifc locations where there are no towns.



Like these strata near the confluence of the Colorado and Little Colorado Rivers, sedimentary rocks *are nearly always deposited as horizontal layers. Note the delta of the Little Colorado at lower right.*
Tad Nichols photo.