Syllabus

GEOLOGY OF THE SAN JACINTO MOUNTAINS
AND REGION

Edited By
Joe Migliore

For the Volunteers & Guests of
Mt. San Jacinto State Park

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Cactus to Clouds: Mt San Jacinto and the Transformation Of The American West

10,834 feet above sea level: the majestic summit of Mt San Jacinto dominates the western horizon of the Coachella Valley, rising precipitously 2 miles above the desert sands of Palm Springs. Mt. San Jacinto is at the very northern tip of the 900 mile long Peninsular Range, and is its highest peak.

For several hundred million years, mostly during the Paleozoic Era the western margin of North America was what geologist call a passive margin, simply defined as a continental edge where nothing much is happening tectonically, that is, no mountain building, subduction or volcanism, That's like the east coast of North America today. Mostly all that is going on there, geologically, is weathering and erosion of existing uplands and deposition of their sediments in low lying areas and adjacent seas. Today, the evidence of those ancient processes at the western passive margin is the stunningly dramatic landscapes of the Colorado Plateau. There, piles of sediment such as sandstone and limestone, thousands of feet thick, have been lifted from near sea level, where they were deposited over hundreds of millions of years, to many thousands of feet above sea level! As that was occurring, simultaneous weathering and erosion have created some of the most beautiful and awesome topography on the planet such as the Grand Canyon of The Colorado, Monument Valley, and Arches, Canyonlands, Capital Reef, Bryce Canyon and Zion National Parks.

What happened from those ancient times of passive deposition to create the landscapes of today, including Mt. San Jacinto of the Peninsular Range, the Sierra Nevada, the Basin and Range Province of myriad interior mountains and intervening desert basins, the Colorado Plateau and, indeed, the Rocky Mountains?

Everything began to change when the super continent of Pangea began to break up about 200 million years ago into separate and massive pieces of the earths crust called tectonic plates. One of those plates, we now know as the North American Plate, began rifting away from the Eurasian Plate, traveling westward. It was the birth of the Atlantic ocean. The western passive margin, as described above, began to overrun the eastern edge of the Farallon oceanic plate of the Pacific Ocean and all hell broke loose. Volcanism, earthquakes and mountain building began along the western margin of North America. Over the next 200 million years the landscape was utterly transformed from the Rocky Mountains to the Pacific Ocean.

What follows is a necessarily brief history describing some of the major tectonic events that have created the modern landscapes of the American west with particular attention to the geomorphic provinces of southern California and the Coachella Valley. The processes continue to this day as evidenced by the ever present threat of catastrophic earthquakes, especially in California, and the great and still active volcanoes of the Cascade Ranges in the Northwest.

GEOLOGIC TIME SCALE

Era	Period	Epoch	MY*	Event (Age, 100 yr Man)
Cenozoic	Quaternary	Holocene	0.01	
		Pleistocene	2.5	Uplift of Mt San Jacinto began ~15 days before 100th birthday
	Tertiary	Pliocene	5	Sierra uplifted (99.9}
		Miocene	24	
		Oligocene	36	
		Eocene	54	
		Paleocene	65	
Mesozoic	Cretaceous		144	Last dinosaurs (98.5)
	Jurassic		208	
	Triassic		245	First dinosaurs (95)
Paleozoic	Permian		286	
	Pennsylvanian		330	First amphibians (94)
	Mssissippian		360	First jawed fish (93}
	Devonian		408	
	Silurian		438	
	Ordovician		505	
	Cambrian		570	First trilobites (88}
Pre-Cambrian			4600	

***MY, Millions of years to beginning**

THINKING LIKE A GEOLOGIST

By Ted Konigsmark, GEOLOGIC TRIPS, Sierra Nevada

Most of us deal with common objects that we can see, measure, feel, and count. We think in terms of inches, feet and miles. We think in terms of seconds, minutes, hours, days, weeks, years, and centuries. We think in terms of ounces, pounds and tons, and in terms of hard and soft, hot and cold. However, to understand the geologic processes (that have formed the Sierra Nevada) you need to think like a geologist. This thinking is not difficult -just different. Here are some guidelines.

Geologic Time

A century may seem like a long time. However, geologists think in terms of millions and hundreds of millions of years. When you think in millions of years, enormous changes can take place even with very slow geologic processes. If you compare the 4.6-billion-year age of the earth to the age of a l00-year-old man, the oldest rocks in the Sierra Nevada were formed when he was 90 years old. The granite was intruded into the core of the mountains when he was 98 years old , and uplift of the Sierra block occurred about a month before his l00th birthday. A geologist must think in years the way an economist thinks in dollars—millions and billions.

Thinking Big

A mountain range such as the Sierra Nevada may seem large, and the rocks that make up the mountains may appear hard and brittle. Indeed, granite, limestone, and many of the other rocks of the Sierra are used as building stones. However, at a scale of miles rather than inches and feet, these seemingly strong and brittle rocks can easily bend and break. One must think big, and recognize that the rocks that make up the earth behave in a different manner when viewed on a large scale. Although upward and downward movements of the earth's surface of 30 or more miles may seem large, these movements are not large when compared to the size of the earth. If the earth were the size of a basketball, an uplift of 30,000 feet on the earth's surface would be equivalent to the thickness of a sheet of paper on the surface of the basketball, a slight imperfection on the basketball.

Living on a Dynamic Earth

Although the earth may seem like a large chunk of hard rock, it is quite different. The earth is dynamic.

The rocks that make up the earth are constantly moving. Parts of the earth's crust are being uplifted and other parts are subsiding. Some continents are being torn apart and others are colliding. The movement of the continents is caused by heat that is churning and moving the rocks deep within the earth. But why are these rocks so hot?

The only cool rocks on earth are those within a few miles of the surface. From the surface, the rocks get hotter with depth.

At a depth of about 60 miles, the rocks are so hot that they behave like warm plastic and flow at very slow rates. This heat is generated by decay of radioactive elements within the rocks.

Since rocks are not good conductors of heat, the heat builds up deep in the earth. The inner solid core and outer fluid core of the earth consist of iron and nickel and are extremely hot. The inner core and outer core are in motion, and rotate at a slightly different rate from the overlying mantle. The plastic-like rocks in the mantle are also in motion, and circulate in huge convection cells that reach from the core of the earth to the crust. These convection cells move the overlying brittle crust, tearing the crust apart over rising currents and carrying the crust downward into the mantle along descending currents. As the crust moves, new mountain ranges are formed in some places, and new ocean basins in other places. The geologist sees the oceans and mountains as temporary. Fortunately, these changes take place slowly. If you watched the surface of the earth in fast-forward on a VCR, you would need a seat belt, and you would be in for a wild and unexpected ride.

Erosion and Deposition

Most rocks are formed deep within the earth where the temperature and pressure is very high. When these rocks are uplifted and exposed at the earth's surface, they are suddenly attacked by rivers, waves, plants, animals, ice, wind and rain. The rocks are also altered chemically. Some minerals combine with the oxygen and hydrogen at the surface to form new minerals. Other minerals simply do not like the low temperatures and pressures at the surface, and change into minerals that are stable at surface conditions.

Although humans like the surface of the earth, most rocks are uncomfortable at the surface and rapidly break down in this harsh environment.

When rocks break down by mechanical and chemical processes at the earth's surface, they form smaller clastic fragments - boulders, pebbles, sand, silt, and clay.

Rivers carry these *sediments* to low spots on the earth's surface and deposit the sediments in *sedimentary basins.* Over millions of years, entire mountain ranges can be worn down by weathering and erosion, until the mountain range is worn to a flat surface near sea level. The sediments that were eroded from the mountains accumulate in sedimentary basins. Sedimentary basins tend to subside as the sediments accumulate, and each new layer of sediment is piled on top of the previous layer of sediment. Over time, piles of sedimentary rocks can accumulate in these basins to thicknesses of tens of thousands of feet. The Great Valley is a large sedimentary basin that has accumulated thousands of feet of sediments that have been eroded from the Sierra Nevada.

Reconstructing the Past

When looking at the rocks exposed in a roadcut, on a mountainside, or along a river, try to erase, in your mind, the present landscape. When the rocks were formed, the landscape was completely different.

Look at the rocks and let them tell you what the landscape was like when the rocks were formed. If you are looking at limestone formed in some tropical sea, imagine yourself floating in the warm water of that ocean.

If there are several different types of rocks in an outcrop, each type of rock may tell a different story. The rocks changed as the landscape changed. To understand the geologic history of the area, the geologist must piece these stories together, like reading an old tattered book with many missing pages.

The Evolving Landscape

The landscape that we see today - the hills, peaks, lakes, sea cliffs, and valleys - are formed from rocks. These rocks are being attacked by various erosional and weathering processes. The shape of the landform depends on the type of rock that is exposed and on how the present weathering and erosion processes are working on the rock. When you look at a mountain, lake, or valley ask yourself several questions. What kind of rock is responsible for the feature? Are the rocks hard or soft? Are they fractured or massive? Are they being attacked by ice, rain, wind, or by chemical weathering? How is the landform changing? What will it look like in a short time - say a few thousand years? See, now you are thinking like a geologist.

Konigsmark, Ted, 2007, *GEOLOGIC TRIPS, Sierra Nevada*, GeoPress, Mendocino, CA, ISBN 0-9661316-5-7

Plate Tectonics Summary

• In the early 1900s *Alfred Wegener* set forth his *continental drift* hypothesis. One of its major tenets was that a supercontinent called *Pangaea* began breaking apart into smaller continents about 200 million years ago. The smaller continental fragments then "drifted" to their present positions. To support the claim that the now-separate continents were once joined, Wegener and others used *the fit of South America and Africa, the distribution of ancient climates, fossil evidence,* and *rock structures.*
• One of the main objections to the continental drift hypothesis was the inability of its supporters to provide an acceptable mechanism for the movement of continents,
• The theory of *plate tectonics,* a far more encompassing theory than continental drift, holds that Earth's rigid outer shell, called the *lithosphere,* consists of seven large and numerous smaller segments called *plates* that are in motion relative to each other. *Most of Earth's seismic activity, volcanism,* and *mountain building* occur along the dynamic margins of these plates.
• A major departure of the plate tectonics theory from the continental drift hypothesis is that large plates contain both continental and ocean crust and the entire plate moves. By contrast, in continental drift, Wegener proposed that the sturdier continents "drifted" by breaking through the oceanic crust, much like ice breakers cut through ice.

• *Divergent plate boundaries* occur where plates move apart, resulting in upwelling of material from the mantle to create new seafloor. Most divergent boundaries occur along the axis of the oceanic ridge system and are associated with seafloor spreading, which occurs at rates between about 2 and 15 centimeters per year. New divergent boundaries may form within a continent (for example, the East African rift valleys), where they may fragment a landmass and develop a new ocean basin.

• *Convergent plate boundaries* occur where plates move together, resulting in the subduction of oceanic lithosphere into the mantle along a deep oceanic trench.
Convergence between an oceanic and continental block results in subduction of the oceanic slab and the formation of a *continental volcanic arc* such as the Andes of South America. Oceanic-oceanic convergence results in an arc-shaped chain of volcanic islands called a *volcanic island arc.*
When two plates carrying continental crust converge, both plates are too buoyant to be subducted. The result is a "collision" resulting in the formation of a mountain belt such as the Himalayas.

• *Transform fault boundaries* occur where plates grind past each other without the production or destruction of lithosphere. Most transform faults join two segments of an oceanic ridge.

Others connect spreading centers to subduction zones and thus facilitate the transport of oceanic crust created at a ridge crest to its site of destruction, at a deep-ocean trench. Still others, like the San Andreas Fault, cut through continental crust.

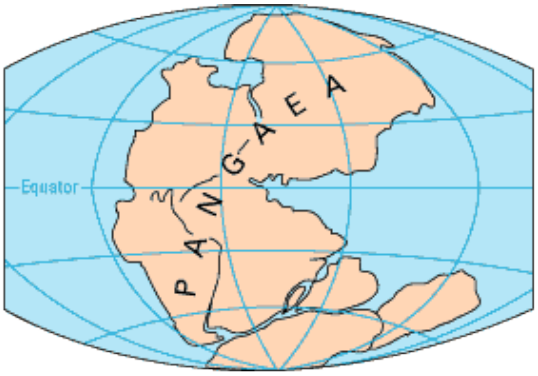
• The theory of plate tectonics is supported by (1) *paleomagnetism,* the direction and intensity of Earth's magnetism in the geologic past; (2) the global distribution of *earthquakes* and their close association with plate boundaries; (3) the ages of *sediments* from the floors of the deep-ocean basins; and (4) the existence of island groups that formed over *hot spots* and that provide a frame of reference for tracing the direction of plate motion.

• Three basic models for mantle convection are currently being evaluated. Mechanisms that contribute to this convective flow are slab-pull, ridge-push, and mantle plumes. *Slab-pull* occurs where cold, dense oceanic lithosphere is subducted and pulls the trailing lithosphere along. *Ridge-push* results when gravity sets the elevated slabs astride oceanic ridges in motion. Hot, buoyant *mantle plumes* are considered the upward flowing arms of mantle convection.

One model suggests that mantle convection occurs in two layers separated at a depth of 660 kilometers. Another model proposes whole-mantle convection that stirs the entire 2900-kilometer-thick rocky mantle. Yet another model suggests that the bottom third of the mantle gradually bulges upward in some areas and sinks in others without appreciable mixing.

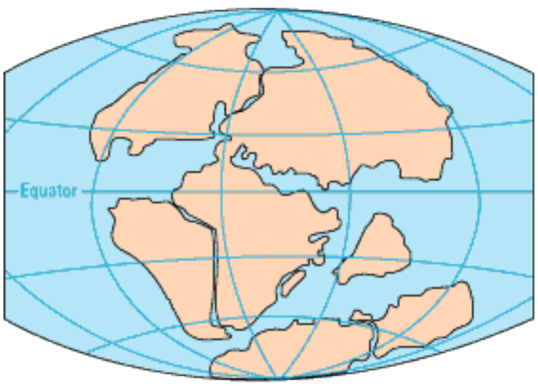
Earth Science, 11th Edition, Edward J. Tarbuck and Frederick K. Lutgens, Pearson Prentice Hall

Breakup of Supercontinent Pangea

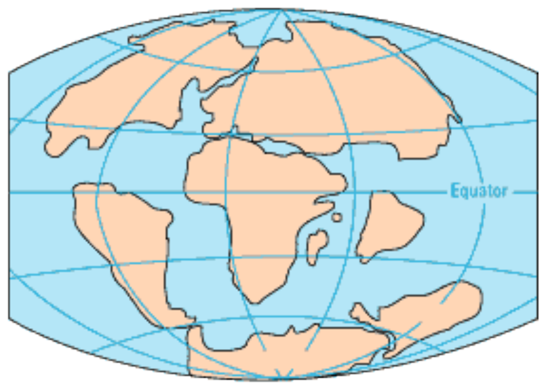


PERMIAN
225 million years ago

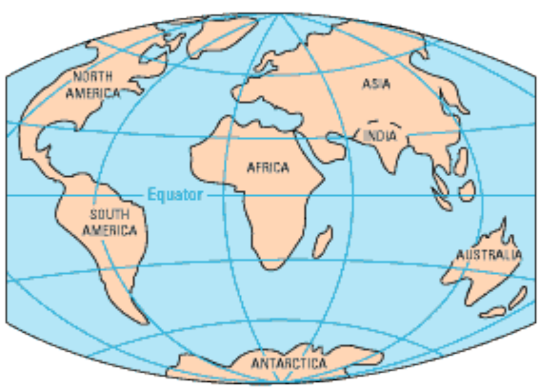
TRIASSIC
200 million years ago



JURASSIC
135 million years ago



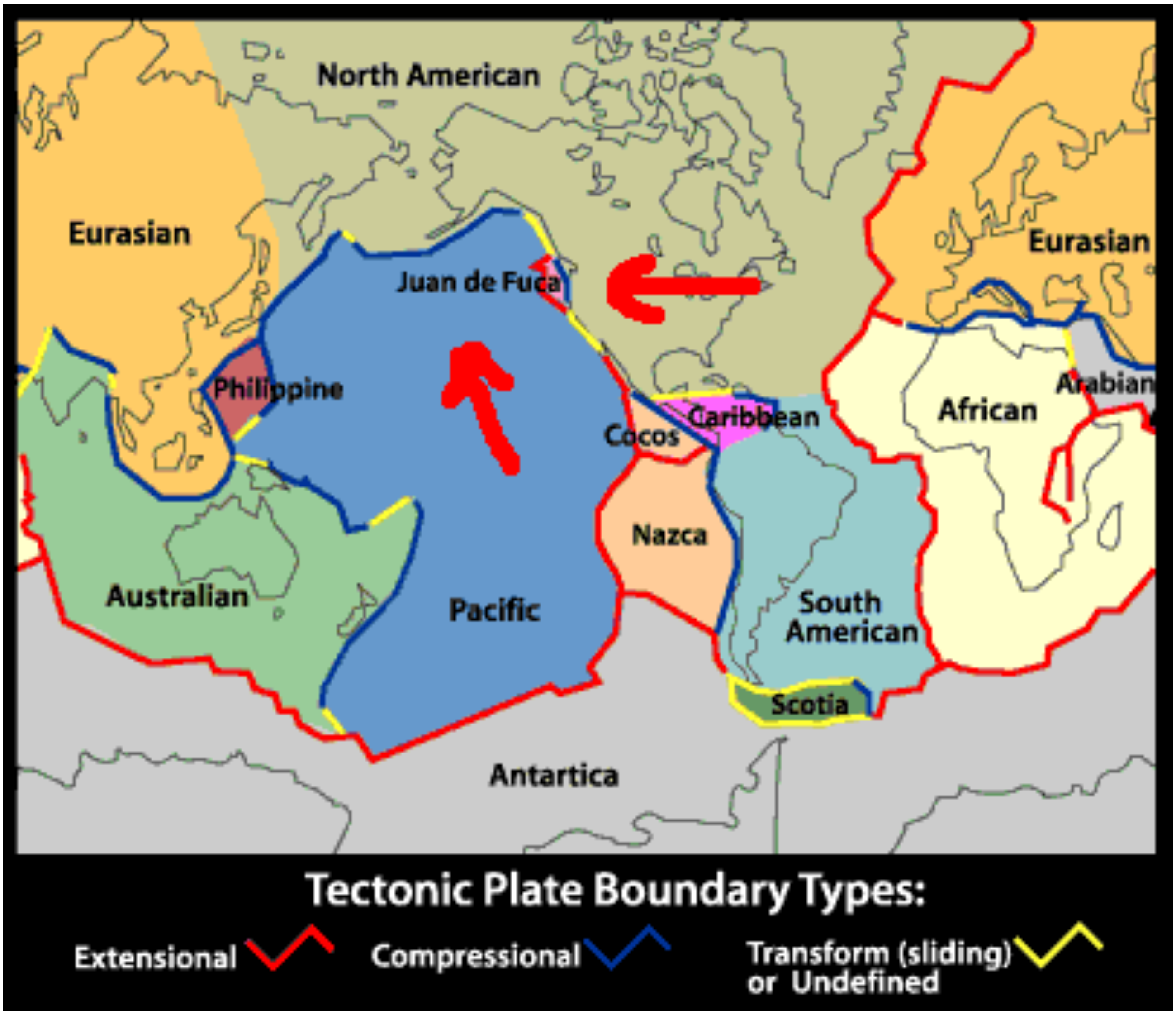
CRETACEOUS
65 million years ago



PRESENT DAY

According to Plate Tectonics theory the supercontinent Pangea began breaking up about 225 million years ago (mid Triassic). All of the plates are still on the move. What will the future bring? Another Supercontinent?

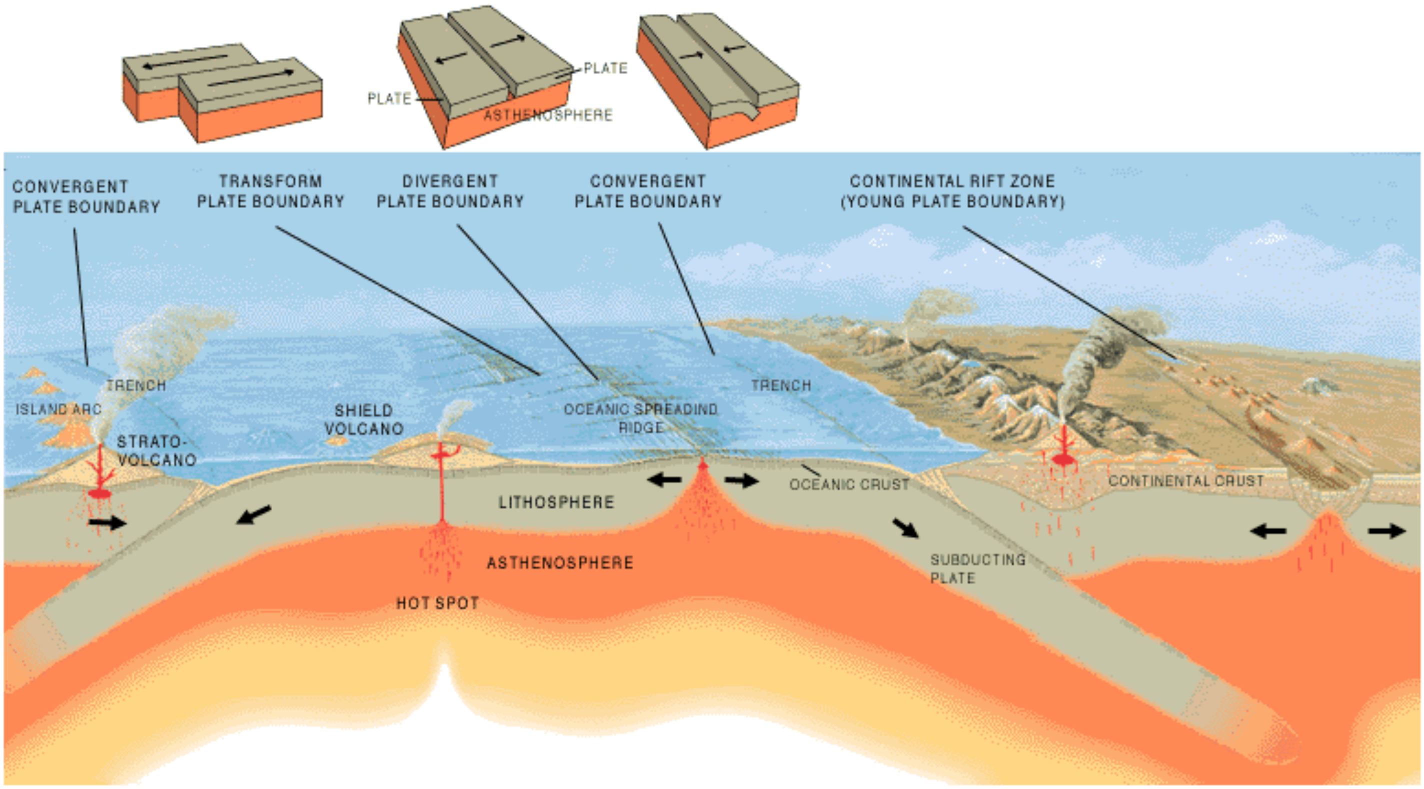
Tectonic Plate Boundary Types



Extensional: Mostly in oceanic setting, adjacent oceanic plates are moving away from each other and magma is emerging creating new oceanic crust (lithosphere).
Compressional: Plates are converging. Three types: oceanic to oceanic, oceanic to continental, continental to continental
Transform: The relative motion between adjacent plates is horizontal, one plate sliding along side the other. Aka. Strike-slip fault.

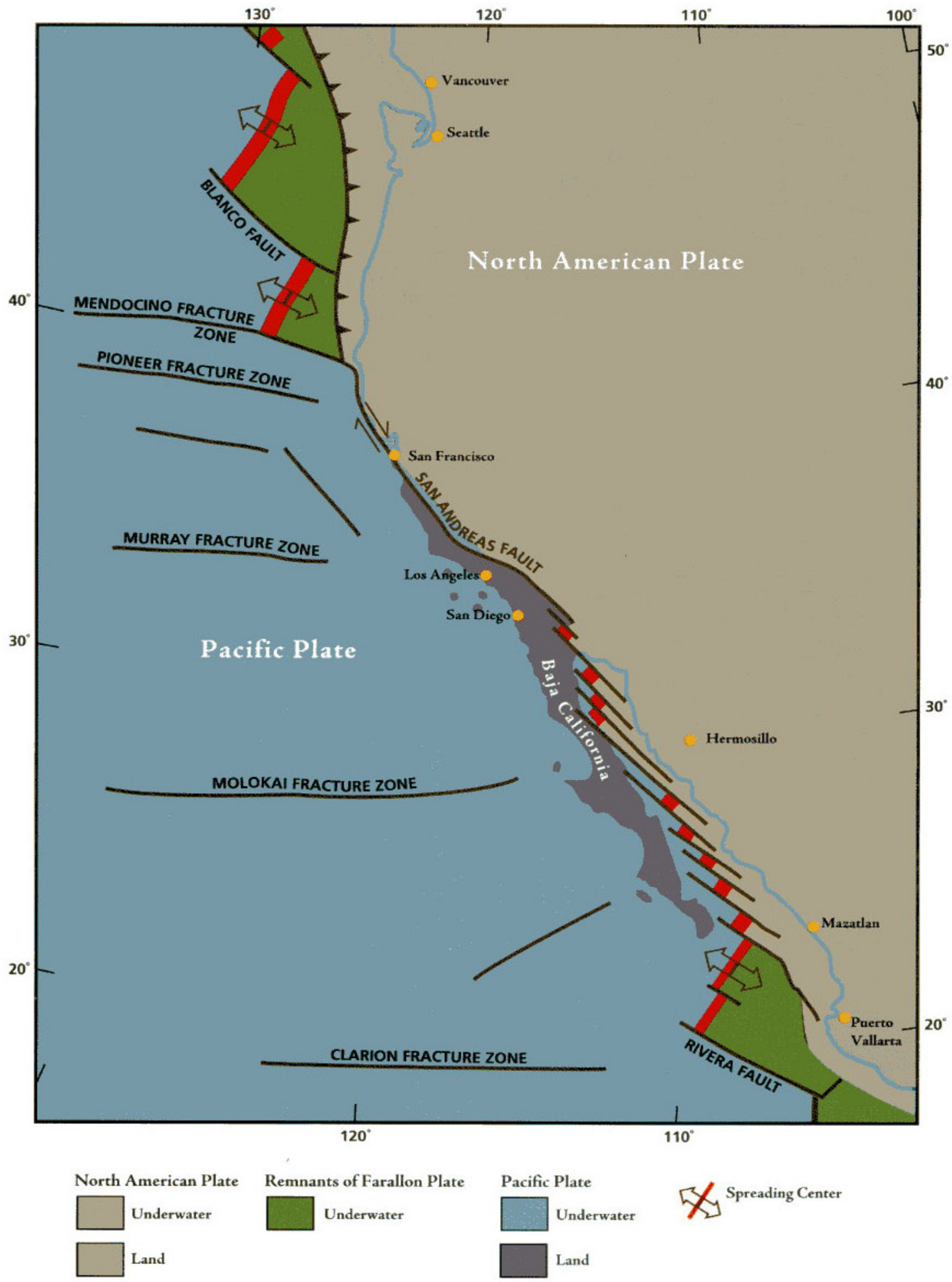
Note: See Plate Tectonics Summary on page 8 for more detail.

Plate Boundaries Illustrated



This Dynamic Planet, Simkin, Unger, Tilling, Vogt, Spall http://geology.usgs.gov/pdf/planet/pdf

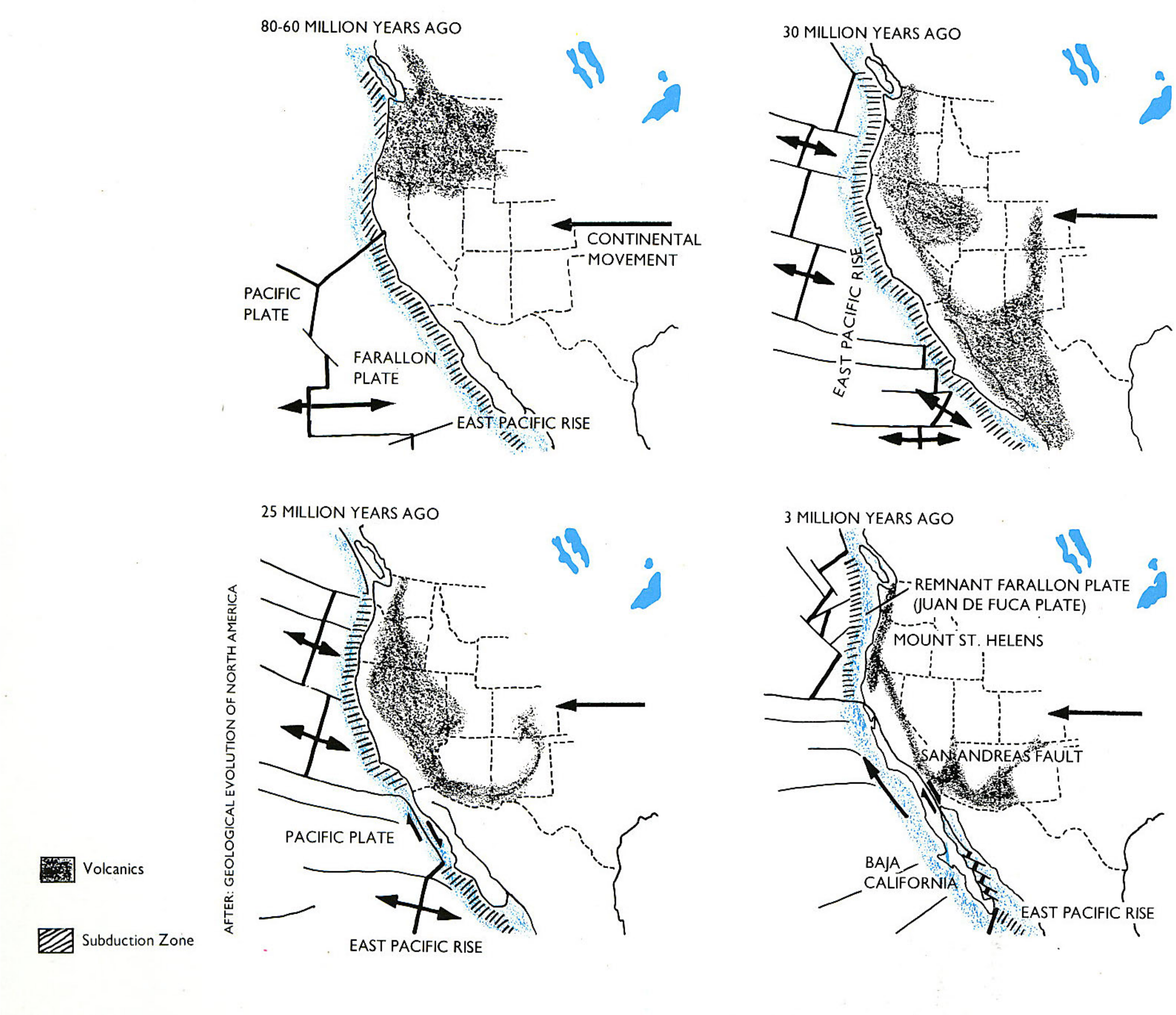
Our Active Margin Today



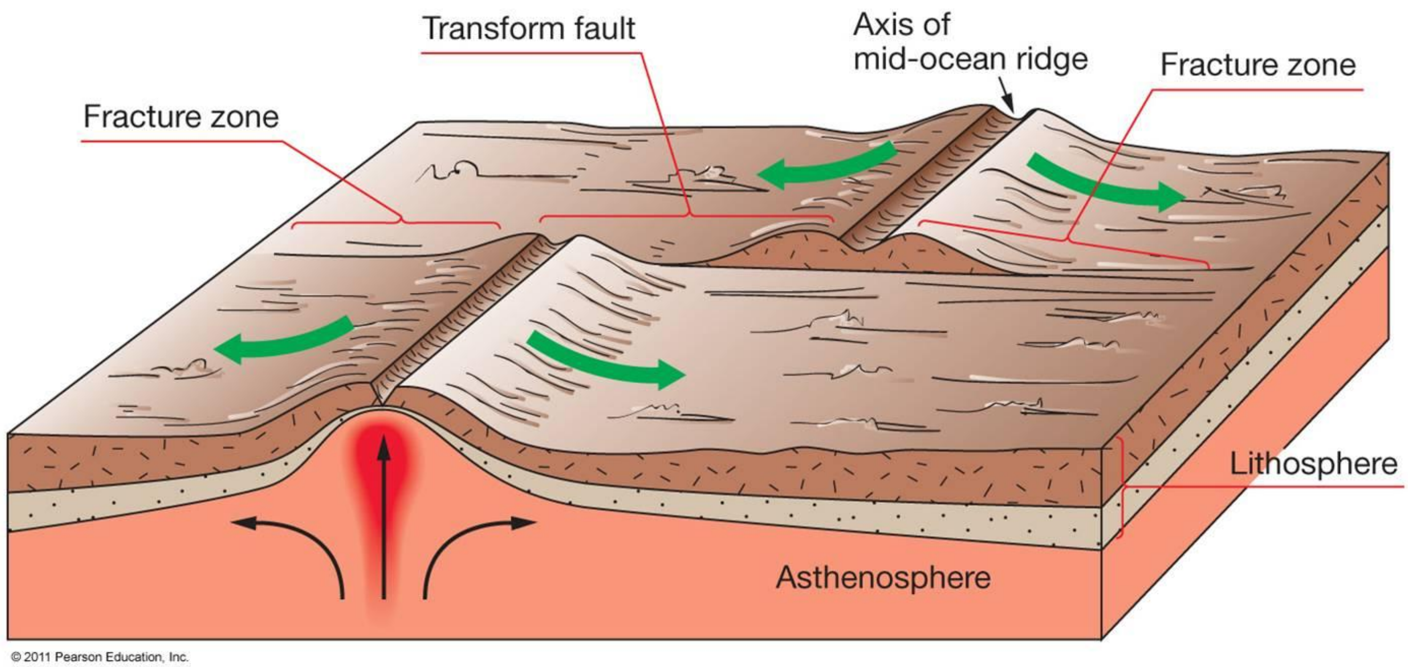
San Andreas Fault as the boundary between the North American, Farallon, and Pacific plates

A Land In Motion, Michael Collier, University of California Press

From Subduction to Transform Boundary
The San Andreas Fault

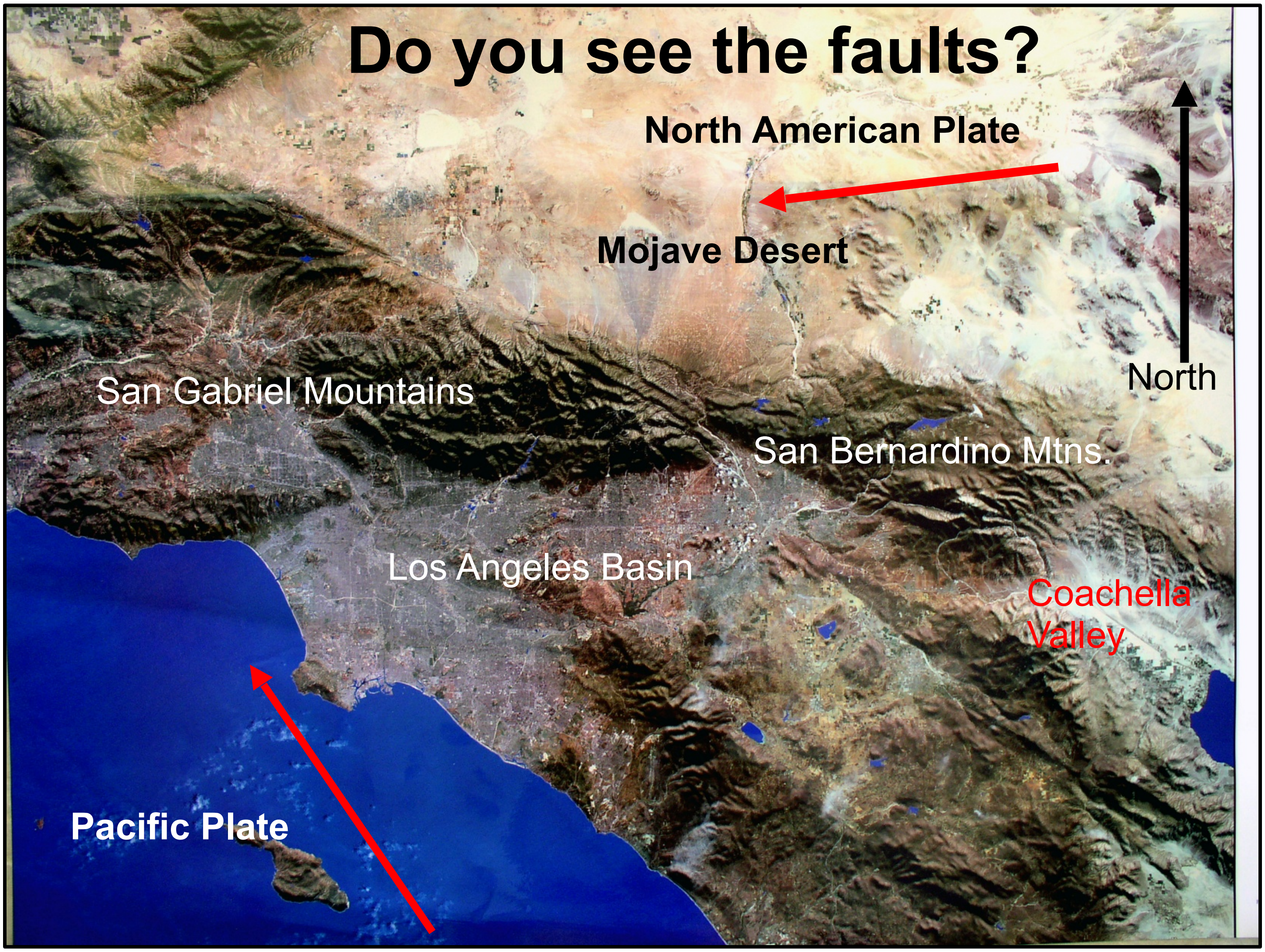


These maps represents 4 snapshots in time as the North American Plate is overrunning the subducting Farallon oceanic plate, eventually coming in contact with the East Pacific Rise spreading center and the eastern edge of the Pacific Plate, at about 25 million years ago. The Pacific Plate, however, moving obliquely away to the northwest is not subducted but begins to drag along side the western margin of the North American Plate progressively capturing more and more of the continental edge. The principal boundary between the two plates is the right lateral strike slip San Andreas Fault, correctly known as a <u>transform</u> fault. A transform fault accommodates the lateral motion between two offset ridge segments of a seafloor spreading ridge where molten rock emerges creating new ocean crust. See Page 11 and 12 to review seafloor spreading and illustration of subducting seafloor being recycled into the earth's interior (mantle).



https://www.youtube.com/watch?feature=player_detailpage&v=tIuk2blBzHs

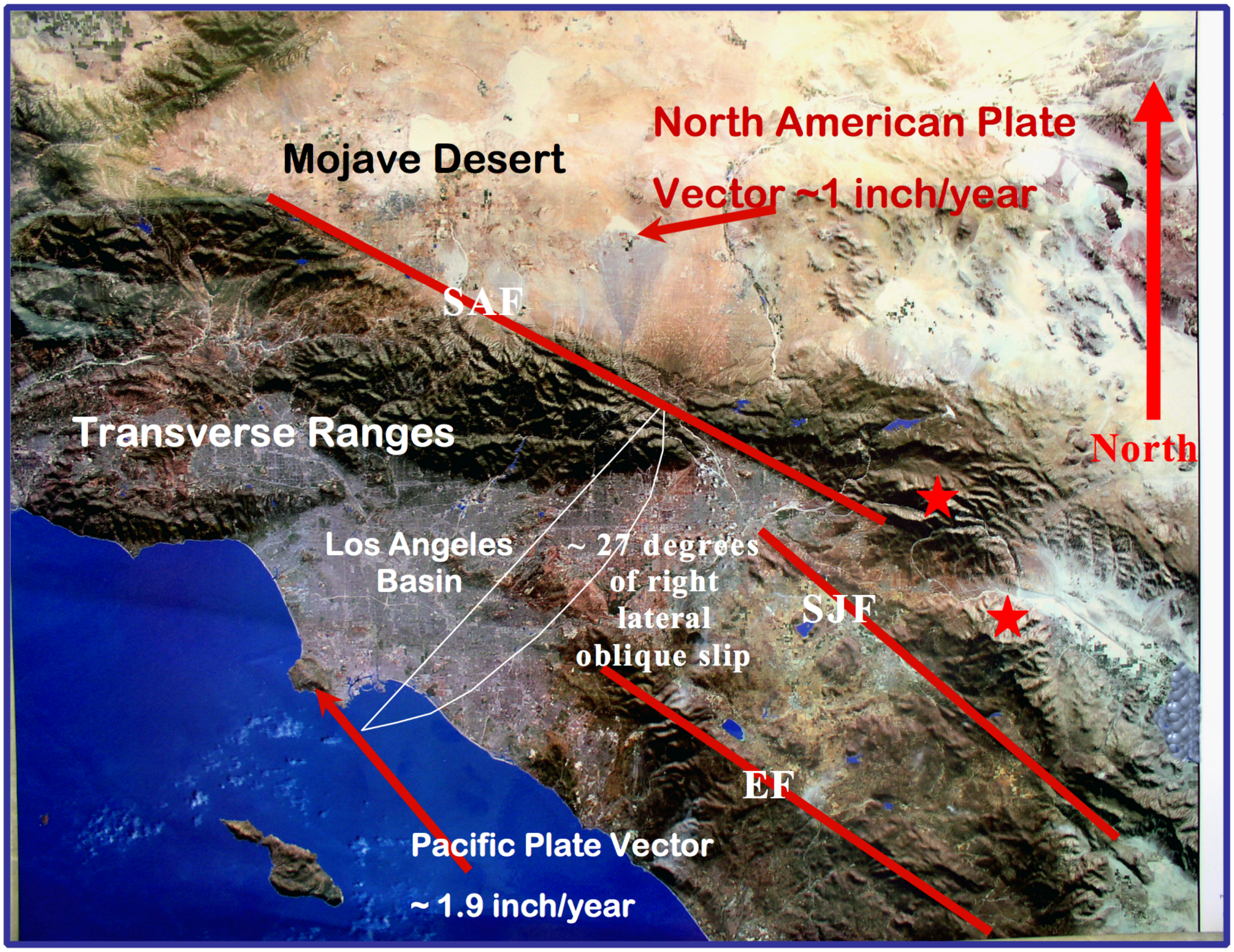
CLICK ON THIS LINK TO WATCH THE ANIMATION OF SEAFLOOR SPREADING



Southern California from Landsat (satellite)

HINT: Look for linear features of the topography that may indicate the presence of a fault in the earth's crust. What types of processes may be the cause of such features including mountains and valleys or depressions? The red arrows represent the direction of motion of the North American Plate and the Pacific Plate, the latter now includes the continental crust of most of western California. Notice the direction of the Pacific Plate is not parallel to the strike (direction) of the fault boundary with the North American Plate. How does that affect the topography?

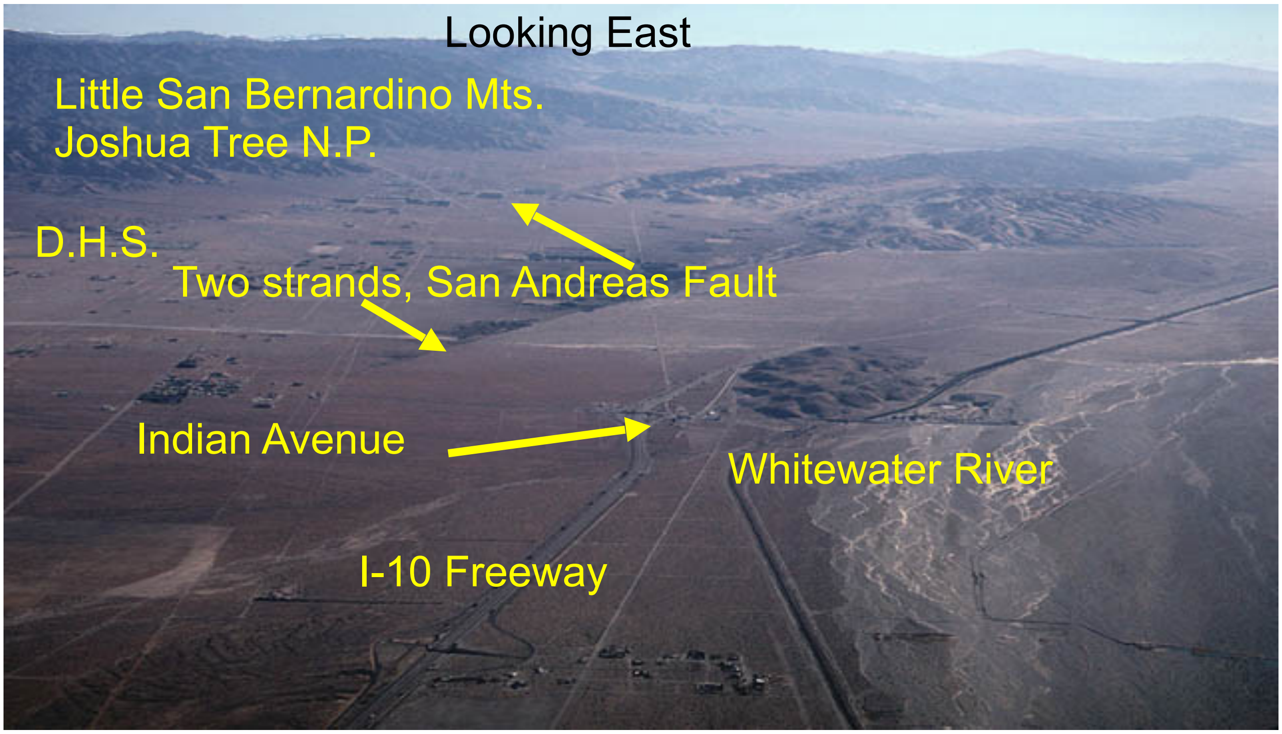
Convergence & Mountain Building

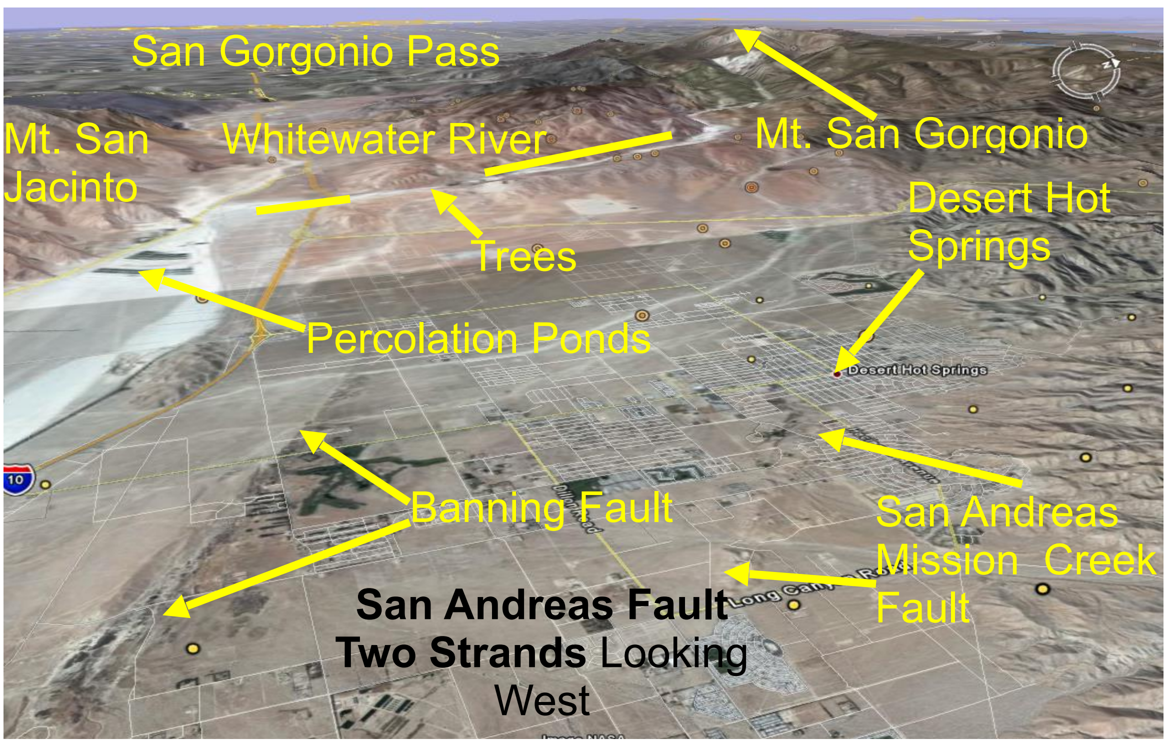


The direction of movement of the Pacific Plate is not parallel to the strike of the San Andreas fault in this region. The continental crust to the west of the San Andreas Fault is moving with the Pacific Plate obliquely along side and into the North American Plate at an angle of 27°. This condition is called *oblique transpression*. Simply put, there is a component of convergence causing compression of the rock along the fault resulting in crustal shortening, deforming the crust into ridges or mountains. In the contiguous United States west of the Rockies it is only the Transverse Ranges and the Uinta Mountains of northeast Utah which run east to west.

(See the illustrations and definitions in the glossary of transpression and transtension)

The San Andreas Fault





San Andreas Fault

Two Strands

Looking West

Geology of The San Bernardino Mountains

General Summary

The San Bernardino Mountains consist of a high, east-trending elongate block that has been uplifted to its present elevation during the last few million years. The west, north, and south margins of this block are tall, precipitous escarpments whose geomorphology reflect the faulting tectonics that have elevated the mountains; the east margin of the block declines more gradually to the Mojave Desert floor.

The north side of the range is bounded by a series of south-dipping faults referred to as the north-frontal fault system (Meisling, 1984; Miller, 1987). The interior of the range is traversed by the east-trending and north-dipping Santa Ana Fault that separates the mountain geomorphology into two main terrains:

- to the north, an extensive, partly dissected plateau that forms the main mass of the San Bernardino Mountains;
- to the south, a more strongly dissected terrain that has been deeply eroded by major stream canyons that head into the interior away from the south edge of the mountains. The highest summits of the San Bernardino Mountains occur in this terrain, including San Gorgonio Peak (11,485 ft).

The southwestern and southeastern margins of the San Bernardino Mountains are traversed by several strands of the San Andreas Fault zone that in part form the geomorphic and structural boundary of the range. These faults separate geologic materials and geologic structures of the San Bernardino Mountains into three main domains (Matti and others, 1992a):

- Rocks in the southeastern San Bernardino Mountains south (outboard) of the Mission Creek strand
- Rocks between the Mission Creek and Wilson Creek strands
- Rocks of the main San Bernardino Mountain mass north (inboard) of the Mill Creek strand

Geologic materials of the San Bernardino Mountains mainly are ancient basement rocks that have been uplifted to their current elevations. These rocks include the following major groups:

- Very old crystalline rocks that are part of the ancient North American continental interior. These include igneous granitic rocks on the order of 1.7 billion years old that locally have intruded even older rocks that originally were deposited as sediments but ultimately were metamorphosed to gneiss before or during intrusion of the 1.7 b.y granites. These ancient North American basement rocks are only locally preserved because they have been obscured by subsequent geologic events.
- The ancient North American basement rocks ultimately formed a continental-margin platform for great thicknesses of marine sand, silt, mud, and calcareous sediment that began to accumulate on the platform about 1 billion to perhaps 900 million years ago (Cameron, 1981, 1982). These sediments accumulated during the Paleozoic Era for several hundred million years before deposition terminated and the sediment pile was warped, folded, faulted and dragged deeper into the Earth's crust where the sediments were metamorphosed to the metasedimentary lithologies (schist, metaquartzite, and marble) we now observe throughout large parts of the San Bernardino Mountains.

- Starting about 230 million years ago in the early Triassic Period, all pre-existing rocks in the San Bernardino Mountains area were injected by a succession of granitic magmas (plutonic bodies) that intruded and enveloped the older rocks. Magma injection was most intense and pervasive during the late Cretaceous Period, between about 80 and 70 million years ago.
- Between 70 million years and about 20 million years before present, little is known about geologic events or geologic materials in the vicinity of the San Bernardino Mountains. Presumably the area was undergoing gradual uplift and erosion of rock material that was transported by streams away from the region, but this history is not well understood.
- Starting about 18 to 20 million years ago in the early Miocene Epoch, stream and lake sediments began to accumulate locally in the vicinity of the San Bernardino Mountains (Meisling and Weldon, 1989) on a low-relief erosional surface that presumably had developed during the preceding geologic interval. Deposition in non-marine environments continued intermittently throughout the next 10 to 15 million years (Miocene and Pliocene Epochs). In the San Bernardino Mountains, vestiges of these deposits can be seen in the western part of the range (Crowder Formation as used by Meisling and Weldon, 1989), in the vicinity of Running Springs in road cuts of State Highway 330, in the vicinity of Big Bear Lake, and in the drainage basin of the Santa Ana River (Santa Ana Sandstone as used by Sadler (1982, 1993).
- Uplift of the San Bernardino Mountains to their current elevation above the Mojave Desert floor and above lowlands to the south occurred in two stages: (1) block faulting and warping perhaps in the late Miocene (11 to about 5 m.y. before present) may have created an ancestral "proto" San Bernardino Mountains of unknown elevation (Meisling and Weldon, 1989); (2) uplift of the range in the Quaternary Period starting about 2 m.y. ago created the elevated and eroding landscape familiar to us today (Dibblee, 1975; Sadler, 1982; Spotila and others, 1999). This uplift history was accompanied by strike-slip faulting and related deformation within the San Andreas Fault zone along the south margin of the range. Interaction between tectonic agents responsible for uplift of the range and tectonic agents responsible for strike-slip tectonics in the vicinity of the San Bernardino Mountains remains a challenge to geologists.
- The modern landscape of the San Bernardino Mountains is a product of erosional dissection by streams and rivers that are gradually stripping away rock products and carrying them downstream to alluvial basins at the base of the range. The next few million years of earth history will witness a competition between erosional agents that will tend to reduce the elevation of the San Bernardino Mountains and tectonic agents that may continue to increase their elevation.

This narrative summary of the Geology of The San Bernardino Mountains was last modified May 26, 2007. There may be newer or revised information which is to be expected as scientific investigation continues.

And further, some research of interest regarding age and rate of uplift of the San Gorgonio block.
Don’t bother with the technical terms, note the highlighted sections.

AbstractCited By (42)
TECTONICS, VOL. 17, NO. 3, PP. 360-378, 1998
doi:10.1029/98TC00378

Uplift and erosion of the San Bernardino Mountains associated with transpression along the San Andreas Fault, California, as constrained by radiogenic helium thermochronometry

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Apatite helium thermochronometry provides new constraints on the tectonic history of a recently uplifted crystalline mass adjacent to the San Andreas Fault. By documenting aspects of the low-temperature (40°–100°C) thermal history of the tectonic blocks of the San Bernardino Mountains in southern California, we have placed new constraints on the magnitude and timing of uplift. Old helium ages (64–21 Ma) from the large Big Bear plateau predate the recent uplift of the range and show that only several kilometers of exhumation has taken place since the Late Cretaceous period. These ages imply that the surface of the plateau may have been exposed in the late Miocene and was uplifted only ~1 km above the Mojave Desert in the last few Mya by thrusting on the north and south. A similar range in helium ages (56–14 Ma) from the higher San Gorgonio block to the south suggests that its crest was once contiguous with that of the Big Bear block and that its greater elevation represents a localized uplift that the Big Bear plateau did not experience. The structure of the San Gorgonio block appears to be a gentle antiform, based on the geometry of helium isochrons and geologic constraints. Young ages (0.7–1.6 Ma) from crustal slices within the San Andreas Fault zone indicate uplift of a greater magnitude than blocks to the north. These smaller blocks probably experienced ≥3–4 km of uplift at rates ≥1.5 mm/yr in the past few Myr and would stand ≥2.5 km higher (**That's over 8000 ft)** than the Big Bear plateau if erosion had not occurred. The greater uplift of tectonic blocks adjacent to and within the San Andreas Fault zone is more likely the result of oblique displacement along high-angle faults (**see TRANSPRESSION in the glossary)** than motion along the thrust fault that bounds the north side of the range. We speculate that this uplift is the result of convergence and slip partitioning associated with local geometric complexities along this strike-slip system. Transpression thus appears to have been accommodated by both vertical displacement within the San Andreas Fault zone and thrusting on adjacent structures.

SANTA ROSA GEOLOGY

A Summary by T. Scott Bryan

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Precambrian Time:

No record whatsoever. Some metamorphic rocks once considered as Precambrian are now taken as Paleozoic Era rocks metamorphosed during the Mesozoic Era.

Paleozoic Era:

As with all of central-southern California, **passive margin** sedimentation consisting of sandstone, silty claystone, and limestone.

Sequence in total = **8,000 feet thick** (originally may have been <u>much</u> more)

A few very poor fossil remnants have been found, some equated with Ordovician, others (in Deep Canyon) with Carboniferous: Thus, start to finish sedimentation over course of ~200 million years

8,000 feet in 200 million years **= net average deposition of 0.0005 inch/year**
(so, just one inch every 2,000 years)

All now metamorphosed (due to Nevadan Orogeny- see Mesozoic Era, below):

Sandstone = quartzite
Claystone = phyllite, schist and some gneiss, uncommon slate
Limestone = marble and dolomite
Metamorphism (see below) produced few mineral deposits of note:
• some minor open stripping of dolomite,
• also in 1800s dark-colored tremolitic (magnesium rich) asbestos from NW side of Pinyon Flat (note Asbestos Mountain and Asbestos Spring as names)

This rock now found in limited areas throughout Santa Rosa and San Jacinto Mountains, **as so-called roof pendants** aka **country rock.**

Within the San Jacinto Mountains it is visible in places such as along Desert View Ridge and within Palm Canyon; it is most readily accessible as the rock exposed in mountain faces directly above Cathedral City and Rancho Mirage.

In the Santa Rosas proper, most of Deep Canyon and Sheep Mountain are composed of these metasediments, as are the hills immediately behind Travertine Point. Elsewhere in the Santa Rosas it occurs only as erratically scattered and small pendants.

Mesozoic Era (part 1 — late Jurassic to early Cretaceous periods)

Define **"orogeny"** (see glossary)
Describe *very basic* Plate Tectonics, especially **"subduction"**

Nevadan Orogeny (which formed the rocks of the
Peninsular [Ranges] Batholith, not the ranges themselves [see below])
Here, three intrusive rock bodies (+ dikes) approximately 100 million years old, and all crystallized at depth of 6 to 8 miles below surface:

• **Ribbonwood Granodiorite** — mostly found south of Deep Canyon, including on Indio Mtn, Martinez Mtn, upper areas of La Quinta Cove.

• **Pinyon Flat Granodiorite** — north of Deep Canyon, such as Pinyon *Flat,* Royal Carrizo, Haystack Mtn and so on (contains large xls of **sphene,** Ca, titanium silicate**)** [These two granodiorites are probably different phases of one magma, since moved into close proximity by Deep Canyon Fault.]

• **Cactus Spring Granite** — much more leucocratic (e.g., light-colored) than the above, and coarse grained in places. The commoner rock of the higher Santa Rosas, including Cactus Spring area, Toro Peak, probably higher water content than in the granodiorites, resulting in mineral deposits including:

  • **Garnet Queen Mine** — contact metamorphism, garnet (not gem) but mined for tungsten **(scheelite)**

  • **Santa Rosa Mountain Mine** — granite pegmatite, mined for **beryl** also the gem tourmaline pegmatites on Thomas Mountain probably also responsible for the Kenworthy-area gold deposits

Mesozoic Era (Part 2 — Late Cretaceous)

Santa Rosa Shear Zone — MAJOR fault zone, probably only small portion now preserved. Total exposed length ~30 miles, average width ~1.5-2 miles <u>Note:</u> all activity very old, probably all more than 60 million years ago

- forms rock at base of mountains at Palm Springs (Tahquitz Canyon south); then
- through Palm Canyon, <u>west</u> of canyon floor (Palm Canyon Fault separates from paleozoic metaseds, which lie east of canyon floor); thence
- onward through Pinyon Flat area to Sugarloaf Mountain; and finally
- southeastward over mountains to head of Martinez Canyon

Composed of crushed rock of all earlier rock types and ages, contacts gradational. Trend is with very steep dip to the east, with faulting of granodiorites east to west (now much modified), sometimes referred to as "Santa Rosa Thrust", but reality shows dip is so steep as to call reverse fault, not thrust. Much evidence for right lateral movement, so is actually oblique fault.

Early Cenozoic Era (65 to ~2 million years ago)
Obviously, a lot of time, but in this there is very little record.
Note: Nevadan Orogeny, etc. produced the rocks that now compose our mountains, but **NOT** the mountains themselves. Modem mountains are young (see below)

This time span evidently a time of gentle terrain. Late in this time frame there may have been some sedimentation, possibly even some volcanic activity:

In Coachella Valley-Imperial Valley there is, for example, the marine Imperial Formation, Pliocene Epoch

Southern Anza Desert- Jacumba area is volcanics, also Pliocene age. NONE such is now preserved here.

Late Cenozoic Era (1.9 million years ago to the present time)

Oldest sedimentary deposits of Cenozoic Era are:

Bautista Beds = silts, sands to coarse gravels deposited in and about lakes of an intermontaine setting, best described as: "a temperate, grassy savannah of gently meandering streams and lakes subject to occasional flooding."

<u>IMPORTANT:</u> Bautista Beds are found in numerous scattered locations from Temecula to Palm Desert (exposed at The Reserve, west of Bighorn; a couple of very small outcrops tentatively as Bautista along TLD Eisenhower Trail) They are age-correlative with the **Palm Spring Formation (Pliocene-Pleistocene).**

Contains vertebrate fossils of early Pleistocene (Irvingtonian) age, including (not inclusive). **<u>Caution:</u>** Do **not** state that all or even any of these can be found "here" but that they <u>have</u> been found in the Bautista Beds and/or the Palm Spring Formation and/or the Borrego Formation within Riverside, Imperial and San Diego Counties.

Phoenicopteryxsp.. .... playa. flamingo
Nothrotheriops shostensis . ... small ground sloth
Borophagus .... bone-crushing (hyenaoid) dog
Cams dims. .... dire wolf
Smilodon gracilis. .... gracile sabertooth cat
Dolichohippus enormous .... giant zebra
Equus bautistensis .. .. western (Bautista) horse
Eqtnishemionus. .... half ass [no kidding!]
Mamnwthus columbi.. .... Columbian mammoth
Gigantocamelus sp .... giant camel
Plus several modern things such as bobcat, Cooper's hawk, western pond turtle, jackrabbit, California vole, pocket gopher and mule deer.

<u>IMPORTANT, repeated from the above:</u> Bautista Beds are found in numerous scattered locations from Temecula to Palm Desert.

Although these deposits are not laterally continuous, they clearly represent similar depositional environments (facies) that co-existed. Therefore, clearly, the mountains of today **could not have existed** when the Bautista Beds were deposited.

Therefore, the existing Santa Rosa Mountains (and for that matter, the San Jacinto Mountains) have been created entirely within the last 2 million years.

Gulf of California

Rifting = re-development of East Pacific Rise spreading centers) began in the south, between La Paz and Mazatlan; **onset about** 25 **million years ago** Progressively, short "angled" ridges formed from south to north. Thus, the youngest part of the Gulf of California is the north. Between each successive spreading ridge segment is a transform fault. Transforms extend beyond the next spreading ridge in line, serving as fault zones in the on-shore areas.

So working northward we have:

- Spreading center, then Elsinore Fault...
- Spreading center, then San Jacinto Fault...
- Spreading center (at Cerro Prieto geothermal field), then Imperial Fault.

• Spreading center (at south end of Salton Sea), then San Andreas Fault. For now, that's it except for theory of new development to north, roughly beneath Desert Hot Springs over to yucca Valley, where the next transform is the fault system that produced the Landers 'quake in 1992

Modern Fault Zones (predominately, the San Andreas and the San Jacinto) —

Age (locally) is "only" about 4 million years. For complex, and not fully understood reasons:

- Total offset on San Andreas Fault in southern California is -130 miles
- Total offset on San Jacinto Fault is -25 miles
- However, in historic times the San Jacinto is considerably more active

It is an aside, but consider the above for only the San Andreas Fault: 130 miles = 686,400 feet 686,400 feet in 4,000,000 years = 0.1716 foot = 2.06 inches per year

Also consider:

1 major (say M~8) earthquake will give ground offset of-20 feet 686,400/20 =34,320

So we can quite confidently state that in its history, "our" portion of the San Andreas Fault has produced >30,000 major to great scale 'quakes 4,000,000/30,000 = 1 quake every 133 years

The most recent, per both geology and Cahuilla, was in Year 1680 (322 years). Like it or not, we are overdue.

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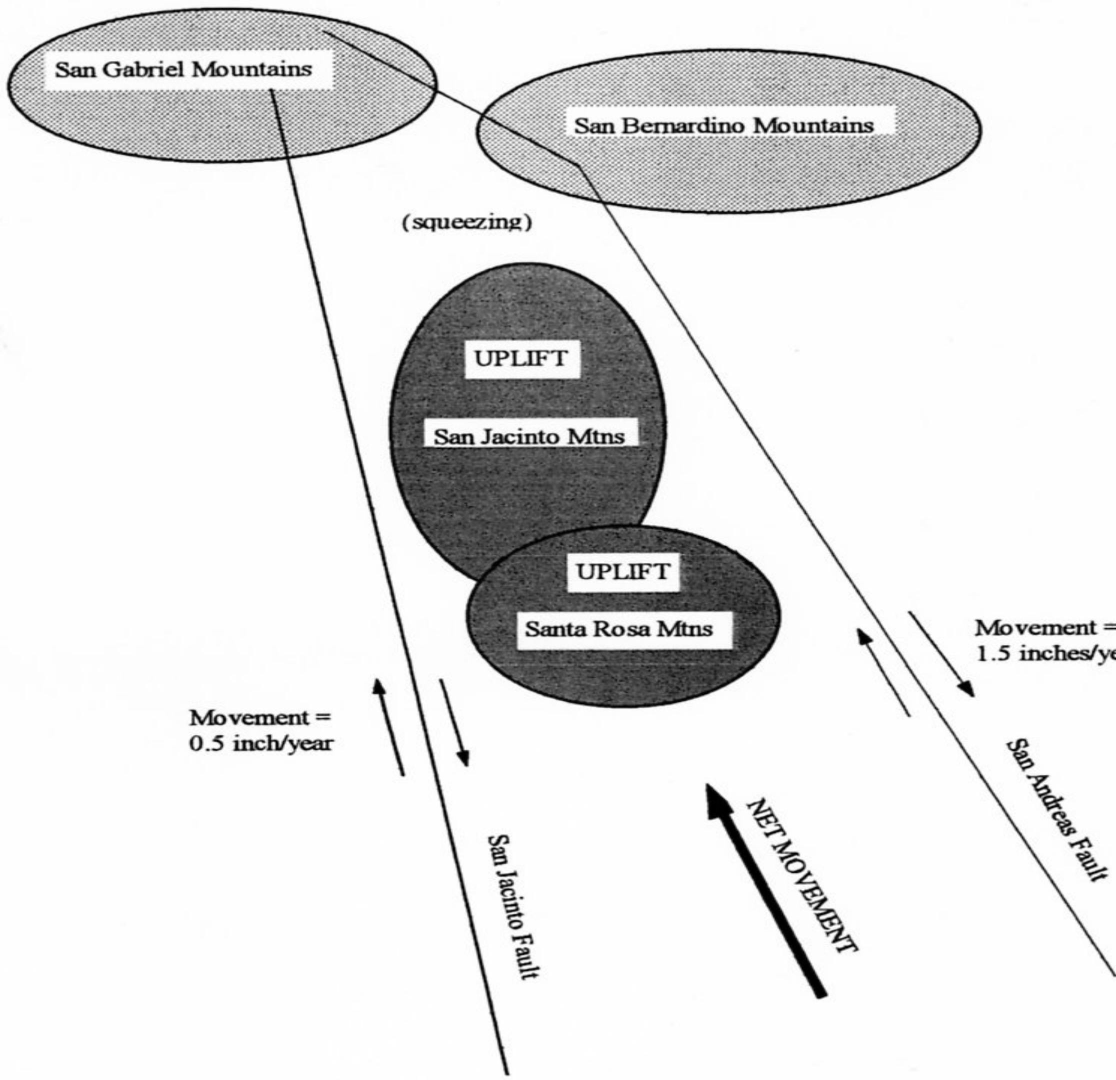
Modern Mountains

It is perhaps easiest to see how and why our mountains have formed, and why they are still forming by using a simplified map:



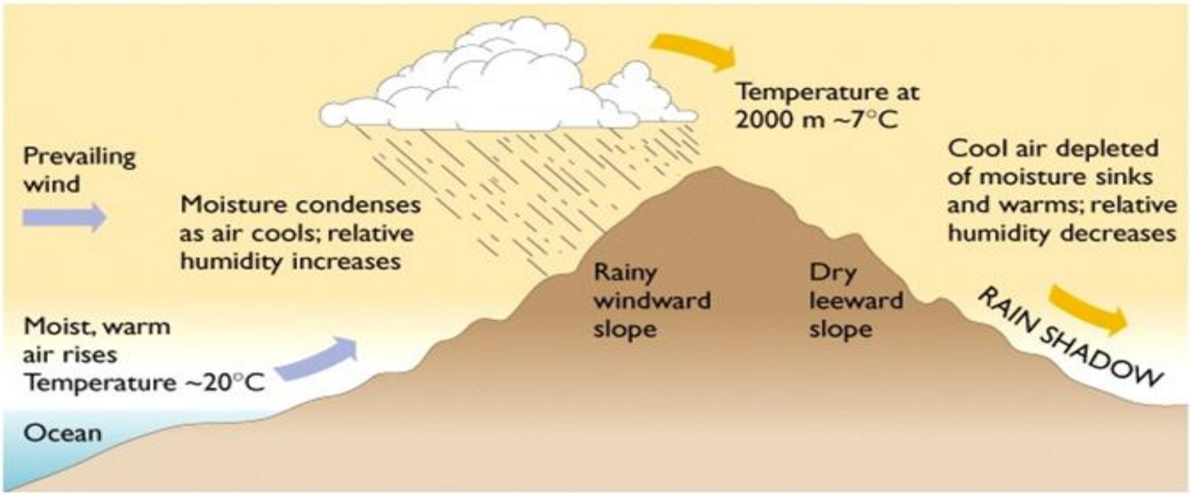
In essence, what is happening is rather simple:

Because of the net motion of the block of ground between the two faults, there is a zone of compression at which the crust has "nowhere to go," except up.

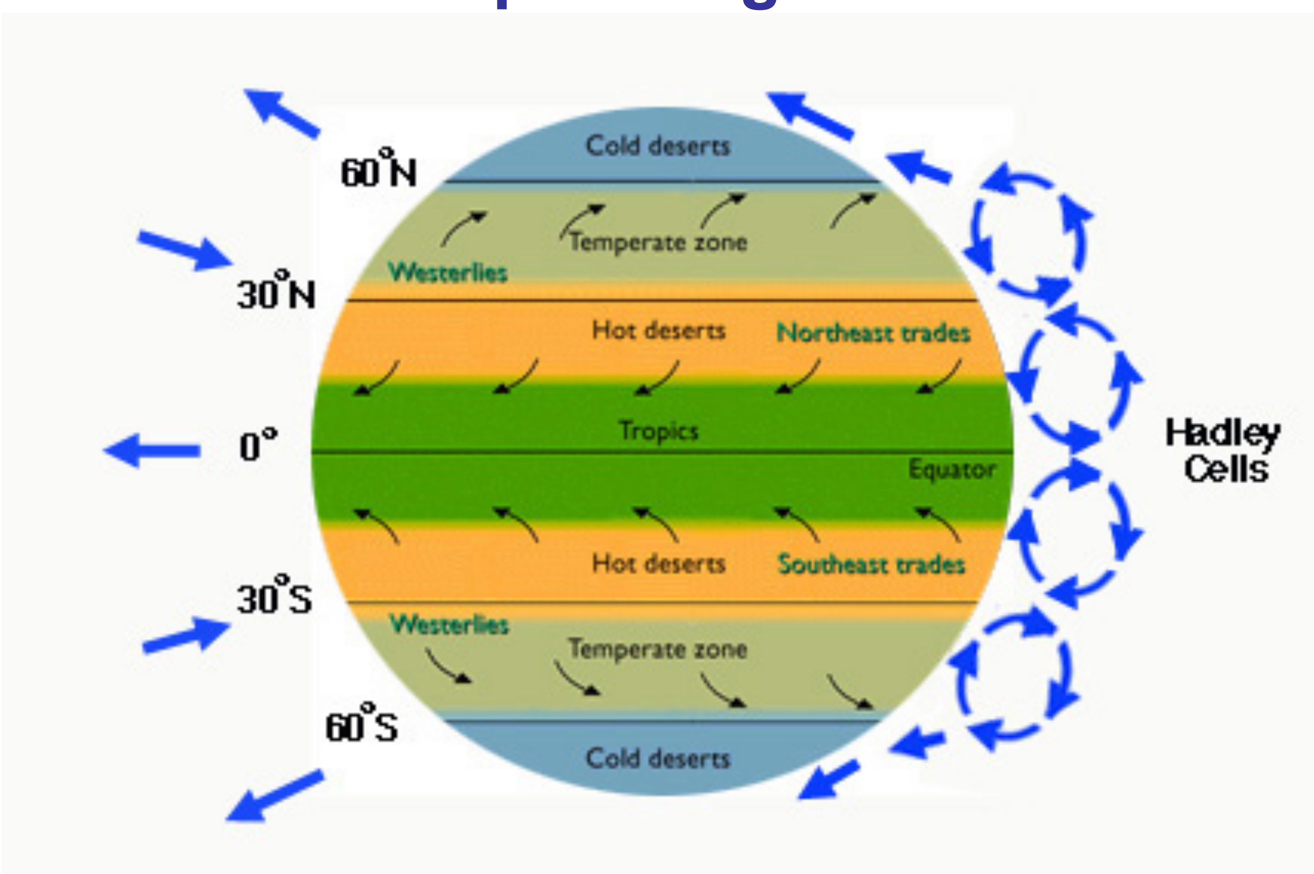
- The direct result of this is the Santa Rosa and San Jacinto Mountain massifs
- A secondary result is internal twisting, resulting in secondary faults such as the Palm Canyon Fault, Deep Canyon area faults, and a miscellany of faults slicing through Indio Mountain.

LIVING GEOLOGY AT ITS BEST!

Rain Shadow Deserts

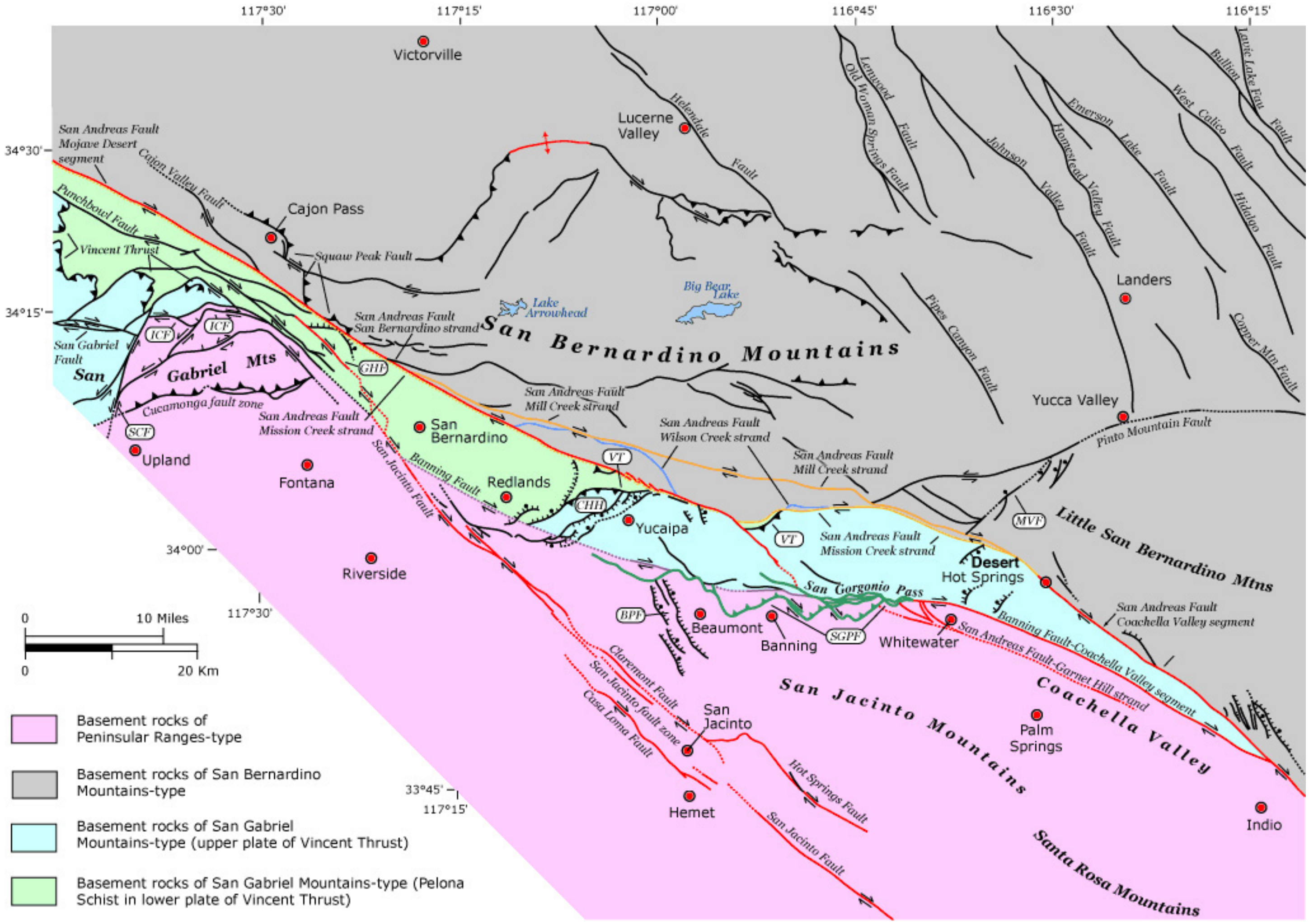


Sub-Tropical High Deserts



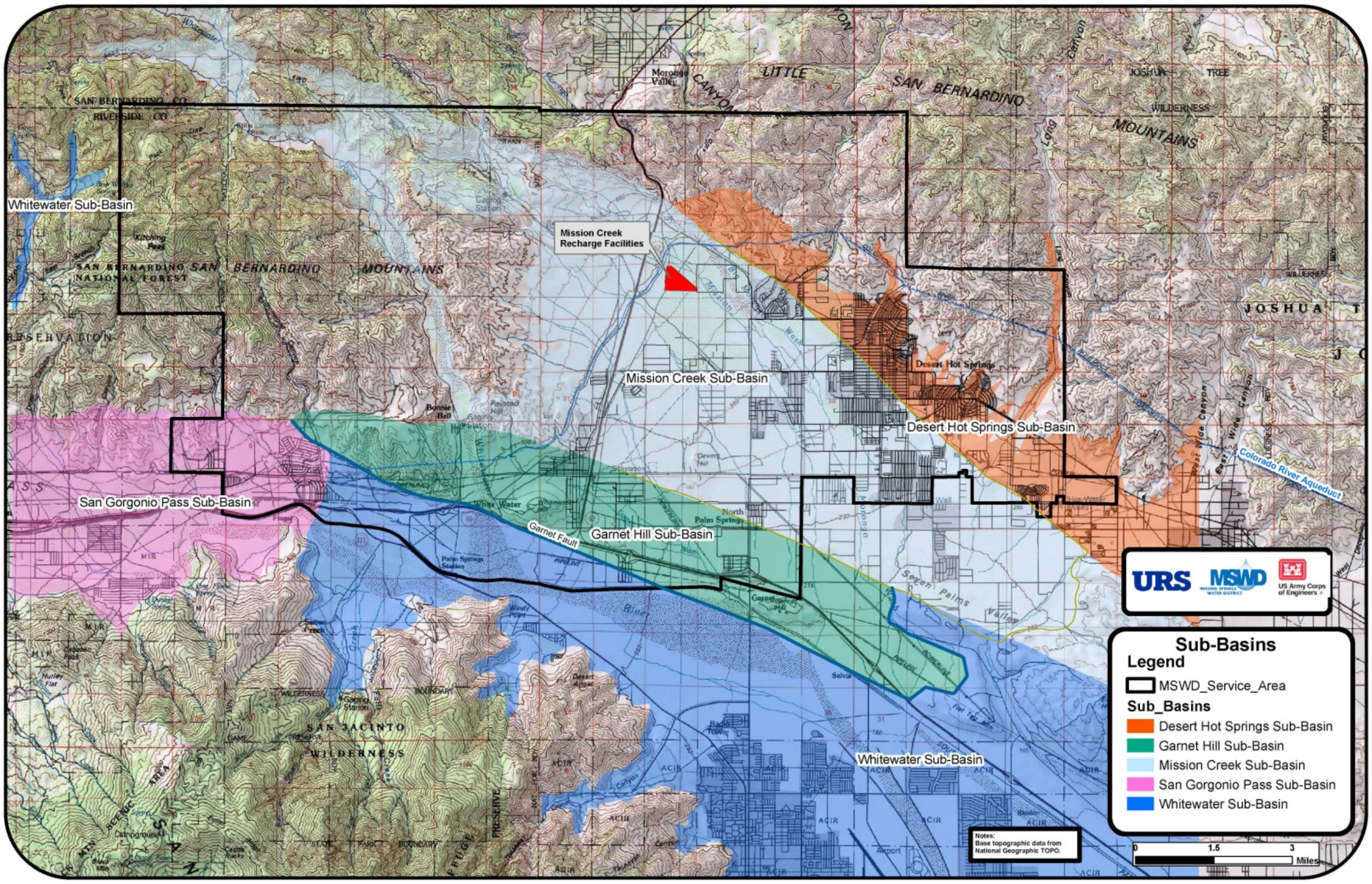
San Andreas Fault Zone

San Bernardino Mts. Segment



This map shows the different basement rock types across the major faults in the region. Over time, horizontal movement along the faults have offset these rock units from their pre-fault positions up 148 miles, as revealed by some studies. The rate of offset on the various faults varies, accounting for the different types of rock juxtaposed across the faults from southeast to northwest as they are being dragged along with the Pacific Plate. On the following map see how these faults separate several ground water basins in this region of the Coachella Valley.

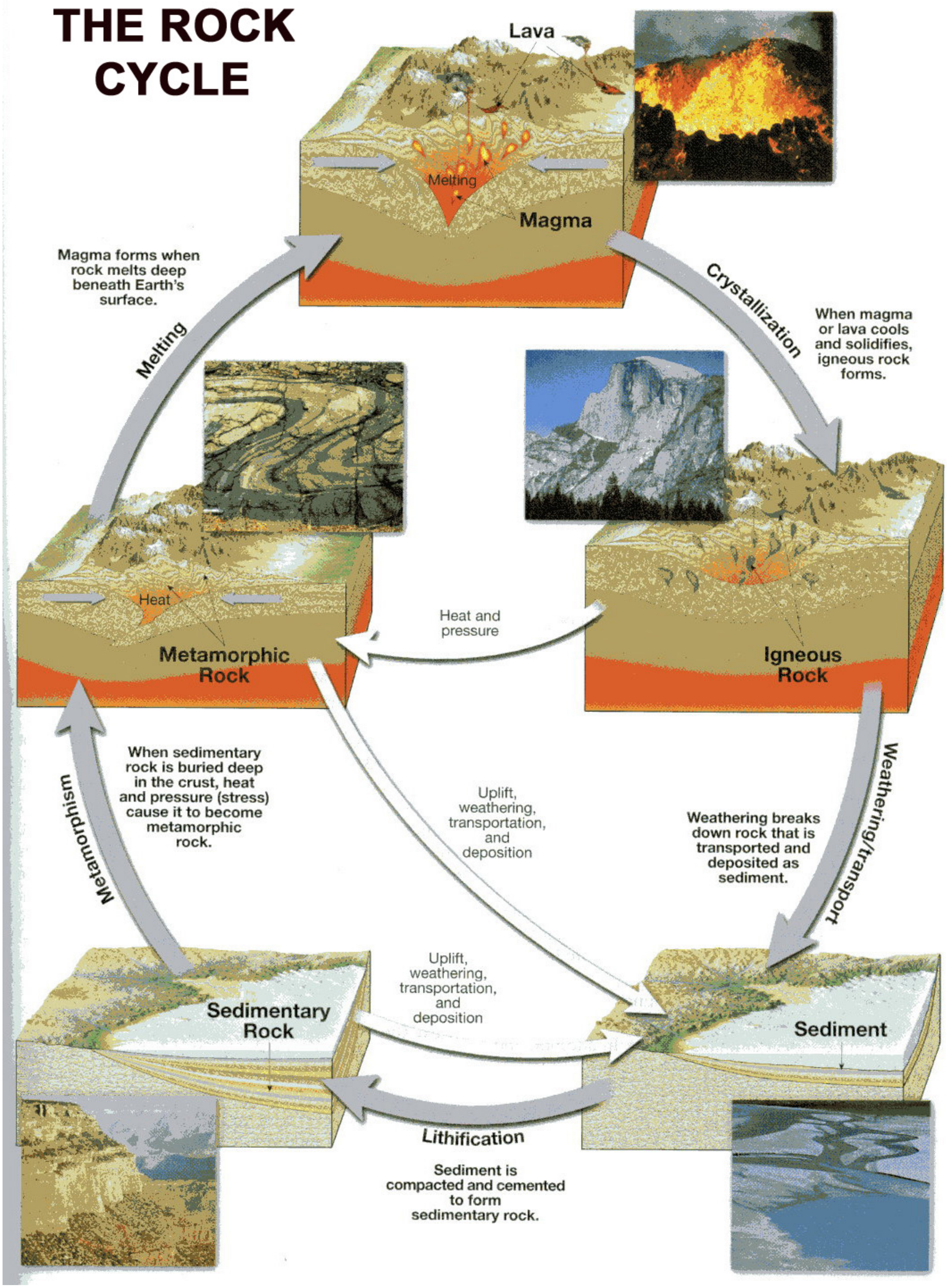
Upper Coachella Valley Groundwater Sub-basins



The basement rocks referred to on the preceding map are buried under many thousands of feet of sediment. These porous sediments are the reservoirs of water accumulating over millennia of runoff from the surrounding highlands. These basins are estimated to contain about 39,000,000 acre feet of water. These days the basins are recharged by minimal natural runoff from the surrounding mountains. Much more importantly is water from the Colorado River Aqueduct. The aqueduct crosses the Whitewater Canyon about a mile north of the I-10 freeway. When water is released here it is collected in the percolation basins downstream where it seeps into the sediments, recharging the Whitewater sub-basin. Similarly, water from the aqueduct is released into the Mission Creek Sub-basin.

On average, an acre foot of water will sustain a family of 4 for one year, but do not presume that all of this water is available for our consumption. There are environmental consequences to drawing down the water table. Conservation is critical for a sustainable water future. Moreover, the water at greater depth is heavily laden with minerals which make it very undesirable for domestic use.

THE ROCK CYCLE



MAGMA

Perhaps the most important point having to do with magma is this:

ONCE UPON A TIME IN ITS HISTORY. *ALL* ROCK WAS MAGMA?

For most purposes, it is probably "good enough" to say that magma is molten rock. To a geologist, that is too simplistic, for two reasons:

- magma is a highly complex chemical material that contains numerous ingredients that do not go into the formation of an ordinary rock;
- magma can exist only under the high temperature-high pressure conditions that exist below the surface of the Earth.

By chemistry, any magma:

- is composed more of silica [SiO2] than any other single ingredient. The silica content can range from as little as (about) 40% to as much as 75% of the total;
- contains some amount of all other chemical elements. Yes, all. However, only seven elements are important to rock formation. These are: iron, magnesium, calcium, aluminum, sodium, potassium and titanium. The other chemical elements are also present, but in very small amounts. Gold, for example, typically amounts to only 0.0000007% (that's seven ten-millionths percent, or roughly seven parts per billion).
- The above items — silica plus elements — always add up to about 95% of the total. The remaining 5% is mostly water along with other gasses such as carbon dioxide. It is this gas content that makes volcanoes explosive.

By temperature and pressure:

- temperature is far more important to magma behavior than is pressure;
- although magma can form in a number of different geological ways, it usually has an initial temperature of around 2,200'F;
- in the same way, pressure is variable, but even only one mile below the surface the pressure is not less than 120,000 pounds (60 tons) per square foot. At the depth of magma formation the pressure is never less than 4,320,000 pounds per square foot (that's >2,000 tons/ft^2), and usually it is much higher than that (up to 20,000,000 pounds per square foot).

Magma, this so-called "liquid" rock, is amazingly non-fluid. Ordinary granite magma (the commonest type of all) is more than 10^{13} (ten trillion) times more viscous than water. Drop a fist-sized chunk of rock into a pool of magma and it would sink at a rate of only four inches per day.

Nevertheless, magma is a molten material and once formed it tends to rise toward the Earth's surface, into an environment of lower temperature and lower pressure. This T-P decrease causes the formation of **igneous rocks**...

IGNEOUS ROCKS

ANY ROCK THAT HAS CRYSTALLIZED FROM COOLING MAGMA

The creation of an igneous rock is an extremely slow process. Look again at the next-to-last paragraph on the previous page. Once formed, it can take magma tens to hundreds of thousands to even millions of years to rise near the Earth's surface. But as it does so, it automatically enters areas of lower temperature. (There's lower pressure, too, but this change is of little importance here). As the temperature drops, the magma's ingredients begin to link together, forming solid, crystalline structures.

Even during these vast spans of time, rather little actual crystallization takes place. Magma is such a viscous material that even atoms find it difficult to move from one place to another, but only if they do so can a crystal grow larger. Therefore, only a few crystals form while magma is rising upward, and any that have grown are usually very small.

So it is that most crystallization — the actual formation of the rock — occurs *after* the magma has reached its final destination. This is most often a few miles below the Earth's surface. Sometimes (at a volcano) it will be on the surface. And there is your first key to the identification of igneous rocks.

Magma can crystallize, and igneous rocks can form, in either one of two geologic environments:

- **Intrusive** — crystallization over a very long period of time, at depth below the surface of the Earth.
  Think **"in"** as **inside** the Earth.
- **Extrusive** — crystallization practically instantaneous, on the surface of the Earth.
  Think "ex" as in exited the Earth.

We don't have to worry about the rare exceptions to this rule here. An igneous rock is either intrusive **or** extrusive, period.

Identifying Igneous Rocks

Any magma can form both intrusive and extrusive rocks. These two environments are dramatically different, though, and the resulting rocks might bear little resemblance to one another even if they are of identical chemistry.

Telling whether a rock is intrusive or extrusive is relatively straight-forward. During the long crystallization history of an intrusive rock, there is ample time for large, megascopic mineral grains to form. By contrast, an extrusive rock is composed of microscopically small crystals. Again, there is no in-between, so here is the **textural key:**

- **Intrusive** — the individual mineral crystals **can** be seen with the unaided eye.
- **Extrusive** — the mineral crystals **cannot** be seen with the unaided eye.

Usually that's all you'll need for interpretation. But there's more.

Chemistry must also be considered. The discussion about magma (page 2 of this .handout) indicated that there is a considerable range in magma chemistry. Necessarily, different kinds of magma yield different kinds of rock, both intrusive and extrusive.

Recall that in magma, silica plus other ingredients (less gas) always adds up to 95%. So the less silica there is, the more of the "other stuff' there must be, and vice versa. In general, rock that contains little silica boasts a lot of iron and magnesium (called *mafic).* These elements form minerals that are dark in color, such as black hornblende and augite or green olivine. On the other hand, a high-silica rock *(sialic [or felsic])* tends to be light in color. It contains minerals such as glassy quartz, gray or pink orthoclase, and white plagioclase. Considered as a gray scale range, it is possible to quite accurately judge the chemistry of the rock by visual inspection alone!

Putting texture and chemistry together, igneous rock classification looks like this:

	Light	chemical color	Dark
Intrusive coarse-grained	**GRANITE** Mostly salt, little pepper	**GRANODIORITE** Salt and pepper	**GABBRO** Mostly pepper
Extrusive Fine-grained Mostly uniform	**RHYOLITE**	**ANDESITE**	**BASALT**
Pyroclastic	**see text..**		

Intrusive igneous rocks, to repeat the single most important identification tool, are coarse-grained so that the individual mineral crystals of the rock are visible to the unaided eye; these crystals typically measure 1/8 to 1/4 inch in dimension. The contrast between the sialic and the mafic minerals gives the rock a "salt—and-pepper" appearance. The three most important varieties of intrusive rock are:

- **Granite** — Granite is the most silica-rich and the commonest intrusive. It is dominated (usually >50% by volume) by the mineral orthoclase (potassium feldspar), which often has a pale pink or gray color. Most of the remainder is glassy quartz. Granite contains rather few mafic mineral grains, so its salt—and-pepper look is dominated by salt. Much of the igneous rock found in The Living Desert's washes is granite, having washed down Deep Canyon from Toro Peak.
  A special variety of granite is called **granite pegmatite.** Generally composed of potassium feldspar and quartz along with little else, it is characterized by extraordinarily large crystals; crystals measuring several inches in dimension are common. Granite pegmatite specimens are occasionally seen in our washes.

• **Granodiorite** is the intrusive rock with a mid-range chemistry. Pure white plagioclase feldspar accompanies the gray-pink orthoclase; quartz must be present but may comprise as little as 10% of the rock. Granodiorite is common in the Santa Rosa Mountains. Light versus dark minerals are close to 50-50 proportions. Often in southern California, granodiorite is called *quartz monzonite.*

Diorite is very similar in appearance to granodiorite, but it is poorer in silica and correspondingly richer in the mafic minerals. Its feldspar is dominated by white plagioclase in place of the gray orthoclase, and there is no quartz whatsoever. The proportion of light versus dark mineral grains is tipped a bit toward the dark end of the scale, so there is somewhat more pepper than there is salt. In southern California, diorite is often called *tonalite.*

• **Gabbro** is the most mafic of the common intrusive rocks. It is dominated by dark green or black mineral crystals with only a little of the plagioclase feldspar (which now is calcium-rich and colored gray rather than white. Hence, this rock is made almost entirely of pepper. Gabbro is uncommon in the Santa Rosa Mountains, but it is abundant in parts of the Little San Bernardinos and in washes near 1000 Palms.

There are, of course, a number of intrusive rocks beside these. Two that you won't see at The Living Desert but which are especially notable are:

• **Syenite** would fall to the left of "granite" on the rock chart of page 4, where it fits because of its chemistry even though it can be very dark in color. There is a significant exposure of syenite in the Orocopia Mountains.

• **Anorthosite** is relatively rare on Earth (the light-colored highlands of the Moon are anorthosite). One of the larger exposures of anorthosite anywhere is in the western part of the San Gabriel Mountains. The northeastern portion of that outcrop is cut off by faults related to the San Andreas. And sure enough, that portion of the anorthosite can be found down here, within and to the southeast of Painted Canyon.

Extrusive igneous rocks will be dealt with more briefly here, as none can be found in our immediate vicinity. Having crystallized on the Earth's surface, they are so fine-grained that the crystals are microscopic in size. The texture is usually quite smooth and there is no salt-and-pepper appearance. The three important extrusive rocks are:

• **Rhyolite** is the chemical equivalent of granite. It most often is of a pale gray color. Some rhyolite can be found at the south end of the Salton Sea, and it is the most important rock type in the Coso Domes and Long Valley Caldera volcanic systems on east side of the Sierra Nevada; the largest single mass in the world is Yellowstone.

• **Andesite**, the equivalent of diorite *(dacite* is the chemical equivalent of granodiorite) is extremely common in the world, being the most abundant volcanic rock of subduction zone volcanoes such as their namesake in the Andes of South America or our Cascade Range. It tends to a medium- to dark-gray color. Once capping all our local mountains, this andesite entirely eroded away millions of years ago.

- **Basalt** is the heavy black rock that most people are familiar with as "lava." Sometimes it is *vesicular,* meaning that it is full of gas bubble holes that formed when it was still molten. Basalt can be found in the small volcanoes at the south end of the Salton Sea, in the Pioneertown Volcanics near Yucca Valley, and in each of the volcanic areas of the Mojave Desert (Amboy, Pisgah, Pitkin, etc. and the Cima Cones of the East Mojave National Preserve).

Pyroclastic is a special category of the extrusive rocks. The name is a hybrid combination of Latin *pyro* for "fire" and Greek *clastic* for "broken," so fire-broken. These fragmental materials are the rocks of somewhat violent volcanic activity, as opposed to the lava flows of quieter eruptions. By and large, the pyroclastics are named on the basis of texture alone, without regard to chemistry. The best known examples of pyroclastic rocks are:

- **Tuff**— Lithified volcanic ash, usually pale in color and light in weight.

- **Pumice** — Formed from volcanic froth, where magma escaping the ground puffed up due to the release of the magmatic gasses to such an extent that the rock is more gas bubble than solid rock. Pumice is the rock that floats on water. Can be found at the Salton Sea.

- **Obsidian**— composed of volcanic glass from where the cooling of magma was so rapid that mineral crystals simply had no opportunity to form. Usually black in color, but may be brownish or reddish and sometimes is beautifully iridescent blue-violet. Obsidian Butte is at the south end of the Salton Sea.

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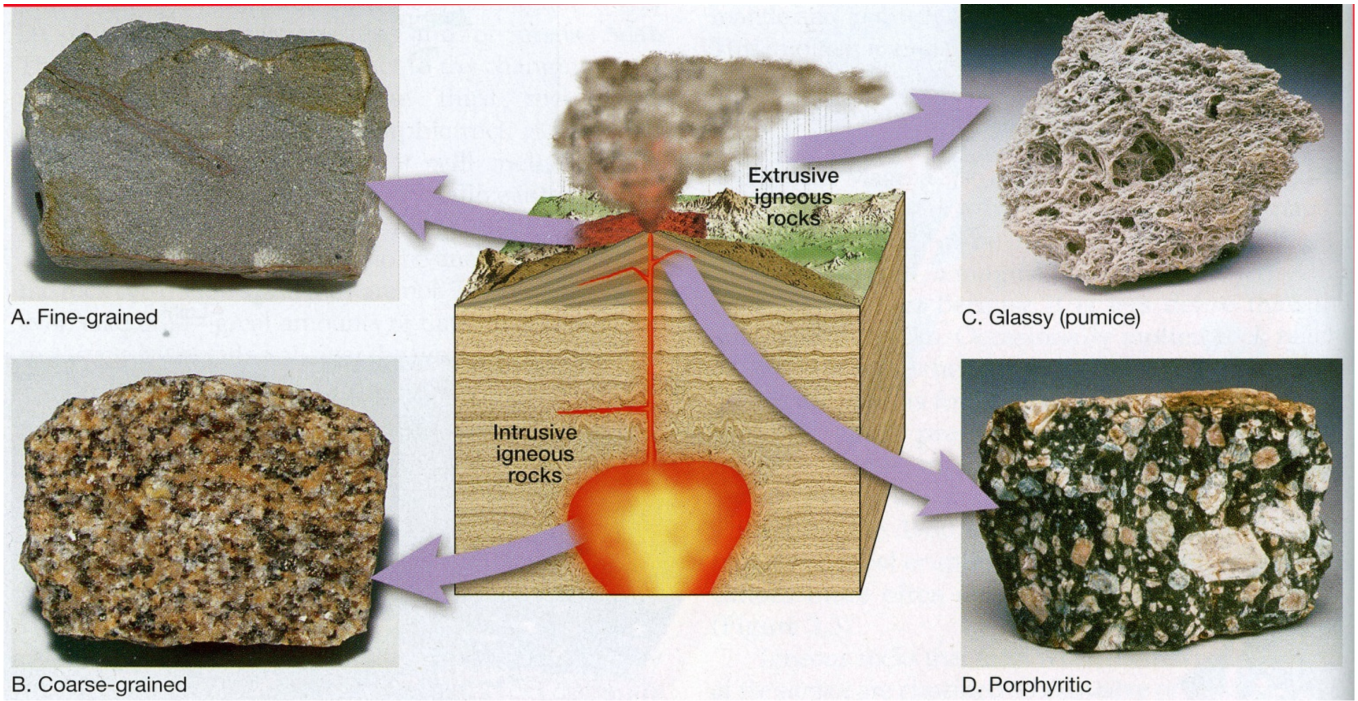
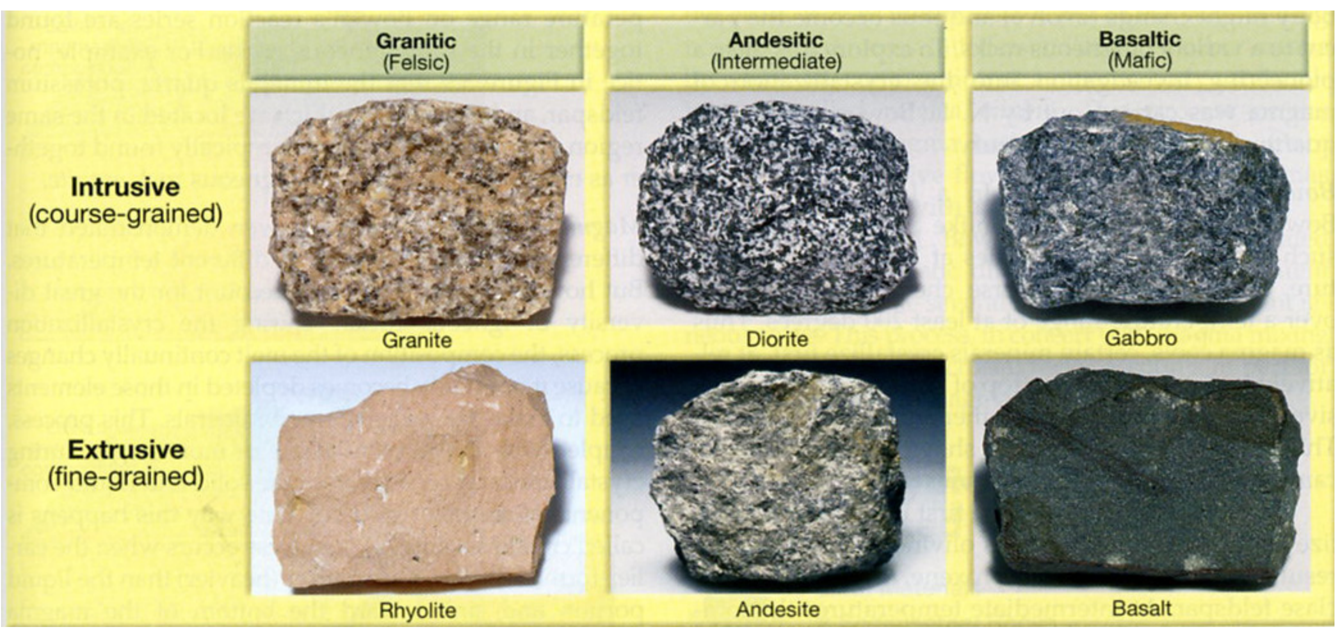
Igneous Rock Textures



Common Igneous Rocks



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METAMORPHIC ROCKS

ANY ROCK THAT HAS RECRYSTALLIZED BECAUSE OF CHANGING TEMPERATURE OR PRESSURE

The name for this category of rocks comes from the Latin terms *meta* meaning "change" and *morph(ology)* meaning "form." As with the metamorphism of a caterpillar into a butterfly, the end result of metamorphic recrystallization often bears little or no resemblance to the original material.

As a category in strict geologic terms, the metamorphic rocks are incomparably the most difficult to understand. They are the rocks whose ingredients have reconstituted themselves into new crystals because of changing temperature and/or changing pressure. The complexity arises because:

- any rock — igneous, sedimentary or older metamorphic — can be metamorphosed.
- the temperature of recrystallization can range from the near-zero of the Earth's surface to well over 1,000°F.
- the pressure of the recrystallization varies in similar fashion, from surface conditions to millions of pounds per square foot.
- sometimes metamorphism will remove some of the ingredients of the original rock; at other times, new ingredients are added; or there may be no net change at all.
- and of course, time plays a strong role: the longer the time frame, the more thorough the recrystallization.

Since all of these factors vary from place to place, they may work together in any combination you can think of. Net result: the variety of metamorphic rocks is nearly infinite.

It is this complexity that provides detailed information to the geologist. For example, some particular combination of minerals (like the magnetite-hastingite mixture of barkevikiejacupirangite*) might be one that can form only within some highly restricted ranges of both temperature and pressure. The rock cannot possibly have formed under any other conditions, so simply seeing those minerals together is an important diagnostic tool. However, being able to make such inferences obviously demands a detailed knowledge of mineralogy. (* I [Scott Bryan] put this in because I love the name!)

Fortunately, you don't really need to know any of this in order to put the metamorphic rocks into name categories. The basic classification ignores mineralogical detail and places the rocks into just two subcategories that (initially, at least) are based entirely on texture rather than composition. The two categories are:

- Foliated — rocks in which the mineral grains are oriented parallel to one another.
- Non-foliated — logically, rocks in which the mineral grains are *not* oriented parallel to one another.

The key to identifying these rocks is to first examine a specimen for foliation. Similar to the grain size distinction between intrusive and extrusive igneous rocks, here a rock either is or is not foliated.

Identifying Metamorphic Rocks

Foliated rocks develop when crystals of one of the metamorphic minerals are oriented in parallel fashion because of confining pressure. Most often these are mica minerals with book-like crystals or amphibole minerals with needle-like crystals. The result looks sort of like this drawing:
Any rock with foliation will tend to break into flat pieces, the surfaces following the foliation. Then, depending upon how thorough the recrystallization has been, there are four main types of foliated rocks:

- **Slate** — minimal recrystallization, foliation often perfect but all crystals microscopically small and invisible to the unaided eye. Dull luster.

- **Phyllite** — recrystallization formed crystals on the verge of visibility with the unaided eye, still not really visible yet large enough to give a silky/satin luster.

- **Schist** — mica crystals large enough to be easily visible to the unaided eye; rock of the same "metamorphic grade" is called **amphibolite** if the foliation is caused by needle-like amphiboles instead of flat micas.

- **Gneiss** — the most extensively recrystallized rock, not only foliated but also distinctly banded with distinct layers of different minerals.

Non-foliated rocks are produced when the recrystallizing minerals have no preferred orientation of their own. They are therefore incapable of producing foliation. The rock looks more-or-less like this: ——————————————
Since there is no structure to depend on, these rocks are named according to composition. Doing so is simple:

- **Marble** — formed from limestone, so coarsely crystalline calcite (calcium carbonate); quite soft as minerals go and easily scratched with a knife blade or steel file, and will "fizz" in acid (even one as dilute as vinegar).

- **Quartzite** — formed from sandstone or siltstone, so densely crystallized quartz; the hardest of common minerals and **cannot** be scratched with a knife blade or steel file, and will **not** fizz in acid (no matter how strong).

- **Hornfels** — formed from some "dirty," impure original material, so of a complex mineralogy.

- **Serpentinite** — formed under low temperature-high pressure conditions from any number of original materials, usually waxy in appearance and some sort of green color. Included here mainly because it is California's official state rock!

Common Metamorphic Rocks

Rock Name	Texture	Grain Size	Comments	Parent Rock
Slate	Foliated	Very fine	Excellent rock cleavage, smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite	Foliated	Fine	Breaks along wavey surfaces, glossy sheen	Slate
Schist	Foliated	Medium to Coarse	Micas dominate, scaly foliation	Phyllite
Gneiss	Foliated	Medium to Coarse	Compositional banding due to segregation of minerals	Schist, granite, or volcanic rocks
Marble	Nonfoliated	Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite	Nonfoliated	Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Anthracite	Nonfoliated	Fine	Shiny black organic rock that may exhibit conchoidal fracture	Bituminous coal

Increasing Metamorphism

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SEDIMENTARY ROCKS

ANY ROCK THAT HAS FORMED FROM WEATHERED DEBRIS ON THF EARTH'S SURFACE

By contrast with the igneous rocks, sedimentary rocks are comparatively easy to deal with, especially if we confine the discussion to the sedimentary materials of the Coachella Valley.

Virtually any rock — igneous, sedimentary or metamorphic — was formed under conditions different from those of the Earth's surface. So take a rock, any rock, and allow it to sit on the ground, exposed to the atmosphere. Because this environment is different (usually radically so) from the environment of the rock's formation, the rock will begin to break down into its constituent mineral grains. A well-known example is the change from granite to decomposed granite. This process is called **weathering.**

Nothing is immune to weathering, but how fast it attacks a rock depends on a series of factors:

- **the chemistry** of the rock or mineral — substances rich in iron and magnesium tend to break down quickly; rocks rich in silica can be nearly immune to alteration.
- **the humidity** of the environment is a strong control — without water there would be no weathering at all; it can form acids and also can freeze
- **the temperature** of the environment is another control — warmer environments tend to be more acidic than cooler areas; much weathering is acid decomposition.
- **the time** involved is critical — this is geology, where rapid events might seem incredibly slow in human terms.

The net result of this is remarkably simple. No matter what the original, unweathered rock, weathering yields just four kinds of sedimentary "stuff": **clastic particles, oxide minerals, clay and dissolved salts.**

Once formed, the weathered debris tends to be eroded and transported from one place to another. Eventually it will be deposited to form a new layer of sediment which, when compressed and lithified, will become sedimentary rock.

Depending on the specifics of composition and mode of formation, sedimentary rocks are placed into three classification groups.

- **Clastic rocks** — remember the Greek *clastic,* for "broken"; these are the rocks formed from the solid particles released by weathering. Roughly half of all sedimentary rocks are clastic.
- **Hydrogenic rocks** — *hydro* for "water" and *genie* for "genesis", and sometimes called the chemical or the evaporite rocks; formed by the evaporation of water.
- **Biogenic rocks** — *bio* for "biological" and *genie* for "genesis", and sometimes called the organic rocks; formed through the agency of biological activity.

Identifying Sedimentary Rocks

Clastic rocks — Identifying the clastic sedimentary rocks is quite simple. It is based on the size of the sedimentary particles that compose the rock and their chemical composition. Clastic rocks are the *only* type of sedimentary rock within the Coachella Valley itself and, in fact, it is possible to find examples of all four varieties in such areas as 1000 Palms and Box Canyon.

Clastic rocks form when the solid particles of weathering are deposited as discrete layers along streams, in lakes or the ocean, or as sand dunes. They are identified strictly on the basis of grain size, according to what is known as the "Wentworth Classification." There are four important size categories, and there are four corresponding kinds of clastic rock:

- **Conglomerate** — the rock that contains rounded pebble or gravel particles (larger than 2 millimeters in dimension) enclosed within a sandy matrix. If the pebbles are angular instead of rounded, then the rock is called "breccia."

- **Sandstone** — the rock that is composed entirely of sand particles (size range 2 millimeters down to 1/16 millimeter). Depending on mineral chemistry, there are many kinds of sandstone, such as "arkose" (feldspar grains) and "greywacke" (rock fragments). Looks and feels like sandpaper.

- **Siltstone** — the rock composed of silt particles (size range 1/16 millimeter down to just 1/256 millimeter). Looks like a very fine sandpaper and barely feels gritty.

- **Claystone** — composed of the clay particles that form from chemical weathering (size always less than 1/256 millimeter). Very soft and smooth feeling. Sometimes called "shale" or "mudstone."

Siltstone and claystone are often indistinguishable in the hand specimen. In that case, the surest way to tell them apart is to chew a bit of the rock: clay is smooth between the teeth while silt is decidedly gritty.

It is entirely possible to have rocks that contain some of two adjacent size catergories, such as a "silty sandstone" or a "silty claystone." However, because it takes more energy to transport large particles than it does small crystals, it would be highly unusual to find something like a "clayey conglomerate."

If any of these rocks contains fossils that are visible to the unaided eye, then the term "fossiliferous" should be added to the basic rock name, such as "fossiliferous siltstone."

Hydrogenic rocks form when water evaporates on desert lakebeds or in restricted marine lagoons, leaving behind the salts (solutes) that were dissolved during weathering. They are classified entirely on the basis of chemistry with absolutely no consideration of crystal size. This group contains only a few members, but three of them are vitally important mineral commodities:

- **Rock salt** — this often is pure sodium chloride (table salt), but as a rock it can include *any* chemical salts in any mixture. Found on many dry desert lakebeds, including the Salton Sea when evaporated away.

- **Rock gypsum** — usually pure gypsum (hydrated calcium sulfate), the main ingredient of plaster and stucco. Mined in the Split Mountain area of the Anza Desert.

- **Borate** — borax and other boron compounds. At Boron, CA is the largest borax mine in the world.

Biogenic rocks are all a result of biology. Some are outright organic in chemical composition; others are inorganic but required biological activity to form them. There are quite a few biogenic rocks but just three of importance to us.

- **Limestone** — the commonest of all biogenic rocks, composed of seashells (mostly microscopic).

- **Coal** — a compressed, distilled accumulation of plant matter. Several varieties are named depending on the amount of compression and alteration; the most important and most familiar is called bituminous coal.

- **Petroleum** — usually liquid (oil) or gas (natural gas) and so not rock, there is a solid form called bitumen; in any case, petroleum is biogenic sedimentary by origin.

The Sedimentary Rocks

Clastic	**Hydrogenic**	**Biogenic**
Conglomerate	Rock salt	Limestone
breccia	chalk	
Sandstone	Rock gypsum	coquina
arkose	Coal	
greywacke	Borate	
Siltstone	(Petroleum)	
Claystone (shale)		

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Sedimentary Rocks

Detrital Sedimentary Rocks		
Texture (particle size)	**Sediment Name**	**Rock Name**
Coarse (over 2 mm)	Gravel (Rounded particles)	**Conglomerate**
Coarse (over 2 mm)	Gravel (Angular particles)	**Breccia**
Medium (1/16 to 2 mm)	Sand (If abundant feldspar is present the rock is called **Arkose**)	**Sandstone**
Fine (1/16 to 1/256 mm)	Mud	**Siltstone**
Very fine (less than 1/256 mm)	Mud	**Shale**

Chemical Sedimentary Rocks			
Composition	**Texture**	**Rock Name**	
Calcite, $CaCO_3$	Fine to coarse crystalline	**Crystalline Limestone**	
Calcite, $CaCO_3$	Fine to coarse crystalline	**Travertine**	
Calcite, $CaCO_3$	Visible shells and shell fragments loosely cemented	**Coquina**	**Biochemical Limestone**
Calcite, $CaCO_3$	Various size shells and shell fragments cemented with calcite cement	**Fossiliferous Limestone**	**Biochemical Limestone**
Calcite, $CaCO_3$	Microscopic shells and clay	**Chalk**	**Biochemical Limestone**
Quartz, SiO_2	Very fine crystalline	**Chert (light colored) Flint (dark colored)**	
Gypsum $CaSO_4 \cdot 2H_2O$	Fine to coarse crystalline	**Rock Gypsum**	
Halite, NaCl	Fine to coarse crystalline	**Rock Salt**	
Altered plant fragments	Fine-grained organic matter	**Bituminous Coal**	

Earth Sciences:Tarbuck and Lutgens 11th ed 2006

Subduction, The Nevadan Orogeny And the Basement Rocks of Mt. San Jacinto

OROGENY: Process by which mountain structures develop.
The process by which structures within fold-belt mountainous areas were formed, including thrusting, folding, and faulting in the outer and higher layers, and plastic folding, metamorphism, and plutonism in the inner and deeper layers. Syn: orogenesis; mountain building; tectogenesis. Adj: orogenic; orogenetic. *AGI*

Please open and read the two links below for a non technical and very useful summary of the tectonic history of the American west leading up to the Nevadan Orogeny and beyond.

http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=3&ved=0CDcQFjAC&url=http%3A%2F%2Fsnobear.colorado.edu%2FMarkw%2FMountains%2F05%2FCaliforniaMtns%2FCalifornia_geologic_history.ppt&ei=RDS7UdelNeS2yAHOhoGwCQ&usg=AFQjCNE3vHYBozy-yUVem5SoHFxMRFrFow&bvm=bv.47883778,d.aWc

http://www.ucmp.berkeley.edu/science/profiles/erwin_0609geology.php

The Peninsular Ranges Batholith

In summary, beginning sometime during the mid Jurassic Period subduction of the Farallon plate commenced and volcanism prevailed along the western edge of the continent for about the next 70 million years. There were 3 pulses of magmatic intrusions into the overlying continental crust, perhaps 6 to 8 miles or more below the surface, creating a 900 mile long series of plutons and batholiths. As these molten igneous intrusive bodies slowly cooled over millions of years the component chemicals crystallize into a variety of minerals creating granular salt and pepper textured *igneous intrusive* rocks with a wide variety of mineral composition. These are generically identified as granitic. (See Bowen's Reaction Series below) Rocks such as these are the ancestral core of the modern mountains of the Nevadan Orogeny, the Peninsular Range (Mt. San Jacinto), Little San Bernardino Mts.(Joshua Tree), San Bernardino Mts. and the Sierra Nevada.

Bowen’s Reaction Series

Because a large variety of igneous rocks exist, it is logical to assume that an equally large variety of magmas must also exist. However, geologists have observed that a single volcano may extrude lavas exhibiting quite different compositions. Data of this type led them to examine the possibility that a single magma body might change (evolve) and thus become the parent to a variety of igneous rocks. To explore this idea, a pioneering investigation into the crystallization of magma was carried out by N. L. Bowen in the first quarter of the twentieth century.

Bowen's Reaction Series. In a laboratory setting, Bowen demonstrated that unlike a pure compound, such as water, which solidifies at a specific temperature, magma with its diverse chemistry crystallizes over a temperature range of at least 200 degrees. Thus as magma cools, certain minerals crystallize first, at relatively high temperatures (top of Figure 3.9). At successively lower temperatures, other minerals crystallize-This arrangement of minerals, shown in Figure 3.9, became known as **Bowen's reaction series.**

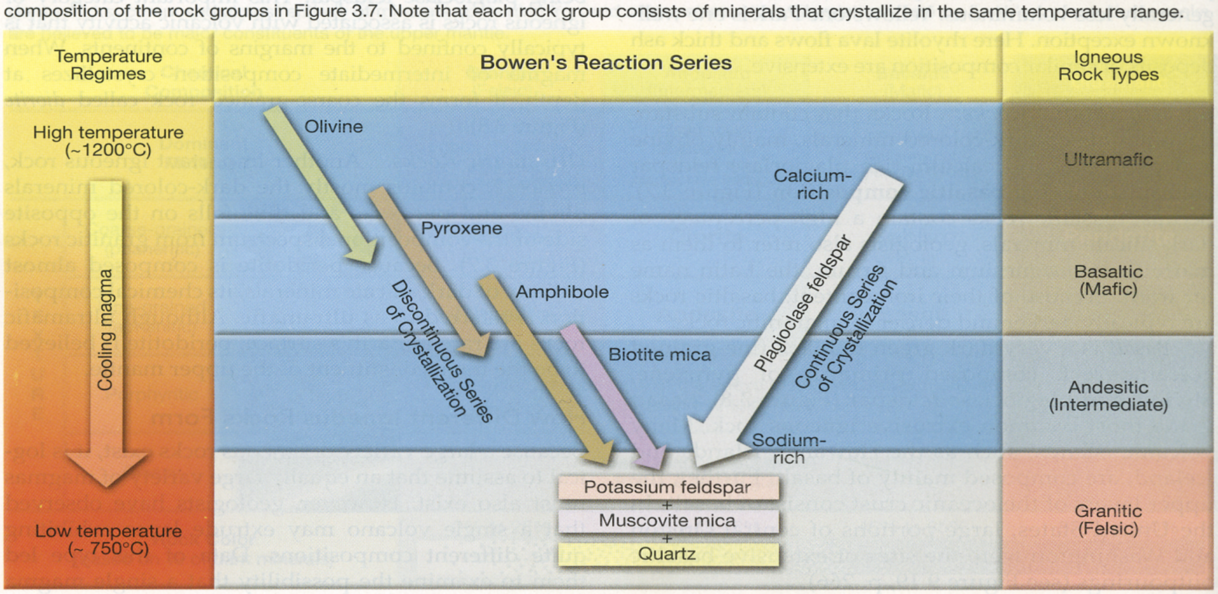
Bowen discovered that the first mineral to crystallize from a mass of magma is olivine. Further cooling results in the formation of pyroxene, as well as plagioclase feldspar. At intermediate temperatures the minerals amphibole and biotite begin to crystallize.

During the last stage of crystallization, after most of the magma has solidified, the minerals muscovite and potassium feldspar may form (Figure 3.9). Finally, quartz crystallizes from any remaining liquid. As a result, olivine is not usually found with quartz in the same igneous rock, because quartz crystallizes at much lower temperatures than olivine. Evidence that this highly idealized crystallization model approximates what can happen in nature comes from the analysis of igneous rocks. In particular, we find that minerals that form in the same general temperature range on Bowen's reaction series are found together in the same igneous rocks. For example, notice in Figure 3.9 that the minerals quartz, potassium feldspar, and muscovite, which are located in the same region of Bowen's diagram, are typically found together as major constituents of the igneous rock *granite.*

Magmatic Differentiation. Bowen demonstrated that different minerals crystallize at different temperatures. But how do Bowen's findings account for the great diversity of igneous rocks? During the crystallization process, the composition of the melt continually changes because it gradually becomes depleted in those elements used to make the earlier formed minerals. This process, coupled with the fact that at one or more stages during crystallization, a separation of the solid and liquid components of magma can occur. One way this happens is called **crystal settling**. This process occurs when the earlier-formed minerals are denser (heavier) than the liquid portion and sink toward the bottom of the magma chamber, as shown in Figure 3.10. When the remaining melt solidifies—either in place or in another location if it migrates into fractures in the surrounding rocks—it will form a rock with a chemical composition much different from the parent magma (Figure 3.10). The formation of one or more secondary magmas from a single parent magma is called **magmatic differentiation**.

At any stage in the evolution of a magma, the solid and liquid components can separate into two chemically distinct units. Further, magmatic differentiation within the secondary melt can generate additional chemically distinct fractions.

▼ **FIGURE 3.9** Bowen's reaction series shows the sequence in which minerals crystallize from a magma. Compare this figure to the mineral composition of the rock groups in Figure 3.7. Note that each rock group consists of minerals that crystallize in the same temperature range.

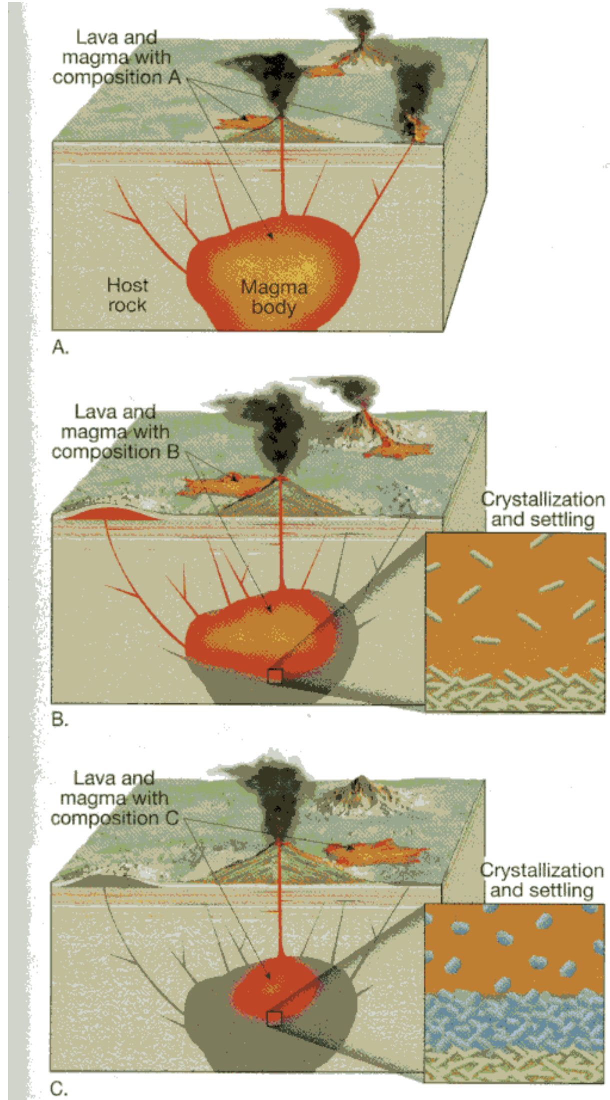


Consequently, magmatic differentiation and separation of the solid and liquid components at various stages of crystallization can produce several chemically diverse magmas and ultimately a variety of igneous rocks.

Assimilation and Magma Mixing. Strong evidence suggests that the chemical composition of a magma can change by processes other that magmatic differentiation. For example, as a magma migrates upward through the crust, it may incorporate some of the surrounding host rock, a process called assimilation. Another means buy which the composition of a magma body can be altered is called magma mixing. This process occurs whenever one magma body intrudes another. Once combined, convective flow may stir the two magmas to generate a fluid with a different composition.

In summary, N.L. Bowen successfully demonstrated that through magmatic differentiation, a single parent magma can generate several mineralogically different igneous rocks. This process, in concert with magma mixing and contamination by crustal rocks, accounts in part for the great diversity of magmas and igneous rocks.

Edward J. Tarbuck, Frederick K. Lutgens, ***Earth Science***
Eleventh Edition, 2006, Pearson Prentice Hall



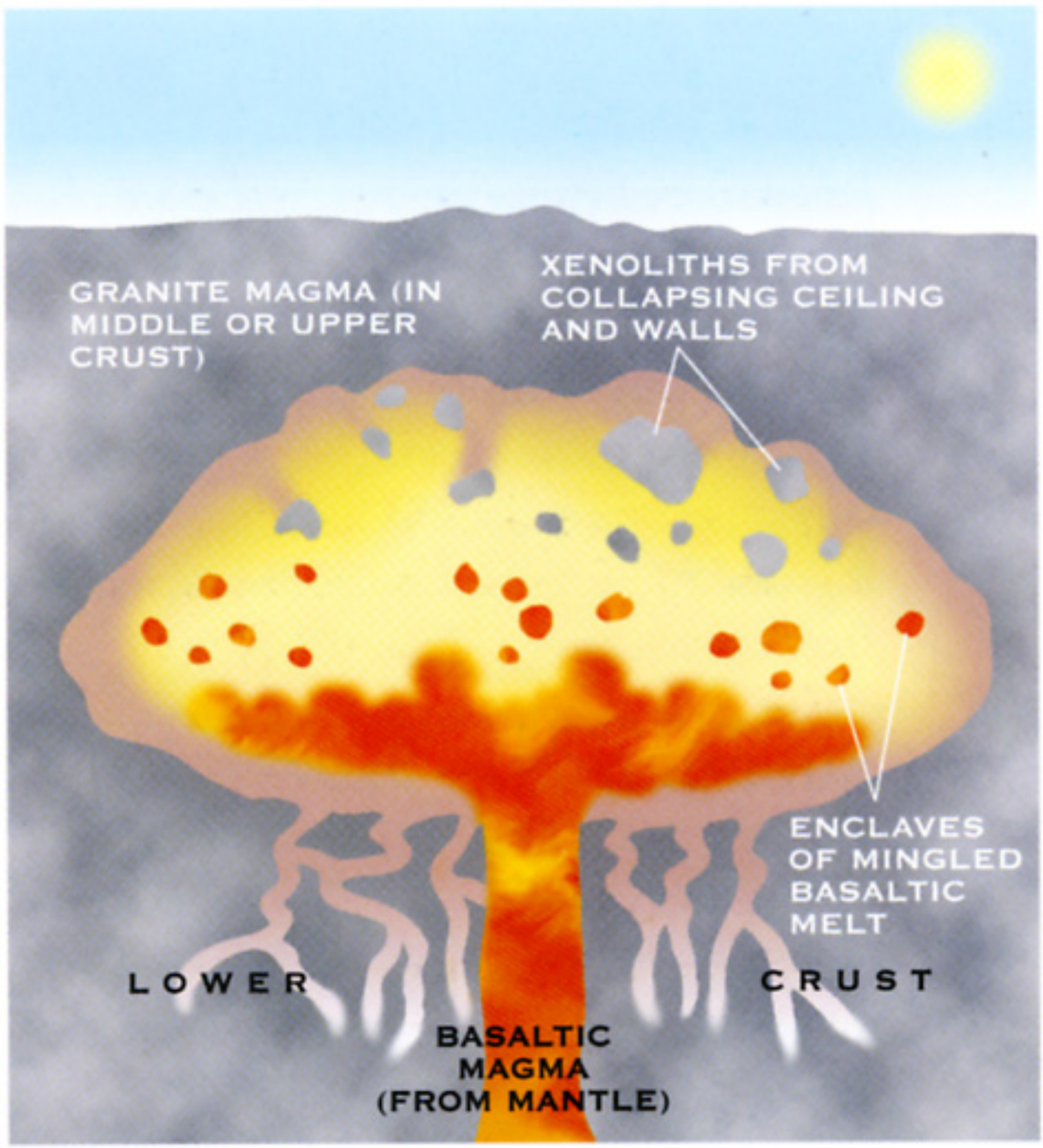
▲ **FIGURE 3.10** Illustration of how a magma evolves as the earliest-formed minerals (those richer in iron, magnesium, and calcium) crystallize and settle to the bottom of the magma chamber, leaving the remaining melt richer in sodium, potassium, and silica (SiO_2) **A**. Emplacement of a magma body and associated igneous activity generates rocks having a composition similar to that of the initial magma. **B**. After a period of time, crystallization and settling changes the composition of the melt, while generating rocks having a composition quite different than the original magma. **C**. Further magmatic differentiation results in another more highly evolved melt with its associated rock types.

Magmatic Differentiation

Other Properties Illustrated:

Enclaves are isolated blobs of basalt magma crystallized within granitic rock.

Inclusions are distinct fragments of foreign rock (xenoliths) enclosed within younger igneous rock.



Two origins for inclusions in granite.

Dikes are veins or tabular bodies produced when magma or mineral laden hydrothermal fluid is injected into fractures in rock.

A granodiorite, aka quartz monzonite, boulder with probable fine grained granitic **dike** of light colored mineral constituents, quartz and feldspar, called **Aplite**.
The dark inclusions may be either enclaves or xenoliths. Your guess is as good as mine.
The thin, sharp edged fragment on the front of the boulder is a great example of **spalling**, a type of exfoliation caused by weathering. Probably this will be pealed off by water freezing and expanding as ice in the space behind acting as a wedge.

The Margin of The San Jacinto Batholith as Seen From The Tram

The basement rock here is quite light in color as you would expect near the top of a magma chamber due to magmatic differentiation. Here the remaining magma is composed primarily of the light colored feldspar and quartz (felsic) minerals which only crystallize at cooler temperatures. The even lighter colored white dikes were injected into fractures later. The much darker dikes have higher concentrations of the magnesium and iron silicate (mafic) minerals which may have come from a later intrusion of magma from depth. From this vantage point it appears that all of the components are rather fine grained indicating relatively rapid cooling. There are also angular inclusions here and there which may be pieces of “country rock” which have fallen into the magma chamber. These are termed zenoliths, meaning foreign rock. To identify these various components accurately it would be necessary to examine them much more closely.

The Country Rock, aka Roof Pendants

These are the metasedimentary rocks derived from the passive margin sediments that were deposited over a couple of hundred million years during the Paleozoic Era. They are easily identified as the flat slabs lying against the lower eastern slopes of Mt. San Jacinto but are also exposed in many locals along the base of the mountain. Deeply buried and subjected to varying degrees of heat and pressure for great periods of time during the subduction of the Farallon Plate, these sediments were metamorphosed (changed) into metamorphic rocks, primarily as follows:

From limestone to marble and dolomite

From sandstone to quartzite

From claystone to phyllite, schist and some gneiss, uncommon slate

Mt. San Jacinto and Vicinity

Questions and Answers (always subject to revision- this is science, and especially geology):

<u>How old are these mountains?</u>

The answer has three parts.
(1) There is substantial evidence that the present regime of uplift began about 2 million years ago (mya) as a result of *transpressive* deformation within the San Andreas Fault Zone especially including the San Jacinto Fault. Geologically the topography is very young. Not so much of the rock of which it is composed.
(2) The granitic core, also referred to as the Nevadan *Orogeny* Batholith represents three major intrusions of *magma* that began at around 200 mya and ended about 75 mya.
(3) Most everything that was here before these magmas were intruded are referred to as "*country rock*", These include *metamorphic rocks*, mostly derived from passive margin *sedimentation* deposited over several hundred million years (Paleozoic Era) up to the early Triassic Period of the Mesozoic Era about 240 million years ago.

<u>Are these mountains still rising?</u>

Yes, the tectonic environment is responsible for uplift and is still at work. An estimate of 0.07 inch of net uplift per year certainly accounts for the mountain's lofty elevation of 10834 feet. This takes into account the constant and previously (wetter Pleistocene) greater rate of weathering and erosion. (do the math) Imagine the height without erosion. Impressive, what happens when given enough time! This is geology!

<u>Why are there so many mountains and valleys in Western North America?</u>

Pacific Ocean crustal plates and the North American plate, the latter on the move to the west, have been pushing and pulling at each other for the last 220 million years, or so, causing all kinds of tectonic mayhem. The boundary between moving plates is called an *active margin*, a zone of volcanism, earthquakes and mountain building.

<u>How old is the San Andreas Fault in the Coachella Valley?</u>

The fault, which is now the principal boundary between the Pacific Plate and the North American Plate, established its present position about 5 mya, but the *strike-slip fault* (*transform* fault) system began about 28 million years ago.

<u>If the San Andreas Fault is the Boundary between the Pacific Plate and the North American Plate why is it so far from the ocean?</u>

About 28 mya when the westward moving North American plate came in contact with the Pacific plate which is moving obliquely away to the northwest, they got stuck together. The Pacific Plate started ripping off pieces of the North American Plate. Over time, more continental crust was ripped off, moving the principal boundary further east. Those pieces, including Baja California, are now part of the Pacific Plate moving along side the continental margin toward the northwest.

<u>Is Western California going to fall into the ocean?</u>

The answer is above. It can't. It's already part of the Pacific Plate, heading for the Aleutian Trench where the Pacific Plate is plunging back into the earth's interior (*subduction*). It might take about 80 million years for us to get there!

<u>How fast is the Pacific Plate moving to the northwest along side the North American Plate?</u>

Overall, about 1.9 inches per year, shared by any number of sub-parallel faults of the San Andreas Fault zone, especially in Southern California. The Coachella Valley segment share is moving at about 1.4 inches per year.

<u>When was the last "major to great" earthquake on the Southern San Andreas Fault?</u>

About 1680. The average interval between big quakes on this <u>100 mile</u> stretch of the fault is about 133 years. No significant little ones in between. Hmmmm!

<u>Why is there desert east of the mountains?</u>

It's called a rain shadow. That's because the mountains cause most of the rain from Pacific storms to fall on the windward side, usually leaving little left for the lee side. Why? Rising air expands and cools lowering its capacity to hold water vapor. When the dew point is reached the water vapor precipitates out as rain or snow.
As the now colder, heavier and drier air flows down the leeward slopes it compresses, heats up and the relative humidity drops. The resulting prevailing conditions are low humidity, intense solar radiation, extreme temperatures, wind, and unreliable rainfall. The average precipitation across the up-slopes of the San Bernardino and San Jacinto Mts. ranges from 30 to 40 inches per year (and dropping). Palm Springs is about 5.5 inches (and dropping). At Indio, the average is just 3.2 inches per year (and dropping).

Where does all that water for the golf courses come from?

The porous sand and gravel sediments in the Coachella Valley are up to four miles deep. Water runoff from the surrounding mountains has been accumulating there for millenia. It's estimated that the upper Coachella Valley aquifers (ground water) contain around 39 million acre feet of water. A family of four will use about 1 acre foot per year. Then there is Colorado River water too, for agriculture, mostly, but also to recharge the aquifer. The Colorado River Aqueduct of the Metropolitan Water District crosses Whitewater Canyon just about 1 mile north of the I-10 Freeway. The Coachella Valley receives a share of Colorado River water that is released into the Whitewater River channel from where it travels a few miles downstream to percolation basins where it is collected to allow infiltration into the sediments, recharging the aquifers. The other Colorado River resource, mostly for agriculture, is from the Coachella Canal coming from the Imperial Dam to the south near Yuma. Some golf courses now use recycled water or Colorado River water and a new pipeline is under construction to deliver recycled water to more golf courses.

Does the Whitewater River flow year around?

It does (usually), within the Canyon, but the water quickly infiltrates the porous sand and gravel deposits along the channel. By late summer the diminishing volume is usually absorbed before reaching the percolation ponds downstream. Notwithstanding local agricultural and urban waste runoff, and runoff resulting from occasional torrential rain events over the mountains, little water makes it to the Salton Sea as it seeps into the sediments.
The 1200 square mile watershed of the Whitewater River is a vital resource in charging the valley aquifers. The very mountains that are responsible for the creation of the rain shadow desert are also the rainmakers that charge the groundwater in the desert valleys, a crucial source for springs, ponds, oases, wells and high water tables all of which help to support a diversity of plant and animal life, including us! What a system! However, in these days of much less precipitation, this runoff is woefully inadequate to keep pace with the withdrawal of water from the valley's aquifers.

Why are there so many trees growing across the canyon at Bonnie Bell?

The Banning strand of the San Andreas Fault crosses the canyon at this point creating a zone of pulverized rock called fault gouge which is impermeable to ground water percolating down-canyon. This fault dam supports the beautiful and lush riparian zone, a perfect locality to set up housekeeping, with plenty of water in the shade of the majestic cottonwood trees. Do you think?

Fault dam supported vegetation occurs in many, otherwise improbable, locations throughout the valley, such as the1000 Palms Oasis on the Mission Creek strand of the S. A. Fault along the north margin of the Indio Hills.

Where does all that sand and gravel come from?

Yes, that's a serious question, especially for young children. Weathering and erosion are the agents that shape the topography and eventually reduce mountains to plains of sediment. There are sediments all around the Whitewater area from loose sand and gravel to very well consolidated (*lithified)* sandstone and conglomerate. Sediments and sedimentary rock provide essential evidence in piecing together the geologic history of this area and, indeed, the planet! Sedimentology is the science concerned with the description, classification, origin and interpretation of sediment and sedimentary rock. What geologists know about the seismic history of earthquake faults is dependant on studying the sediments across faults. Understanding the past activity of a fault is the best predictor of future earthquakes in time and place, crucial to public safety, if not peace of mind, in California earthquake country.
The flood plain of the river is one the most important sources of sand for the sand dune habitat of the Valley, which, before development, covered about 100 square miles. Now, only about 5% remains.

Glossary of Geologic Terms

ALLUVIAL FAN: A fan-shaped deposit of sediment built by a stream where it emerges from an upland or a mountain range into a broad valley or plain. Alluvial fans are common in arid and semiarid climates but are not restricted to them.

AQUIFER: A permeable body of rock or sediment capable of containing ground water.

BAJADA: An alluvial plane formed as a result of the coalescing of adjacent alluvial fans forming a continuous inclined plane along a mountain front.

BASAL UNIT OR CONGLOMERATE: A well-sorted, lithologically homogeneous conglomerate that forms the bottom stratigraphic unit of a sedimentary series and that rests on a surface of erosion, thereby marking an unconformity; esp. a coarse-grained beach deposit of an encroaching or transgressive sea. It commonly occurs as a relatively thin, widespread or patchy sheet, interbedded with quartz sandstone. *AGI*

BASALT: An aphanitic (crystalline structure cannot be seen with unaided eye) volcanic rock composed principally of the dark iron/ magnesium silicates (mafic). This is the rocky crust (lithosphere) of the ocean basins, heavier than the continental crust, with a specific gravity of 2.7

BASEMENT COMPLEX: Undifferentiated rocks underlying oldest identifiable rocks in any region. Usually sialic, crystalline, metamorphosed. Often, but not necessarily, Precambrian. A series of rocks generally with complex structure beneath the dominantly sedimentary rocks. In many places, these are igneous and metamorphic rocks of either early or late Precambrian, but in some places these may be much younger, as Paleozoic, Mesozoic, or even Cenozoic. See also: complex Syn: fundamental complex

BATHOLITH: A body of igneous rock 40 miles square or more in area, emplaced at great or intermediate depth in the earth's crust. Larger than a pluton.

CATACLASTIC METAMORPHISM: Textural changes in rocks in which brittle minerals and rocks are broken and flattened as a result of intense folding or faulting; produces fragmentation of rocks as coarse-grained breccias and fine-grained mylonites.

CONCORDANT – DISCORDANT: Intrusive bodies are concordant when they form parallel to features such as sedimentary strata, discordant if they cut across existing structures.

COUNTRY ROCK: A general term for rock surrounding an igneous intrusion.

DIKE: A tabular intrusive rock that occurs across strata or other structural features of the surrounding rock. Cross cutting relationships are an important principle used in relative dating. An intrusive rock body is younger than the rock it intrudes. A fault is younger than the rock layer it cuts.

ENCLAVE: Typically, basaltic magma is hotter and more fluid than granitic magma and can form blobby masses as it invades molten granite. These blobs may circulate high up into the granitic melt, later to crystallize in place, forming rounded dark inclusions, called enclaves, within the granite.

EXFOLIATION: The breaking off of thin concentric shells, sheets, scales, plates and so on, from a rock mass, measuring from a centimeter to several meters in thickness. The loosened rock is spalled, peeled or stripped.

FAULT: A fracture in rock along which the adjacent rock surface are differentially displaced.

FELSIC: Igneous rock composed predominantly of the light colored minerals feldspars and quartz as in granite and it's extrusive (lava) equivalent, rhyolite.

FOLIATION: A planar feature in metamorphic rocks, produced by the secondary growth of minerals. Three major types are recognized: slaty cleavage, schistosity, and gneissic layering. The type of foliation characterizing gneiss, resulting from alternating layers of the constituent silicic and mafic minerals.

GNEISS: Metamorphic rock with gneissic cleavage. Commonly formed by metamorphism of granite. In a metamorphic rock, commonly gneiss, the coarse, textural lineation or banding of the constituent minerals into alternating silicic (light colored minerals) and mafic (dark minerals) layers. Formed under highest temperature and pressure of regional metamorphism deep in the earth's crust.

GRABEN: Elongated, trench like, structural form bounded by parallel normal faults created when the block that forms the trench floor moves downward relative to blocks that form the sides.

HORST: Elongated block bounded by parallel normal faults in such a way that it stands above blocks on both sides. An elongate, relatively uplifted crustal unit or block that is bounded by faults on its long sides. It is a structural form and may or may not be resultant of erosional processes. Etymol: German: no direct English equivalent. CF: graben

IGNEOUS: Said of a rock or mineral that solidified from molten or partly molten material, i.e., from a magma; also, applied to processes leading to, related to, or resulting from the formation of such rocks. Igneous rocks constitute one of the three main classes into which rocks are divided, the others being metamorphic and sedimentary. Etymol: Latin ignis, fire. See also: magmatic; plutonic; pyrogenic; hypabyssal; extrusive. *AGI* **Intrusive:** cooling slowly at depth. (Granitic) **Extrusive:** cooling quickly at the surface

(Lavas)

INCLUSION: A rock fragment incorporated into a younger igneous rock.

INDURATION: The hardening of rock material by the application of heat or pressure or by the introduction of cementing material. Indurated sediment is sedimentary rock.

INSELBERG: A steep ridge or hill left when a mountain has eroded and found in an otherwise flat, typically desert plain.

A prominent isolated residual knob, hill, or small mountain rising abruptly from an extensive erosion surface in a hot, dry region (as in the deserts of southern Africa or Arabia), generally bare and rocky, although partly buried by the debris derived from its slopes. Etymol: German Inselberg, island mountain.

MAFIC: Rock composed predominantly of the ferro (iron)/magnesian silicates which are generally dark, as basalt or its intrusive equivalent, gabbro.

METAMORPHISM: A process whereby rocks undergo physical or chemical changes or both to achieve equilibrium with conditions other than those under which they were originally formed (weathering arbitrarily excluded from meaning). Agents of metamorphism are heat, pressure, and chemically active fluids. (METAMORPHIC ROCKS)

MIGMATITE: Mixed rock produced by intimate interfingering of magma and invaded rock. A composite rock composed of igneous or igneous-appearing and/or metamorphic materials that are generally distinguishable megascopically i.e. naked eye. See also: composite gneiss *AGI*

MYLONITE: From rock flour and or minerals crystallized at metamorphism. Destroyed by deformation and particles streaked out. Forms with large scale thrust faults subjecting rocks near the thrust plane to shearing stress, drawing out in direction of movement. Assoc. with mountain formation. Fine-grained rock formed by grinding during intense folding or faulting associated with cataclastic metamorphism. *AGI*

NORMAL FAULT: (aka dip-slip fault) A fault usually of greater than 45 degrees dip from the surface, in which the top side (hanging wall) appears to have moved down relative to the other side (footwall). Due to extension or pulling apart. See Reverse Fault.

OROGENY: The tectonic processes by which mountain structures develop, typically involving thrusting, folding, faulting, metamorphism and the generation of large volumes of magma. Syn: orogenesis; mountain building; tectogenesis. Adj: orogenic; orogenetic. *AGI*

PLAYA: A depression in the center of a desert basin, the site of occasional temporary lakes.

PLUTON: A body of igneous rock formed beneath earth surface by consolidation from magma (molten rock beneath the surface). A body of medium to coarse-grained igneous rock that formed beneath the surface by crystallization of a magma. Often the basis of Orogenesis as with the Sierra Nevada.

REVERSE FAULT: The hanging wall moves up relative to the footwall due to compression or convergence, one side pushing against the other.

SCHIST: 1. Metamorphic rock dominated by fibrous or platy minerals. Has schistose cleavage and is product of regional metamorphism.
2. A strongly foliated crystalline rock, formed by dynamic metamorphism, that can be readily split into thin flakes or slabs due to the well developed parallelism of more than 50% of the minerals present, particularly those of lamellar or elongate prismatic habit, e.g., mica and hornblende. The mineral composition is not an essential factor in its definition unless specifically included in the rock name, e.g., quartz-muscovite schist. Varieties may also be based on general composition, e.g., calc-silicate schist, amphibole schist; or on texture, e.g., spotted schist. See also: magnesian schist; pelitic schist. CF: paraschist *AGI*

SEDIMENTARY: Rocks formed by the accumulation of sediment in water (aqueous deposits) or from air (aeolian deposits). The sediment may consist of rock fragments or particles of various sizes (conglomerate, sandstone, shale); of the remains or products of animals or plants (certain limestones and coal); of the product of chemical action or of evaporation (salt, gypsum, etc.); or of mixtures of these materials. Some sedimentary deposits (tuffs) are composed of fragments blown from volcanoes and deposited on land or in water. A characteristic feature of sedimentary deposits is a layered structure known as bedding or stratification. Each layer is a bed or stratum. Sedimentary beds as deposited lie flat or nearly flat. See: stratified rocks.

SIAL: A term coined from chemical symbols for silicon and aluminum. Designates composite of rocks dominated by granites, granodiorites, and their allies and derivatives, which underlie continental areas of globe. Specific gravity considered to be about 2.67

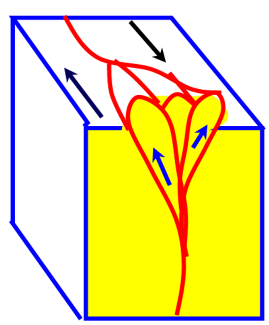
a. A layer of rocks, underlying all continents, that ranges from granitic at the top to gabbroic at the base. The thickness is variously placed at 30 to 35 km. *AGI*

b. A petrologic name for the upper layer of the Earth's crust, composed of rocks that are rich in silica and alumina; it may be the source of granitic magma. It is characteristic of the upper continental crust. Etymol: an acronym for silica + alumina. Adj: sialic. CF: sialma Syn: sal; granitic layer. *AGI*

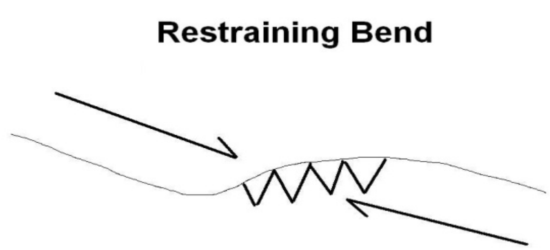
STRIKE-SLIP FAULT: A fault whose direction of movement is parallel to the strike of the fault. Horizontal displacement or offset as the San Andreas Fault. Also a *transform* fault.

SUPERPOSITION: Law by which, if a series of sedimentary rocks has not been overturned, topmost layer is always youngest and lowermost always oldest.

TRANSPRESSION: The simultaneous occurrence of strike-slip faulting and compression, or convergence, of the Earth's crust. In areas of transpression, rocks can be faulted upward to form a positive flower structure.

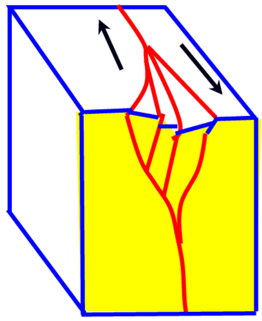


Uplift

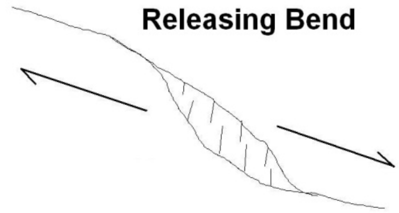


Right lateral strike-slip

TRANSTENSION: The simultaneous occurrence of strike-slip faulting and extension, rifting, or divergence of the Earth's crust. In areas of transtension, rocks can be faulted downward to form a negative flower structure.



Sag



Right Lateral Strike-slip

TUFA: Calcium carbonate, $CaCO_3$, formed in stalactites, stalagmites, and other deposits in limestone caves, as incrustations around mouths of hot and cold calcareous springs, or along streams carrying large amounts of calcium carbonate in solution.
Sometimes known as travertine or dripstone. Freshwater algae use carbon dioxide in photosynthesis precipitating the lime. This usually occurs in shallow water where algae can grow in abundance on resistant rock surfaces.

UNCONFORMITY: Buried erosion surface separating two rock masses, older exposed to erosion for long interval of time before deposition of younger. If older rocks were deformed and not horizontal at time of subsequent deposition, surface of separation is angular unconformity. If older rocks remained essentially horizontal during erosion, surface separating them from younger rocks is called a disconformity. Unconformity that develops between massive igneous or metamorphic rocks exposed to erosion and then covered by sedimentary rocks is called nonconformity.

XENOLITH: Rock fragment foreign to igneous rock in which it occurs. Commonly inclusion of country rock intruded by igneous rock.

Sources: Leet, L. Don. 1982. *Physical Geology, 6th Edition.* Englewood Cliffs, NJ: Prentice-Hall

Dictionary of Mining, Mineral, and Related Terms

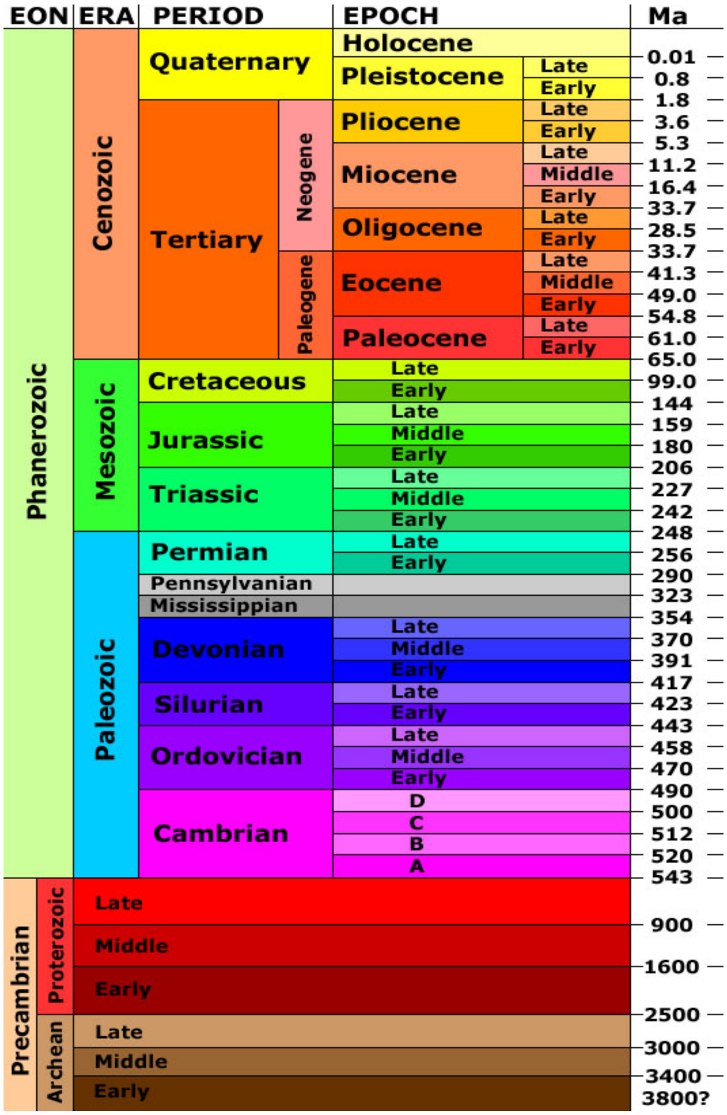
Dictionary of Geology and Mineralogy, Second Edition, McGraw-Hill

Geologic History of Southern California, Eastern Transverse Ranges

Geologic Age	Rock Units	Geologic Events in the Region
Archean 4000 to 2500 Ma	No rocks of this age are known in California.	The oldest rocks in North America are of Late Archean age and are found in the Canadian Shield region and locally elsewhere in the Rocky Mountain region.
Early to Middle Proterozoic 1879 to 1659 Ma	Plutonic rocks and various metamorphic gneisses, marble and quartzite in the Mojave Desert region.	Trans Rodinian Mountain Range derived from older sedimentary, igneous, and metamorphic rocks during a period of mountain building associated with continental collisions of tectonic plates.
Late Proterozoic 1000 to 542 Ma	Thick beds of sandstone, limestone, dolomite, and shale (and their metamorphic equivalents-quartzite, marble, and slate). Not in immediate vicinity of Whitewater Canyon	Uplift and erosion wore down ancient mountain ranges enough for shallow seas to transgress across the region. Passive-margin-style deposition continue along the California margin through the end of Proterozoic time into the following Cambrian Period of the Paleozoic Era creating a massive pile of sedimentary formations nearly 3000 meters thick. Supercontinent of Rodinia begins to break up around 800 Mya
Paleozoic Era 542 to 251 Ma	Consisting mostly of limestone and dolomite, preserve evidence of the evolution of marine life forms. The oldest sedimentary rocks of the Cambrian Period preserve an abundance of fossil algae (stromatolites) and locally contain an abundance of early invertebrate fauna, including trilobites.	The seas continued to advance and retreat across the region through the Late Paleozoic Era, resulting in the formation of more fossiliferous limestones of Pennsylvanian and Permian age. Farther to the west, deeper water conditions persisted. By the end of the Era Earth's landmasses have collided and merged into single supercontinent, Pangea. North America is located near the Equator.

Mesozoic Era Triassic, Jurassic and Cretaceous Periods 251 to 65 Ma	Volcanism and granitic magmatic intrusions with regional metamorphism of older sedimentary material and rocks.	The supercontinent of Pangea begins to break up with the opening of the Atlantic Ocean. In early Triassic time, an extensive volcanic-arc system began to develop along the western margin of the North American continent. In Southern California, this volcanic arc would develop throughout the Mesozoic Era to become the geologic regions known as the Sierra Nevada Batholith, the Southern California Batholith (in the Peninsular Ranges), and other plutonic and volcanic centers throughout the greater Mojave region. All pre-existing rocks in the San Bernardino Mountains area were subjected to regional metamorphism as they were injected and enveloped by a succession of granitic magmas (plutonic bodies) that intruded the region. Magma injection was most intense and pervasive during the late Cretaceous Period, between about 80 and 70 million years ago.
Cenozoic Era Tertiary Period Paleogene, sub Period i.e. Paleocene, Eocene and Oligocene 65 to 23 Ma	Vast sedimentary deposition	Volcanism ceased along the continental margin but moved much farther to the east. Much of the region that is now Southern California underwent extensive uplift and erosion, and over time the landscape wore down and probably became an extensive pediment (rolling lowlands with a few mountains) bordered on the west by a coastal plain, shallow embayments, and coastal uplands. Rivers and stream carried vast quantities of sediments and deposited them in offshore basins along the continental margin. Granites and gneisses begin to be exposed.
Neogene sub Period Miocene 23 to 5 Ma	Coachella Fanglomerate (stream sediments) Olivine Basalt unit Imperial Formation Deposition of Coachella Fanglomerate (Late Miocene?)	Subduction progressively gives way to transform faulting and the beginning of the San Andreas Fault system. Possible early incursion of Gulf of California into San Gorgonio Pass region due to extensional phase in late Miocene responsible for (Imperial Formation) fossiliferous marine sediments near the Pass and other locations in the Salton Trough.

Pliocene 5 to 2.58 Ma **Quaternary Period** **Pleistocene 2.58 to .011 Ma**	Cabazon Fanglomerate (late Pliocene) in San Gorgonio Pass.	About 5 Mya the San Andreas Fault stepped east to its current position as the main boundary between the North American Plate and the Pacific Plate. The Baja Peninsula began to separate from mainland Mexico and begin its gradual migration northward. The rift valley between the Mexican mainland and Baja California eventually flooded with marine-water conditions extending northward into the Salton Trough region. Uplift of the San Bernardino Mountains to their current elevation above the Mojave Desert floor and above lowlands to the south occurred in two stages: (1) block faulting and warping perhaps in the late Miocene (11 to about 5 m.y. before present) may have created an ancestral "proto" San Bernardino Mountains of unknown elevation; (2) uplift of the range in the Quaternary Period starting about 2 m.y. ago created the elevated and eroding landscape familiar to us today. This uplift history was accompanied by strike-slip faulting and related deformation within the San Andreas Fault zone along the south margin of the range. Interaction between tectonic agents responsible for uplift of the range and tectonic agents responsible for strike-slip tectonics in the vicinity of the San Bernardino Mountains remains a challenge to geologists.
Holocene 11Ka to present	Older surficial sediments; South from the San Jacinto Mts., Alluvial fanglomerate derived from rising San Bernardino Mts as small remnants in east and central Whitewater Canyon.	\Sea level continued to rise following the peak of continental glaciation during the last ice age (Wisconsin age, about 15,000 years ago) when sea level was as much as 350 to 400 feet (~120 meters) lower than present levels. Early human populations migrated into the California region starting about 10,000 years ago (possibly earlier). Many large mammalian species that lived in the region became extinct at the beginning of the Holocene Epoch. The California Gold Rush beginning in 1849 initiated one of the greatest human migrations in modern history.



References:

http://geomaps.wr.usgs.gov/socal/geology/geologic_history/

http://geomaps.wr.usgs.gov/socal/geology/transverse_ranges/san_bernardino_mtns/index.html

D.D. Trent and Richard Hazlitt, 2002, Joshua Tree National Park Geology, Joshua Tree National Park Association, ISBN 0-9679756-1-1

Kristin Mc Dougall, Richard Z. Poore, Jonathan Matti
Age and Paleoenvironment of the Imperial Formation near San Gorgonio Pass, Southern California,
Abstract, Journal of Foraminiferal Research, v. 29 no. 1, January 1999

Geologic Events in the Joshua Tree National Park Region

GEOLOGIC AGE			ROCK UNITS	GEOLOGIC EVENTS IN THE JOSHUA TREE REGION
CENOZOIC	QUATERNARY – HOLOCENE	0.01 MA	dune sands, playa lake sediments, alluvial fans	10,000 years ago to the present: faulting, uplift and earthquakes; weathering, mass wasting and erosion add sediment to desert valleys and canyons as present arid climate established.
CENOZOIC	QUATERNARY – PLEISTOCENE	1.6 MA	playa lake sediments, alluvial fans.	Minor volcanism and major faulting in nearby areas of the Mojave Desert. Ice Age climate swings back and forth from glacial to warm interglacial extremes. Alluvium floods valleys and canyons during interglacials; alluvial fans form; pediments and inselbergs emerge as soil cover erodes.
CENOZOIC	TERTIARY	66 MA	alluvial fans being deposited	10 Ma to present: rise of coastal ranges and the Sierra Nevada creates rain shadow across Mojave region. 10 – 25 Ma: warm, semiarid climate nurtures a savanna grassland in the Mojave region and promotes formation of thick soils on bedrock in the Joshua Tree region. 25 – 30 Ma: Subduction ends as San Andreas fault begins to form. 15 – 30 Ma: widespread volcanism throughout southern California, possibly including eruption of lava flows in Pinto and Hexie Mountains. 50 Ma: Erosion begins widely exposing granite and gneiss. Plutonism ends.
MESOZOIC	CRETACEOUS	144 MA	mafic and felsic dikes monzogranite of 49 Palms Oasis White Tank monzogranite Queen Mountain monzogranite	Continued subduction and plutonism along the entire western edge of the North American plate. (Cretaceous granites make up most of the cores of today's Sierra Nevada, San Bernardino and Little San Bernardino Mountains.) (Age of Queen Mountain pluton uncertain; it may be Jurassic)
MESOZOIC	JURASSIC	200 MA	Gold Park diorite	Continued subduction and plutonism.
MESOZOIC	TRIASSIC	251 MA	Twentynine Palms megacrystic quartz monzonite	About 250 Ma: subduction of the oceanic plate beneath the North American plate initiates plutonism in western North America. Nevadan Mountains begin forming.
PALEOZOIC		545 MA	(no record)	Probable marine sedimentation, but record removed by erosion.
PRECAMBRIAN	PROTEROZOIC		various gneisses, marble, quartzite	800 Ma: breakup of Rodinia. Joshua Tree region a young continental shelf probably receiving sediments derived from erosion of the Trans-Rodinian mountains. 1870 to 1650 Ma: Trans-Rodinian mountains form in the region accompanied by metamorphism and plutonism.

Geologic column of major geologic events and rock units in the Joshua Tree National Park region. MA = one million years.

Selected Reading

Bruce A. Bolt, 2004, *Earthquakes, Fifth Edition*, W.H. Freeman and Company, ISBN 0-7167-5618-8

Michael Collier, 1999, *A Land in Motion*, University of California Press ISBN 0-520-21897-3

Edward J. Tarbuck and Frederick K. Lutgens, 1985, *Earth Science, Fourth Edition,* Merrill Publishing,

Edward J. Tarbuck and Frederick K. Lutgens, 2006, *Earth Science, Eleventh Edition,* Pearson Prentice Hall, ISBN 0-13-149751-0

Paul Remeika and Lowell Lindsay, 1992, *Geology of Anza-Borrego: Edge of Creation,* Sunbelt Publications, ISBN 0-932653-17-0

D.D. Trent and Richard W. Hazlitt, 2002, *Joshua Tree National Park Geology,* Joshua Tree National Park Association, ISBN 0-9679756-1-1

John McPhee, 1993, *Assembling California,* Farrar, Straus and Giroux, ISBN 0-374-5293-2

John McPhee, 1999, *Basin and Range,* Farrar, Straus and Giroux,

Richard J. Proctor, 1968, *Geology of Desert Hot Springs-Upper Coachella Valley area, California, Special Report 94,* California Division of Mines and Geology,

Robert P. Sharp and Alan F. Glazner, 1993, *Geology Underfoot in Southern California,* Mountain Press Publishing Company, ISBN 0-87842-289-7

Robert P. Sharp and Alan F.Glazner, 1997, *Geology Underfoot in Death Valley and Owens Valley,* Mountain Press Publishing Co., ISBN 0-87842-362-1

Patrick L. Abbott, 1999, *The Rise and Fall of San Diego,* Sunbelt Publications, ISBN 0-932653-31-6

Dictionary of Geology and Minerology, Second Edition, 2003, McGraw-Hill

Companies, ISBN 0-07-141044-9

Chris Pellant, 2002, *Rocks and Minerals,* Smithsonian Handbooks, DK ISBN 0-7894-9106-0

Keith Heyer Meldahl, 2011, *Rough-hewn land*: *A geologic journey from California to the Rocky Mountains*, University of California Press, ISBN 978-0-520-25935-5

Web Sites

W. Jaquelyne Kious and Robert I. Tilling, 1996, *This Dynamic Earth,* on line edition, http://pubs.usgs.gov/publications/text/dynamic.html

Tom Simkin, John D. Unger, Robert I. Tilling, Peter R. Vogt, Henry Spall 1994, *This Dynamic Planet* http://geology.usgs.gov/pdf/planet.pdf

About Geology, Web Site http://geology.about.com/cs/maps_platetectonic

Southern California Earthquake Data Center, Web Site http://www.data.scec.org/

Geology of Joshua Tree National Park; A 3-D Photographic Tour including The Coachella Valley Preserve and the Mecca Hills, Web Site http://3dparks.wr.usgs.gov/joshuatree/index.html

Geology of The Colorado Desert http://seis.natsci.csulb.edu/deptweb/SkinnyCalSites/Colorado/colorad_osum.html

The San Bernardino Mountains http://wrgis.wr.usgs.gov/docs/wgmt/scamp/html/scg_trans_sbmt.html

…..and many more. Whatever the topic or question, just ask a search engine like Google or Yahoo. Be mindful of the source for reliable and current information.

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The San Diego Natural History Museum

The *Fossil Mysteries* exhibition explores the prehistoric record of the San Diego region from the Cretaceous Period to the Pleistocene Epoch. This geologic timeline extends from the Hadean Eon through the Holocene Epoch.

GEOLOGIC TIMELINE

Cenozoic Era (Recent Life). Two periods: Quaternary and Tertiary

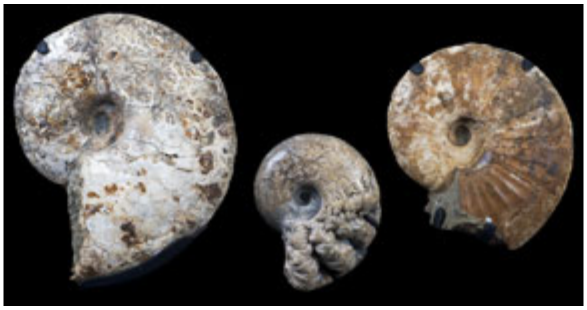
Quaternary Period: Holocene and Pleistocene Epochs

Time	Geologic Development	Life Forms
Holocene Epoch 10,000 years ago to the present	The Holocene Epoch may be an interval between glacial incursions, typical of the Pleistocene Epoch and therefore not a separate epoch in itself. However, it is a period marked by the presence and influence of *Homo sapiens*. During this time, the glaciers retreat, sea levels rise, the climate warms, and deserts form in some areas.	Human civilization develops. Activities of mankind begin to affect world climates. The extinction of other species continues.
Pleistocene Epoch 2.5 million -10,000 years ago	This epoch is best known as the "Great Ice Age." Ice sheets and other glaciers encroach and retreat during four or five primary glacial periods. At its peak, as much as 30% of the Earth's surface is covered by glaciers, and parts of the northern oceans are frozen. The movement of the glaciers alters the landscape. Lakes, such as the Great Lakes in North America, are formed as ice sheets melt, and retreat. Global warming begins after the last glacial maximum, 18,000 years ago.	The oldest species of *Homo*—*Homo habilis*—evolves. The flora and fauna in the regions not covered by ice are essentially the same as those of the earlier Pliocene Epoch. Mammalian evolution includes the development of large forms: woolly mammoth, woolly rhinoceros, musk ox, moose, reindeer, elephant, mastodon, bison, and ground sloth. In the Americas, large mammals, such as horses, camels, mammoths, mastodons, saber-toothed cats, and ground sloths, are entirely extinct by the end of this epoch.

Tertiary Period: Pliocene, Miocene, Oligocene, Eocene, and Paleocene Epochs

Time	Geologic Development	Life Forms
Pliocene Epoch 5-2.5 million years ago	The emergence of the Isthmus of Panama changes ocean circulation patterns and coincides with the formation of an Arctic ice cap. Plate tectonic interactions result in the uplift of the Sierra Nevada, formation of the Cascade Range, and onset of strike-slip faulting on the San Andreas Fault. In Europe, the Alps continue to rise. The global climates become cooler and drier.	Camels and horses are abundant throughout North America. Ground sloths also evolve and the Great American interchange between South and North America begins. Primates continue to evolve, and the australopithecines—antecedents to *Homo sapiens*—develop late in the Pliocene in Africa. In North America, rhinoceroses and ordeodonts become extinct.

Miocene Epoch 24-5 million years ago	Modern ocean currents are essentially established. A drop in sea level near the end of the Epoch isolates and dries up the Mediterranean Sea, leaving evaporite deposits on its floor. The climate is generally cooler than the Oligocene Epoch. A cold transantarctic ocean current isolates the waters around Antarctica, and the continent becomes permanently frozen.	Mammal forms are essentially modern, and almost half of modern placental mammal families are present. The ancestor of mastodons disperse into North America. Almost all the modern groups of whales are present, as well as the early seals and walruses. Many modern birds—herons, rails, ducks, eagles, hawks, crows, sparrows—are present in Europe and Asia. Higher primates undergo substantial evolution; advanced primates, including apes, are present in southern Europe and Asia. *Carcharocles megalodon*, the largest predaceous shark ever to have lived, inhabits the seas. The coasts are submerged and kelp forests develop. On land, grasslands replace forests over large areas on several continents.
Oligocene Epoch 34-24 million years ago	Tectonic plate movement is still very dynamic. Africa and Europe nearly collide, closing the Tethys Sea and leaving as a remnant the Mediterranean Sea. Volcanism and fragmentation of western North America is associated with the emplacement of major ore deposits. The southern ocean forms and the climate is generally temperate. Glaciation begins in Antarctica.	Representatives of modern mammals become the dominant vertebrate life form, including horses, pigs, true carnivores, rhinoceroses, elephants, and camels. Oreodonts diversify in North America. Early primates appear in North America, and early apes appear in Egypt. Many archaic mammals become extinct. The earliest representatives of modern cetaceans (baleen and "toothed" whales) evolve. Grasslands expand, and forest regions diminish.
Eocene Epoch 55-34 million years ago	Plate tectonics and volcanic activity form the Rockies in western North America. Erosion fills basins. Continental collisions between India and Asia culminate in the Alpine-Himalayan mountain system. Antarctica and Australia continue to separate and drift apart. The climate is subtropical and moist throughout North America and Europe.	Early forms of horse, rhinoceros, camel, and other modern groups such as bats evolve in Europe and North America. Creodonts and ruminant ungulates evolve. Archaic whales (archeocetes) evolve from terrestrial meat-eating ungulates. Sirenians (dugongs and manatees) first evolve in the shallow Tethys Sea.
Paleocene Epoch 65-55 million years ago	During the Paleocene, the vast inland seas of the Cretaceous Period dry up, exposing large land areas in North America and Eurasia. Australia begins to separate from Antarctica, and Greenland splits from North America. A remnant Tethys Sea persists in the equatorial region.	Mammalian life diversifies, spreading into all major environments. Placental mammals eventually dominate the land, and many differentiated forms evolve, including early ungulates (hoofed animals), primates, rodents, and carnivores.

Mesozoic Era (Middle Life). Three periods: Cretaceous, Jurassic, and Triassic.		
Time	**Geologic Development**	**Life Forms**
Cretaceous Period 144-65 million years ago	The continents—while not in their current positions on the Earth—are shaped much as they are today. South America and Africa separate, and the Atlantic ocean widens. A circum-equatorial sea, Tethys, forms between the continents of the Northern and Southern Hemisphere. The westward movement of North America forms the ancestral Rocky Mountains and the ancestral Sierra Nevada. Sea levels rise, submerging about 30% of the Earth's present land surface. The global climate is generally warm. The poles are free of ice.	Dinosaurs and other large reptiles peak as the dominant vertebrate life form on Earth. Dinosaurs extend their range throughout every continent. Horned dinosaurs are common, while armored ankylosaurs and spiky nodosaurs are rare. In the shallow seas, invertebrates live in great diversity. **Ammonites** are a dominant group. Gastropods, corals, sea urchins flourish. The early flowering plants (angiosperms), modern trees, and many modern types of insects evolve. Near the end of the Cretaceous Period, several mass extinctions occur, including the extinction of five major reptilian groups: dinosaurs, pterosaurs, ichthyosaurs, pleisosaurs, and mosasaurs. Extinctions also occur among ammonites, corals, and other marine invertebrates. 
Jurassic Period 206-144 million years ago	The supercontinent of Pangea begins to breakup as North America separates from Eurasia and Africa. The Atlantic Ocean begins to form. Tectonic plate subduction along western North America causes the Earth's crust to fold and mountains form in the western part of the continent.	Reptiles adapt to life in the sea, in the air, and on land. Dinosaurs are the dominant reptile on land. *Archaeopteryx*, the first bird, evolves. Early amphibians, extinct by the late Triassic, are succeeded by the first frogs, toads, and salamanders. Mammals are small, shrew-like animals. Plant forms are dominated by the cycads and cycadeoides. Conifers and gingkoes are widespread.
Triassic Period 248-206 million years ago	Pangaea covers nearly a quarter of the Earth's surface. The Triassic Period, unlike the previous periods, is marked by few significant geologic events. Toward the end of the Triassic Period, continental rifting begins to break apart the supercontinent. The general climate is warm, becoming semiarid to arid.	Life began to diversify after the end-Permian extinction. Early dinosaurs evolve. Many are bipedal, fast, and relatively small. The largest Triassic dinosaurs are only 20 feet (6 meters) in length—small when compared to later Mesozoic forms. Marine reptiles evolve, such as ichthyosaurs and plesiosaurs. Ferns, cycads, ginkgoes, and conifers flourish. Mass extinctions occur at the end of the Triassic Period, reducing some marine and terrestrial groups, such as the ammonites, therapsids, early reptiles, and primitive amphibians, by as much as 75 percent.

Paleozoic Era (Ancient Life). Six periods: Permian, Carboniferous, Devonian, Silurian, Ordovician, Cambrian		
Time	**Geologic Development**	**Life Forms**
Permian Period 290-248 million years ago	A single supercontinent, Pangaea, forms as Earth's landmasses collide and merge. Pangaea extends across all climatic zones and nearly from one pole to the other. This supercontinent is surrounded by an immense world ocean. Extensive glaciation persists in what is now India, Australia, and Antarctica. Hot, dry conditions prevail elsewhere on Pangaea, and deserts become widespread.	Invertebrate marine life is rich and diverse at the beginning of the Permian period. Toward the end of this period, mass extinctions occur among large groups of corals, bryozoans, arthropods, and other invertebrates. 99% of all life perishes. On land, insects evolve into their modern forms; dragonflies and beetles appear. Amphibians decline in number, but reptiles undergo a spectacular evolutionary development of carnivorous and herbivorous, terrestrial and aquatic forms. Ferns and conifers persist in the cooler air.
Carboniferous Period 354-290 million years ago	Two major land masses form: Laurasia (North America, Greenland, Eurasia, and Scandinavia) to the north of the equator, and Gondwana (South America, Africa, peninsular India, Australia, and Antarctica) to the south. Collisions between Laurasia and Gondwana form major mountain ranges. Coal-forming sediments are laid down in vast swamps. Global climatic changes occur, changing from warm and wet to cooler and drier. The result is a long interval of glaciation in the southern hemisphere.	The diversification of fish from the Devonian Period continues in both marine and freshwater environments, though armored fish become extinct. Benthic (bottom-dwelling) marine communities include a variety of invertebrates: crinoids, blastoids, and brachiopods. The **ammonites** are common in open marine waters. Insects, such as cockroaches, flourish. The first reptiles evolve. Land environments are dominated by plants, from small, shrubby growths to tall trees. Early club mosses, horsetails, forest trees (Cordaites), and ferns are common.
Devonian Period 417-354 million years ago	Europe and North America collide, forming the northern part of the ancestral Appalachian mountain range. Europe and North America straddle the equator. Africa and South America are positioned over the South Pole. The climate is generally warm and moist.	This period is dominated by various forms of fish—armored fish, lungfish, and sharks. **Ammonites** evolve from nautiloids and become one of the dominant invertebrate forms. As the ozone layer forms, the first air-breathing arthropods—spiders and mites—evolve on land. Amphibians evolve and venture onto land. Plant life, including lowland forests of giant psilophyta plants, develop and spread over the planet.
Silurian Period 443-417 million years ago	The North American, European, and Asian land masses are situated on or near the equator. Laurentia and Baltica collide. Gondwana sits in the south polar region. Shallow flooding of continental areas deposits sediments; later withdrawal of ocean water leaves oxidized "red beds" and extensive salt deposits.	Life in seas is still dominated by invertebrates: corals, arthropods, and crinoids. Rapid evolution occurs among suspension feeders, and pelagic (open ocean) predators, such as nautiloids, become abundant. Fish evolve jaws. Late in the Silurian Period, the first sharks appear. The earliest land plants are represented by leafless, vascular plants called psilophytes.

Ordovician Period 490-443 million years ago	The barren continents of Laurentia, Baltica, Siberia, and Gondwana are separated by large oceans. Shallow seas cover much of North America at the beginning of the period. As the seas recede, they leave a thick layer of limestone. Later in the period, the seas recover North America, depositing quartz, sandstones, and more limestone.	Metazoan invertebrates are still the dominant form of life on Earth. Corals, crinoids, and clams evolve, as well as the first early vertebrates—primitive fish with bony armor plates. Late in the Ordovician Period, mass extinctions of marine life occur, opening niches for benthic (bottom-dwelling) and planktonic (floating, swimming) organisms.
Cambrian Period 540-490 million years ago	Sedimentary rocks (sandstone, shale, limestone, conglomerate) form in shallow seas over the continents. Rodinia begins to break up into northern and southern portions. Gondwana in the south incorporates South America, Africa, Antarctica, and Western Australia as well as peninsular India and parts of Arabia. The global climate is generally mild.	Marine metazoans with mineralized skeletons, such as sponges, bryozoans, corals, brachiopods, molluscs, arthropods, and echinoderms, flourish. One group of arthropods, the trilobites, are particularly dominant in the shallow-water marine habitats. Plant life is limited to marine algae.

Precambrian Time. Three Eons: Proterozoic, Archean, and Hadean.		
Time	**Geologic Development**	**Life Forms**
Proterozoic Eon 2.5 billion years ago-540 million years ago	The supercontinent Rodinia forms approximately 1.1 billion years ago. Plate tectonics slows to approximately the same rate as the present. Large mountain chains form as the continents collide. Quartz-rich sandstones, shales, and limestones are deposited over the continents. Oxygen levels increase as life on Earth develops the ability to obtain energy through photosynthesis. The late Proterozoic is an "Ice House" world.	Eukaryotes (single-celled organisms with a nucleus) evolve. These are more advanced forms of algae and a wide variety of protozoa. Eukaryotes can reproduce sexually, which makes genetic diversity possible, as well as the ability to adapt to and survive environmental changes. Multi-celled, soft-bodied marine organisms (metazoans) evolve.
Archean Eon 3.9-2.5 billion years ago	The Earth's permanent crust is formed. Vast amounts of metallic minerals are deposited. The oceans and atmosphere result from volcanic outgassing.	The earliest life forms evolve in the seas. They are the prokaryotes—single-celled organisms with no nucleus—cyanobacteria (blue-green algae). The earliest bacteria obtain energy through chemosynthesis (ingestion of organic molecules).
Hadean Eon (Azoic) 4.5-3.9 billion years ago	The Earth forms as a solid planet.	No evidence of life yet known.

Courtesy of the San Diego Natural History Museum