Rocks and Geology in the San Francisco Bay Region

Igneous Rocks
Volcanic Tuff
Pinnacles National Monument, Monterey County

Sediments
Gravel Bar
Coyote Creek, Santa Clara County

Metamorphic Rocks
Migmatite
Arroyo Seco Canyon, Monterey Canyon

Sedimentary Rocks
Conglomerate Rock with Calcite Vein
Sea Cliff at Gazos Creek, San Mateo County

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By Philip Stoffer

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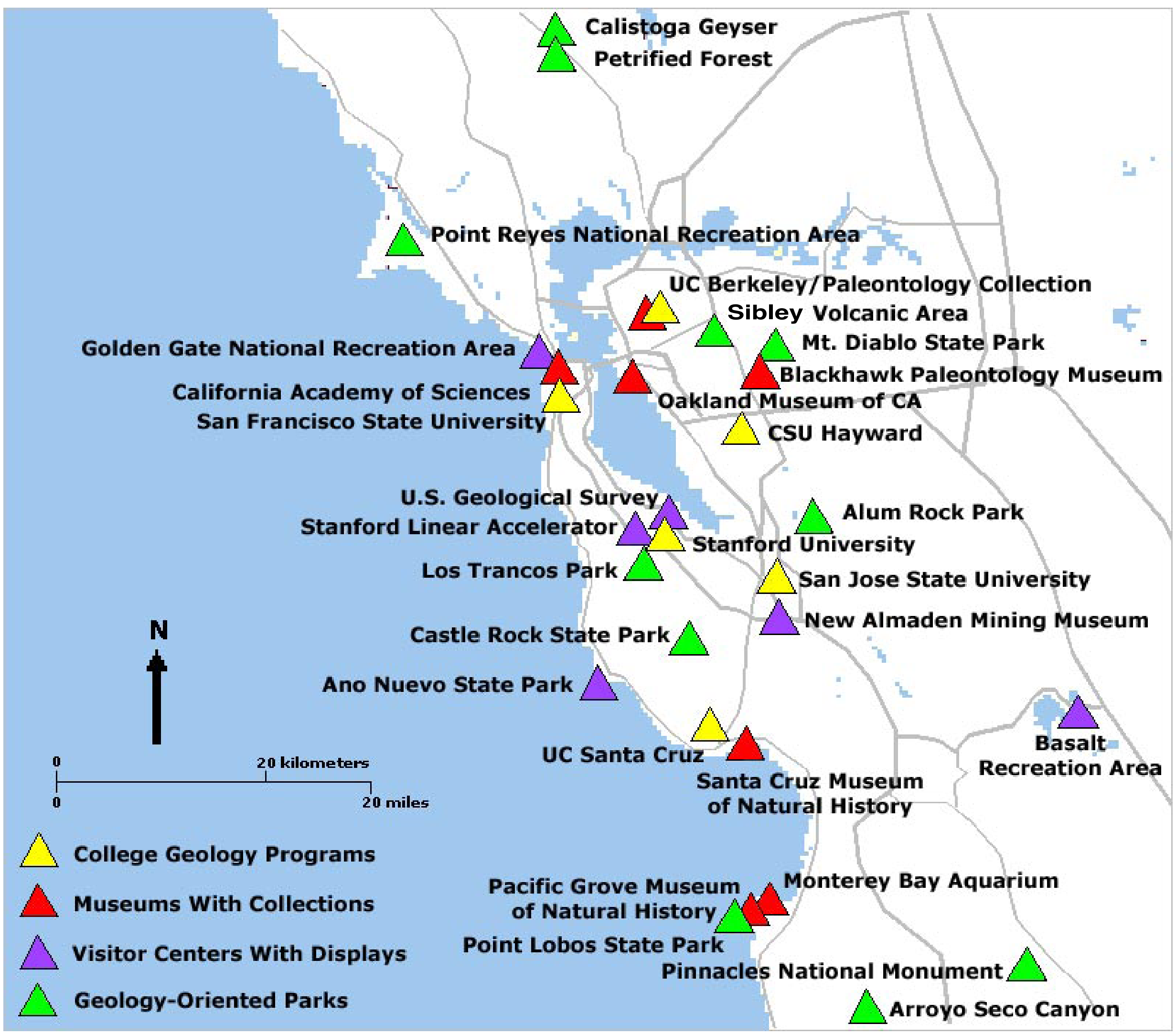
Introduction

The landscape of the San Francisco Bay region is host to a greater variety of rocks than most other regions of the United States. The reason for this diversity in rock types is related to the region's geologic setting along the western margin of the North American continent. Continental margins experience relatively intense geological activity compared to most places over time.

This guide to rocks in the San Francisco Bay region is intentionally generalized to serve some of the needs of novice rock enthusiasts, teachers, students (of all ages), and geologists and other scientists. This comes at a price, however, because the natural world is vastly more diverse and complex than even the most eloquent scientist could possibly explain concisely. Whereas this guide provides descriptions of about four-dozen common rock types, observations of the variety of natural materials on practically any gravel bar in the region will demonstrate how difficult it is to assign samples to any rock classification scheme. Along with common rock descriptions, selected discussions are added to provide information about how geologists interpret the origin and significance of rocks. It is this additional information that transforms an ordinary rock sample into a knowledge portal into Earth's history, the evolution of the modern landscape, and the ongoing natural processes occurring both undersea and underground.

The discussions that follow often introduce "the cart before the horse." This is because it is nearly impossible to present the most simplified scientific information without introducing appropriate terminology. This has been intentionally avoided. Figure numbers are also left out, so that discussion on most individual pages stand-alone. This guide isn't intended to serve as a textbook, but rather as a reference source to supplement other information resources. If you need more information check out some of these San Francisco Bay region parks, museums, college geology departments, and visitor facilities for more geologic information. Searching on the World Wide Web will also lead to amazing resources. Many of the rocks illustrated in this guide are on display in the U.S. Geological Survey Library at 345 Middlefield Road in Menlo Park. However, the best ones lie where they occur in the field and hopefully you will go there to observe them!



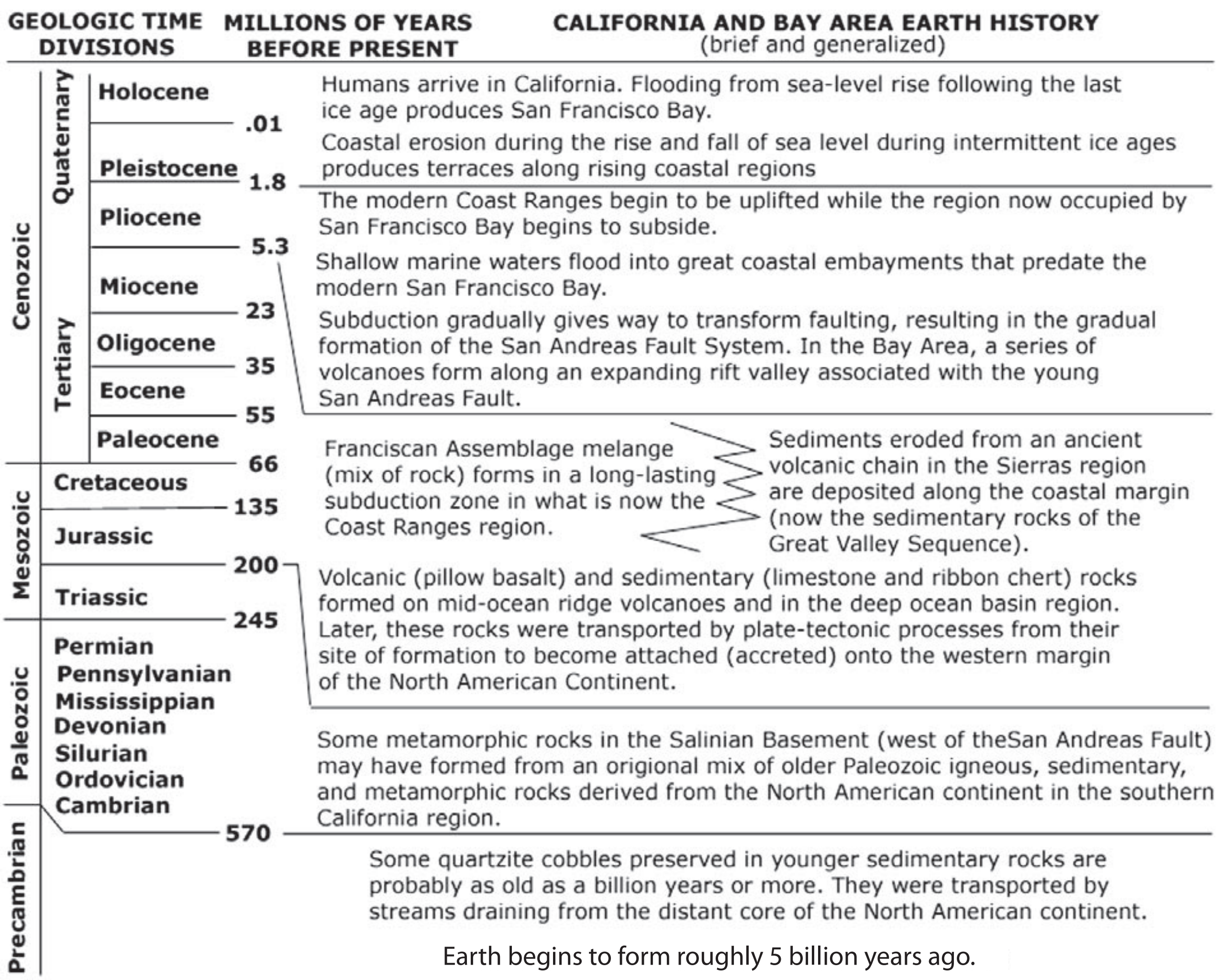
Map showing locations of geology-oriented parks, visitor centers, museums, and college programs in the San Francisco Bay region.

Geologic Time

Perhaps the most fundamental concept in the study of the Earth and the universe is the concept of geologic time. As our understanding of the great antiquity of the Earth developed, names were assigned to segments of time defined in units ranging from thousands of years (in the relatively recent geologic past to historic times), to many millions or billions of years (in the distant geologic past). Geologists use the geologic time scale to define the ages of rocks and the fossils they may contain, and to define when geologic events occurred.

Geologic time is divided into four great eras. The Precambrian Era encompasses all time from the beginning of the known universe, the formation of the galaxy, the solar system, the accumulation of materials that became the Earth, and the organization of the early Earth into differentiated parts including early continents, oceans, and atmosphere. The oldest known rocks on the Earth are roughly 4 billion years old, and some of the earliest sedimentary rocks display evidence that organic life was forming and evolving already in this early period. The Paleozoic Era began roughly 570 million years ago. Paleozoic means "ancient life." It was during this period that multicellular organisms flourished and diversified, particularly invertebrates in the shallow oceans, then fish, land plants, amphibians, and reptiles. The Mesozoic Era (meaning "middle life") began roughly 245 million years ago and its start is defined by a mass extinction when nearly all life forms of the Paleozoic vanished, possibly from a variety of natural environmental calamities occurring simultaneously. During the Mesozoic dinosaurs flourished, and early mammals and flowering plants appeared. The Mesozoic ended in catastrophe, in part caused by at least one major asteroid impact. The Cenozoic encompasses from 65 million years ago to the present, and is highlighted by the evolution and diversification of mammals, birds, and modern plants (particularly flowering plants and grasses). It is near the end of this era that primate evolution yielded modern humans.

Eras are subdivided into periods (such as the Tertiary and Quaternary periods of the Cenozoic Era). Periods are in turn subdivided into epochs (such as the Pleistocene and Holocene epochs of the Quaternary Period). Time is parsed even further where geologic events and detail are more clearly resolved.



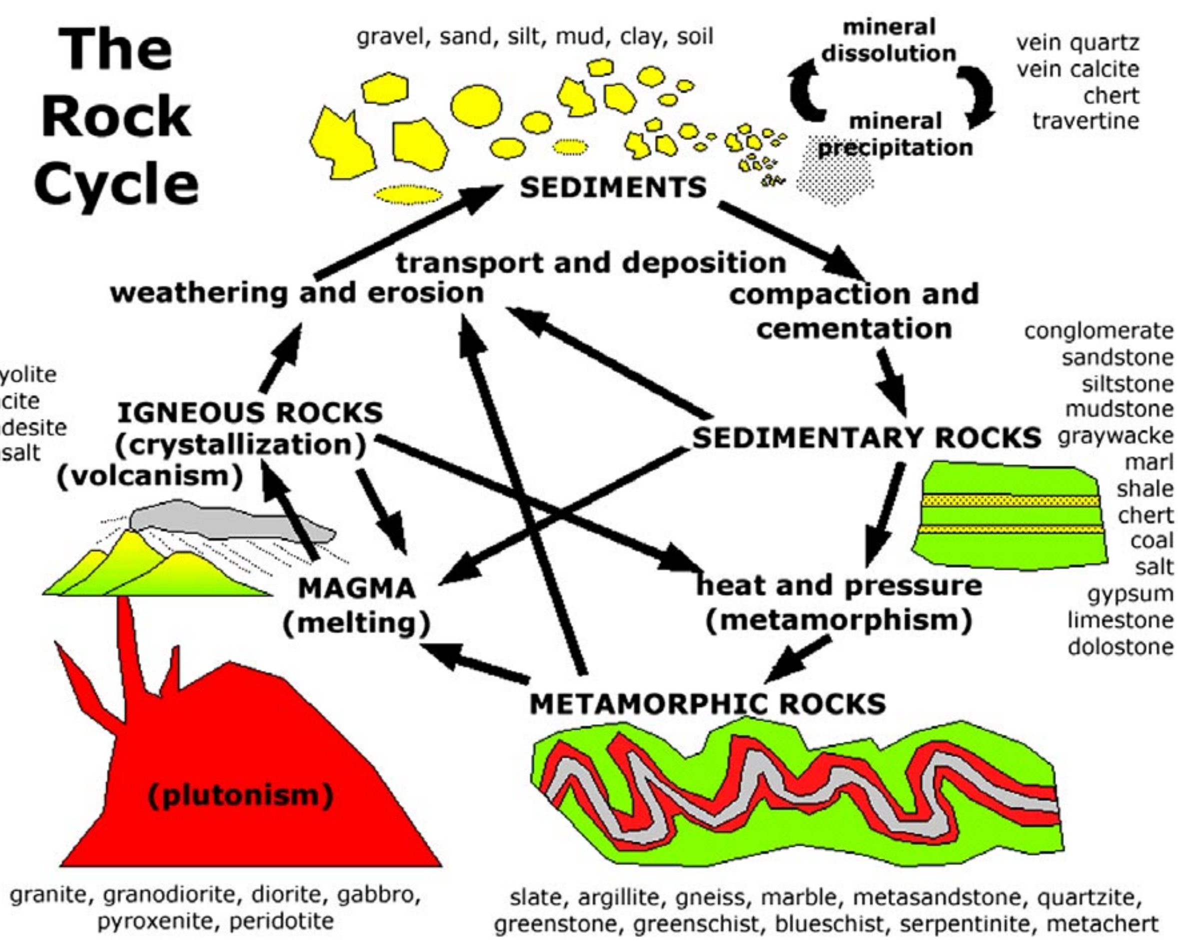
Generalized geologic time scale for the San Francisco Bay region.

The Rock Cycle

Geology is also the story of processes and products formed on or below the Earth's surface. To simply identify the name of a rock is a relatively elementary task (don't let them kid you... even the most experienced petrologist can have a hard time without sophisticated tools). However, developing an understanding of a rock's occurrence, origin, and geologic significance and value (both economic and intellectual) is the greater mission within the science of geology.

The figure below illustrates the "rock cycle," a model that portrays the origin of the three basic rock groups (igneous, sedimentary, and metamorphic) and the interrelated nature of Earth materials and processes that transform one rock type into another over time. Arrows on the diagram below show the different paths that Earth materials may follow in the courses of formation and transformation. Igneous rocks form from the cooling of molten material. Sedimentary rocks form from sediments eroded and deposited in sedimentary environments, either on land or most often under water in an oceanic setting. Metamorphic rocks form from the chemical and physical alteration of preexisting rocks, usually deep within the crust of the Earth. The occurrence of different rock types on the surface of the Earth demonstrates that the world is a dynamic place, with materials forming, migrating, reforming, changing, and reforming again and again over great periods of time.

The rock cycle highlights this crucial link between geologic time, geologic processes, and the Earth materials produced. The diagram below also includes the common names of rocks. Names applied to rocks not only imply both textural and compositional characteristics but also are directly linked to their mode of origin. Discussion of each of the rock groups and rock types are presented later in this text. It is also important to note that rocks consist of chemical substances called minerals. Minerals are naturally occurring, inorganic elements or compounds that have an identifiable chemical composition, and typically have an orderly internal crystalline structure. Minerals occur as fragments or grains that make up rocks. Rocks are aggregates of minerals (usually more than one type of mineral). In most cases, it is difficult to identify the mineral content of rocks without the use of a hand lens. Identifying rocks also requires knowledge of rock texture characteristics, and an "open eye" approach to where the rock occurs relative to features on the landscape. For instance, if there are volcanoes around you, there is a very good chance that you are standing on a volcanic rock. However, things aren't always that easy, especially in the San Francisco Bay region where so much has happened, is happening, and will likely continue to happen geologically.



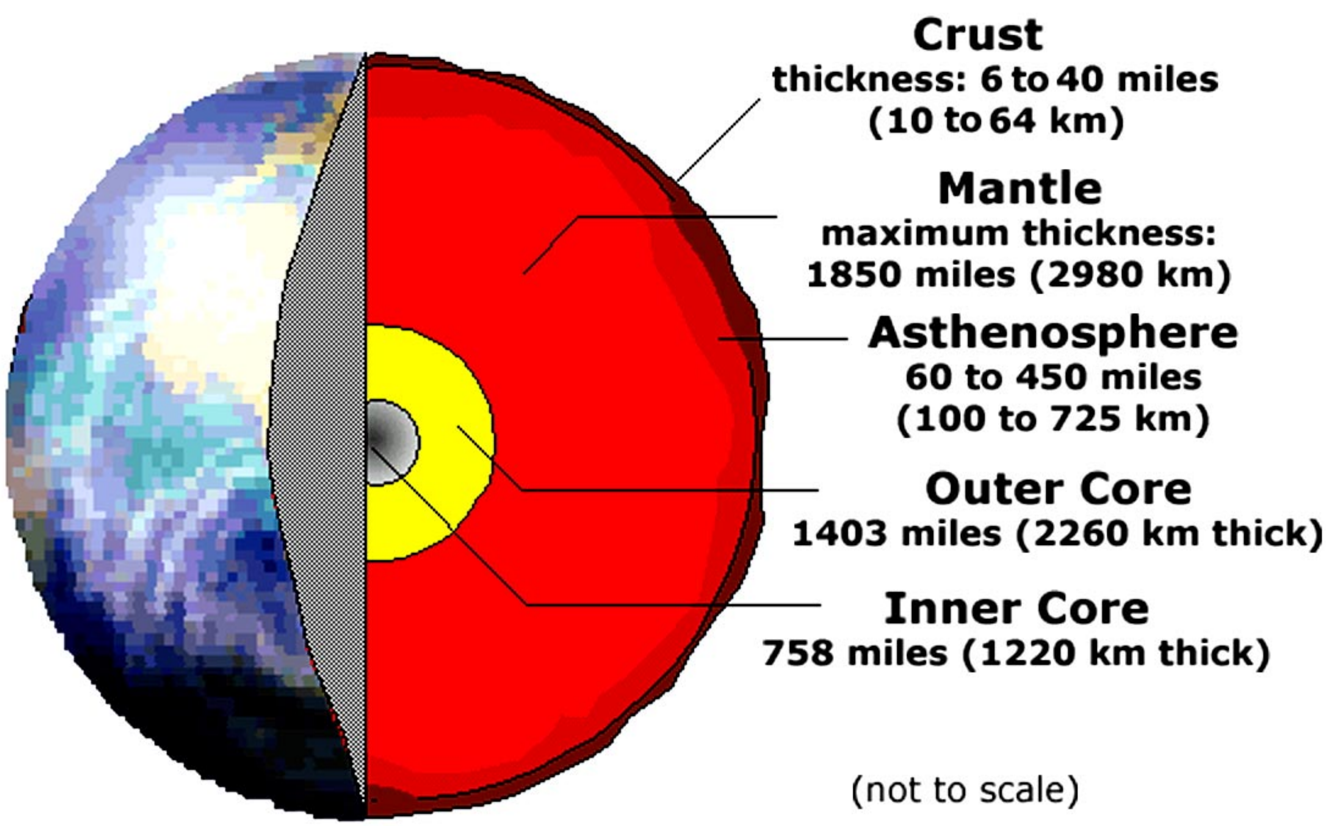
The rock cycle illustrated.

Plate Tectonics

The rock cycle is fundamental to the greater, all-encompassing theory of plate tectonics. This body of knowledge explains the character, origin, and occurrence of the diverse rock types exposed around the world, and especially throughout the San Francisco Bay region. Before the theory of plate tectonics, geologists had little idea about how the geology of the region was created. The theory has evolved over time and has involved the careers of perhaps thousands of geologists supported by hundreds of research organizations around the world. Perhaps most crucial to investigation and discovery has been the ongoing exploration of the sea floor beneath the ocean basins. The combination of technological advances in geochemistry, geophysics, paleontology, and other geologic disciplines have aided in measures to support and revise the theory over time.

The internal structure of the Earth has been revealed by the study of seismic shock waves generated by earthquakes and subterranean nuclear blasts. The ball of the Earth consists of several distinct layers. The central inner core is 758 miles (1221 km) thick and probably has a metallic composition similar to nickel/iron meteorites. The outer core is a molten metallic layer about 1403 miles (2259 km) thick. Above the core is the mantle, a layer having two zones—the lower mantle (average thickness of 1348 miles [2171 km]) and the upper mantle, called the asthenosphere (average thickness of 447 miles [720 km]). The crust is the relatively light outer solid skin that ranges in thickness between 6 and 40 miles (10 and 64 km).

The uppermost hundred kilometers of the mantle and the crust are called the lithosphere. In general, the lithosphere is both solid and rigid in character, and it is within this zone that all earthquakes occur. Beneath the lithosphere, the asthenosphere is so hot that it is near the point of melting. In this interval the rock behaves in a ductile manner, flowing under the extreme pressure rather than breaking. This zone is also the source of magma that may eventually migrate to the Earth's surface. Rocks in this zone are easily deformed, flowing slowly as a result of temperature-controlled density currents. The mechanism for this flux is straightforward: rock heated from the core and mantle below expands and rises. Near the Earth's surface, heat conducted slowly toward the atmosphere is ultimately radiated into space. This heat loss causes the rocks to cool, condense, and sink. The thermal exchange process has been occurring throughout Earth's history, causing material to rise, cool, sink, and heat up again.



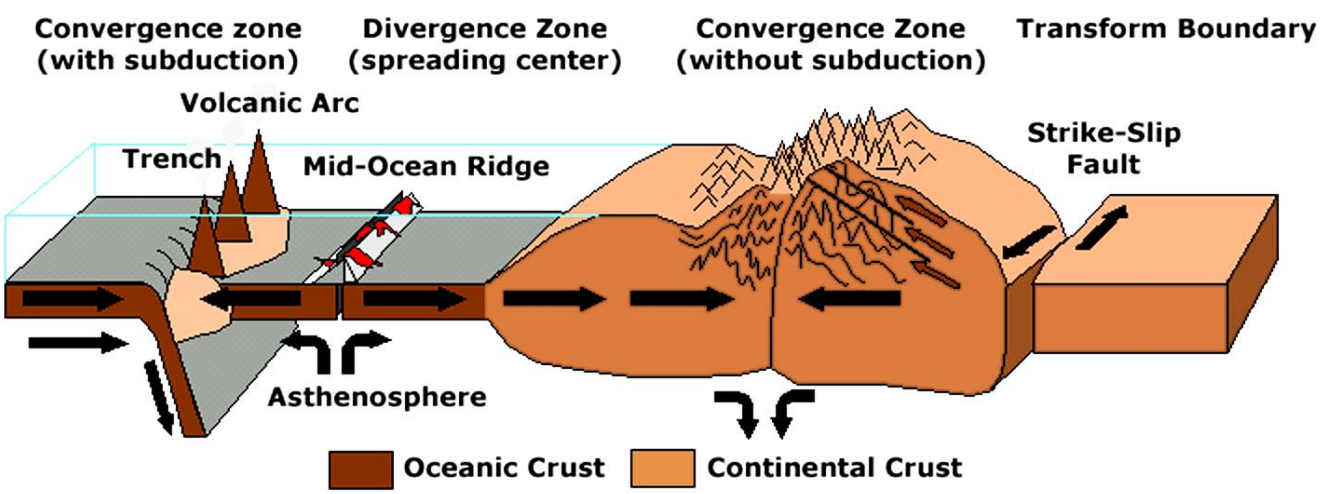
Structure of the Earth showing the core, mantle, and crust.

Due to the great pressure in the mantle, rock cannot melt but they can flow plastically. Rocks can only melt if temperatures are high and pressure is low enough (as in the asthenosphere and also within the crust if conditions are right). As a result the crust "floats" on the "fluid" mantle in a similar manner to the way icebergs float on the sea. Generally, where the crust is thin or of dense composition, ocean basins occur. Where the crust is thick or less dense in composition, continents occur and may rise above sea level. The rising and sinking of material within the mantle drags or pushes the crust of the Earth in the form of great plates. Where mantle material rises by convection the crust is pulled apart. Places where this occurs on the Earth's surface are called divergence zones. It is along these spreading centers where new ocean crust forms. Igneous rocks produced in these zones have a mafic chemical composition (rock rich in iron and magnesium). Spreading centers define divergent boundaries of crustal plates. The Mid-Atlantic Ridge is an extensive undersea mountain range that runs down the center of the Atlantic Ocean and is an example of a divergence zone.

The new crust formed along a divergence zone is generally both thin and relatively hot. Magma derived from the mantle is extremely hot, typically greater than 1100ºC (2000ºF). Through time, the new crust is carried or pushed away from its place of origin. As the new crust cools it becomes denser. This new basaltic crust generally makes up the rocks underlying the world's ocean basins. Sediments derived from continents blanket the ocean crust forming thick layers of sedimentary rock. The most ancient rocks found in the San Francisco Bay region originally formed in settings typically associated with divergence zones (particularly serpentinite, pillow basalt, and limestone).

As new crust is formed older crust is recycled back into the mantle. This occurs along convergent zones or boundaries where crustal plates collide. A convergent boundary exists between two crustal plates where one plate overrides another, usually along the margins of continents. The rocks within continental landmasses are generally felsic (granitic) in composition and are therefore less dense than the mafic rocks that underlie ocean basins. As a result, continental crust overrides oceanic crust. Oceanic crust sinks back into the asthenosphere along a subduction zone. Subduction zones consist of a great fault, or series of faults, defining the boundary between two converging crustal plates, and occur in association with ocean trenches. Ocean trenches occur at convergent zones along many plate boundaries, especially along the margin of the Pacific Ocean. This region is known as the "Ring of Fire" because where convergence zones occur there are typically both trenches and numerous volcanoes, many of which are active. A chain of volcanoes associated with a subduction zone is called a volcanic arc.

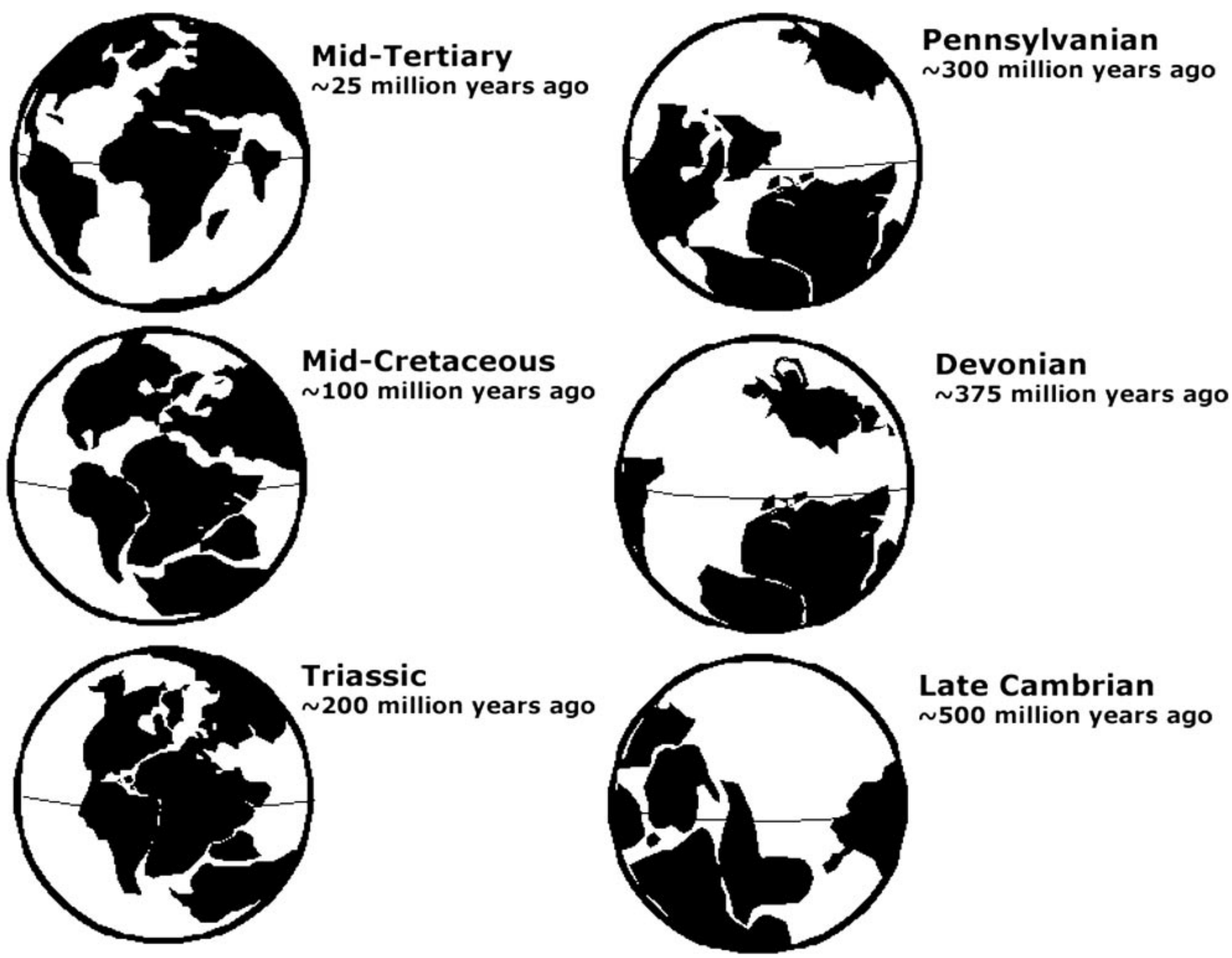
As the ocean crust sinks it drags rock material with it, including sediments saturated with seawater. Moving downward, this material gradually heats up and may partially melt. In the process, however, a natural refinement process occurs. Minerals that cannot withstand high temperatures (such as quartz) melt first, and minerals that can withstand higher temperatures (such as most mafic minerals) remain solid. As a result the molten material that forms in association with subduction zones is of felsic composition (mainly granite and rhyolite). Above the sinking slab of crust within subduction zones the surface is dotted with both active and extinct volcanoes. For instance, the modern Cascade Range extending from northern California to Washington is an example of an active volcanic arc. The Sierra Nevada was a volcanic arc that was active long ago, but is now extinct.



A plate tectonics model illustrating divergent, convergent, and transform plate boundaries.

Another type of convergent boundary forms when two continental landmasses collide. Because most continental rocks are too light to sink into the mantle, the rock piles up and forms massive mountain ranges. The best modern example of this is the Himalayas; the high mountain range formed as the Indian subcontinent collided into southern Asia. Before the two continents collided, a massive volume of sediments accumulated in a seaway between the two landmasses. Today, high in the Himalayas it is possible to find rocks bearing remains and traces of marine organisms that lived in that seaway.

All crustal plates are in motion. For instance, North America is cruising westward relative to Europe at a rate of about 4 cm per year. (Christopher Columbus's journey would be 20 m farther now!) This may seem insignificant, but in the framework of geologic time this process becomes important. The figure below shows the arrangement of the continents as they existed at different times in Earth history (over many millions of years ago). For instance, roughly 250 million years ago all of the continents were assembled in a single, great landmass geologists named Pangaea. This "supercontinent" lasted for many millions of years, and then it gradually broke apart. A great, developing rift system slowly gave rise to the Atlantic Ocean, splitting Pangaea into separate continental masses. This rift zone, or system, eventually became the spreading center associated with the Mid-Atlantic Ridge. The breakup of Pangaea was gradual, beginning with the opening of the Mid-Atlantic Ocean basin between North America and northern Africa. This happened between the "Triassic" (200 million years ago) and the "mid-Cretaceous" (100 million years ago; see figure below). This was followed by the opening of the South Atlantic, between Africa and South America, and finally by the opening in the North Atlantic in the Arctic regions between Europe, Greenland, and North America (see mid-Tertiary below). The North American Plate includes both the more ancient North American continental landmass and the younger crust beneath the western Atlantic Ocean basin west of the Mid-Atlantic Ridge.



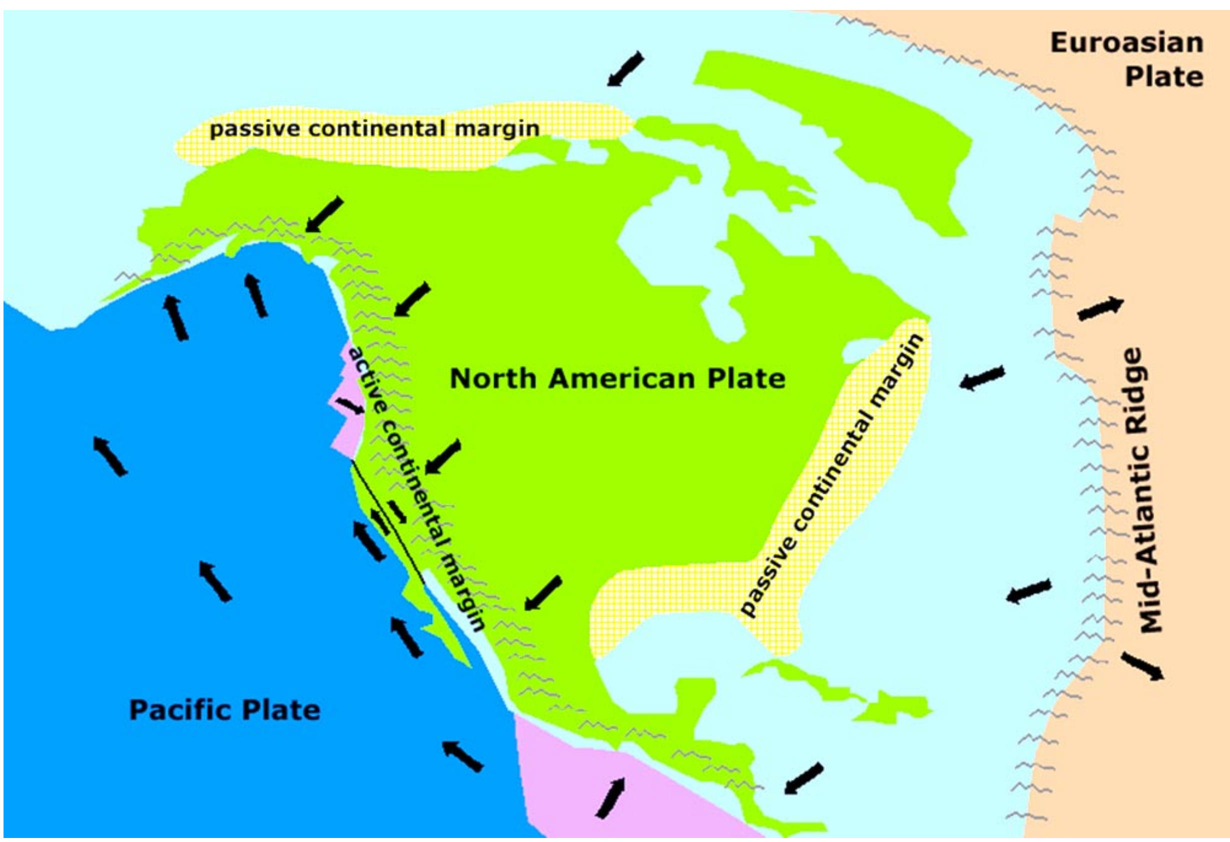
The changing configuration of continental landmasses through time.

Active Versus Passive Continental Margins

The geologic history and plate tectonics story of California doesn't make sense without a discussion of "active" and "passive" continental margins. A passive continental margin exists on the side of continents where the continental crust has "fused" with the adjacent ocean crust. In these regions strong earthquakes are rare, volcanic activity is relatively nonexistent, and forces of erosion dominate the gradual evolution of the landscape relative to tectonic forces uplifting the landscape. The landscape is generally subdued (low relief) and relatively small changes in sea level drastically affect the shoreline configuration of the oceans. In these regions over long periods of time, mountain ranges are worn away by weathering and erosion. Through time, over hundreds of millions of years, river systems gradually carry sediments from inland areas to the shore regions. In warm, shallow marine settings along the continental shelf great organic reef systems also generate large volumes of carbonate sediment. Gradually the marginal regions along continents fill in with great accumulations of sedimentary material.

The modern Atlantic coast of North America is a classic example of a passive continental margin because the North American continent is fused to the oceanic crust under the western side of the Atlantic Ocean. The Mid-Atlantic Ridge is a spreading center (divergence zone) that defines the eastern edge of the North American Plate. The eastern edge of the North American continent is now in the middle of the North American Plate. A great pile of sedimentary material now blankets the eastern edge of the continent, extending eastward from the Appalachian Mountains, beneath the coastal plain to the continental shelf and beyond into the deep ocean. This great sediment-filled basin extends from Canada to Florida and along the gulf coast. A similar sediment-filled basin extends along the North Slope of Alaska and northwestern Canada. Both regions are considered passive continental margins.

In contrast, an active continental margin is a coastal region where tectonic forces (faulting, volcanism, and uplift) tend to dominate over forces of erosion. They occur where the edge of a continent defines a plate boundary and convergence is occurring. The western edge of the North American continent is an active continental margin. Along the western margin of the North American continent there are large mountain ranges (like the Sierra Nevada and the Coast Ranges), and active volcanic chains, like the Cascades volcanic arc of northern California, Oregon, and Washington. Relative to the East Coast, the West Coast experiences an abundance of earthquakes and volcanic eruptions. The rugged western landscape dominated by mountains, volcanoes, and canyons is a reflection of the relatively active tectonic activity in the region. Material eroded from the land may be carried downward along with other crustal rocks into a plate margin subduction zone. Some of these materials may be metamorphosed and become part of great blocks the material that may becomes accreted to the continent. Some of it may melt and migrate to eventually form new igneous rocks, and some may vanish into the mantle.

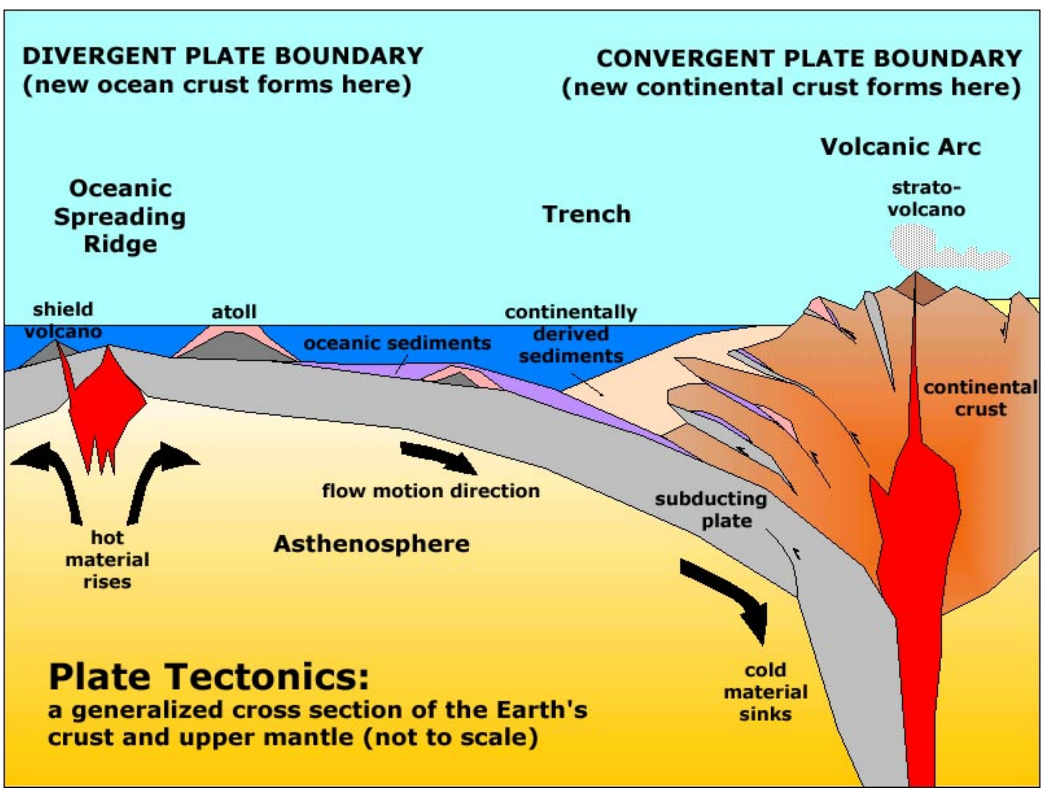


Map showing the active and passive continental margins in relation to the boundaries of the North American Plate.

Plate tectonics is the driving force behind most geologic changes occurring on the surface as well as deep in the crust. The processes associated with plate tectonics through the expanse of geologic time are responsible for the gradual accumulation of continental landmasses through the process of accretion. This complex process is illustrated as follows. As subduction proceeds, the melting of crustal rocks results in a natural refinement of Earth material. When crust sinks into the mantle, some mineral materials melt at lower temperatures than others. The "low temperature" material that forms tends to have a felsic composition (rich in silica and aluminum; the primary components of quartz and feldspar minerals). When this material crystallizes to form new rock, it is typically less dense than crustal rock that makes up the mantle or ocean crust. In this manner, more and lighter felsic material becomes incorporated into the lithosphere. As a result, small island chains, like the Philippines and Japan, grow steadily larger through time. Throughout Earth history small landmasses have been constantly forming and being pushed around by plate motion. Some of these landmasses eventually are forced against the edges of continents. Because the overall density of their felsic rocks and sediments are relatively low, rather than being forced downward into a subduction zone they become attached (accreted) along the edge of the continent. In this manner the smaller land masses and the thick sequences of sedimentary deposits caught between colliding plates are squashed beneath rising mountain ranges along active continental margins.

The North American continent has grown steadily larger by the slow process of continental accretion. This process began with formation of the Canadian Shield, an ancient assemblage of landmasses that now forms the central core of the continent (called a craton). The rocks of the Canadian Shield are dominantly igneous and metamorphic rocks, approximately between 2.8 to1.8 billion years old, with some rocks preserving radiogenic dates that are much more ancient. At different times in Earth history, the western edge of North America was an active continental margin, undergoing stages of mountain building and continental accretion. At other times, the western edge of the continent was dominantly a passive margin, such as during much of Late Precambrian time (700 to 570 million years) and through much of the Paleozoic Era (570 to 225 million years). During this extensive period of time, the western edge of the North American continent was in a tropical setting, receiving large quantities of sediments derived from the continental interior in addition to accumulating large quantities of carbonate sediments (reefs and algal mud) deposited in shallow, marine environments. At the end of the Paleozoic, the western edge of the North American continent was near the Nevada/California border region. Through time, the western margin of the continent became an active plate margin again with subduction zones forming and reforming as smaller land masses and island arcs collided with the continent, slowly building the continental margin westward to its current location.

It wasn't until the middle of the Mesozoic (the Jurassic Period) that rocks began to form that would eventually become the dominant part of what is now the San Francisco Bay region. Older rocks that may have existed in the region were either transported elsewhere or recycled back into the crust and mantle



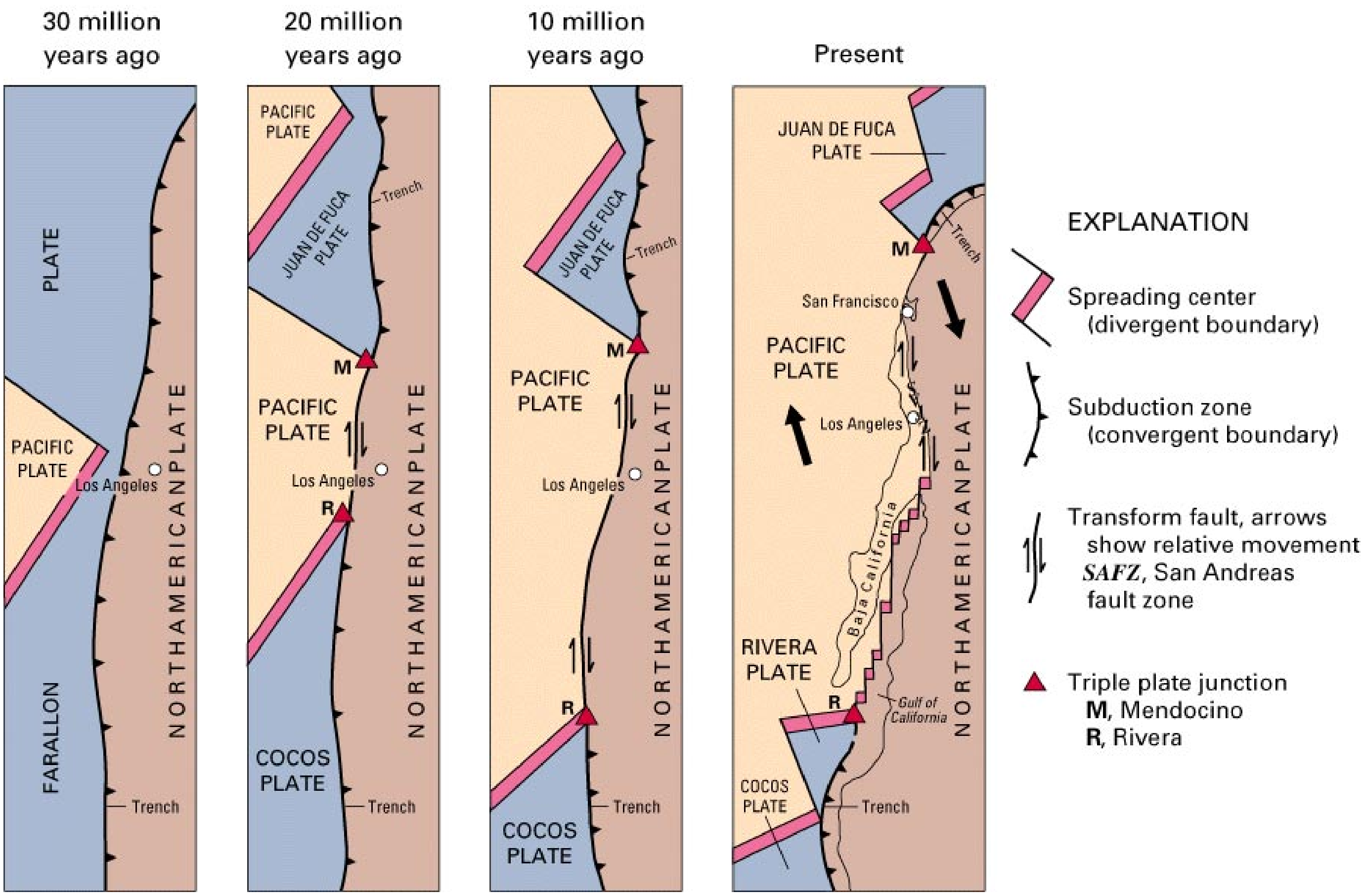
A simplified plate tectonic model for the western margin of North America useful for explaining the origin of many rock types found in the San Francisco Bay region.

along a subduction zone. The oldest rocks preserved in the region probably formed as igneous intrusions or volcanic flows on submarine volcanoes associated with a spreading center along a divergent plate boundary. Marine sediments were gradually deposited on top of these volcanic rocks, mostly from the buildup of skeletal remains of plankton and wind-blown dust. Later, as these rocks were gradually rafted toward the continental margin, they were blanketed with a thick sequence of sediments eroded from continental sources. Through time, much of the oceanic crust that existed in the region in the past was subducted back into the mantle or incorporated back into the continent through accretion.

Beginning roughly 200 million years ago, the opening of the Atlantic Ocean basin along a divergent plate boundary on the eastern side of the North American continent was counterbalanced by the development of a convergent boundary on the western side of the continent. This convergent boundary setting with a subduction zone operated nearly continuously for nearly 160 million years, intermittently interrupted as small landmasses derived from distant sources rafted in and collided with the western margin of the continent. The figure on the previous page generally illustrates the geologic settings associated with the subduction zone complex that dominated the western margin of North America for this long period of time. However, starting roughly 30 million years ago, changes in plate configurations along the western edge of the North American continent gradually changed the entire geologic framework of California. Subduction gradually gave way to transform faulting, resulting in the formation of the San Andreas Fault system.

Evolution of the San Andreas Fault system

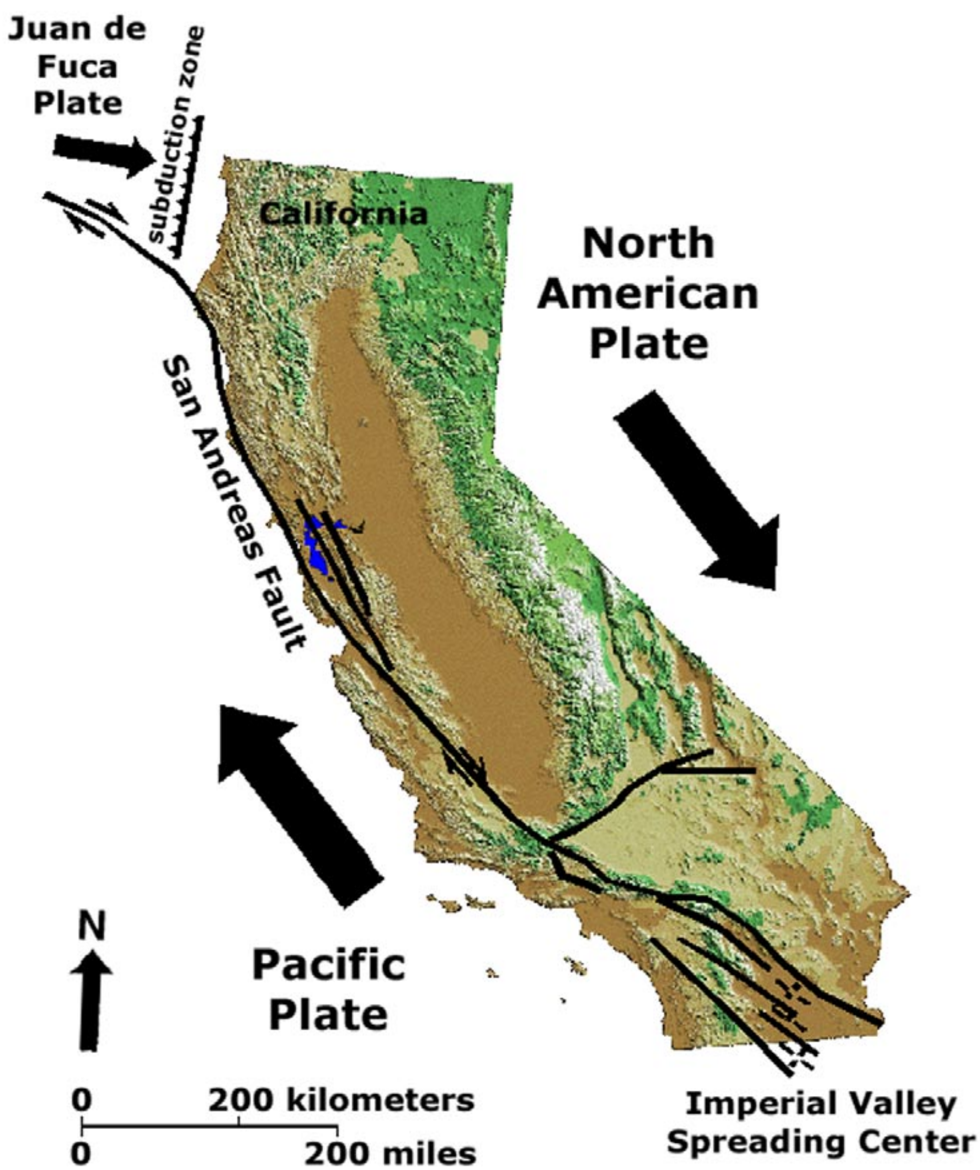
Transform faults result from a shearing motion in the crust. This results in the formation of a fault system in which one landmass moves gradually past another, or where two plates are sliding past each other. The classic North American example is the San Andreas Fault in California. Los Angeles and Baja California are attached to the Pacific Plate, which is slowly grinding northward relative to the eastern side of the fault attached to the North American Plate. It the future, the land that is now Los Angeles will gradually move northward, past San Francisco, and then onward towards Alaska. The figure below illustrates the changing plate geometry of the west coast for the past 30 million years involving the interactions of several plates—the North American Plate, the Pacific Plate, and the Farrallon Plate. The San Andreas Fault formed as the Farollon Plate disappeared beneath the western margin of the North American continent. (Existing remnants of



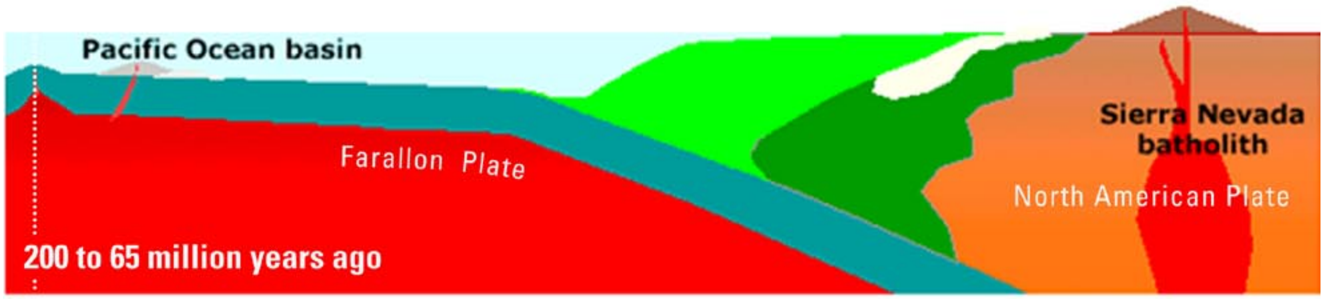
Formation of the San Andreas Fault system through time (from "This Dynamic Earth" (http://pubs.usgs.gov/pdf/planet.html) modified from USGS Professional Paper 1515).

the Farallon Plate include the smaller Cocos Plate and Juan de Fuca Plate). As the Farallon Plate disappeared, the North American Plate came in contact with the Pacific Plate. This collision of the Pacific Plate with the North American Plate changed the convergent plate boundary into a transform boundary, resulting in the ongoing formation of the San Andreas Fault system. In the early stage of formation of the fault system, volcanic eruptions occurred in many areas along the fault zone as new fracture systems propagating through the crust created passageways for magma migration toward the surface. Remnants of many of the volcanic centers occur throughout the bay region, particularly in the east bay hills and in the north bay region.

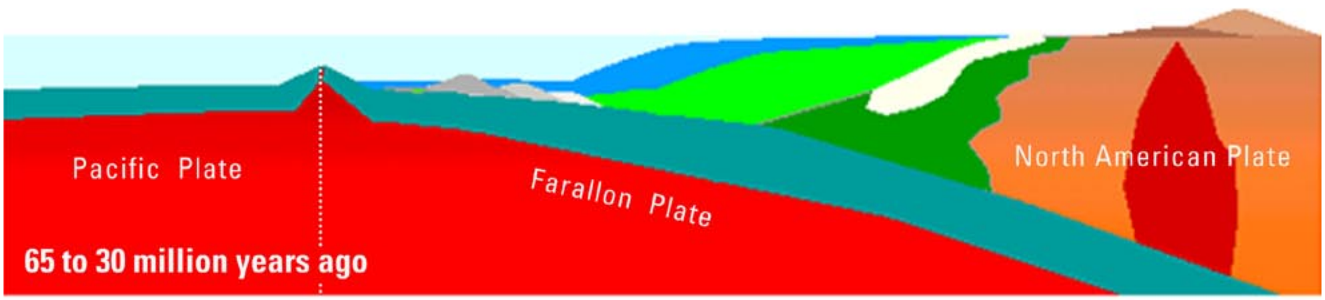
The San Andreas Fault system is a dominant geologic feature along the west coast of North America, and has been host to a number of great earthquakes in historic times where different portions of the fault moved. These major quakes include the 1857 Tejon Pass Earthquake (affected a San Andreas Fault segment roughly southeast of Los Angeles to Coalinga), the 1868 Hayward Earthquake (affecting the Hayward, Calaveras, and San Andreas Faults between Coalinga and Hollister), and the 1906 San Francisco Earthquake (affecting the San Andreas Fault segment from near San Jose northward to where it runs offshore at Cape Mendicino). Numerous other significant earthquakes have occurred along the San Andreas Fault, but these quakes were perhaps the most powerful quakes that also affected the longest intervals of the fault system. The San Andreas Fault system is perhaps the best-known and most studied fault in North America, but it is only part of the greater tectonic setting of western North America. Fault systems along the eastern Sierra Nevada and in portions of the Great Basin extending as far east as central New Mexico may be part of a greater system of faults that really define the complex western boundary of the North American Plate.



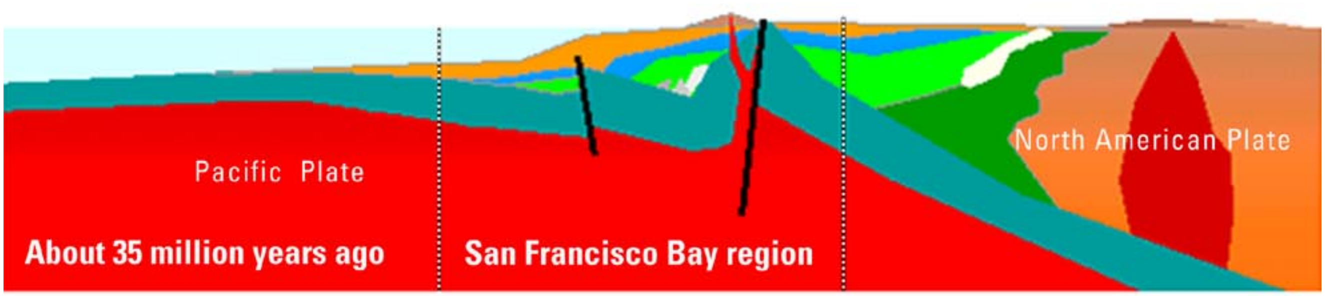
Shaded relief map of California showing the San Andreas Fault system and plate motions.



200 to 65 million years ago processes associated with the subduction of the Farallon Plate dominated the California continental margin, producing the volcanic arc that formed the core of the Sierra Nevada. Small landmasses from throughout the Pacific Basin were accreted onto the continental margin while erosion dumped sediments into the ocean basin.

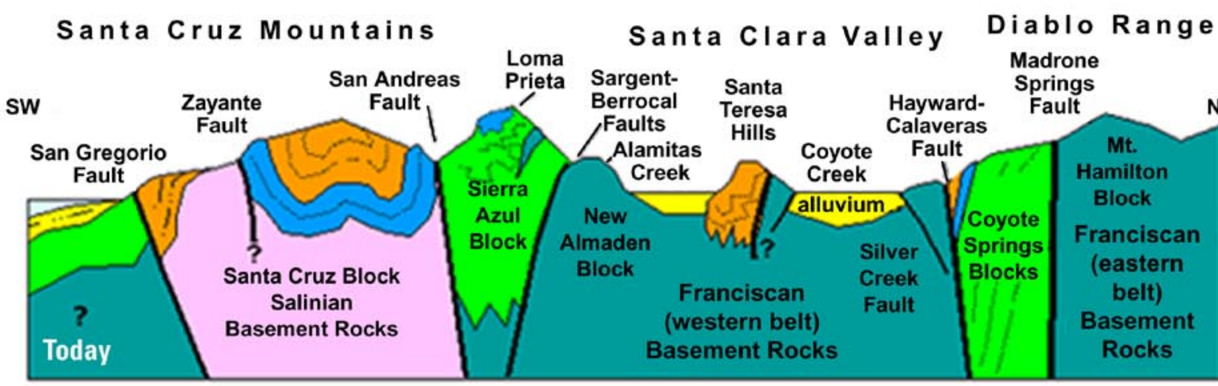


65 to 30 million years ago, more rapid relative plate convergence shifted igneous melting associated with subduction far to the east (into the Rocky Mountains region), ending volcanism in the Sierra Nevada region. Erosion continued to wear down the landscape. The eastern Pacific basin continued to receive vast quantities of sediments.



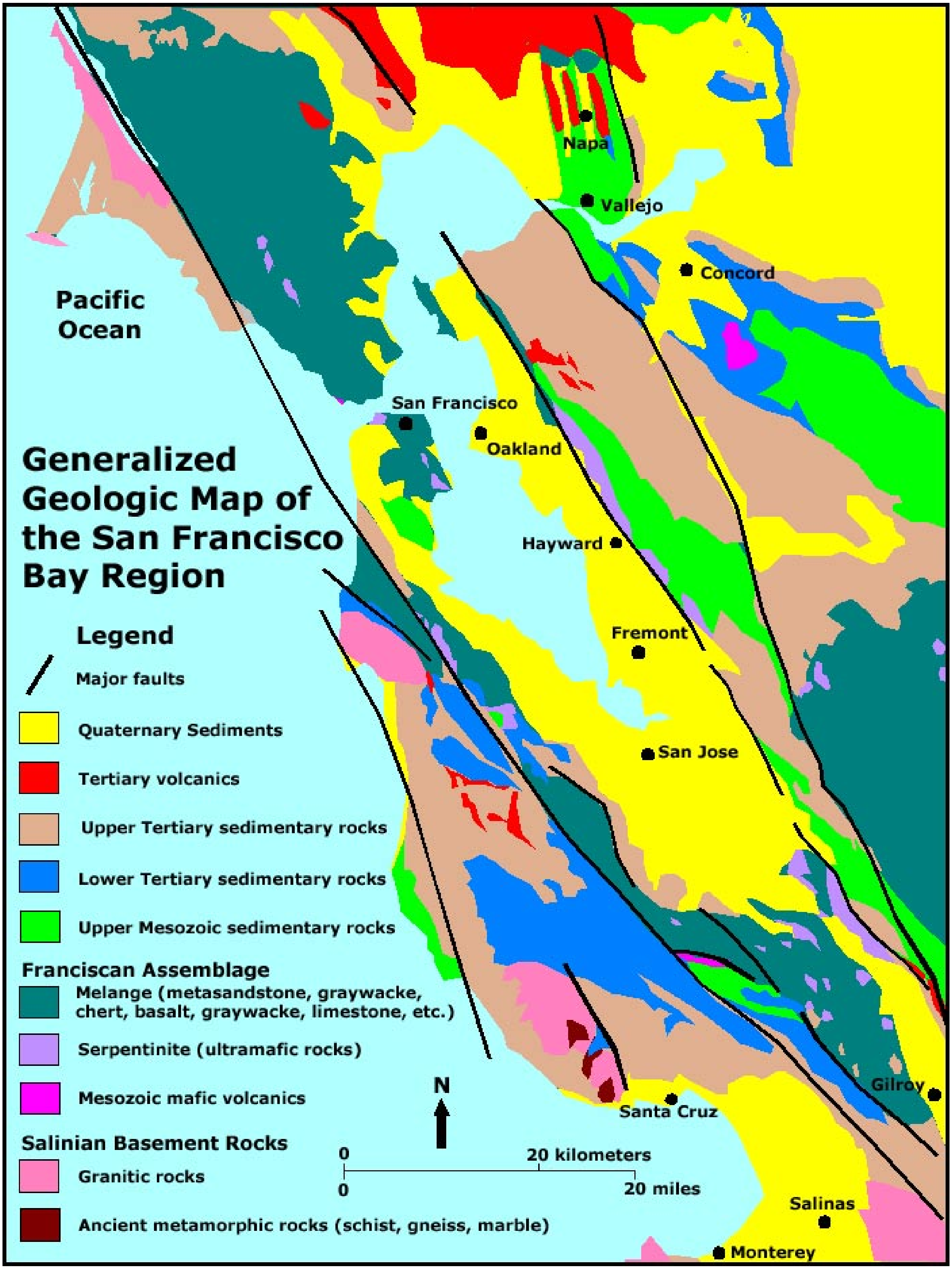
Starting around 35 million years ago, the westward moving North American Plate began to override the spreading center between the vanishing Farallon Plate and the Pacific Plate (to the west). This caused a change in relative plate motion from subduction to transform motion. The new transform fault becomes the San Andreas Fault System. In early stages of development, volcanoes erupt along the newly forming fault system.

San Francisco Bay Region Today



Today, the geology of the San Francisco Bay region is dominated by the San Andreas Fault system that consists of a series of interconnecting faults with intervening discoordinate tectonic terranes (blocks). Some of these blocks have moved several hundred kilometers north of their place of origin. The cross-section of the San Francisco Bay region is expanded above.

Evolution of western North America and cross-section of the San Francisco Bay region.



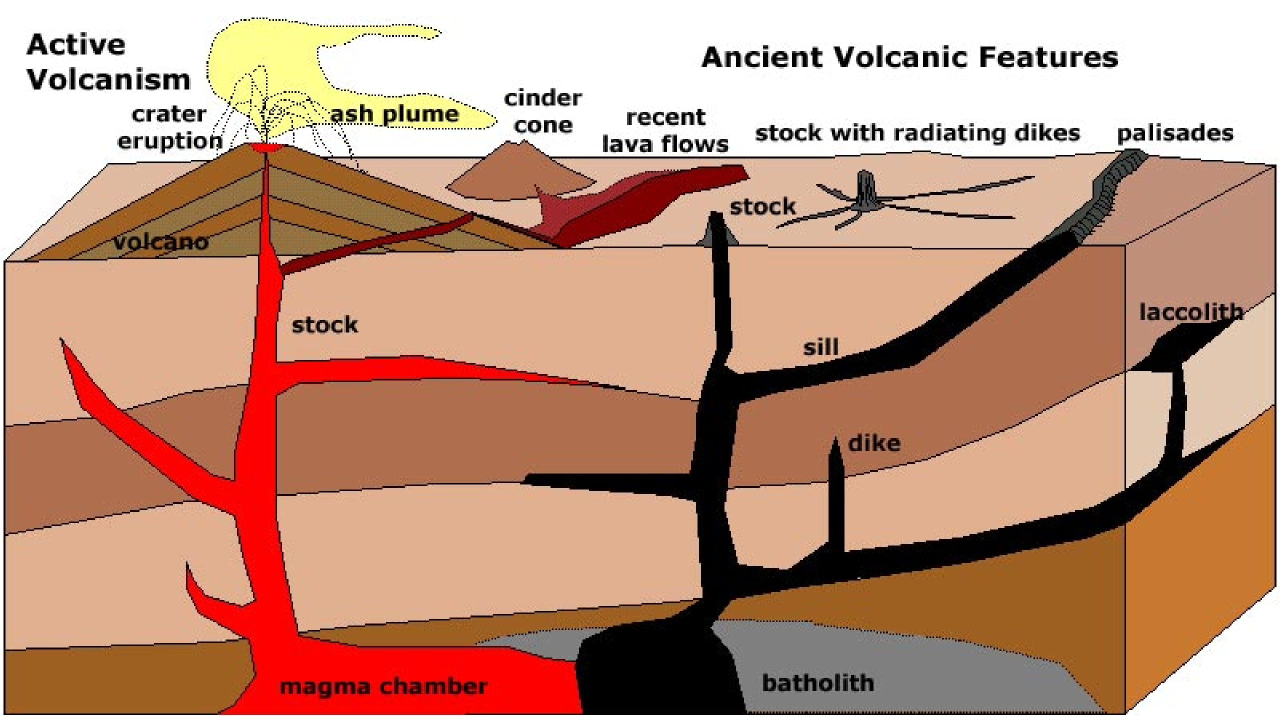
Generalized geologic map of the San Francisco Bay region.

Igneous Rocks and Processes

Igneous rocks form from the cooling and solidification of molten material called magma. The heat that produces magma has its source deep within the Earth. The heat is, in part, a relic of the original gravitational energy transferred by the collisions of asteroids and planetesimals with young planet Earth. Additional heat is generated from radiogenic decay. More heat may possibly come from tidal forces between the Earth, Moon, Sun, and other planets. Magma is derived from the melting of preexisting crustal rocks or from sources below the Earth's crust. The formation and movement of magma in the subsurface is called plutonism (after "Pluto," Greco/Roman god of the underworld). When magma cools in the subsurface it slowly forms rock through the process of crystallization. The chemical and physical reactions that take place in cooling magma result in the formation of interlocking mineral crystal grains (minerals such as quartz, feldspar, and mica). The mineral grains (crystals) are of a visible size, giving the rock a crystalline texture. Intrusive igneous rocks have a composition and texture that varies with the composition of the magma and physical conditions under which the rock formed.

When magma manages to migrate upward onto the surface, the result is volcanism (a volcanic eruption). A volcano forms as molten rock and solidified volcanic debris are ejected onto the surface and accumulate near the eruption site. In addition to rock material, large quantities of water vapor and gases are vented from volcanoes. When magma flows on the surface the material is called lava. The release of pressure during eruptions can produce ash clouds that may travel long distances. Rocks that form on the surface are called extrusive igneous rocks. The rapid cooling of molten material on the surface hinders crystallization; as a result, extrusive igneous rocks tend not to display an abundance of visible mineral grains. Extrusive igneous rocks (of volcanic origin) take on a texture consistent with the manner or eruption, such as frothy or blocky lava rock, a condensed volcanic ash, or even natural glass (obsidian).

Intrusive igneous rocks form from magma that cools very slowly, deep underground. Rock is an excellent insulator of heat, so magma in a magma chamber may take many thousands of years to cool, allowing plenty of time for mineral crystal grains to form and grow, especially if the magma is rich in dissolved fluids that promote crystal growth (like carbon dioxide or water). A body of rock formed from magma migrating and solidifying deep in the subsurface is called a pluton or an igneous intrusion. Huge intrusions, covering areas greater than one hundred square kilometers are called a batholith. Batholiths typically contain many separate intrusions that form over a relatively long period of time. Other types of intrusions typically form at shallower crustal depths; these include stocks, dikes, and sills. A stock is smaller than a batholith and typically represents the subsurface passage that fed molten material to a volcano or field of volcanoes over time. Sills and dikes are layers of igneous rock that typically form along fault zones, fractures, or between and parallel to sedimentary layers. A laccolith is a blister-shaped intrusion. Stocks, sills, dikes, laccoliths and other intrusions are remnants of past igneous activity and are exposed at the surface long after erosion has stripped away any ancient volcanoes and other overlying rocks and sediments that may have existed in an area.



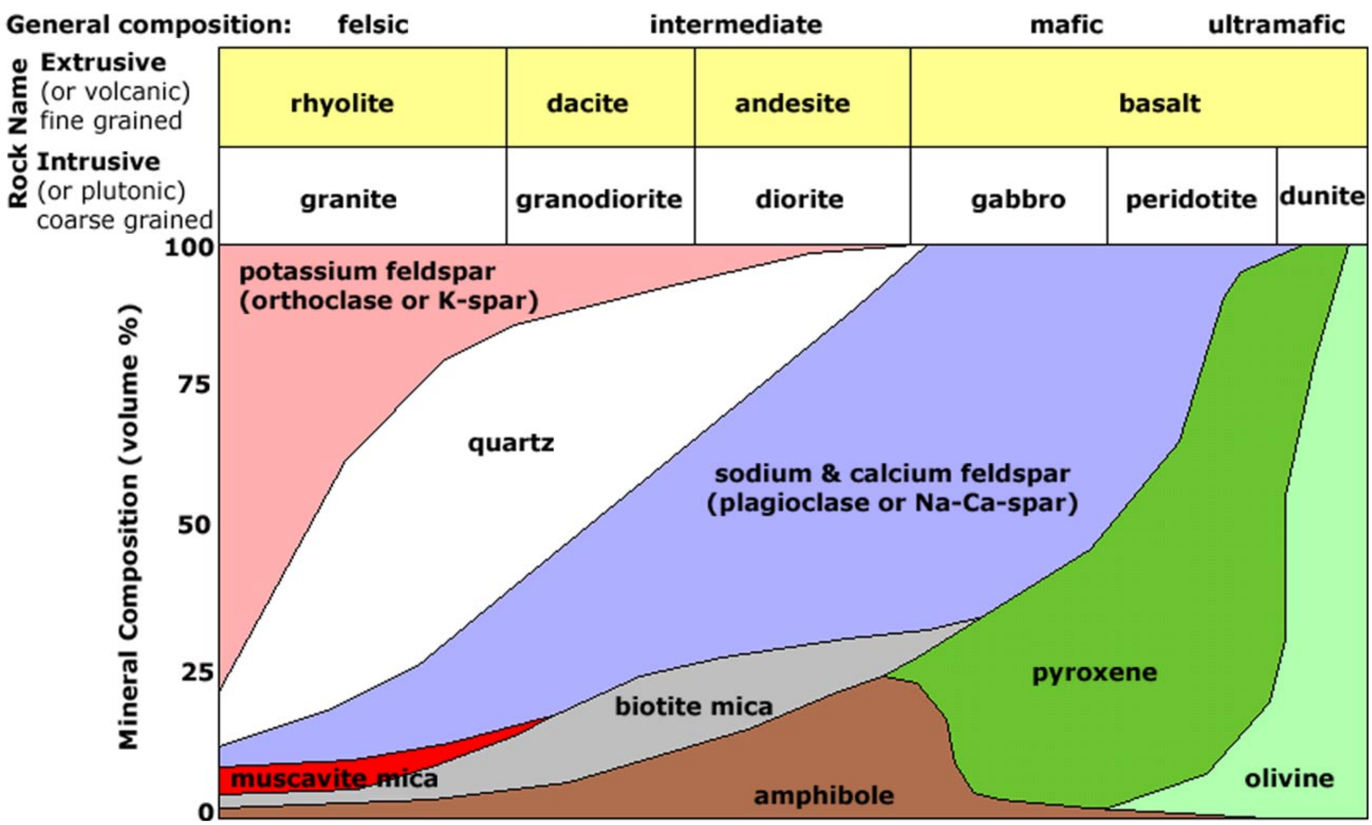
Geologic features associated with modern and ancient igneous activity.

Classification of Igneous Rocks

Igneous rocks are classified by the geologic environment where they formed from the crystallization of molten material, and perhaps more importantly, by their mineral composition. Rocks that form underground are called intrusive igneous rocks, whereas rocks that form on the surface are called extrusive igneous rocks. Intrusive igneous rocks (like granite or gabbro) typically display visible mineral grains that are fairly easy to recognize with a little training. Extrusive rocks are more difficult to clearly identify because the mineral grains are typically invisible. However, the general composition of an extrusive rock is reflected by its color and density characteristics. General composition types include felsic (which is a mnemonic word derived from "feldspar" and "silica"), and mafic (which means rich in magnesium and iron, Fe). Felsic rocks tend to be light colored (white, pink, yellow), and are typically much less dense than mafic rocks that are typically dark (gray, brown, or black). A simplified igneous rock classification system is presented below.

The classification chart illustrates that rhyolite (a felsic extrusive rock) has the same mineral composition as granite (an intrusive igneous rock) and is composed dominantly of the minerals potassium feldspar (K-spar), quartz, and lesser amounts of plagioclase feldspar, mica, hornblende, and other minerals. Likewise, basalt (a mafic extrusive rock) has the same mineral composition of the mafic intrusive rock, gabbro.

This generalized composition of felsic and mafic can be subdivided into intermediate (between felsic and mafic composition), and ultramafic (rocks extremely enriched in magnesium and iron). Rocks of intermediate composition include diorite (intrusive) and andesite (the extrusive equivalent). Ultramafic rocks have special significance, in that they probably are derived from the mantle. They are relatively unstable on the Earth's surface, and are typically metamorphosed. In nature and in simplistic interpretation, igneous rocks that make up most continental crust typically have a felsic composition (such as rhyolite and granite). The mafic rock basalt is the dominant rock type that makes up most ocean crust. Rocks of intermediate composition are derived from the mixing of continental and oceanic crust. Interestingly, intrusive and extrusive igneous rocks of nearly every composition listed below can be found in the greater San Francisco Bay region—a reflection of its complex geologic history.



A general classification of igneous rocks.

Intrusive Igneous Rocks

Intrusive igneous rocks form from the slow crystallization of magma underground. Slow cooling results in the growth of visible interlocking grains of mineral crystals.

Granite

Rock characteristics: Granite is a felsic rock with dominant minerals—orthoclase (a pink, potassium-rich variety of feldspar), quartz, and lesser amounts of mica (both silvery muscovite or black biotite), hornblende, and plagioclase (white to gray, sodium-rich varieties of feldspar). Note that the word "granite" is used fairly liberally. Many rocks called "granite" are technically something different. The word "granitoid" or "granitic" implies felsic to intermediate intrusive rocks of many varieties, including granite. The sample illustrated here is a granite pegmatite displaying a large radiating cluster of hornblende crystals and large crystal masses of mica, quartz, and feldspars: both pink (orthoclase) and white (plagioclase). A pegmatite is an exceptionally coarse-grained igneous rock with large interlocking crystals, typically forming as masses in dikes and veins, especially along the margins of batholiths. They represent the last and most hydrous magma to crystallize, and sometimes contain rare minerals enriched in the elements boron, lithium, uranium, and rare earths.

Bay region occurrence: Granitic rocks occur as mountain-sized masses and as intrusive bodies in older rocks (schist, gneiss, and limestone) throughout the Salinian Block, west of the San Andreas Fault with large areas of exposure in the Gabilan Range, in the Santa Cruz area, Montara Mountain, and at Point Reyes. Granitic materials also occur in gravels throughout the San Francisco Bay region.

Granite from Point Lobos, Monterey County.

Pegmatite from San Lorenzo Creek, Santa Cruz County.

Granodiorite

Rock characteristics: Granodiorite is a felsic variety intrusive igneous rock containing mostly feldspar (but more plagioclase than orthoclase (K-spar) as in granite), quartz, hornblende, biotite, amphibole, and including accessory minerals such as magnetite, pyrite, and other minerals. It is typically a light-gray rock peppered with small black mafic crystals (biotite and hornblende). It usually has a massive, unstratified appearance, heavily fractured, and sometimes contains granitic dikes and intrusions (as in this stream cobble sample from Santa Cruz).

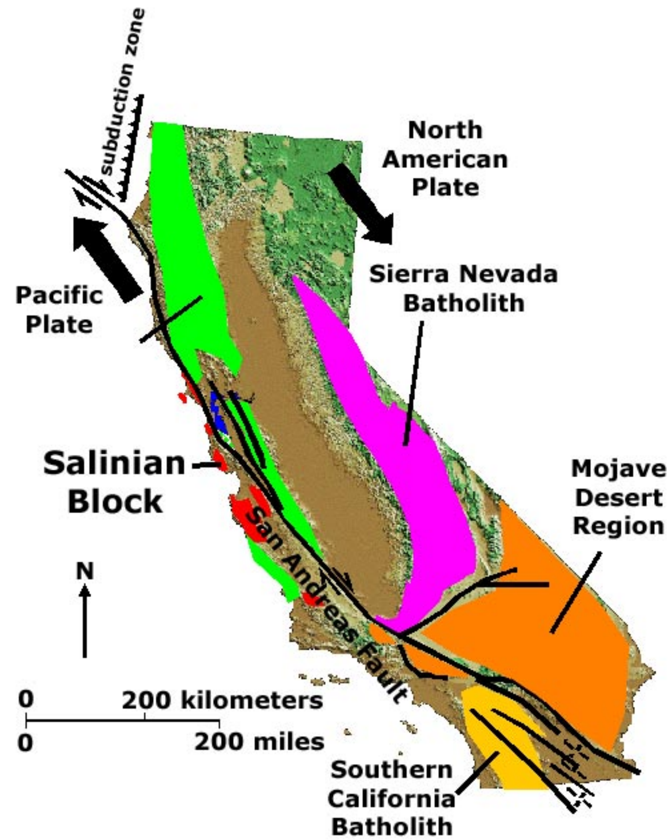
Bay region occurrence: Granodiorite is perhaps the most common intrusive igneous rock found in California. Most of the "granite" mined in the region is really granodiorite. Granodiorite is abundant in the Salinian basement rocks throughout the region west of the San Andreas Fault with exposures through the Gabilan Range, the western Santa Cruz Mountains around Ben Lomond Mountain, Montara Mountain, and at Point Reyes. Large active "granite" quarries exist near Davenport and Aromas in Santa Cruz County. Granodiorite from these quarries is used extensively as railroad bed and construction aggregate.

A granodiorite boulder from San Lorenzo Creek, Santa Cruz County.

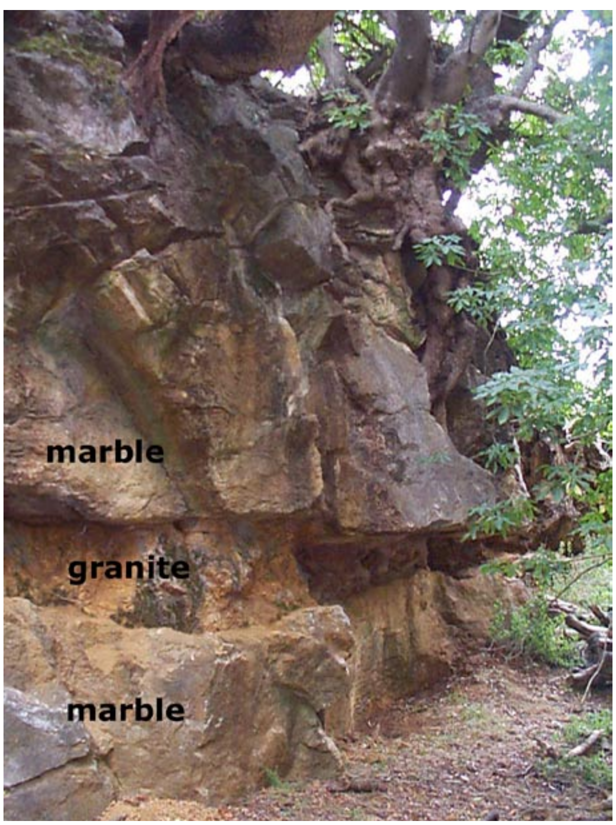
Why Are There Felsic Intrusive Igneous Rocks in the San Francisco Bay region?

Throughout the central California Coast Ranges some bedrock consists of igneous rocks including granodiorite and lesser amounts of granite, diorite, and gabbro. These igneous rocks occur in association with metamorphic rocks, particularly gneiss, schist, and marble. These rocks crop out in areas west of the San Andreas Fault, with prominent exposures at Point Reyes, Montara Mountain, throughout the Santa Cruz Mountains, the Salinas Mountains, the Gabilan Range, and the Monterey Peninsula region. These rocks form the "basement" (oldest crystalline rocks) of the Salinian Block (a block being a region underlain basically by the same kind of rocks and bounded by faults). These rocks are in striking contrast to the rocks that occur mostly east of the San Andreas Fault throughout the central and northern Coast Ranges (including the Diablo Range, San Francisco, and Marin County). The basement rocks in this region are called the Franciscan Assemblage, which includes a very mixed variety of sedimentary, igneous, and metamorphic rocks that were originally derived from oceanic crust, ocean sediments, and even rocks derived from the mantle.

The granitic rocks in the Salinian Block baffled scientists for years before a clear understanding of plate tectonics and the nature of the San Andreas Fault system were resolved. The Salinian Block's igneous and metamorphic rocks most resemble similar rocks from the southern Sierra Nevada batholith (a batholith is a region made up of large igneous intrusions of similar age and composition). Some rocks resemble other rocks in the Mojave Desert and in southern California. Geologists believe that through time, rocks that make up the Salinian Block were ripped away from the southern Sierra Nevada and were rafted northward with the other rocks making up the Pacific Plate side of the San Andreas Fault system. The marble in the Salinian Block predates the Mesozoic igneous intrusions, and may be much, much older.



Map showing granitic terranes in California, including the Salinian Block.



A granite intrusion exposed in a marble quarry in the Salinian Block (University of California Santa Cruz campus).

A "granite" quarry near Aromas (Santa Cruz County) yields crushed stone and rock that is closer in composition to granodiorite and diorite than true "granite."

Diorite

Rock characteristics: Diorite is of intermediate composition. It is called “salt and pepper” rock because of its nearly equal proportions of light, felsic minerals (mostly plagioclase and quartz) and dark, mafic minerals (amphibole and biotite). Diorite is close in composition to granodiorite, and it requires fairly close inspection to differentiate the two rocks. Diorite typically contains no orthoclase feldspar (pink potassium feldspar). This sample from Santa Cruz displays a xenolith, a name for a piece of bedrock intruded by magma that broke off and was carried along before becoming incorporated into the rock when the magma cooled into stone. Xenoliths can range in size from pebbles to house-sized or even mountain-sized blocks depending on the size of the intrusion.

Bay region occurrence: Diorite occurs as intrusive bodies in the Salinian basement rocks. It occurs as mappable units in exposures in the Santa Cruz Mountains and Gabilan Range, and can be found as clasts in gravel deposits (conglomerates) throughout the region.

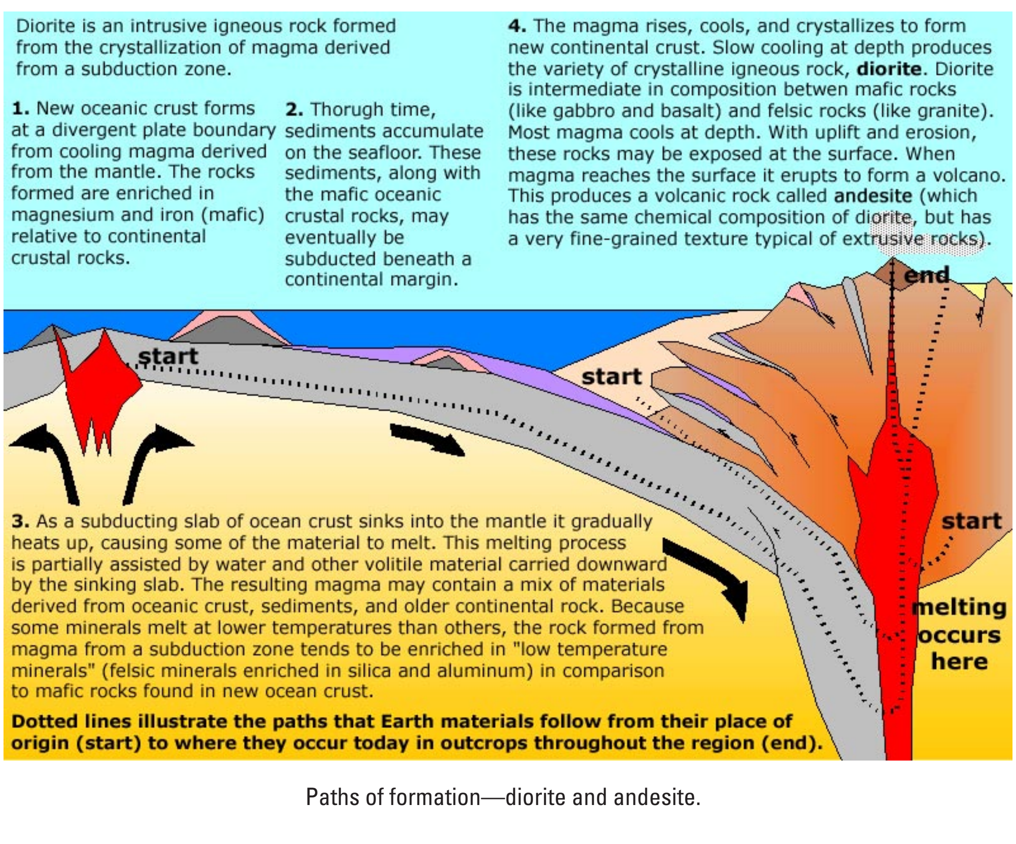
Gabbro

Rock characteristics: Gabbro is typically a dark gray, greenish gray, to black rock (mafic in composition) with visible crystals of plagioclase feldspar (Ca-rich varieties), hornblende, pyroxene, and lesser amounts of biotite mica, magnetite, and other minerals.

Bay region occurrence: occurs as small intrusive bodies in the Salinian basement (associated with granite and diorite intrusive bodies) with sizable occurrences in the region around Watsonville and Santa Cruz (Santa Cruz County), and in the Gabilan Range. Pyroxene-rich varieties of gabbro can also be found in association with basaltic intrusions and serpentinite bodies in exposures throughout the Diablo Range, particularly in the region around Mt. Diablo and farther south in the Clear Creek/New Idria region.

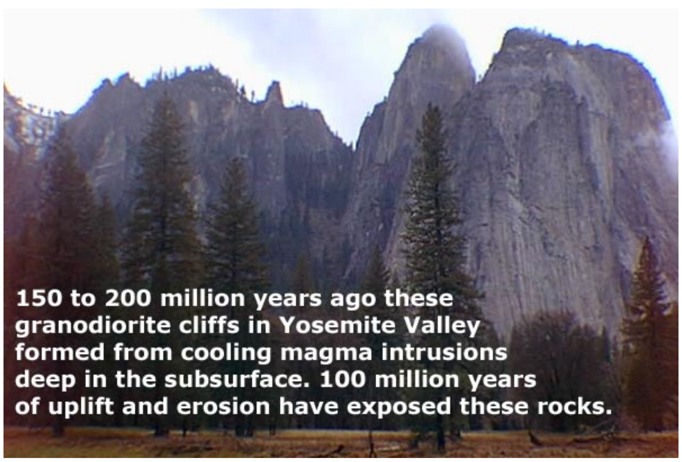
Diorite from a “granite” quarry near Aromas, Santa Cruz County.

Gabbro from southern Santa Cruz County.



Paths of formation—diorite and andesite.

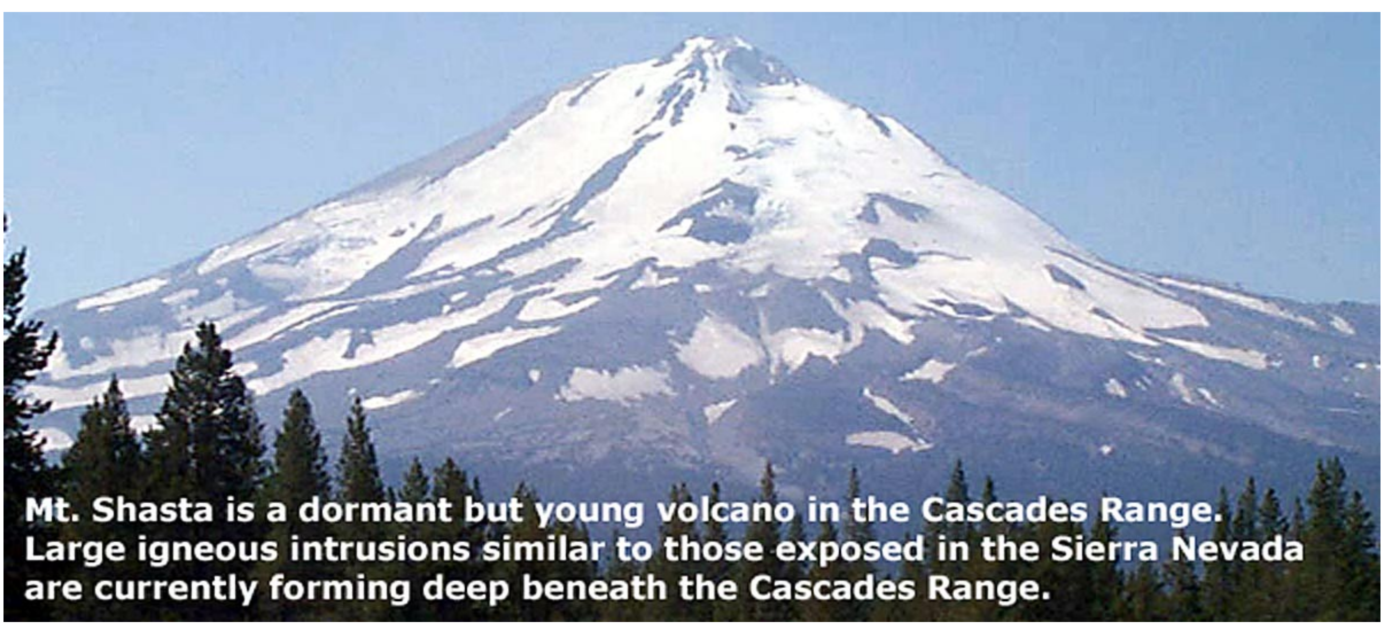
Igneous rocks of intermediate composition form in convergence zones. Subduction associated with convergent plate boundary conditions along the western margin of North America has persisted for nearly 250 million years (since North America split away from the African and Eurasian continents). Subduction ended in southern California with the formation of the San Andreas Fault system beginning about 20 million years ago. However, in northern California, Oregon, and Washington (north of the San Andreas Fault trace), subduction, and its associated volcanic processes, is still occurring, producing the Cascades volcanic chain. Mt. Shasta is the southernmost and largest of the Cascades volcanoes. In the past, a great chain of volcanoes must have existed in the region now occupied by the Sierra Nevada, however these volcanoes have long since eroded away. The chilled magma chambers that formed far below those ancient volcanoes are now exposed by ongoing erosion of the range. The rocks exposed in the Sierra Nevada are chemically very similar to the modern Cascades volcanic rocks. However, in contrast, they cooled very slowly far underground forming the more crystalline intrusive igneous rocks, diorite, granodiorite, and granite.



Rocks from the Mantle?

Plate tectonics theory suggests that hot mantle rock gradually rises toward the surface beneath oceanic spreading centers. As the hot rock rises, the release of confining pressure allows some of this mantle rock to melt. This molten material intrudes upward, forming new oceanic crust. Some of the mantle rock itself may become incorporated in the ocean crust. When complex faulting occurs along plate boundaries, sometimes pieces of mantle rock are transported upwards and are exposed at the surface. Because mantle rocks originally form at great depth they tend to be quite unstable both physically and chemically in the surface environment. Most exposures of rocks that were originally derived from the mantle have been converted to serpentinite. However, in some cases some of this rock has survived and has been recognized on the surface. Our current understanding of the composition of the mantle is that the rocks are of “ultramafic” composition, in that they consist of silicate minerals that are very enriched in iron and magnesium (and other metals such as calcium and chromium), more so than typical oceanic crust or especially continental crustal rocks. Mantle rocks are differentiated from crustal igneous rocks by their composition. They sometimes preserve their coarse-crystalline rock textures and original flow banded foliation that formed during the gradual upwelling of rock far below a spreading center. San Francisco Bay region examples of probable mantle rock include pyroxenite (rich in pyroxene minerals) and peridotite (a rock rich in the minerals, olivine, pyroxene, and chromite). Again, unaltered mantle rock is a very rare occurrence, but ultramafic rocks, both of igneous and metamorphic origin, are common in select areas.

The modern Cascades volcanoes are a modern model for the formation of the ancient Sierra Nevada batholith.



Pyroxenite

Rock characteristics: Pyroxenite is an ultramafic plutonic rock chiefly composed of pyroxene minerals, with accessory minerals including hornblende, olivine, spinel, biotite, and Ca-feldspar. Pyroxene minerals typically occur in short, stout masses that display prismatic near-right-angle crystal cleavage and are typically black to pale green in color.

Bay region occurrence: Pyroxenite typically occurs in association with serpentinite, typically occurring as isolated outcrop masses or in resistant boulders along stream gravel bars. Massive ultramafic bodies in the San Francisco Bay region occur in the Franciscan basement east of the San Andreas Fault, with large bodies occurring in the southeastern foothills of the Santa Cruz Mountains, including on Mt. Umunhum. The Diablo Range has numerous large exposures of ultramafic rock from Mt. Diablo southward to San Benito Mountain and beyond. Yerba Buena Ridge on the east side of Highway 101 in southern San José is dominantly serpentinite, some of which preserves an original mantle-rock texture created by coarse crystalline rock flowing under extreme pressure.

Pyroxenite from Clear Creek, San Benito County.

Peridotite

Rock characteristics: Peridotite has two varieties—harzburgite (a rock that contains more olivine than pyroxene) and dunite (a rock consisting almost entirely of olivine). Peridotite typically displays a coarse crystalline texture and is both very dark and very dense. In harzburgite, the pyroxene is greenish, grayish to black. Some peridotite is rich in bronzite, a golden-brown, massive crystalline iron-rich variety of the mineral enstatite. In harzburgite and dunite, the olivine is brown, greenish brown to black and has a more glassy texture than the pyroxene. Accessory minerals include magnetite, chromite, and serpentine minerals. It may contain traces of plagioclase.

Bay region occurrence: Unaltered peridotite is a relatively rare occurrence in the San Francisco Bay region, and true dunite probably doesn't occur in the region. Peridotite can be found in coarsely crystalline serpentinite bodies, particularly within the core of serpentinite blocks that preserve a "ghost" texture of the original coarse crystals grains of the parent rock. Weathered blocks of serpentinized peridotite have a brown "hob-nail" surface where the less altered and more resistant pyroxene stands out relative to the serpentinized olivine.

Peridotite from alluvial gravels, Arroyo Seco Canyon, Monterey County.

Chromite Ore

Rock characteristics: Chromite is essentially pure chromium oxide. It is a brownish to iron-black to brownish-black mineral of the spinel group. Chromite ore displays octahedral crystals and occurs as an accessory mineral in ultramafic igneous rocks. The dense crystals of chromite typically sink and accumulate at the bottom of an ultramafic magma chamber, forming dense, pod-like masses in association with pyroxenite, peridotite, and serpentinite.

Chromite ore from Clear Creek, San Benito County.

Bay region occurrence: Small chromite masses have been mined from serpentinite areas throughout the Diablo Range. This sample is from the Clear Creek area of San Benito County. Small chromite deposits have been mined throughout the San Francisco Bay region, but larger chrome mining operations have been conducted further south in the Diablo Range. Chromium-enriched deposits (both natural and manmade sediments and fill) are blamed for high concentrations of chrome in ground water in some areas. Elevated chrome concentrations are toxic to both plants and animals (including humans).

Anorthosite

Rock characteristics: Anorthosite is dominated by plagioclase feldspar (calcium- and sodium-rich variety of feldspar including anorthite, labradorite, and bytownite); it is not a mafic or ultramafic rock, but it occurs in association with both rock groups. In mantle-derived rock found on the surface, plagioclase feldspar occurs in association with pyroxene, olivine, and other mafic minerals. Interestingly, anorthosite is perhaps a dominant rock-type found on the moon!

Bay region occurrence: Anorthosite occurs in association with some intrusions in ultramafic rock masses in the Santa Cruz Mountains and in the Diablo Range. This sample came from a gravel bar near Lexington Reservoir in San José.

Anorthosite from Mt. Umunhum, Santa Clara County.

Jade

Characteristics: Jade is a semiprecious gemstone (rock) with a waxy or felt-like appearance (due to the microcrystalline texture of its mineral grains). It can be found in colors ranging from white, yellow, green (jade), gray to black. Jade can consist of two different minerals—nephrite and jadeite. Nephrite is a softer variety amphibole group mineral, whereas jadeite is a harder, denser pyroxenite group mineral. Both types occur in association with serpentinized ultramafic rocks that have experienced a moderate to high degree of metamorphism.

Bay region occurrence: Nephrite jade is scarce, but the more common variety, jadeite, can be found in stream gravel bars and on beaches associated with ultramafic rocks throughout the Coast Ranges.

Jadeite from San Benito County.

Extrusive Igneous Rocks

Extrusive igneous rocks form from the cooling of molten material that has erupted on the surface of the Earth, as in a volcanic eruption. Extrusive rocks include lava flows and pyroclastic material, such as cinders or volcanic ash. The rapid cooling of molten rock hinders crystallization processes, so extrusive igneous rocks tend to have a fine-grained texture. In some cases, crystals that formed at depth are carried with the molten material to the surface. These crystals, called phenocrysts, appear to float in a matrix of finer-grained rock material.

Basalt

Rock Type: mafic (rich in iron and magnesium).

Characteristics: gray to black, fine-grained, sometimes displays frozen gas bubbles (vesicular texture), and sometimes contains phenocrysts of feldspar (Ca-rich varieties), hornblende, pyroxene, biotite mica, sometimes quartz or olivine.

Bay region occurrence: Basalt occurs throughout the Bay Area with more ancient occurrences associated with the remnants of submarine volcanoes preserved in

Basalt from near Anderson Reservoir, Santa Clara County.

the Franciscan Assemblage throughout the region. Notable occurrences are in the Marin Headlands and near Morgan Hill at the spillways of Uvas and Anderson Reservoir dams. More recent volcanic eruptions that produced rock of basaltic composition are also located throughout the San Francisco Bay region with notable occurrences throughout Napa and Sonoma Counties, in the Berkeley and east bay hills region, and in the Stanford hills. Younger basaltic rocks also occur in the vicinity of Anderson and Coyote Reservoirs in the south bay, and at the Basalt Recreation Area near San Luis Reservoir.

Andesite boulder from San Luis Reservoir, eastern Merced County.

Andesite

Rock Type: intermediate.

Characteristics: light to dark gray, sometimes with reddish to greenish hues; fine-grained, sometimes displays bubbles (vesicular texture), frequently has a brecciaed texture (tuff) and sometimes contains phenocrysts of feldspar (Ca and Na rich varieties), quartz, hornblende, pyroxene, and biotite mica. This sample shows flow banding that formed as the rock cooled.

Bay region occurrence: Volcanic rocks of andesite composition occur in the north bay in portions of the Sonoma/Clear Lake volcanic region, and in exposures throughout the Pinnacles National Monument area. Cobbles of andesite can be found in stream gravels and conglomerate beds of all ages throughout the region. Andesite outcrops also occur in Henry Coe State Park.

Rhyolite from the stream gravels in Monterey County.

Rhyolite

Rock Type: felsic (rich in silica and aluminum).

Characteristics: light gray, typically pink to red, fine-grained, sugary texture, usually has a brecciaed texture (tuff) and sometimes contains phenocrysts of feldspar (Na-rich varieties), quartz, hornblende, and biotite mica.

Bay region occurrence: Rocks of true rhyolite composition are rare in the San Francisco Bay region; exceptions include volcanic material from the Pinnacles National Monument area, stream cobble and conglomerate, and shipped-in construction materials.

Lava flowing into the sea at Hawaii Volcanoes National Park.

Pillow Basalt—How Does It Form?

When flowing basaltic lava meets ocean water it quickly chills on the surface to become stone. However, because rock is an excellent insulator, the molten rock below the chilled crust will continue moving under the weight of the molten rock streaming behind it, forming tubes of lava. These lava tubes frequently burst, bifurcating into spreading fingers of lava across the seabed. In places the newly formed tubes swell into pod-like masses before freezing to rock. In cross section, an accumulation of these frozen fingers of lava look like stacked pillows. Ancient pillow basalt occurs in outcropping throughout

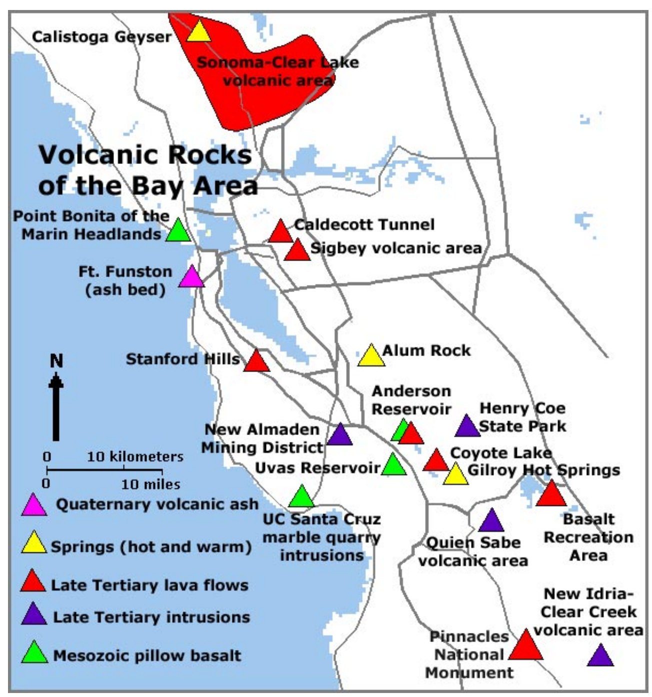
Pillow basalt at Point Bonita in the Marin Headlands.

Pillow basalt with limestone in Uvas Reservoir spillway, Santa Clara County (the hammer handle is one foot long for scale).

the San Francisco Bay region (such as these at Point Bonita in the Marin Headlands). At Uvas Reservoir (near Morgan Hill) limestone occurs between basalt pillows. At the time this pillow basalt formed, the water was shallow and warm enough for lime mud to accumulate on the seabed; such conditions might have occurred on top of a submarine volcano). Today, lime mud accumulates only in tropical to subtropical marine settings. These rocks must have traveled a great distance from where they originally formed. Gradual plate tectonic motion over millions of years can do this.

Volcanic Rocks in the San Francisco Bay Region

The regional landscape preserves the evidence of volcanism that occurred throughout its geologic past. The oldest rocks in the region record evidence of undersea volcanism (pillow basalt) and igneous intrusions that formed deep in the Earth. The region experienced significant periods of volcanism during the formation of the San Andreas Fault system in the late Tertiary (roughly 15 to 8 million years ago). Important mineral deposits formed in association with some of these volcanism episodes (particularly the emplacement of mercury ores). The Sonoma volcanic area is the youngest and largest in the San Francisco Bay region and is still relatively hot (as shown by the existence of geysers and hot springs in the area). The map below shows a number of areas where volcanic rocks can be observed. Many other volcanic rock localities and hot spring areas occur throughout the region that are not shown on the map. Although there are no known active volcanoes in the San Francisco Bay region, great explosive volcanic eruptions in the Cascades and in the western Great Basin region blanketed the region with massive ash deposits in the not too distant past, and could potentially do so again in the future.

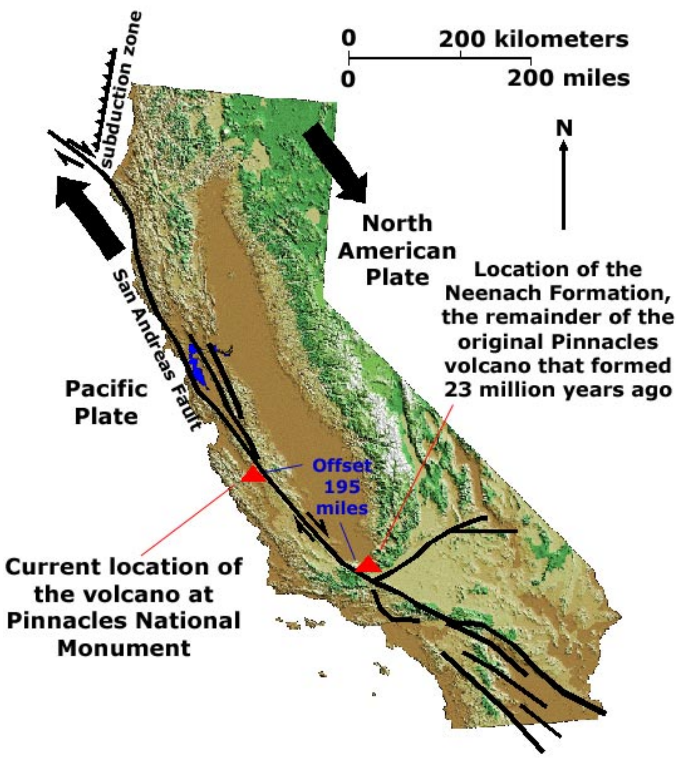


Map showing the location of volcanic rocks in the San Francisco Bay region.

Pinnacles Volcanic Area—A National Monument for Half of a Volcano

Roughly 23 million years ago, a volcano formed near the southern end of what is now the Great Valley (in the region between Bakersfield and Los Angeles). At the climax of its formation, it was roughly 2 miles high (similar to a high Cascades volcano in Oregon). Fortunately for geologists, the volcano formed straddling the San Andreas Fault. Since the end of its eruption cycle, the western side of the volcano (on the Pacific Plate) has moved about 195 miles northwest of a smaller remnant still attached the North American Plate on the eastern side of the fault. This offset volcano is one of many "match points" that geologists have been able to use to establish distances of offset and rates of fault movement through time.

Erosion over 23 million years has stripped away nearly the top mile of rock from the original volcano. The remnants of the volcanic stocks and the steep bedded layers of the volcano's lower flanks are all that remain of the original volcano. The rock is chiefly of rhyolite and andesite composition, and has the texture of a breccia or tuff, an extrusive igneous rock with a rough, sometimes frothy texture and a chemical and mineralogical composition similar to granite (rich in silica and aluminum oxides). The rock formed from the accumulation of many volcanic eruptions through time. Some fossil wood is preserved in the volcanic deposits, suggesting that forests had time to grow back between eruptions.



Map showing the migration of the Pinnacles volcano.

View of the High Pinnacles (eroded volcanic rocks) in Pinnacles National Monument.

Hydrothermal Deposits

Where volcanism occurs, there are associated processes that affect the surrounding host rock. Fluids released from the magma, along with fluids in the surrounding rock, migrate through porous spaces in the surrounding rock and especially along fissures, fractures, and faults. With the changing chemical conditions of these fluids as they interact with the bedrock, minerals are either dissolved or precipitated. Where these fluids reach the surface, hot springs and fumaroles (gas vents) occur and are typically the location of surficial mineral deposits. Fissures and fractures underground can become places where minerals accumulate, typically forming quartz and calcite veins, but in some places in the San Francisco Bay region other minerals occur, including ore minerals of mercury, copper, lead, and other metallic and non-metallic minerals.

Travertine

Characteristics: A soft white, yellow, or gray rock consisting of layered microcrystalline to fine fibrous crystals of calcite. It occurs in fracture fillings and on surfaces of caverns in limestone, and around springs. Notable occurrences include springs at Alum Rock Park in San Jose, on Fremont Peak, and along streams throughout the Santa Cruz Mountains.

Travertine from Fremont Peak, San Benito County.

Hydrothermally Altered Basalt

Characteristics: yellow, orange, to reddish gray, typically displaying the frothy, vesicular texture of the original basalt. Cavities are frequently filled with rock crystal (quartz), chalcedony, common opal, and calcite crystals (both dogtooth style crystals and fibrous varieties), and occasionally pyrite, copper minerals, fluorite, and frequently cinnabar. Hydrothermally altered rock can be found wherever volcanic rock occurs. However, the mineral replacement processes make the rock typically much harder and denser than the original host rock. It is usually abundant on downstream gravel bars.

Hydrothermal-altered basalt from Coyote Creek, Santa Clara County.

Calc-Silicate Rock

Characteristics: yellow, orange, and pale green, brown to gray, typically forming in fissures in limestone or serpentinite host rock. It typically has abundant mineral-filled cavities frequently containing rock crystal (quartz), calcite, and cinnabar. This is the host rock for most of the mercury ore (cinnabar) mined in the New Almaden Mining District in southwestern San Jose, with scattered occurrences throughout the eastern Santa Cruz Mountains and in the region around New Idria in the central Diablo Range.

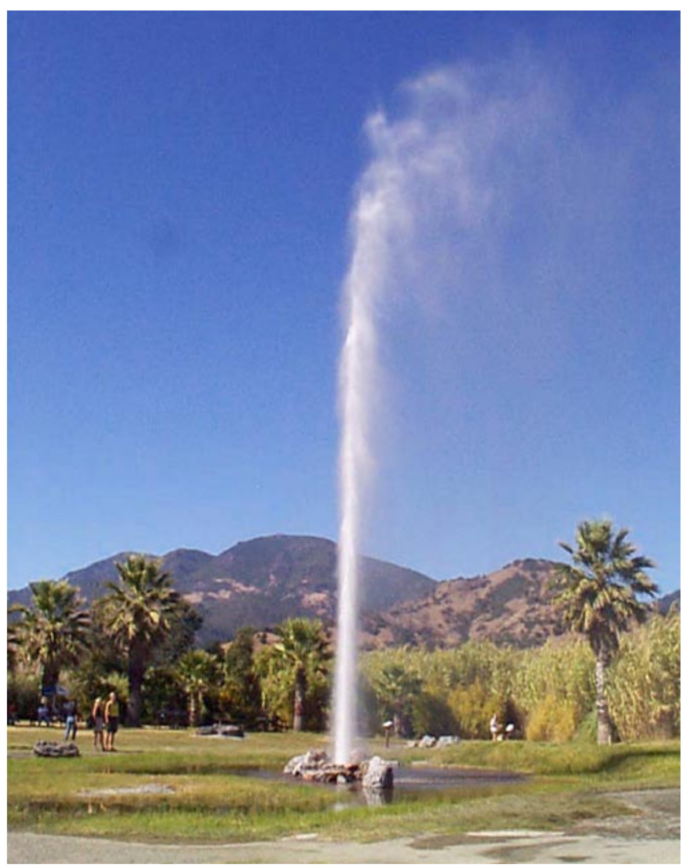
Calc-silicate rock from the Cinnabar Hills area, Santa Clara County.

Springs, Warm Springs, and Hot Springs and Their Deposits

Some precipitation seeps into the ground. As this water migrates downward, it reaches a point where the available pore space in fractures and between rock grains is nearly completely saturated with water. This level is called the water table and is basically defined by the static level that water will rise to in a well. The water table is not a flat surface, but rather roughly follows the general topography of the landscape. Where there is both permeability in the ground and differences in elevation of the water table, ground water will gradually flow in the direction from high to low. A spring is a passage where water flows freely from the ground. Springs basically define locations where the water table intersects the land's surface, and sufficient water volume, pressure, and permeability exist to allow water to discharge.

As ground water migrates it continuously equilibrates with the temperature of the rock and the chemistry of the materials it encounters. Depending on conditions mineral compounds will dissolve into or precipitate from ground water, sometimes simultaneously. In areas of "recent" (geologically speaking) or ongoing volcanism, heat originally derived from magma will be transferred into the migrating ground water. This heat can then be transferred to springs at the surface.

In general, shallow ground water basically is in temperature equilibrium with the annual average temperature of



The Calistoga Geyser (Old Faithful Geyser of California) in northern Napa Valley, evidence that the Sonoma volcanic field is still relatively young and hot.

any particular location, but may vary seasonally. A "warm spring" is any water discharge site where the ground water is continuously at least several degrees higher than the annual or seasonal temperature average. A "hot spring" is a spring that has a temperature greater than human body temperature (98ºF). Where temperatures reach the boiling point of water near the surface, boiling hot springs, geysers, and fumaroles (steam vents) may occur. In some cases, the water may contain fluids derived from magma (including water, CO_2, sulfurous gases, and dissolved matter).

Perhaps the most common rocks associated with spring deposits are travertine and tufa. Travertine is a finely crystalline, massive deposit of calcium carbonate (calcite). Tufa typically consists of microcrystalline calcite sometimes preserving organic remains. Travertine and tufa spring deposits are common in areas where limestone is abundant in the subsurface. Hot springs in volcanic areas typically precipitate silica (SiO_2) with other mineral matter forming a rock called siliceous sinter. These rocks form where chemical and temperature changes drive mineral precipitation reactions.

Travertine being deposited by springs along Stevens Creek Canyon Road (Santa Clara County).

Cinnabar (Mercury Ore) And the New Almaden Mining District

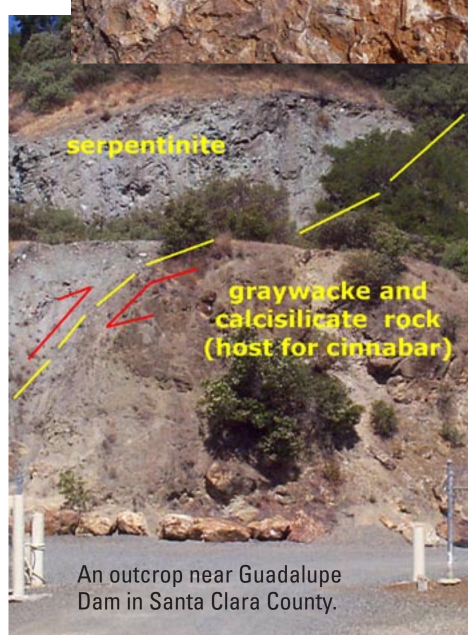
Cinnabar (HgS), mercury ore, was mined in the hills southwest of San José from the late 1820's until 1976. The New Almaden Mining District was the largest producer of mercury in North America. Company records indicated that over a million flasks of mercury were produced from the mining district (a flask holds roughly 65 pounds of liquid mercury). More than 95 percent of the production occurred before 1900, with the most productive years occurring in the decade following the Civil War. The majority of the mercury produced was used for gold mining and production in the Sierra Nevada region.

The cinnabar deposits probably formed in association with a period of volcanism in the region roughly 10 to 12 million years ago. Hydrothermal fluids (hot mineral water and gases) migrated along faults and fractures in the serpentinite bedrock, altering the bedrock while precipitating calcite and quartz (calc-silicate rock) and cinnabar. Outcrops near Guadalupe Reservoir (right) display typical fracture filling of the calc-silicate host rock. Cinnabar is typically deep red in color, but ranges to brown and black, and sometimes displays tiny droplets of liquid mercury on its surface. Be aware that cinnabar is quite toxic and especially shouldn't be handled by children. Also, food grown in mercury-contaminated areas (including fish) may also contain hazardous levels of mercury. When in doubt, leave it alone!

San Cristobal Mine shaft entrance and ruins on Mine Hill in Almaden Quicksilver County Park, Santa Clara County.

Cinnabar in calc-silicate rock (Guadalupe Dam).

Calc-silicate rock in altered serpentinite (Guadalupe Dam).



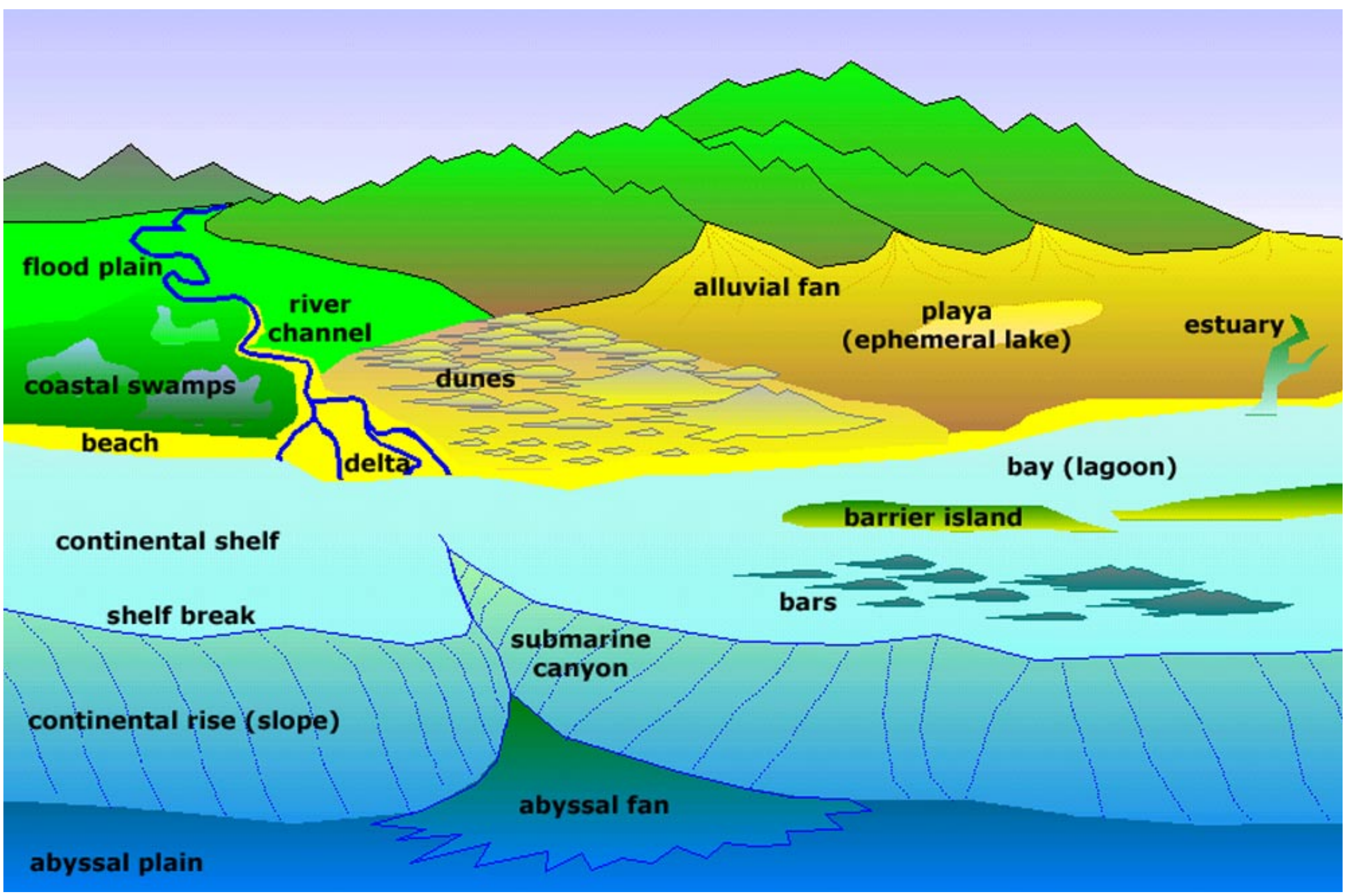
An outcrop near Guadalupe Dam in Santa Clara County.

Sedimentary Rocks and Processes

The daily influences of the atmosphere and water slowly physically disintegrate and chemically decompose rocks exposed at or near the surface. These processes are collectively called weathering. Many processes contribute to converting rocks into smaller sediments. For example, rainwater may seep into cracks and freeze; the expansion of ice can create tremendous forces, enough to break rock. Likewise, roots penetrate into cracks and expand. Resistant fragments become sediments, whereas soluble compounds dissolve and are carried away by flowing water on the surface and underground. Erosion involves the transport of sediments by an "erosion agent," such as running water, waves, wind, or glacial ice. Rocks are broken down from larger to smaller fragments: boulders, cobbles, gravel, sand, silt, and microscopic clay-sized particles. The finer the particle, the more easily it is transported. In this manner sediments become sorted into size fractions by waves, running water, or wind.

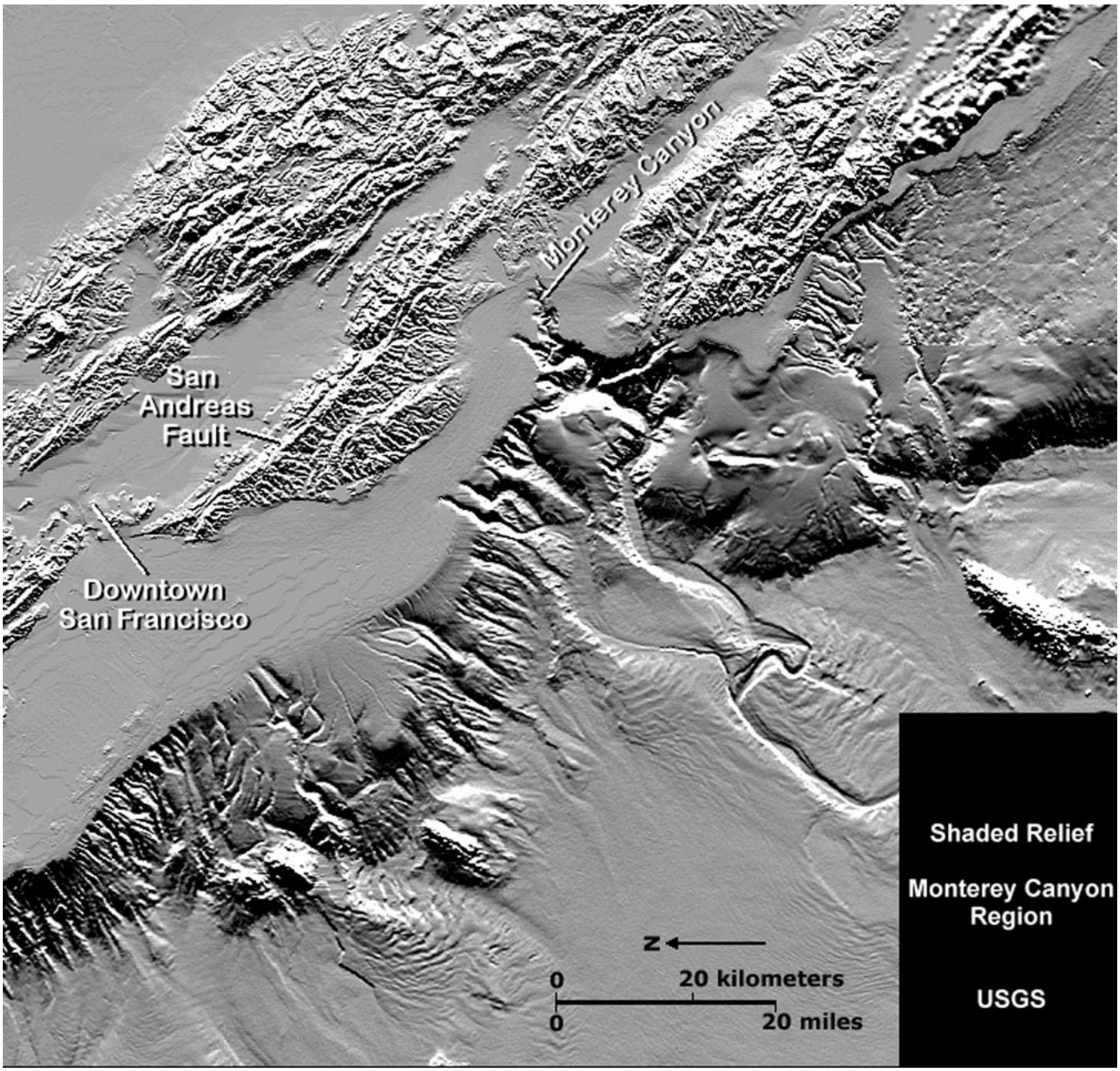
Sediments are transported and deposited in a variety of depositional environments. On land, sedimentary environments include stream flood plains, swamps, dunes and desert basins. Along the coastal regions sediments accumulate in river deltas, lagoons, beaches, and barrier islands. Most sediment ultimately comes to rest in the ocean, accumulating in massive deposits that form the continental shelves, or continuing to the deep basins beyond the continental shelf margin.

As sediments accumulate, the weight of overlying layers causes compaction. Dissolved minerals precipitate in pore spaces, cementing grains together. The process of lithification involves the combined effects of compaction and cementation, resulting in the formation of sedimentary rocks. Sedimentary rocks consist of pieces or fragments of rock (clasts), minerals precipitated from water, or a combination of the two sources. Sedimentary rocks are generally named after their primary clast sizes and their mineral constituents (with some exceptions).



Depositional environments where sediments may accumulate.

The image below combines topographic and bathymetric data for the greater San Francisco Bay region and illustrates the extent of different sedimentary environments, as they exist today. The image is also useful for interpreting the kinds of sedimentary environments that existed in the past that are now preserved as sedimentary rock formations exposed in mountainous areas and road cuts in the region. For instance, the vast majority of the sediments deposited in the region today are on the continental shelf and in the deep-ocean basin beyond the continental slope. Many of the sedimentary rocks exposed in the Santa Cruz Mountains and the Diablo Range formed in similar offshore settings in the geologic past and were subsequently uplifted to their present locations by tectonic forces and then exposed by erosion. In contrast, stream and other terrestrial deposits only represent a small portion of the sedimentary environments in the region today, and this contrast is also reflected in the sedimentary geologic record. Terrestrial deposits tend to be eroded away rather that be preserved, but this isn't always the case. For instance, the occurrences of coal mines in the Diablo Range are a testament of forested swamps in the region in the geologic past.



Bathymetry and topography shaded relief image of the San Francisco Bay region (from: http://terraweb.wr.usgs.gov/TRS/projects/Monterey/).

Soil

The breakdown of rock into soil is a slow process that is going on practically everywhere around us and especially beneath us. Most of the landscape around us doesn't consist of exposed rock. In most places you would need to dig down many feet, even hundreds of feet, before you encountered "fresh" (unaltered) bedrock. This is because chemical and mechanical processes combine to break down rocks, leading to the formation of soil. The word soil has two meanings. In its perhaps more familiar sense, it is the natural medium for the growth of land plants. Technically, soil includes all unconsolidated materials above bedrock. The entire section from bedrock to the surface is called a soil profile and can be subdivided into soil horizons (O, A, B, and C). A typical soil profile consists of:

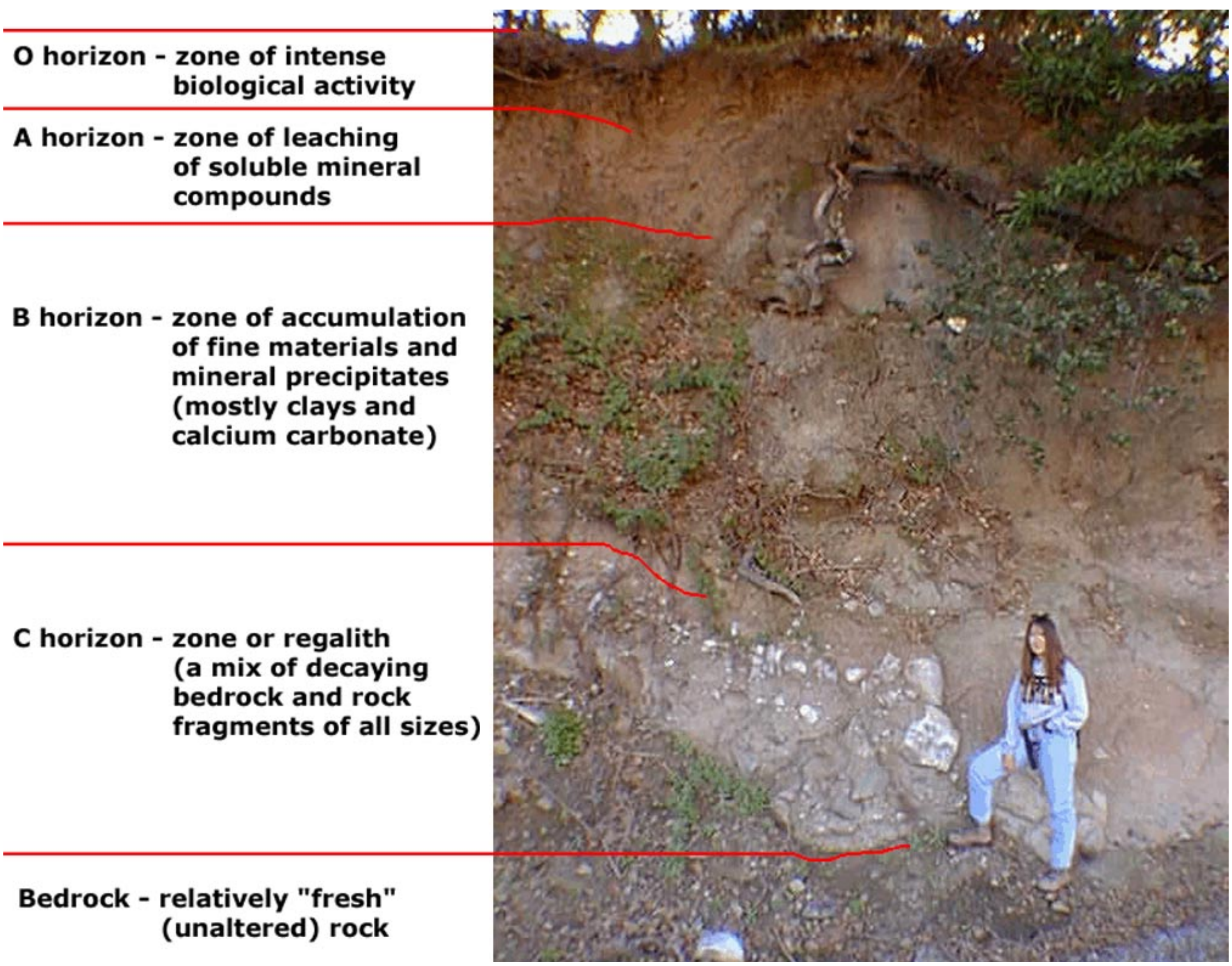
O Horizon—At the surface organic mater accumulates. This organic detritus, called humus, is mostly decomposing plant debris. This horizon (O) is where biological reworking of material is most intense (mixing both organic material and material derived from the parent rock).

A Horizon—Below the organic-rich surface layer the combination of organic acids and water from precipitation leaches more soluble compounds from the parent rock material. This horizon (A) tends to have a dark stain from the organic acids and consists of materials that are more resistant to weathering (like quartz sand). This interval, sometimes called the "zone of leaching" it typically loose and friable.

B Horizon—Below the "zone of leaching" is the "zone of accumulation." This is where fine material carried by water percolating downward settles out and accumulates. Clay-size grains fill in between grains, and during dry periods, minerals dissolved in water precipitate. The B horizon tends to be quite dense and impermeable. Clays in this interval may expand when wet, and shrink and crack when they dry out.

C Horizon—This interval consists of slightly decayed parent rock material but hasn't experienced the degree of leaching and accumulation that has occurred in the A and B horizons. The C horizon is characterized by large blocks to small chips of bedrock, most of which display some evidence of breakdown or alteration through the interaction with ground water.

There are many kinds of soils. The character of the soil depends on factors such as amount of precipitation (and evaporation), the physical and chemical characteristics of bedrock, plant cover, hill slope, temperature, and other factors. The formation of soil is significant in that most sediment is derived from the erosion of soil.



A complete soil profile exposed by wave erosion along the shore of Calero Reservoir in Santa Clara County.

Layers in Sedimentary Rock

Most sedimentary rocks display layering. However, the layering can be on many different scales, ranging from paper-thin clay layers in a hand specimen to massive layers that crop out along a whole mountainside. Layering reflects many different sedimentation processes but with common characteristics. The parallel layers in sedimentary rocks are called strata. Strata generally preserve the gentle, flat-lying surface character of their original depositional environments. Sedimentary rocks frequently contain fossils, the remains, traces, or imprints of plants or animals from the geologic past. They also preserve a host of sedimentary structures including ripple marks, raindrop impressions, desiccation cracks, and other features that are useful tools for interpretation of ancient environmental settings.

Because sedimentary rocks form near the surface, they may ultimately become exposed to weathering and erosion. However, in certain geologic settings such as in a sedimentary basin along the margin of a continent, they may be subjected to increasing burial. Because sedimentary rocks typically preserve layers (strata) that reflect their original, flat-lying mode of deposition, they are useful in interpreting geologic changes that have happened through time. For instance, they may reveal such processes as folding or faulting that have occurred with mountain uplift after the original sediments had been deposited. Geologists group strata into sets ranging from smallest to largest—bed, unit, member, formation, and group. A bed might represent sediments deposited in a single event, such as a giant sea storm, flood, or ash layer from a volcanic eruption, whereas a formation or group might represent the entire accumulation of sediments deposited through an entire period of geologic time lasting many millions of years. The most commonly referred designation is formations and their member subdivisions. A formation is a body of rock strata that consists dominantly of a certain rock type or combination of types, and typically is mappable across a wide area or region. Sedimentary formations may also preserve fossil plant and animal associations that exist together because of closely similar life patterns, habits, and climatic requirements at the time the sediments were deposited.

The law of original horizontality suggests that in any depositional setting, denser materials under the influence of gravity will settle to the bottom of a depression, with sediments filling in spaces to create an even surface. The law suggests that a water-laid stratum, at the time it was formed, must continue laterally in all directions until it thins out as a result of non-deposition or until it abuts against the edge of the original basin of deposition. The law of superposition says that lower areas will fill in first, with younger sedimentary deposits accumulating on top (oldest rocks on the bottom, youngest on top). However, these two rules wouldn't make sense without another law to help us explain how we see sedimentary rock outcrops. Once a sedimentary stratum has formed, tectonic forces can uplift or distort the originally flat-lying beds. The law of cross-cutting relationships basically states that rocks are older than the forces that change them: for instance, the rocks have to be older than the fault that breaks them, folds that reflect tectonic deformation, or igneous material that was intruded into them. To produce geologic maps, geologists measure the changes in sedimentary stratification (away from their original horizontal orientation) to map the structures of the earth that have resulted from subsequent tectonic modification of the rocks that later have been exposed by erosion on the land's surface.

Sea cliffs at Wilder Ranch State Park (Santa Cruz) display flat-lying strata consisting of mudstone that formed from mud deposited several million years ago on a seabed similar to the modern outer continental shelf. Ongoing tectonic uplift associated with the formation of the Santa Cruz Mountains has exposed these strata on the land's surface. They are now being gradually destroyed by coastal erosion, with most of the sediments returning to the continental shelf or beyond to the deep-ocean basin.

What Strata Can Reveal About Earth History

Layers of shale exposed in a road cut along the Mt. Hamilton Road in Santa Clara County were probably originally formed from clay-rich sediments deposited in deep water. With time the mud was compacted and cemented into shale. The law of original horizontality suggests these strata were originally flat lying. Tectonic forces subsequently tilted the rocks, possibly concurrent with the uplift of the Coast Ranges.

A small fault offsets strata exposed along the sea cliffs near Gazos Creek (San Mateo County in Año Nuevo State Park). Layers “A” and “B” are offset about two meters (a rock hammer provides scale). The law of crosscutting relationships suggests that the fault is younger than the sedimentary layers.

Layers tectonically folded into down-warped sedimentary strata (a geologic structure called a syncline) are exposed at low tide at the James V. Fitzgerald Marine Reserve in San Mateo County. The law of original horizontality suggests that the sediments were originally deposited in horizontal layers. The law of crosscutting relationships suggests that the sedimentary layers are older than the forces that folded them.

Sediments and Sedimentary Deposits

Erosion is the wearing away of rock, soil, and preexisting sediments by processes involving weathering, mass wasting, and the action of streams, wind, waves, glacial ice, and ground water. Erosion involves the movement of material (sediments) from one place to another. This can include clastic sediments ("clastic" simply means rock fragments) or material dissolved in water. Once sediments reach a final destination (a depositional environment) they can undergo lithification, the processes of converting sediments to sedimentary rock. This typically involves compaction (loss of pore space and the interlocking of grains) and cementation (the binding of grains by the precipitation of mineral cements, such as silica, calcium carbonate, clays, or iron oxide minerals). Common sediments and their equivalent sedimentary rock are listed below. Note that not all sedimentary rocks are formed from erosion byproducts but may form as a result of precipitation by chemical or organic reactions or a mixture of all of the above.

The coastal environment is perhaps the easiest place to watch the progress of geologic change, particularly in the San Francisco Bay region where winter storms cause a tremendous amount of erosion of the beach and the base of sea cliffs. This leads to landslides and slumps that carry sediment from the hillsides to the surf zone. Sand is carried by wave energy to offshore bars where it can accumulate. During the summer months the more quiet daily tidal cycle allows waves to gradually transport sand from offshore bars back onto the beach. Through time, the constant recycling and winnowing of the sediment concentrates the more durable mineral grains (particularly quartz sand and gravel), while the finer materials (clays) stay in suspension and get transported out to sea where they settle to the bottom in deeper, quieter water. In this manner sand tends to accumulate and concentrate in the coastal zone, an environment that ranges from upper beach dune areas to the region offshore where wave energy begins to influence the sea bottom (roughly at about 30 meters depth). With the constant supply of sediments from rivers and streams and the erosion of the coastline, with time, the amount of sandy sediment that accumulates in the coastal zone is tremendous.

Compounding the progress of sand accumulation in the coastal zone are the influences of tectonic uplift and subsidence. In the San Francisco Bay region many active earthquake faults are gradually or episodically moving the landscape. For instance, the sea cliffs at Thorton/Ft. Funston Beach (shown at right) are a great accumulation of sediments deposited in the coastal zone in many different sedimentary environments. Geologists named this thick sequence of sand-dominated deposits the Merced Formation. This sequence of strata was deposited in a slowly subsiding basin that because of changes in the geometry of the San Andreas Fault system is now slowly rising and being exposed once again to coastal erosion. The Merced Formation preserves evidence of many cycles of sea level rise and fall through the Pleistocene Epoch, the geologic time period representing a series of ice ages that began roughly 1.8 million years ago and ended about 10,000 years ago. With each ice age, great continental glaciers slowly formed and then melted during intervening warm periods. Sea level change during each glaciation's cycle was in the range of 160 to 500 feet (about 50 to 150 m). Fossiliferous marine beds alternating with terrestrial beach dune and shore deposits suggest that the Merced Formation preserves evidence of at least nine glaciations cycles in the past 600,000 years.

Classification of clastic sediments and sedimentary rocks.

Clast Size	Size Class*	Sediment/Rock Name
>256 mm	boulders	sediment = gravel rock = conglomerate
64-256 mm	cobbles	
4-64 mm	pebbles	
2-4 mm	granules	
1-2 mm	very coarse sand	sediment = sand rock = sandstone
.5-1 mm	coarse sand	
.25-.5 mm	medium sand	
.125-.25 mm	fine sand	
.063-.125 mm	very fine sand	
.032-.063 mm	silt	sediment = mud rock = mudstone, siltstone and shale
<.032 mm	clay	

*Udden-Wentworth sediment size classification (Wentworth, 1922)

Classification of chemical and organic sedimentary rocks.

Sediment or Mineral Constituents	Rock Name
Limey sediment composed of calcareous skeletal material (algae, shells, coral, etc.) or calcite preciptated from water	limestone
calcite in limey sediments can be altered by sea water and converted to dolomite	dolostone
calcium sulfate precipitated from sea water through evaporation processes	gypsum and anhydrite
sodium chloride (halite) precipitated from sea water through evaporation processes	rock salt
silica precipitated by chemical changes in water or by biological activity	chert
carbon derived from organic material	coal

Beach and sea cliffs at Thorton/Ft. Funston Beach.

Sedimentary Rocks

Conglomerate

Rock characteristics: A coarse-grained clastic sedimentary rock composed of rounded to subangular fragments larger than 2 millimeters in diameter (pebbles, cobbles, and even boulders) set in a fine-grained matrix of sand or silt, and commonly cemented by calcium carbonate (calcite), iron oxides, silica, or hardened clay. Conglomerate is the consolidated equivalent of gravel.

Bay region occurrence: Conglomerate occurs throughout the San Francisco Bay region with notable occurrences in the Pigeon Point area (San Mateo County coast), as terrace gravels throughout the south bay region (particularly along Highway 101 near Anderson Reservoir) in the Santa Cruz Mountains with large exposures on Loma Prieta Peak, at Point Lobos on the Monterey Peninsula, and at the lighthouse on Point Reyes.

Conglomerate of undetermined age formed from well-rounded stream gravel consisting mostly of sandstone and chert derived from the Diablo Range. This sample is from a gravel bar along Coyote Creek.

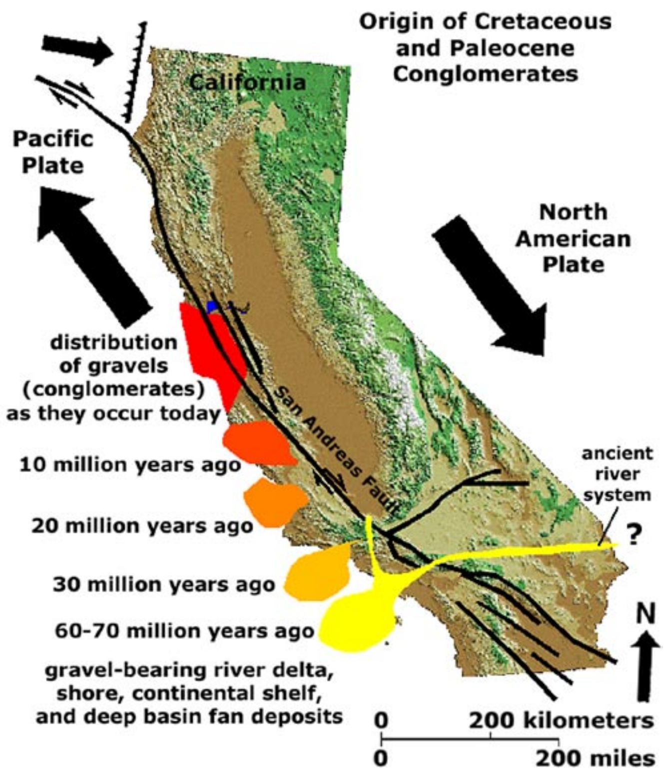
Conglomerate from the Pigeon Point Formation (Cretaceous). Cobbles consist of very well rounded pieces of volcanic rock (mostly andesite) probably worked by marine currents and deposited in the deep-ocean basin.

This sample is technically a “volcanic breccia” formed on the flank of an ancient submarine volcano. The volcanic cinders are cemented together by limey clay deposited on the sea floor. This sample is from Uvas Creek near Morgan Hill.

Conglomerate containing a mix of rounded and angular fragments of serpentinite and sandstone, and cemented by calcite and clay. It probably formed fairly recently as a stream deposit near the source where the gravel was derived. This sample is from Clear Creek in San Benito County.

Origins of conglomerates—Fast moving rivers and ocean currents can transport gravel long distances. Within gravel deposits it is sometimes possible to find materials of unique composition that can be correlated to a definitive source. Studies of gravel deposits in rocks of all ages in the California coastal ranges show that river systems originating from destinations possibly as far away as central Mexico to the Canadian Shield have provided sediments to coastal California in the past (these river systems no longer exist today due to changes in the landscape). For instance, certain types of quartzite and igneous rocks with unique mineral compositions found in ancient gravel deposits throughout the Santa Cruz Mountains can be recognized in similar gravel deposits as far away as Santa Barbara, the Mojave, and possibly even Wyoming! These gravel deposits, along with the fossils they contain, help geologists to understand the changes in the landscape and geologic settings through time. This information has also helped to prove the rate of offset motion along the San Andreas Fault through time.

Conglomerate bearing marine fossils near the top of Loma Prieta Peak in Santa Cruz County.



Origin of Cretaceous and Tertiary conglomerates in the region. The diagram shows movement of the gravels after deposition as a result of tectonic forces.

A modern stream gravel bar along Coyote Creek in Santa Clara County.

Sandstone

Rock characteristics: A clastic sedimentary rock composed of 80 to 90 percent sand-size grains set in a matrix of silt or clay and more or less firmly united by a cementing material (commonly silica, iron oxide, or calcium carbonate); the consolidated equivalent to sand.

Bay region occurrence: Sandstone occurs throughout the San Francisco Bay region with notable occurrences along the crest of the Santa Cruz Mountains, forming the massive cliffs at Castle Rock State Park. Similar rock sandstone outcrops occur at Chitactac-Adams Heritage Park in southern Santa Clara County, along Highway 101 between San Juan Bautista and Salinas; throughout the sea cliffs of the Purisuma Formation in Santa Cruz; at Año Nuevo State Park; between Bean Hollow and Pescadero State Beaches; at Half Moon Bay; at Fort Funston Beach; and near Rodeo Beach in the Marin Headlands. Many of these sandstone outcrop areas contain beds rich in marine invertebrate fossils.

Fossiliferous sandstone from the crest of the Santa Cruz Mountains. Although the rock is full of marine invertebrate shells, mostly late Tertiary gastropods, clams and barnacles, it is still considered sandstone, not a conglomerate.

Sandstone from near Guadalupe Reservoir (Santa Clara County). Uniform sand deposits form from natural refining processes. Rivers transport a mix of cobbles, gravel, sand, silt, and clay. Once these sediments reach the ocean, wave action or marine currents constantly rework and refine sediment fractions. Gravel accumulates in the highest energy environments and is subjected to heavy reworking. Sand migrates and accumulates where wave energy and currents dissipate, whereas silt- and clay-sized material is transported far offshore to quieter, deeper water. Massive sandstone bodies represent ancient sedimentary environments, such as beaches or barrier islands, sand bars formed on the continental shelf, or sand accumulations in the deep ocean near the base of the continental slope. These deep-water deposits form when underwater landslides entrain large quantities of sediments down slope in the form of density currents called turbidity flows (muddy water is denser than clear water and therefore, it sinks). These create deposits called turbidites that consist of interbedded sandstone, mudstone, and shale, and sometimes, conglomerate.

Fossiliferous sandstone (Purisuma Formation, late Miocene) from New Brighton Beach near Capitola, Santa Cruz County. This piece preserves mollusk shells and a portion of whalebone offset by a tiny fault (bottom).

A massive outcrop of sandstone rises out of Guadalupe Reservoir near Almaden-Quicksilver Park in Santa Clara County (right). Marine fossils preserved in outcrops such as these provide reminders that shallow seas once covered the region long before the Santa Cruz Mountains formed.

Massive outcrops of sandstone occur scattered throughout the San Francisco Bay region, particularly along the crest of the Santa Cruz Mountains. Exceptional outcrops of sandstone in Castle Rock State Park (right) display an unusual weathering pattern called "tafoni." When precipitation soaks into porous sandstone, some of the mineral cement dissolves. As the rock dries out, capillary action brings moisture along with dissolved minerals to the surface. As the water evaporates, the minerals precipitate. In this manner, the rocks actually break down from the inside out as this weathering process removes the mineral cement below the surface. The wind and weather help to sculpt away the softer rock, leaving the more resistant, tightly cemented surface rock behind. Goat Rock (shown here) is one of many popular scenic hiking and rock climbing destinations at Castle Rock State Park.

Native Americans used sandstone outcrops for many purposes. Sandstone outcrops occur along Uvas Creek at Chitactac-Adams Heritage Park in southern Santa Clara County (left). Many of the outcrops display an abundance of mortar holes used for grinding and preparing food and also display petroglyphs (carved symbols in the rock).

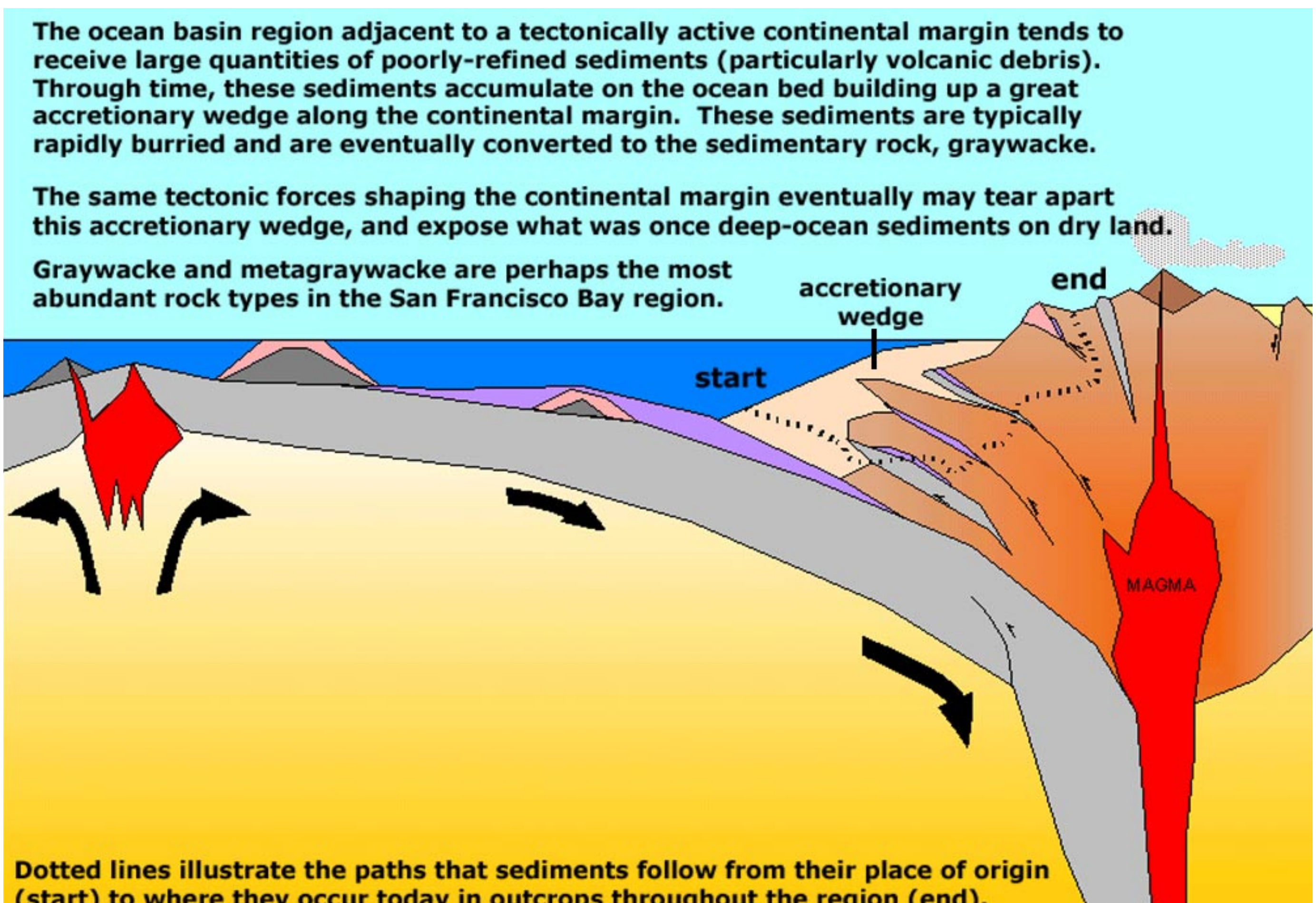
Graywacke—An Old Sedimentary Rock Term With A New Meaning

Graywacke is an old German term, now generally applied to a dark, firmly indurated, coarse-grained sandstone to siltstone that consists of poorly sorted angular to subangular grains of quartz and feldspar, with a variety of dark rock and mineral fragments, embedded in a compact clayey matrix. Where perhaps the preferred terminology for naming sedimentary rock is to focus on the host sediment (for example, "sand" for sandstone), the term graywacke now also implies a general environment of origin adjacent to an tectonically active plate margin where streams draining a volcanic mountain range dump large quantities of poorly sorted sediments into an ocean basin setting. Graywacke commonly exhibits graded bedding (thick layers containing coarse-grained sand at the base and finer-grained mudrock on top) and was probably deposited by submarine turbidity currents.

Bay region occurrence: The term "graywacke" can perhaps be loosely applied to the majority of clastic sedimentary rocks that crop out in the region. Practically any brown or gray "dirty" sandy sedimentary rock exposure in the Santa Cruz Mountains or the Diablo Range could be called a graywacke. Exceptional exposures of true graywacke turbidites are exposed at Bean Hollow State Beach and near Rodeo Beach in the Marin Headlands. Graywacke is abundant in Franciscan Assemblage rocks practically wherever they occur. Throughout the Diablo Range these rocks have experienced varying grades of metamorphism, ranging from relatively soft mudstone to dense metasandstone.

Graywacke at Bean Hollow State Beach.

Path to formation—graywacke.



Mudstone and Siltstone

Rock characteristics: Sedimentary rock composed of indurated mud and having the texture and composition of shale, but lacking its fine lamination or fissility (ability to break apart into tiny flakes). The difference between the two is that siltstone is greater than 50 percent silt, and mudstone is greater than 50 percent clay. Both rock types tend to be brittle. Siltstone tends to be flaggy, splitting into thick layers and displaying current structures. Both rock types preserve marine fossils (mostly microscopic plankton), including occasionally fish scales, bone, and invertebrate shells and their traces. Mud and silt tend to be deposited in deeper water conditions below wave base on the continental shelf or in bays.

Bay region occurrence: The Santa Cruz Mudstone, a Miocene rock formation, forms sea cliffs throughout northern Santa Cruz County. The Monterey Formation, another Miocene-age rock formation, crops out in massive cliff exposures throughout the Salinas Range between Carmel and Arroyo Seco Canyon. Mudstone and siltstone of "graywacke" composition is perhaps the most abundant rock type in the region, cropping out throughout the Santa Cruz Mountains west of the San Andreas Fault and along the flanks of the Diablo Range (accessible exposures occur along the Mt. Hamilton Road in Santa Clara County).

Santa Cruz Mudstone (from near Davenport). This sample displays a weathering pattern of banded, brown rings and spots called liesgang rings. It forms as is iron oxide precipitated by ground water influenced by alternate periods of wetting and drying.

Siltstone from Arroyo Seco Canyon, Monterey County. Note the flaggy splitting character of the rock.

Marlstone

Rock characteristics: Marlstone is an indurated rock consisting of a mix of clay, mud, sand, and an abundance of calcareous material, mostly shell material. It sometimes contains a green grainy mineral called glauconite, a mineral that typically replaces marine invertebrate fecal material. These rocks form sediments typically deposited in shallow marine conditions.

Bay region occurrence: Fossiliferous marlstone is not uncommon throughout the Santa Cruz Mountains.

A marlstone shell hash from the Purisuma Formation from a beach at Capitola, Santa Cruz County.

A block of marlstone from Stevens Creek, Santa Cruz Mountains.

Shale

Rock characteristics: A fine-grained clastic sedimentary rock formed by the compaction of clay, mud or silt. Shale differs from mudstone in that it has finely laminated bedding structure along which the rock splits readily (a property of shale called fissility). This characteristic of fissility is greatest in shale that formed from mud enriched in clay and depleted in silt or coarser materials. In fresh exposures, shale is a well-indurated sedimentary rock, but it tends to quickly break down into small flakes and clay mud when exposed to surface weathering. Shale formed from mud deposited in the ocean, bays, or swamps tends to be greenish to bluish gray to black (rich in organic matter) or red to brown when formed from mud in a terrestrial environment, such as a floodplain soil.

Bay region occurrence: Shale tends to break down so quickly that landscape underlain by shale tends to be well forested or grass covered. It occurs in association with sandstone in most areas; however, massive exposures of shale occur along the eastern flank and foothills of the Diablo Range. This thick belt of sedimentary rock is called the Great Valley Sequence, and is perhaps easiest to see exposed along the shores of San Luis Reservoir along Highway 152 between Pacheco Pass and Los Baños. This great belt of sedimentary rock is many thousands of feet thick and crops out in the foothills west of Interstate 5 from Tracy to Bakersfield and beyond. It represents mud that accumulated along the western edge of the continent long before the Coast Ranges were uplifted. Shale occurs interbedded with sandstone and conglomerate in sedimentary deposits called turbidites. These represent undersea landslide deposits that accumulated in the deep ocean setting at the base of the continental slope. Also throughout the region, the combination of shearing action by fault motion and exposure to ground water have converted pulverized rock into a flaky mudrock that has the appearance and composition of shale but lacks its original bedding structure. In some cases the original rock may have been shale.

Interbedded shale and sandstone (turbidites) exposed at Bean Hollow State Beach along the San Mateo Coast.

Shale of the Great Valley Sequence crops out in badlands in the Panoche Hills, south of Los Baños.

Limestone and Dolostone

Rock characteristics: Limestone is a sedimentary rock consisting chiefly of the mineral calcite ($CaCO_3$, calcium carbonate), with or without magnesium carbonate. Common impurities include chert and clay. Dolostone is a sedimentary rock that is enriched in the magnesium-carbonate mineral, dolomite, $CaMg(CO_3)_2$. A carbonate rock is considered dolostone if it is greater than 50 percent dolomite. Limestone fizzes vigorously when exposed to hydrochloric acid; dolomite fizzes poorly by comparison. The two rocks frequently occur together. Limestone is typically white, pale gray to black (due to high organic content). Dolostone is light gray to pink.

Bay region occurrence: Limestone and dolomite are common in areas west of the San Andreas Fault with large mining operations near Stevens Creek near Cupertino, and an abandoned quarry near Rockaway Beach along the San Mateo Coast. Fremont Peak south of Hollister is a massive outcropping of limestone and dolostone. Smaller masses of these rocks crop out throughout the Santa Cruz Mountains with notable exposures near Uvas, Calero, and Lexington reservoirs in the south bay. Limestone nodules (called concretions) occur in the Cretaceous Great Valley Sequence, with exposures around Anderson Reservoir and throughout the eastern flank of the Diablo Range.

Limestone (tan to bluish-gray) with chert (gray) from the Cinnabar Hills near Calero Reservoir in the south bay. Limestone was mined in the area before the reservoir was constructed.

A rock consisting of alternating layers of dolostone (pink) and chert (red), from hillside exposures south of Morgan Hill.

An unusual limestone consisting dominantly of fossil oyster shells. This example is from the southern Santa Cruz Mountains.

Concretions—Nature's Time Capsules

Concretions are small to large rounded nodules that form in sedimentary rocks, typically in shale or sandstone. Concretions form slowly as minerals precipitate from ground water around a "nucleation site." A nucleation site can be a shell or bone, a piece of organic matter, or even a mineral grain. Minerals such as calcite, dolomite, or limonite precipitate and grow pervasively in the microscopic voids in between sedimentary grains. Over hundreds or even millions of years concretions can continue to grow. Sometimes fossils inside are well preserved.

Examples of concretions and the fossils they preserve can be seen in abundance in the sea cliffs at Año Nuevo State Park. These exposures are part of the Purisuma Formation of late Miocene to Early Pliocene age (roughly 8 to 5 million years old). These sedimentary rocks formed from sediments deposited on the shallow continental shelf. They were uplifted and exposed to coastal erosion by the greater forces lifting the Santa Cruz Mountains and the coast.

Concretions eroding from the sea cliffs at Wilder Ranch near Santa Cruz. These concretions formed in the marine sediments of the Santa Cruz Mudstone.

A concretion exposed in the sea cliff at Año Nuevo displays an abundance of well-preserved fossils inside.

A limestone septarian concretion from the Great Valley Sequence exposed along the shore of Anderson Reservoir. Concretions grow slowly through rock-water reactions in shallow sediments. As they mature, they may desiccate; the desiccation fissures then become sites for mineral precipitation, such as calcite or barite.

Chert

Rock characteristics: Chert occurs in practically any color of the visible spectrum. In the region its occurrence is typically red (jasper) or gray, green, brown, or black. Chert's texture is compact, very fine-grained, and has a blocky to conchoidal fracture. In outcrop, chert occurs in layers with thin shale partings, reflecting how these rocks originally formed from ocean mud (biogenic ooze from the buildup of the remains of siliceous plankton) deposited on the deep ocean floor far from any sources of terrigenous sediments. The thin shale partings probably represent periods when dust from distant continents periodically was blown into the deep ocean setting, or alternatively, these shale partings represent cyclic periods when organic productivity declined in the ocean setting. Not all chert displays layering. Silica (SiO_2), the primary mineral component in chert, is relatively soluble under certain conditions; it also melts at fairly low temperatures relative to other rocks, Therefore, it is easily altered to different forms, either through hydrothermal activity or other metamorphic processes.

Bay region occurrence: Perhaps the most famous exposures of chert beds are in the Marin Headlands north of the Golden Gate Bridge. Layered chert can be found in Franciscan Assemblage rocks throughout the San Francisco Bay region, with notable exposures on the road up Mt. Diablo, along Mt. Umunhum Road in southwest San José, and the spillway area at Anderson Reservoir near Morgan Hill. Morgan Hill "poppy jasper" has been mined as an ornamental gemstone.

Folded white chert from the Diablo Range (Coyote Creek, Santa Clara County).

A beach cobble of chert derived from the Monterey Formation displaying alternating layers of black phosphatic chert and white porcellanite (Waddell Creek Beach, Santa Cruz County).

Folded marine chert layers exposed along the road on Mt. Diablo.

Gypsum

Rock characteristics: Gypsum (hydrous calcium sulfate, $CaSO_4$-$2H_2O$) occurs as clear, white, yellow to gray, thin to thick-bedded layers interbedded with shale or other sedimentary rocks. In some cases, it occurs in anhydrous form (called anhydrite, plain $CaSO_4$). The rock forms from the evaporative concentration of salty water, either seawater or briny ground water. In the geologic past, gypsum precipitated in isolated bays in arid regions along the coast. A perhaps more common crystalline variety, a mineral called selenite, is common in weathered shale slopes where it crystallizes from evaporating ground water in fractures and along bedding planes.

Bay region occurrence: The occurrence of gypsum (and selenite) is limited to only the most arid locations in the region. Traces of it occur on shale slopes, particularly in landslide deposits, along hillsides in the east bay, but it is common to abundant throughout the lower shale-covered hillsides along the east side of the Diablo Range.

Selenite (gypsum) crystals litter the surface below the location where crystals formed along a sand-filled fracture. Exposures like this are common in the hills along the east side of the Diablo Range.

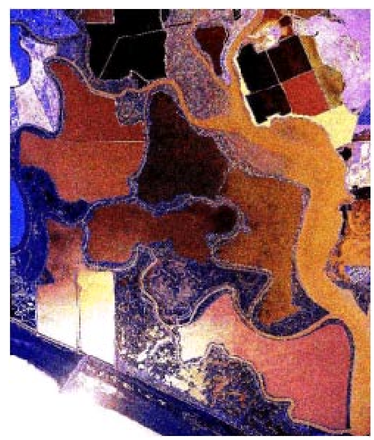
A 40-cm-long, double-terminated selenite crystal from the Panoche Hills region.

Rock Salt

Rock characteristics: Rock salt is a rock made up of the mineral halite, along with other impurities. Purified halite is common table salt (sodium chloride, NaCl). Rock salt forms from the evaporative concentration of seawater.

Bay region occurrence: Natural salt can be found in the upper tidal zone where wave splash is trapped in depressions and evaporates. Small patches of salt crystals will temporarily build up during hot, dry periods along the coast, but vanish with the first good storm. Rock salt is manufactured artificially by pumping seawater through a series of salt evaporator ponds in the San Francisco Bay area. Salt crystallizes to a pink, massive crystalline form when supersaturated conditions are achieved; the pink coloration is primarily due to algae trapped within the salt.

Rock salt (halite crystals).

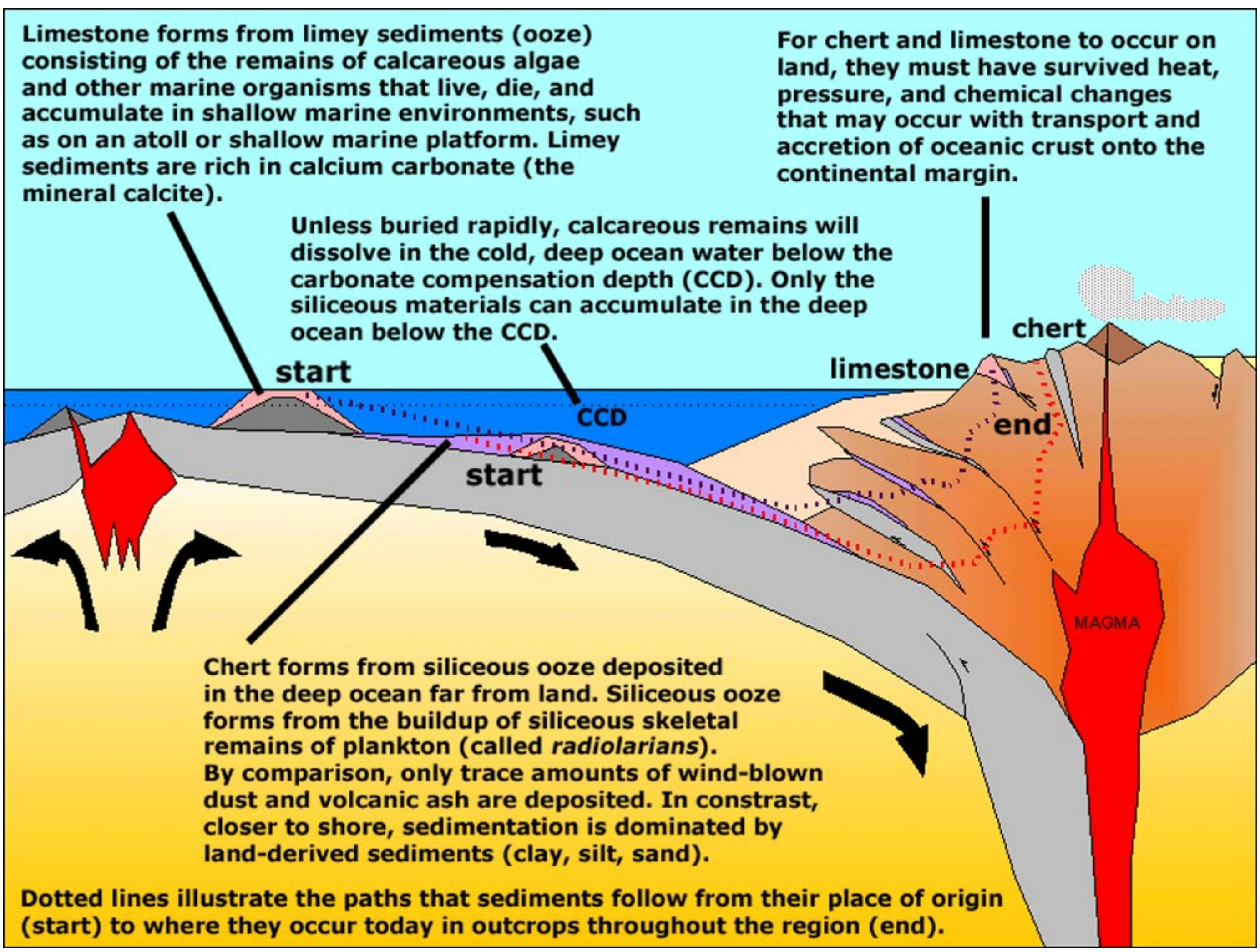


Salt evaporator ponds in northern San Pablo Bay (enhanced satellite image).

Limestone versus Chert and the Carbonate Compensation Depth (CCD)

Chert and limestone occur in scattered locations within the Franciscan Assemblage rocks throughout the region, sometimes occurring separately, sometimes interbedded. These two rock types support an interesting story about the original ancient ocean crust and sediments that were eventually accreted onto the continent (now exposed throughout the region). On the basis of where calcareous sediments and siliceous sediments are forming today (eventually becoming limestone and chert, respectively), geologists can interpret the kinds of locations where these rocks formed in the past. Critical to this interpretation is the concept of the carbonate-compensation depth (CCD). The CCD is the depth at which calcium-carbonate concentrations in sediment decreases most rapidly and is defined as the depth at which the rate of dissolution of solid calcium carbonate equals its rate of supply. Just as cold soda holds dissolved carbon dioxide better than warm soda, the same is true of calcium carbonate dissolved in seawater. In shallow, warm water environments, calcium carbonate (calcite) is a byproduct of biological respiration. Some of this calcite is incorporated into the skeletons of organisms (particularly calcareous algae). If the amount of calcareous material accumulating on the sea floor is faster that the rate it dissolves, then lime mud (ooze) will build up, possibly becoming limestone through time. Inversely, if the water is too cold and deep, calcium carbonate will not be preserved in sediments, rather the remains of plankton that produce siliceous skeletons will accumulate to produce siliceous ooze that possibly may become chert through time. Changing water depths or ocean temperatures may result in alternating layers of calcareous and siliceous sediments.

The occurrence of massive limestone and chert deposits in the region suggests that rock materials were transported long distances from their place of origin to where they occur today. Limestone deposits in the region may represent carbonate sediments that built up on or around ancient volcanoes or uplifts, possibly associated with a divergent plate boundary (spreading center), whereas chert-dominated rocks represent cooler ocean crust that had migrated away from the spreading center areas into deeper water settings, yet far enough away from shore not to receive sediments from land. This is another method used to interpret the regional geologic history.



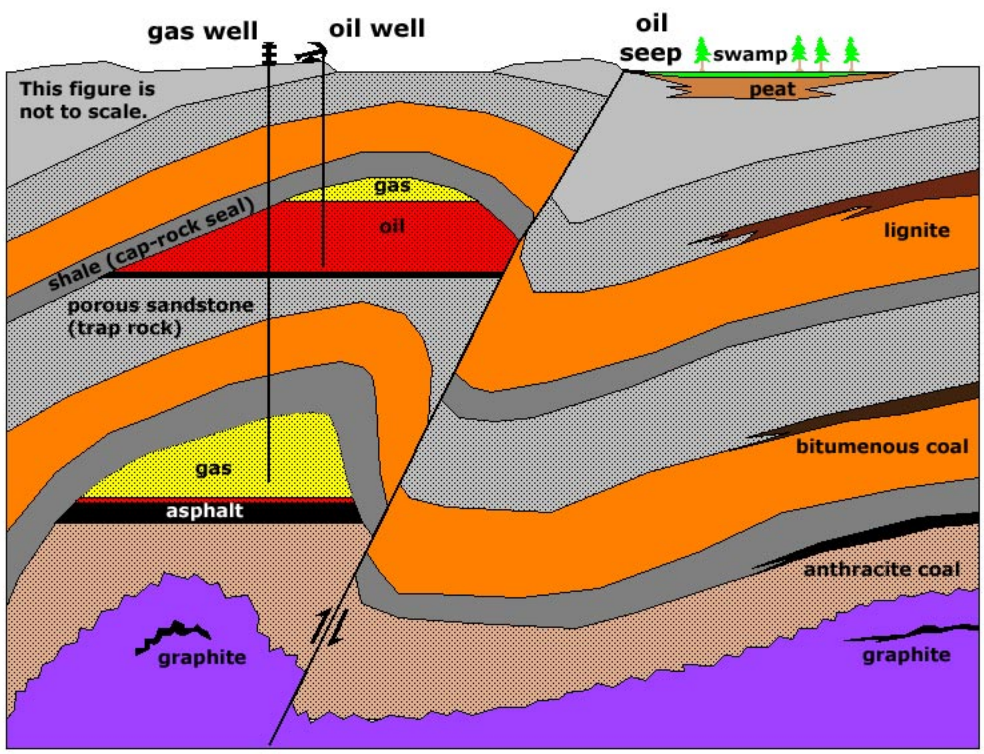
Paths to formation—limestone and chert.

Organic Residues and Rocks (Petroleum and Coal)

When plants and animals die, their organic residues are in most cases consumed or decay under attack of microorganisms. What remains is gradually oxidized by exposure to free oxygen in the air or dissolved in water. In some sedimentary environments, however, organic residues can become isolated from organic decay or oxidation, such as by sinking into a swamp or by being rapidly buried by marine sediments. With time and increasing burial (and associated increasing geothermal temperature with depth), organic residues undergo chemical alteration along with the surrounding sediments. Organic residues may be converted to petroleum or coal. In general, ancient marine organic matter is the primary source of petroleum, whereas coal formed from ancient land plants.

Petroleum is a general term for all naturally occurring hydrocarbons, whether gaseous, liquid, or solid. When exposed to the geothermal heat over a long period of time, organic matter gradually loses its volatile compounds (including H_2O, CO_2, and natural gas consisting of light hydrocarbons like methane, propane, and others). Some of the organic matter will convert to liquid oil and can migrate and accumulate in an "oil pool" if geologic conditions are right. Petroleum geologists search for oil in places where they know organic-rich rocks have been exposed to the right amount of heat for the right amount of time to "generate oil." Without enough time and heat oil won't form. Too much heat over time can overcook the oil, and it will break down to form natural gas and asphalt. Geologists also look for special conditions where fractures and pore spaces in the rock will allow petroleum to migrate and accumulate in a "trap." Because petroleum is less dense than water, it will migrate upward toward the surface. However, if an impermeable layer impedes this upward migration, an oil pool will accumulate in porous rocks beneath a cap rock seal (such as a shale layer overlying a folded, porous sandstone layer).

Natural asphalt formed in oil-bearing rocks by the evaporation of volatiles (removal of gases and light-weight hydrocarbons). Asphalt can form deep in the subsurface where geothermal heat can degrade oil, and it can form near the surface where oil seeps onto the surface or where oxidation reactions and microorganisms attack shallow oil pools. Natural asphaltic sand (or tar sand) can be found in outcrops in many places along the coast in San Mateo and Santa Cruz Counties. The knowledge of oil seeps and tar sand deposits in the San Francisco Bay region led to some of the earliest petroleum exploration and economic production of petroleum in California. Several dozen exploratory wells were drilled in the region, and small oil fields were



Simplified diagram showing the relationship of increasing depth (increasing heat and pressure over time) to the production of different kinds of organic residues and rocks.

This pumping jack in a bank parking lot in Los Gatos is connected to one of the last remaining oil wells in the region; however, it is not actively producing oil.

Natural tar sand (sand impregnated with asphalt) can be found in sea cliffs and in gravel deposits by the shore and along streams in many places along the coast in San Mateo and Santa Cruz counties, such as this cobble of tar sand washed up on the beach in Half Moon Bay. Fossils and sedimentary structures help differentiate natural asphalt rocks from manmade materials that have been dumped or reworked by erosion, but the natural and manmade materials are essentially identical in character.

developed and tar recovery efforts were conducted in Santa Clara County near Gilroy (the old town of Sargent), in Moody Gulch (west of Cupertino), and in San Mateo County in the region around Pescadero and Half Moon Bay. More significant resources were discovered and developed in the Great Valley along the eastern flank of the Diablo Range. Most of California's oil and gas has been produced in southern California in the region between Bakersfield, Los Angeles, and along the coast and offshore around Santa Barbara. There is currently no known significant petroleum production in the San Francisco Bay region.

Asphalt

Asphalt is a dark brown to black viscous liquid or low-melting-temperature solid bitumen that consists entirely of hydrocarbons. Asphalt is a residue formed by the removal of lighter volatile hydrocarbons (gases and fuel-grade oils) from crude oil through evaporation or distillation. It can form in several ways. Bacterial decay of natural oil releases hydrogen from hydrocarbons, concentrating carbon residues. The same effect can happen from the natural overheating of oil at great depth—oil breaks down forming natural gas and asphalt or even pure hydrogen gas and carbon (as graphite) under extreme pressure and temperature conditions. However, most asphalt (or tar) found naturally on the surface forms mostly from the bacterial degradation of oil migrating to the surface or near-surface environment.

Natural asphalt can be found coating surfaces of boulders and outcrops along the base of sea cliffs at Wilder Ranch State Park in Santa Cruz County.

Coal

Coal is 50 percent by weight and more than 70 percent by volume carbonaceous material, including inherent moisture, formed from compaction and induration of variously altered plant remains similar to peat. Differences in degree of metamorphism (rank) and in the range of impurity (grade) are characteristics of coal and are used to describe and classify it. With burial, dead plant material may become peat. With increasing time and burial plant material will progressively lose its volatile components (hydrogen, oxygen, and others). With increasing metamorphism peat will become lignite, subbituminous coal, bituminous coal, and anthracite. Lignite is very low grade, whereas anthracite is very high-grade coal that is nearly pure carbon.

Deposits of subbituminous grades of coal and lignite occur in many places throughout the region in Tertiary- and Quaternary-age sedimentary rocks. Low-rank and -grade coal was discovered and mined in Alameda and Contra Costa Counties in the Mt. Diablo Mining District where over 3,500,000 tons of coal was produced. The majority of production occurred at the Black Diamond Mine near the now abandoned mining town of Tesla. Smaller but economic quantities of coal were mined in the Corral Hollow Mining District in Alameda County and at Stone Canyon in Monterey County. Nearly all California coal production occurred before 1900. Coal occurs in small, intermittent seams in many places in early Tertiary sedimentary rocks throughout the Coast Ranges, but mostly along the eastern flank of the Diablo Range. Small coal deposits can be found in the hills around Portola Valley. Lignite can be found in the sea cliffs at Thorton and Funston Beaches in San Mateo County and in the Miocene and younger sediments throughout the region southeast of Hollister.

Subbituminous coal from the Black Diamond Mine located near the abandoned mining town of Tesla in Alameda County.

Graphite

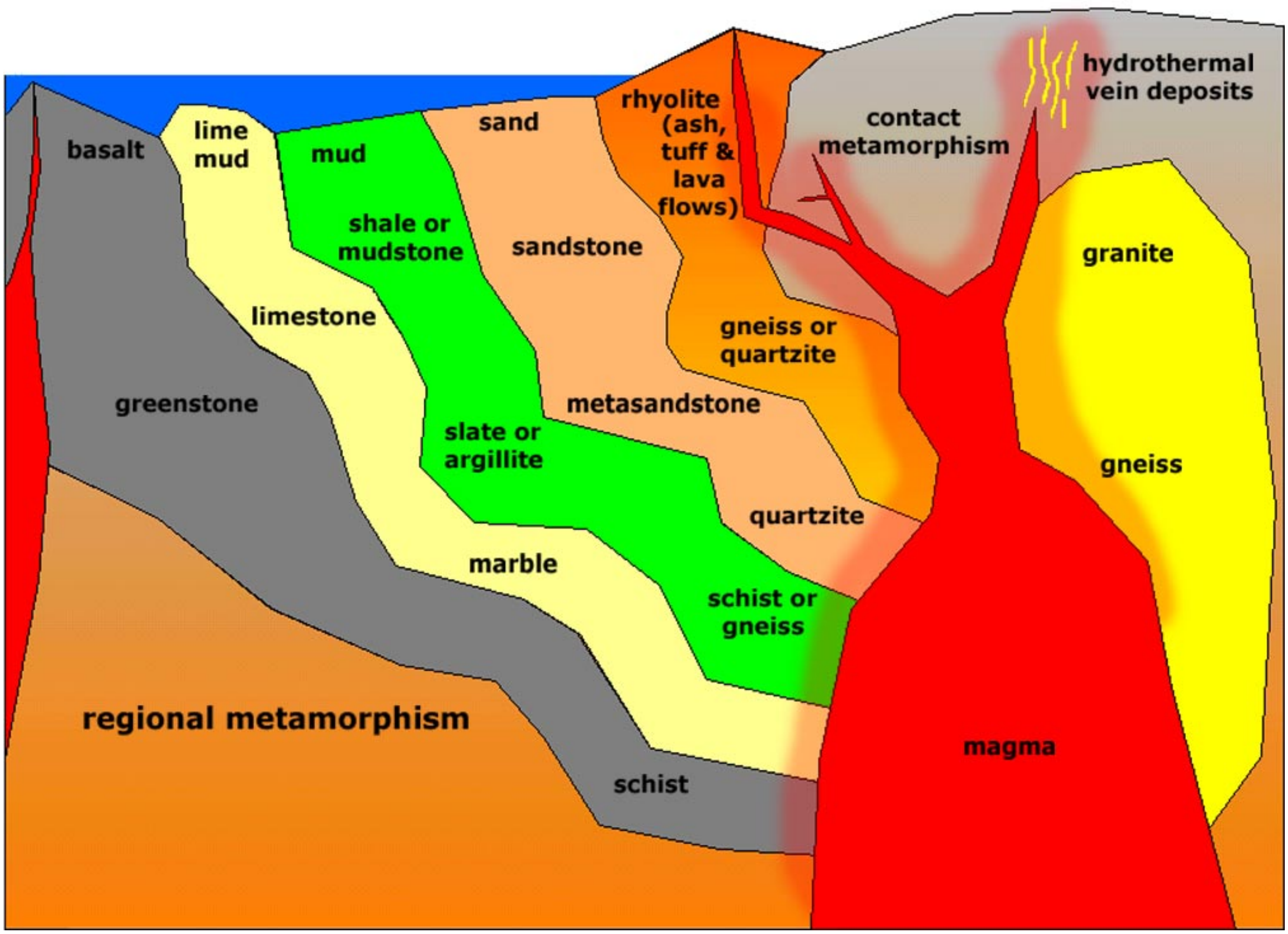
Graphite is a naturally-occurring crystalline carbon mineral that is opaque, gray to black, soft, and greasy to the touch, and may occur in fine grained masses, platy crystalline form, or more commonly, disseminated as crystalline flakes amongst other mineral grains. Graphite is a common mineral component in metamorphic rocks that were originally derived from sedimentary rocks containing organic matter (possibly as either coal or asphaltic residue), but can also form by igneous processes. Graphite can be found disseminated in schist and marble in Salinian basement rocks in Santa Cruz County. Small deposits were mined in Sonoma County and elsewhere in California, particularly in the Sierra Nevada foothills and in region around Los Angeles. The easiest way to determine if a rock contains graphite is that your hands still get a dirty gray color after handling rock samples that have been washed. Pencil "lead" is actually graphite (but modern pencil lead is synthetic).

Schist bearing graphite from Santa Cruz County.

Metamorphic Rocks and Processes

Processes involving the folding or faulting of rock are called tectonism. Tectonic forces move rocks from one geologic setting to another. This movement, through time, results in both physical and chemical changes to the rock. As rocks sink further into the crust, the combinations of heat, pressure, and the interaction of hot mineralizing fluids alter their original chemical composition and physical structures. Minerals stable at low temperatures recrystallize into different minerals stable at higher temperatures and pressures. This process, called metamorphism, results in the formation of metamorphic rocks. Igneous, sedimentary, and preexisting metamorphic rocks may all be subjected to metamorphism. With increased heating all types of rock will eventually melt, forming magma, which too can migrate to form new igneous rock. Metamorphism is gradational, ranging from low grades to high grades for both temperature and pressure parameters. For low-grade metamorphism, the original host rock is fairly easy to determine, but determination grows progressively difficult with increasing metamorphism.

A metamorphic rock is any rock derived from preexisting rocks by mineralogical, chemical, and(or) structural changes, essentially in a solid state, in response to marked changes in temperature, pressure, shearing stress, and chemical environment at depth in the Earth's crust. The diagram below illustrates the progression of earth materials from their origin through increasing metamorphic grades. Regional metamorphism implies that metamorphic processes affect a great volume of rock throughout a widespread area in the Earth's crust (such as in the formation of a mountain range during the collision of continental landmasses). Local metamorphism is what the name implies, metamorphic processes affecting a smaller volume of rock, such as within a fault zone or near an igneous intrusion. The alteration of rock by heat and fluids derived from an igneous intrusion is called contact metamorphism.

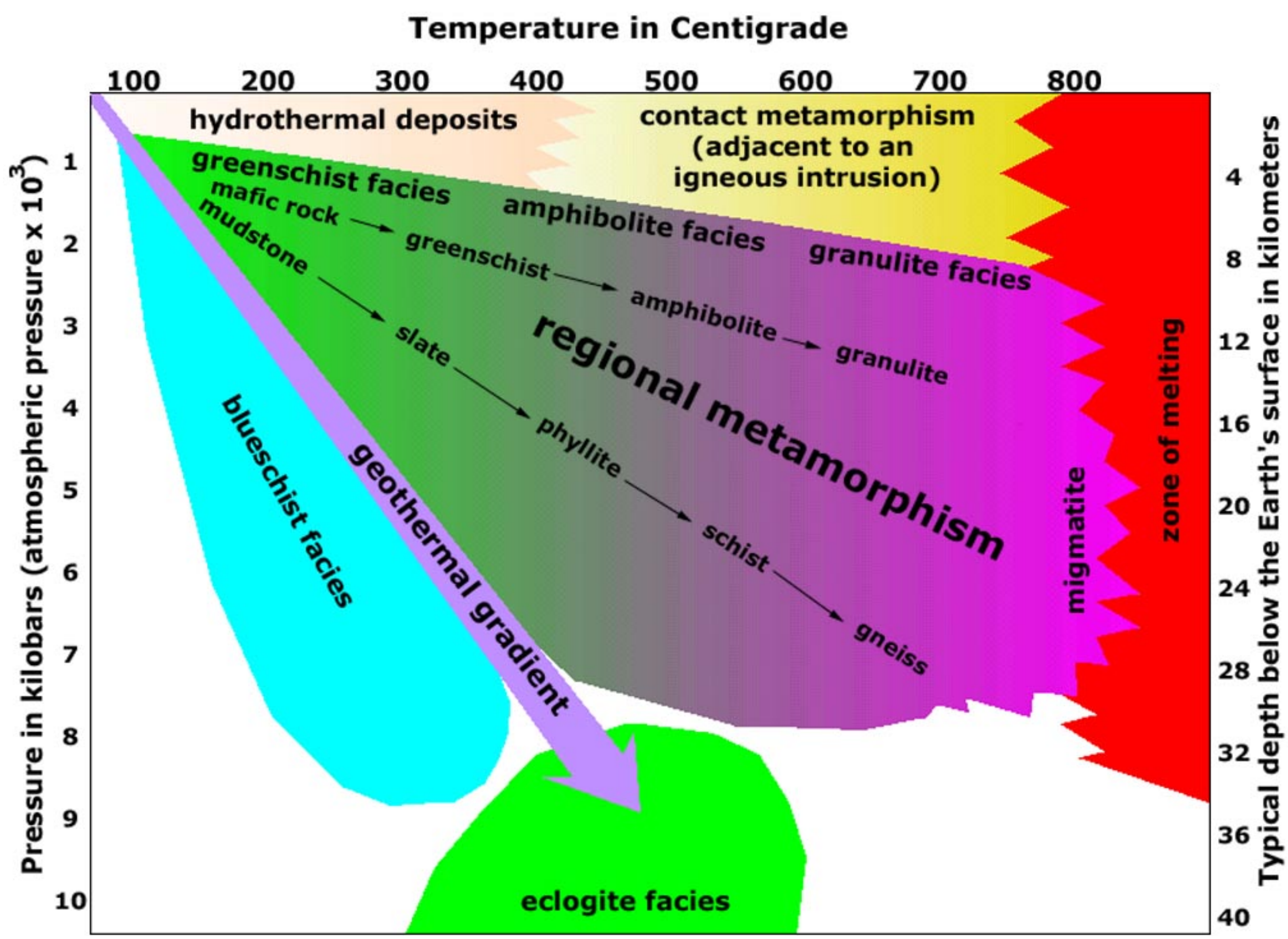


This simplified diagram illustrates the relationships of metamorphic rocks with their parent materials.

Temperature and Pressure Related Processes in Metamorphism

Both pressure and temperature go up with increasing depth into the Earth. In most places, this mutual relationship between increasing pressure and temperature conditions with depth is called the average geothermal gradient that is approximately 72°F/mile (25°C/kilometer). Conversely, as Earth materials are subjected to increasing pressure and depth through time, they gradually equilibrate to the physical and chemical conditions of their physical environment. However, conditions are not uniform beneath the surface. For instance, in subduction zones where cool surface rocks are sinking into the crust and upper mantle, the pressure increases with depth at a normal rate, but temperature does not. Where magma is rising, such as at a spreading center or under a volcanic arc, the temperature gradient is higher than the average geothermal gradient. Through time and changing geologic conditions, new minerals (and rocks) form at the expense of preexisting materials. Some of these minerals require specific conditions to form. The pressure/temperature range in which a group of minerals form within the Earth is called a metamorphic facies.

The diagram below illustrates the range of temperature and pressure (also average depth) that different metamorphic facies develop below the surface. It is important to note that "average geothermal gradient" scarcely applies to the complex geologic environments found along the margin of continental plates (especially in California). Other factors are significant relating to metamorphism. In regions where mountain ranges are gradually developing over a long period of time, rocks throughout a broad region can be subjected to deep burial before being gradually uplifted and exposed at the surface by erosion. Regional metamorphism is a term that applies to metamorphism throughout a broad region. This is opposed to settings where metamorphism occurs in localized areas, such as contact metamorphism that occurs around the margins of an igneous intrusion. Also, hydrothermal alteration from migrating fluids in the subsurface can result in local metamorphism. When the temperature of the rock increases to the melting point of minerals in the rock, either higher temperature metamorphic minerals will form, or the "low temperature" minerals will melt and the molten material (magma) may migrate (forming dikes and intrusions) if differential pressure conditions are right. High-grade metamorphic rocks that contain many small intrusions are called migmatite.



Pressure, temperature, and depth relationships in the formation of metamorphic rocks.

Metamorphic Rocks

Slate

Rock characteristics: A compact, fine-grained metamorphic rock that possesses cleavage and hence can be split into slabs and thin plates. Most slate was formed from shale. Slaty cleavage is a splitting character of fine-grained rock along planes parallel to the orientation of fine, platy mineral grains formed in the process of low-grade metamorphism. Minerals in slate, such as chlorite and cericite (a white mica), have a platy mineralogical structure similar to micas (biotite and muscovite). During metamorphism, as these mineral crystals form from preexisting clay minerals they align themselves in a direction perpendicular to the principle direction of force crushing the rock (a term geologists call the direction of "crustal shortening" during regional metamorphism, typically during a mountain-building period). Whereas shale splits along bedding planes, slate splits along cleavage planes formed along parallel layers of the platy metamorphic minerals.

Bay region occurrence: Slate occurs amongst metamorphosed graywacke, argillite, and sandstone in Franciscan Assemblage rocks throughout the region. Exposures occur along the eastern flank of the southern Santa Cruz Mountains, particularly around Lexington Reservoir near San José. It also occurs throughout the metamorphic rocks exposed in the core of the Diablo Range, with accessible exposures along the Mt. Hamilton Road and throughout the vicinity of Henry Coe State Park.

Slate from near Lexington Reservoir, Santa Clara County.

Argillite

Rock characteristics: Argillite is a compact rock, derived form mudstone or shale, but shows a higher degree of metamorphism than either of those rocks. For instance, under a hand lens, tiny flakes of mica may be seen along fracture surfaces. Argillite lacks the fissility of shale or the cleavage of slate.

Bay region occurrence: Argillite occurs throughout the Franciscan Assemblage rocks exposed throughout the core of the Diablo Range and the southeastern Santa Cruz Mountains (same as slate).

Argillite from Clear Creek in San Benito County.

Metasandstone

Rock characteristics: Metasandstone is sandstone that shows evidence of having been exposed to metamorphism.

Bay region occurrence: Metasandstone occurs throughout the Franciscan Assemblage rocks exposed throughout the core of the Diablo Range with massive exposures in eastern Alum Rock Park near San José and throughout the Henry Coe State Park region. Exposures occur along the eastern flank of the Santa Cruz Mountains, with exposures around Lexington Reservoir and in Uvas Canyon County Park in southwest Santa Clara County.

Metasandstone from San Benito County.

Metaconglomerate

Rock characteristics: Metaconglomerate is conglomerate that displays evidence of metamorphism. Typically, gravel clasts in the rock display traces of "stretching" or crushing, and the matrix material shows evidence of recrystallization.

Bay region occurrence: Metaconglomerate occurs in association with metasandstone. Examples of metaconglomerate can be seen throughout the core of the Diablo Range with exceptional exposures throughout the range southeast of Hollister. Metaconglomerate occurs between Gazos Creek and Pigeon Point along the San Mateo Coast, and occurs in scattered outcrops throughout Henry Coe State Park.

Metaconglomerate from San Benito County.

Metachert

Rock characteristics: Metachert is a dense, very fine grained (crypto-crystalline) quartz-rich rock. It occurs in practically any color, though dominantly brown, red (jasper), orange, or white. Green, gray, blue, to black metacherts are not uncommon. Pure silica is clear to white; it is the impurities (mostly clays and iron oxide) that give chert its color. With progressive metamorphism, the original sedimentary bedding of marine cherts vanishes. Because chert is dominantly quartz, it flows at moderately low temperatures and pressures. In addition, silica dissolved in ground water will precipitate to form chert even at great depths in the crust, typically replacing other minerals.

Bay region occurrence: Metachert is abundant throughout the region occurring in many cases as resistant blocks or rocky ridges rising above the surrounding soil-covered hillsides (geologists call these features knockers). Chert is abundant in Franciscan Assemblage rocks wherever they occur. Examples of where metachert knockers occur in abundance throughout Santa Clara County such as in the Cinnabar Hills area around Calero Reservoir; in Santa Teresa County Park in south San José; throughout Henry Coe State Park; in Joseph Grant County Park along the Mt. Hamilton Road. It also occurs throughout northern Marin County. Because metachert is hard, durable, and abundant, it can be found as cobbles and pebbles in stream gravel bars throughout the region.

Metachert from the southern Santa Cruz Mountains displays a wide range of colors.

Chert breccia from Coyote Creek, Santa Clara County.

Quartzite

Rock characteristics: Quartzite is a dense, extremely hard quartz-rich rock that displays a frosty texture, conchoidal fracture, and is typically white, but it is commonly gray, pink, red, or black. Quartzite occurs in all metamorphic grades. If the rock is clearly derived originally from sandstone, the correct term to apply is metasandstone. This is because quartzite can form from any rhyolite, chert, siltstone, aplite-granite, or any quartz-rich rock. Although most quartzite is probably derived from ancient quartz sandstone, it is difficult to say explicitly what the original parent rock was that formed quartzite.

Bay region occurrence: Metasandstone occurs in the Franciscan Assemblage throughout the region; some of it could be called quartzite. Quartzite occurs as gravel-, cobble-, to boulder-sized blocks, most of which are derived from Cretaceous and Tertiary-age conglomerates. These are commonly found reworked in stream gravels throughout the region. These rocks tend to be well rounded and their surfaces display “percussion marks”—curved, conchoidal fractures that formed as the rocks crashed into other rocks as they were transported along rushing streams. Many have broken surfaces formed from the shattering effect of faulting when they were deeply buried at different times in their past. Because quartzite cobbles are highly durable, they may survive many cycles of erosion and deposition. Quartzite cobbles derived from conglomerate beds are perhaps the oldest rock material in the region, and may share a common origin with quartzite cobbles found throughout western North America from the Canadian Shield to Mexico. Some of these reworked quartzite cobbles may be billions of years old.

A reworked quartzite cobble from San Lorenzo Creek, Santa Cruz County.

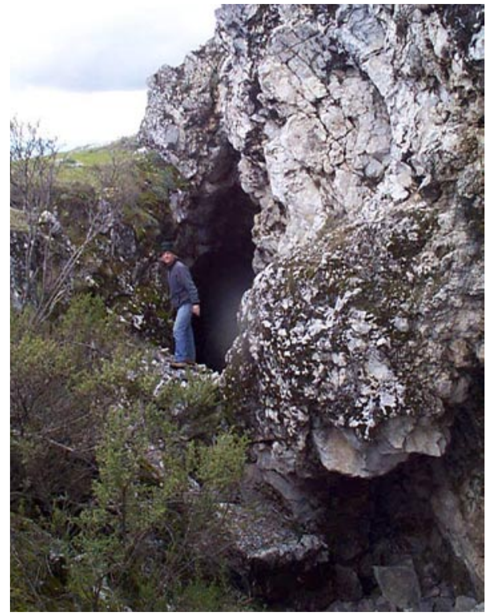
Marble

Rock characteristics: Marble is essentially pure calcite but may contain traces of dolomite, graphite, pyrite, quartz, mica, and other minerals. In most occurrences, marble is considered to have formed from limestone; however, any calcite-rich rock (sedimentary or igneous) can become marble with either regional or contact metamorphism.

Bay region occurrence: Marble occurs throughout the Salinian basement west of the main trace of the San Andreas Fault. Large masses of high-grade marble occur in the southwestern Santa Cruz Mountains throughout the Ben Lomond Mountain area and throughout the Gabilan Range, with large outcrop areas on Fremont Peak. Pits from historic mining operations occur throughout the University of California Santa Cruz campus. In these high-grade occurrences, the marble occurs in association with mica schist and gneiss. Low-grade marble and limestone occur as scattered masses in Franciscan Assemblage rocks throughout the region, with large quarries and pits located near Rockaway Beach on the San Mateo coast. Active mining operations of limestone and low-grade marble are in progress in the eastern Santa Cruz Mountains along Stevens Creek near Cupertino and along Lime Kiln Creek near Lexington Reservoir. Marble and limestone masses occur throughout the Cinnabar Hills in southern San José with historic mining conducted in the vicinity of what is now Calero Reservoir. This marble and limestone occurs as small to hill-sized blocks in a “mélange” (mix) of serpentinite, graywacke sandstone, argillite, metasandstone, and greenstone (metabasalt).

Marble from the University of California Santa Cruz campus.

Marble's role in the making of California—In 1846, after being told by Mexican authorities to leave California, John C. Fremont lead his followers to the highest peak in the Gavilan Range (between Monterey and San Benito Counties). There, on what is now called Fremont Peak, his men erected a small earthen fort and raised the first American flag to fly over California. Soon afterward, the Mexican General Jose Castro prepared to dislodge the Americans. Outnumbered five to one, Fremont retreated to Sutter's Fort. Although the affair was a military loss, it bolstered American sentiment to gain California.



It was possibly the mines, such as this one, in the marble that attracted John C. Fremont and his followers to what is now Fremont Peak. At the time, these mines produced cerrusite ($PbCO_3$), a grayish-white ore that was the only known source of lead for gun shot in the region.

Fremont Peak, San Benito County.

An active limestone mine along Stevens Creek in Santa Clara County.

Marble, and its sedimentary parent, limestone, continues to be mined in the region, primarily for road aggregate and, to a lesser degree, as lime for cement. Cement production requires significant amounts of energy to bake the rock. The primary mineral, calcite ($CaCO_3$), is heated, driving off carbon dioxide, leaving lime (CaO). Early lime production used large quantities of charcoal derived from the forests in the Santa Cruz Mountains. By 1910, nearly all the forested areas were stripped from the Santa Cruz Mountains before environmental outcry and dwindling wood supply basically ended the industry. Large active quarries, such as this one along Stevens Creek, are now heavily regulated. They produce only a fraction of the lime now consumed in construction in the region.

Marble was mined in the Santa Cruz Mountains as early as the 1850's; production peaked in the early 1920's. In this time period, the Santa Cruz Marble was the only large-scale source of lime for cement available in the entire Pacific basin. Cement from Santa Cruz was used to rebuild San Francisco after the 1906 earthquake, and lime from these mines were used in the construction of the Panama Canal. Marble and limestone are still mined in the in the Santa Cruz Mountains.

Historic lime-kiln processing works located on Bay Street on the University of California Santa Cruz campus.

Mica Schist

Rock characteristics: Mica schist is a medium- to high-grade foliated metamorphic rock that consists dominantly of mica (biotite, muscovite, or other flaky sheet mica minerals); other common minerals that occur with mica include: quartz, tourmaline, garnet, pyrite, kyanite, plagioclase, epidote, and many others. "Foliated" means that the crystal grains in a metamorphic rock are aligned, producing a layered texture (not sedimentary bedding). Mica must make up greater than 50 percent of a metamorphic rock for it to be considered mica schist. In bright sunlight, the abundance of mica gives the rock a bright, glittery appearance. Mica is a sheet silicate mineral that easily peels into flakes when picked at with a knife blade. Because mica is a very soft mineral it usually preserves evidence of having been folded under great pressure, and because mica schist forms under high pressure and temperatures, it is frequently intruded by small quartz-rich igneous veins (called aplite dikes).

Bay region occurrence: Mica schist occurs in Salinian basement rocks west of the San Andreas Fault, with perhaps its best-known abundance occurrence in pockets scattered across Ben Lomond Mountain in the Santa Cruz area. It occurs with marble and gneiss in abandoned quarries on the University of California Santa Cruz campus and along the San Lorenzo River Gorge. Mica schist occurs as remnant host rock (xenoliths) in larger granite bodies throughout the Salinian basement exposed in the Monterey Peninsula region, the Gabilan Range, and elsewhere in the region. It occurs as clasts in conglomerate beds and can be found as isolated cobbles in stream gravels (originally the mica schist was derived from the southern Sierra Foothills and then incorporated into reworked sediments).

A cut slab showing folded bands of mica schist with cross-cutting quartz-rich dikes (lower right). High-grade metamorphic rock cut with small light-colored dikes is called a migmatite.

Schist with kyanite crystals from along San Lorenzo Creek in Santa Cruz County.

Gneiss

Rock characteristics: Gneiss is a banded (foliated) rock formed by regional metamorphism. It is rich in quartz and feldspar that occurs in bands of mineral grains, alternating with dark mica, hornblende, amphibole or other characteristic minerals. Gneiss forms from the metamorphism of granitic rocks, sedimentary rocks, or other metamorphic rocks.

Bay region occurrence: Gneiss occurs in the Salinian basement rocks west of the San Andreas Fault with massive exposures in the Ben Lomond Mountain area around Santa Cruz, in the Gabilan Range, and in conglomerate beds and stream gravels downstream of these areas.

Layered gneiss from along San Lorenzo Creek in Santa Cruz County.

Greenstone (Metabasalt)

Rock characteristics: Greenstone is a term applied to any compact dark-green altered or low-grade metamorphosed basic igneous rock that owes it green color to the minerals chlorite or epidote. Ancient pillow basalts frequently preserve their original volcanic flow structures and gas vesicles but have been chemically altered to greenstone.

Bay region occurrence: Greenstone occurs in Franciscan Assemblage rocks throughout the region. Greenstone is easily seen at Point Bonita in the Marin Headlands. Near Morgan Hill, greenstone crops out at the boat-dock parking lot at Anderson Reservoir and in the spillway at Uvas Reservoir. The durable character and relative abundance of metabasalt makes it a common rock in most stream gravel bars throughout the region.

Greenstone from Coyote Creek, Santa Clara County.

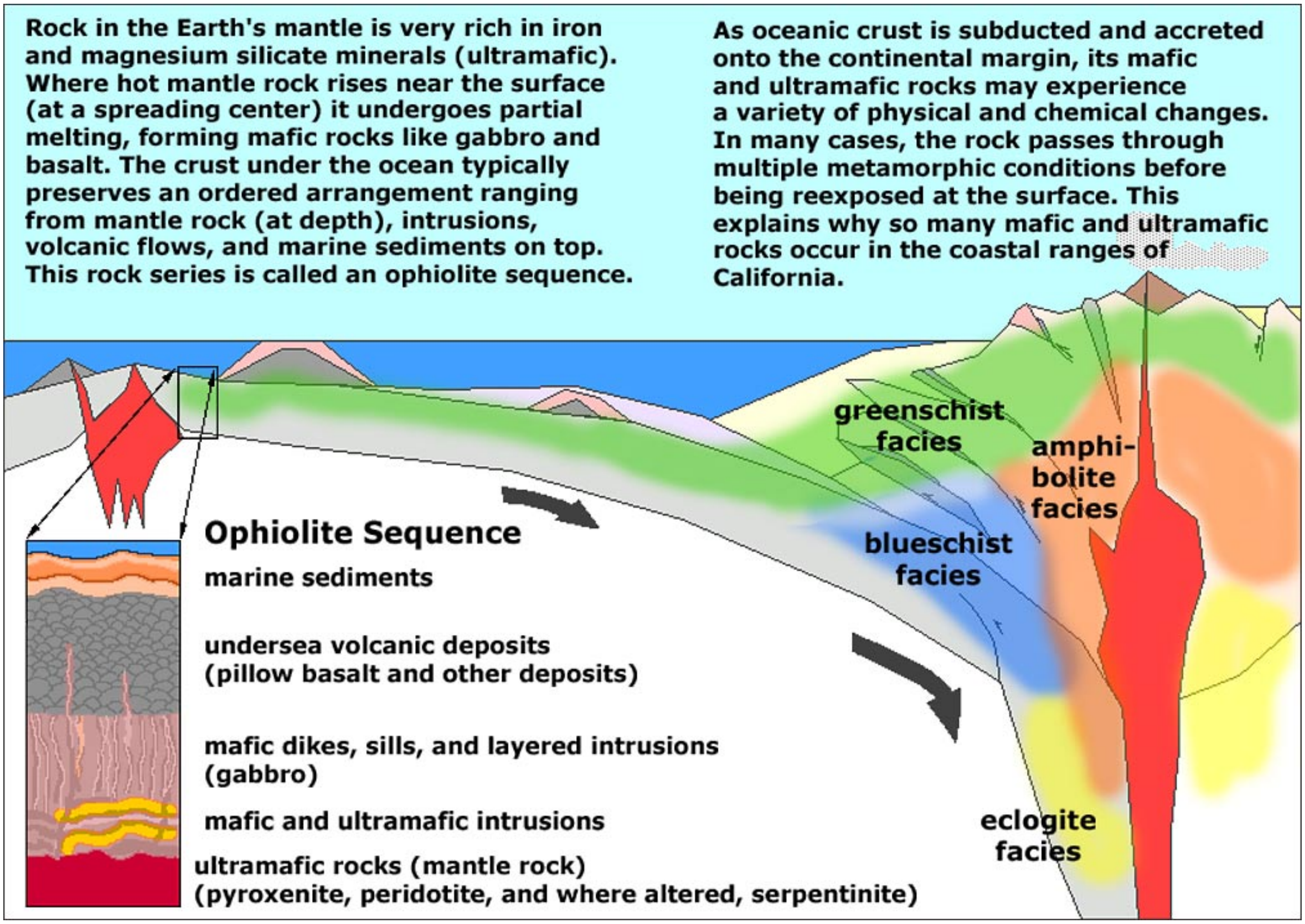
Serpentinite

Rock characteristics: Serpentinite (the rock) is made up of a variety of serpentine minerals, including the most common variety, antigorite (typically light-to-dark green, tough, compact, and often in pleated masses), lizardite (typically occurs as a white to green, scaly textured mass), and sometimes contains thin veins of chysotile (a yellow-green, fibrous variety of asbestos). Serpentinite forms from the metamorphism of mantle-derived ultramafic rocks (peridotite) and oceanic crust in a water-rich environment. When ultramafic rocks are exposed to the wet, low temperature, low pressure near the Earth's surface, they may gradually convert to serpentinite.

Bay region occurrence: Serpentinite is abundant throughout the eastern foothills of the Santa Cruz Mountains, east of the main trace of the San Andreas Fault. Exceptional exposures occur in the sea cliffs just west of the Golden Gate Bridge (in Golden Gate National Recreation Area), and along Highway 280 throughout the vicinity of Crystal Springs Reservoir. In the south bay, serpentinite exposures crop out at Guadalupe Reservoir, throughout Almaden-Quicksilver County Park, and on hillsides throughout Santa Teresa Hills and the Cinnabar Hills (including Calero County Park). Exceptional exposures are located at Chesbro Reservoir dam near Morgan Hill. The Edenvale Hills that line the eastern side of Santa Clara Valley are dominantly serpentinite, with exposures throughout the Metcalfe Motorcycle Park and the Field Sports Park areas. Serpentinte crops out in many places throughout the Diablo Range. The New Idria-Clear Creek area in Fresno and San Benito Counties is an area rich in mineralized serpentinite-dominated ultramafic rocks.

A serpentinite sample dominated by lizardite, a mineral that gives the rock a soft, soapy feel.

A serpentinite sample dominated by the green, frothy-, fibrous- or earthy-textured serpentine mineral antigorite. The veins are filled with a type of asbestos called chrysotile (also a serpentine mineral). The "hob nail" texture of the rock reflects the crystalline texture of the original mantle rock (peridotite) before it was converted to serpentinite.



Serpentinite and other ultramafic rocks in the San Francisco Bay region reflect many different degrees of metamorphism.

Hazards associated with serpentinite—In fresh outcrops or road cuts, serpentinite appears as a chaotic mass of mixed blue, green, and gray pod-shaped rocks within a surrounding scaly or pulverized-appearing rock matrix. This appearance is caused by the expansion of the rock when unconfined at the Earth's surface and its ability to absorb abundant water as it weathers to soil (which it does relatively quickly). These characteristics help make hilly areas underlain with serpentinite bedrock prone to landsliding and failure during earthquake shaking. The natural abundance of asbestos in serpentinite may be a health threat in some areas where wind or human activities generate dust clouds. Naturally high concentrations of heavy metals, particularly chromium and mercury, can also present a chemical hazard in ground water or surface runoff, particularly downstream of mining or landfill operations involving serpentinite bedrock or earth fill.

A landslide formed in weathered serpentinite bedrock along the Limekiln Trail near Lexington Reservoir, Santa Clara County.

Greenschist

Rock characteristics: Greenschist is a schistose metamorphic rock whose green color is due to the presence of the minerals chlorite, epidote, or actinolite. This low-grade regional metamorphic rock forms in variable-pressure and low-temperature metamorphic environments (between 300 to 500ºC or 570 to 930ºF).

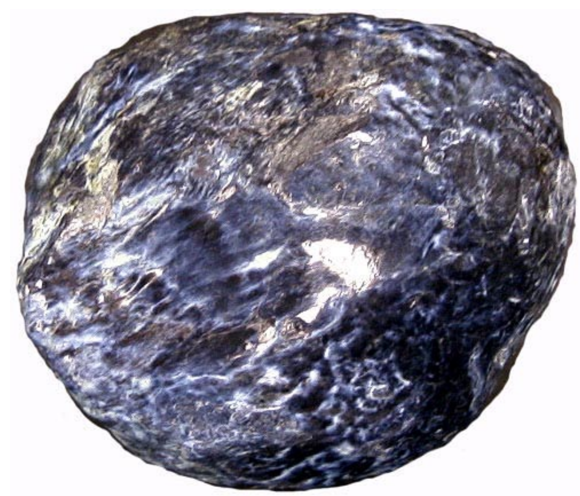
Bay region occurrence: Greenschist occurs in scattered pods in Franciscan Assemblage rocks, particularly in serpentinite belts with exposures throughout the central Diablo Range, throughout the north bay, and in the Cinnabar Hills region between New Almaden and Morgan Hill.

Greenschist from Coyote Creek, Santa Clara County.

Blueschist

Rock characteristics: Blueschist is a metamorphic rock type (or metamorphic environment) that forms at high pressures and low temperatures, such as in a subduction zone where cool crustal rocks sink into the mantle. The dominant mineral in blueschist in the region is glaucophane, a blue-to-black platy amphibole mineral. Blueschist rocks on the surface suggest that the rocks survived a complex geologic transport history—ocean crust that had survived being deeply buried in a subduction zone before being thrust upward to the surface.

Bay region occurrence: Blueschist occurs in scattered pods or belts in Franciscan Assemblage rocks, typically in association with serpentinite. Scattered exposures occur throughout the Diablo Range and in the southeastern Santa Cruz Mountains in the region between Lexington Reservoir and Morgan Hill.



Blueschist from near Lexington Reservoir, Santa Clara County. This sample of glaucophane schist is naturally polished by the scour of recent fault motion along the base of a landslide.

Amphibolite Schist

Rock characteristics: Amphibolite schist forms in high-temperature, high-pressure regional metamorphic environments. The rock is dominated by small to large crystals of various amphibole minerals (greenish, gray to black mafic minerals with blade-like crystals). Hornblende is a common mineral in the amphibole group. Plagioclase, mica, quartz, magnetite, garnet, and other minerals can occur in amphibolite schist.

Bay region occurrence: Amphibolite schist occurs in scattered pod-like masses in Franciscan Assemblage rocks in association with blueschist and other metamorphic rocks. Occurrences include small areas in the Cinnabar Hills between New Almaden and Morgan Hill and scattered throughout the Diablo Range.

Amphibolite schist from Arroyo Seco, Monterey County.

Granulite

Rock characteristics: Granulite is a high-grade regional metamorphic rock type (or metamorphic environment) that forms at high temperatures and moderate to high pressures in the middle to lower crust. The rock typically contains red garnet (pyrope), is rich in quartz, and may contain a variety of other high temperature/high pressure metamorphic minerals. It typically has an even-grained, visibly crystalline texture (granoblastic) with porphyroblasts of garnet (crystals that grow at the expense of the surrounding rock).

Bay region occurrence: Granulite occurs in Salinian basement associated with the older schists and gneisses that predate the granodiorite and diorite intrusions. Granulite occurs in the Ben Lomond Mountain area southward into the Gabilan Range (including around Fremont Peak). It also occurs in the Sierra de Salinia (Salinian Range) in Monterey County in association with migmatites.

Granulite displaying garnets, Santa Cruz County.

Eclogite

Rock characteristics: Eclogite is a high-grade regional metamorphism rock type (or metamorphic environment) that forms at very high pressures and moderate to high temperatures in a lower crust setting (such as deep within a subduction zone. The rock is typically mafic in composition (rich in pyroxene), garnet (pyrope), but may also contain quartz, pyrite, glaucophane, kyanite, and other minerals. Eclogite has a granoblastic texture (a crystalline granular texture), with porphyroblasts of garnet and pyrite.

Bay region occurrence: "Eclogite-like" rocks occur in the region in association with blue schist and amphibolite schist. Examples occur in northern Marin County near Mt. Tamalpias and on Angel Island, but true eclogites occur further north in portions of the northern Coastal Ranges. Ultramafic rocks derived from slivers the mantle material found in the region formed in similar pressure and temperature conditions but are not considered eclogites. Eclogites are associated with metamorphic materials formed in a subduction zone.

Eclogite displaying garnet-rich folded layers.

Migmatite

Rock characteristics: Migmatites represent middle to lower crustal metamorphic environments where rocks were hot enough that they begin to melt and the molten material began to separate from the higher temperature minerals that have not yet melted. The low-temperature minerals become molten (mostly quartz) and begin to flow, filling fractures in the surrounding host rock. The result is that the dikes and intrusions typically have a light color in relation to the surrounding host rock. Typically, many small dikes and intrusions crisscross each other. Migmatites represent a boundary condition between high-grade metamorphism and the melting associated with the formation of batholiths and large intrusions.

Migmatite (schist with granitic-granulite dikes and intrusions) exposed along Arroyo Seco Creek in Monterey County.

Bay region occurrence: Migmatite can be seen in many areas throughout the Salinian basement, with exceptional exposures in Arroyo Seco Canyon in Monterey County.

Additional Resources

Excellent general field guides to rocks and minerals include:

National Audubon Society, 1995, Field Guide to Rocks and Minerals: New York, Alfred A. Knopf, Inc.

Motanna, A., and others, 1978, Simon and Schuster's Guide to Rocks and Minerals: New York, Simon & Schuster, Inc.

Many definitions provided in this text were modified after:

Jackson, Julia A., (ed.), 1997. AGI Glossary of Geology, 4th Edition. Alexandria, VA: American Geological Institute. 769 p.

Many excellent resources are available on the World Wide Web. Here is a small selection of starting points for getting more geologic information about the San Francisco Bay region:

USGS on-line geologic maps and publications about the San Francisco Bay Area include:

San Francisco Bay Region Geology website. This website prepared by the USGS Western Earth Surface Processes team provides access to dozens of regional geologic maps and reports. It is online at http://sfgeo.wr.usgs.gov.

Stoffer, P. & Gordon, L., 2001, Geology and Natural History of the San Francisco Bay Area. 2001 Fall Field Conference Guidebook, National Association of Geoscience Teachers, Far Western Section: U.S. Geological Survey Bulletin 2188, online at http://geopubs.wr.usgs.gov/bulletin/b2188/.

Access USGS—San Francisco Bay and Delta is a website is a portal to many data sets, reports, publications, digital maps of many kinds including subjects relating to marine studies, regional weather, earthquake information, regional landscape and bathymetry, geologic mapping, water resources, biology, hazards, wetlands and more. It can be found online at: http://sfbay.wr.usgs.gov.

Many other resources can be found in the USGS Library at 345 Middlefield Road in Menlo Park, CA. The USGS Library catalog and the National Geologic Map Database are available free online at http://library.usgs.gov.

Many classic books exist about rocks, minerals, and fossils in California, but most are now out of print. Publications used to research this report include:

California Department of Natural Resources, 1943, Geologic Formations and Economic Development of the Oil and Gas Fields of California: California Division of Mines and Geology Bulletin 118, 773 p.

California Department of Natural Resources, 1951. Geologic Guidebook of the San Francisco Bay Counties: California Division of Mines and Geology Bulletin 154, 392 p.

California Division of Mines and Geology, 1966, Minerals of California, Centennial Volume (1866-1966): California Division of Mines and Geology Bulletin 189, 559 p.

California Division of Mines and Geology, 1966. Mineral Resources of California: California Division of Mines and Geology Bulletin 191, 450 p.

Bailey, E.H. and Everhart, D.L., 1964, Geology and Quicksilver Deposits of the New Almaden District, Santa Clara County, California: U.S. Geological Survey Professional Paper 360, 201 p.