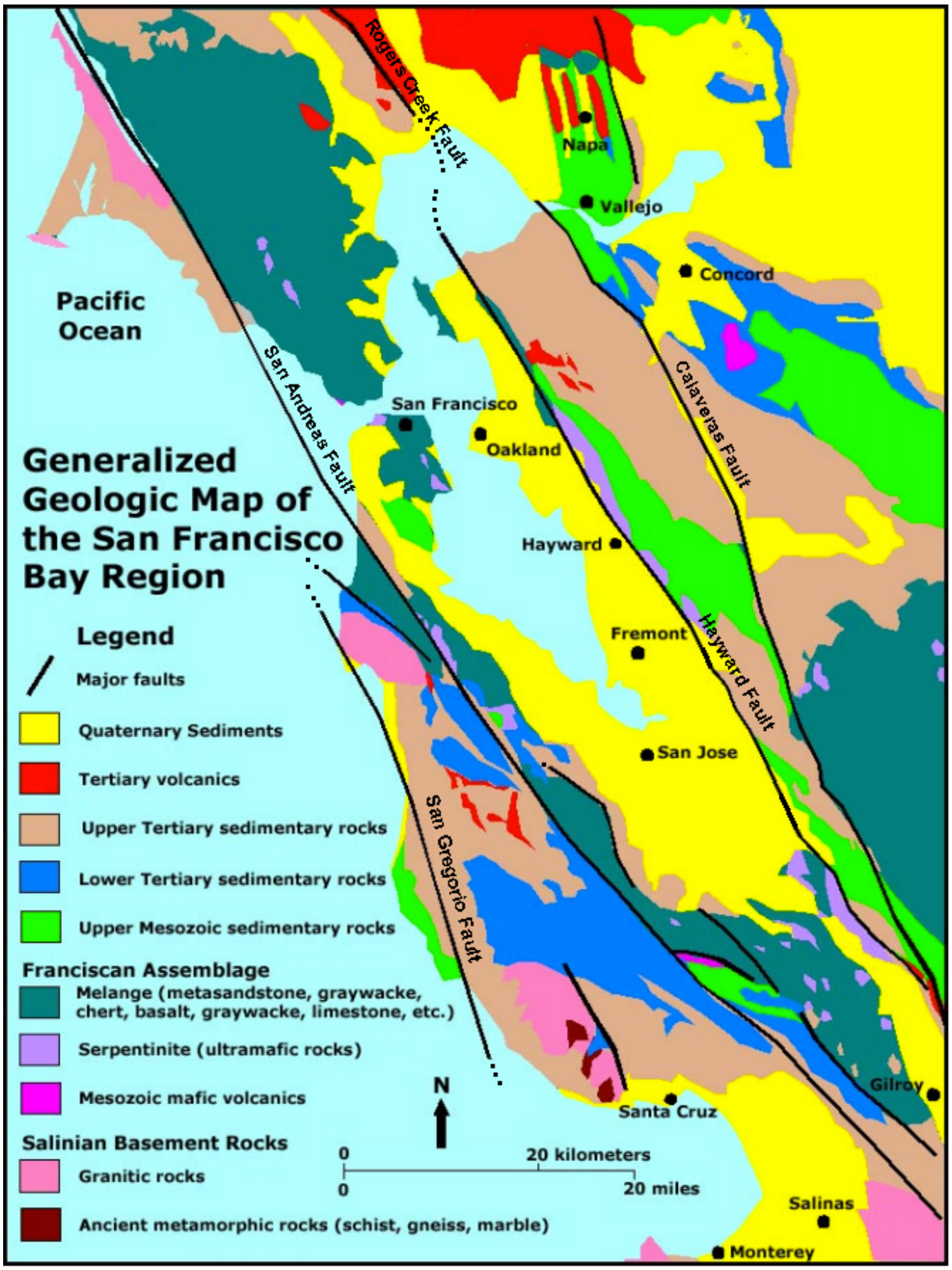
Geology of the San Francisco Bay Region – Doris Sloan
(Annotated by Francesca Verdier)

ch 1. The Bay Area and the Processes that Shape its Geology

Today's Bay Area landscape is only 1 to 2 million years old – and will look totally different in another million years. Its hills are rising and eroding rapidly. The San Francisco Bay is less than 20,000 years old. At the time of the last glaciation, 20,000 years ago, it was a wide grassy valley.

The Bay Area has a large variety of rocks; its basic patterns are shown below.



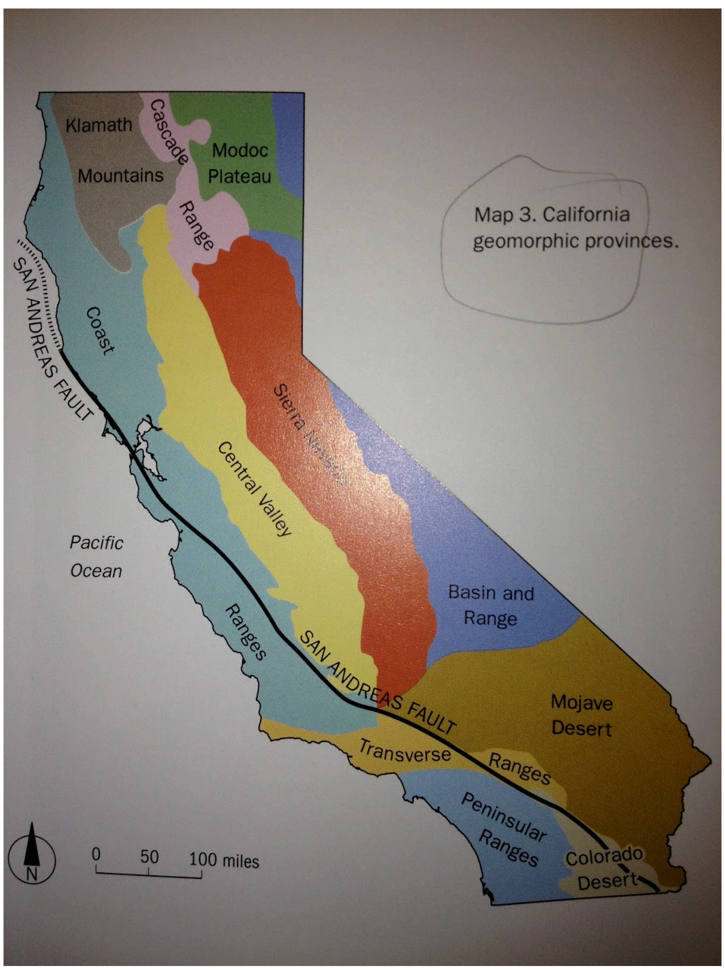
Many of its rocks have traveled great distances in time and space to get here. Some, like our blue-green serpentinite, originally came from far below the earth's surface. Millions of years of movement along faults have rearranged the rocks into a geologic complexity.

The oldest rocks – Franciscan, Great Valley, Salinian Complex, were formed mostly during the Mesozoic Era (~250 – 65 mya). Many of the widespread sedimentary and volcanic rocks were formed in the Tertiary (now replaced by Paleogene and Neogene) 65 to 2.6 mya. Many of the youngest geological materials – from the Quaternary Period – are not yet rock.

Some geologic processes occur quickly, like earthquakes, floods, and landslides. Others operate over hundreds to millions of years, such as the uplifting and wearing down of hills, and the movement of tectonic plates.150 million years ago the Bay Area was a vast Ocean. Its shoreline was where the Sierra foothills are now, or even further east. Great volcanoes were erupting in what is now eastern California. 10 million years ago there was land, but not as it is today. A long ridge of hills lay where the bay is today. About 1 million years ago the East Bay Hills and Mount Diablo began to rise.

The geologic processes that shaped the landscape may be very different from those that formed the rocks in that landscape. Many Bay Area rocks are many millions of years old, formed when this area was under water

Geographically the Bay Area is in the Coast Range Province. California's geomorphic provinces are shown below.



The Bay Area is a hilly place; its many hills and valleys generally run northwest to southeast, like California itself. The highest mountains are Copernicus Peak (4,373 ft), Mount Hamilton (4,209 ft.) – both close to each other in Santa Clara County east of Joseph D. Grant County Park, Mount St Helena (4,344 ft) in Napa, Sonoma, and Lake Counties, Mount Diablo (3,849 ft.) in Contra Costa County, and Mount Tamalpais (2,604 ft.) in Marin County.

The mighty Sacramento – San Joaquin River system flows into the bay through Carquinez Strait and out to the ocean through the Golden gate. The Russian River cuts a wide valley as it flows south into the Bay Area and then makes an abrupt turn westward to the ocean. On the west is a long coastline, steep and rocky in some places, with wide beaches or calm bays at others.

The Bay Area landscape is shaped by a variety of geologic processes, including tectonic activity, which moves pieces of earth's crust up, down, and sideways; weathering and erosion, which wear the high places down; deposition of sediment eroded from the high places; and coastal processes where land meets sea. Many of the geologic processes that operated in the past are still going on.

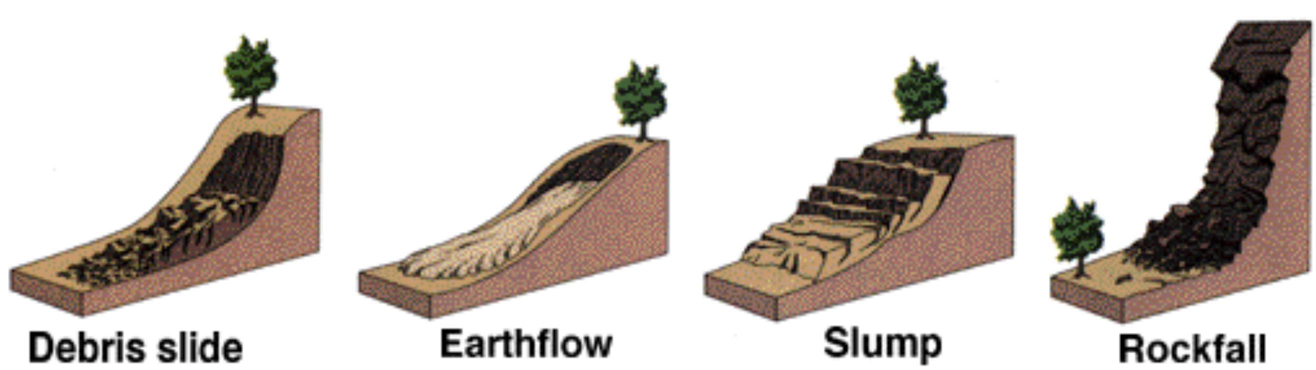
At the Surface: Weathering and Erosion

Weathering is the chemical or mechanical process of altering and breaking up rock into smaller and smaller fragments. Chemical weathering changes the minerals in rocks or dissolves them. Mechanical weathering physically breaks up the rock. Living organisms, ranging in size from microbes to tree roots, often are agents of both chemical and mechanical weathering.

One of the first steps in weathering is oxidation of iron-bearing minerals in the rock. The rock becomes more brown as the iron oxidizes.

The process of erosion carries the products of weathering from high to low places, often via water flows, and deposits them as sediments in river beds or lakes and ultimately the ocean. Along the way the particles may rest on an alluvial plain. These weathered products are initially loose. Over time they get compacted and turn into rock.

Four types of landslides are common in the Bay Area. Debris slides consist of broken materials that fall. Earthflows – which occur when water saturated material flows downhill like a very thick liquid – produce a hummocky ground surface. Slumps occur when loosely consolidated materials slide down along a curved surface. Rockfalls consist of materials that fall through the air.



http://www.ux1.eiu.edu/~cfjps/1300/slidetypes.html

A hazard in young unconsolidated sediments is liquefaction during an earthquake – shaking can turn them into a slurry unable to support the weight of structures.

Where Sea Meets Land

Weathering along the coast is rapid where rocks are soft or very fractured.

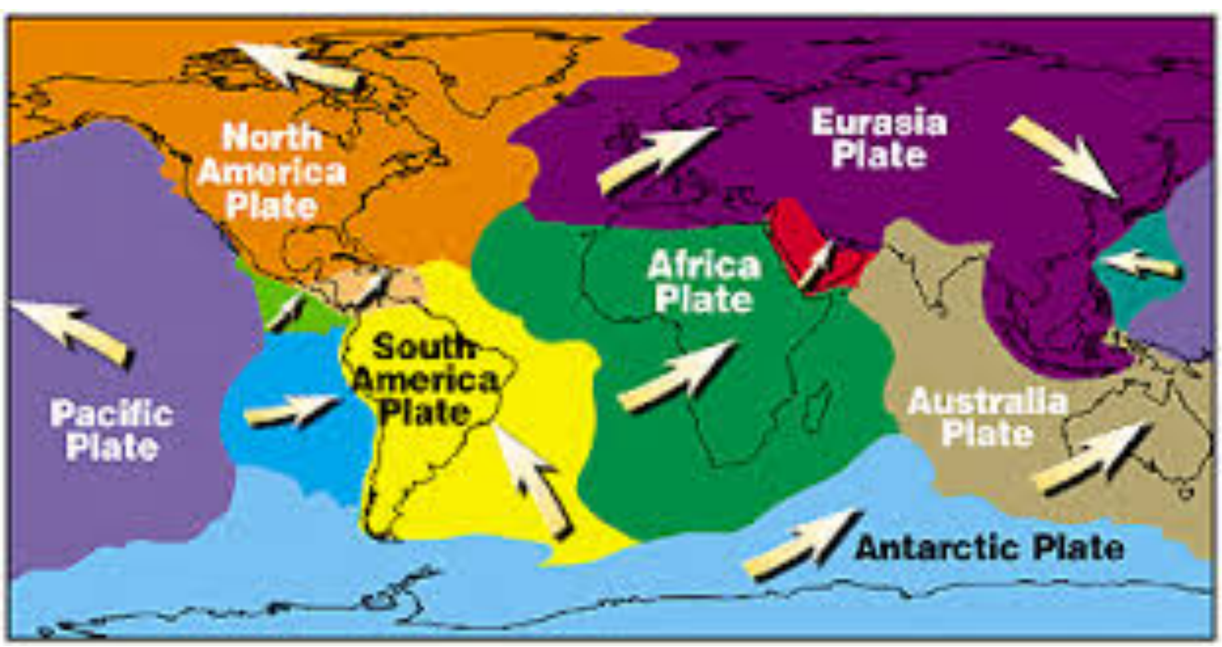
Erosion by waves takes several forms. The mechanical force of the waves fractures rocks. The force of water compresses air in cracks in the rock and breaks it apart to form caves and arches. Erosion of a sea cliff is speeded at its base which is undercut by waves. Sea stacks are remnants of the most resistant rocks, left behind as softer ricks erode.

As waves erode the edge of the land, they form a wave-cut platform. Along tectonically active coats, the wave-cut platform may be uplifted to form a marine terrace. Then a new wave-cut platform is carved at sea level. These actions can produce layers of terraces, which are often covered by beach deposits and by sediment eroded from uphill.

Beaches have a wide variety of sands that vary in size, color, and composition of the grains, depending on the surrounding rock. Major winter storms can remove a lot of sand from beaches.

ch.2. The Plate Tectonic Framework

Plate tectonic processes are fundamental to the geology of the Bay Area. Every aspect of our landscape is the result of living in an active boundary between the North American and Pacific tectonic plates. "Tectonics" refers to movements of the earth's lithosphere, which consists of the solid crust and the uppermost solid part of the underlying mantle. The lithosphere is broken up into 7 large plates and many smaller ones. The major ones are the African, Antarctic, Eurasian, Indo-Australian, North American, Pacific, and South American Plates. Some consist primarily of oceanic crust, some are continents, and some are a combination of both. They are constantly in motion, riding on the asthenosphere, the hot, plastic layer of the upper mantle just below the lithosphere.

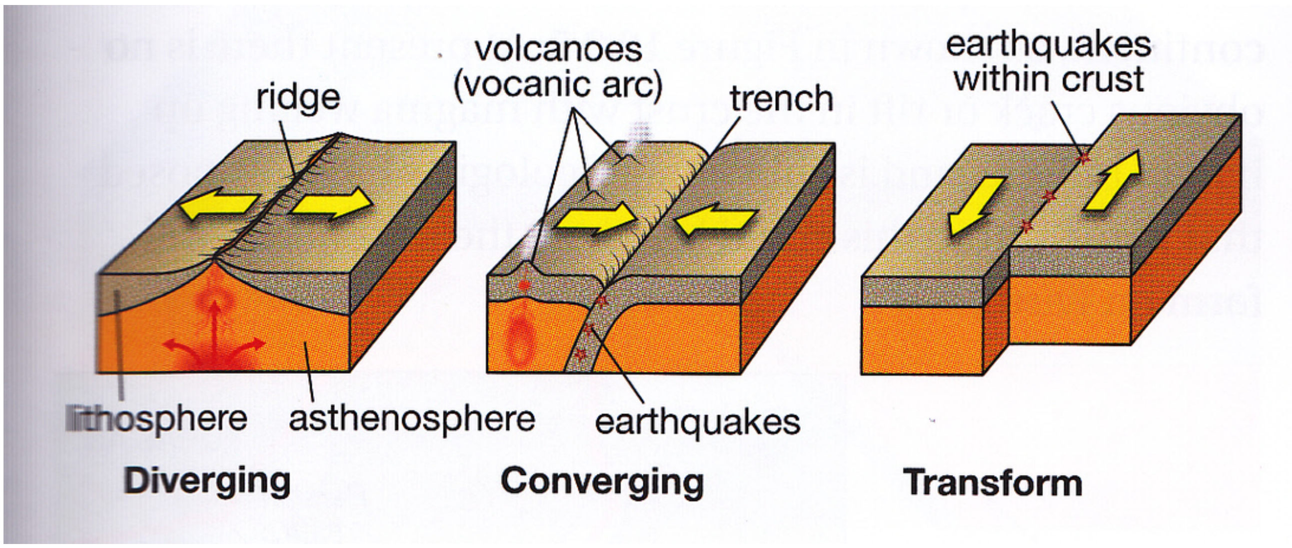


https://www.quora.com/What-are-7-major-tectonic-plates-in-the-world

Tectonic activity bends and breaks the crust into hills and valleys along the many faults that divide the Bay Area, rearranging the rocks in the process. The East Bay Hills, Mount Diablo, and the Santa Cruz Mountains are each the product of tectonic movement and are all under 2 million years old.

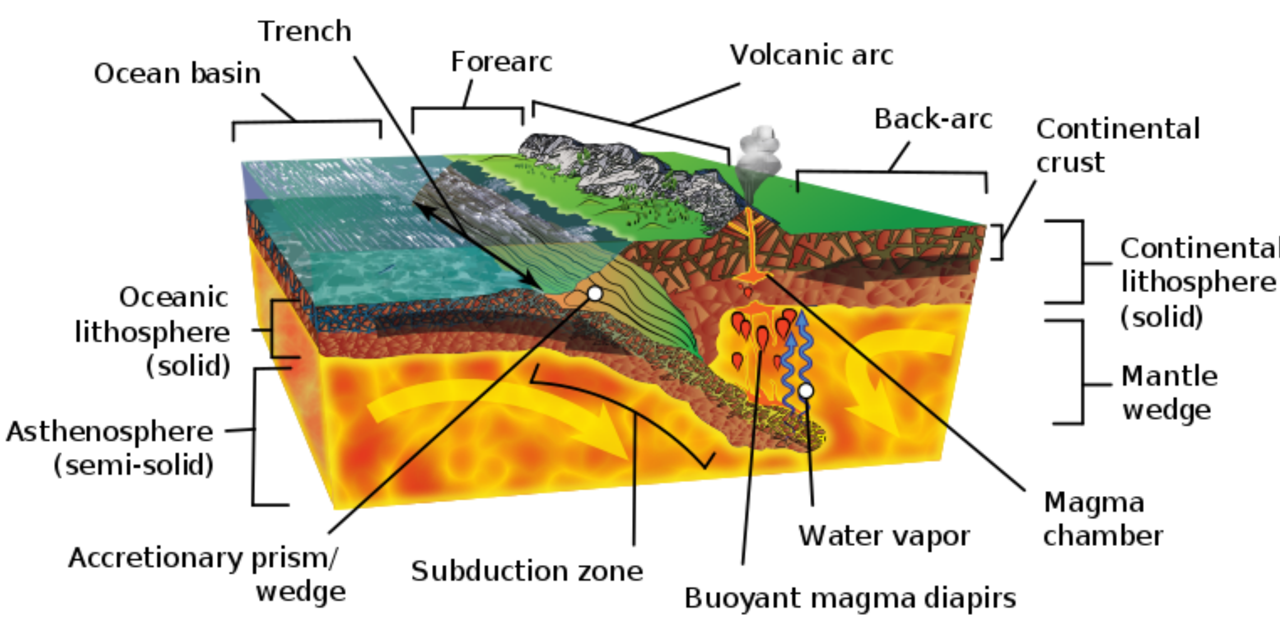
The Dance of the Plates

The plates are in constant motion; they separate and spread apart, they converge (collide), or they slide past each other.



http://year9scienceourchangingearth.weebly.com/plate-boundaries.html

Diverging plates bring up magma from the mantle to create new oceanic crust. Large earthquakes and high volcanic mountain ranges occur at converging plates, where the denser plate sinks beneath the other plate in a process called subduction. When an oceanic and a continental plate converge the denser oceanic plate subducts beneath the lighter continental plate.



http://opengeology.org/textbook/2-plate-tectonics/

The oceanic crust is carried ever deeper into the earth, where it heats up and melts, forming magma, which rises through the rocks of the continental plate toward the surface, because it is less dense that the colder rock around it. The magma accumulates in magma chambers and may rise to the surface, where it erupts, forming a volcanic arc. When subduction ends the volcanoes stop erupting and the magma chamber cools slowly and crystallizes, partly as granitic rock. Over millions of years the overlying rock may erode away, exposing the granitic rock, which is one of the signatures of past subduction.

At a transform, or sliding, plate boundary, plates slide past each other along major faults called strike-slip faults. The San Andreas Fault System is composed of mostly strike-slip faults along which the Pacific Plate is sliding north past the North American Plate.

California's Dynamic Past

About 145 mya, in the Mesozoic Era, the eastward-moving Farallon Plate (the predecessor of today's Pacific Plate) began to collide with the North American Plate. For almost 100 million years the Farallon Plate was subducted beneath the North American Plate. Large magma chambers formed and magma rose to the surface to form a chain of volcanoes in present-day eastern California. The Farallon Plate brought to California both oceanic crust from thousands of miles west and marine sediments that were deposited on the crust as it travelled. Some of this crust and sediments were scraped off as the plate was subducted in a process called accretion to form an accretionary wedge. During more than 100 million years of subduction accretion brought together many of the different types of Mesozoic rock we see today in the Bay Area.

About 25 or 30 million years ago the Farallon Plate was almost entirely consumed beneath the North American Plate and the Pacific Plate first met the North American Plate. Subduction stopped and the Pacific Plate started to slide northward past the North American Plate. Strike-slip movement along the San Andreas Fault replaced subdution over millions of years. The transition from subduction to sliding along the San Andreas Fault gradually progressed northward and reached the Bay Area about 15 million years ago. Today subduction is still taking place in northern California, Oregon, and Washington, producing occasional large earthquakes and forming the active Cascade Range volcanic chain, which includes Lassen Peak, Mount Shasta, Mount St. Helens, and Mt. Rainier.

The Bay Area's Network of Faults

In central California today the dominant motion between the Pacific and North American Plates is strike-slip (sliding). The Pacific Plate is sliding past the North American Plate at about 1.6 inches per year. The boundary between the Pacific and North American Plates is not a sharp one; movement between the plates affects a broad zone of faulting that extends across the entire Bay Area and eastward.

The San Andreas Fault System has two major branches in the Bay Area: the San Gregorio and San Andreas Faults along the coast and the East Bay Fault System (mainly the Calaveras and Hayward Faults). The branches join south of San Jose. Faults to the east include the Rodgers Creek – Headsburg – Maacama Fault and the Green Valley Fault.

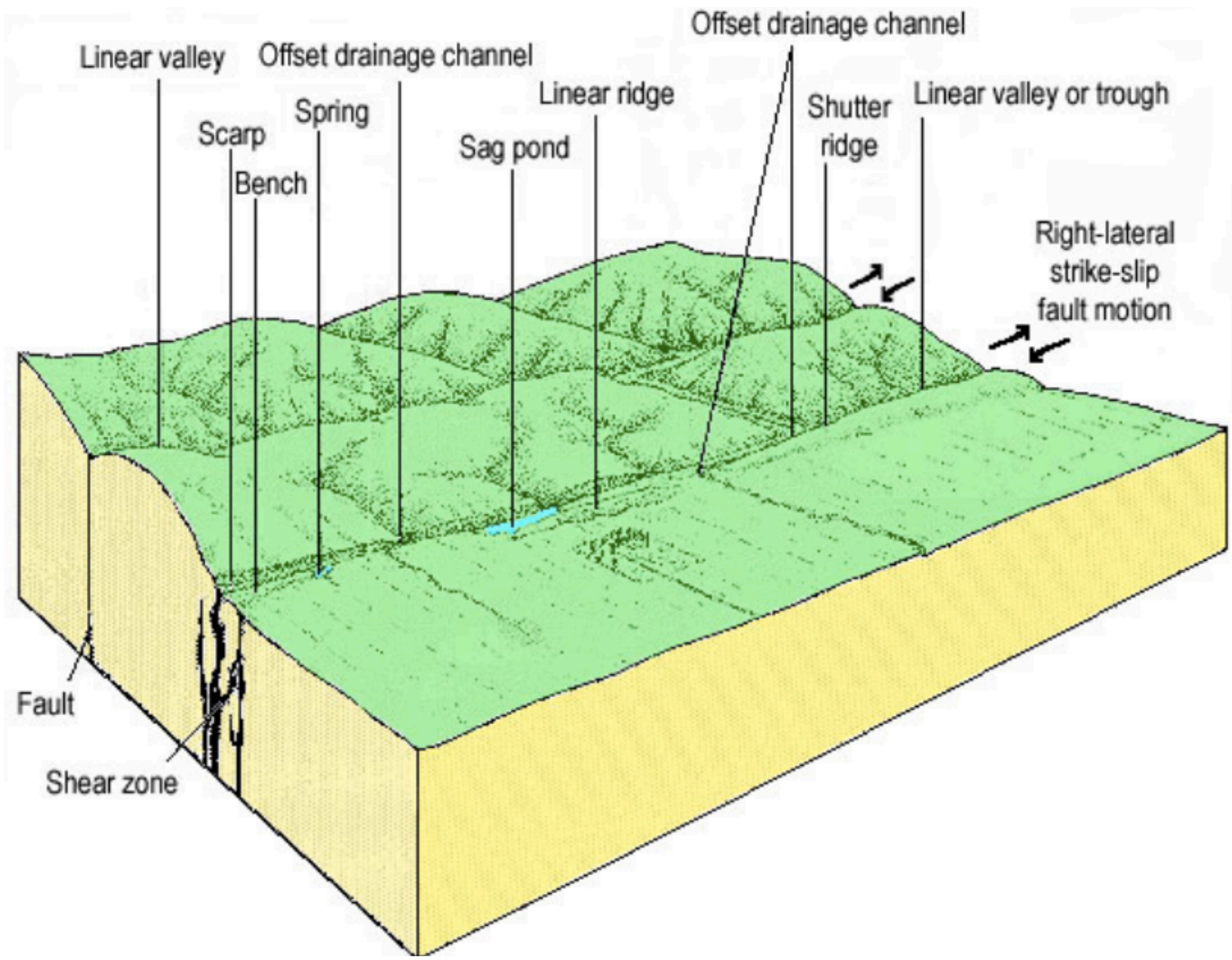
https://www.researchgate.net/figure/6-Faults-and-plate-motions-in-the-San-Francisco-Bay-Region-USGS-Yellow-lines-show_fig3_236436902

http://eps.berkeley.edu/~wenk/TexturePage/Publications/Lecture3.pdf

Earthquakes are triggered by the release of energy when a fault ruptures. Strong earthquakes take place where sections of a fault have been blocked and strength energy builds up until it overcomes the strength of the rocks. Sections of faults may be locked for hundreds of years, resulting in very large quakes like that in 1906 (magnitude 7.8), when rocks west of the fault slid past the eastern rocks as much as 21 feet. In the 1989 Loma Prieta earthquake (magnitude 6.9) the horizontal movement was about 6 feet, although the fault didn't break to the surface.

Another type of fault movement is creep, a slow horizontal movement of one side of a fault past the other. Creep does not result in earthquakes. The Hayward Fault is creeping at a rate of almost ¼ inch per year along much of its length.

Movements along faults over a long period of time produce recognizable features in the landscape. Rocks along a fault may be ground up, making it more easily eroded to form valleys. Streams can be offset, making abrupt turns. Sag ponds are water-filled depressions along the fault.



https://pubs.usgs.gov/of/2005/1127/chapter1.pdf

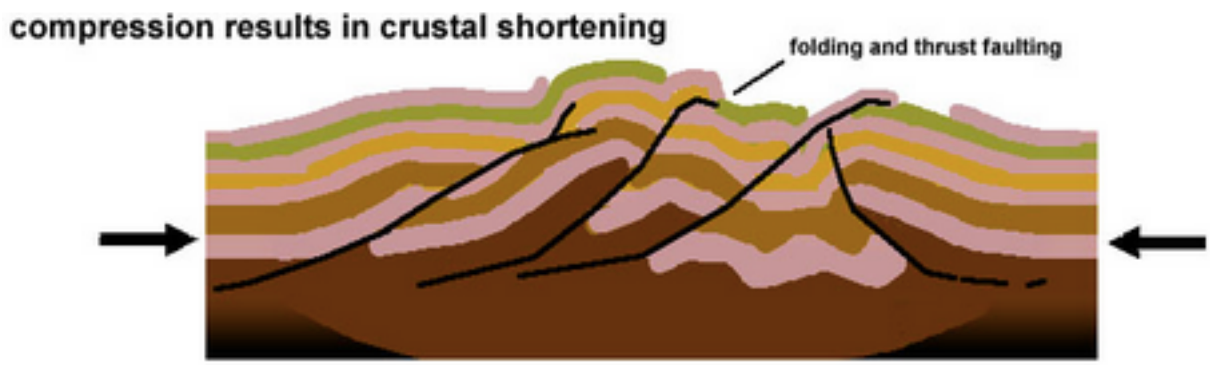
In order to tell now much movement has occurred along faults in the past geologists match distinctive rock formations on either side of the fault. For example, The Pinnacles, which lie west of the San Andreas Fault, were formed in Southern California about 23 mya. They match the Neemach Volcanics, which lie east of the San Andreas Fault in the Mohave Desert. The San Andreas

Fault has carried The Pinnacles 192 miles north to their current location over the past 23 million years.

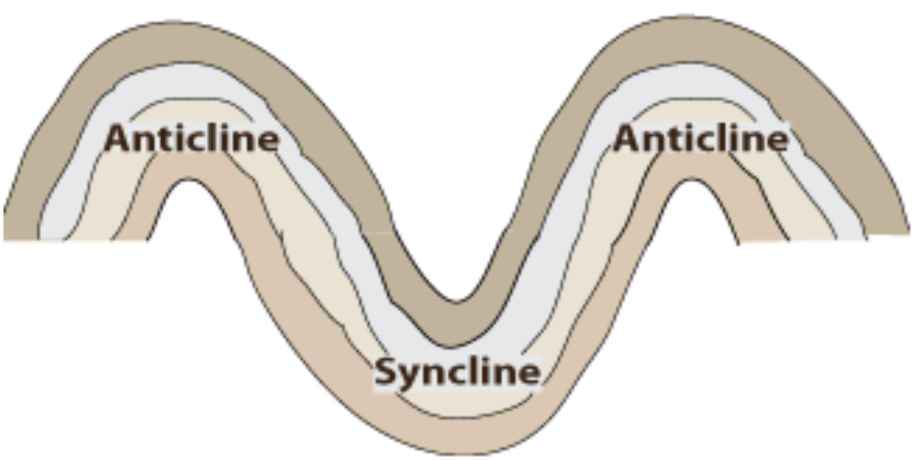
Squeezing the Bay Area

About 3.5 million years ago (or perhaps even earlier) the Pacific and North American Plates began to collide at a slight angle instead of just slipping past each other. This is known as compression and it produced Mount Diablo and the East Bay Hills. Today 90% or more of the movement is strike-slip and 10% or less compression.

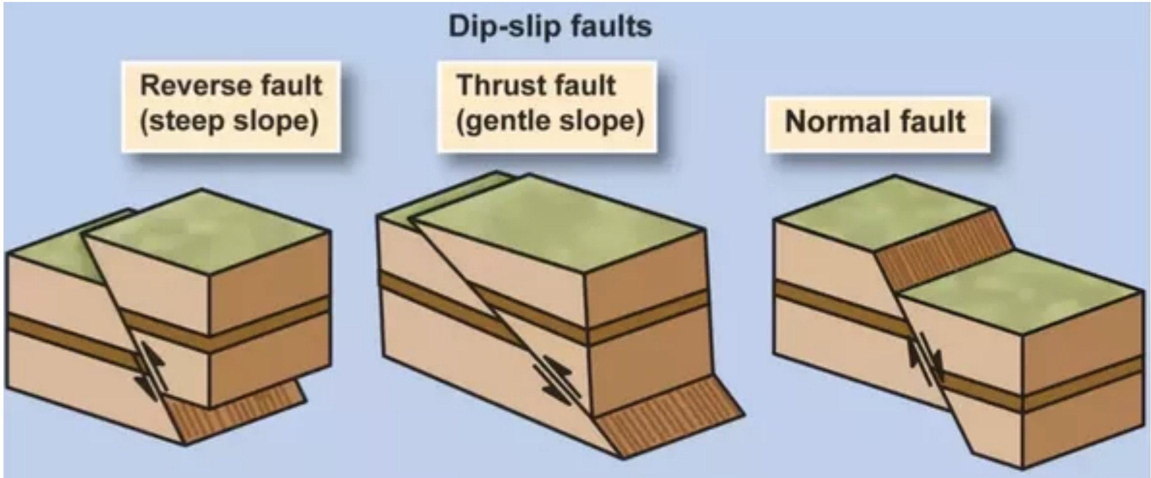
Compression thickens the crust by folding (bending) and by faulting (breaking). A convex upward fold is called an anticline; a concave downward fold is a syncline. Thrust faults, a type of fault in which one block slides up and over another at a low angle, are common in the Bay Area. Mount Diablo and Mount Tamalpais are moving up along thrust faults. Transpression has shortened the crust in a northeast-southwest direction so that today Mount Diablo is closer to San Francisco than it was 1 million years ago.



http://www.geologycafe.com/class/chapter6.html

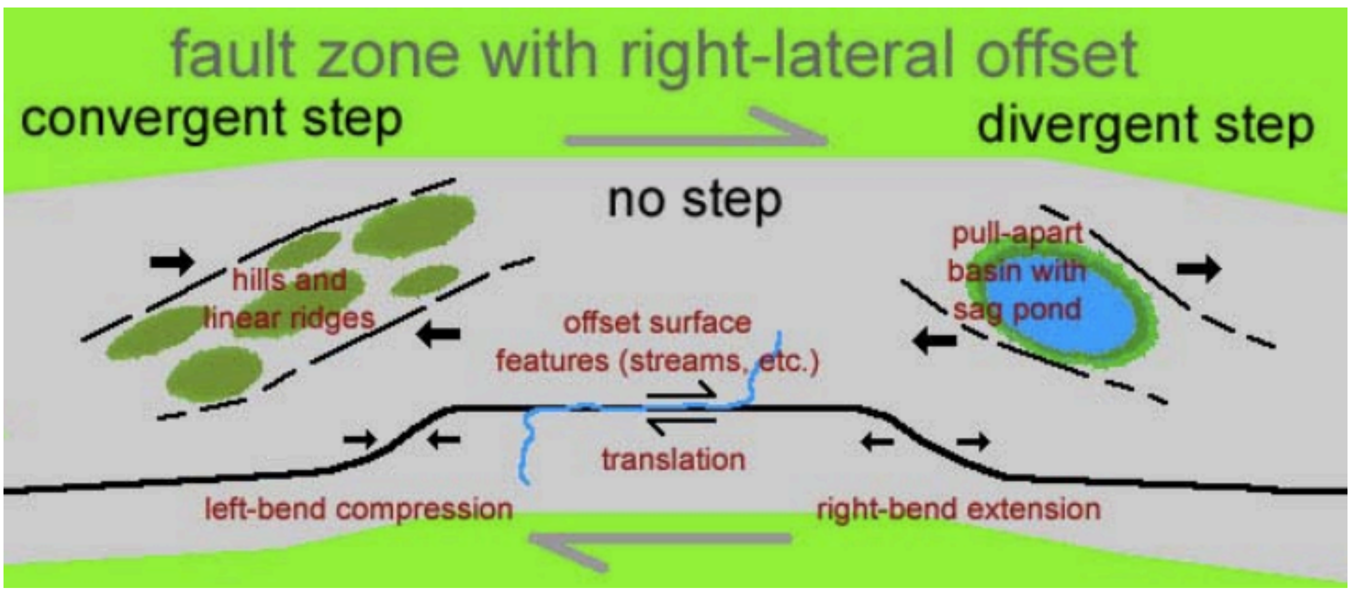


https://foothill.edu/fac/klenkeit/virtual/fault/process3.php



https://earthscience.stackexchange.com/questions/10583/why-should-this-be-a-thrust-fault

Crustal folding is intensified where a fault bends or is offset. Compression and uplift produce hills; extension and down-dropping produce valleys. Much of the present hilly topography of the Bay Area is related to thrust faulting along offsets or bends in faults.



https://pubs.usgs.gov/of/2005/1127/chapter1.pdf

The Bay Area's Complex Structure

The major active faults divide the Bay Area into 3 large blocks:

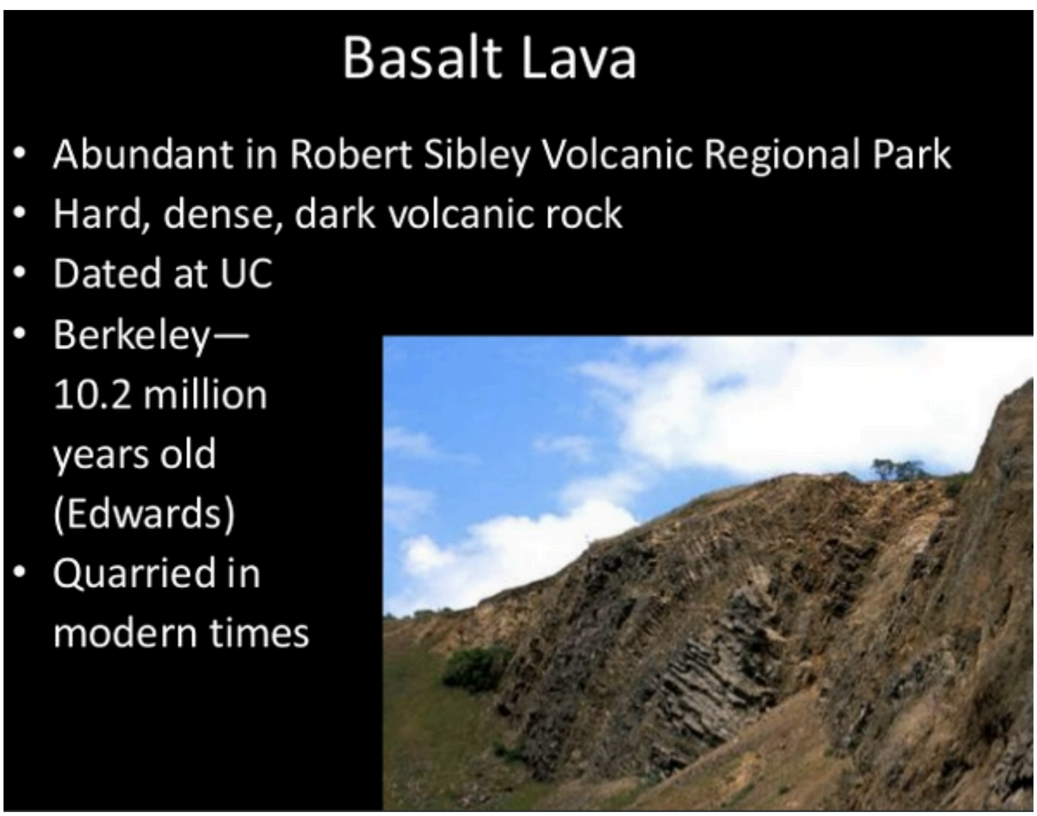
1. the Salinian Block, west of the San Andreas Fault
2. the San Francisco Bay Block, between the San Andreas and Hayward Faults
3. the East Bay Block, east of the Hayward Fault

Coastal San Mateo County, most of the Santa Cruz Mountains, Point Reyes, and Bodega Head are in the Salinian Block and are moving northwestward. 2 million years from now Point Reyes will be 50 miles north of its current location.

ch. 3 The remarkable rocks of the Bay Area

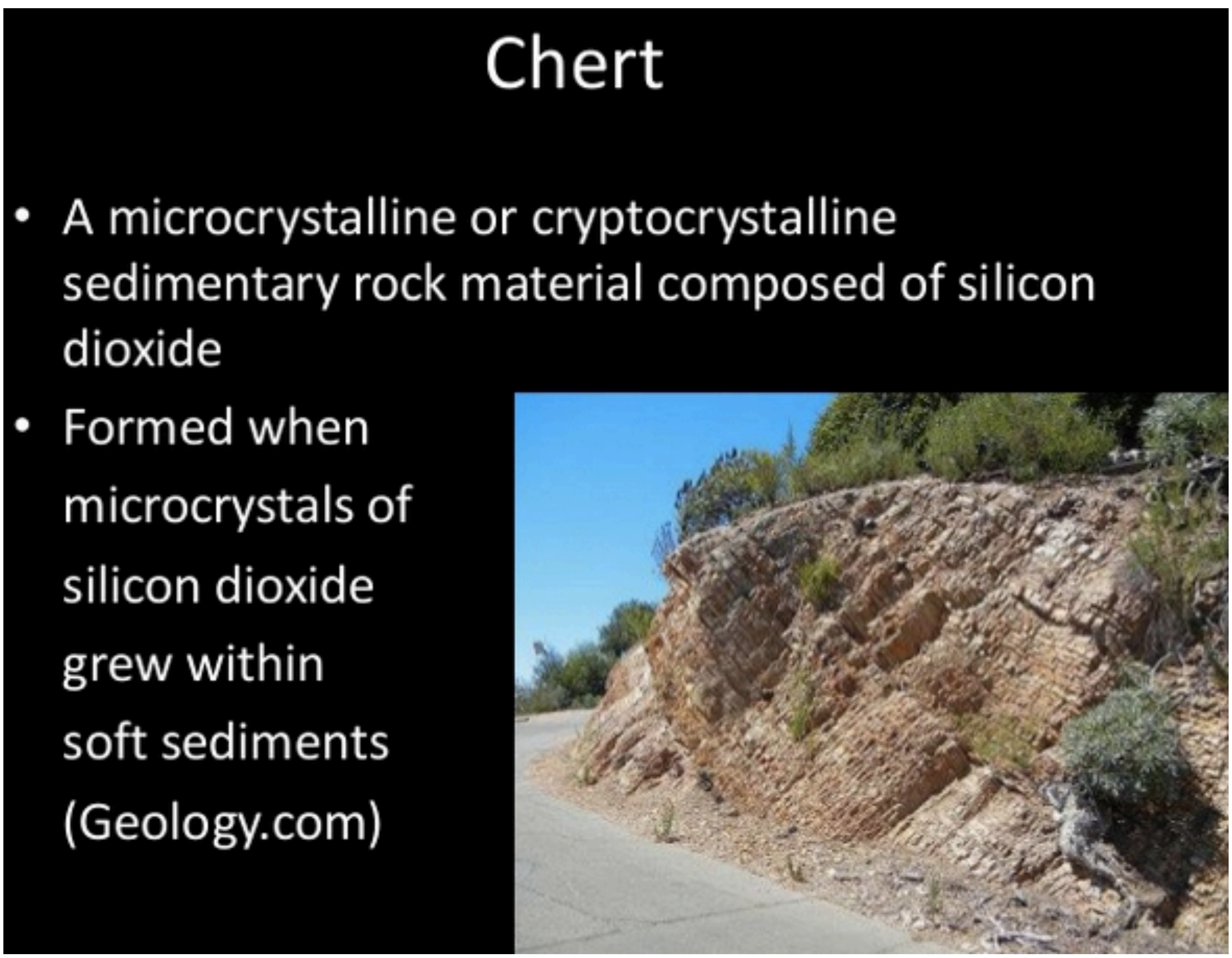
Because of our plate tectonic history we have a crazy-quilt pattern of rocks, a results of movement along ancient and young faults. All 3 basic types of rocks are present in the Bay Area:

1. **Igneous rocks** are formed as molten rock (magma) hardens. **Plutonic rocks** (also called **Intrusive rocks**) form from magma that cools underground. **e.g. granite** (contains mostly potassium feldspars and has a low percentage of dark iron and magnesium minerals), granodiorite (contains more calcium and sodium feldspar and has more dark minerals), diorite (composed of various silicate minerals). **Volcanic rocks** (also called **Extrusive rocks**) form from magma that erupts and cools at the surface. **e.g. obsidian, basalt** (formed from magnesium and iron rich lavas), tuff (formed from volcanic ash), rhyolite (which is silicon rich), andesite (intermediate in composition between basalt and rhyolite).
2. **Sedimentary rocks** are formed from sediments at the earth's surface. They can be formed **from fragments of other rocks, e.g. sandstone, shale** (from mud), greywacke (sandstones that contain grains of various sizes and composition), conglomerate; **from organic materials** like the skeletons of plants and animals, **e.g. limestone** (from calcium carbonate skeletons of marine organisms), radiolarian chert (from microscopic radiolaria silica skeletons); from **chemical precipitation, e.g. salt**.
3. **Metamorphic rocks** are formed from rocks subjected to heat and pressure, e.g**. marble** (derived from limestone), **slate** (derived from shale), **schist** (is split into thin sheets that alternate between granular minerals like quartz and feldspar and mica), **gneiss** (has bands of light and dark minerals, **serpentinite** (from serpentine minerals which contain a metal like magnesium, iron, nickel, aluminum, zinc or manganese combined with silicon (or iron or aluminum) and O_5 and $(OH)_4$.



https://www.slideshare.net/susangard/history-and-geology-of-the-oakland-hills

http://eps.berkeley.edu/~wenk/TexturePage/Publications/Lecture3.pdf



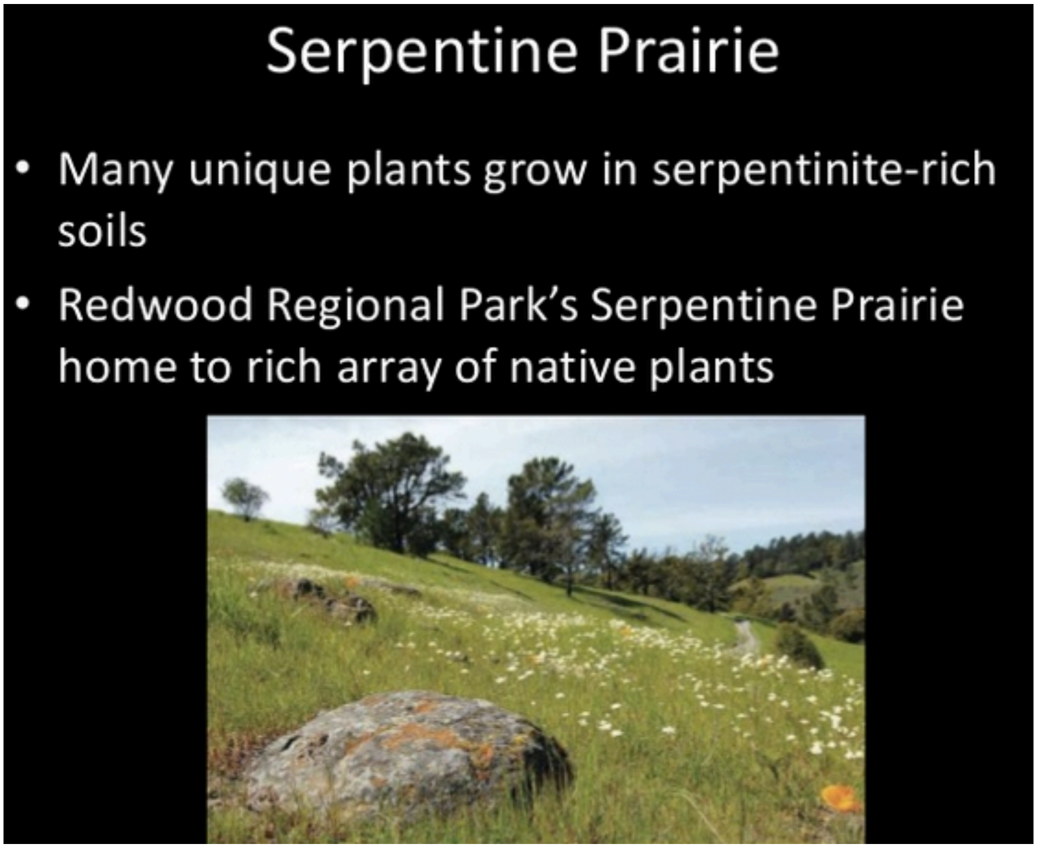
http://eps.berkeley.edu/~wenk/TexturePage/Publications/Lecture3.pdf

Actinolite Schist

- Found in Joaquin Miller Regional Park
- Foliated metamorphic rock dominated by the mineral actinolite
- Actinolite: dark greenish-colored amphibole calcium Ferromagnesian hydroxy-silicate that forms long blades or needle-like crystals (St. John)

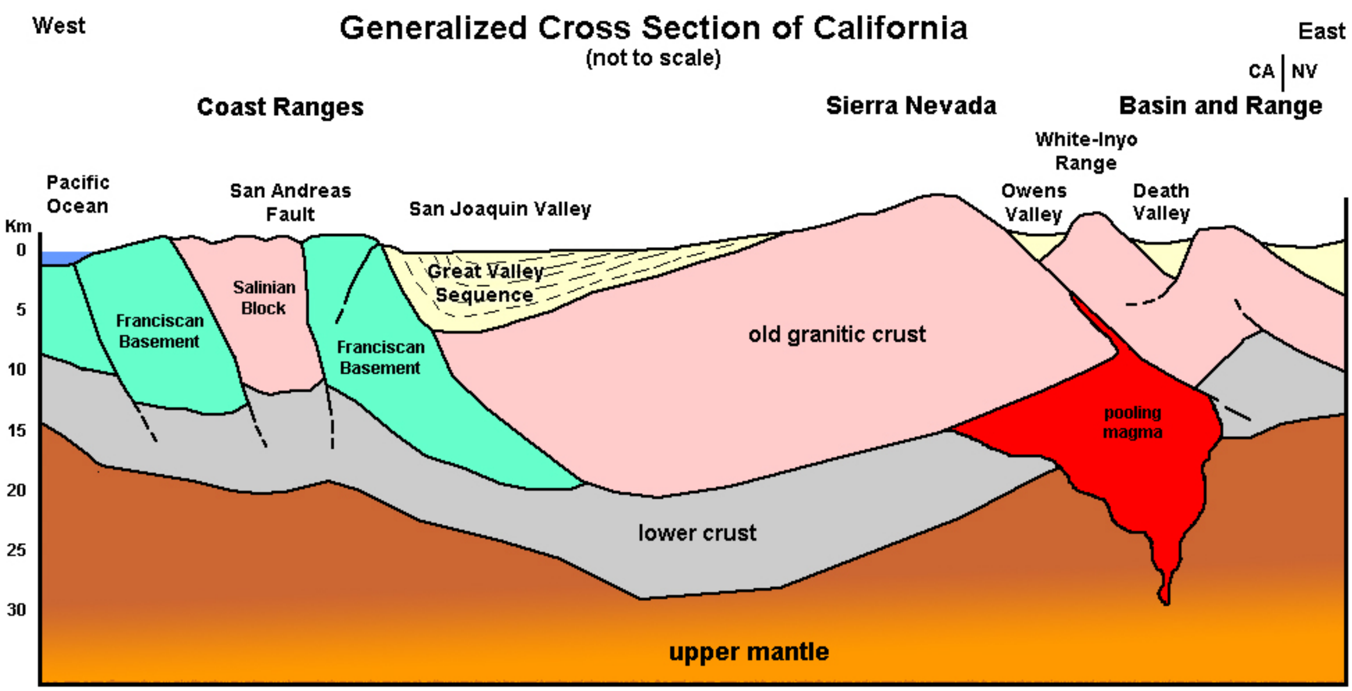
Serpentinite

- Composed of one or more serpentine group minerals
- Metamorphic version of peridotite—deep-seated, low-silica rock that forms upper mantle and bottom of oceanic plates
- Study of serpentinite in California contributed to understanding of modern plate tectonic theory
- Unique association with California due to gold deposits and thought to promote slower ‘creep’ along faults (Romans 2010)



Rocks formed at about the same time and place are called **formations**. Different rocks related by tectonic events are called **complexes**.

Older rocks, the "basement rocks" form the underpinnings of the Bay Area. They date from Mesozoic plate collisions and are called the Franciscan, Great Valley, and Salinian Complexes.



http://gotbooks.miracosta.edu/geology/regions/great_valley.html

The Franciscan Complex

The base of the Franciscan Complex is often the upper part of ancient ocean crust – **pillow basalt** from 100 to 200 mya. When lava erupts from the ocean the outside hardens but the inside remains soft and more lava flows through it in long tubes whose ends look like pillows.

As the lava interacts with seawater it can develop a greenish color from chlorite and other iron bearing minerals – in which case it is called **greenrock**.

https://ww2.kqed.org/quest/2011/03/24/geological-outings-around-the-bay-shell-beach/

The marine sediment that was deposited on top of the ocean crust basalt is largely composed of the silicon skeletons of microscopic single-celled animals called radiolarian. This became **radiolarian chert** – which began to accumulate in the Pacific Ocean near the equator about 200 mya. The radiolarian skeletons rained down for 100 my as the oceanic plate slowly made its way eastward


https://skinny.typepad.com/rockpoemphoto/2008/03/radiolarian-che.html

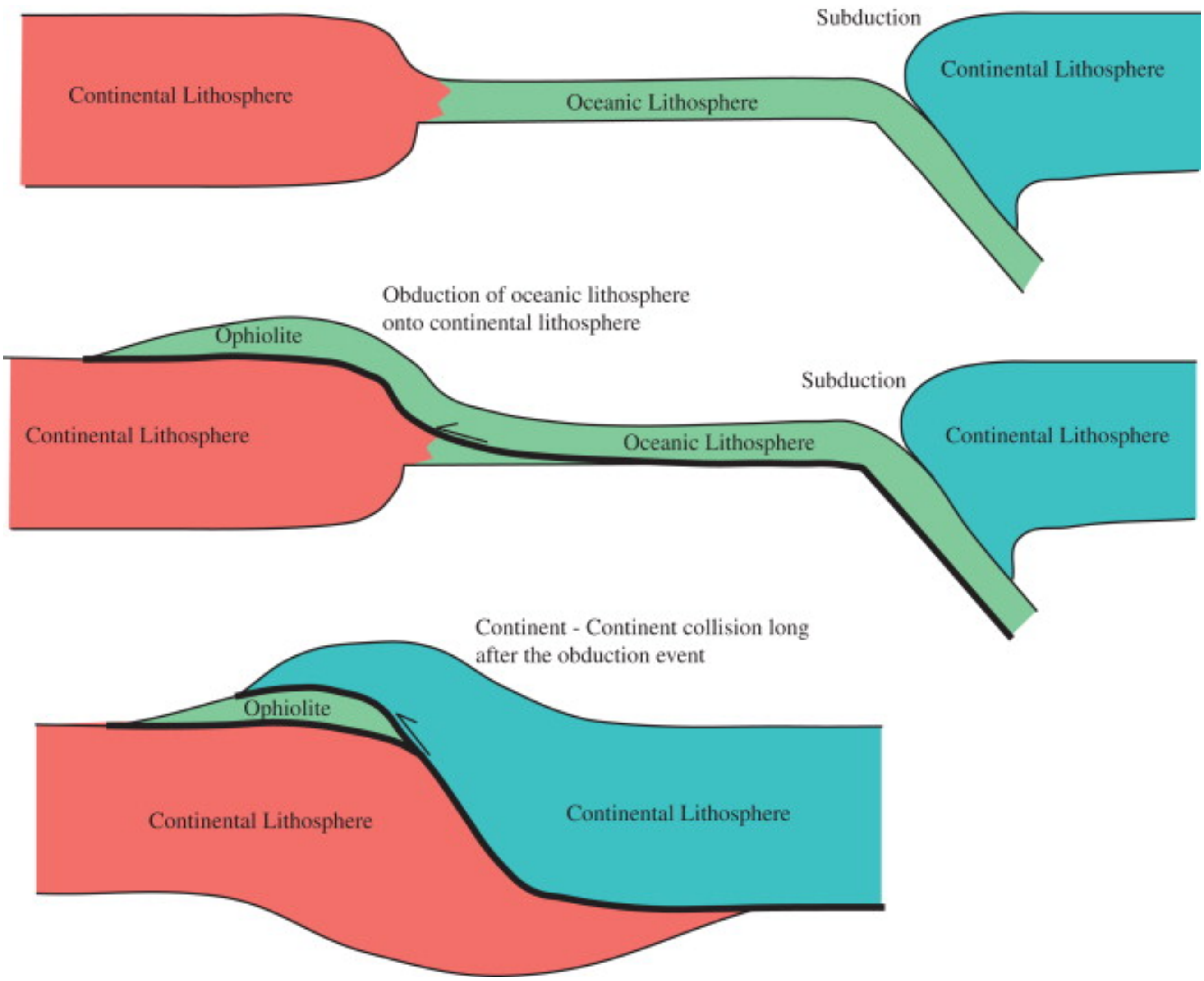
As the Mesozoic Farallon Plate collided with the North American plate great quantities of sediment eroded off the North American Plate. These sediments hardened into a sandstone called greywacke, which is gray when fresh but weathers to brown. It is a “dirty” sandstone with a wide range of particle sizes and compositions. Its mineral composition varies from place to place. Some was created by underwater landslides that fist deposited the heavier particles and then finer and finer ones – this resulted in alternating layers of sandstone and shale. About 80% of the Franciscan Complex consists of greywacke and shale.


https://www.nps.gov/goga/learn/education/graywacke-sandstone-faq.htm

The Great Valley Complex

The Great Valley complex was also formed by Mesozoic plate tectonics. It includes 2 sequences: rocks from the upper mantle and ocean crust called the Coast Range Ophiolite, and marine sedimentary rocks that were deposited on the ophiolite, called the Great Valley Sequence.

An ophiolite is a segment of ocean crust and mantle tectonically exposed on land by obduction (overthrust), usually when an ocean basin closes. An ophiolite sequence consists of variably altered oceanic rocks, including marine sediments, ocean crust, and part of the mantle. The name ophiolite means "snakestone" from "ophio" (snake) and "lithos" (stone) in Greek. The rock sequence is named for the brilliant green, snake-like serpentine minerals which form in altered ocean crust and mantle. (from https://blogs.agu.org/georneys/2011/02/10/geology-word-of-the-week-o-is-for-ophiolite/)



https://www.sciencedirect.com/topics/earth-and-planetary-sciences/ophiolite

The **Coast Range Ophiolite** includes plutonic rocks of the upper mantle, basaltic volcanic rocks of the ocean crust, rocks transitional between these two, and metamorphosed upper mantle rock – the blue-green serpentinite. In the Bay Area a long belt of serpentinite is found on the eastern side of the Coast Ranges. Serpentinite forms a rubbly landscape because it makes only a thin soil cover, where a restricted flora grows. The photo below shows a Serpentinite outcrop on the coastal bluffs of the Presidio.

https://www.nps.gov/goga/learn/education/serpentinite-faq.htm

The **Great Valley Sequence** consists of marine sedimentary rocks of Jurassic and Cretaceous age. These rocks are as much as 30,000 feet thick – almost 6 miles of sediment, consisting of dozens of layers of Sandstone, shale, and conglomerate. The photo below shows Great Valley Sequence sandstone at Lake Berryessa.

https://en.wikipedia.org/wiki/Great_Valley_Sequence

The Salinian Complex

This third type of basement rock was also formed by Mesozoic plate tectonics and consists of plutonic rocks. They occur only west of the San Andreas Fault in Marin, Sonoma, and San Mateo Counties and on the Farallon Islands. They are rich in silica and are called granitic and are similar to the granitic rocks of the Sierra Nevada. A few even older metamorphic rocks like schist exist as well.

Younger Rocks

Resting on these basement rocks are younger sedimentary and volcanic rocks that have formed in the last 65 million years. They record the change from a colliding to a sliding plate boundary, and from a marine to a terrestrial environment.

At the end of the Mesozoic, 65 mya, the continental shoreline was to the east along the present Sierra foothills, and the Bay Area was still ocean. As subduction continued (till about 25 mya) local faulting created regional marine basins. At times a drop in sea level or local tectonic movements formed shallow marine basins. Many varieties of sediment – future sandstone, shale, and chert – accumulated in these basins.

One of the most widespread of these is the Monterey Formation. It contains microscopic fossils of single-cell plants (diatoms) and animals (foramifers). A similar rock is the Claremont Formation found in the East Bay. Both have thin layering and weather to a light color. The first photo below shows the highly fractured Claremont formation black shale exposed near the Hayward fault in Berkeley. Tectonic movements have brought this sedimentary rock from depth to the surface and rotated the beds from horizontal to vertical. The second photo is of the Claremont chert formation with lupine on Claremont Avenue.

https://www.researchgate.net/figure/Photograph-of-the-highly-fractured-Monterey-equivalent-Claremont-formation-black-shale_fig3_301909655


http://www.nhwildlife.net/album4/slides/Chert-MG30.html

Young volcanic rocks are not common in the Bay Area except in the North Bay. Smaller outcrops occur in the East Bay Hills and on the Peninsula. Several types are present: lava flows, volcanic mudflow rocks, and tuff, which consists of solid fragments of volcanic ash, crystals, and bits of cooled lava. The lavas vary in chemical composition: basalts are low in silica and generally dark; rhyolites are silica rich and light in color; andesites are intermediate in silica and color.

Two volcanic eruptions have left important deposits in the Bay Area: one in eastern California about 774,000 years ago deposited the Bishop Tuff, and one from a volcano near Lassen Peak about 570,000 years ago deposited the Rockland Ash.

The Bay Area volcanic rocks were produced mostly by local eruptions from small volcanoes and vents. The Diablo Range volcanics are 11-13 my old; the East Bay Hills ones 9 – 10.5 my old; the Sonoma ones 2.6 – 8 my old; and the Clear Lake ones 10,000 to 2 my old.

ch. 9 The East Bay

The East Bay is a young and dynamic landscape. It stands out for its fault activity, diversity of rocks, and geologic variety. The hills of Alameda and Contra Costa counties are at most 2 million years old and are still going up. Here we can see the transition from a colliding to a sliding plate boundary, and from deep ocean to shallow sea to land.

More than a dozen active faults slice through the East Bay. They are part of the San Andreas Fault System. Compression between the faults has formed its hills and thrust up Mount Diablo in the past million years or so.

Along the San Francisco Bay lie the flatlands, a gently sloping alluvial plain formed from bits of rocks eroded from the rising hills. Over the past million years the many creeks that drained the hills carried sediment toward the bay and built up the flats. Three major creeks, San Leandro, San Lorenzo, and Alameda, have formed large alluvial fans. Here and there you can see bay and willows that grew along the creeks.

Just east of the alluvial plain, the long ridge of the East Bay Hills stretches from San Jose to the San Pablo Bay. Rocks spanning the geologic history of the Bay Area from the Mesozoic plate collusion to young stream deposits can be found in these hills.

The hills are still rising, squeezed up between the Hayward Fault on the west and the Calaveras Fault of the East.

The East Bay Hills of today look very different from those of 100 years ago – they are tree covered, mostly with introduced eucalyptus and Monterey pine. They used to be grasslands, with redwoods and bay trees in the moister canyons and oaks on the drier exposures.

Further east are wide valleys, rolling hills, Mount Diablo, and the rugged Mount Diablo range in the south. These last two high areas are islands of Mesozoic rock in a sea of younger sedimentary rock.

The urbanized north-south valley from Concord to Pleasanton along highway 680 is underlain by alluvium washed out from the surrounding hills.

East of the hills lie the meandering sloughs of the Delta. Before development, vast wetlands lined the Sacramento and San Joaquin rivers. Extensive marshes and a network of sloughs (swamps - areas of low-lying ground where water collects) existed where the rivers joined. Each spring the rivers flooded, bringing fresh sediment and nutrients to the marshes. As marsh vegetation died, it built up into thick peat deposits. In the late 1800s levees were built around the Delta islands and the rich peat soil was farmed. But the levees stopped the annual sediment input and the peat soils compacted, dried out, and blew away. The island surface behind the levees got lower and lower.

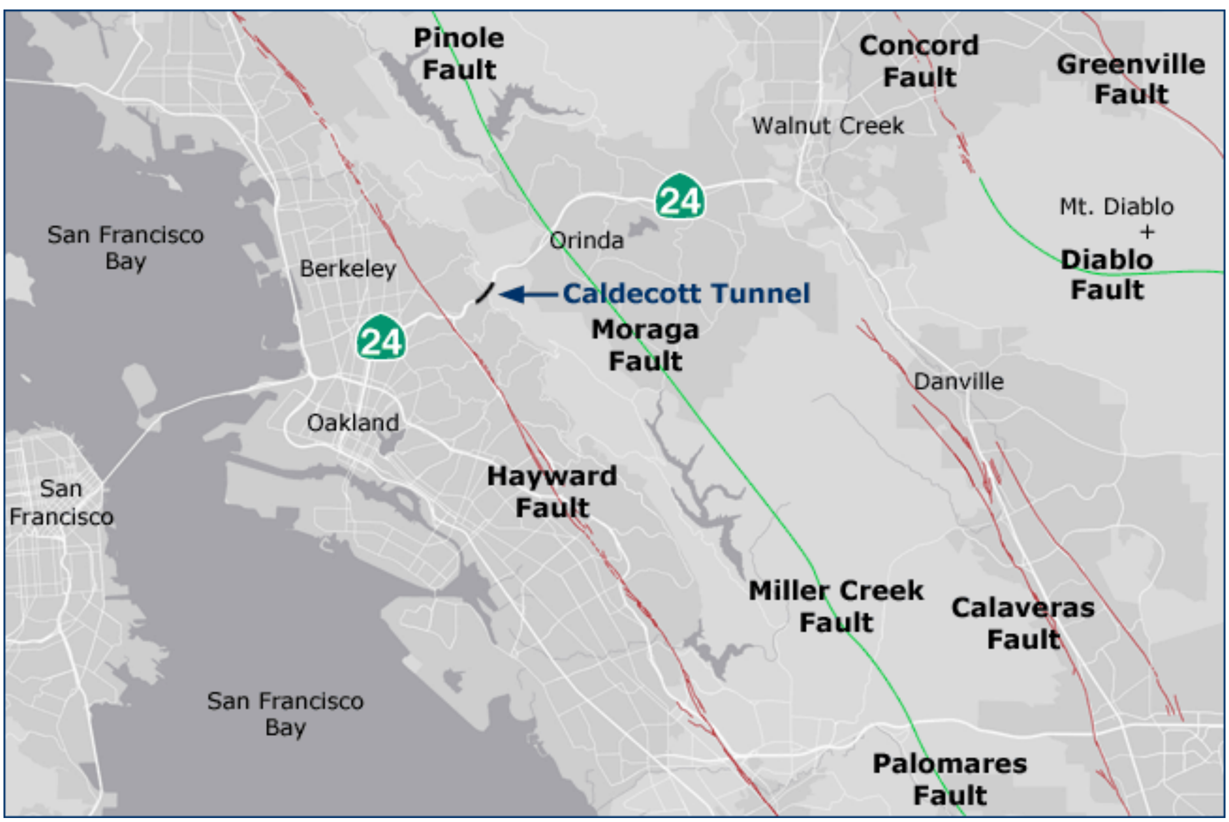
The creeks that drain the East Bay all flow into the San Francisco Bay. Creeks east of the hills take long circuitous routes. San Pablo and Wildcat creeks flow north along the hills into San Pablo Bay. Walnut Creek flow northward into the wetlands of Pacheco Creek and into Suisan Bay. Alameda Creek (the longest and largest creek in the East Bay) flows southward along the hills, through them at Nils Canyon (highway 84), then into the bay. All the creeks east of Mount Diablo flow into the Delta, which drains to the bay via San Joaquin river tributaries.

Map 24. Map of the East Bay faults and creeks.

The East Bay Fault System

The major fault systems are shown in the 3 images below.

http://seismo.berkeley.edu/blog/2016/11/18/the-missing-link.html



http://www.ucmp.berkeley.edu/exhibits/caltrans/fourthbore2.php

http://temblor.net/earthquake-insights/the-rodgers-creek-and-hayward-faults-are-revealed-to-be-one-fault-capable-of-a-magnitude7-4-earthquake-2046/

The dominant movement of these faults is right lateral strike-slip. This maze of faults divides the East Bay into more than a dozen slivers of rock, each with its own geologic story. The East Bay Fault System was initiated about 12 million years ago. the faults have not all been active at the same time; movement may shift from one fault to another. Over the past 12 million years about 110 miles of offset has occurred, mostly on the Hayward Fault, moving rocks northward. The highest part of the East Bay Hills – Mission Peak to Monument Peak in Fremont – occurs where the Hayward and Calaveras Faults almost converge and movement steps over from one to the other.

There are also many thrust faults in the East Bay. They shove older rocks over younger rocks, as the Mount Diablo Fault is uplifting Mount Diablo. These kinds of faults have been active in the past 3.5 million years.

The Hayward Fault is the most prominent and is marked by typical features of a fault zone: landslides, springs, offset streams, and linear valleys (like the one rte. 13 runs through). The last major earthquake on the Hayward Fault was in 1868. The Hayward Fault also moves by fault creep, averaging 1/10 to 2/10 of an inch per year; this does not produce earthquakes or shaking.

The Mesozoic Subduction Record

The basement – or oldest – rocks are the same Francsican and Great Valley Complex rocks foung elsewhere in the Bay Area.

All the **Franciscan Complex rocks** – basalt, chert, greywacke, and metamorphic rocks – can be seen in the East Bay, particularly in the Diablo Range and on Mount Diablo. However, only a few Franciscan outcrops stick up through the alluvial plain in the East Bay.

Good exposures of graywacke and shale layers can be seen at the east end of the Richmond Bridge and at Point San Diablo, in the East Sore State Park, in Albany Hill, and in Piedmont.

The beautiful reddish radiolarian chert is well exposed at Cooyote Hills Regional Park in Fremont (e.g. Red Hill).

Franciscan basalt is in a large quarry at the southern end of the Coyote Hills, just south of the Dunbarton Bridge toll plaza.

A variety of rocks of the Marin Headlands Terrane and mélange can be seen at Mount Diablo. Metamorphic rocks embedded in Franciscan mélange occur in El Cerriyo, Kensington, nd in Little Yosemite in Sunol regional Wilderness. Yolla Bolly greywacke is in the northern end of the Diablo Range south of Livermore and in the El Cerrito hills.

Large outcrops of the **Coast Range Ophiolite** and the overlying **Great Valley Sequence of marine sedimentary rocks** occur in the East Bay. Discontinuous outcrops of serpentinite can be seen along the Hayward Fault from Richmond south to Fremont, in the Diablo Range, and on Mount Diablo.

An unusual volcanic rock in the East Bay Hills at Oakland is the Leona Rhyolite. Pyrite (iron sulfide), chalcopyrite (iron copper sulfide), and sulfur were quarried from it.

Great valley sequence marine sedimentary rocks can be seen in road cuts along Skyline Blvd, Pinehurst Road, and Redwood Road in Oakland – sandstone, shale, and the unusual Oakland Conglomerate. It contains large volcanic cobbles – an excellent place to see this is Skyline Blvd. several miles south of Redwood Rd.

Good crops of sandstone can be seen along the trails of Carquinez Strait Regional Shoreline. The largest mass of Great Valley rocks extends from Mount Diablo south to the Altamont Hills – you can see them along Marsh Creek Road, which follows a valley cut into the soft shale. They were deposited by turbidity currents. You can see sandstone rich layers deposited closer to the shore on the north side of the road, 3.2 miles east of Morgan Territory Rd. Fine grain shale layers deposited further from the shore are near Altamont Pass.

From Sea to Land

Deposited on the Franciscan and Great Valley Complex basement rocks is a thick sequence of younger sedimentary and volcanic rocks. They tell the story of how this area emerged from the sea and became land. Microfossils in the rock show that the long range trend, starting about 25 million years ago, was to shallowing water and gradual uplift. Rocks formed in the East Bay about 11 to 12 million years ago contain fossil mollusks that lived in shallow waters near the shore. They are preserved in rocks called the **Briones Formation**, which is a resistant sandstone that forms prominent ridges from Briones Regional Park to Mission Peak.

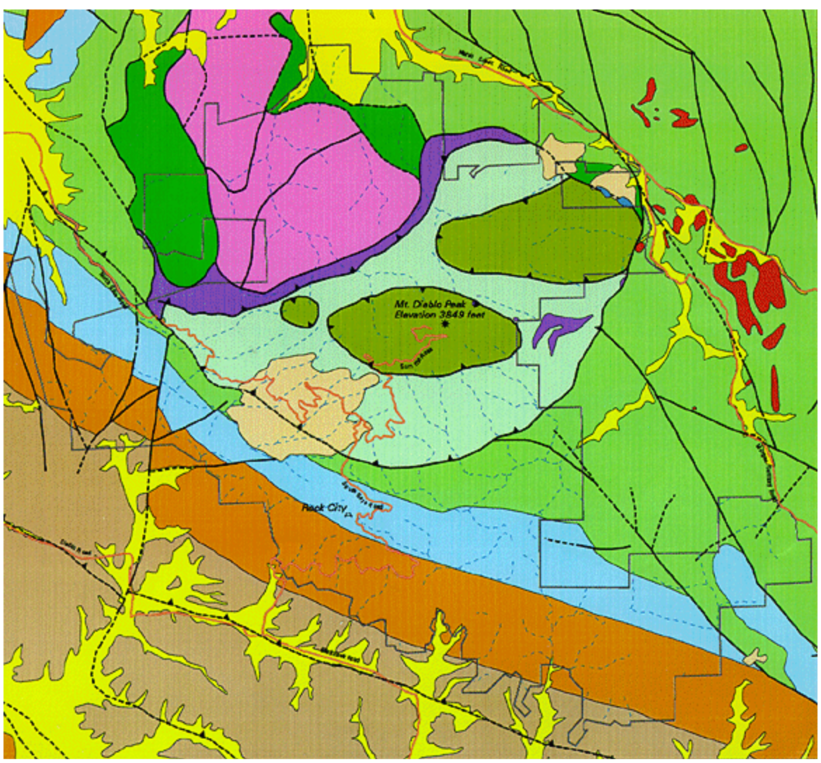
Somewhat younger rocks are no longer marine – they are terrestrial deposits, indicating that by about 10 million years ago the area was uplifted above sea level. A rich fossil site at Blackhawk Ranch on the south side of Mount Diablo contained bones of saber-toothed cats, horses, mastodons, camels, an small mammals that lived there about 9 to 10 million years ago. Similar fossil remains were found near Orinda and in the San Joaquin Valley. Younger sediments, from 10,000 to 2 million years old, contain fossils of mammoths, ground sloths, huge bison, and many other animals. From the fossil record we know that for more than 10 million years large mammals roamed a rich grassland that stretched across the East Bay and into the Central Valley.

Parts of the Livermore Valley are filled with more than a mile of gravel and sand deposited from streams. The younger ones, deposited in the past 2 million years, are called the Livermore Gravels in the southern part of the valley and the Sycamore Foundation of the rolling Tassajara Hills to the north. The gravel and sand are poorly consolidated (not yet rock) – you can see what they look like in the former quarries of Shadow Cliffs regional Recreation Area. The alternating sand and gravel layers indicate stream activity – streams carry coarser materials during floods, and finer sands and silts when they flow gently. Older sediments are from the Sierras and the Diablo Range. The Altamont Hills began to rise 6 million years ago, cutting off the Sierra rivers. In the past few million years Mount Diablo and the East Bay Hills started risind, contributing their sediments. Although these sediments are young, they are folded in a gentle syncline – indicating the ongoing tectonic activity.

Special Places to Explore

Mount Diablo is a small mountain of ancient rock. It is not a volcano. The volcanic rocks near the top are from volcanoes that erupted long ago and far to the west and deep beneath the ocean. Moun Diablo stands up in the landscape today because it is still being thrust up and because the Franciscan and Great Valley rocks at the top are more resistant to erosion than the younger sedimentary rocks that surround the mountain.

Mount Diablo is the product of the slight compression between the Pacific and North American Plates; it is the result of movement on the Mount Diablo Thrust Fault. In the map below the 3 olive green areas are Franciscan Complex basalt and chert, surrounded by Franciscan Complex mélange. The purple is serpentinite.



http://opticalmineralogy.blogspot.com/2012/01/mount-diablo-ophiolites-exploration.html

The rocks at the top are from the Mesozoic subduction. Franciscan rocks underlie Mount Diablo Peak, North Peak, and Mount Olympia on the northeastern side. Fine examples of tightly folded reddish chert and pillow basalt are exposed along Summit Road. On the northwestern side Eagle Peak and Mount Zion are underlain by Great Valley Complex rocks, including basalt and diabase (a fine- to mediumgrained, dark gray to black plutonuc igneous rock). These two areas are separated by a band of seroentinite. The sandstone windcaves at Rock City are formed by rainwater dissolving the cement that holds the sand grains together. The 8-mile hike on the Trail Through Time shows you many of these rocks.

Black Diamond Mines Regional Preserve tell the geologic story after subduction ended. It is named for the coal deposits that formed as the land emerged from the sea. This coal formed about 50 mya. The coal seams occur as layers in the estuarine sadstone of the Domengine Formation – much of it a beautiful white. It is resistant to erosion and underlies the prominent ridge above the mines. The next younger layer is the softer Nortonville Shale, which forms the valley just north of the mines. Its fossils show that it was deposited in a deep marine basin. On the north side of this valley is another ridge of resistant sandstone, the Markley Formation. The preserve headquarters sits on the Sidney Flat Shale, which sits between the two sandstone layers of the Markley Formation. The most northerly ridge is rock with a bluish cast, the Neroly Formation, which is 9 to 11 my old. It consists of volcanic sediment deposited by rivers flowing west from the Sierra Nevada. By this time norther Contra Costa County was land.

The sand at Black Diamond is of a high-grade silica one, perfect for glass making. It was mined from the 1920s to the 1940s.

In the **East Bay Hills** the sedimentary rocks in the ridge of hills that extends from San Pablo Bay south to the Diablo Range records the change from deep marine to terrestrial environments. Spectacular road cuts along hwy 24 just east of the Caldecott Tunnel reveal a sequence of layered rocks representing marine, alluvial, and volcanic environments. The rocks were lying flat when they formed 9 to 16 mya, but as the East Bay Hills pushed up they were folded and faulted. The section between the Caldecott Tunnel and the Orinda exit is folded into a broad syncline (down fold). Erosion resistant volcanic rocks (the **Moraga Volcanics**) form the high ridges at either end of the syncline, and soft easily eroded lake-bed sediments are exposed in the middle at Gateway Blvd.

The Caldecott Tunnel was blasted through a ridge of the resistant **Claremont Foundation**. This rock is 14 to 16 my old and was formed in a deep marine basin. It is made up largely of the skeletons of diatoms and foramifers. Much of it consists of thin bands of whitish chert, which is well exposed along Skyline Blvd. above the tunnel.

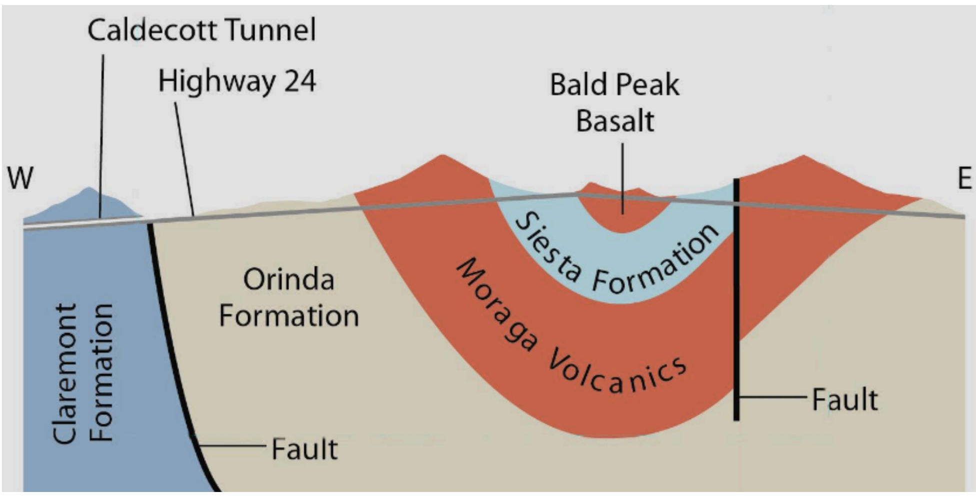
If you unfold the hills and lay them out lying on top of the Claremont Foundation are younger layers of sansdtone and conglomerate called the **Orinda Formation**. In the hwy 24 cutout they are the distinctive red and gray layers on both sides of the freeway as you leave the east end of the tunnel. These rocks are 10 to 12 mya and are not marine; they were deposited bt streams flowing across an alluvial plain. About 2 million years of rock are missing between the Claremont and Orinda formations, probably removed by fault action. During the time represented by this missing rock record, the area was uplifted and became land.

Some of the pebbles in the Orinda Formation conglomerate are distinctive Franciscan rocks, showing that the streams that deposited them flowed from the west. (Note: the Franciscan rocks have since moved northward about 60 miles along the Hayward Fault and are now in northern Sonoma County.) The Orinda pebbles were deposited before the East Bay Hills were uplifted., when the land to the west of the Hayward Fault was a ridge of Franciscan rocks, not a valley (filled today by the San Francisco Bay). Creeks draining this ridge carried sediment eastward to the edge of the shallow marine sea, where the towns of Orinda, Lafayette, and Walnut Creek are now.

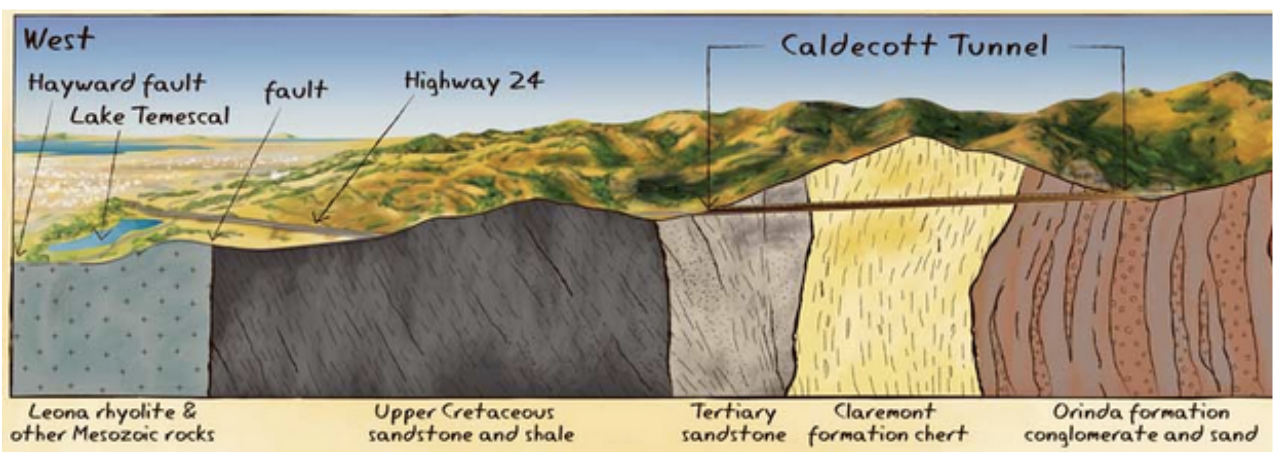
About 10 mya the southern East Bay was the site of volcanic activity related to the beginning of movement along the Hayward Fault. For almost 1 million years lava and volcanic ash periodically covered the alluvial plains. Basaltic flows called the **Moraga Formation** erupted from 10 to 9 mya from Round Top in Robert Sibley Regional Preserve and other vents. These lavas flowed over the alluvial plain in many separate flows.

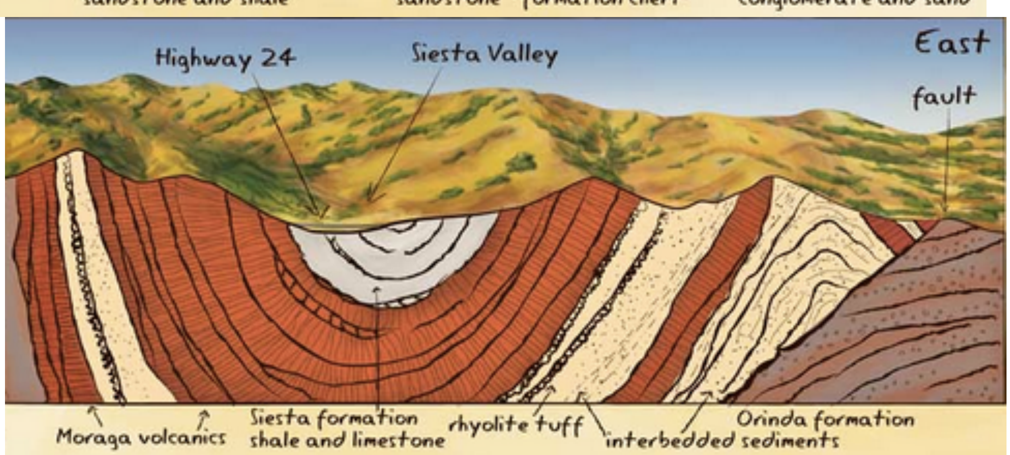
You can see them along hwy 24 east of the Caldecott, where they are steeply tilted, and form the prominent ridge on either side of the syncline. The base of most of tehse flows is red – the iron in the sediments and lava was oxidized by the hot lava to form a bright red color. The lava flows are also exposed o Grizzly Peak Blvd. north of Fish Ranch Rd.

One of the lava flows dammed a creek and formed a lake. Fine-grained light gray lake bed sediments, called the Sierra Formation, are present along hwy 24 at the Gateway Blvd. interchange. They are now folded into the center of the syncline. About 9 mya another volcanic eruption formed the Bald Peak Basalt, which poured over the lake bed sediments.



http://eps.berkeley.edu/~wenk/TexturePage/Publications/Lecture3.pdf





https://baynature.org/article/from-the-inside-out/

The photo below shows sandstone and conglomerate of Orinda Formation (foreground) and Moraga volcanic basalts (right) east of the Caldecott Tunnel.

https://baynature.org/article/from-the-inside-out/

The photo below shows a pillar of Moraga Formation lava, looking across Strawberry Canyon and the Bay from Grizzly Peak Boulevard in northernmost Oakland.

https://ww2.kqed.org/quest/2011/08/25/geological-outings-around-the-bay-the-moraga-formation/

The photo below shows the folded rock formation called Claremont chert on Skyline Blvd. near Sibley Volcanic Regional Preserve.

https://baynature.org/article/from-the-inside-out/

The photo below shows sandstones of the Briones Formation covered with orange lichen, along a trail at Mission Peak Regional Park in Fremont.

https://baynature.org/article/from-the-inside-out/

http://eps.berkeley.edu/~wenk/TexturePage/Publications/Lecture3.pdf

See also “The geology and paleontology of the Caldecott Tunnel's Fourth Bore” - http://www.ucmp.berkeley.edu/exhibits/caltrans/index.php.