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Notes for Sunday Workshop #3:

"Late Cenozoic development of the Pacific-North American plate boundary, with particular emphasis on
The Rotation of the Transverse Ranges: what happened, how we know it happened, and how it created Southern California's unique geography, climate, ocean currents and biological richness."

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These notes are accompanied by a data CD:

"Atwater Educational Geological Animations and Materials, 03/11."

The CD includes present and near-future materials offered free for non-profit educational purposes at the website
http://emvc.geol.ucsb.edu

Notes for Sunday Workshop #3,   NAGT-FWS Spring 2011 Meeting

Late Cenozoic development of the Pacific-North American plate boundary, with particular emphasis on
The Rotation of the Transverse Ranges: what happened, how we know it happened, and how it created Southern California's unique geography, climate, ocean currents and biological richness.

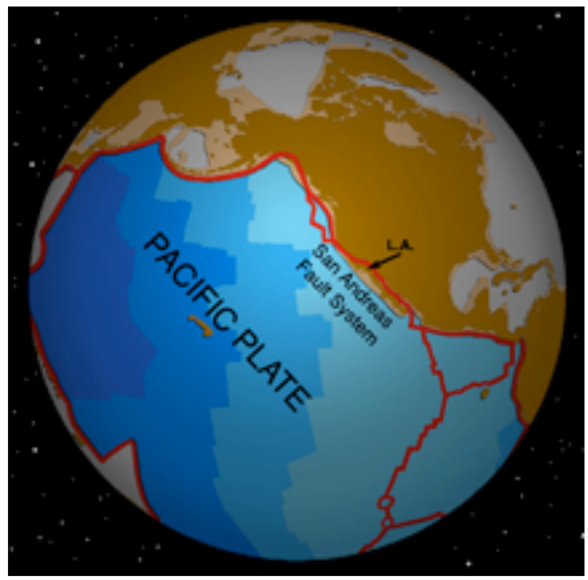
In this workshop, we will use computer animations and a physical hands-on model to explore the evolution of the San Andreas plate boundary and its geological implications for Southern California.   Along the way, we will also address some common plate tectonic misperceptions that tend to impede the understanding of this history; notes for these subjects are appended at the end, pages 15 and 16.

Note: Ma = million years ago.
Note: .mov names refer to movies included in the CD: "Atwater Educational Geological Animations and Materials, 03/11".

A. Origin and development of the San Andreas Plate Boundary.

At present, the Pacific plate fills most of the north Pacific basin and the San Andreas fault system forms the plate boundary between the Pacific and North American plates in California and northwestern Mexico.

NoPacific_80.mov



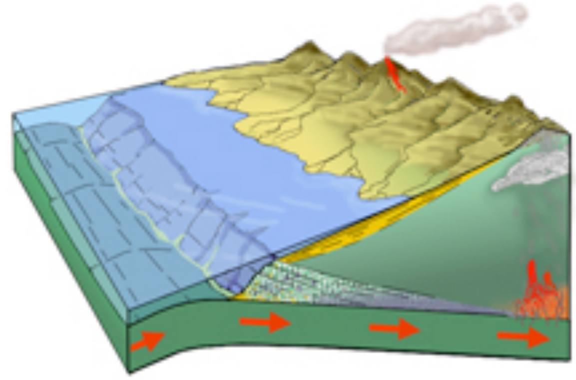
1.

During most of Jurassic, Cretaceous, and early Cenozoic time, the plate geometry was very different. The Pacific plate was much smaller and the Farallon and other oceanic plates were subducting beneath the rim of North America.

NoPacific_80.mov

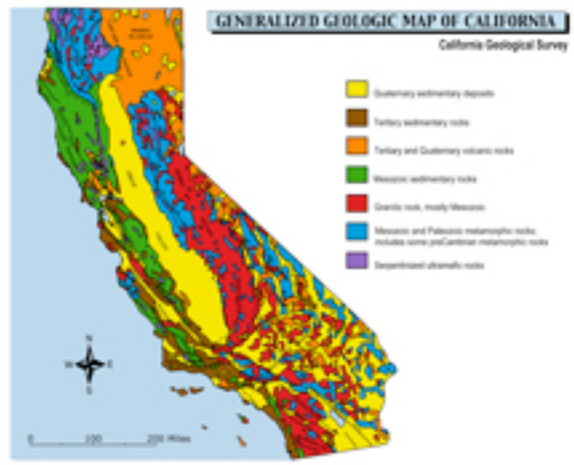
2.

Subduction Oc-Cont.mov



3.

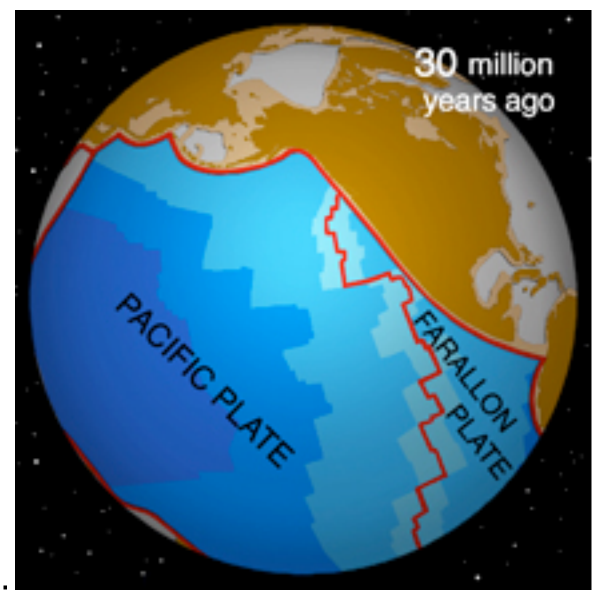
Much of the Mesozoic geology on this generalized map of California was formed during this long era of subduction. This includes the Sierra Nevada granites in red (formed in the roots of arc volcanoes), the Great Valley formations in yellow (sediments deposited in the arc-trench gap), and the Franciscan formation in greens and purples (formed in the accretionary wedge). These belts are repeated, somewhat attenuated and broken, west of the San Andreas fault.



4.

The Pacific-Farallon spreading center drifted slowly to the northeast and North America drifted slowly to the southwest, so that the spreading center approached the subduction zone along the edge of North America and the intervening Farallon plate became ever smaller.

NoPacific_80.mov

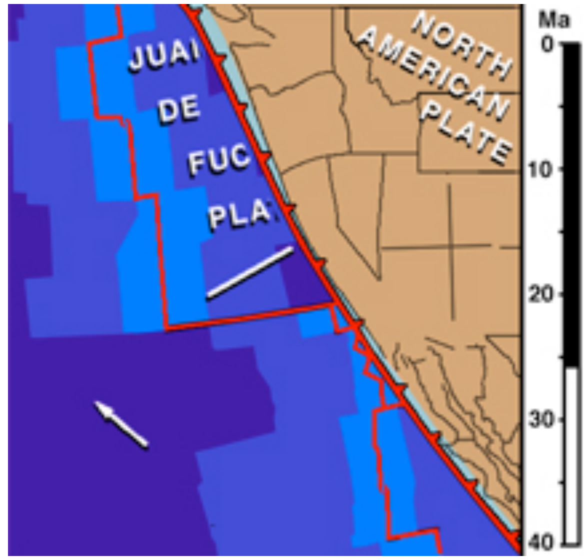


5.

About 25 Ma, segments of the spreading center began to arrive at the trench. Some spreading segments were subducted under the continent, while others stalled offshore, transferring their last remnants of the Farallon plate to the Pacific plate. In either case, new segments of the Pacific plate edge came into contact with the North American plate and the San Andreas plate boundary was formed and then lengthened.

Pac-NoAm_38.mov

6.

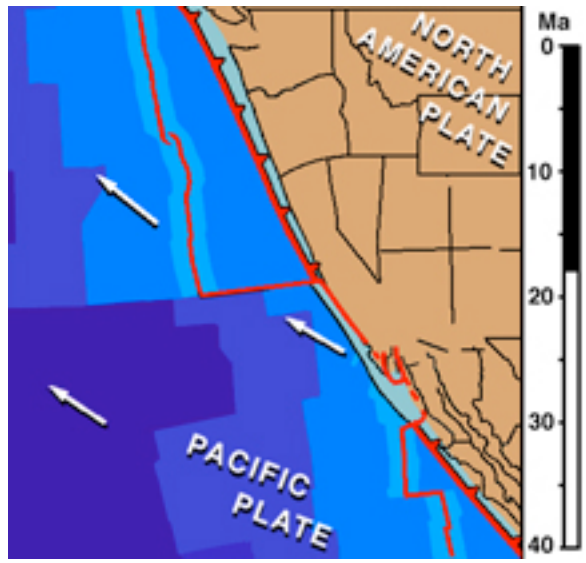


As each new segment was added to the Pacific-North American contact zone, the new plate boundary first lay at the edge of the continent, then “jumped” inland when pieces of the continental rim broke off and joined the Pacific plate. This process can be generalized into three jumps (1, 2, &3).

1: About 20 Ma, the portion of the continental rim from Mendocino to northern-most Baja came off (the Mendocino-Monterey part may have broken off a little earlier: 25 – 23 Ma?)

Pac-NoAm_38.mov

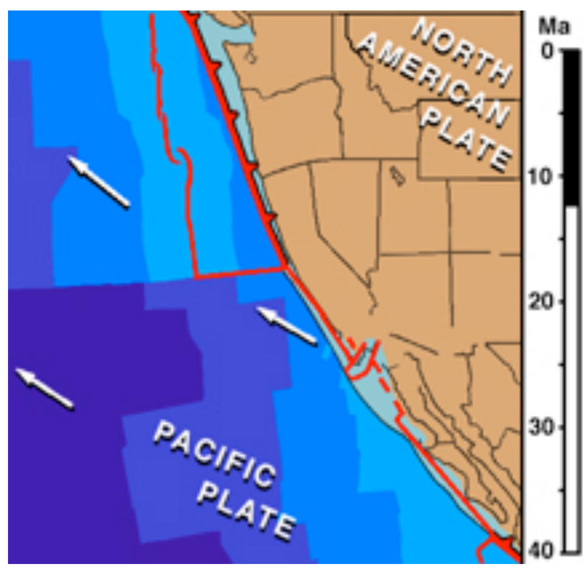
7.



All of the mid-ocean ridge segments off Baja California appear to have ceased spreading about 12.5 Ma, lengthening the Pacific-North America contact zone far to the south. A new plate boundary formed on the Pacific side of Baja.

Pac-NoAm_38.mov

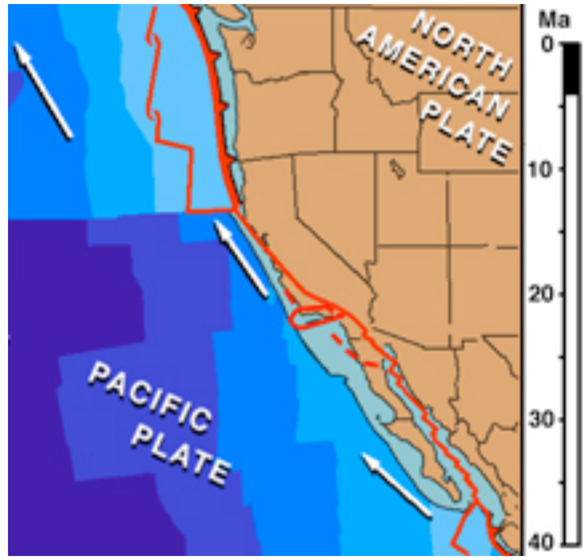
8.



2: About 5 Ma, Baja California broke off as a single, intact piece and joined the Pacific plate. The Pacific-North America plate boundary "jumped" inland to the future location of the Gulf of California.

Pac-NoAm_38.mov

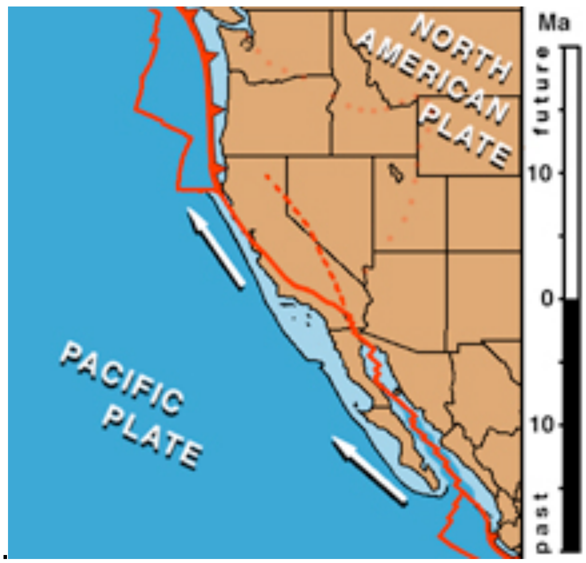
9.



3: Presently, eastern California is breaking apart and the "California Plate" is beginning to move in the Pacific plate direction.

Pac-NoAm_Future.mov

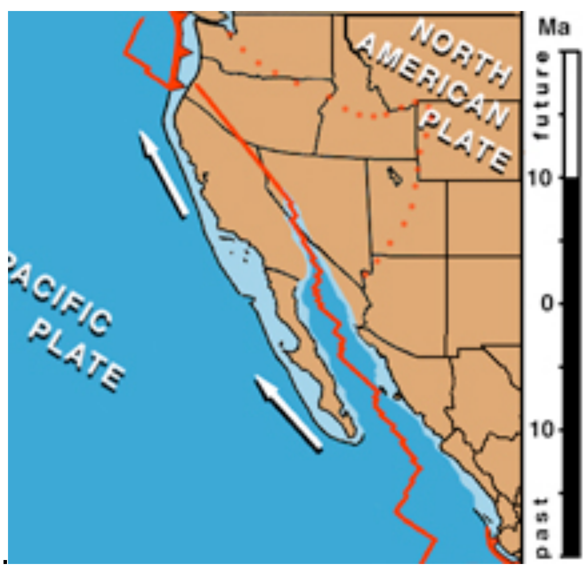
10.



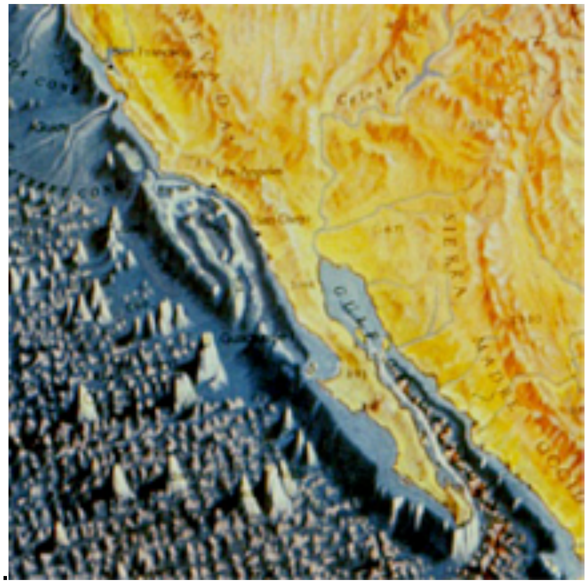
In the future, the present-day trace of the San Andreas fault may become inactivated. The new Pacific-North America plate boundary will probably run northward through the Mojave and east of the Sierra Nevada.

Pac-NoAm_Future.mov

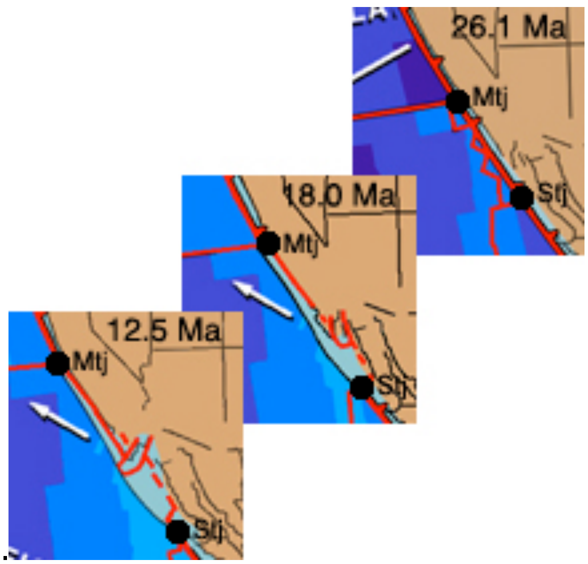
11.



The Southern California/northern Baja California area (SCal/NBaja) has repeatedly born the brunt of these various developments and reorganizations in the San Andreas plate boundary. Onshore, this is reflected in our complex and highly variable topography. Offshore, the continental shelf has been broken up and disordered – unique in the world in its complexity.

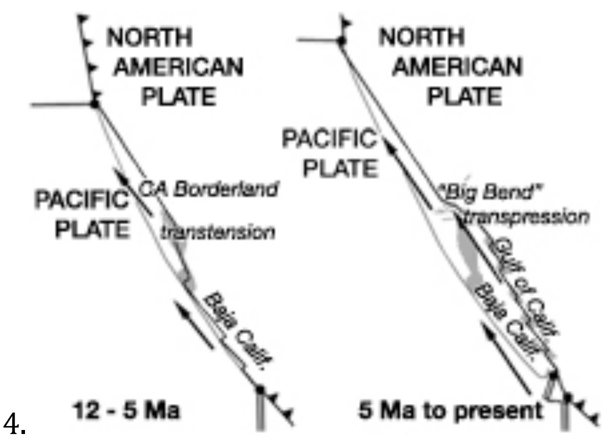
12. 

The Pacific plate made its first contact with North America in the SCal/NBaja region about 25 Ma and began to tear off pieces. As the contact zone grew from 25 to 12.5 Ma, the Mendocino triple junction (Mtj) moved steadily up coast, but the southern triple junction (Stj) kept jumping around along the continental rim off SCal/NBaja, causing breakups and general havoc in the Continental Borderland.

13. 

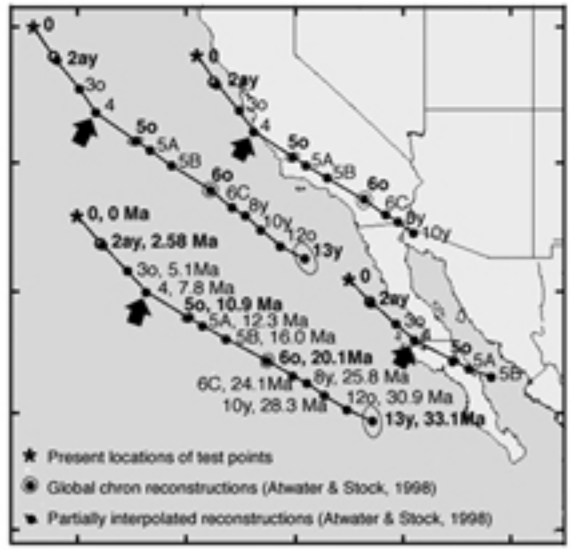
Sometime between 12 and about 5 Ma, Baja California was gradually shifted to the Pacific plate so that the plate boundary in Southern California had to switch from a connection with the offshore triple junction (a transtensional geometry) to a connection with the new Gulf of California spreading system (a transpressional geometry).

after Fig.2 in Atwater 1998, AAPG guide SCI

14. 

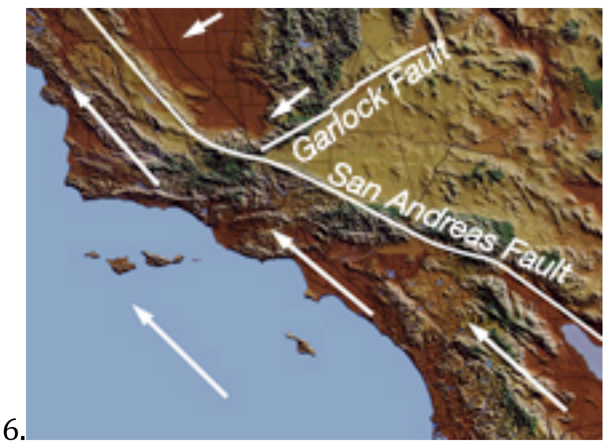
Furthermore, about 8 Ma the Pacific-North American plate motion vector changed, from a more extensional NW direction to the present NNW direction. This also added a transpressional component all along the San Andreas.

after Fig. 2 in Atwater and Stock, 1998



15.

Meanwhile, extension in the Owens/Panamint/Death Valley region has been increasing the offset on the Garlock Fault, increasing the size of Big Bend and making the San Andreas fault geometry less and less tenable.



16.

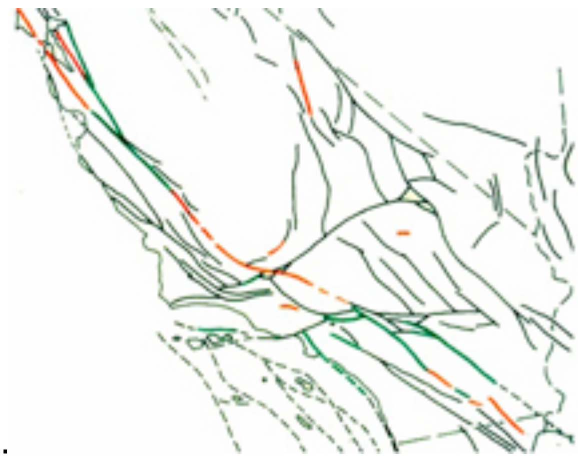
Finally (and most fun), the Transverse Ranges block didn't shift quietly to the Pacific plate like the other pieces but, rather, rotated approximately 110 degrees clockwise, causing all sorts of wonderful geo-mayhem, as follows.

B. Rotation of the Transverse Ranges Block and its geological implications.

The east-west trending Transverse Ranges lie crossways to all the other geographic features in Southern California and to most structures in western North America.

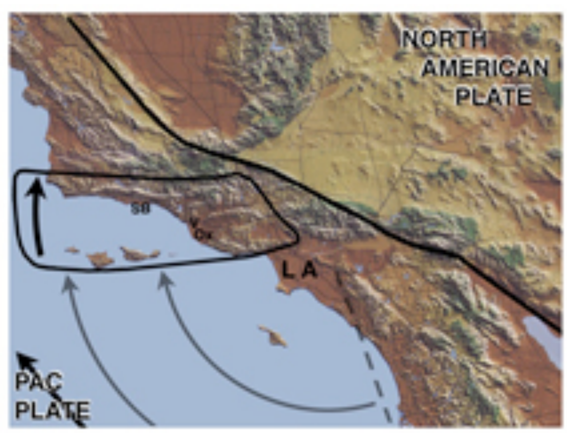
20.

All the faults in the borderland and in central coastal California come up the Transverse Ranges block and stop.



21.

Our present explanation for this odd geometry is that the Transverse Ranges block has been rotated approximately 110 degrees clockwise. Since the block is much longer than it is wide, this rotation could only occur because the plates were coming obliquely apart during the most of the Miocene, as shown in Figure 16, above. The lessening of expansion at about 8 Ma occurred after much of the rotation.

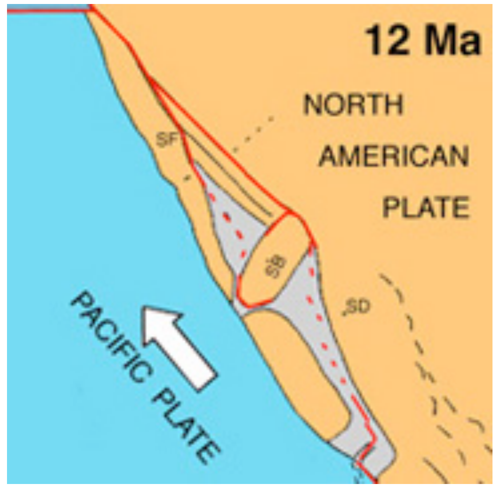


22.

This simplified version of the evolution of the San Andreas system demonstrates how the Transverse Ranges block rotated between its two huge neighbors and shows the opening of space around the block that allowed its rotation,

California_20.mov

23.



This movie shows a closer view of the rotation.

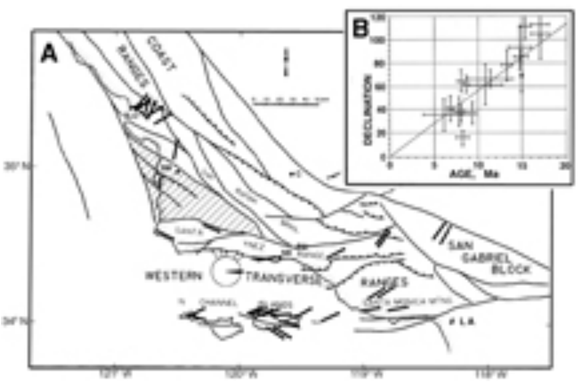
SoCal1_Tectonics.mov

24.

The most convincing evidence for the rotation comes from the paleomagnetic directions recorded in the rocks of the Transverse Ranges block. The magnetic vectors in rocks older than Miocene point to the east or east-southeast while vectors in rocks outside the region mostly point northward. Younger rocks in the block only experienced the later parts of the rotation, so their magnetic vectors are less rotated.

from Hornafius 1985 & Luyendyk 1991

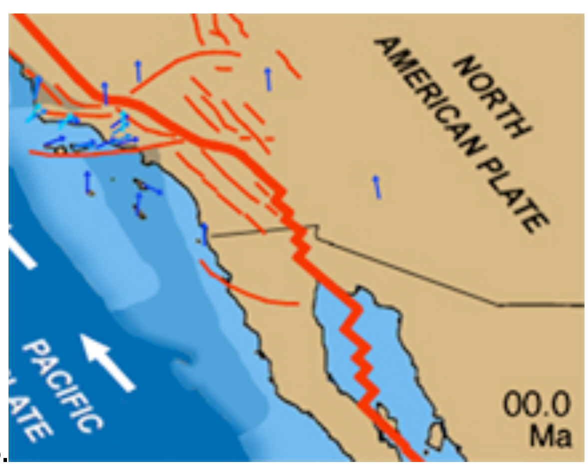
25.



This is the same movie as in Figure 24, but with the paleomagnetic vectors added in blue. It shows how the vectors rotated with the blocks. Lighter blues are for younger rocks.

SoCal2_PMag.mov

26.



Another piece of evidence supporting the rotation comes from the odd distribution of the Poway conglomerates. These rocks contain very distinctive porphyritic maroon cobbles of 150 million year old volcanic rocks, the "Poway clasts".

They are found in the in Eocene river fills crossing the mountains behind San Diego and in delta deposits in the beach cliffs at La Jolla, where they erode out and collect on the beach.

27. 

They are also found on the northern Channel Islands of San Miguel, Santa Rosa, and Santa Cruz, presently separated from La Jolla by hundreds of km and deep marine basins.

The sources of the Poway clasts are thought to be lavas of a Jurassic arc volcano far to the east and south in Sonora.

Outcrops of Poway rocks on Santa Cruz Is.

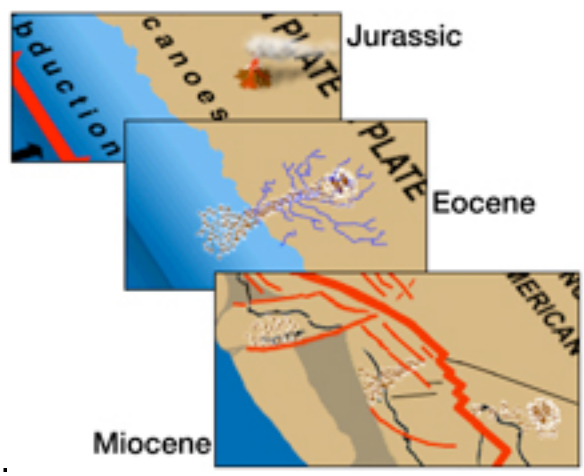
These observations of the Poway rocks suggest the following story.

28. 

Jurassic: the lavas were erupted from a volcano over the subduction zone that was active along the North American rim.

Eocene: Broken pieces of the lava were rounded and carried westward down a large river, the Ballenas River, and deposited in the riverbed and in a delta on the continental shelf.

Miocene: the rotation of the Transverse Ranges and the displacements of Baja California and San Diego since they were captured by the Pacific plate have conspired to break up and scatter the pattern. *SoCal3_PowayConglom.mov*

29. 

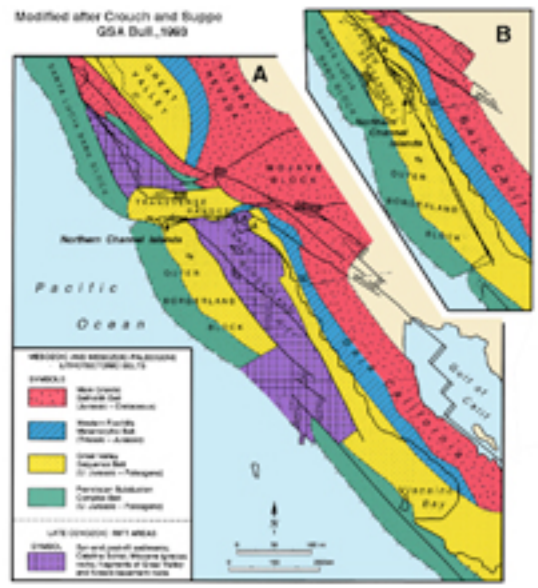
Present day outcrop locations of Poway conglomerates in Sonora San Diego and on the northern Channel Islands (brown regions surrounded by white).

SoCal3_PowayConglom.mov

30.

As described for Figure 4, the Mesozoic rocks of northern and central California contain the classic belts that form over subduction zones. In southern California the pattern is more disrupted, but many of the regions are similar to the basic belts.

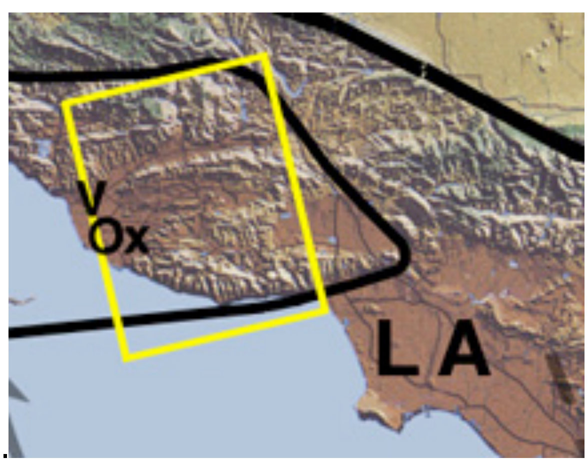
Part A shows the designation by Crouch and Suppe of regions corresponding to the various belts, colored to match the geologic map of Figure 4. A new color, purple, designates the young basins that opened up around the rotating block. When the purple regions are removed, the San Andreas offsets are undone, and the Transverse Ranges block is back rotated, the original belts can be approximately restored, as shown in part B. *after after Fig.1 in Atwater 1998, AAPG guide to SCI*



31.

The stratigraphic sections observed on and around the Transverse Ranges block contain many rocks and relationships that elucidate events in the rotation story and in the evolution of the San Andreas system in Southern California.

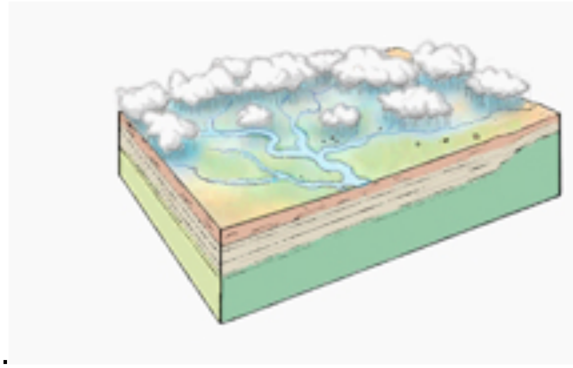
These are animated in block diagram fashion for a block approximately outlined by the yellow rectangle. It includes Ventura, Oxnard, Simi Valley, the Santa Clara River valley and various mountain ranges.



32.

Early Cenozoic rocks suggest a relatively unbroken land, with marine sands and shales depositing on the continental shelf. These include the Juncal, Matillija, Cozy Dell, and Coldwater Formations. In the Oligocene, sea level dropped and the Sespe Formation was deposited on a broad flood plain, with brightly colored sediments and lots of fossils. *TR1_Oligocene_Sespe.mov*

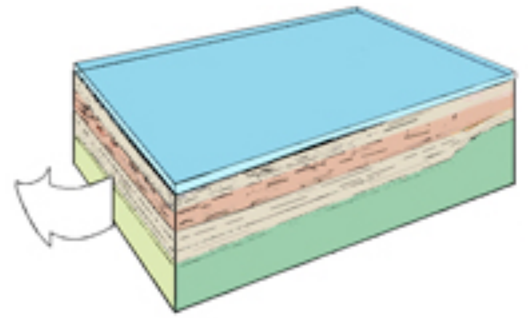
33.



In early Miocene, the block began to break away from the continent and rotate.

TR2_Miocene_Rot,ConVolc&MontFm.mov

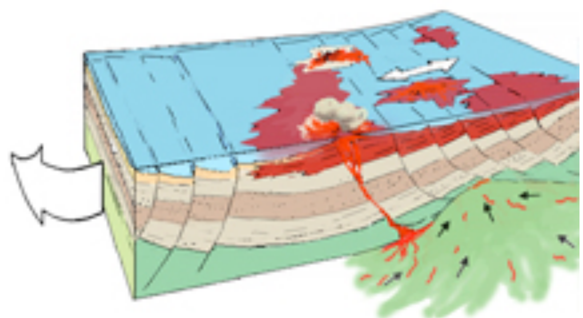
34.



The rifting and thinning of the crust set off a mid-Miocene volcanic event, erupting the Conejo volcanics of the Santa Monica mountains and numerous similar lavas on the Channel Islands and along the southeastern edge of the Los Angeles basin.

TR2_Miocene_Rot,ConVolc&MontFm.mov

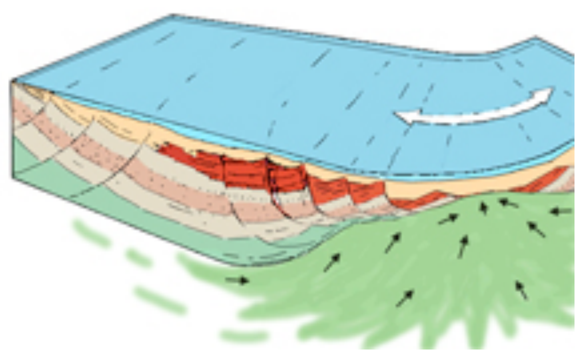
35.



The crust on the trailing edge of the rotating block was faulted and severely thinned, forming a complex of deep marine basins, including the Los Angeles and inner borderland basins. These basins were filled from above by the Monterey Formation and from below by a core-complex-like upwelling of blueschists from the middle crust.

TR2_Miocene_Rot,ConVolc&MontFm.mov

36.

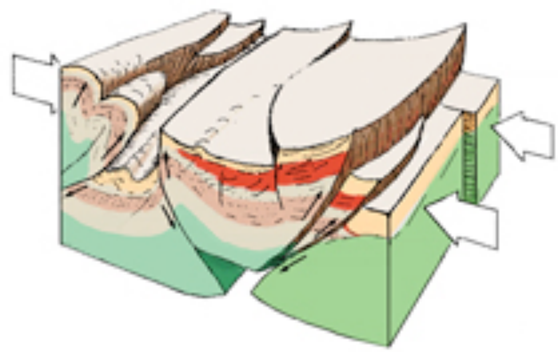


The blueschists are assumed to represent highly metamorphosed Franciscan formation rocks that were subducted deep beneath the continent. They form the basement rocks of the Palisades Peninsula and Catalina Island, and they occasionally outcrop in isolated breccia deposits, such as the one at Dana Point. More dispersed blueschist fragments are found in deposits on Santa Cruz Island and elsewhere.

37.

Near the end of the Miocene, most of southern California went into compression. As described for Figure 14, this was probably the result of the transfer of Baja California to the Pacific plate and the consequent shift inland of the southern San Andreas plate boundary. In the Transverse Ranges, old normal faults were converted to high angle reverse faults, and folding and mountain building began in earnest. In this animation, erosion and deposition were purposely ignored to bring out the magnitude of the deformations.

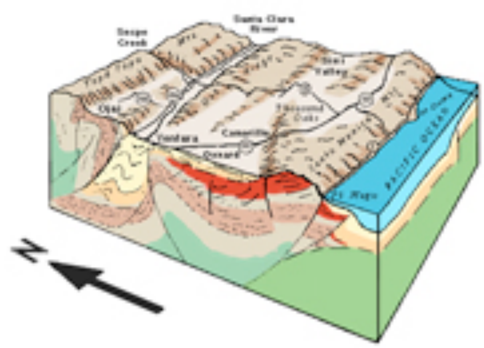
TR3_PlioPleist_Shortening.mov



38.

With the effects of erosion and sedimentation and the addition of roads and towns, we have our final block.

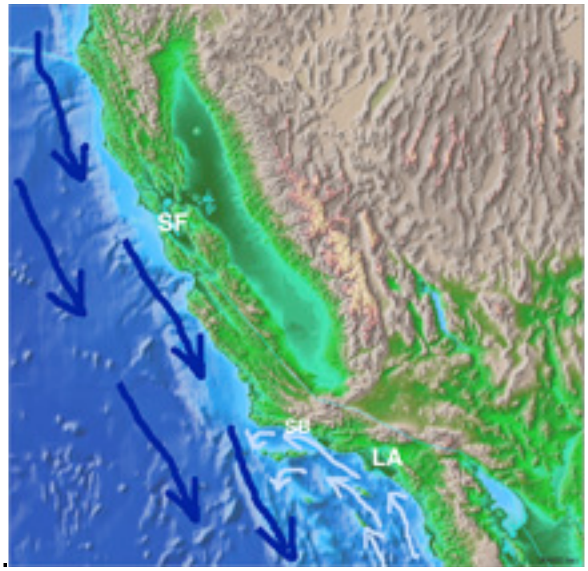
TR3_PlioPleist_Shortening.mov



39.

The geographic arrangement of the Transverse Ranges and the resulting corner in the coastline have many special properties that enhance the pleasure, of Southern California living. Most of the year, the cold Alaska current that keeps San Francisco and Santa Cruz swimmers in wet suits bypasses southern California and drives a northward flow of warmer waters along the coast. The mixing of these waters fosters a rich and diverse ocean ecosystem.

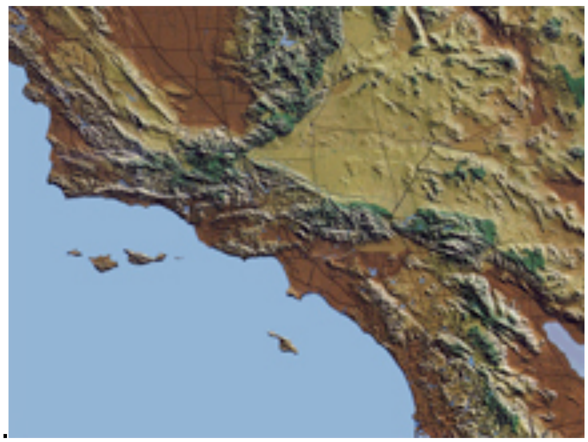
The offshore islands and rough borderland bathymetry tend to diffuse large ocean waves and tsunami waves.

40. 

The steep southern exposures of the mountainsides keep us warm in winter and catch the rain.

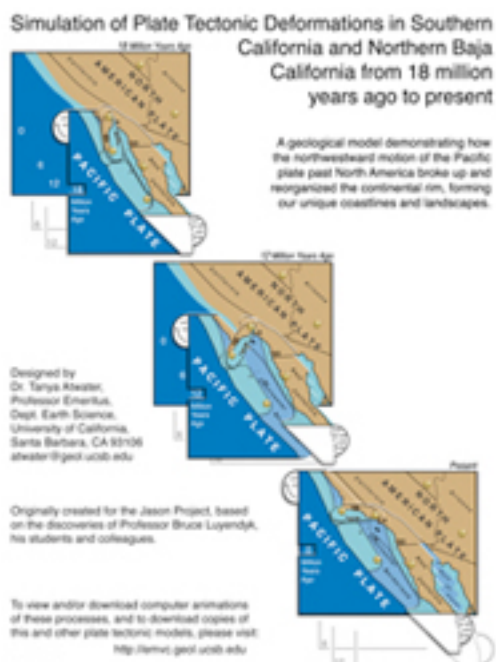
On the downside for Santa Barbara, the arrangement of high east-west mountains next to the coast tends to intensify the Santa Ana wind effect, resulting in occasional furious, hot, dry, fire-encouraging "sundowner winds".

Best of all, all this wild topography makes southern California an infinitely interesting and beautiful place to live and work and play. Aren't we lucky!!

41. 

In the last part of the workshop, we will play with a mechanical model that roughly simulates the last 18 million years of deformation in Southern California.

The model comes in a packet along with materials that may be useful for teachers and their students. We will look through them and discuss them and, as always, I will be looking for comments and suggestions.

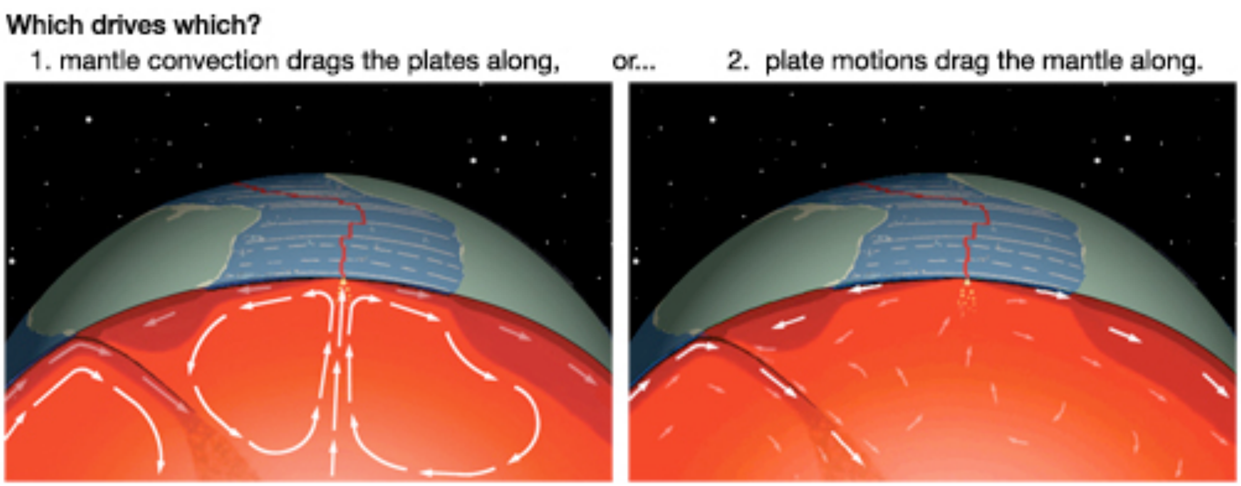
42. 

Some common plate tectonic misperceptions that can lead to difficulties in understanding the evolution of the San Andreas plate boundary (to be addressed in group discussions):

The nature of sea floor spreading centers and mantle convection cells.

The analogy that is commonly used to explain mantle convection is a boiling pot of liquid with some froth (the plates) floating around on top. The mantle is indeed convecting, carrying cold materials downward and hot materials upward, but the geometry and driving forces are quite different from those suggested by the boiling pot analogy, as follows:

The plates, themselves, are the tops and down-going sides of the mantle convection cells. Thus, these parts of the cells are relatively rigid and have clear, well-known geometries and motions. The return portions of the convection cells (with sideways and upwelling motions) occur in the weak asthenosphere so that they are much more diffuse and disorganized. (Probably, the only localized deep mantle upwellings lie beneath hot spots.) Thus, the cold plates, themselves, by virtue of their high densities, drive the motions of the mantle convection cells, not vice versa.



SoAtlantic_Convection.mov

This implies that the spreading centers are **not** fixed over deep mantle upwellings. Rather, they are passive cracks that keep being pulled apart between two diverging plates, creating low pressure zones which are drawing the mantle into them. That is to say, the plates themselves, wherever they come apart, cause the upper mantle to well up.

In this model, the spreading centers are free to move over the mantle; they simply follow their plates around, splitting the differences between the motions of their two plates.

Spreading center drift in the Pacific.

This model of spreading centers is particularly crucial for the understanding of plate motions within the Pacific Ocean basin. In all the ocean basins the spreading centers drift, but in the Pacific, it is a blatant and inescapable fact. The Pacific spreading centers have drifted great distances with respect to one another, with respect to the deep mantle, with respect to the spin axis, and with respect to the surrounding continents and subduction zones.

Destruction of subducted spreading centers and formation of "slab windows".

This model also greatly simplifies our understanding of mantle relationships under the rim of North America and in many other places where spreading centers have been subducted. When a spreading center is subducted, it loses its ability to freeze rock and make new plate, so a hole (a "slab window") appears in the downgoing plate and grows wider as the old plate falls away. In this way, the driver of mantle upwelling is dispersed and the spreading center is destroyed.

The development of a slab window beneath Southern California is widely believed to have caused the firestorm of volcanism that occurred there at the beginning of the Miocene, about 25-20 Ma. Evidence of this volcanism is common inland, in the Mojave. In coastal regions it has been carried up coast, so that patches of it are found throughout the California Coast Ranges.

The assertion that spreading centers are destroyed soon after they enter subduction zones runs counter to persistent rumors that the East Pacific Rise is alive and well under Utah and is pushing the Basin and Range apart. Even if this spreading center persistence were possible, the time-space patterns of Basin and Range deformation are entirely different than those that would be predicted by the East Pacific Rise geometry. Likewise, it negates the idea that the East Pacific Rise somehow slipped under Baja California and is now responsible for the spreading in the Gulf of California. In this case, Pacific sea floor patterns show that many of the spreading centers segments quit spreading before they ever reached the coast, and the NNW trends of the transform faults in the Gulf are well aligned with the faults in the San Andreas system. Thus, the Gulf is part of the Pacific-North American plate boundary and is being pulled apart by the movement of Baja with the Pacific plate.

Plate boundary "jumps".

All plate boundaries should be viewed as frozen most of the time, allowing the plates to move past one another only during earthquakes. Each time the crust accumulates enough stress to break, it will break along the weakest line in the region. The weakest line is usually the previous break, so the plate boundary location is usually maintained. However, conditions can change (e.g., crustal cooling, heating from new volcanism, development of geometric snags) so that a new weak region can appear, causing the plate boundary to "jump" to the new location.

Global vs. local causes for plate boundary reorganizations.

Changes observed over time along a plate boundary can be caused both by global changes in plate motions and by regional/local changes in plate boundary configurations. For example, likely causes for the Mio-Pliocene change of tectonic regime in Southern California from transtension to transpression include a (global) change in Pacific-North America plate motions about 8 Ma and the (regional) transfer of Baja California to the Pacific plate about five million years ago. Also, the rotation of the Transverse Ranges block within the plate boundary causes all sorts of interesting local geo-events that have nothing to do with the global plate scheme.