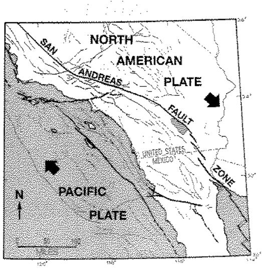
Baja California: The Geology of Rifting

You can think of Baja California as a fragment that used to be firmly attached to North America, but that has been pulled away along with everything else west of the San Andreas fault.

by Joann M. Stock

Left: Blocks cut by a series of faults have tilted over like dominoes as the Pacific plate pulled away from the North America plate in Baja California, stretching and deforming the surface. At lower left, white ash overlies the edge of a darker volcano, the same volcano shown on page 19. (Photo by John Shelton)
Below: The Pacific plate and the North America plate meet at a complicated boundary; they are sliding past each other along the San Andreas fault system in California, but farther south are moving apart.



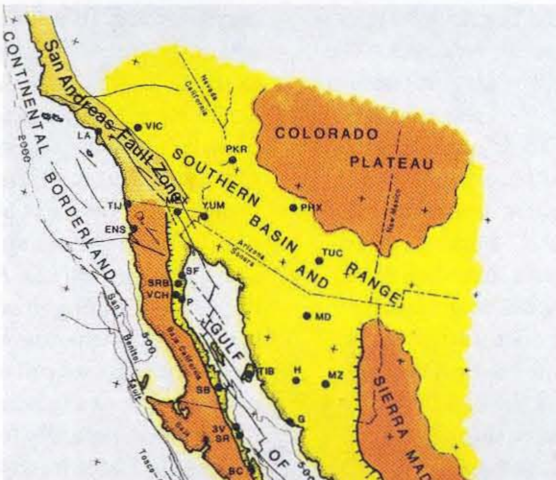
Those of us who live in the Los Angeles region know that this is an area of active tectonics. We have earthquakes; we have many large mountains nearby that are testimony to the great power of the forces that are moving and deforming the surface of the earth here; and we have the San Andreas fault as our local tourist attraction. But this great fault is not just local. Besides extending northward it also continues south toward the Gulf of California, where a series of structures represents its continuation under water. All of these structures are part of the major boundary between the Pacific plate and the North America plate. So even though we don't think of Los Angeles and the Gulf of California as being similar in many ways, they're tectonically connected because they sit on the same plate boundary and suffer many of the same kinds of deformation due to motions between these two plates.

The Pacific plate and the North America plate are two of many plates that are moving relative to each other on the surface of the earth. As these plates move, they control the main zones of active deformation, including volcanism, faulting, folding of rocks, and earthquakes. These plates are very thin—about 100 kilometers thick—in relation to the radius of the earth, which is about 6,400 kilometers. This thin skin of rigid material (the lithosphere) floats on top of a separate system of convecting mantle, which surrounds the earth's core. Deformation on the surface is mostly concentrated along the boundaries where these rigid plates are bumping up against each other or drifting apart. Because the plates are moving on the surface of a sphere, the geometry of the boundary is usually complicated, and the regions where the plates meet often look quite different from one another, even along the same boundary. There are places, for example, where the Pacific plate is just sliding by the North America plate sideways. This is characteristic of the San Andreas fault system in California; we think of North America holding still and the Pacific plate sliding northward. In Alaska, however, the Pacific plate is bending down and pushing underneath North America, where these two plates collide in what we call a zone of compression or convergence, or a subduction zone. Zones of compression typically form chains of volcanoes, such as the Cascades in Oregon and Washington or the volcanoes along the Aleutian islands in Alaska. But in the Gulf of California, where the boundary between the Pacific and North America plates is at a slightly different angle, the plates are actually moving apart. This rift has opened up the gulf itself.

The moving plates form a self-consistent system of rigid caps, so that while some lithosphere is getting pushed down under overriding plates, new lithosphere is constantly forming where the plates are moving apart. This usually occurs between oceanic plates, at midocean spreading centers, where new magma circulates up through the crack. As the plates move apart, at rates of typically a few centimeters per year, new undersea volcanism freezes onto the edge of the plates, making them bigger and adding a zone of new ocean floor in the middle of the existing ocean.

In the Gulf of California, the relative plate movement is about five centimeters annually.

Below: The San Andreas fault system continues into the Gulf of California creating strike-slip faulting through the extensional province. Yellow indicates land that has undergone extension, while the orange areas to the west and east have remained relatively stable. The region of Baja California discussed here is near the northwest corner of the gulf, roughly between San Felipe (SF) and Puertecitos (P). The Landsat image at upper right shows that area (San Felipe is in the top right corner bordering the gulf). In this false-color image, blue (band 1) represents blue visible light, green (band 4) is near infrared, and red (band 7) is middle infrared. The escarpment runs diagonally down from top left. The red volcanic rocks just below the center are a series of volcanoes about 6 million years old, aligned along normal faults parallel to the escarpment. (Image processing was done at JPL by R. Crippen, L. Barge, M. M. Miller, and J. M. Stock.)



Where the faults of the San Andreas system begin to plunge into the gulf, we expect to see, in addition to strike-slip faults, extensional faulting caused by the stretching of the plate as it pulls away and by the uneven geometry of the edges of the plates, which opens up extensional basins as the irregular pieces slide past each other. The Salton Sea is in one such extensional basin. What's happening under the waters of the gulf is a bit hard to map because of all the sediment that has spilled in from the Colorado River. But geophysics has played a useful role in locating the earthquakes that demarcate some of the active faults within the gulf, and from the seismicity it appears that this end of the San Andreas system continues to be a very complicated boundary.

My work has focused on a region in the northeast corner of Baja California, which has in particular suffered extensional faulting and deformation due to the gulf's opening. This area is dominated by a high mountain range, part of the Peninsular Ranges running from Mount San Jacinto to San Diego, crossing the international border, and continuing down into northern Baja California. There's a very abrupt topographic escarpment on the eastern side of the Peninsular Ranges, which in general coincides with a set of active faults. Many of the faults in this region are seismically hazardous, as are most of the faults of the San Andreas system; a magnitude 6.8 earthquake occurred on the San Miguel fault in northern Baja California in the 1950s, but most haven't been active very recently. Basically, everything to the east of that escarpment has been extended due to gulf-related faulting, while

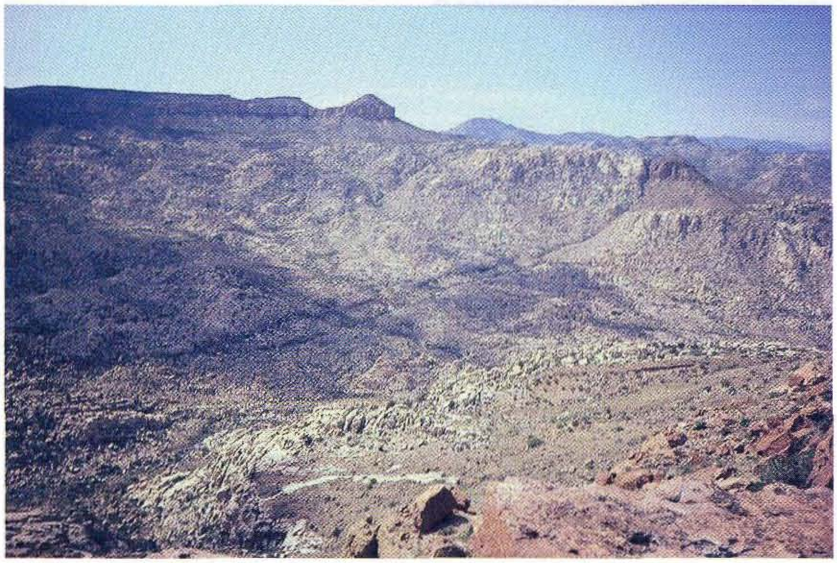
Left: The view east over the extensional province from the edge of the escarpment is a bleak landscape of desert basins and ranges. Below (top to bottom): View north along the escarpment near Valle Chico; grad student Tim Melbourne collecting paleomagnetic cores; and Arturo Martín of CICESE measuring striations on a fault plane.

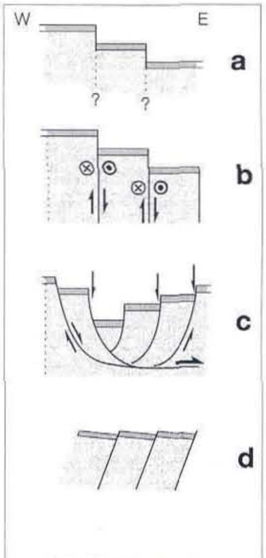
material to the west is relatively unextended and geologically stable (not deforming). On the map on the opposite page, yellow indicates all the areas that have been extended. The orange region has been relatively stable in recent geologic time; that is, there are not a lot of faults or tilting or earthquakes. This rift system is very asymmetric: it's much wider east of the gulf, on mainland Mexico, than west of the gulf, in Baja California; but on the western edge it's well exposed, while on the mainland much of it is buried under sand; the geology of that region still has much to tell us that hasn't yet been discovered.

The landscape of this northern corner of Baja California resembles a combination of the Sierra Nevada and the Mojave Desert. Looking out from the edge of the escarpment to the east over the extensional province, you see a series of basins and ranges, much like the Mojave or other desert regions in California. And like those deserts, it's full of rattlesnakes and cactus, but that doesn't stop us from mapping there.

When my students and I (along with our Mexican colleagues from the Centro de Investigación Cientifica y de Educación Superior de Ensenada—CICESE) go on mapping expeditions, we generally drive as far as we can if there are roads at all or arroyos we can drive in; then we camp for about a week and just hike out from the main campsite. If there are no roads where we want to go, we backpack in. For those excursions we have to wait until rainy times of the year so that there's water to drink; much of this region has no year-round groundwater. On our trips we spend our days walking around, mapping the rocks, making detailed geologic maps, and collecting samples to take back home to date and do lab work on. We pay particularly close attention to the faults that cut the rocks. By studying fault planes—measuring their orientation in map view, studying how they're inclined, and looking at the directions of the striations that formed as the two sides slid by each other—we can determine how much displacement has occurred on the fault and in what direction. And if we know the age of the rocks we can tell when it happened.

Two other kinds of geological research—studies of the magnetization directions of volcanic rocks, and remote-sensing data—have helped us put together the picture of this region's geologic evolution. Professor of Geobiology Joe Kirschvink and his Caltech paleomagnetics class have collected a lot of data that's been very useful to us. They drill cores in the volcanic rocks and then take them back to the lab to analyze the direction of the magnetization. (Because the direction of the magnetization is locked in when the rock cools, it reflects the direction of the earth's magnetic field at the time of the volcanic eruption. Since the direction of the earth's magnetic field lines is always slowly varying, and completely reverses every few hundred thousand years or so, each volcanic layer, or unit, acquires a direction that should be constant from place to place within the unit, but that might be different from the direction of magnetization of units that are older or younger.) We can use this information to determine whether in some regions the rock has been rotated about vertical axes since it was deposited, and we can also use it to tell





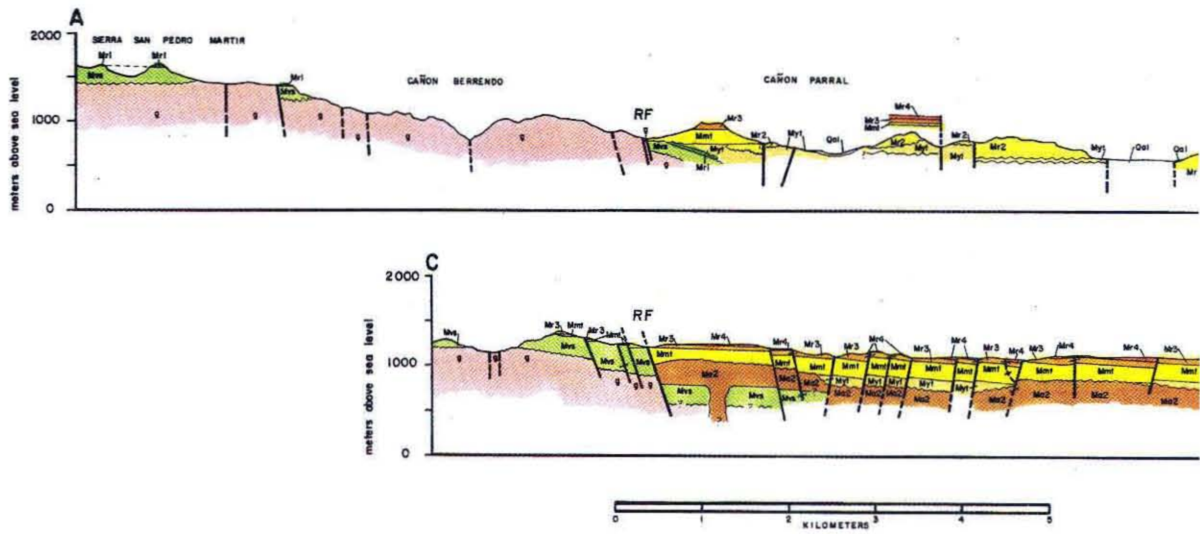
Observation of stairstep blocks (a) could mean that the blocks are sliding past each other with strike-slip motion (perpendicular to the plane of the page) (b); or that they become curved at depth and flatten out (c). Faulting and extension in originally flat layers (d) might have caused blocks to fall over like dominoes during extension (e).

something about the age of the rock. Remote-sensing data, such as the combination of visible and infrared reflectance of various rock units, helps us to distinguish different kinds of rocks, especially different compositions of volcanic rocks, and also to search for evidence of young faulting by looking at differences in soil development in valleys containing the active faults.

So, armed with information from these kinds of techniques, we look at the rocks that we can see and try to interpret their history. And then we can build structural models for how the blocks between the faults might have been moving in order to have created the landscape that we see. One example would be a series of steep faults along which a single layer has been stepped down progressively from west to east like a staircase, where the displaced layer corresponds to the steps and the faults correspond to the risers —(a) at left. There are a couple of possible interpretations for this. Perhaps these are mostly strike-slip movements, as the blocks slide past each other (b). If the layer was slightly tilted to start with, then sliding bits of it sideways along vertical faults could create this kind of pattern. Or perhaps, and this seems to be more consistent with what we've seen in Baja California, what we see represents just the uppermost surface of a series of steep normal faults (with slip up and down, rather than sideways in the fault plane) that are curved at depth and become flat. Then they might end up in a flat surface of detachment—what we call a detachment fault (c). In that case, the whole block on the left moves away from the block on the far right and everything else above the detachment fault falls into the hole created by this extension. This is what we think is happening along the topographic escarpment controlled by those big normal faults in Baja California. Another structural example might be a series of faults that are associated with tilting in the originally flat-lying rock layers (d). Such a scenario might have started off as a set of upright fault-bounded blocks that tilted over like a set of dominoes during the extension (e). Or perhaps the base surface became detached, allowing them to slide and fall over. This also represents extension.

The narrow zones on earth where extensional faulting occurs are known as rift systems. In the evolution of rift systems in general, where an ocean basin develops, it would start with some high-angle faulting, accommodating a little bit of extension as the two sides of the rift move apart, and some volcanism. This stage corresponds to a continental rift something like the East African rift valleys or the Rio Grande rift. Then as the two sides move farther apart, the rift subsides below sea level. New magma starts to come in and form real ocean floor, as along a typical mid-ocean ridge, with underwater volcanism all the way along the rift. As it subsides below sea level, the submarine volcanic rocks get covered with sediment that might have marine fossils in it. The Red Sea is usually given as an example of a rift that's in this state of evolution. The Gulf of California is similar to the Red Sea in many ways but with one big difference: the Red Sea is already forming true oceanic crust at its center. In the Gulf of California we have a pro-

Left: Along the escarpment seen from Berrendo Canyon one can see 11-million-year-old stratified rocks (dark colored) on top of granite. One dark-colored piece to the right is the same age but has slid down along the fault that is visible running down diagonally from right to left.
Right: The top cross section, going from west (left) to east shows the same scene. The 11-million-year-old rocks are in green, and the slipped piece can be seen along one of the high-angle faults cutting the escarpment. These older rocks exhibit more displacement than the younger ones (6 million years old) shown in yellow, orange, and brown. Going farther to the east, the faulting increases and involves the younger rocks, seen clearly in the lower cross section, farther south along the same axis.
Below: A 6-million-year-old volcano is covered with ash.

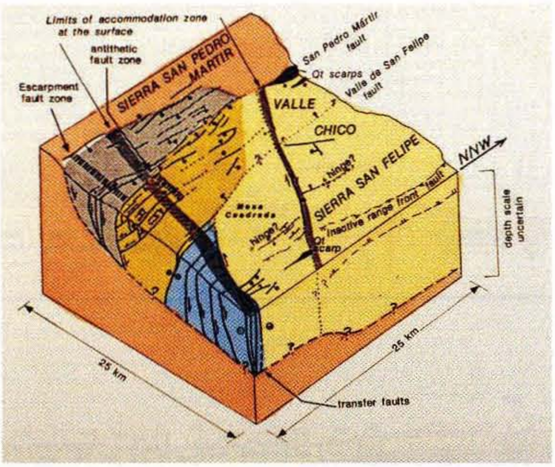


gression from true sea floor with underwater lavas forming in the very southernmost gulf to an area that's still largely extending by faulting and receiving continental sediments in the north. If we took an underwater sample from the seafloor in the northern gulf, we would probably just get sediment, not fresh lava. There is fresh lava coming in, but it's beneath the sediment; it's not poking all the way up to the surface. So within the gulf we have a transition from real ocean floor in the south to what is still a region of continental extension in the north. If this rifting continues, we expect to end up eventually with something like the Atlantic Ocean; in other words, a really big ocean basin with an active plate boundary in the middle—a spreading center with underwater volcanoes. But neither the Red Sea nor the Gulf of California has progressed that far.

What does this extensional faulting actually look like on land, where we can see the effects? The escarpment, a big normal-fault system, has experienced extension, and everything to the east has slid toward the Gulf of California. But the western side of Baja California is still high country, the continuation of the Peninsular ranges; one mountain, Picacho del Diablo, is over 3,000 meters, or 10,000 feet, high. This escarpment has played a big role in the history of Baja California's settlement, because it forms a daunting topographic barrier. It's still a challenge for humans; no roads cross it anywhere in the region where we've been working. Since there are no reliable sources of water in most of the region, there haven't been many settlements. Some people live in the high country—nice piñon pine country—and this is where the Spanish missionaries founded their missions. They didn't settle down in the desert where there are rattlesnakes and no water.

Unfortunately, the region with rattlesnakes and no water—the extensional province—is the one that interests us. And actually the desert is a great place to study geology because you can see everything; there aren't a lot of bushes covering up the rocks. What are the most important features that a geologist looks for? We see old volcanoes, such as the one at left, which is draped with ash layers, either from its own eruption or that of a volcano nearby. All of the rocks in this picture are about 6 million years old. The aerial photo on page 14 shows some rocks that form the edge of small cliffs next to some small faults. Rocks are being dropped down along the fault systems, similar to the "domino" fault system in the schematic drawing on the opposite page.

In another example we see stratified rocks on top of granite, cut by a fault (above, opposite page). The rocks on either side of the fault are the same sequence but the right (east) side has slid down along the fault. Combining all the observations of the faulting along the escarpment in this region, we can draw some cross sections going from west to east (above). These show high-angle faults near the escarpment's edge on the west (left); going east the faulting seems to get more pervasive and involve younger rock units. Knowing the ages of the rocks is key to understanding this picture; for example, we know that these are 11-million-year-old and older rocks. And we know from comparing them with



Above: This model illustrates what geologists *think* is going on on the western edge of the extensional province. East-sloping extensional fault systems (gray) and west-sloping ones (gold) both feed into a flatter fault below. Pink represents areas of unextended granite, while strike-slip faulting (perpendicular to the plane of the page) is occurring at the edges of the blue region.
Above right: Six-million-year-old rocks in "domino" blocks, dropped by a series of faults and then rotated, create the zigzag pattern here. Unfaulted 3-million-year-old rocks on top of them indicate that extension here had stopped by then.
Below: Young faulting is evident in the tilted fossil beds visible in road cuts near the coast.

the 6-million-year-old rocks in the picture on the previous page that they exhibit more displacement than their younger counterparts. This tells us that faulting in this region started before 6 million years ago, and, in fact, about half the faulting along the escarpment here had occurred between 11 and 6 million years ago.

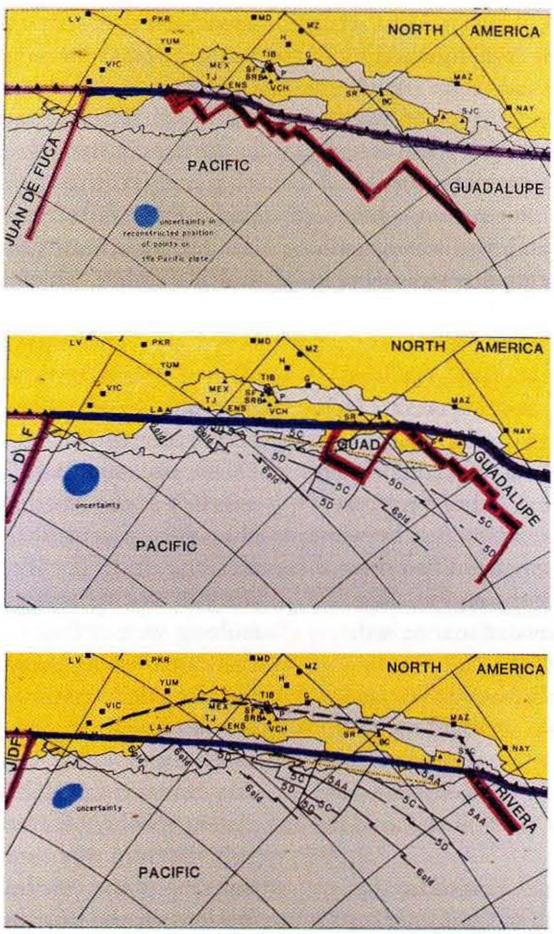
We can combine this information to build a structural model of the western edge of the extensional province (above, left). We think the escarpment fault systems that slope steeply eastward probably feed into a flatter fault at depth. Then there's a series of westward-sloping faults that may "sole," or bottom out, into the same flatter fault. There are also some examples of strike-slip faulting within this region. Moving toward the east one sees more and more evidence of extensional faulting. As we go east, we can see that some of the same rock layers high on a hill to the west have dropped down into a valley—a relative vertical displacement of about 800 meters. And it just gets worse—or more geologically exciting, depending on your perspective—the farther east you go.

Driving along the east coast of Baja California from San Felipe to Puertecitos, you pass by outcrops where you can pick fossils out of young (2 million years old or younger) marine sediments and continental sediments near the beach (left). These are also cut by faults. And up a nearby canyon we can see a set of layers that have been dropped by a series of faults (above, right)—a nice example of a set of fault-bounded "domino" blocks that have rotated, tilting the layers about 50 degrees. These 6-million-year-old rocks are overlain by a cap of 3-million-year-old volcanic rocks that are not faulted. So in this place we can conclude that there was a lot of early extension between 6 and 3 million years ago that then stopped.

Other evidence for young faulting comes from the highly tilted fossiliferous beds close to the coast. Little closed drainage basins up on the mesas also indicate active strike-slip faulting stepping from one fault strand over to another and pulling apart a little basin in between. We can see evidence of disruption of drainages occurring along some young faults, and we can find lines of bushes, and even palm tree oases, along some of the faults, suggesting that they may be extremely young. So that tells us that there has been a history of motion from at least 6 million years up to the present in the area we have been studying.

If we make a very simple assumption that all of the Pacific–North America plate motion had gone through the Gulf of California, we come up with a problem. Calculating backward, the amount of slip needed to close up the gulf is about 300 kilometers, which would take us back 6 million years, moving at 50 millimeters per year or 50 kilometers per million years. (The value of 50 millimeters per year is the average rate for the last 3 million years, determined from the fault systems in California and also from other global data on plate motions.) But if we close the gulf up that much, we run into several problems. First, the continental margin isn't well aligned, so it leaves a big hole at the south end and too much overlap at the north. Second, we have

So while the strike-slip faulting zone was short originally, between 20 and 10 million years ago it grew longer, developing eventually into the San Andreas fault and the plate boundary within the Gulf of California.



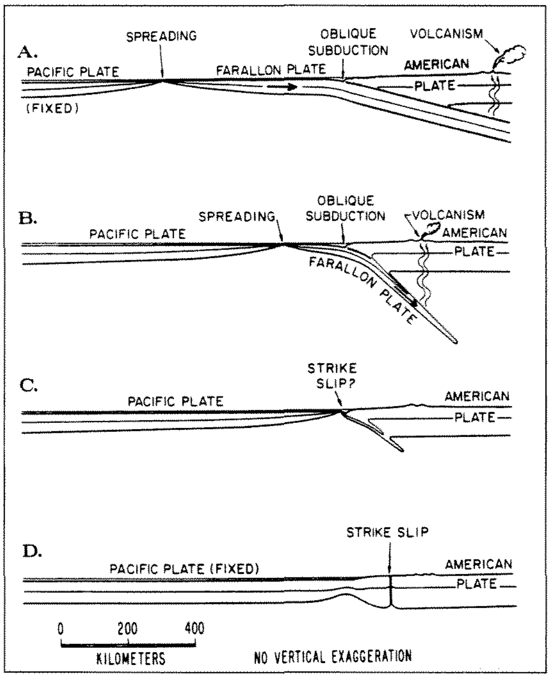
Twenty million years ago (top), with Baja California squashed back up against Mexico (it's unclear how that might have looked), the Guadalupe plate would have been subducting under North America in a collision zone (purple) with a spreading ridge (red) between Guadalupe and the Pacific plate offshore. By 12 million years ago, this spreading center moved southward (center), the Guadalupe plate stuck onto the Pacific plate, and the strike-slip boundary (blue) between North America and the Pacific plate lengthened. By 10 million years ago this boundary had started to relocate into what is now the Gulf of California (black dashed line). In all these pictures North America is held fixed, but in reality all of the plates in the picture are moving relative to the other plates.

evidence of extensional faulting as early as 12 million years ago (in marine deposits actually as early as 15 million years), and we know that the San Andreas fault system in California, which should connect down into the northern gulf, started moving long before 6 million years ago. So we think that there was a significant amount of tectonism or deformation occurring in this region before 6 million years ago, and therefore we need a more complicated story to explain the gulf's opening.

If we go back to the maps of the plate motions and use global plate reconstructions to figure out where the plates would have been, what we see is that 20 million years ago Baja California would be closed back up to mainland Mexico, and we would have a spreading ridge between the Pacific plate and the Guadalupe plate (which was originally a small fragment of the Farallon plate, which has now disappeared). The ridge would have been offshore, and so in between Guadalupe and North America there would have been a zone of convergence or collision, where the Guadalupe plate was going underneath North America. South of the Guadalupe plate, the Cocos plate (which still exists) would have also been subducting underneath North America. But by 10 or 11 million years ago the Pacific-Guadalupe ridge stopped spreading, and the Guadalupe plate got stuck onto the Pacific plate. The spreading center between the Pacific and Cocos plates kept moving farther to the south. We end up with a picture like that at left, with a new plate boundary being created at the western North American margin, creating a big zone of strike-slip faulting representing the motion between the Pacific and North America plates. So while the strike-slip faulting zone was short originally, between 20 and 10 million years ago it grew longer, developing eventually into the San Andreas fault and the plate boundary within the Gulf of California.

There should have been a volcano chain inland from where the Guadalupe plate was being compressed against North America. And we do, in fact, see evidence for those volcanoes having existed in Baja California. They are 23 to 16 million years old in northern Baja California and as young as 11 million years old in southern Baja California. Although they're blanketed by a lot of younger rocks in the extensional province, we find the cores of these volcanoes still preserved, and we can date them. So it's reasonable to assume that before the gulf opened, eastern Baja California, including the area of the present gulf, might have looked like Alaska or the Cascades.

After volcanism stopped and extensional faulting began, the early gulf might have looked

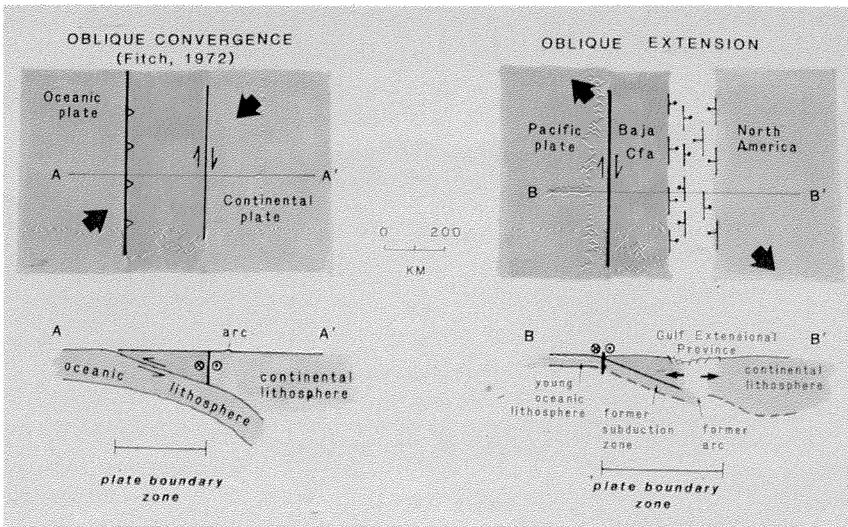


In a west-to-east cross-section view of plate activity near Baja California, the Farallon plate (of which the Guadalupe plate was part) subducts under North America, creating volcanism, while the Farallon and Pacific plates meet in a spreading ridge offshore. The spreading ridge moves in as the Farallon plate disappears under the American continent, and the Pacific and North America plates abut and begin to slide past each other in a strike-slip boundary. (Tanya Atwater in *The Geology of North America*, The Geological Society of America, 1989.)

We infer that this extension in the gulf was occurring at the same time as the faulting west of Baja California, so that Baja California was a peninsula that had faulting on the east side (extension) and faulting on the west side (strike-slip) going on simultaneously.

something like Death Valley—which is also a big extensional basin bounded by high mountain ranges and controlled by normal faults. As the extension continued, the early gulf region would have been sporadically flooded with ocean waters, so it would have started looking more like the Salton Sea or the Imperial Valley region, where water periodically comes in and then leaves again for awhile. The fossils in the marine sediments in the extensional basins around the margins of the gulf and ages on overlying lava flows indicate that there are marine rocks as old as 13 million years on Isla Tiburon off the Sonoran coast. This matches up to the region between San Felipe and Puertecitos in northeastern Baja California, where we find marine rocks at least as old as 6 million years and maybe older. So we know that between 13 and 6 million years ago seawater filled the basins in the northern part of the region. We haven't found exposed evidence of marine sediments of this age in the southern gulf, but it seems likely that the sea probably filled in some of the southern gulf then also. Around the gulf there are numerous regions with exposed marine fossils younger than 6 million years old, but we think a lot of the opening of the gulf occurred far earlier.

The scenario we have come up with for the tectonic evolution of the Gulf of California includes extension in the northern gulf starting at about 15 to 12 million years ago, while subduction- or convergence-related volcanism continued in the southern gulf. This is consistent with the disappearance of the Guadalupe plate, which shrank considerably starting from the north at about that time. By about 15 million years ago it was gone from the west side of northern Baja California, but it was still west of southern Baja California, a fact we see reflected in the difference in the ages of the volcanic rocks on the peninsula. This suggests that the northern half of the gulf might have started to open earlier than the southern gulf, or at least started to suffer extensional faulting earlier, which is consistent with what we see in the structures and the marine sedimentation there. Then by about 12 million years ago all of the plate convergence west of Baja California would have stopped, and there would have been a zone of strike-slip faulting between the Pacific plate and Baja California, which was still attached to the North America plate. And this is also when it seems that extension was occurring all along the gulf. We infer that this extension in the gulf was occurring at the same time as the faulting west of Baja California, so that Baja California was a peninsula that had faulting on the east side (extension) and faulting on the west side (strike-slip) going on simultaneously. Between 6 and 4 million years ago the plate boundary between the North America and the Pacific plates probably became more localized within the gulf. So from that time on is when we start thinking of the gulf being the center of the plate motions, or the location of most of the plate-boundary deformation. Around this time, 4 million years ago, the modern faults within the gulf evolved, faulting that is still continuing within the extensional province, although probably at a slower rate than initially. And even though we think that most of the plate-boundary



We think there are other places on the earth where similar fragmentation has happened earlier and other places where it is still happening.

Shown schematically in map view and cross section, the scenario (above right) represents what probably happened during the change in plate boundaries in between stages C and D of the cross sections on the opposite page. Baja California starts to pull obliquely away from North America before it is firmly attached to the Pacific plate. Thus, strike-slip faulting still occurs on the west, while extensional faulting develops on the east. This separation of oblique motion into two parallel zones with different kinds of movement is analogous to the separation often seen at oblique convergent boundaries (left).

deformation has been concentrated within the gulf for the past few million years, we still don't see a well-developed ocean basin. That's still in the process of formation in the gulf.

In another way of looking at it, as the Guadalupe plate was being pushed down under North America, forming a little chain of volcanoes at the convergence zone, the seafloor spreading axis between Pacific and Guadalupe was located quite a ways offshore to the west of Baja California. As the seafloor spreading axis moved closer and closer to North America, the Guadalupe plate got smaller and smaller till it reached a limit where it was no longer dense enough to sink. Then it probably just got stuck onto the Pacific plate, creating a zone of strike-slip faulting offshore. At some point the strike-slip motion might have jumped inland to form what is now the Gulf of California.

But what we think *really* occurred is illustrated in the final model above, in which Baja California is a small, independent plate, with motion on the west and east at the same time. With strike-slip motion offshore to the west, the Gulf of California is extending on the right (to the east), not exactly perpendicular to the plate boundary, but rather at an oblique angle. A series of extensional basins develops in the gulf, initially continental extension that later turns into what now starts to be real seafloor spreading. You can think of Baja California as a fragment that used to be firmly attached to North America, but that has been pulled away along with everything else west of the San Andreas fault. (And we in Los Angeles are sitting on the northern extension of this same fragment, which is now mostly attached quite firmly to the Pacific plate.) The process of the extensional faulting taking over all of the plate motion took a long time to complete—probably from about 15 million years ago up until 4 million years ago. And during that time this little fragment was pushed along with motion on both sides.

This isn't a unique situation in the geological record. We think there are other places on the earth where similar fragmentation has happened earlier and other places where it is still happening. Farther south along the Mexican margin, for example, it looks as if other blocks may be about to break off and attach to plates other than the North America plate. So we're interested in this as an example of a common geological process. We haven't figured out all the details yet; we're just scratching the surface of the geological information that's available. But we and our Mexican colleagues hope to keep working in Baja California until we can put the whole picture together. □

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