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Time, Faults, and Moving Plates

A Recipe for Southern California

Time is Nature's way of keeping everything from happening at once.

—John Wheeler

In one second, the backyard of an oceanfront home may disappear as the bluff beneath it collapses. In one day, a storm may sweep away a beach. In one year, some Californians will see cracks open in their lawns and driveways as their property oozes downhill on slow-moving landslides. In any given decade, the odds are good that a big earthquake will shake California. In fifteen million years, the slow creep of the Earth's tectonic plates will put Los Angeles next to San Francisco. The processes that shape our world operate over a vast range of time scales, from seconds to millions of years. But our lives encompass events on the short end of Nature's clock, and that makes it hard to appreciate the power of long-term change. To understand how the Southern California coast came to be, we need to move beyond human time and get our minds around geologic time, or what geologists call *deep time*. The reason is simple. Geological processes such as erosion, the uplift of mountains, or the movements of the Earth's tectonic plates may seem trivially slow over human time. But give these processes millions of years, and they can accomplish stunning work.

We all know big numbers when we see them, but the years of deep time—millions and billions of years—are hard to grasp. Big numbers are *always* hard to grasp. Who among us, for example, has a good feel for *one billion* of anything? One billion dollars is close to Bill Gates's annual income, so here's a way to put such a number into perspective: one billion dollars per year ÷ 365 days per year ÷ 24 hours per day ÷ 60 minutes per hour ÷ 60 seconds per minute = $31.71 per second. In other words, Bill Gates earns about $32 per second, around the clock, all year long. Now imagine that Gates is walking down the sidewalk when someone stops him and says, "Bill, I need some financial advice. I'll pay you for whatever your time is worth." Gates responds, "OK, that'll be $96 for the last three seconds. How else can I help you?"

If that scenario gave you a better sense of one billion, let's try for 4.56 billion—the age of the Earth in years. Imagine a ninety-five-gallon bathtub (a large household bathtub) filled to the brim with medium-grained sand. (Geologists classify sand precisely, so "medium-grained" means that the grains range from 0.25 to 0.5 millimeters in diameter, which is typical of many beach sands, as well as standard table salt.) Let each grain represent one year. Wet one fingertip and dip it in the brim-full tub. About five hundred grains cling to your fingertip, representing roughly the number of years since Columbus crossed the Atlantic. Scoop up one-eighth of a teaspoon, or about eight thousand grains. That represents the years since the dawn of human agriculture. Now scoop up a heaping tablespoon, roughly two hundred thousand grains. You hold the entire existence of our species, *Homo sapiens*. The brim-full bathtub holds about 4.5 billion grains, representing the age of the Earth. Pour that tablespoon back. Do you see a difference? Compared to deep time, human time is virtually nonexistent.

What does the vastness of geologic time mean for the formation of California? You might think I'm about to make an argument for California's ancientness, but no. Geologically speaking, California is young—although still almost unfathomably old by human standards. Two hundred million years ago (about four gallon-buckets of sand in the tub), California didn't yet exist. North America ended in what is now western Nevada, and had you stood then, say, where Reno is today, you would have gazed west not at the Sierra Nevada and the rest of California, but at ocean waves and deep blue sea. Had you watched for the next hundred million years, you would have seen California arrive, piece by piece, from the ancient Pacific Ocean. Islands, seamounts, and vast chunks of ocean floor, carried by the Earth's tectonic plates, landed on the continent's edge, one behind the other, to assemble California. (I'll give you a fuller explanation of how this happened—and how we know—in chapter 4.) About twenty million years ago, mighty faults, some of them precursors of the modern San Andreas fault, began to slice up this collection of imported rock and send it on the move yet again. That interval—the past twenty million years—is my focus in this book. That's not much compared to the age of the Earth. In the bathtub analogy, it's about seven cups of sand. But it's still a vast span—enough deep time to pack a wallop.

Here's a story to show you how.

MEXICAN PEBBLES FAR FROM HOME

In the ocean thirty miles south of Santa Barbara lie the four Northern Channel Islands—Anacapa, Santa Cruz, Santa Rosa, and San Miguel—stretching west in a line out to sea from the end of the Santa Monica Mountains near Los Angeles. San Miguel is the westernmost. It faces six thousand miles of open Pacific Ocean, and thus gets blasted by some of the fiercest winds and largest waves anywhere in Southern California. The day I hiked across the island was typical, with a fierce wind yanking at my hat, shooing sand across the dunes, and tearing spray off the cresting swells. Winding my way down through the dunes to Simonton Cove, on the island's western shore, I found some very special pebbles in beach outcrops scrubbed clean by the waves. The pebbles were smooth and round, and on average about the size of a baseball. They lay encased in upended layers of Eocene* sand and gravel. They were not, I knew, native to San Miguel Island—or even to California. These pebbles were emigrants from Mexico.

Rock made of many smooth, rounded pebbles is called conglomerate, and it forms wherever breaking waves or flowing rivers tumble rock pieces and wear them smooth. Conglomerate is a common rock, but the pebbles in the conglomerate on San Miguel Island contain an uncommon curiosity: distinctive purple-maroon pebbles of rhyolite—a type of volcanic rock—sparkling with crystals of quartz and feldspar (figure 1.1). The rhyolite pebbles are so distinct—both visually and in their detailed chemical makeup—that geologists can confidently trace their origin to the exact volcanoes from which they eroded. Incredibly, those volcanoes, now long dead, are in Sonora, Mexico—*more than five hundred miles from San Miguel Island.* And that's not all. In the San Diego suburb of Poway, and in sea cliffs by La Jolla, you can find pebbles that are dead ringers for the ones on San Miguel Island. These, too, could only have come from near the same volcanoes in Sonora. How

* The Eocene period extends from fifty-six million to thirty-four million years ago. See the Geologic Time Scale at the front of the book.

FIGURE 1.1. (a) Eocene-age conglomerate from Mexico, now on San Miguel Island. We know that this rock traveled here from Mexico because it contains distinct purple-maroon volcanic pebbles that could only have eroded out of volcanic lava beds more than five hundred miles away in Sonora. The surrounding geology indicates that the pebbles were flushed into the ocean as part of a deep-water delta near the mouth of the Eocene (and now long extinct) Ballena River. (b) Close-up with my finger pointing at one of the purple-maroon pebbles. The outcrop is part of the Cañada Formation in Simonton Cove on the northwest side of San Miguel Island. (Photographs by the author.)

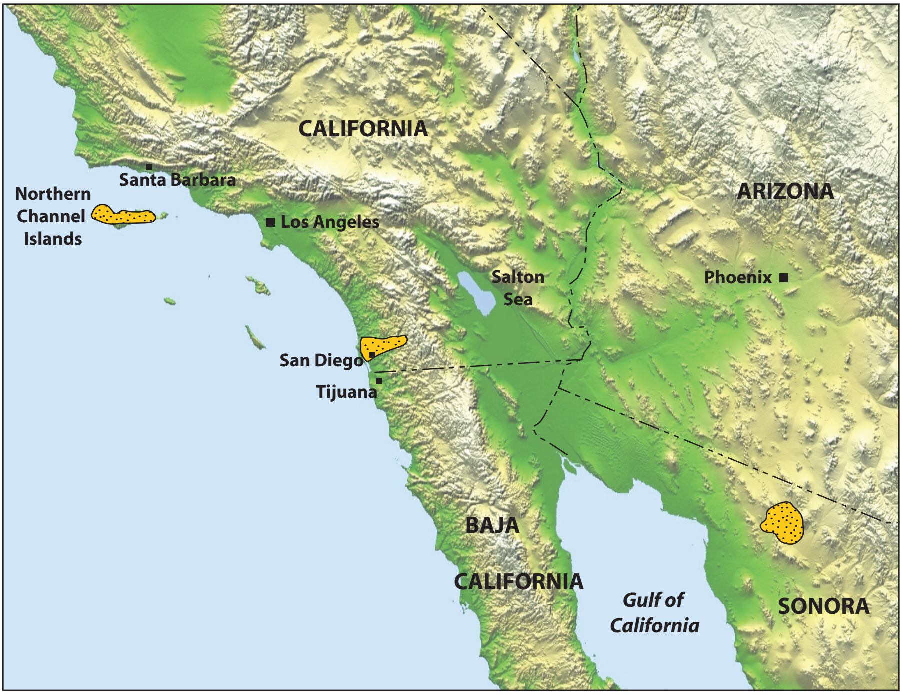


FIGURE 1.2. Distinctive Eocene-age riverbed pebbles on the Northern Channel Islands are also found around San Diego and near their source volcanoes in Sonora, Mexico (stippled yellow areas). The pebbles represent the remains of the forty-million-year-old Ballena River that was sliced apart by faults as the Pacific Plate slid northwest past the North American Plate. Figure 1.4 portrays the tectonic events that led to the pebbles' current distribution. (Shaded relief base from NASA, with labels added.)

did pebbles eroded from Mexican volcanoes migrate two hundred fifty miles to San Diego and five hundred miles to San Miguel Island (figure 1.2)?

The answer lies in the relentless creep of the Earth's tectonic plates. San Miguel Island today lies mostly on the Pacific Plate. The remains of the Mexican volcanoes lie on the North American Plate. San Diego occupies the fault-slivered zone in between (figure 1.3). The Pacific and North American Plates are sliding side-by-side past each other about two inches per year (a number first determined by matching up rock bodies split when the Gulf of California began to open about 5.5 million years ago, and confirmed today by global positioning system [GPS] measurements). That side-by-side shifting has carried the Mexican

FIGURE 1.3. A belt of active faults more than two hundred miles wide marks the boundary between the Pacific and North American tectonic plates in Southern California. Movements along these faults have created most of the region's mountains, valleys, islands, and offshore basins. As the Pacific Plate heads northwest, it runs into the Big Bend in the San Andreas fault to create the Big Squeeze—a region of colossal compression that, among other things, is actively pushing up the Transverse Ranges. We'll explore the story of the San Andreas fault and the Big Bend/Big Squeeze in chapter 3. (Shaded relief base from NASA, with labels added.)

pebbles to where they are now. The story (summed up in figure 1.4) goes like this: About forty million years ago, a now extinct river, known to geologists as the Ballena River, flowed southwest from the Mexican volcanoes, carrying the distinctive pebbles toward the ocean. (The Gulf of California had not yet opened, so the river flowed uninterrupted to the Pacific.) About eighteen million years ago, sidling movements between the Pacific and North American plates began to split the pebbly deposits of the old riverbed. The easternmost section of the riverbed remained near its source in Sonora. The middle section slid northwest to where San Diego is now. The western section—the part of the river that poured into the ocean to form a deep-water delta—slid farther northwest, to where San Miguel and the other Northern Channel Islands are today (figure 1.4).

This story links directly to Southern California's large-scale geologic evolution, the details of which I'll give you in chapter 4. But you may be wondering: What's the connection here with deep time? Remember that the Pacific Plate slides past the North American Plate at just two inches per year—a spectacularly slow rate in human time. (A snail that fast would take three and a half centuries to cross my sixty-foot-wide suburban backyard.) But watch what happens when deep time comes into the picture. Two inches per year times eighteen million years (about how long ago the side-by-side movements between the two plates began in Southern California) equals 36 million inches, which is 540 miles—or almost exactly the distance that the pebbles on San Miguel Island now lie from their source volcanoes in Mexico. The message is as simple as it is powerful: Processes that seem trivially slow over human time can accomplish stunning work over geologic time.

THE PACIFIC PLATE–NORTH AMERICAN PLATE BOUNDARY

The story of the migrant pebbles on San Miguel Island highlights the most important geologic force at work in Southern California: side-by-side sliding of large blocks of the Earth's crust along big faults. Figure 1.3 shows that most of these faults trend northwest–southeast. This makes sense; that alignment allows the Pacific Plate to slide northwest past the North American Plate. Earthquakes happen whenever movements between the two plates cause one of these faults, every now and then, to snap. The San Andreas fault is the longest and most important—it's the big gorilla of California's faults—but the San Andreas doesn't act alone. Dozens of faults, spread across a zone more than two

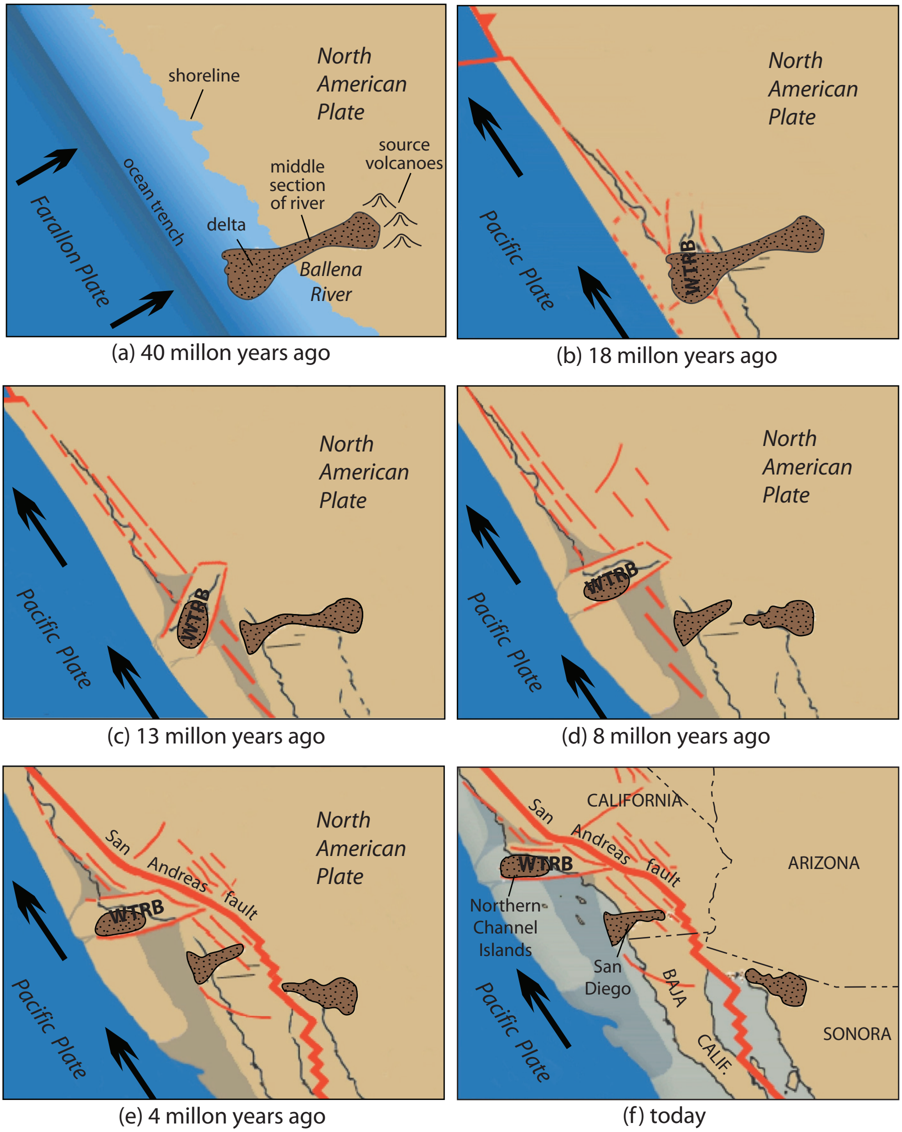


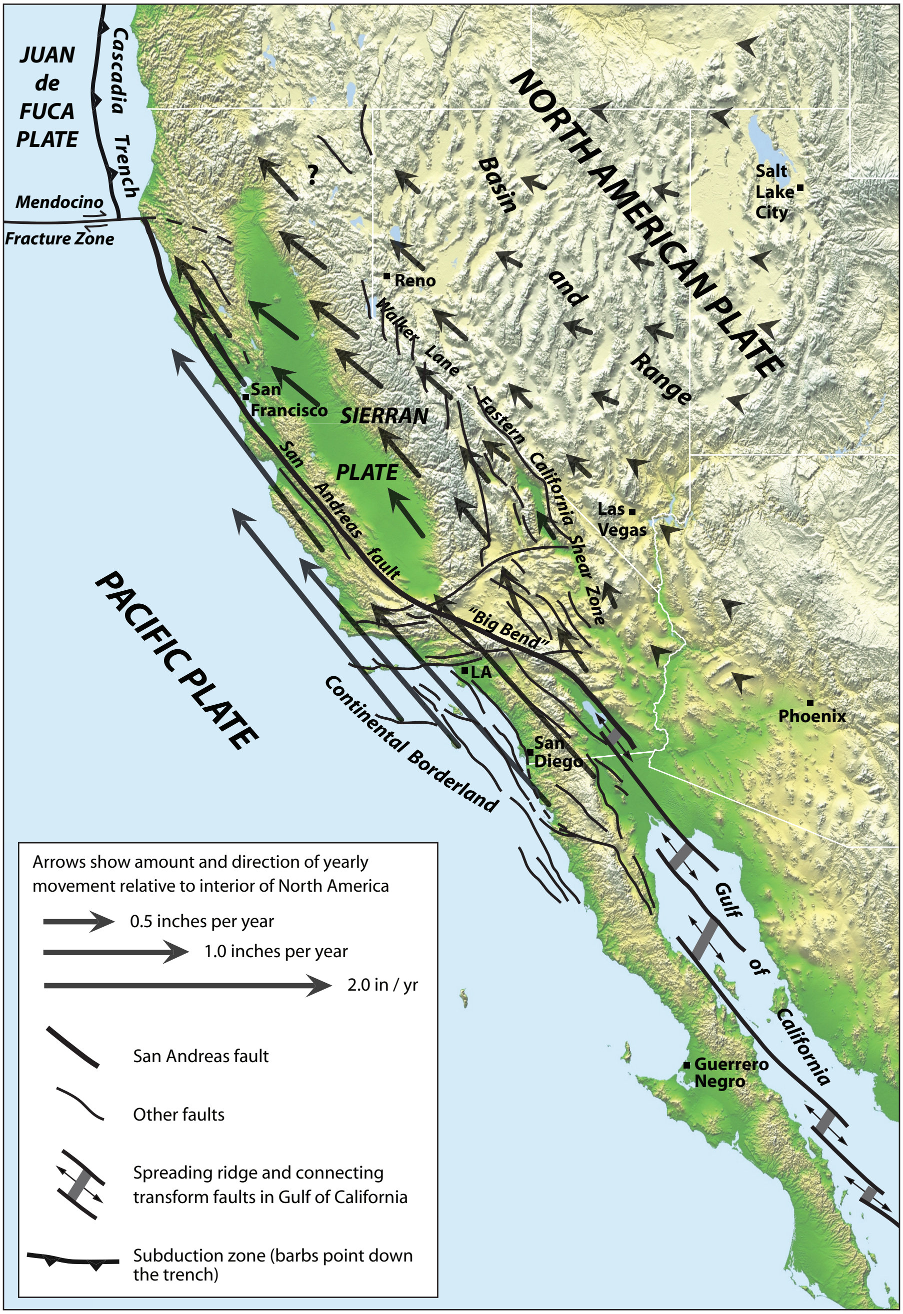
FIGURE 1.4. How faults and plate movements sliced up the remains of the ancient Ballena River and, in the process, created Southern California's present geography. Red lines mark faults. "WTRB" marks the Western Transverse Ranges Block of crust, which includes the Northern Channel Islands, the Santa Barbara Channel, and the Santa Monica and Santa Ynez mountains. The WRTB once lay near San Diego before the Pacific Plate captured it, spun it clockwise, and shipped it northwest. We'll look at the details and the supporting evidence for these developments in chapter 4. (Adapted from an animation by Tanya Atwater, University of California, Santa Barbara.)

hundred miles wide, allow the side-by-side movement of the two plates to happen.

This idea—that the boundary between the Pacific and North American plates is a wide zone of shifting faults rather than a single fault—is vital for understanding the geology not just of Southern California, but of the entire western United States. To see what I mean, look at figure 1.5, which shows the results of precision GPS measurements made at various places across the western United States over the past several decades. The arrows show how fast various places are moving in relation to the continental interior. One way to visualize this is to imagine pounding a huge nail through, say, Kansas to pin North America in place; those arrows in figure 1.5 show how various areas west of the Rockies would *still move.* (In other words, western North America is slowly tearing apart—a topic to which I'll return in a moment.) You can see that the fastest movements (longest arrows) lie on the Pacific Plate, showing that it moves northwest about two inches per year in relation to the continental interior. Slightly to the east, notice the cluster of arrows on the area marked as the Sierran Plate, showing that it moves northwest about one-half inch per year. The Sierran Plate,* which includes California's Great Central Valley and Sierra Nevada, seems to be dislodging from the rest of the continent because of what we call the *Big Bend* in the San Andreas fault (marked in figure 1.3). Because of the curve in the fault at the Big Bend, the Pacific Plate pushes like a shrugging shoulder against the south end of the Sierran Plate, shoving it north and cracking it away from the land to the east. But as the arrows in figure 1.5 show, the Pacific Plate is moving northwest faster than the Sierran Plate, and that means the rocks along the Big Bend are being severely crushed. That gives the Big Bend region of the San Andreas fault its other geologic moniker: the *Big Squeeze.* The crushing forces within the Big Squeeze make it one of California's most earthquake-prone regions—a story that we'll explore in chapter 3.

Besides earthquakes, another product of the Big Bend/Big Squeeze is the Transverse Ranges, shown in detail on the map of Southern California at the front of the book. The Transverse Ranges—which include the Santa

* You won't find the Sierran Plate marked in most geology textbooks, but like all plates, it is a large, coherent block of lithosphere (the outer rigid rock layer of the Earth that is broken up into moving plates) that moves on its own, its edges marked by zones of active earthquakes. The San Andreas fault system marks the west edge of the Sierran Plate. Its east edge is marked by another belt of active faults called the Walker Lane–Eastern California Shear Zone (figure 1.5).


JUAN de FUCA PLATE
Cascadia Trench
Mendocino Fracture Zone
NORTH AMERICAN PLATE
Basin and Range
Salt Lake City
Reno
Walker Lane - Eastern California Shear Zone
San Francisco
SIERRAN PLATE
San Andreas fault
Las Vegas
"Big Bend"
LA
San Diego
Phoenix
PACIFIC PLATE
Continental Borderland
Gulf of California
Guerrero Negro
?
Arrows show amount and direction of yearly movement relative to interior of North America
0.5 inches per year
1.0 inches per year
2.0 in / yr
San Andreas fault
Other faults
Spreading ridge and connecting transform faults in Gulf of California
Subduction zone (barbs point down the trench)

Monica, Santa Ynez, San Gabriel, and San Bernardino mountains—get their name from their east–west alignment, transverse to the mostly northwest–southeast alignment of other mountains in California. Pinch a watermelon seed between your thumb and forefinger. Your thumb represents the Pacific Plate and your forefinger the Sierran Plate, pushing against each other in the Big Squeeze. The seed is the Transverse Ranges, popping upward to escape the pressure. Some parts of the Transverse Ranges are rising nearly one-half inch per year, making them the fastest-growing mountains in North America. They are also—not coincidentally—some of the steepest, most landslide-prone, and most earthquake-prone mountains in the nation.*

Returning to figure 1.5 and continuing east, notice the arrows across the Basin and Range Province, which spreads across all of Nevada and parts of neighboring states. The lengths of the arrows decrease eastward, telling us that points on the west side of the Basin and Range are moving northwest faster than points on the east side. In other words, the entire Basin and Range is *stretching*—the opposite of what is happening in the Big Squeeze. That stretching, which began some fifteen to twenty million years ago, explains why the Basin and Range looks the way that it does. The region gets its name from its washboard tempo of mountain ranges and intervening basins (valleys), all lined up generally north–south and divided from one another by large faults. Stretch the Earth's crust east–west, and it will break apart along north–south

* For the story of landslides from the San Gabriel Mountains laying waste to the suburbs of northern Los Angeles, see "Los Angeles against the Mountains" in John McPhee's book *The Control of Nature*.

FIGURE 1.5 (OPPOSITE). Western North America is slowly tearing apart across a belt of active faults that stretches from offshore California east to Utah and Arizona. The lengths of the arrows reflect the yearly rates of movement of particular points in relation to the continental interior, based on global positioning system (GPS) measurements reported by Kreemer et al. (2012). Regions west of the San Andreas fault, which include Baja California and the San Diego and Los Angeles areas, are mostly attached to the Pacific Plate and are moving northwest as much as two inches per year in relation to the interior of North America. The Sierran Plate, which lies between the San Andreas and Walker Lane fault systems, moves northwest a little more than a half-inch per year. The Basin and Range has already stretched by more than two hundred miles since its inception some fifteen to twenty million years ago, and it continues to widen today by nearly a half-inch per year. As the western United States breaks apart, one or more ocean basins may eventually open up through California or Nevada, as shown in figure 1.6. (Shaded relief base from NASA, with labels added.)

aligned faults. Blocks of rock that are rising along these faults make the ranges of the Basin and Range, while blocks that are dropping make the basins (valleys) in between. Since its inception, the Basin and Range has stretched by *more than two hundred miles* in some areas. And the work goes on. Each year, the drive between Reno and Salt Lake City increases by about half an inch (GPS measurements prove it). The American West is a living landscape, reshaping itself a bit every year as the Pacific Plate grinds northwest past the North American Plate and drags pieces of our continent along with it.

Before we return to Southern California, let me speculate a bit on what those movements shown in figure 1.5 might mean for the future of the western United States. In figure 1.6, I propose three not-too-fanciful scenarios for what the western part of the country may look like in the geologic future. Each scenario portrays a possible geography about fifteen million years from now. Each assumes that the Pacific Plate will continue to scrape northwest past the North American Plate at its present rate of two inches per year.

In scenario 1 in figure 1.6, the San Andreas fault takes over as the main locus of side-by-side motion between the two plates. Baja California and coastal California, including the Los Angeles and San Diego areas, shear away from the rest of the continent to form a long, skinny island. A short ferry ride across the San Andreas Strait connects Los Angeles to San Francisco.

In scenario 2, the San Andreas fault sputters out, and the Walker Lane—Eastern California Shear Zone (marked in figure 1.5) takes over as the main locus of motion between the two plates. All of California west of the Sierra Nevada, together with Baja California, shears away from the rest of the continent. The Gulf of California extends north like a growing wedge to become the Reno Sea, which divides California from western Nevada. Residents of Nevada gambol and gamble along the shores of their new-formed ocean. The scene is reminiscent of how the Arabian Peninsula split from Africa to open the Red Sea some five million years ago.

In scenario 3, central Nevada splits open through the middle of the Basin and Range, where the highly stretched crust is already thin and weak. The widening Gulf of Nevada divides the continent from a large peninsula composed of Washington, Oregon, California, Baja California, and western Nevada. The scene is somewhat like Madagascar's origin when it split from eastern Africa to open the Mozambique Channel.

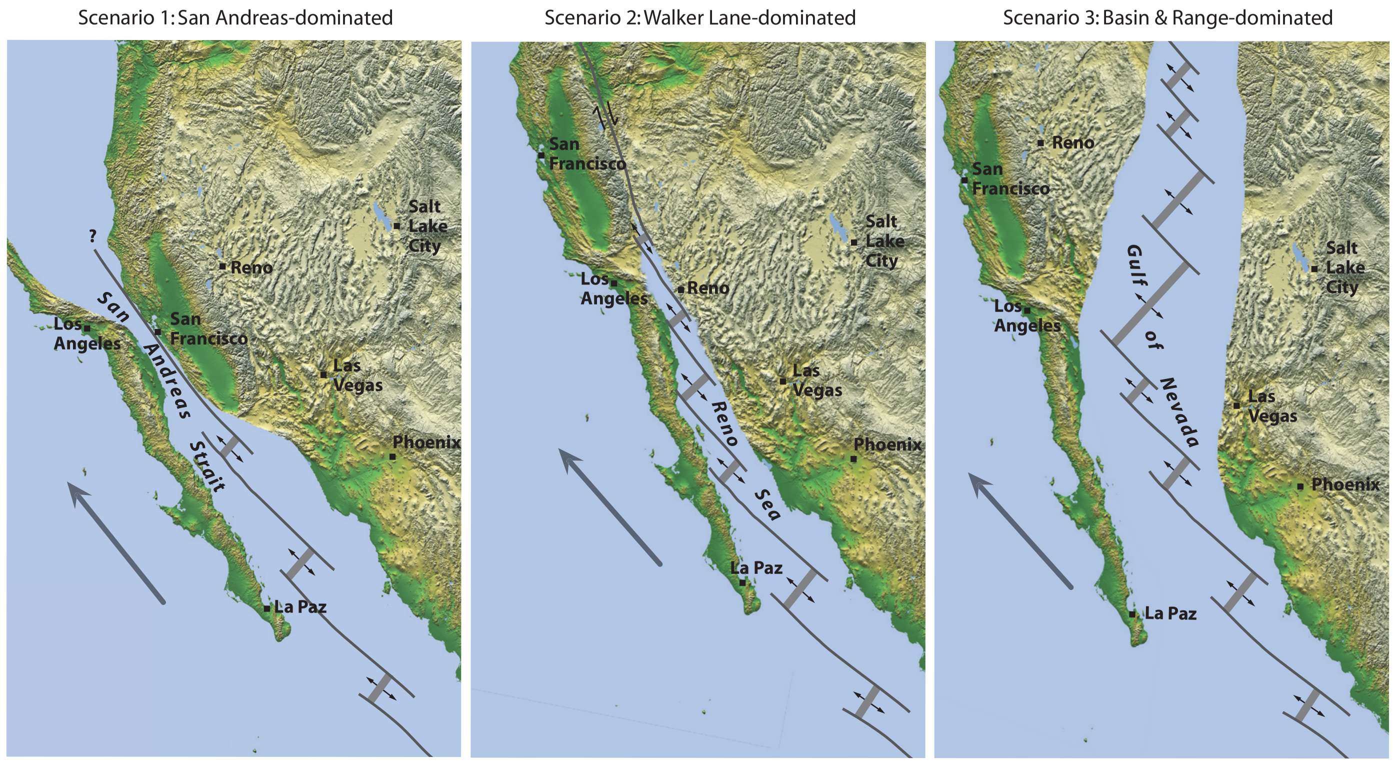


FIGURE 1.6. Possible geographies of the American West some fifteen million years in the future. (Shaded relief base from NASA, with labels added; from Meldahl 2011.)

Those scenarios encompass a range of possible outcomes; the actual result may combine all three. But every projection points to one conclusion: continental fragmentation, and eventual beachfront property in the deserts of the American West.*

EARTHQUAKES WITHIN THE PLATE BOUNDARY

Returning our focus now to Southern California, let's consider what that two-hundred-mile-wide, fault-fractured boundary between the Pacific and North American plates means for us today. One consequence is earthquakes.

Southern California is a geologic work-in-progress, and earthquakes are its growing pains. More than any other force, earthquakes have created Southern California's landscape. This may seem odd, given that most of us—even if we live here for years—will probably feel only a few moderate shakes and perhaps never experience a "big one." But that speaks mostly to the limits of human time. If we stretch our view out across geologic time, our perspective changes. Over millions of years, the cumulative work of numerous earthquakes can do stupendous landscaping. Practically all the mountains, valleys, islands, and deep offshore basins of Southern California exist *because* of earthquakes—many millions of earthquakes— each doing its part to shift a portion of the Earth's crust up, down, or sideways a few inches (small quake) or a few feet (large quake) at a time. Think back to those pebbles on San Miguel Island, and imagine the number of earthquakes it must have taken to move those rocks, lurch by lurch, five hundred miles from Mexico.

Southern California experiences thousands of earthquakes every year. Most are too small for any of us to feel, but seismometers (sensitive ground-motion instruments) may pick up a dozen or more quakes *every day* throughout Southern California. Large quakes are much rarer than small ones. A very large quake may not happen in Southern California for fifty years, or one may rip loose in the next five seconds—we can't know. (My money says it'll be sooner rather than later, and I'll tell you why in chapter 3.) The only certainty is that earthquakes, large and small, have been crackling across Southern California for millions of years and will continue. Earthquakes are our constant reminder that much of California (especially the area west of the San Andreas fault)

* These ideas are adopted from my book *Rough-Hewn Land: A Geologic Journey from California to the Rocky Mountains* (University of California Press).

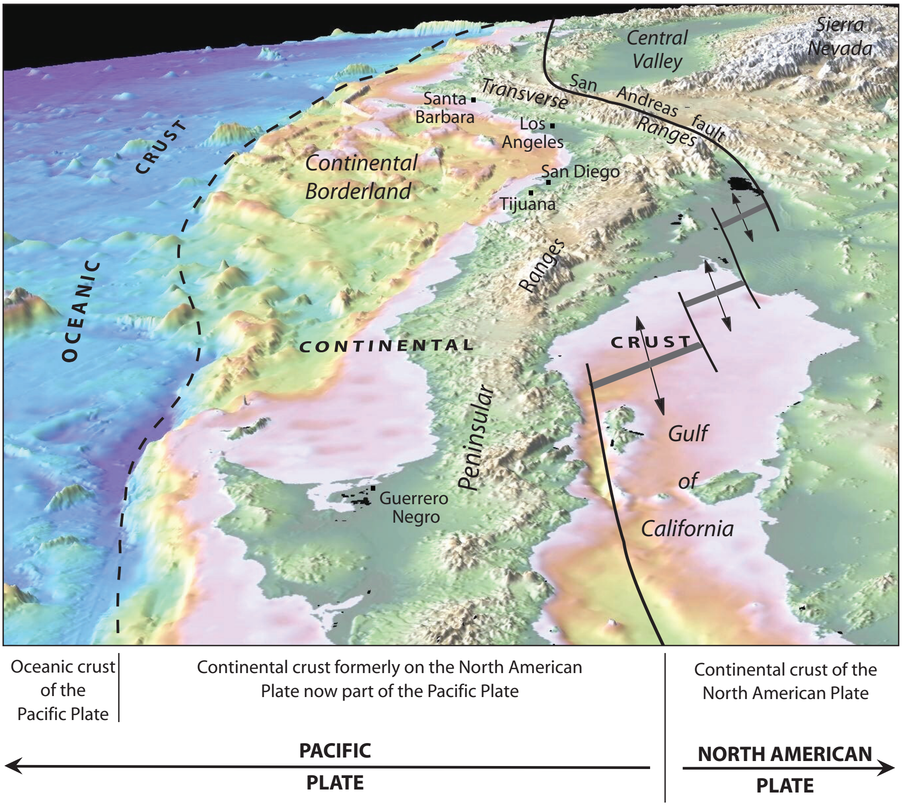


FIGURE 1.7. This image looks obliquely north–northwest from above Baja California toward Southern California, with the ocean removed and colors representing elevations and water depths. The dashed line to the west (left) divides continental crust (which underlies land and shallow ocean areas) from oceanic crust (which underlies the deep Pacific). Notice that the boundary between continental and oceanic crust is not the same as the boundary between the Pacific and North American tectonic plates, which passes north up the Gulf of California to merge with the San Andreas fault. This is because the Pacific Plate contains large portions of continental crust that were *once part of North America.* These portions include Baja California, the Continental Borderland, and coastal California west of the San Andreas fault. In chapter 4, we'll explore how these former pieces of North America ended up hitching a ride with the Pacific Plate. (Color relief base from GeoMapApp, www.geomapapp.org, with labels added.)

doesn't belong to North America. We ride mostly with the Pacific Plate, and earthquakes are a direct consequence of the Pacific Plate hauling big portions of western California toward Alaska (see figure 1.7). The long-term fate of coastal Southern California, tectonically speaking, is linked more to Hawaii, Easter Island, and other places on the Pacific Plate than to, say, El Centro or Bakersfield.

The Sunken Continental Borderland

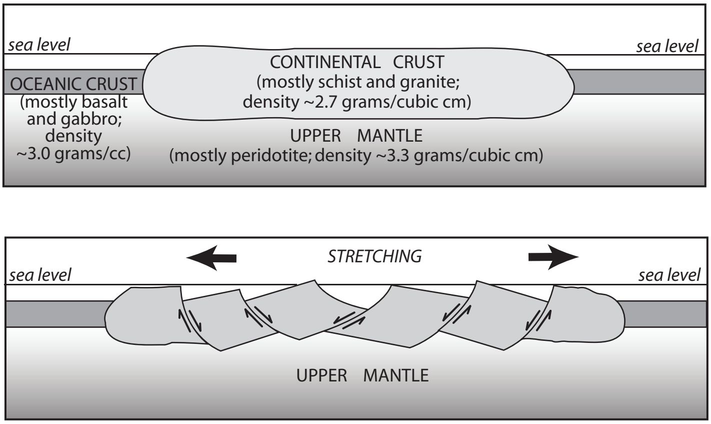
Will coastal California sink into the ocean if it splits away from the rest of the continent along the San Andreas fault? I hear this question surprisingly often. The notion may trace back to the 1978 movie *Superman,* starring Christopher Reeve as Superman and Gene Hackman as Lex Luthor, the villain. Lex Luthor's get-rich scheme is to buy large tracts of cheap land in the California desert east of the San Andreas fault. He then plans to explode a nuclear missile along the fault, which will dump western California into the sea and make him the owner of hundreds of miles of sparkling new beachfront property. (Spoiler alert: Superman stops him.)

Luthor's plan had a fatal flaw. Continents are made of relatively thick, low-density rock that floats buoyantly in the denser rock of the mantle beneath (see figure). A branch that breaks away from a floating log won't sink; its buoyancy doesn't depend on being attached to the log. Likewise, a piece of continent that splits away from the rest won't sink into the mantle; it's buoyancy doesn't depend on being attached to the rest of the continent. The buoyancy of thick, light continental rock keeps the continents above the sea in most places. By contrast, the denser, thinner rock that forms the deep ocean floor floats low in the mantle and thus lies well below sea level. (The concept that the thickness and density of crustal rock controls how high or low it floats in the mantle, and thus its elevation, is called *isostatic equilibrium.*)

Having said that, there *is* a way to make continental rock founder at least partly below sea level. It can happen where faults stretch and thin the continental crust. Just as a thick iceberg will rise higher above the water than a thin one, so a thick piece of continental crust will float higher in the mantle than a thin piece. If a thick iceberg breaks apart into smaller, thinner pieces, none of those will float as high as the original. Likewise, if a thick piece of continental crust stretches and breaks into thinner pieces, none of those crustal pieces will float as high in the mantle as before. This is why the Continental Borderland is mostly below sea level—despite being made largely of conti-

THE SOUTHERN CALIFORNIA BIGHT AND THE CONTINENTAL BORDERLAND

Now that we've explored some aspects of Southern California's plates, faults, and earthquakes, let me introduce some of the region's coastal geology and oceanographic features (as a prelude to deeper detail to come in later chapters).



The Earth's continental crust is composed of rock that is thicker and less dense than oceanic crust—the rock of the deep ocean floor. This makes the continents float high in the Earth's mantle, so that the continents rise above the ocean surface in most parts of the world (upper diagram). But if the continental crust stretches and breaks up along faults, parts of it may sink below sea level, leaving just a few areas standing high enough to form islands. That is what we see in the Continental Borderland (lower diagram).

nental crust. As the Pacific Plate, sliding northwest, tore away pieces of the North American continent to create the Continental Borderland (a story we'll explore in chapter 4), the crust stretched and broke apart into several blocks (lower image on the figure). Today, the highest parts of some of these blocks poke above the sea as islands or lie barely awash as shoals like Cortes Bank, Tanner Bank, Thirty-Mile Bank, and others. The deepest parts of the foundered blocks create basins like the Santa Barbara, San Nicolas, Santa Monica, and Catalina basins. For a fuller view of the broken-up continental crust of the Continental Borderland, see figure 1.7.

From Oregon south to Point Conception, the California coast faces generally west. But at Point Conception the coast takes a right-angle turn to the east, so that someone standing on the beach at Santa Barbara looks south toward the ocean, not west. From Point Conception to San Diego, the shape of the coast describes a broad curve, 260 miles long, looking somewhat like a bite out of a big cookie. This is the

Southern California Bight, shown in detail on the map of Southern California at the front of the book. ("Bight" is a nautical term for a large inward curve in a coast that is larger and less confined than a bay.)

The Southern California Bight faces a collection of islands, shallow banks, and deep basins offshore called the Continental Borderland (see figure 1.7 and the map of Southern California). As the name suggests, the rocks of the Continental Borderland, although largely underwater today, are mostly pieces of continental crust (see text box). In fact, the Continental Borderland was once part of the North American Plate, as were Baja California and much of California west of the San Andreas fault. As I explained above, these former pieces of North America today are traveling mostly with the Pacific Plate. Why did they shift over? The answer is that the Pacific Plate kidnapped them (a story we'll explore in chapter 4). As the Pacific Plate dragged the rocks of the Continental Borderland northwest, it stretched them and broke them up into multiple blocks. The shifting of these blocks—up, down, and sideways along faults—has created the Continental Borderland's rugged topography (mostly underwater) of islands, shallow banks, undersea ridges, and deep basins (see text box for more detail). If you could drain the ocean and fly across the Continental Borderland, you would see a fault-fractured landscape not unlike Nevada's Basin and Range. That's because both regions formed in much the same way—by wide-scale stretching of the crust. Flood Nevada so that only the highest peaks poke out as islands, ring those islands with forests of kelp, and you have a fair image of the Continental Borderland. The Patton Escarpment (see the map of Southern California at the front of the book) marks the western edge of the Borderland. That's where the seafloor geology shifts from fault-shattered blocks of continental crust to the oceanic crust of the Pacific Plate. Figure 1.7 portrays this shift clearly.

CURRENTS AND WAVES IN THE SOUTHERN CALIFORNIA BIGHT

The Southern California Bight and the Continental Borderland make oceanographic conditions in Southern California different from those in areas to the north. The water in the bight is warmer, and wave behavior more complex, than north of Point Conception. The reasons come down to ocean currents and the blocking of ocean swells by the islands. The story begins with the California Current.

The California Current flows south along North America's west coast about ten miles per day, with a volume greater than fifty Amazon Rivers. The current carries cold water south as part of a great loop of cur-

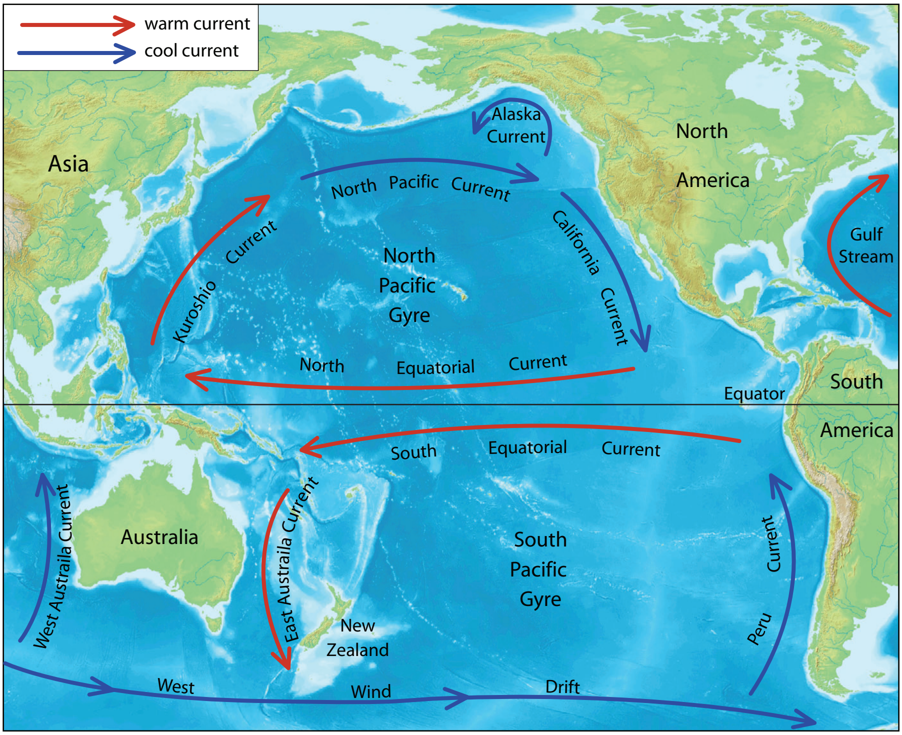


FIGURE 1.8. The world's ocean currents form large loops, called *gyres,* driven by major belts of prevailing winds. The California Current forms part of the North Pacific Gyre. The current carries cold water from the North Pacific toward the equator. For closer views of the California Current, see figures 1.9 and 1.10.

rents called the North Pacific Gyre, which cycles clockwise around the North Pacific. A water molecule takes about five to six years, on average, to travel the whole way around the gyre (figure 1.8). Along most of California's coast, the California Current flows close to shore, keeping coastal waters cold and sending cool air and abundant fog inland. But where the coast angles east at Point Conception, the current continues south, taking it far from the mainland. By the latitude of San Diego, the current is more than 150 miles offshore. I sometimes hear kayakers and surfers along San Diego's beaches talking about how the "California Current" carried them south along the beach, but this local shore-parallel current—called a *longshore current*—has no connection to the much larger California Current 150 miles to the west. (The longshore current flows in whatever direction the waves happen to be going as they

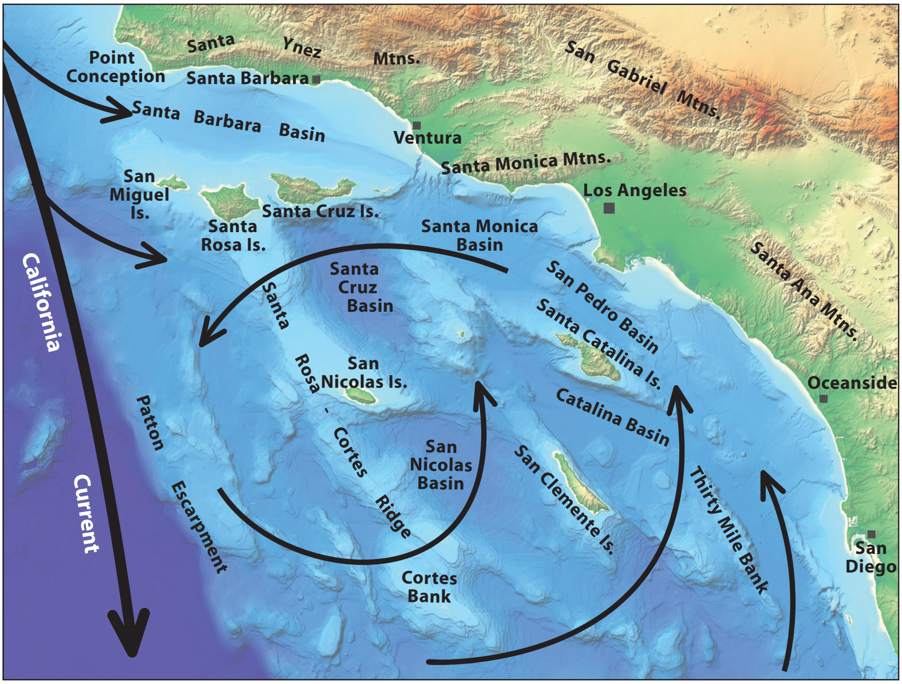


FIGURE 1.9. Ocean circulation within the Southern California Bight. The eddy pattern shown is highly generalized; actual circulation is complex, with many small eddies forming and unraveling within the larger cycle. Some water from the California Current enters the Southern California Bight at its north end, but mostly the California Current stays west of the Continental Borderland, the western edge of which is marked by the Patton Escarpment. The shore-parallel currents that you may feel along a local beach are not related to the currents here. Those are longshore currents, and they flow along the beach in whatever direction the waves happen to be heading that day. Longshore currents do not extend seaward past the surf zone (the zone where the waves are breaking). (Shaded relief base from NOAA, with labels added; based on Hickey 1992.)

approach the beach at an angle, and that can change from day to day.) As the California Current flows along the edge of the Patton Escarpment, it drags past the water in the Southern California Bight, setting up large counterclockwise eddies (figure 1.9). This eddy circulation means that new water comes into the bight from both the north (cool water) and the south (warm water). This, along with the eddies corralling water within the bight, makes bight waters consistently warmer than anywhere else along the California coast, as you can see in figure 1.10.

Ocean waves approach the Southern California Bight from all directions in the Pacific, but most commonly from the west and northwest.

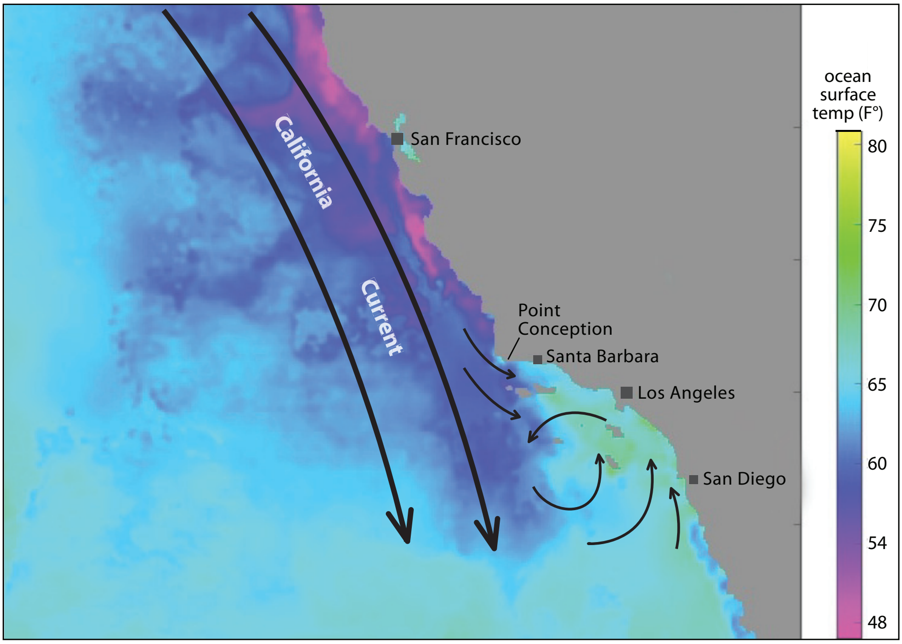


FIGURE 1.10. Typical ocean surface temperatures along the California coast in August (temperature scale on right). North of Point Conception, the cold California Current flows close to land, keeping coastal waters cool year round. Water temperatures drop even more when deep waters upwell along the coast (purple areas), which happens whenever surface waters are pushed away from land by prevailing winds and the Earth's rotation (Coriolis effect). Where the coast angles east at Point Conception, the California Current continues south, taking it far from the mainland. Waters in the Southern California Bight are therefore consistently warmer than waters north of Point Conception. (Image from NASA's Jet Propulsion Laboratory, http://ourocean.jpl.nasa.gov/SST, with labels added.)

That's because storms frequently whip up large waves in the northernmost Pacific, particularly in the late fall, winter, and early spring. As these northwest swells approach the bight, two things control their power and behavior. First is the orientation of the coastline. The southwest-facing shoreline of the bight reduces the impact of west and especially of northwest approaching swells, which are partially blocked by Point Conception. By contrast, south and southwest swells (most common in summer) hit the bight more-or-less straight on. Second, the bight faces the maze of islands and shallow banks that make up the Continental Borderland. Just as pieces of furniture in a room cast shadows from a sunbeam, so the islands cast *swell shadows* (areas of smaller waves behind the islands) across some parts of the bight, while opening *swell*

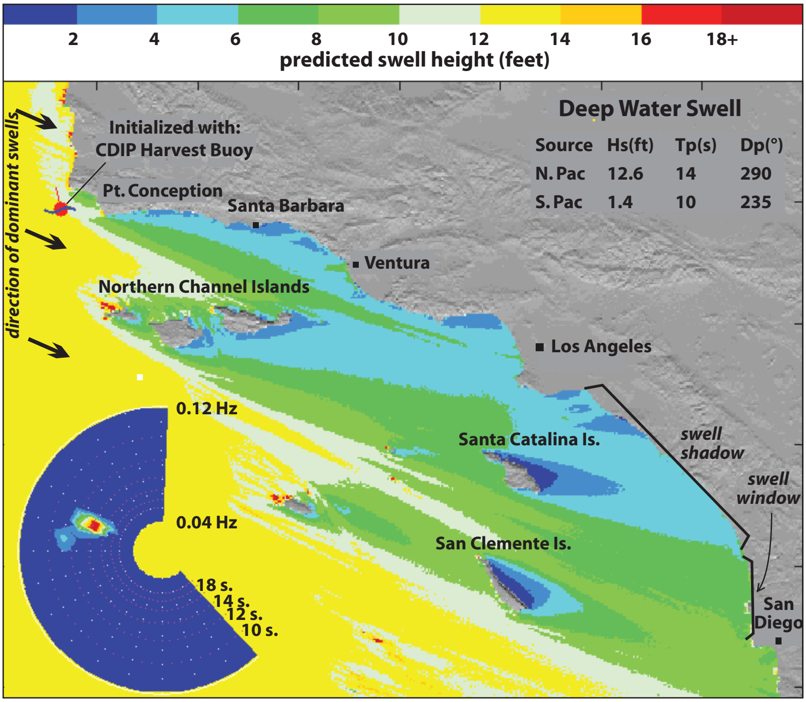


FIGURE 1.11. The direction of wave approach and the shadowing effects of islands control wave sizes in the Southern California Bight. The color bar corresponds to predicted wave heights. On the day shown, deep-water swells with a period (i.e., time between successive wave crests) of 14 seconds and a height of 12.6 feet are approaching from compass direction 290 degrees (20 degrees north of due west). The largest waves are along the coast north of Point Conception because the coast there faces the oncoming swells. Coastal wave heights drop dramatically south of Point Conception, both because the coastline faces southwest (and thus receives the northwest swells indirectly) and because the islands and shallow banks of the Continental Borderland dampen approaching waves. Notice the *swell shadow* on the mainland cast by the sheltering effect of Santa Catalina Island and the Northern Channel Islands, and the *swell window* near San Diego formed by waves approaching through the gap between Santa Catalina and San Clemente islands. Swell shadows and swell windows control the location and quality of surfing waves in Southern California—a topic we'll explore in chapter 5. (Image from the Coastal Data Information Program, Scripps Institution of Oceanography, http://cdip.ucsd.edu/; with black text, lines, and arrows added.)

windows (areas where waves pass unimpeded between the islands) across other parts, as shown in figure 1.11. And just as the shifting angle of the Sun throughout the day causes parts of a room to go from light into shadow, and vice versa, so wave sizes in the bight change—sometimes daily—with shifts in the direction of arriving swells. This makes Southern California one of the most complex wave- and surf-forecasting regions on the west coast—a topic to which we'll return in chapter 5.