PART I

CALIFORNIA

For an extremely large percentage of the history of the world, there was no California. . . . Then, a piece at a time—according to present theory—parts began to assemble. An island arc here, a piece of a continent there—a Japan at a time, a New Zealand, a Madagascar—came crunching in upon the continent and have thus far adhered.

JOHN MCPHEE, 1998

The formula for a happy marriage? It's the same as the one for living in California: when you find a fault, don't dwell on it.

JAY TRACHMAN

We learn geology the morning after the earthquake.

RALPH WALDO EMERSON, 1883

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GOLDEN GATE

The Farallon Islands poke like rotten teeth out of the Pacific Ocean thirty miles west of San Francisco. The islands get in the way of deep currents, forcing cold, nutrient-rich waters to the surface. Like garden fertilizer, the nutrients—iron, nitrate, and phosphate mostly—trigger blooms of tiny plant-like phytoplankton. Life converges on the plankton. Seabirds swarm the skies. Seals and sea lions crowd the shoal waters. Hunger pulls them toward the sea, but fear keeps them near the shore. The fat sea mammals form a 24/7 snack stand for Great White sharks. Boatloads of tourists motor out from San Francisco to bob on the swells, scanning the ocean with binoculars. If they're lucky, they'll have a *Discovery Channel* moment—the one where a 2000-pound shark erupts from the water with a seal twisting in its bloody jaws.

The Farallon Islands are made of granite. On the face of it that seems a dry fact, for granite is an exceedingly common rock. It forms much of the basement rock of the continents and the uplifted cores of many continental mountain ranges. But *continental* is the key word here. Granite is a continental rock. Finding it on an oceanic island is strange. You could spend your life wandering around Hawaii or Tahiti or most of the other islands of the Pacific and never find a speck of granite. What is a continental rock like granite doing out at sea on the Farallon Islands?

The unexpected answer comes when we compare the islands' granite to granite from mainland California. The granite of the Farallon Islands, it turns out, is nearly identical in age and chemistry to granite found in the southern Sierra Nevada—300 miles southeast and nearly 100 miles inland from the California coast. The Farallon

Islands, in other words, appear to be pieces of the Sierra Nevada that have split away from the continent and wandered out to sea. The reason is the San Andreas fault. Starting about eighteen million years ago, motion along the fault snipped off a large piece of the southern Sierra Nevada and slid it northwest toward San Francisco. Salinian Block is the name given to this chunk of dispossessed Sierra Nevada granite. The block includes the Farallon Islands and much of coastal California north and south of San Francisco. If present trends continue, the Farallon Islands, riding with the Salinian Block, will arrive at the coast of Alaska in about seventy million years.

For many people, the notion of a big chunk of the southern Sierra Nevada presently offshore of San Francisco and drifting toward Alaska falls somewhere between disturbing and impossible. It's a fair reaction. It comes from viewing the Earth through the lens of human time—a perspective that gives the illusion of stability to a world that, over geologic time, is radically mobile. A flash of a strobe light on a dance floor gives the same illusion. The dancers in that microsecond appear frozen in place, even though they're actually in continual motion. In human time, the continents and ocean basins appear fixed and permanent. To know that the Atlantic Ocean is forty-three feet wider today than when Columbus crossed it lifts, just a little, the veil of our illusion. We need to tear that veil away to see the Earth as it really is. When we do that, we see a different planet. Continents don't stay put. They drift like loose barges across the face of the Earth. Where they tear apart, new ocean basins open. Where they crunch together, ocean basins disappear and mountains rise in their place.

This action happens because the Earth's outer rind is split into moving plates of rock (frontispiece figure). The plates range fifty to one hundred miles thick, and several hundred to several thousand miles across. They move, in various directions, a few inches each year (figure 1.1). Continents are not plates, but they form parts of some plates. The continents ride like passengers on the plates, going where the plates take them, rearranging the face of the Earth over geologic time. Just about every major geologic feature on Earth—including volcanoes, earthquakes, mountain belts, metal and mineral deposits, and the large-scale features of the ocean floor—results from the movements of these plates. This discovery, called plate tectonics, stands at the pinnacle of human insight, shoulder-to-shoulder with biological evolution, the structure of the atom, quantum physics, and the expansion of the universe. Its power undergirds nearly everything that we'll explore in this book. The Earth's moving plates have written the story of the American West.

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As you leave the Farallon Islands and ride the swells back to San Francisco, the first piece of the mainland to loom out of the fog is usually Point Bonita, a small peninsula that pokes like a crooked finger into the Golden Gate. A lighthouse at the tip of the point warns ship captains to steer clear of the dark cliffs and skerries that shatter

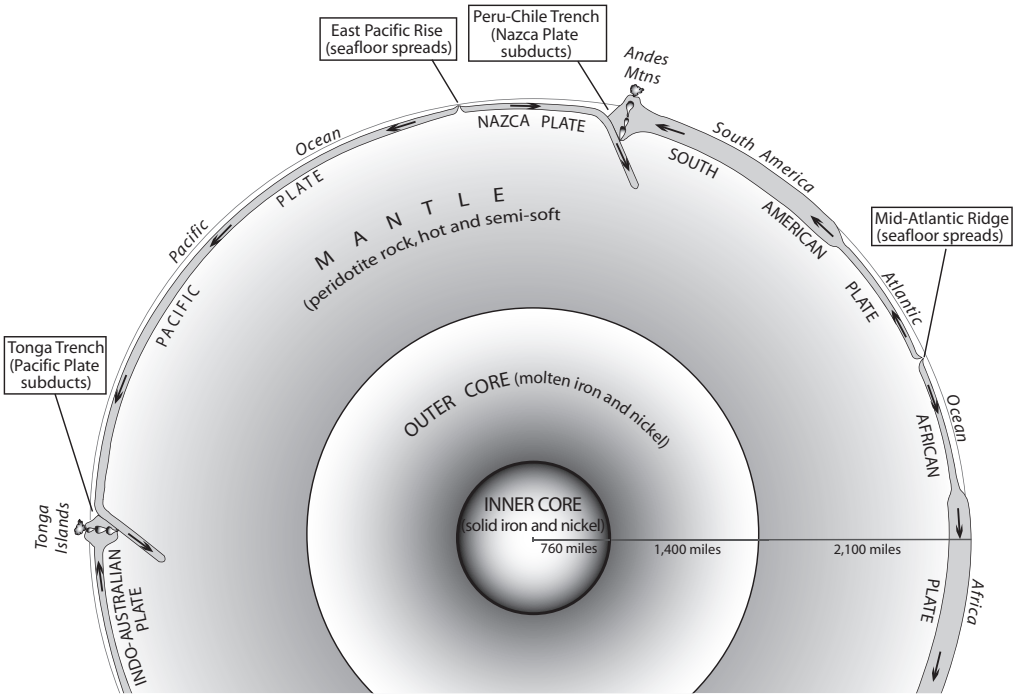

FIGURE 1.1

A schematic slice through the Earth bisecting the Indo-Australian, Pacific, Nazca, South American, and African plates. Plates grow apart from one another at mid-ocean ridges through seafloor spreading and come together at ocean trenches, where one plate dives beneath the other in the process of subduction. For clarity, the diagram greatly exaggerates the thickness of the plates, the depth of the oceans, and the topographic relief of the land surface. (If I had drawn the diagram to scale, the ocean would be thinner than the thinnest line, and the Andes and the Tonga Islands would be near-invisible bumps.)

the Pacific swells to white. The rock of Point Bonita is not granite but pillow basalt: greenish-black volcanic lava taking the form of pillow-sized blobs stacked upon one another like sacks of grain (figure 1.2).

The pillow basalt at Point Bonita and the granite of the Farallon Islands are utterly different rocks; you would more easily confuse Martin Luther King, Jr. and Eleanor Roosevelt. But they have one thing in common—they have both traveled a long way. In fact, the Point Bonita pillow basalt has traveled *several thousand miles* to end up here at the Golden Gate—a tectonic journey that makes the wandering granite of the Farallon Islands seem a homebody by comparison. The pillow basalt testifies to an epic tale of crustal mobility, powered by the Earth's moving plates. To understand this story, we need to look at how the Earth creates and destroys its ocean floor.

Pillow basalt (also called pillow lava) forms from lava eruptions on the deep seabed at mid-ocean ridges—broad undersea mountain belts that wrap around the planet like

FIGURE 1.2
View from the air looking east toward Point Bonita in the Marin Headlands, with the Golden Gate Bridge beyond (top). All around the point are superb exposures of pillow basalt—heaped blobs of dark volcanic basalt (bottom) that once formed part of the deep ocean floor several thousand miles west of California.

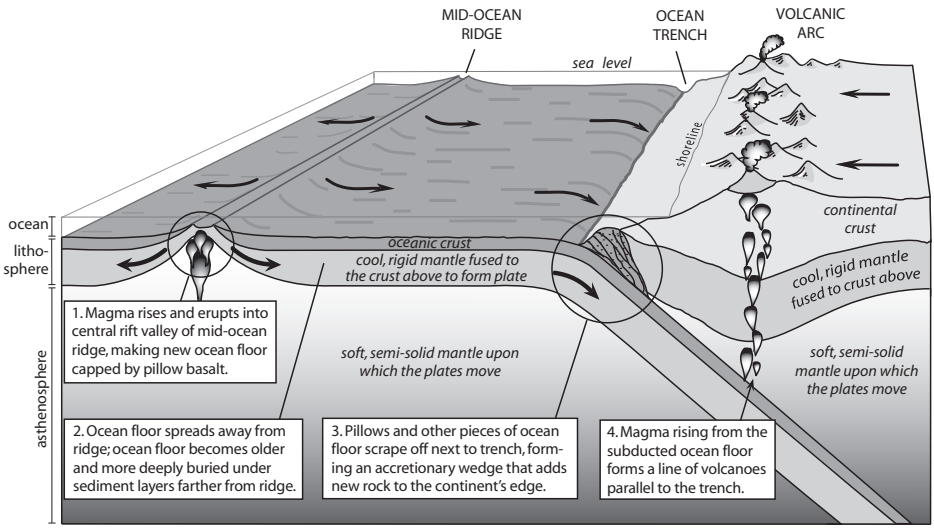

FIGURE 1.3
The movements of the Earth's plates center on two opposing processes: seafloor spreading and subduction. Seafloor spreading at mid-ocean ridges forms new ocean floor, capped by pillow basalt. Subduction at ocean trenches destroys the ocean floor, except for pieces that scrape off next to the trench to form an accretionary wedge. For clarity, the diagram greatly exaggerates the vertical topographic relief of the ocean floor and the land surface.

the seams on a baseball. Deep rift valleys run down the centers of these ridges. The ocean floor slowly splits at these rifts, and lava wells up into the gap to congeal like blood in a wound. The lava squeezes out as toothpaste-like gobs, glowing red for an instant before the cold seawater quenches it into mounds about the size of a bed pillow. As the seawater circulates through cracks in the hot rock, chemical changes trigger the growth of chlorite minerals, which tint the black basalt green.

Take a submarine down to the central rift valleys of the Mid-Atlantic Ridge or the East Pacific Rise, and you can see the seabed splitting and the lava erupting and forming pillows. Cruise along the deep seabed in either direction away from these central rifts, and the pillows become more deeply buried in seabed muck. That muck—technically known as ooze—is made mostly of microscopic plankton remains. Geologists, by puncturing the deep seabed with thousands of drill holes, have learned two important things about this ooze and the pillow basalt underneath it. First, drill down through enough ooze and you eventually hit pillow basalt. Second, the farther you go from a mid-ocean ridge, the thicker the ooze and the older the pillow basalt beneath it.

These facts tuck neatly into the concept of seafloor spreading—the Earth's system for manufacturing new ocean floor (figure 1.3). After lava erupts at a mid-ocean ridge to form pillows, it makes room for new lava by spreading away in opposite directions, like two oppositely moving conveyor belts. As the seabed spreads from the ridge, planktonic

ooze slowly buries the pillows under ever-thicker layers. The world's mid-ocean ridges spread in this conveyor belt-like manner about two inches per year, on average.[1] That's a plodding pace in human time, to be sure—but so what? Compared to geologic time, human time is virtually insignificant, like a couple of still-frames in a feature-length movie. Take two inches per year over the entire 40,000-mile-long mid-ocean ridge system and watch what happens when geologic time takes over. In 2.4 million years, the Earth will manufacture an area of ocean floor equal to that of the lower forty-eight U.S. states. And in 158 million years—a span less than 4 percent of the age of the Earth—that pace of seafloor spreading will create an area of ocean floor equal to the surface area of the entire planet![2]

What happens to all of this newly minted ocean floor? With the seabed constantly splitting and growing from its mid-ocean ridges, you might expect the planet to be swelling like a balloon. But it's not, because the ocean floor is destroyed apace with creation. This happens at ocean trenches—great troughs where the ocean floor bends down beneath a neighboring plate to plunge into the Earth's hot interior (figure 1.3). This process—called subduction—consumes the ocean floor almost as fast as seafloor spreading produces it.

Almost.

Subduction, it turns out, doesn't eat up every square foot of ocean floor churned out by seafloor spreading. There is a small—but crucial—imbalance between the creation of the ocean floor and its destruction. That imbalance has created California. It explains (among other things) how pillow basalt has ended up at Point Bonita in the Golden Gate.

As the seafloor slides into an ocean trench, the edge of the adjacent plate can act like a plow blade, scraping off slivers of seafloor rock. Anything sticking up from the seafloor—submarine plateaus, seamounts, or even entire islands—can get scraped off as well. If a continent tries to follow the ocean floor into a trench, it won't go far.[3] Instead, after going a little way down the trench, the edge of the continent may lever a piece of ocean floor up out of the sea like a pig wedging a truffle out of the ground. The astonishing result—played out over the scope of geologic time—is that *continents grow bigger as pieces of oceanic rock collect against their edges.* Stand anywhere in western Mexico, California, Oregon, Washington, British Columbia, or Alaska, and you stand—more often than not—on pieces of former ocean floor that have been scraped or lifted off the deep seabed and marooned on North America's western edge, mostly during the last 200 million years (figure 1.4).

The reason this has happened comes down to North America's long history of westward migration, combined with the eastward migration of pieces of old ocean floor that have slid underneath or collided with North America's western edge. Two hundred and fifty million years ago, our continent was firmly stuck to Eurasia and Africa as part of the supercontinent Pangaea. But about 200 million years ago, North America began to tear away and head west. New ocean floor created by seafloor spreading in the young, growing Atlantic had to be balanced by destruction of ocean floor elsewhere. That hap-

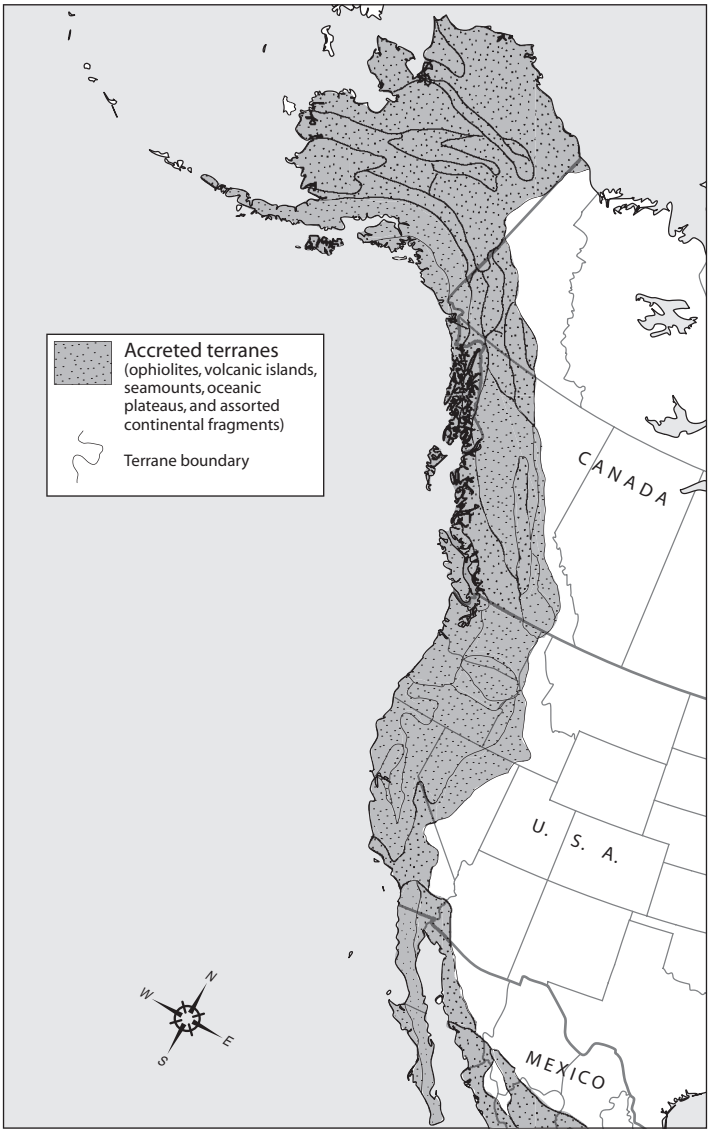

FIGURE 1.4

The growth of western North America. The western edge of the continent comprises vast strips of immigrant rock, called accreted terranes, brought here by subduction from far out in the ancient Pacific Ocean. Before they docked onto the continent, these terranes were pieces of oceanic crust, volcanic islands, seamounts, oceanic plateaus, and fragments of small continents. Like groceries piling up at the end of a checkout-line conveyor belt, they have collected, one behind the other, against the continent's western edge, mostly during the last two hundred million years. We distinguish individual accreted terranes by the great faults that separate them and the far-flung rocks and fossils within them.

pened as the continent overrode or collided with multiple pieces of ancient Pacific Ocean floor. Much of this old seabed went under the continent, but several million square miles of it glommed onto the continent's western edge, adding the new geologic real estate shown in figure 1.4.

Now we can circle back to Point Bonita and shine the light of these concepts on the pillow basalt there. More than one hundred million years ago, the pillows formed part of the seabed of the Farallon Plate—a big oceanic plate that once plunged under North America's western edge. Instead of sliding down the trench with the rest of the plate, the pillow basalts that we now see at Point Bonita sheared off next to the trench to join what is called an accretionary wedge. Jammed against the continent, the rocks of the accretionary wedge became new land for California (figures 1.5 and 1.6).

The pillow basalt at Point Bonita is just the tip of this accretionary rock iceberg. Pillow basalts crop out throughout the Marin Headlands above Point Bonita, on the Twin Peaks near downtown San Francisco, high above sea level on Mount Diablo east of Berkeley, and in dozens of other places throughout the Bay Area. What city but San Francisco could feature a tourist guidebook called *A Streetcar to Subduction,* which will take you to outcrops of these deep-sea rocks by way of public transportation? Franciscan Complex is the name given to this collection of deep-sea rocks that collected in the accretionary wedge above the Farallon Plate. You'd be hard-pressed to find a more mixed-up, fault-shattered mess of rock on Earth. The Franciscan Complex is what happens when subduction takes quadrillions of tons of old seabed and jams it against the edge of a continent.

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Above Point Bonita and its pillow basalts, the land rises steeply in mottled shades of coastal scrub to form the north shoulder of the Golden Gate. These are the Marin Headlands, a piece of near-wild California, where raptors, bobcats, mountain lions, and coyotes far outnumber people. Grim concrete relicts of military readiness dot the headlands: gun batteries from two world wars and a surface-to-air missile battery from the Cold War. When active, the gun batteries could fire 2100-pound shells as far as the Farallon Islands. Most of the old gun batteries on the Marin Headlands sink their foundations not into pillow basalt, but chert—another abyssal import scraped off the Farallon Plate.

After pillow basalts form and spread away from mid-ocean ridges, they catch a steady rain of planktonic debris (ooze) from the waters above. Many plankton cells contain lacy microscopic skeletons made of calcium carbonate or silica. The calcium carbonate skeletons often dissolve under the pressure and cold of the abyss, but the silica ones usually don't. Instead, they settle like fine snow onto the pillowed seabed, where they eventually harden into chert—a siliceous rock that breaks in scalloped curves like thick glass. Chipped by skilled hands, chert becomes arrowheads and

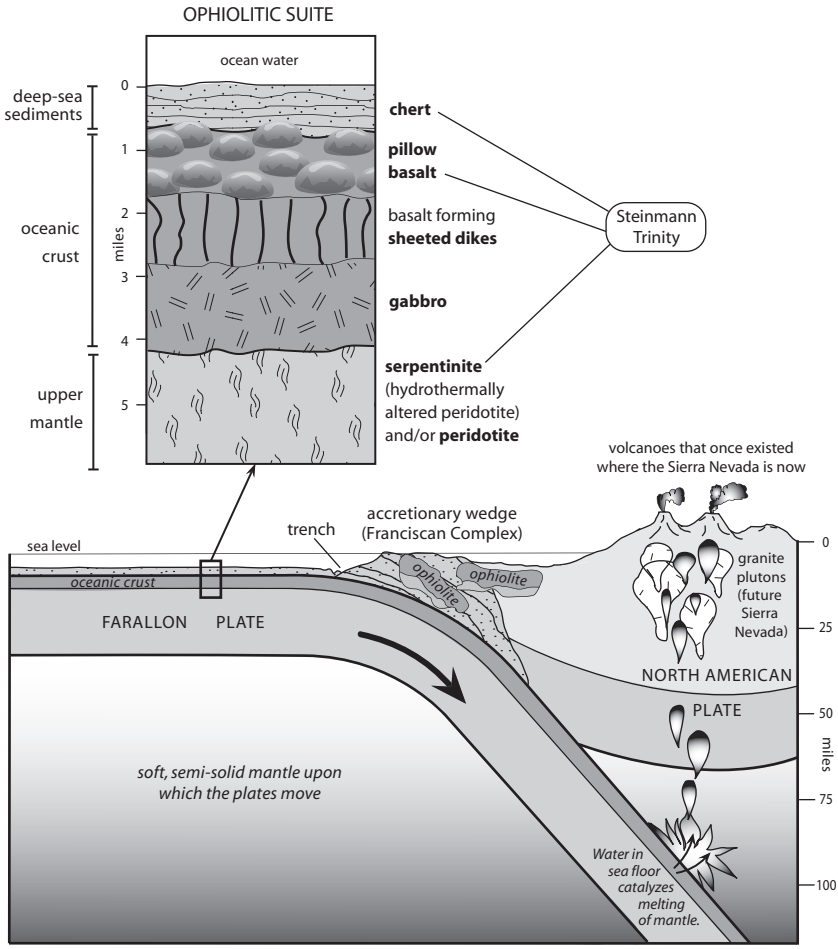

FIGURE 1.5

An east–west cross section portraying the Farallon and North American plates about one hundred million years ago. Magma, coughed up from the subducting Farallon Plate, rises and erupts as arc of volcanoes where the Sierra Nevada is today. Magma that doesn't make it to the surface solidifies underground to make granite that would later rise to form the Sierra Nevada range (see chapter 4). To the west, in what is now the San Francisco Bay area, pieces of the Farallon Plate scrape off and collect into an accretionary wedge: a fault-slivered mass of displaced deep-sea rock. The remains of this hodgepodge today comprise a geologic unit known as the Franciscan Complex. The three rocks of the Steinmann Trinity—chert, pillow basalt, and serpentinite—occur abundantly within the Franciscan Complex, particularly around the Golden Gate.

A complete *ophiolitic suite*—a vertical slice through the oceanic crust and upper mantle, as shown in the top part of the figure—comprises a five-fold grouping from top to bottom of (1) chert and/or other deep-sea sediments, (2) pillow basalt, (3) sheeted dikes of basalt (representing magma injected into fractures in the spreading ocean floor below the erupting pillows), (4) gabbro (rock from the same magma that made the basalt pillows and sheeted dikes but which cooled slowly deep in the ocean crust), and finally (5) serpentinite and/or peridotite (the rock of the Earth's mantle below the oceanic crust).

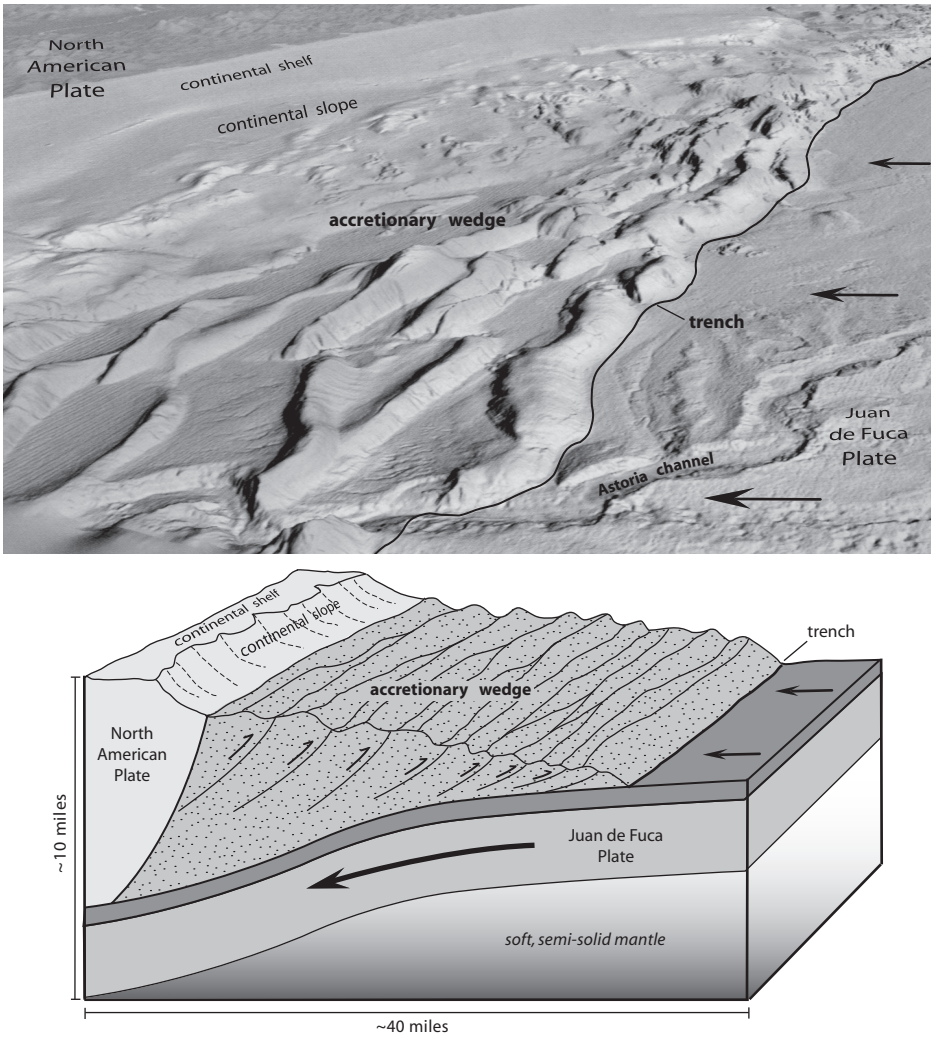

FIGURE 1.6

This accretionary wedge, forming today off the coast of Oregon, represents a modern analog to how the Franciscan Complex in the San Francisco Bay area formed. The wedge is accumulating from layers of sediment scraped off the Juan de Fuca Plate, a tail-end remnant of the Farallon Plate that subducts today beneath southern British Columbia, Washington, Oregon, and northern California. The image of the seafloor reconstructed from sonar images (top) looks obliquely south across the accretionary wedge with the ocean removed. Notice the "rumpled-towel" appearance of the seafloor. The block diagram (bottom) illustrates the inferred pattern of faults and folds formed as layers of seabed rock scrape off the subducting plate to join the growing accretionary wedge.

FIGURE 1.7
About 160 million years ago, these chert beds lay several miles below sea level in the tropical Pacific perhaps two thousand miles from California. Originally flat lying, they bunched up like wet laundry as they scraped off to join the accretionary wedge forming above the subducting Farallon Plate. The exposure lies along Conzelman Road in the Marin Headlands. Note bored spouse for scale.

spear points. (Flint is chert in archeological clothing.) When subduction scrapes pillows off the seabed, the chert above the pillows comes along for the ride. The chert layers often scrunch into fantastic contortions as they mash into the accretionary wedge (figure 1.7).

The chert in the Marin Headlands comes mostly from microscope creatures called radiolarians, a common form of siliceous plankton. The radiolarians date from the Early Jurassic to Middle Cretaceous time periods, meaning from about 200 million to 100 million years ago. (See the geological time scale at the front of the book.) Most of the radiolarians found in the Marin Headlands are of tropical species that lived in the warm equatorial waters of the ancient Pacific. Think about what this means—the chert that we now see in the Marin Headlands must have traveled all the way from the equator, *some 2,000 to 3,000 miles,* before subduction added it to California's doorstep. Most of California is built of equally well-traveled rocks.

My favorite stop in the Marin Headlands is Battery 129, an abandoned gun battery perched on bluffs high above the Golden Gate. Battery 129 draws tourists like bears to honey; the view of the Golden Gate Bridge, and of downtown San Francisco beyond, is the best that can be had outside of a helicopter ride. But forget the view, I tell anyone who will listen. A much more dramatic sight lies in the nearby road cut. If you go to the Marin Headlands, don't miss the chance to put your nose on the road cut by Battery 129

(figure 1.8). The cut exposes a cross section of the Jurassic ocean floor, where layers of brick-red chert can be seen lying directly on top of pillow basalt. Lay your hands on these rocks and time shifts to 160 million years ago, to the floor of the tropical Pacific, three miles below sea level and more than 2,000 miles from California. The weathered and crumbling pillows under your hands are now fresh lava, squeezing like incandescent toothpaste out of the splitting seabed, glowing for an instant before the cold water quenches them to stone. Move upward now and lay your hands on the chert. Now billions of microscopic radiolarians are settling through the dark waters to bury the seabed in a rising tide of siliceous ooze. All the while, the conveyor belt-like movement of the Farallon Plate is carrying the seabed northeast, toward the trench that once lay off California's coast. There, the seabed bends like a down escalator into the trench. The chert and pillow basalt seemed destined to disappear into the bowels of the planet—but they don't. Instead, they shear off to join the great accretionary wedge above the Farallon Plate. Crowded and squeezed upward by other rock wedging in from behind, they rise slowly out of the sea. And so, here they are today, remarkably unmangled considering their incredible journey. You can see and touch all of this history in this one outcrop—one that captures a span of time nearly one million times longer than the history of the United States.

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Turning away from Battery 129, I stand with other tourists looking down into the Golden Gate. Four times a day, the Moon tugs an average of 436 billion gallons of seawater (enough to fill about 1,100 football stadiums) back and forth through the three-and-a-half mile-wide strait, where the tidal waters churn with powerful currents and eddies. Engineers in the 1930s, building what was then the world's longest suspension bridge, had to contend with these currents. And they faced a larger problem: how to anchor the two colossal concrete piers that would hold up the twin towers of the Golden Gate Bridge.

For the north pier, the engineers dug into the bedrock below the Golden Gate and found hard, competent chert and pillow basalt. No worries there—support for the north pier was assured. The south pier was more problematic. The bedrock on the south side of the Golden Gate is mostly a soft, slippery rock called serpentinite. The south pier would have to stand on this soft rock, in powerful tidal currents, within two miles of the San Andreas fault, which, in 1906, had unleashed the great earthquake that leveled most of San Francisco.

To make a foundation for the south pier, the engineers decided to hollow a cavity out of the serpentinite, 110 feet deep and an acre across, and fill it with concrete like a dentist packing a root canal. Such a footing would still need to sit on reasonably competent rock, however; otherwise, it would be like pouring concrete into a mold of butter. In December 1934, the engineers finished an inspection well that pierced deep into the

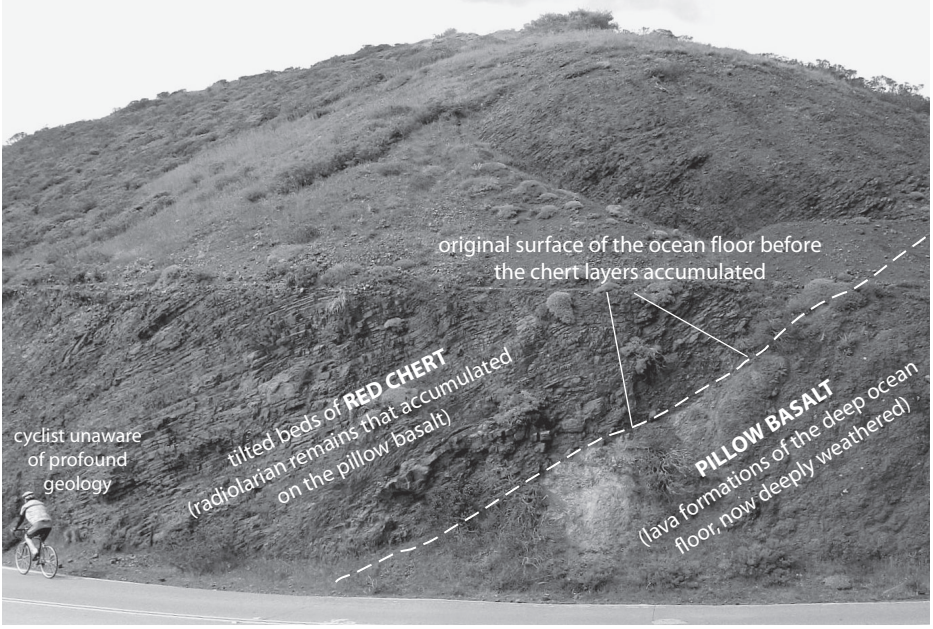

FIGURE 1.8
This road cut near Battery 129 in the Marin Headlands exposes a slice of mid-Jurassic (roughly 160-million-year-old) ocean floor, from the pillow basalt of the oceanic crust up through the layers of brick-red chert that accumulated on top of the pillows. Fault movements have tilted the whole sequence toward the west (left).

serpentinite below the strait. The highlight of the effort came as the distinguished Berkeley geologist Andrew Lawson was lowered into the well. San Francisco held its collective breath as Lawson whacked away with his rock hammer deep in the well. Lawson emerged and pronounced the serpentinite sound. "The rock of the entire area is compact, strong serpentine remarkably free from seams of any kind," he reported. "When struck with a hammer," he added, "it rings like steel." San Francisco cheered. The city would have a Golden Gate Bridge.

It's hard to reconcile what Lawson found with what you can see today in the blue-green bluffs near Fort Point, where the Golden Gate Bridge takes off from San Francisco (figure 1.9). Here, as little as 300 yards from the bridge's south pier, the serpentinite is about the worst excuse for a rock that I've ever seen—riven with fractures, slick as soap, and soft enough to carve with your fingernail. Anyone who visits these bluffs and feels the serpentinite disintegrating between his on her fingers could be forgiven for taking a sudden interest in the Golden Gate ferry schedule. Granted, the bridge has stood up well to earthquakes since it opened in May 1937. It has yet to face the ultimate test, however—a repeat of the 1906 San Andreas earthquake.