CHAPTER FOURTEEN

From Natural Selection to Plate Tectonics

I found, on landing [at Guafo Island], that the formation of the island, like that of [Guamblin] and [Ipun] Islands, is a soft sandstone, which can be cut with a knife as easily as a cake of chocolate.

—Robert FitzRoy

"*Faro Guafo, faro Guafo, cambio,*" Daniel barked into the walkie-talkie, imitating the monotone and cadence of military speech, a mischievous smile covering his face. Receiving no response, he repeated, "Guafo lighthouse, Guafo lighthouse, over." Six of us sat around an aluminum camp table in an orange-and-blue dome tent sheltering us from the mist on the beach outside. As I finished a Chilean breakfast of mashed avocado on toast while tottering on a three-legged campstool sinking into the sand, I contemplated the day's task. Carry a couple of hundred pounds of GPS equipment, tools, and batteries five miles down the shore and up a 500-foot cliff to the lighthouse, home of the only permanent inhabitants on Isla Guafo.

The *Beagle* visited here twice in 1834–5. On the first visit—while Darwin was with Sulivan surveying the eastern shore of

Chilóe—FitzRoy thought the geology of the island interesting and unusual. He brought Darwin back for a look, but Darwin was not too impressed. It would be a century and a half before the real importance of this island emerged.

On May 22, 1960, the sailors in the lighthouse on Isla Guafo had the ride of their lives during the greatest earthquake of the twentieth century—and a ringside seat for what was to follow. About ten minutes after the earthquake, the sailors watched in awe as the sea withdrew about a third of a mile to the west. Farther out to sea they could see a great wave forming, then moving rapidly toward them. The first megawave was followed by three more, reaching more than thirty feet above the beach.

Two days later the sailors discovered that their dock, a flat shelf carved in the rock, was useless, far above the water. The island had been uplifted about ten feet.

The understanding of this great earthquake represents a watershed in the development of what is now called plate tectonics—the concept that the geology and physiography of Planet Earth are determined by the movements of great plates on the surface of the planet above a viscous mantle. And also marked another success in the energetic and ultimately fruitful, but sometimes disharmonious back and forth between the geologists, like Darwin, who base their observations on what the they see for themselves in the field, and their more mathematically inclined brethren who argue from a basis in physical theory. Our expedition to Isla Guafo aimed to push that understanding even further, to advance understanding of the processes going on in the time period between great earthquakes.

The branch of geology that deals with the large-scale processes that shape the earth's crust—how seemingly solid layers of rock are folded and faulted to form mountain ranges, how continents are formed, and including how and why an island might bob up and down—has its own name: tectonics. And the ripening of the ideas that make up modern tectonics, plate tectonics—between the time that Darwin abandoned his explanation for Glen Roy and our adventures on Isla Guafo—is a tangled skein of story lines, a heady mix of personality and institutions, of observation and theory, and of curiosity versus pragmatism. The story involves not only purely geology, but advances in physics, chemistry, and . . . evolution.

One key thread through these snarls is the maturation of Darwin's idea of a fluid beneath the earth's crust, an idea that he shared with his contemporaries Charles Babbage and John Herschel. This thread twists through many corners of science, including the study of that most basic physical force, gravity.

To back up just a little, the force of gravity is proportional to mass, and for a planet, the gravity on its surface is related to its density, and the variation of density within it. Isaac Newton, writing in *Principia* in 1687, made an intuitive estimate of the density of the earth. Newton guessed the density was "five or six times greater than if it consisted all of water." Not too far off from the modern value of 5.51 gm/cm3 (with water at 1.0). Pierre Bouguer, the real brains of the French expedition to South America in the 1700s, tried to test another of Newton's ideas. Newton suggested that a plumb bob suspended at a point near a large mountain would be deflected slightly toward the mountain by its gravitational attraction. Bouguer tried this experiment near the large volcano Chimborazo, which was then thought to be the highest mountain on earth. He calculated that the plumb bob should be deflected about 103 seconds of arc from the vertical, but was disappointed that the measured value was only about 7½ seconds. "One can say," he concluded, ". . . [that] mountains act at a distance, but that their action is much less considerable than the scale of their volume." Since Chimborazo was a volcano, he thought that it might be partially hollow, and that perhaps this was the problem.

Measurement techniques improved, but understanding of how and why the measurements of gravity varied upon the surface of the earth was elusive. When Sir George Everest, the surveyor general of India, discovered that his plumb bobs were deflected toward the mass of the Himalayas—but again not as much as was predicted by theory—a whole new area of inquiry, later named isostasy, began. Was the attraction reduced because the rocks of the Himalayas were less dense than those of the surrounding region, or because the mountains had the same density, but had a root of low-density rocks that penetrated into the higher density of the earth's mantle below? Many geologists were a little confused by the debate and why it was important. But once again, those curious raised beaches and that pesky ice played a role.

Thomas Jamieson—to whom Darwin had finally yielded on the question of Glen Roy—first pieced together a history sea level during the ice ages in Scotland. Jamieson argued that Scotland had been significantly depressed by the weight of the thousands of feet of ice piled up on it, but then gradually rose after the melting of the ice. This, he concluded, was the best explanation for the raised beaches of England and Scotland and the slow rising of Sweden. Jamieson also noted one peculiar fact that he did not explain. Parts of Scotland experienced a period of submergence just after the ice had melted. Jamieson did not anticipate that the melting of the glaciers led to a rapid rise in sea level throughout the oceans, inundating low-lying land. In contrast, the rebound of the land after the melting of the ice was a much slower process—one that is still going on today.

In the late 1880s as Jamieson's ideas were finding their way to America, Grove Karl Gilbert, a pioneering geologist of the U.S. Geological Survey, found the Glen Roy of the United States—on a massive scale—in the region surrounding the Great Salt Lake. Gilbert found and mapped four ancient shorelines of the lake, the highest about one thousand feet about the current level. The ancient lake—he named it Lake Bonneville—covered about ten times the area of the current Great Salt Lake. But unlike Glen Roy, Lake Bonneville filled a closed depression. There was no mystery about what dammed this lake.

From careful measurements of the elevations along the shorelines of the former lake, Gilbert discovered something amazing.

The shorelines were not flat, as the shorelines at Glen Roy were perceived to be. Shorelines on mountains that were once islands and peninsulas near the center of the lake were nearly two hundred feet higher than those on the periphery. The level of the shorelines was a mirror image, albeit subdued, of the depth of water in the ancient lake. Gilbert hypothesized that the earth's crust was like an elastic plate—overlying a highly viscous, yielding substrate—and had been bowed down by the extra weight of two thousand cubic miles of water. Gilbert was an exceptional geologist, combining skill in the field with an appreciation for mathematical approaches and physical understanding. At the time, he was unique.

What geologists saw led them to believe that the crust of the earth had had the ability to move around, to be mobile. This belief was anathema for many scientists grounded in physics and mathematics. If the common sense-interpretation of a geologic observation didn't agree with the physics as understood at that time, it couldn't be correct. This erroneous way of thinking extended even into the twentieth century. The leader of this group was William Thomson, the British physicist later ennobled as Lord Kelvin, and not only did Thomson oppose mobility, but his views about the age of the earth also came to vex Darwin, endangering the acceptance of natural selection. Fortunately, eventually, physics would catch up.

Geologists who adopted Lyell's point of view—that the geology of the earth was shaped by ongoing processes—quickly realized that the earth had to be very old. Darwin estimated at least three hundred million years. Lord Kelvin estimated the age of the earth by imagining it as a cooling iron sphere, and settled on an estimate between twenty and one hundred million years, a number that Darwin believed was inadequate to allow the progress of evolution by natural selection.

The discovery of radioactivity in the 1890s began a whole new ball game. First, heat generated by the decay of the naturally occurring radioactive elements completely invalidated Kelvin's calculations. Second, as understanding of the radioactive isotopes resulting from these same decay processes progressed through the twentieth century, this understanding provided a clock to measure the age of the earth and to date events in its history. Now, with the earth's age reliably determined at about 4.6 billion years, Darwin has all the time he needed, as well as a clock to time evolution's progress.

But Kelvin's conceptual model of the earth as a rigid iron sphere also impeded other aspects of thinking about the earth. Even Darwin's son, George Henry Darwin, who became a colleague of Kelvin's at Cambridge, and a pioneering mathematical geophysicist, saw no room for some kind of fluid layer. Following Kelvin, he too was convinced that the earth was "throughout a solid of great rigidity."

In the first decade of the twentieth century the new science of seismology produced two discoveries that complicated the picture. From the beginning, seismologists identified the two types of waves that propagated through the earth, as predicted by the theory of the French mathematician Pierre-Simon Laplace. The first to arrive was called the primary, or P-wave, and the second to arrive, the secondary, or S-wave. The faster P-waves are analogous to the sound waves that carry our voices through the air and the shrieks of dolphins through the ocean. These waves compress the medium as they pass through it. S-waves are different. When they pass through the earth, or indeed any solid, they jerk it from side to side or up or down, with a motion that is transverse to the direction that the wave is going. Only solids can transmit S-waves, not fluids like air, water, or the molten rock that Darwin imagined beneath the earth's crust. This was highlighted by the discovery of the earth's core by Robert Oldham in 1906 and confirmed by Sir Harold Jeffreys, a professor at Cambridge, about twenty years later. Oldham discovered that beginning at a depth of about eighteen hundred miles, nearly halfway to the center of the earth, there is a fluid core through which S-waves do not pass. This was far too deep to provide the kind of ice-over-a-pond situation that Darwin imagined.

In 1909 a Croatian with a name that twists the tongue of an English speaker, Andrija Mohorovičić, studied the waves from an earthquake near Zagreb on seismograms recorded at new seismological observatories across central Europe. To his surprise, on the seismograms recorded at distances greater than about two hundred miles from the earthquake, he found two groups of primary waves. Mohorovičić concluded that the faster group had propagated within the earth's mantle. What he discovered, and was named in his honor, the Mohorovičić discontinuity, or Moho for short, marks the bottom of the crust and top of the mantle. There was no evidence for anything like a fluid layer. This was another big problem for Darwin's idea of the crust floating on lava, like ice upon on a pond.

In 1906 the famous earthquake shook San Francisco and gave the strongest indication to date that earthquakes were generated by movement on "faults." While fractures and offsets in rocks and mountainsides had been long noted by geologists, the possibility that the largest of these, now referred to as faults, could continue for hundreds, even thousands, of miles, emerged slowly. The 1906 earthquake, however, provided spectacular evidence of the horizontal offset and the immense distance over which it could extend along a fault. Something that would have warmed Lyell's heart.

In the months after the 1906 earthquake G. K. Gilbert and others documented horizontal offsets of up to twenty feet or more along a three-hundred-mile stretch of the San Andreas fault. Before the earthquake, this "line or narrow zone characterized by peculiar geomorphic features" running for six hundred miles through the coastal mountains of California was recognized by geologists and local residents alike. Thus arose the understanding of the San Andreas fault as a modern day source of large earthquakes. The paradigm of an "earthquake fault" was born. But one puzzle remained. Land surveys showed that the displacements after 1906 decreased with distance from the fault. Far from the fault there was no change. Fortunately for the future of earthquake science, the commission charged with investigating the event reached out to an Easterner and non-geologist, Harry Fielding Reid.

Reid, a professor at Johns Hopkins and member of the upper crust in Baltimore, was trained as a physicist, spending time in Germany and England with the likes of Lord Kelvin. But increasingly Reid chose to study geologic phenomena. Reid was asked to look at the pattern of these movements of the land, and his insight has proved long-lasting. Reid hypothesized that the process leading up to and during the earthquake was much like what happens when you take a stick in your hands to break it. As you bend the stick, elastic strain is stored in the stick. When the stick finally breaks, the elastic strain is released, and the two pieces of the stick fling apart. But in the case of an earthquake, what was bending the stick?

Also about the time that Darwin was giving up on Glen Roy, a young Austrian, Eduard Suess, was also thinking about both natural selection and tectonics. Suess would argue that the presence of fossils of an ancient and extinct fern called *Glossopteris* in South America, Africa, India, and Australia (where Darwin himself had found these fossils) indicated that these land masses had once been joined in a single continent that he called Gondwanaland. Darwin noted that certain species represented by the fossils that he had collected in South America, such as the giant sloths, as well as their descendents the modern tree sloths, the guanaco and llama, and armadillo, were all unique to the Americas and Caribbean. Again, somehow, they had evolved in isolation from the other continents. But the rocks containing the fossil ferns *Glossopteris* were much older. The evidence from the fossils suggested that South America had been joined to the other continents at the time of Gondwanaland, then later isolated, before finally rejoining with North America.

Curious minds had long noticed the striking congruence of the coastlines of eastern South America and western Africa, appearing like the outlines of two giant pieces of a puzzle, longing to be put back together. In 1912 the German meteorologist Alfred Wegener took up the cause where Suess left off, and with a vengeance. He began publicizing his own theory of tectonics that he called "continental drift," hypothesizing that the continents had moved around, drifting to their current positions. He matched not only the coastlines and Suess's fossil ferns, but also a variety of other rock formations on continents that were now separated by thousands of miles of ocean. Wegener picked up a few important followers for his ideas, especially Alexander du Toit in South Africa, Arthur Holmes in the UK, and Harvard professor Reginald Daly, but most geologists—particularly in the United States—either thought the idea was absurd, or at least too speculative to be useful or taken seriously. And just as Darwin criticized Agassiz for being unscientific in his hypothesizing the previous extent of glaciers, so critics attacked Wegener.

Sadly, Wegener had no Hooker to gently explain to him—as Hooker had indirectly intimated to Darwin back in the 1840s—that to gain credibility in a field of science different from one's own, it was necessary to labor in those trenches too. Wegener didn't spend his eight years with barnacles. And a bit like the anonymous author of the speculative *Vestiges of the Natural History of Creation**—who preceded Darwin in publicizing in 1844 the then-scandalous idea of evolution of the species, but without a satisfactory, much less persuasive, mechanism to explain the process—Wegener was smashed by his critics. He was only able to attract a small following among geologists as he, tragically, died a relatively young man during an ill-fated expedition on the Greenland ice sheet.

Over the next several decades the debate about continental drift sputtered along between the drifters and anti-drifters. The drifters didn't go away, but neither did they produce compelling evidence. The paleontologists, most notably the South African du Toit,

* The author was later revealed to be Robert Chambers, a Scottish journalist.

continued to see patterns in the distribution of plant and animal fossils that supported the idea. Later, geochemists who studied the ages and composition of the oldest rocks on the continental shields also saw matches across the presumed connections, and joined in. Geologists in the alpine countries, just as a century before, were impressed by the complexity of the structure of the Alps and increasingly saw evidence for large-scale horizontal displacement and mobility. In Britain, Arthur Holmes promoted the idea that continental drift was a consequence of a process called convection in which giant currents of hotter rock somehow rise in the mantle, then sink when the rock cools, in an overturning motion as in a giant pot of simmering soup. Opposing Holmes was the seismologist Sir Harold Jeffreys, an implacable foe of continental drift, who argued that the mantle was too strong and that flow in the mantle was impossible, notwithstanding the evidence for isostasy and postglacial uplift. Most American geologists regarded continental drift as if it were science fiction. Many likened the movement of the continents to battleships plowing through solid rock. How could it possibly work?

While some seismologists, like Jeffreys, focused their attention on the structure of the earth, others were intrigued by the location and distribution of earthquakes and how they might be related to geology. One leading group was the Seismological Laboratory at Caltech, known simply as the Seismo Lab. Originally founded near Caltech as a part of the Carnegie Institution of Washington in 1921, it was transferred to Caltech in 1937. The group's leaders, Beno Gutenberg, Charles Richter, and Hugo Benioff, although all trained in math and physics, devoted considerable energy to the descriptive aspects of earthquake studies. Richter and Gutenberg pioneered earthquake magnitude, but also a description of where earthquakes occurred, the seismicity of the earth. Most of the earth's earthquakes (and volcanoes as well) occur around the margins of the Pacific Ocean, the so-called Ring of Fire. But they also documented some important subtleties, like narrow bands of earthquakes running down through the middle of the Atlantic, Indian, and Pacific Oceans. While most earthquakes occur within about twenty miles of the surface of the earth, Benioff—and independently, Kiyoo Wadati, a Japanese seismologist—recognized that some earthquakes around the Pacific Rim occur in planar zones that dip landward beneath the coasts down to depths as much as four hundred miles. These zones are now called Benioff, or Wadati-Benioff zones, in their honor.

Meanwhile other seismologists showed that the earth's crust was indeed thicker beneath most mountain ranges, partially, if not completely, supporting the iceberg-like model of isostasy. In contrast seismologists investigating the crust beneath the oceans discovered that it was fundamentally different, thinner and more dense, than the crust beneath the continents.

After Chile was battered by the great earthquake in 1960, no one found a fault. The geologic origin of the earthquake presented a huge puzzle. Then, on Good Friday, March 27, 1964, another great earthquake struck—half a world away from Isla Guafo—in Prince William Sound, Alaska. Although not quite as large as the Chilean earthquake, it too was a giant earthquake, and still holds the record for second place since score has been kept. And studies of this earthquake in Alaska, half a world away, held the keys to understanding the earthquake in Chile.

Between 1960 and 1964 seismographic instrumentation had improved significantly—as had interest in seismology generally—owing to the possibility of using seismic waves to detect nuclear explosions and to differentiate them from natural earthquakes. Both the geologists and newly energized seismologists were on top of this earthquake.

Geologists flew to Alaska and began their investigations in the field. The seismologists studied the records on their permanent instruments, and some took portable instruments to the field to determine more precise locations and depths of the thousands of aftershocks spread across a region 250 by 500 miles, from the Aleutian trench landward beneath the coastal waters and mountains of Alaska. Instrumentation and techniques available at the time did not allow a very precise depth of the main shock, but most of the aftershocks were shallower than about twenty-five miles.

George Plafker—a tall, brash, USGS field geologist with dark, wavy, slicked-back hair and a degree from Brooklyn College—was one of the first on the ground. Already an Alaskan veteran, he hopped rides with a bush pilot, visiting small fishing villages around Prince William Sound, and as far to the west as Kodiak Island. The tsunami following the earthquake damaged many coastal towns and villages, obliterated some. Initially George was looking for a fault that broke the surface of the ground, something like G. K. Gilbert found after the 1906 San Francisco earthquake, a gash offsetting fences and roads by several feet. Except for a relatively short fault on one island, it wasn't there.

Instead, what he found over much of the area were barnacles newly elevated above the high tide line, dying. Species that usually lived in the zone between the limits of the tides were now high and dry, just what Maria Graham, FitzRoy, and Darwin had seen in Chile. Elsewhere he found evidence for subsidence. He collected measurements from tide gauges, land surveys, and interviews. Fishermen, he would later say often, have a keen sense of where sea level is and when it changes. As his fieldwork continued over the summer of 1964, he discovered that new, young barnacles began to grow and colonize just below the new, post-earthquake high tide line. The difference between the upper limits of the pre- and post-earthquake barnacles provided a measure of the change in the level of the land during the earthquake. Eventually he cataloged more than eight hundred measurements of vertical changes over one hundred thousand square miles.

George shared some of his preliminary measurements with a prominent seismologist, Frank Press, then the director of the

Seismo Lab at Caltech. Press would later go on to MIT, and subsequently to be President Jimmy Carter's science advisor, and then president of the National Academy of Sciences. But in 1964 he was trying to use George's data to understand the Alaska earthquake. He and a bright young Caltech senior, David Jackson, plotted twenty-six of George's data on a profile perpendicular to the coast and to the trend of the aftershocks of the main shock. Press and Jackson compared these data to some simple calculations from the emerging theory of elastic dislocations. Their conclusion, published in *Science* magazine less than a year after the earthquake, was that the earthquake occurred on a vertical fault with the Pacific side up and the Alaska side down. The hypothesized fault, located along the hinge line separating the zone of uplift from the zone of subsidence, extended from within a few miles of the surface to a depth of 60 to 120 miles.

George Plafker might not have been on quite such an august academic track, but he was not so sure that Press and Jackson were right. For one thing, their hypothesized fault didn't fit with the geology at all. The geology of the islands and coastal mountains was characterized by folds and shallowly dipping thrust faults suggesting compression perpendicular to the Aleutian Arc. The surface fault that George and his colleagues did find showed the landward side was up and the seaward side down, opposite to the sense suggested by Press and Jackson. A few months after Press and Jackson's paper appeared, George published his more complete data set and an array of arguments for why the 1964 earthquake had not occurred on a deep vertical fault, but rather on a shallow thrust fault, extending landward from the Aleutian Trench and gently dipping to the north, beneath the Alaskan coast.

Over the preceding decade seismologists had been struggling to use their observations to determine orientation of the fault responsible for an earthquake and the direction of slip upon it. It was still a work in progress. There were many problems, both practical and theoretical. But what had not been possible for the 1960 earthquake seemed almost within the reach of the seismologists for the 1964 earthquake. The theory available at the time allowed them to determine the orientation of two perpendicular planes: one, the plane of the fault, the second, a plane perpendicular to the direction of fault motion, but they could not distinguish which plane was which. For the Alaska earthquake one plane indicated a vertical fault with the seaward side up, as Press and Jackson suggested, the other a very shallowly dipping, almost flat, thrust fault, with the landward side thrusting up and out over the ocean as George contended.

In publications and at scientific meetings the debate about the 1964 earthquake raged on. After George made a presentation at a meeting in 1967, another well-known earthquake geologist from Caltech, Clarence Allen, approached him with a suggestion: why didn't he go to Chile to see what level changes had occurred during the 1960 earthquake? With Allen's help, George got a small grant, took leave from the USGS, and went to Chile.

Just as in Alaska, George traveled the length and breadth of the area affected by the earthquake. He chartered a fishing boat to visit the remote Chonos Islands far to the south. Where he couldn't visit, including Isla Guafo, he obtained reports from credible observers. For Guafo he had two independent measurements made by Chilean naval officers. He obtained data from Chilean surveys made before and after the earthquake. In all he collected vertical change data at 155 sites. The resulting picture was quite similar to Alaska, although in Chile most locations along the coast subsided during the earthquake, while uplift was largely limited to the offshore islands, with Islas Guamblin and Guafo reporting the two largest values. This time, in writing up his results, George teamed with another USGS scientist, Jim Savage, an expert in elastic dislocation calculations himself. George's data was well fit by a shallow dipping thrust fault. The case was closed. Both these great earthquakes occurred on shallow dipping thrust faults, with the continent thrusting up and out over the ocean.

During this time the old debate about continental drift warmed up to a fever pitch. In 1963 two geologists at Cambridge University, F. J. Vine and D. H. Matthews, had an amazing insight. Oceanographers had mapped an extremely puzzling pattern of magnetic anomalies across the oceans around the world. One clue seemed to be that the anomalies were vaguely symmetrical about the mid-ocean ridges. The Cambridge pair realized that this pattern was consistent with a recently proposed idea called seafloor spreading. The idea was that the seafloor was formed by the solidification of volcanic rocks at the mid-ocean ridges, then the new rocks were split in two and moved away from the ridge by upward and outward circulating convection currents in the earth's mantle below. Vine and Matthews knew that as the rocks cooled they would be magnetized by the earth's magnetic field as it existed at that instant. Further, it had just been shown that the earth's magnetic field alternated polarity over the last three and a half million years. They posited that the ocean floor on each side—as it moved away from the ridge—acted as if it were a humongous piece of magnetic tape, faithfully recording the history of the magnetic field as it shifted back and forth from one polarity to the other, over the millennia.

Gradually the data and techniques available to the observational seismologists allowed them to make reliable determinations of the fault orientation and slip direction, if not the essential ambiguity between them. Lynn Sykes and a group at Columbia University in particular, made these determinations for earthquakes along the mid-ocean ridges, elsewhere beneath the oceans, and in the Benioff zones. What they found exactly fit the models proposed for sea floor spreading at the mid-ocean ridges. In the upper parts of Benioff zones they agreed with George Plafker's conclusions from the great Alaskan and Chilean earthquakes. Piece by piece the picture came into focus. The mid-ocean ridges were the consequences of the upgoing limb of convection currents, while the ocean trenches, their associated Benioff zones, and giant thrust earthquakes were all consequences of the corresponding down-going limb.

By the early 1970s, the revolution was complete. The rebels were in control of the castle. The geological sciences had a new paradigm combining continental drift, seafloor spreading, and convection currents. It was called plate tectonics. Plates form at the mid-ocean ridges. They move away at rates of a few inches per year, carried by thermal convection currents in the earth's mantle below. Some plates are purely oceanic, others carry continents upon them. The deep trenches of the oceans, including those around the margins of the Pacific Ocean, are the results of one plate, typically the denser oceanic plate, sliding beneath another, typically the continental plate. This is the newly named process of subduction, which also leads to melting above the down-going plate and to the formation of volcanoes. The San Andreas and other great faults are the boundaries between plates sliding past one another. When two plates bearing less dense, buoyant continents collide, neither is willing to subduct, and the resulting crash gives rise to the largest mountains on earth, including the Himalayas.

Once, as I stood in my waders, sinking into the mud on the bank of Alaganik Slough in the delta of Alaska's Copper River, George Plafker stood above, retelling the story of his battle with Frank Press and the geophysicists about the 1964 Alaskan earthquake. It was mid May, early spring in Alaska. Minutes before I had watched a pair of trumpeter swans paddling in a pond, then take off gracefully, just skimming the water until they gained altitude and lifted into the sky.

George, now in his late eighties, is slowing down just a touch, but still riding his bike, and still sharp as a tack. As a graduate student I had attended a seminar that George gave on the 1960 Chilean earthquake. A few years later I learned not to try to keep up with an Alaskan field geologist when he drank me under the table one night after an earthquake meeting. Here on the banks of the Alaganik in the 1980s, George had found a sequence of buried layers that told the history of repeated great earthquakes in Prince William Sound prior to 1964. We were revisiting the site as part of a group on a field trip to see the deposits at his classic site. He loves to tell the stories of his Alaskan and Chilean adventures, and with only a bit of prodding he retold this one. I asked George what he thought Frank Press had been thinking during their face-off. George said that Press had told him later that he had only made one mistake, and that George had caught him in it. Despite working closely with geophysicists over many years, he delights in needling them. Hanging in a frame on the wall of his office is an inscription of what George calls "Plafker's Law." The law states, "When the geology and geophysics clash, throw the geophysics in the trash." One can easily imagine that—in retrospect—this epigram would have given Darwin a chuckle, remembering his difficulties with Lord Kelvin. Notwithstanding the value of George's experience, I'm not quite ready to accept his law. Progress, it seems to me, benefits from multiple views. Nonetheless, George stands with Maria Graham, FitzRoy, and Darwin on the list of top geologic contributors to the understanding of great subduction earthquakes.

One place affected by the great Chilean earthquake that George Plafker had not been able to visit himself was Isla Guafo. I was tickled to be there. From the point of view of plate tectonics, Isla Guafo is a very special place. It rides the leading edge of the South American Plate, as the oceanic Nazca Plate slides beneath it. Guafo's proximity to the edge of the plate, only thirty-five miles to the west, explains the large uplift during the 1960 earthquake. Few places on the planet—above sea level at least—share such an intimate view of subduction.

The year before my visit to Guafo—even as I was looking for deposits from ancient tsunamis in central Chile with Brian

Atwater—Daniel Melnick and Marco Cisternas were astonished to discover that Isla Guafo was sinking. Now, a year later, in 2008, we were back to fill in the story.

When Daniel and Marco first walked on the rocky platform extending seaward from the beach at low tide, they were shocked to find something sandwiched between the sand of the beach and the rock below, something completely out of place. Lying on the platform, above the tide pools, was a layer of peaty organic soil with the roots of bushes still visible, a freshwater soil now being actively eroded and washed away.

As they looked more closely, the plot thickened. The erosion of the soil exposed the holes bored into the soft mudstone by a small mollusk, holes still occupied by their empty shells. These creatures—with the charming name of *Petricola patagonica*, given them by Darwin's French contemporary, Alcide d'Orbigny—spend the happy days of their lives below the limits of the tides. Now their empty shells were many feet above that level. It seemed likely that for these poor *Petricolas*, May 22, 1960, was a very bad day indeed.

But that wasn't all. As Marco—a master of observation—poked around in the eroding soil, he made another remarkable find, a piece of plastic that he recognized from his school days. In the early 1970s a Pinochet-era government program distributed a protein supplement powder, Fortesan, to Chilean schoolchildren to improve their nutrition. Now, three and a half decades later, Marco recognized the remainder of a plastic bag, clearly labeled, that once contained the Fortesan that he had been given as a child.

With these seemingly disparate discoveries, this episode of the geologic story of the island slowly came into focus. At the time of the 1960 earthquake, as Guafo rose about ten feet, it lifted the rocky platform—with the *Petricolas* sadly attached—from below the level of the low tide to above the level of the high tide. There, as the years passed with the platform above the reach of salt water, a freshwater soil rapidly developed upon it. Then at some point the island began to sink, allowing the waves and tide to erode the new soil away.

What was going on and why?

Three days before, in front of the church on the town square in Puerto Montt, I had finally met Marco Cisternas. Marco, a tall bespectacled man with short salt and pepper hair and a quick sense of humor would serve as the adult-in-residence for our team. With him was Marcelo Lagos, who had been the silver-tongued guide for our team the previous year.

After a few minutes, Cesar Vera, a small, but powerfully built young man, joined us. "Our professional digger," Marco introduced him. Marco knew Cesar and his family well from many years of studying tsunami deposits on their land near Maullín, on the coast west of Puerto Montt.

Later that afternoon I also met Daniel Melnick, our leader, who I previously only knew through his publications on Isla San María. Many Chileans might mistake Daniel, a tall young geologist with receding blond hair and bright blue eyes, for a gringo. Until he opens his mouth. Though currently living and working at the University of Potsdam in Germany, Daniel is Chilean, and switches effortlessly back and forth between refined *castellano* and native slang. With him was Kako Rodríguez, a witty, gnomish mountain guide hired by Daniel to handle our logistics.

After Daniel and Kako finished rushing around town, gathering the last of our supplies, we drove south from Puerto Montt, crossed by ferry to the large island of Chilóe, then drove a hundred miles further to Quellón. There, despite our arrival after midnight in pouring rain, Daniel had arranged for dinner. The next morning we met Kapi, the captain of the converted fishing boat, the *Tirana*, that would take us on to Isla Guafo.

After a delay for the weather to improve, we set off around the southern end of Chilóe to the outpost of Inío, then across the twenty-mile stretch of open sea to Isla Guafo. Crossing the heaving open water, with swells rolling in from the Pacific, my sympathy for Darwin and his propensity toward seasickness found new dimensions.

On the morning of our planned hike to the lighthouse, Daniel, Marcelo, Kako, and I shouldered our heavy loads. Most annoying was an awkward set of long orange plastic pipes that we carried by turns. Eventually the mist lifted, and the sunshine sparkled off the waves crashing on the rocks along the beach. Sea birds strode the beach and soared above, piercing the air with the familiar squawk of gulls, and occasionally the metallic, duck-like honk of the *bandurrias*. Oystercatchers prowled the tide pools. Graceful, long-necked cormorants, unfazed by the waves sloshing at their feet, surveyed the scene.

One bird, the *caranca*, always appeared in pairs, a bright white male and a dull black female, constantly walking the beach within a few feet of one another. "They mate for life," Daniel explained with a smile. "No divorce, no infidelity, no messing around with other birds." Later I learned that in English we call the caranca by a considerably less romantic name, the beach goose.

Most of the hike was along a narrow, rocky beach crammed between a high cliff and the sea. After about four miles the cliffs were broken by a large landslide. Here, aided by a long rope anchored to trees, we pulled ourselves and our loads, including the vexatious orange pipes, to the top of the cliff. Following a faint trail through the dense rain forest, we emerged on a windswept headland overlooking the Pacific. The lighthouse loomed into view.

Daniel had two objectives. First, he planned to install a permanent GPS station that would record continuously, receiving power and nominal oversight from the lighthouse and its staff. Our troublesome orange plastic pipes would protect the cables carrying power to, and data from, the receiver antenna. He also wanted to repeat, with a portable GPS instrument, a survey done fifteen years before to learn how Guafo had moved in the intervening years. Both of these instruments were much more accurate than the ordinary GPS unit in a car, or a handheld GPS taken on a hike, yielding measurements accurate to about a tenth of an inch.

Leaving Kako to begin the installation of the permanent station, Daniel, Marcelo, and I set off to find the markers left by the previous surveyors. One site at the top of the cliff immediately seemed problematic. A step off the trail the grass and bushes were knee high. Even worse, it appeared that active landslides had been eating back into the cliff where we thought the site should have been. After a brief, fruitless search for some kind of monument, we abandoned the effort.

We hiked down a steep switchbacking trail to the water and the rock surface that had been uplifted ten feet or more in 1960. A concrete path led to a simple pier on the rocks. A small white shrine, topped by a cross, and containing a small statue of the Holy Virgin stood on a ledge. Somewhere near here a small brass monument, about the size of a dime, should be fixed in the rock. We began to search.

Daniel found it first, a tiny disc of metal, fixed on the surface in the expanse of rock. Here we carefully set up the antenna exactly over the indentation in the center of the disc, and connected the receiver and batteries, which we placed in weatherproof boxes behind the shrine.

Returning to the lighthouse, we had more work to do installing the permanent station. The sailors insisted we stay for dinner, and we still had a five-mile hike back to our camp. As I projected our estimated time of arrival back at camp, I realized that I had committed a blunder beyond foolish. I had failed to bring a headlamp.

Though long and challenging, our return was otherwise uneventful. I found my way along the rocky beach in the soft light of my colleagues' headlamps, arriving at our tents after midnight.

The next two weeks sped by in a flash. Most of our work was in Cesar's pits in the magical rain forest that rose behind the beach. To reach them one would first pass through thorny nalca plants with giant leaves and dense bushes of wild fuchsia. Farther back the first red-barked arrayán trees appeared with dense bushes at ground level. A hundred yards from the beach rose a Tarzan-esque jungle with vines and delicate air ferns hanging from giant trees. Sunlight does not reach the ground here and neither did my feet. I swung from fallen log to root.

I often paired with Marco taking notes as he stood in a pit almost out of sight below me describing the deposits. Even during breaks from the rain—with spectacular sunshine high above the forest canopy—the water table in the forest was so high that the pits quickly filled with water. My notes would go along fairly cleanly, until Marco would pass me a sample of sand or mud for my opinion. Notwithstanding the waterproof paper of my notebook, its pages frequently turned into a muddy mess.

What we found were buried soils like the one on the beach created after the 1960 earthquake, but older and likely indicating previous episodes of uplift and subsidence. We searched for samples of organic material we could use to date with carbon-14. In one pit we dug into the remains of an ancient *curanto*, the still locally popular method of cooking shellfish and potatoes by burying them in the sand with the coals of a fire.

In the evenings our dinner conversations in the dome tent were dominated by what we were finding at Guafo and the seemingly clear evidence that Isla Guafo, once uplifted in the 1960 earthquake was now sinking rapidly. One night the conversation expanded from the ups and downs of Isla Guafo to include Isla Santa María, some 450 miles to the north. Daniel and I shared our experiences and views about what was happening there. I told Daniel about the chart that I had found of the *Beagle*'s survey at Isla Santa María made shortly after the uplift of the island in the 1835 earthquake. He too was now suspicious that Santa María was sinking. It would be simple enough, we both thought, to get some kind of echo sounder with a GPS to repeat the *Beagle* survey, to see what we might find.

We resolved to give it a try.

After two weeks of fieldwork at Isla Guafo, finishing the installation of the permanent GPS station, and retrieving the portable station and its data, we awoke to see Kapi's *Tirana* bobbing off the beach. We were on our way home. Over the two weeks we had accumulated many interesting "facts," as Darwin would have described them. But did we have enough to unravel the history of ups and downs at Isla Guafo?

Back in Germany in the months that followed, Daniel processed the GPS data and submitted our samples for carbon-14 dating. The results confirmed some tentative correlations of the buried soils in the different pits that we had made in the field. It appeared that we had evidence for six distinct episodes of vertical change ranging from about 1315 B.C.E. to about 1360 A.D.

And the GPS data? Isla Guafo was moving to the east at the rate of almost two inches per year, and sinking at almost half an inch per year. A very good collection of "facts" was beginning to emerge, facts to illuminate the movements of the island in the periods between earthquakes.