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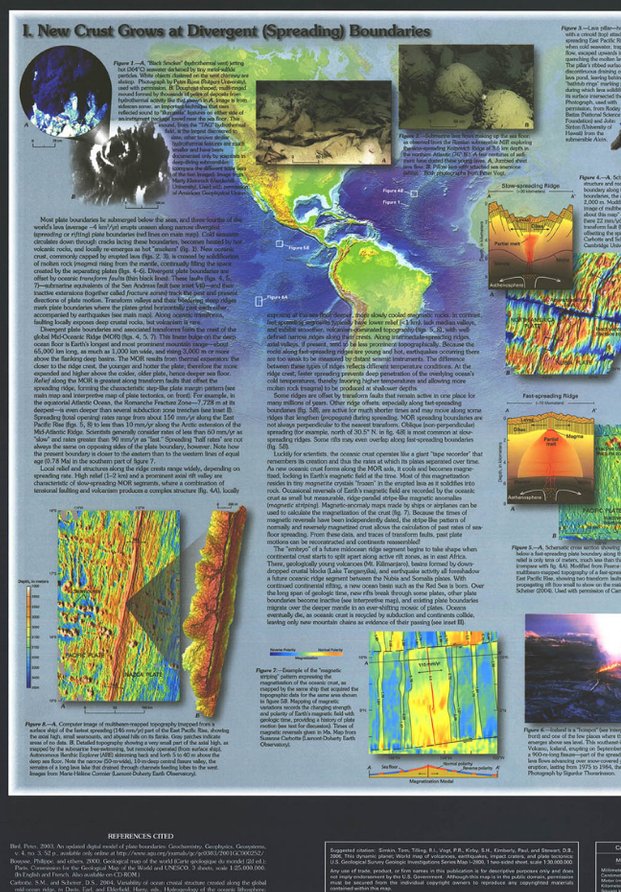
GEOLOGIC INVESTIGATIONS SERIES MAP I-2800
THIS DYNAMIC PLANET—
World map of volcanoes, earthquakes, impact craters, and plate tectonics
By Tom Simkin, R.I. Tilling, P.R. Vogt, S.H. Kirby, Paul Kimberly, and D.B. Stewart
2006

I. New Crust Grows at Divergent (Spreading) Boundaries



Most plate boundaries lie submerged below the seas, and three-fourths of the world's lava (average ~4 km³/yr) erupts unseen along narrow divergent (spreading or rifting) plate boundaries tied from on many land. Cool seawater circulates down through cracks lacing these boundaries, becomes heated by hot volcanic rocks, and locally re-emerges as hot "smokers" (fig. 1). Near-surface crust, commonly capped by erupted lava (figs. 2, 3), is created by solidification of molten rock (magma) rising from the mantle, continually filling the spaces created by the separating plates (figs. 4–6). Divergent plate boundaries are offset by oceanic fracture zones (the thin black lines in figs. 1 and 7)—submarine equivalents of the San Andreas fault (see inset VII)—and their inactive extensions together called *fracture zones* trace the past and present directions of plate motion. Transform valleys and high, faulted ridges typically mark plate boundaries where the plates grind horizontally past each other, accompanied by earthquakes (see main map). Along oceanic ridges, the faulting locally exposes deep crustal rocks, but volcanism is rare.

Divergent plate boundaries and associated volcanism and transform faults (two of the global Mid-Oceanic Ridge (MOR) (figs. 4, 5, 7). This linear bulge on the ocean floor is Earth's longest and most prominent mountain range—averaging some 65,000 km long, as much as 1,000 km wide, and rising 3,000 m or more above the flanking deep basins. The MOR results from hot (partially molten) rock in the mantle that is less dense than the cooler, stronger mantle rock around it (fig. 4). Consequently, hot mantle rock rises passively in a slow, solid-state convection system, partially melting in response to the drop in pressure as it approaches the surface. The resulting magma, being less dense than the rock it displaces, rises by buoyancy and collects in magma chambers, some of which feed volcanoes and small intrusions (fig. 4–6). Hot mantle rock also rises directly to shallow depths under the ridge crest, further spreading it and lowering the pressure on it, thereby causing more melting. Most of the MOR is present along transform faults that offset the spreading ridge, forming the characteristic step-like plate margin pattern (see main map and interpretive map of plate tectonics, on front). For example, in the equatorial Atlantic Ocean, the Romanche Fracture Zone—7,728 m at its deepest—is even deeper than several subduction zone trenches (see inset B). Spreading (total opening) rates range from about 150 mm/yr along the East Pacific Rise (figs. 5, 8) to less than 10 mm/yr along the Arctic extension of the Mid-Atlantic Ridge. Scientists generally consider rates of less than 60 mm/yr as "slow" and rates greater than 90 mm/yr as "fast." Spreading "half rates" are not always the same on opposing sides of the plate boundary, however. Note how the present boundary is closer to the eastern than to the western coast of Iceland (see age (0.78 Ma) in the southern part of figure 7.

Local relief and structures along the axis of the ridge crests range widely, depending on spreading rate. High relief (1–2 km) and a prominent axial rift valley are characteristic of slow-spreading MOR segments, where a combination of tensional faulting and volcanism produces a complex structure (fig. 4A), locally

Figure 8.—A. Computer image of multibeam-mapped topography (tracked from a surface ship) of the fastest spreading (146 mm/yr) part of the East Pacific Rise, showing the axial high, small seamounts, and abyssal hills on the flanks. Area (arches indicate areas of no data. B. Detailed topography showing a very small part of the axial high, as mapped by the submarine Alvin, including lava flows erupted from the narrow axial summit trough. Arrows point to the latest lava flows. Data courtesy of Scripps Institution of Oceanography (SIO) and Woods Hole Oceanographic Institution (WHOI). Multibeam surveys were conducted by SIO, WHOI, and the Lamont-Doherty Earth Observatory of Columbia University.

exposing at the axial high (locally, fresh slowly cooled magmatic rocks. In contrast, fast-spreading segments typically have lower relief (~1 km), less median valleys, and more abundant volcanic constructions (figs. 4, 5), with only subdued (sometimes absent) axial rifting. Along intermediate-spreading ridges, axial relief is present, and it has some prominence topographically. Because the moist along fast-spreading ridges are young and hot, earthquakes occurring there are so weak to be measured by distant seismic stations. The difference between these types of ridges reflects different temperature conditions. At the ridge crest, faster spreading promotes greater penetration of the relatively cool seawater, thereby fostering higher temperatures and allowing more melt (rock magma) to be produced at shallower depths.

Some ridges are offset by transform faults that remain active in one place for many millions of years. Other ridge offsets—especially along fast-spreading boundaries (fig. 5B), are active for much shorter times and may move along some ridges that are lengthen (propagate) rapidly. MOR spreading boundaries are not always perpendicular to the nearest transform. Oblique (non-perpendicular) spreading (for example, north of 30.5° N. in fig. 6B) is most common at slow-spreading ridges. Some rifts may even develop along fast-spreading boundaries (fig. 5B).

Luckily for scientists, the oceanic crust operates like a giant "tape recorder" that remembers its creation and thus the rates at which its plates separated over time. As new oceanic crust forms along the MOR axis, it cools and becomes magnetized, locking in Earth's magnetic field at the time. Most of this magnetization resides in tiny magnetite crystals ("boxes" in the erupted lava as it solidifies into rock. Occasional reversals of Earth's magnetic field are recorded by the oceanic crust as small but measurable, ridge-parallel stripe-like magnetic anomalies (*magnetic stripes*). Magnetic-anomaly maps made by ships or airplanes can be used to calculate the magnetization of the crust (fig. 7). Because the times of magnetic reversals have been independently dated, the stripe-like pattern of normally and reversely magnetized crust allows calculation of past rates of sea-floor spreading. From these data, and traces of transform faults, past plate motions can be reconstructed and continents reassembled.

The "embryo" of a future midocean ridge segment begins to take shape when continental crust starts to split apart above a hot spot (fig. 9A) or other hot mantle. There, geologically young volcanoes (Mt. Kilimanjaro), basins formed by down-dropped crustal blocks (Lake Tanganyika), and earthquake activity all foreshadow a future oceanic ridge segment between the Nubia and Somalia plates. With continued continental rifting, a new ocean basin such as the Red Sea is born. Over the long span of geologic time, new rifts break through some plates, other plates become abandoned, ancient inactive (see interpretive map), and existing plate boundaries migrate over the deeper mantle in an ever-shifting mosaic of plates. Oceans eventually die, as oceanic crust is recycled by subduction and continents collide, leaving only new mountain chains as evidence of their passing (see text III).

Figure 2.—Example of the "magnetic stripes" pattern expressing the magnetization of the oceanic crust, as mapped by the same ship that acquired the topographic data for the same area shown in figure 5B. Mapping of magnetic variations reveals the changing strength and polarity of Earth's magnetic field with time. Normally magnetized crust (the magnetic lines tend to be broader, because magnetic reversals given in Ma. Map from Raymond Duncan (Lamont-Doherty Earth Observatory).

Figure 3.—Lava pillow—hollow and 2 m high—photographed by submersible *Alvin* spreading East Pacific Rise. The pillar formed when cold seawater, trapped below a lava flow, erupted upwards in a thin stream, quenching the molten lava pooled around it. The pillar's fitted surface resulted from discontinuous draining of the still-fluid lava pond, leaving behind hollow "bathtub rings" marking phases. Note the lack of sediment, which is rather incorrect for pillar. Photograph, used with permission, from Ridley Bastos Pictorial Science Foundation and John Sinton (University of Hawaii) from the submersible *Alvin*.

Figure 4.—Schematic cross section showing inferred structure and rock types at a slow-spreading plate boundary along the Mid-Atlantic Ridge. Along such boundaries, the maximum local relief can be as much as 9 km, as compared to about 2 km for fast ridges. Image of midocean-ridge topography from "Voyage to the Bottom of the Sea" by Heezen and Tharp, 1977, with permission, from Marie-Hélène Cormier (Lamont-Doherty Earth Observatory).

Figure 5.—Sea floor topography, as viewed from the Russian submersible *MIR* exploring the slow-spreading Mid-Atlantic Ridge (A) and the fast-spreading East Pacific Rise (B). Note the much greater relief of the former. Both photographs from Woods Hole Oceanographic Institution (WHOI).

Figure 6.—Schematic cross section showing inferred structure and rock types at a fast-spreading plate boundary along the East Pacific Rise. Here, the local relief is only tens of meters, much less than that along slow-spreading ridges (compare fig. 4). Image of midocean-ridge topography from "Voyage to the Bottom of the Sea" by Heezen and Tharp, 1977, with permission, from Marie-Hélène Cormier (Lamont-Doherty Earth Observatory). Modified from Carbotte and Scheirer (2004). Used with permission of Cambridge University Press.

Figure 7.—Detailed topography and magnetic-stripe pattern of the Reykjanes Ridge, the southernmost segment of the Mid-Atlantic Ridge that is above sea level (Iceland). Data from Ridley Bastos Pictorial Science Foundation and John Sinton (University of Hawaii) from the submersible *Alvin*.

Figure 8.—Iceland's "hotspot" (see interpretive map of plate tectonics, on front) and one of the few places where the global Mid-Oceanic Ridge system emerges above sea level. This southeast-trending aerial view shows Krafla volcano (behind the lake) and its associated fissure system. The lake, dotted with small islands, occupies the caldera formed during the 1975–84 Krafla fissure eruption. Photograph by Sigurdur Thorarinsson, used here following over-the-counter ground. During this 9-year eruption, lasting from 1975 to 1984, the fissure widened by 8 m. Photograph by Sigurdur Thorarinsson, used here following over-the-counter ground.

Figure 9.—Schematic cross section showing inferred structure and rock types below a fast-spreading plate boundary along the East Pacific Rise. Here, the local relief is only tens of meters, much less than that along slow-spreading ridges (compare fig. 4). Image of midocean-ridge topography from "Voyage to the Bottom of the Sea" by Heezen and Tharp, 1977, with permission, from Marie-Hélène Cormier (Lamont-Doherty Earth Observatory). Modified from Carbotte and Scheirer (2004). Used with permission of Cambridge University Press.

MORE ABOUT THIS MAP

INTRODUCTION

Our Earth is a dynamic planet, as clearly illustrated on the main map (on front) by its topography, over 1,500 volcanoes, 44,000 earthquakes, and 170 impact craters. These features largely reflect the movements of Earth's major tectonic plates and many smaller plates or fragments of plates (including microplates). Volcanic eruptions and earthquakes are awe-inspiring displays of the powerful forces of nature and can be extraordinarily destructive. On average, about 60 (if Earth's 550 historically active volcanoes erupt in any given year. In 2004 alone, some 5,000 earthquakes were magnitude 6 or above, some of which caused casualties and substantial damage.

THE DYNAMIC EARTH

As the main map shows, earthquakes and volcanoes are not randomly scattered over Earth's surface. Instead, most are concentrated along certain continental edges, along island chains, or along oceanic ridge crests. Although geologists have long known this, it has been only in the past 40 years that a concept has emerged to satisfactorily link these observations. This unifying concept, called *plate tectonics* (see Kious and Tilling, 1996), is now widely accepted and has revolutionized the earth sciences. Table 4 in the online version of this map (http://www.minerals.si.edu/Adjmap) lists some notable milestones and pioneers in the development of the plate tectonics theory.

Earth's outermost layer (the relatively stiff and rocky *lithosphere*) is a mosaic of large tectonic plates that move relative to one another at speeds measured in tens of millimeters per year—or about the same rate as our fingernails grow. Plates are cold, dense, and strong enough to resist most large deformation. They average about 80 km thick, but are generally thicker under continents than under oceans. Plates are composed of Earth's relatively thin surface rind (the crust) and the topmost 75 km or so of the 2,900-km-thick mantle. Over 50 separate plates are recognized by some specialists (for example, Bird, 2003), but the 15 that we name cover more than 95 percent of Earth's surface.

Plates move on a viscous, slowly flowing layer of hotter, softer mantle (the *asthenosphere*). Plate movement represents the top of a large-scale circulation system (convection) driven by Earth's escaping heat—that extends deep into the mantle. Mantle flow is like the sluggish movement in a pot of thick soup boiling on a stove. Such flow transports the plates horizontally on Earth's surface. Where plates grind against each other, stresses can build up and be released intermittently when rocks break or slide along *faults*, causing earthquakes. Near some plate boundaries, molten rock (*magma*) can rise from the surface from as deep as many tens of kilometers to erupt to form volcanoes. Some plate boundaries cannot be narrowly defined, but instead are diffuse, encompassing broad areas (see interpretive map of plate tectonics, on front).

Data information associated with plate movements is concentrated in the boundary zones between shifting plates, explaining why so many earthquakes and volcanoes are found along or near plate boundaries. Nevertheless, active volcanoes and large earthquakes also can occur in plate interiors, which are not immune from plate tectonic forces.

FEATURES OF THE MAP

Topography

Earth's topographic features are largely the expression of plate tectonics, modified by erosion. In the oceans, however, scattering of light in seawater prevents "seeing" most of the sea floor from aircraft or orbiting satellites. Radar waves, like light waves, also cannot penetrate deep into seawater, but they have been used successfully to map the ocean surface from satellites. The mapping technique (*satellite radar altimetry*) involves the measurement of small undulations of the sea surface—tens of kilometers across but only a few centimeters to meters in height—produced by slight differences in gravitational attraction of sea-floor mountains and valleys. These small variations in sea surface height mimic, and are proportional to, the actual topographic features of the sea floor. Satellite radar data provide global coverage, but resolve only the larger sea-floor features. Photographs or high-resolution topography are available for only a tiny fraction of 1 percent of the world's ocean floor. See inset I for examples of sea-floor mapping at various scales).

The sea floor topography shown on the main map was produced from satellite-radar mapping of the sea surface, augmented in places by data obtained by ship-based acoustic (echo-sounding) techniques. Sea-floor topography is typically "visualized" as computer-generated, colored maps. In reality, however, the deep ocean floor is sunless, totally dark, unless artificially lit by light. Land-surface topography is obtained by using similar satellite technology, but here radar mapping from space gives a direct measure of surface features. Shading—as if the topographic images were illuminated by an artificial sun—is added to enhance the third dimension (height) and highlight the visualization of features.

A Mercator map projection is used, both for its familiarity and for ease of transferring information from other Mercator projection maps. This projection exaggerates the relative size of high-latitude areas, and here omits coverage beyond about 72° N. and 70° S. on the main map. Polar projections in lower corners (65°–90°) complete the coverage of the planet at the equatorial scale of the main map.

Earthquakes

Earthquakes are vibrational motions produced mostly by rupture of rock along faults. The most common measure of earthquake "size," based on the amount of seismic ground motion, is called magnitude. This concept was introduced in the mid-1930's by seismologist Charles F. Richter. He measured a seismic-wave characteristic called *amplitude* (the height of the peak seismic wave recorded by standard seismographs at a standard distance from the earthquake source). Because peak amplitudes vary over such an enormous range among earthquakes, the Richter scale is logarithmic: a magnitude-6 earthquake has 10 times the peak amplitude and releases about 30 times more energy than a magnitude-5 earthquake. A magnitude-3 earthquake is about the smallest that can be felt by humans, and the largest ever recorded was 9.5. In general, the larger the magnitude, the larger the rupture area and movement along the fault. Small-magnitude earthquakes occur much more frequently than large-magnitude earthquakes (see earthquake explanation on front).

Most locations of earthquakes (epicenters) are determined from the precise arrival times of seismic waves at global seismic stations, the known speeds of those waves, and the principle of triangulation. Our ability to locate earthquake epicenters has greatly improved during the last decade because of sensitive digital seismic instruments and improved data processing. On the main map, modern accurate epicenters show that most earthquakes are closely clustered along plate boundaries. The most demanding test of earthquake-location accuracy is along oceanic plate boundaries that are typically distant from seismic stations on land. Comparisons of the new earthquake locations with the similarly improved mapping of oceanic plate boundaries shows that most of these earthquakes occur nearly along transform fault segments. In contrast, spreading ridge crests, linked by these transforms, generate few detectible earthquakes, because plates there are too thin and weak to allow large stresses to build.

A small number of intraplate earthquakes are shown (as hexagons) on the main map despite their pre-1900 dates or failure to meet the precise location criteria of the main data set. These—as shown by notable earthquakes nos. 1, 4, and 5 (table 3)—are important reminders that devastating earthquakes also occur, albeit rarely, far from active plate boundaries.

Volcanoes

Volcanoes are shown in four categories on the basis of their most recent known eruption in the past 10,000 years. Because repose intervals between eruptions can be thousands of years, and because the historical record in many parts of the world is only a few hundred years, we have made only minor graphical distinction between the map symbols for the first three categories. Thus, any one of them might erupt within our lifetimes. Remember, though, that most of Earth's volcanoes occurs along the midocean ridge crests, where countless submarine eruptions take place each year—sight unseen—deep in the ocean.

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Conversions and Abbreviations

Multiply	By	To obtain
Millimeter (mm)	0.03937	Inch (in)
Centimeter (cm)	0.3379	Inch (in)
Meter (m)	3.281	Foot (ft)
Kilometer (km)	0.6214	Mile (mi)
Square kilometer (km²)	0.3861	Square mile (mi²)
Cubic kilometer (km³)	0.2399	Cubic mile (mi³)
Diameter (D)	Mega-annum (Ma)	million years ago
Magnitude (M)	annum or / an-Ma	

II. Sea Floor Disappears as Plates Sink Along Deep Ocean Trenches

Subduction zones occur where a plate created by sea-floor spreading comes together or converges with another plate by sinking (or subducting) beneath it. A deep trench typically forms on the ocean floor where the subducting plate bends downward toward the deep mantle (figs. 1–3). More than 75 percent of all earthquakes occur in subduction zones, by dip between plates and rupture within descending plates (called slabs), forming inclined zones to depths as great as 690 km below the surface. Huge amounts of oceanic crust (~20 km³/yr, or ~3 km³/yr of sea-floor and are consumed along trenches during subduction. As slabs sink deep into hotter mantle, they warm, lose most of their stored water, and eventually soften to a state incapable of producing earthquakes or earthquakes.

Subduction earthquakes have caused untold damage throughout human history, killing over 450,000 people in the past 40 years alone. This figure includes the effects of large shallow earthquakes that displace the sea floor, generating high-speed ocean waves (called *tsunamis*) that can travel great distances, devastating coastal communities (see fig. 4 and table 3).

The process of volcanic building begins with the initially cold slab descending into the hotter mantle, warming and dehydrating as the water it contains is "squeezed out." These low-density fluids rise from intense pressure, triggering partial melting of the hot, weak mantle above. Because this melted material (or *magma*) is less dense than the surrounding solid mantle, it rises buoyantly (or "floats"). Some of the magma accumulates in near-surface magma chambers, and some migrates to Earth's surface where it erupts and forms chains of volcanoes—called *island arcs* in oceans or *volcanic arcs* on land—that typically parallel the nearby trench (see schematic cross section, on front, and fig. 3).

Subduction-zone eruptions can be either explosive, producing airborne and ground-hugging fragmental deposits, or non-explosive, producing lava flows. Arc volcanoes built from both fragmental materials and lava flows typically have steep conical cones called *stratovolcanoes* (fig. 5). Volcanic arcs contain nearly 80 percent of historically active land volcanoes, including those producing some of Earth's most destructive eruptions (see table). Some island arcs, such as those north of New Zealand, have only isolated plate divergence behind them (back-arc spreading), and resemblies spreading at oceanic ridges (compare figure 4 and figure 6, on front).

During subduction, sediments and crustal rocks on the downgoing part of the downgoing slab can be scraped off (or accreted) to the upper plate. The sinking plate can also mechanically erode the bottom of the upper plate. Also the eroded material also can be added to the base of the overriding plate at greater depth (*subduction erosion*). Some oceanic lithosphere slabs beneath a continent, modified or formed by the continued processes of accretion, thickening by squeezing), underplating, and volcanism. South America, with its 9,000-km-long Andes mountain chain formed by these processes, producing Earth's highest volcanoes (see table 2).

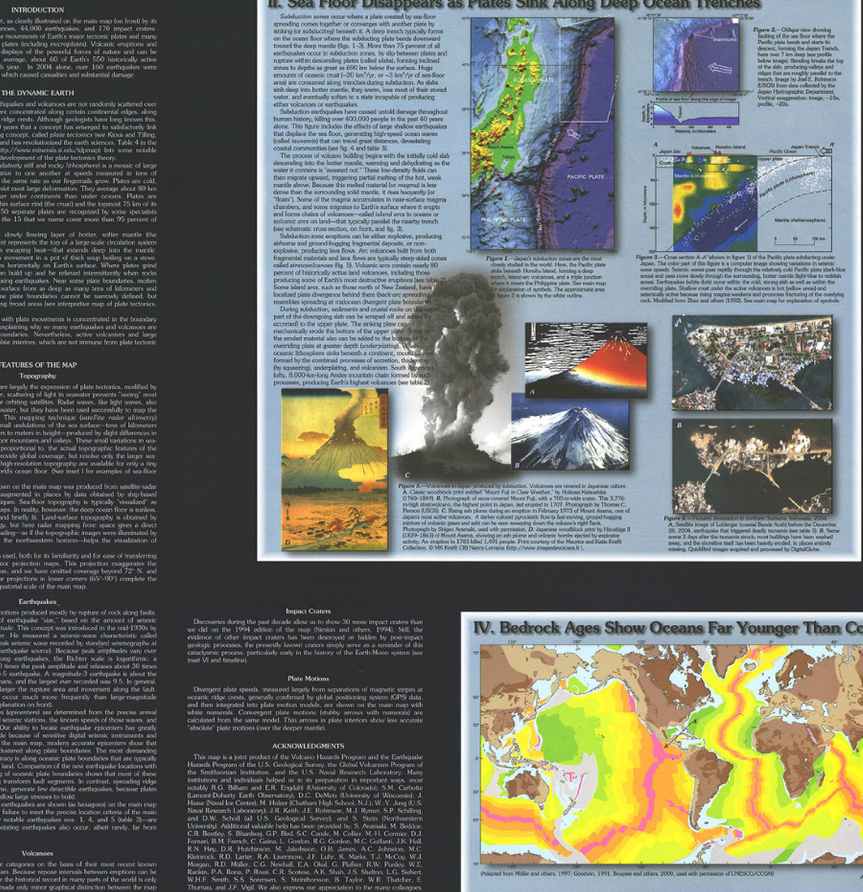

Figure 1.—Japan's subduction zones are the most closely studied in the world. Here, the Pacific plate slides beneath Honshu Island, forming a deep trench, island-arc volcanoes, and a thick section where it meets the Philippine plate. See main map for location of symbols. The approximate area of figure 2 is shown by the white outline.

Figure 2.—Oblique view showing faulting of the sea floor where the Pacific plate bends and starts to subduct beneath Honshu Island, Japan. Note more than 5 km of relief. Data below image. Bending breaks the top of the slab, producing valleys and ridges that are roughly parallel to the trench. Image by Joel C. Robinson (USGS) from data collected by the Japan Hydrographic Department. Vertical exaggeration: Image, ~10x; profile, ~20x.

Figure 3.—Cross section A–A' shown in figure 1) of the Pacific plate subducting under Japan. The color part of this figure is a computer image showing variations in earthquake wave speeds. Seismic waves pass rapidly through the relatively cold Pacific plate (dark-blue area) and pass more slowly through the surrounding, hotter mantle (light-blue to white) areas. Earthquakes (white dots) occur within the cold, strong slab as well as within the overriding plate. Such slabs are the source of most of the world's deep earthquakes and seismically active because rising magma weakens and processes fracturing of the overlying rock. Modified from Zhao and others (1992). See main map for explanation of symbols.

Figure 4.—Volcanoes in Iceland produced by subduction. Volcanoes are revered in Japanese culture. A. Classic woodblock print entitled "Mount Fuji in Clear Weather," by Hokusai Katsushika (1760–1849). Photograph of woodcut owned Mount Fuji, with a 700-m-wide crater. This 3,776-m-high stratovolcano, the highest point in Japan, last erupted in 1707. Photograph by Thomas C. Pamon (USGS). C. Steam and ash plume during an eruption in February 1973 of Mount Asama, one of Japan's most active volcanoes. A dense cold pyroclastic flow is fan-moving, ground-hugging mixture of hot rock debris and gas) is visible on the volcano's upper flank. Photograph by Shigeo Aramaki, with permission. D. Japanese woodblock print by Hiroshige (1829–1863) of Mount Asama, showing an ash plume and volcanic bombs ejected by explosive eruption. An eruption in 1783 killed 1,151 people. Print courtesy of the Museum of Natural and Rural Earth Collection. © MK Kraft/ CNI Nancy-Lorraine (http://www.imagendelcorsen.fr).

Figure 5.—Volcanoes in Japan. Mount Fuji, a classic stratovolcano, viewed from the Fuji Five Lakes area. Photograph by Hiroshi Ui (Hokkaido University).

Figure 6.—Iceland's Laki eruption (1783–84), one of the largest historical eruptions, produced 14 km³ of lava flows and 3 km³ of ash. Lava fountains reached 1,400 m high. Lava flows covered 565 km² of land, destroying 20 farms and killing 9,350 people, mostly from famine caused by the eruption's effects on livestock and crops. Photograph by Sigurdur Thorarinsson.

Figure 7.—Map showing the Yellowstone calderas and older volcanic centers (outlined in red). The northward-trending alignment and age progression of these centers are thought to represent the "volcanic trail" of a northward-moving hotspot fed by mantle plume. Modified from Pierce and Morgan (1992, pl. 1).

Figure 8.—Iceland (1,972 photograph, taken during the Heimen Surtsey, showing a fountaining fissure of water-and-steam jetting from Old Faithful Geyser in a region of Wyoming later designated as the first U.S. national park (Yellowstone). In periodic, powerful bursts of geothermal energy, contrast to seasonal park visitors. Photograph by William Henry Jackson.

Figure 9.—Volcanoes in Alaska. Mount Redoubt, a stratovolcano, viewed from the Kenai Peninsula. Photograph by Arnold Gardine (Bowman 1869–1942) taken about 1912, when the volcano was a single peak. Mount Redoubt has since lost its summit in a violent explosion. Photograph by Peter J. Lyon, 1966, used with permission of Fine Arts Museums of San Francisco, Museum Collection AGN62249.

Volcanoes
Japan Trench
Pacific Ocean
Japan Sea
Honshu Island
PACIFIC PLATE
Mantle (Asthenosphere)
A
A'
Depth, in k