

Figure 1.—The Hawaiian Islands form

Ridge-Emperor Seamount Chain,

volcanism (see text); red dots indicate

which was formed by intraplate

selected hotspots (see interpretive

map of plate tectonics, on front).

View prepared by Joel E. Robinson (USGS).

by Joel E. Robinson (USGS).

Figure 3.—A schematic cut-away view along the island chain,

showing the inferred mantle plume that has sustained the

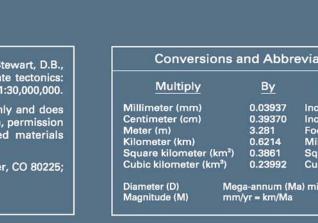
Hawaiian hotspot on the overriding Pacific plate. The geologic

ages of the oldest volcano on each island are progressively older

to the northwest, consistent with the hotspot model for the origin

of the Hawaiian Ridge-Emperor Seamount Chain. View prepared

the southeastern end of the Hawaiian



North America plate

distribution of ash-fall deposits from

three powerful caldera-forming

over the past 2 million year (Izett and Wilcox, 19

Inset (black outline) indicates the area shown

Most of Earth's active volcanoes are found along plate boundaries, but some

occur within plate interiors. The best examples of such intraplate volcanoes are

those of Hawaii, nearly 4,000 km from the nearest plate boundary (fig. 1). The

Hawaiian Islands are the above-sea-level summits of volcanoes that form the

southeastern end of the Hawaiian Ridge-Emperor Seamount Chain (figs. 1, 2).

the past 80 million years by the combined processes of magma formation,

eruption, and movement of the Pacific plate over a mantle source—called a

melting anomaly or hotspot—generally assumed to be relatively fixed in

when its position became fixed. Then the northwesterly plate movement

prevailed, forming the Hawaiian Ridge "downstream" from the hotspot.

position. The sharp bend in the chain (fig. 1) is still not well understood despite

intensive research. A recent explanation is that the northern segment (Emperor

Seamount Chain) formed as the hotspot migrated southward until about 45 Ma,

Many scientists attribute the Hawaiian and some other hotspots to narrow

nelting of the mantle produces new magma that collects into blobs that rise

sea floor. After many eruptions, the growing submarine volcano may emerge

above sea level as an island volcano. Continued movement of the Pacific plate

eventually carries each volcano away from the sustaining hotspot. Then,

eruptive activity stops, the volcano subsides as the plate cools and contracts,

submarine but growing Lō'ihi (figs. 2, 3)—presumably still lie above, and are

presently tapping, the Hawaiian hotspot. Midplate oceanic lavas are more fluid

than those that build stratovolcanoes along convergent plate boundaries; they

great distances from eruptive vents, form gently sloping shield volcanoes such

Intraplate volcanism also occurs in continental interiors. For example, the

cataclysmic eruptions (fig. 6)—each associated with caldera collapse—during

the past 2 million years. When an explosive eruption expels magma from a

subsurface reservoir, the overlying volcano may collapse into the resulting void,

leaving a shallow depression, or caldera, in place of the more familiar conically

thousands of kilometers from their source calderas (fig. 6). The Yellowstone

Ma). The geologic ages of the volcanic centers of the Snake River Plain are

America plate over a Yellowstone hotspot, presumably sustained by a long-

lived, relatively fixed, mantle plume. However, we emphasize that commonly

progressively older to the southwest (fig. 7). This age progression has been

geologically young (<17 Ma) volcanism that slashes across the Rocky

shaped volcano. Ash-fall deposits from these huge eruptions have been mapped

volcanic plateau lies at the northeastern end of the Snake River Plain, a zone of

Mountains, a mountain belt composed primarily of much older rocks (2,790–65

interpreted as resulting from volcanism associated with the passage of the North

held ideas such as rooting of thermal plumes deep in the mantle (>200 km) are

topics of ongoing scientific debate. Yellowstone's most recent volcanic activity

magmatic system are evident from its present-day spectacular expressions of

occurred about 70,000 years ago, but ground-deformation measurements

indicate that the caldera is restless. The dynamics of its still-hot subsurface

geothermal energy, including Earth's most active geyser system (fig. 8).

Yellowstone Volcano (Yellowstone National Park) has produced three

usually erupt nonexplosively, and some eruptions can last for decades (figs. 2,

4). Over geologic time, repeated outpourings of fluid lava, which can travel

as Hawaii's Mauna Loa (fig. 5).

eventually sinking below sea level to form a flat-topped seamount. Recently

active Hawaiian volcanoes—Kīlauea, Mauna Loa, and the present-day

plumes of hot, but not molten, material rising through the mantle (fig. 3). Partial

hrough the overriding plate and ultimately erupt to form a new volcano on the

severed from their feeding magma sources, the eruptions ultimately cease. Even

as a new volcano grows over the hotspot, it undergoes erosion. However, once

This 6,000-km-long, mostly submarine volcanic mountain range formed over

V. Eruptions Through Plate Interiors Build Hotspot Volcanoes

Pacific plate

Figure 2.—Oblique view of the principal Hawaiian Islands and (the still submarine) Lō'ihi Volcano. Inset gives a closer view of three

of the five volcanoes that form the Island of Hawai'i (historical lava flows are shown in red). The longest duration historical

eruption on Kīlauea's east-rift zone at Pu'u 'Ō'ō (inset), which began in January 1983, continues unabated (as of spring 2006).

PACIFIC PLATE

The Hawaiian Hotspot

INTRODUCTION Our Earth is a dynamic planet, as clearly illustrated on the main map (on front) by its opography, 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 of Earth's 550 historically active volcanoes are in eruption each year. In 2004 alone, over 160 earthquakes were

MORE ABOUT THIS MAP

THE DYNAMIC EARTH As the main map shows, earthquakes and volcanoes are not randomly scattered over it has been only in the past 40 years that a concept has emerged to satisfactorily link 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/minsci/tdpmap) 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 of its 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 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 relieved intermittently when rocks break or slide along faults, causing earthquakes. Near some plate boundaries, molten rock (magma) can rise to the surface from as deep as many tens of kilometers and erupt to form volcanoes. Some plate boundaries cannot be narrowly defined, but instead are diffuse, encompassing broad areas (see interpretive map of plate tectonics Most deformation 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 volcanism and large earthquakes also can occur in plate interiors, which are not immune from plate tectonic

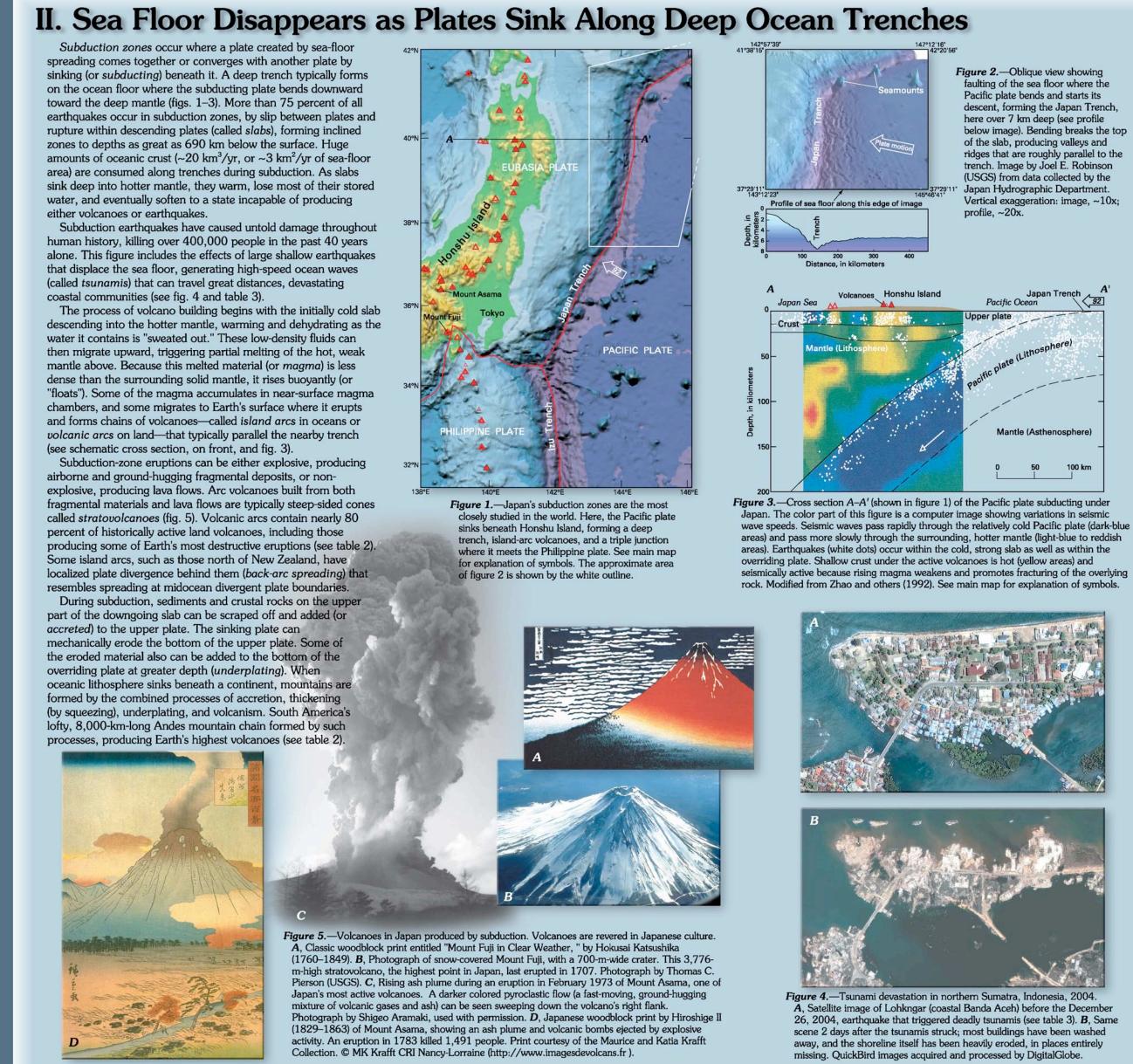
FEATURES OF THE MAP

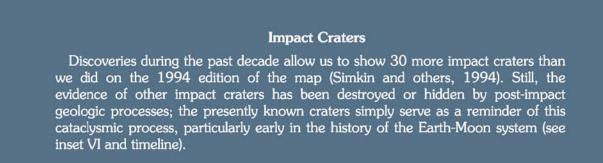
Earth's topographic features are largely the expression of plate tectonics, modified by ocean surface from satellites. This mapping technique (satellite radar altimetry) involves the measurement of small undulations of the sea surface—tens of kilometers surface height mimic, and are proportional to, the actual topographic features of the sea floor. Satellite-radar data provide global coverage, but resolve only the larger seafloor 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 Apping at various scales.)

The sea-floor topography shown on the main map was produced from satellite-radar and the sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor topography shown on the main map was produced from satellite-radar and sea-floor 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 and briefly lit. 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 at 20° above the northwestern horizon—helps the visualization of 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 we have omitted coverage beyond 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 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-1930s by eismologist Charles F. Richter. He measured a seismic-wave characteristic called *implitude* (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, Map 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 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 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 volcanism occurs along the

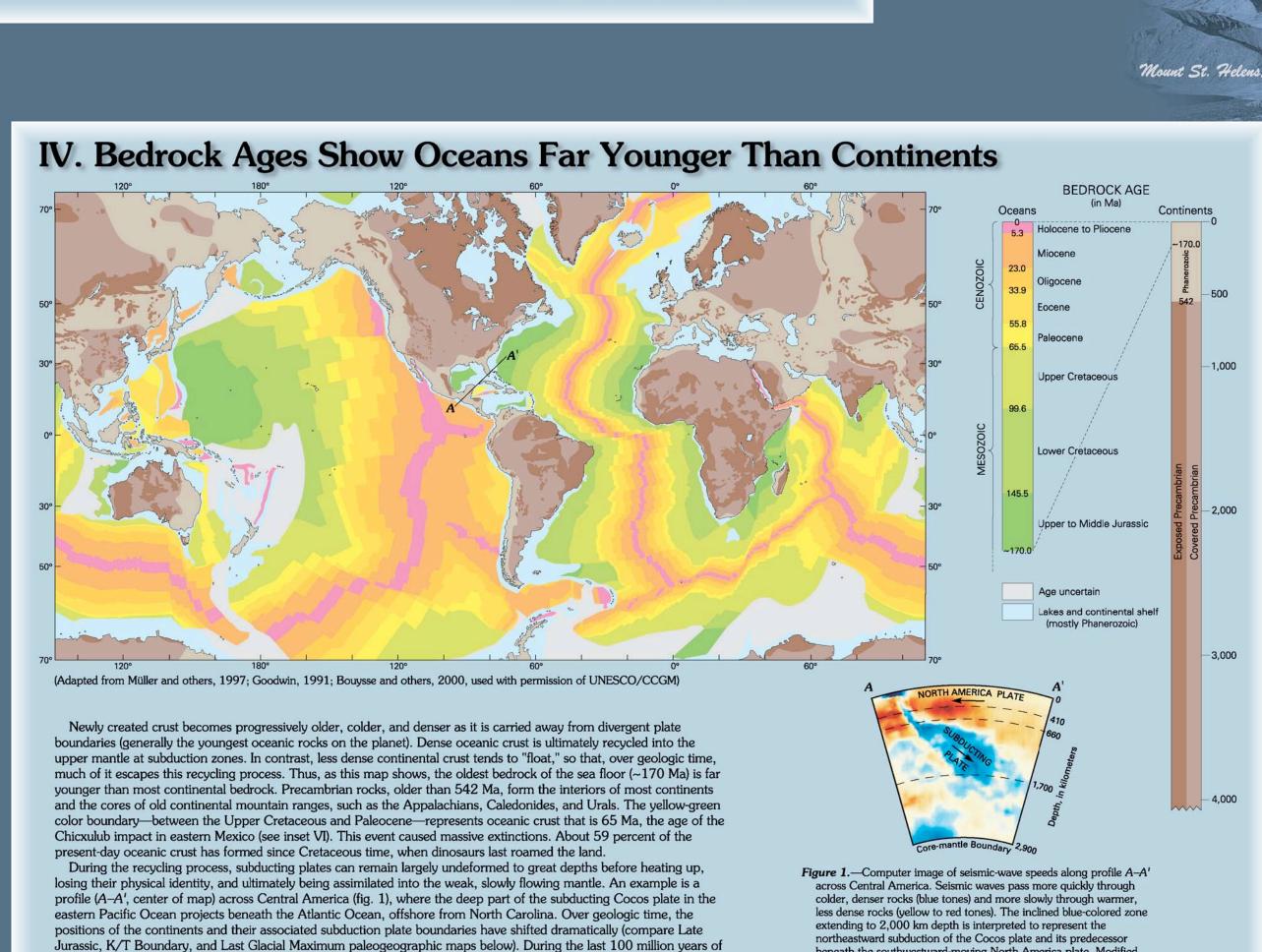


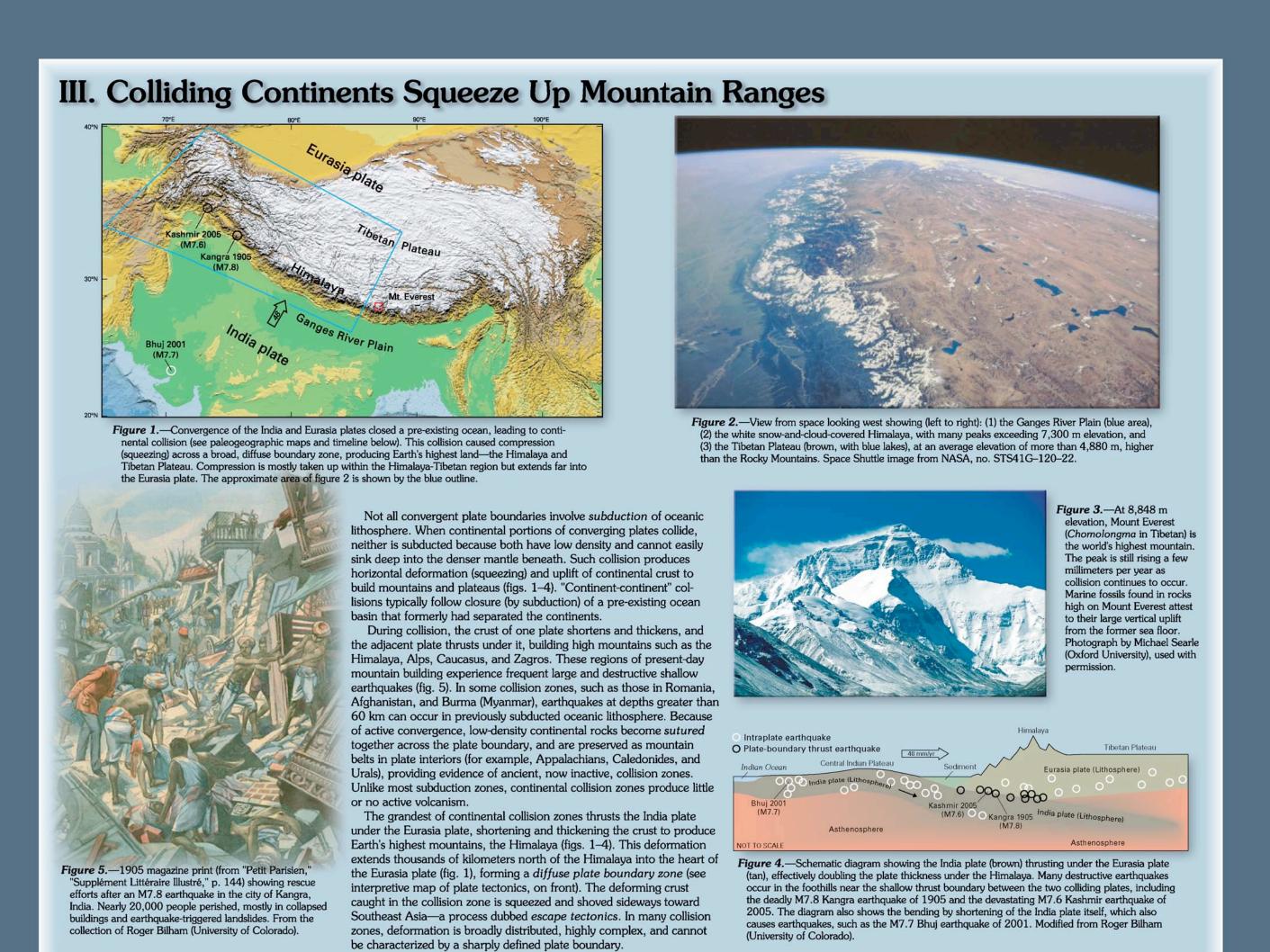


Divergent plate speeds, measured largely from separations of magnetic stripes at and then integrated into plate motion models, are shown on the main map with white numerals. Convergent plate motions (stubby arrows with numerals) are calculated from the same model. Thin arrows in plate interiors show less accurate "absolute" plate motions (over the deeper mantle).

This map is a joint product of the Volcano Hazards Program and the Earthquake Hazards Program of the U.S. Geological Survey, the Global Volcanism Program of the Smithsonian Institution, and the U.S. Naval Research Laboratory. Many institutions and individuals helped us in its preparation in important ways, most

notably R.G. Bilham and E.R. Engdahl (University of Colorado); S.M. Carbotte (Lamont-Doherty Earth Observatory); D.C. DeMets (University of Wisconsin); J. Hasse (Naval Ice Center); M. Holzer (Chatham High School, N.J.); W.-Y. Jung (U.S. Naval Research Laboratory); J.R. Keith, J.E. Robinson, M.J. Rymer, S.P. Schilling, and D.W. Scholl (all U.S. Geological Survey); and S. Stein (Northwestern University). Additional valuable help has been provided by: S. Aramaki, M. Beddoe, C.R. Bentley, S. Bhardwaj, G.P. Bird, S.C. Cande, M. Collier, M.-H. Cormier, D.J. Fornari, B.M. French, C. Gaina, L. Gordon, R.G. Gordon, M.C. Guffanti, J.K. Hall, R.N. Hay, D.R. Hutchinson, M. Jakobsson, O.B. James, A.C. Johnston, M.C. R.N. Hay, D.R. Hutchinson, M. Jakobsson, O.B. James, A.C. Johnston, M.C. R.N. Hey, D.R. Hutchinson, M. Jakobsson, O.B. James, A.C. Johnston, M.C. Kleinrock, R.D. Larter, R.A. Livermore, J.F. Luhr, K. Marks, T.J. McCoy, W.J Morgan, R.D. Müller, C.G. Newhall, E.A. Okal, G. Plafker, R.W. Purdey, W.E Rankin, P.A. Rona, P. Rossi, C.R. Scotese, A.K. Shah, J.S. Shelton, L.G. Siebert W.H.F. Smith, S.S. Sorensen, S. Steinthorsson, B. Taylor, W.R. Thatcher, E. Thurnau, and J.F. Vigil. We also express our appreciation to the many colleagues geoscience teachers, and students who provided thoughtful comments and helpful advice on how to improve the previous editions (1989, 1994) of this map and text.



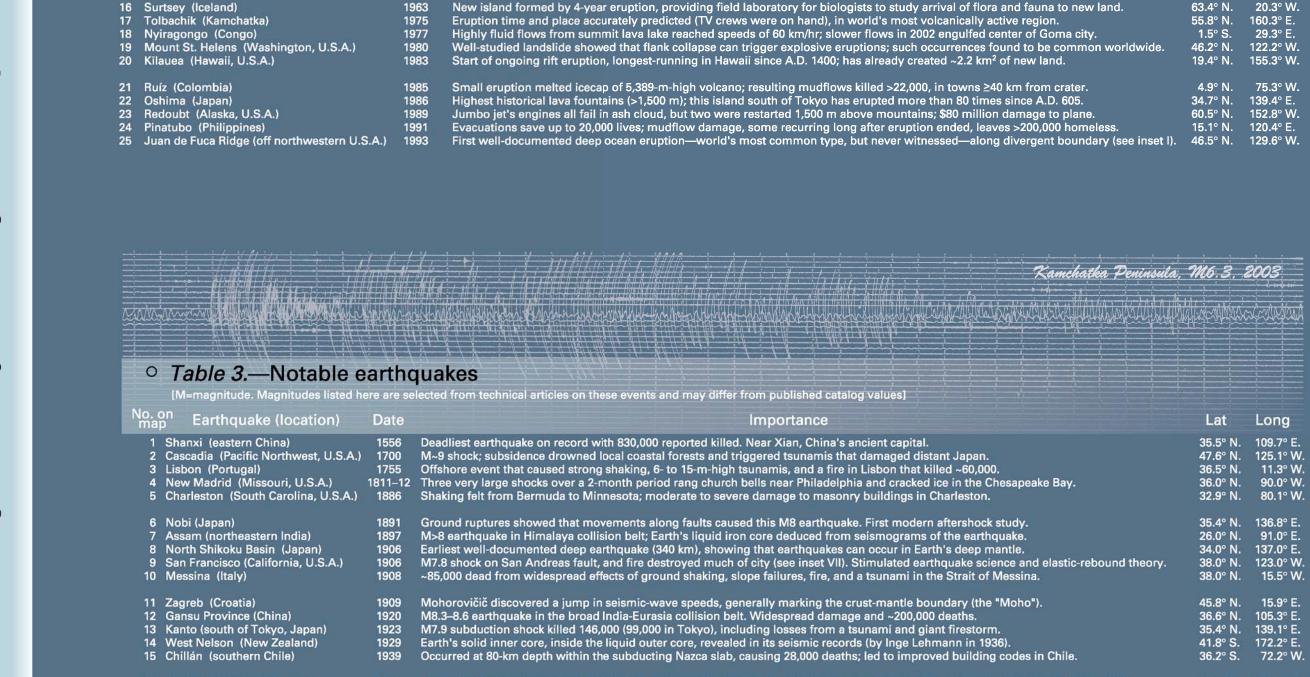


2 Santorini (Greece)
3 Etna (Italy)
4 Vesuvius (Italy)
5 Taupo (New Zealand)

11 Krakatau (Indonesia)

12 Montagne Pelée (West Indie:13 Santa María (Guatemala)

4 Novarupta-Katmai (Alaska, U.S.,



2 Ma Huge eruption (2,500 km³ of magma) blanketed western U.S. with ash (>2 cm in California, 1,500 km away; see inset V).

540±90 Explosive eruption formed caldera, later filled by the sea; regional volcano observatory established after 1937 eruption.

High-speed, incandescent pyroclastic flows kill 28,000 in minutes; response launched modern volcanology.

5,000 killed when volcano erupts after long repose; growth of lava dome began 20 years later and continues to date.

Largest 20th century eruption (including "Valley of Ten Thousand Smokes"); sound heard 1,200 km away.

Volcano birth in cornfield witnessed by farmers; cinder cone grows to 336-m height in first year, to 424 m by 1952.

Caldera collapse; 40-m-high tsunamis kill >34,000; explosions heard >4,500 km away; vivid sunsets.

1640 B.C. Bronze Age caldera-forming eruption influenced decline of Minoan civilization; tsunami may have inspired biblical flood legends.

1500 B.C. First historically documented eruption; Europe's largest volcano, Etna has been frequently active since.

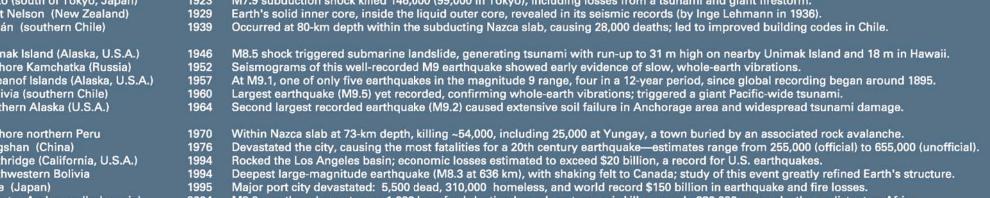
A.D. 79 Pompeii and Herculaneum buried; earliest known written account for any eruption, by Pliny the Younger.

16,000 km² (15 percent of North Island) devastated; only a tranquil caldera lake now marks the eruption site.

~700 World's highest active volcano, at 6,887 m; no known historical eruptions, but strong fumarolic activity.
 1783 Enormous lava flows; livestock poisoned by volcanic fluorine and 10,000 Icelanders starve; cooled Europe's climate.
 1792 Japan's deadliest eruption; collapse of dome produced debris avalanche and tsunami, killing 14,500.
 1815 Largest historical explosive eruption, resulting in ~60,000 deaths and 1816's "year without summer" (June snow in New England!).

14.8° N. 91.6° W.

61.1° N. 147.6° W.





Plates slide horizontally past each other along transform plate boundaries. Transforms

occur both on land and in the ocean basins, linking spreading ridges and other plate

boundaries. They typically produce shallow earthquakes, with accompanying ground

faulting and generally little or no volcanic activity. Two well-known continental examples

are the North Anatolian fault (Turkey) and the San Andreas fault system (California). The

interpretive map of plate tectonics, on front); this and similarly broad zones elsewhere also

can be described as consisting of one or more *microplates*. Although most of the motion

substantial movements also involve many smaller faults in a wide zone from western Nevada

many damaging earthquakes, including the famous M7.8 San Francisco shock of 1906 (fig.

3), the M7.1 Imperial Valley earthquake of 1940 (fig. 4), and the M6.7 Northridge jolt

The surface expressions of continental transform plate boundaries depend

largely on the orientation of the boundary in relation to the direction of plate

motion across the boundary. For the San Andreas system, faults that veer

to the left (or to the west when looking north) of the direction of Pacific

thus forming mountains such as the Transverse Ranges in

plate motion produce compressive (squeezing) deformation and uplift,

southern California (figs. 1, 2). This deformation also splinters

the western fringe of the North America plate, forming a

microplate extending from the San Andreas fault to

smaller faults east of the Sierra Nevada. Conversely,

extensional ("pull-apart") deformation and

subsidence, producing topographic lows

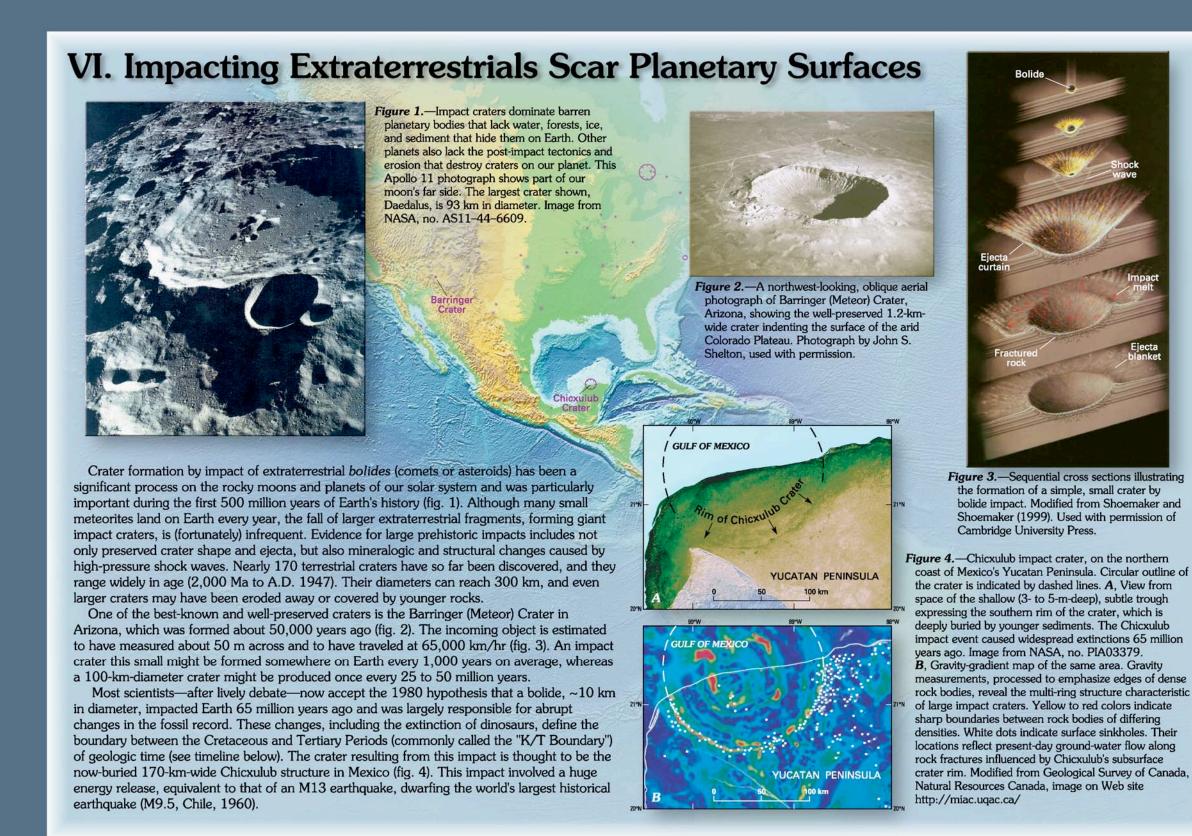
fault segments that veer to the right cause

between the North America and Pacific plates occurs along the San Andreas fault itself,

to offshore California (figs. 1, 2). Sudden movements within this system have produced

of 1994 (table 3, no. 23).

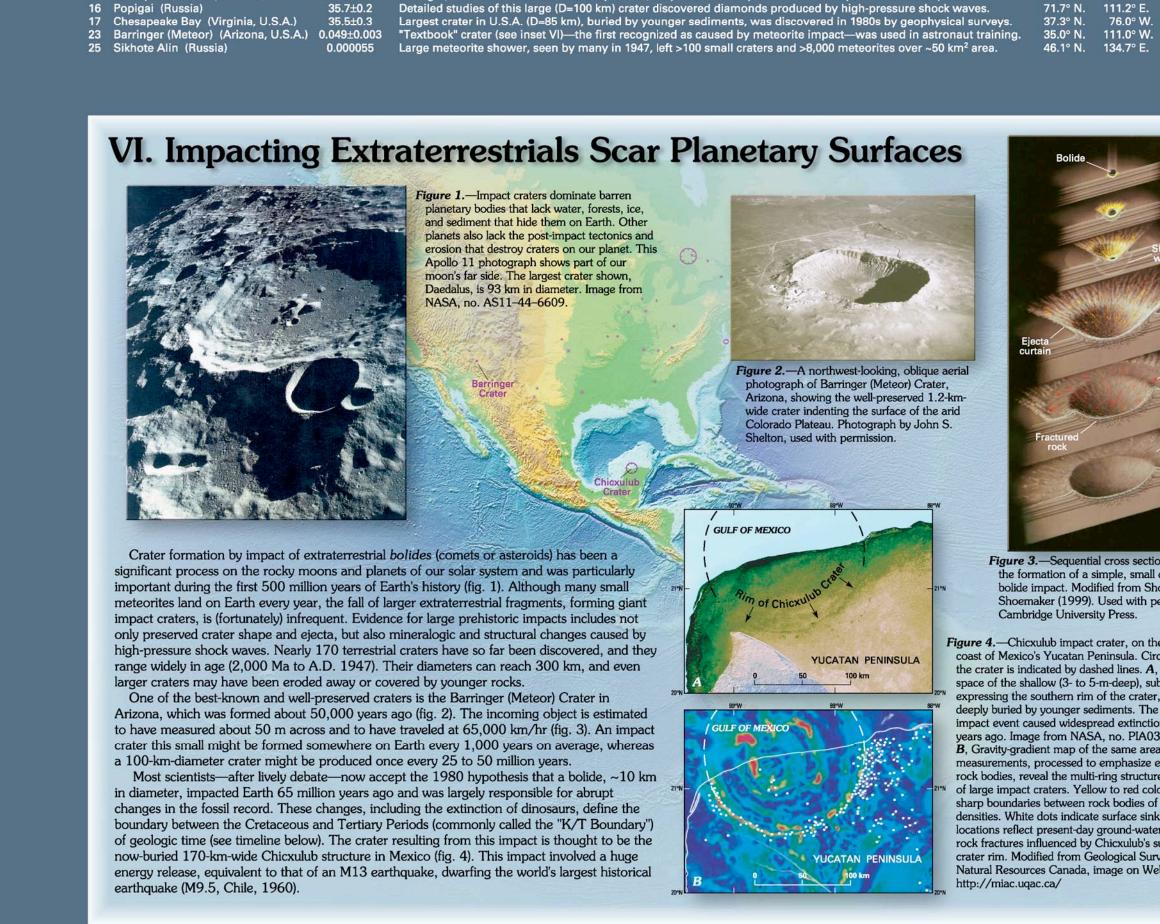
San Andreas system is a family of related faults in a diffuse plate boundary zone (see



Farly mammals Beginning of rifting between North America and Africa Oldest rock known from

37.2±1.2 Younger, smaller crater inside Sudbury (no. 3); only known example of a second impact in the same place.

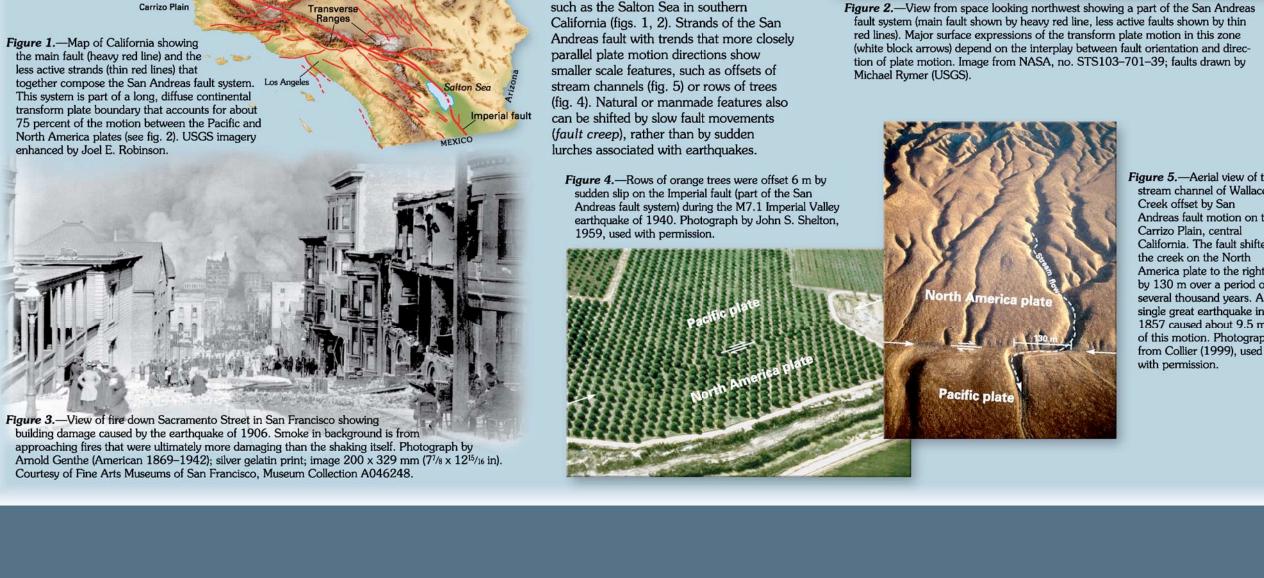
eastward subduction under the Americas, the positions of the active plate boundaries have gradually shifted westward

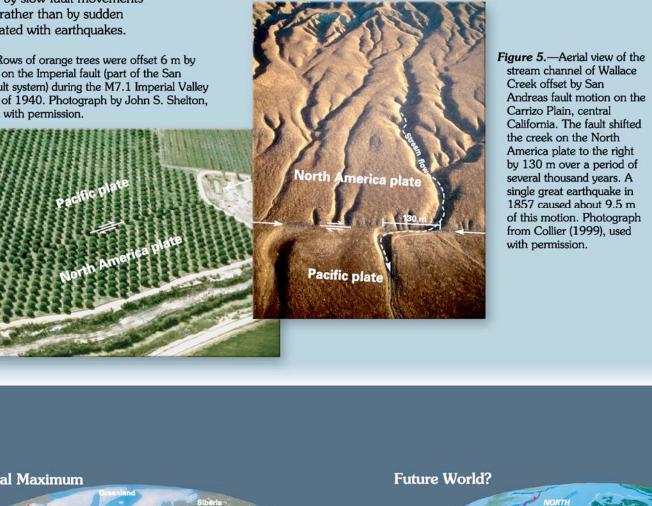


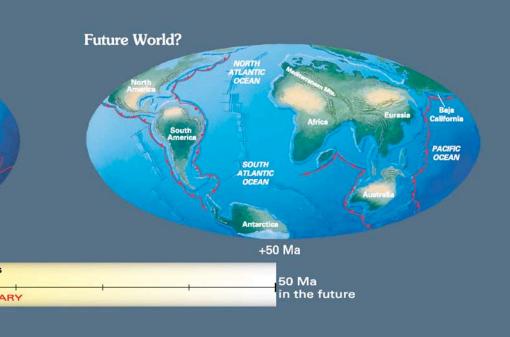
by more than 1,000 km.

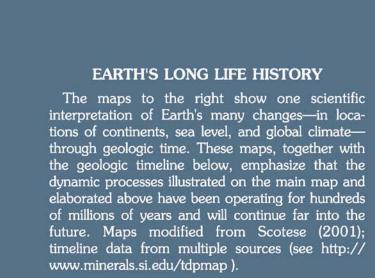
13 Chicxulub (Mexico) 64.98±0.05 Produced K/T (dinosaur) extinction event and global ejecta (with "fingerprint" iridium layer); see inset VI.

14 Montagnais (Nova Scotia, Canada) 50.50±0.76 First crater recognized at sea (buried on continental shelf); nearly all other known craters are on land.









illion years ago (Ma)

600 million years ago (Ma)

Series GVP-3. (Available online at http://www.volcano.si.edu/world/

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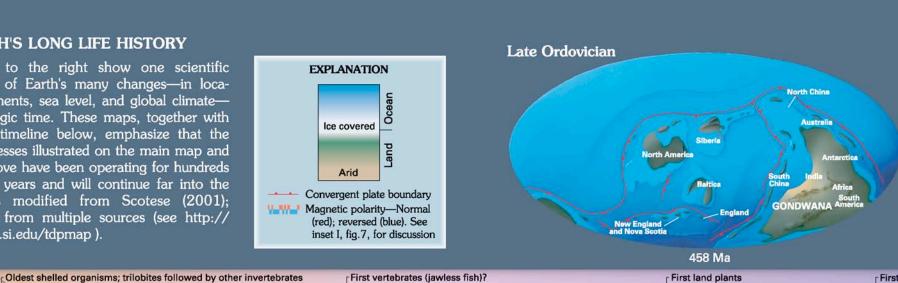
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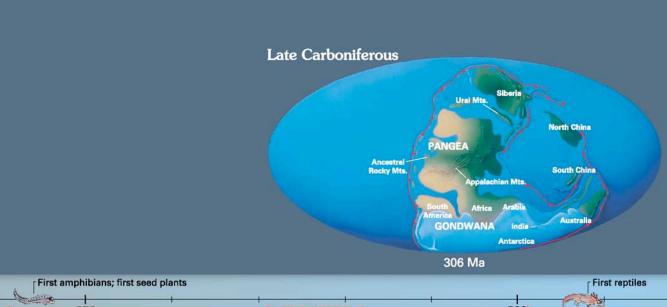
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Paris, Commission for the Geological Map of the World and UNESCO, 3 sheets, scale 1:25,000,000.







Mauna Loa, a classic shield volcano, as

viewed from the Hawaiian Volcano Observatory. Photograph by Robert I.

gure 4.—A high lava fountain

helicopter (circled) gives scale.

olcanoes National Park).

Figure 7.—Map showing the Yellowstone caldera and older

volcanic centers (outlined in red). The southwest-trending

represent the "volcanic trail" of a continental hotspot fed by a

mantle plume. Modified from Pierce and Morgan (1992, pl. 1.)

Figure 8.—Historic (1872) photograph, taken during

the Hayden Survey, showing a towering fountain of

water and steam jetting from Old Faithful Geyser in a

region of Wyoming later designated as the first U.S.

national park (Yellowstone). Its periodic, powerful

bursts of geothermal energy continue to fascinate

park visitors. Photograph by William Henry Jackson.

alignment and age progression of these centers are thought to

etting from the Pu'u 'Ō'ō vent on Kīlauea's east-rift zone in 1984;

Photograph by Mardie Lane (Hawaii









beneath the southwestward-moving North America plate. Modified

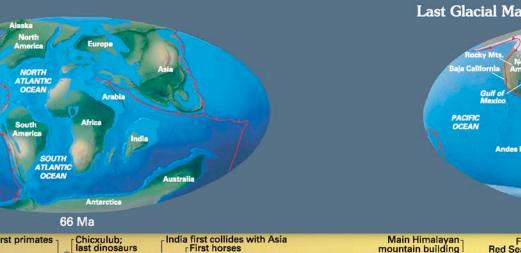
San Francisco

PACIFIC OCEAN

100 200 km

from Kárason and van der Hilst (2000). Used with permission of

American Geophysical Union.



See expanded timeline above

50

Peak of banded iron formation (95 percent are 1,900 to 2,500 Ma)

First microbial structures (Gunflint Formation) (Northwest Territories, Canada)

Meteoric bombardment of Moon forms major craters, many of which are later filled with mare basalt Birth of Solar System, 4,566±2 Ma; accretion over first ~8 Ma, Earth formed over first ~120 Ma Cooling of lunar mantle ends voluminous volcanism on Moon Oldest megascopic algae Explosion of multicellular life First stromatolites End of oxygen-poor atmosphere Youngest lunar volcanism