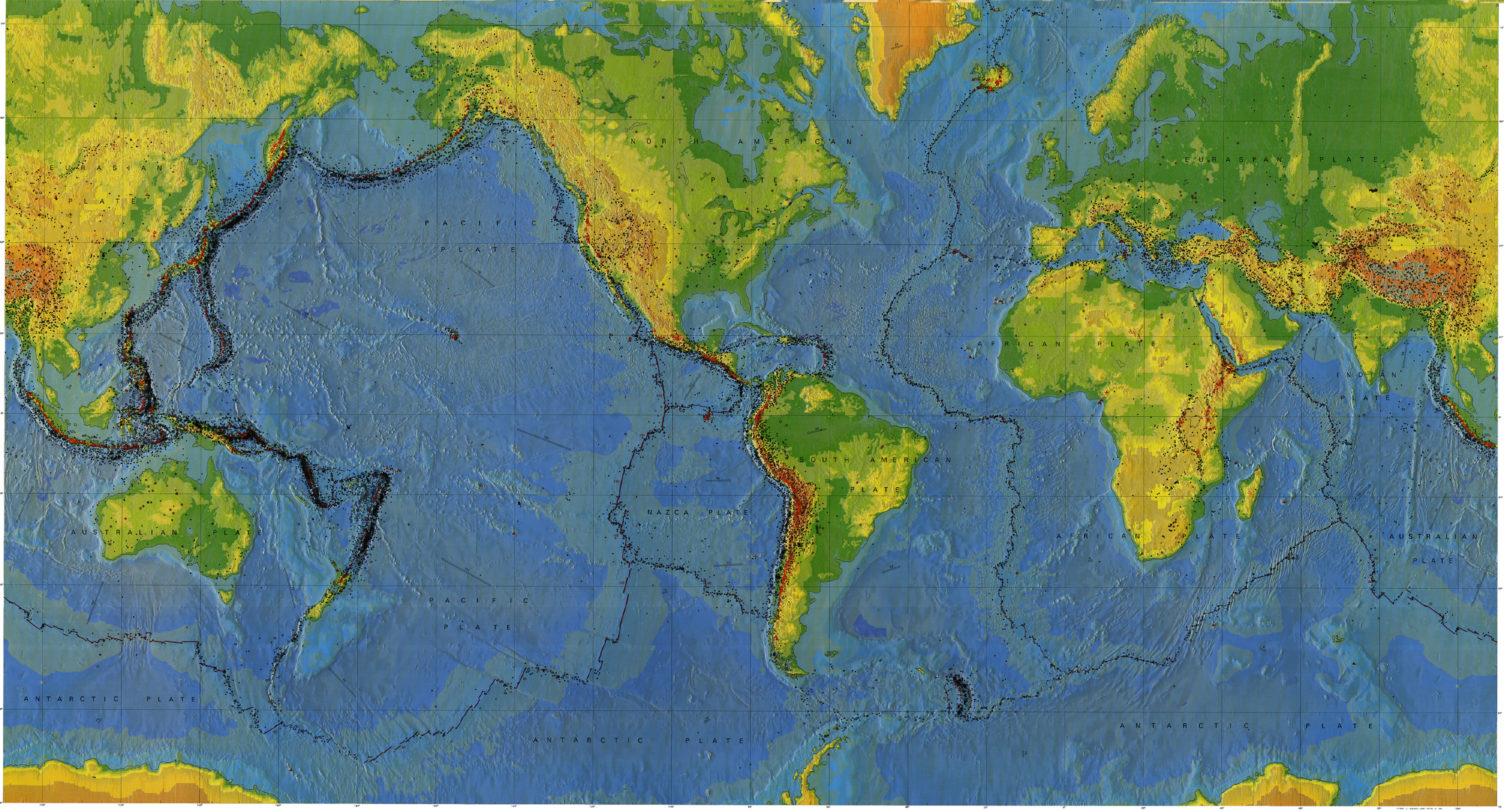

NOTE

This map shows the Earth's physiographic features, the current movements of its major tectonic plates, and the locations of its volcanoes, earthquakes, and impact craters. The use of color and shaded relief helps the reader to identify significant features of the land surface and the ocean floor. Over 1500 volcanoes active during the past 10,000 years are plotted on the map in four age categories. The locations (epicenters) of over 24,000 earthquakes, largely from 1960 through 1990, are plotted in three magnitude categories and in two depth ranges.

The map is intended as a teaching aid for classroom use and as a general reference for research. It is designed to show prominent global features when viewed from a distance and more detailed features upon closer inspection.

INTRODUCTION

Volcanic eruptions and earthquakes are awe inspiring displays of the powerful forces of nature and can be extraordinarily destructive. Some societies have been devastated by them. About 60 of the Earth's 550 historically active volcanoes are in eruption each year, but far more volcanism takes place unobserved on the ocean floor. Steady earth movements often culminate in rock fractures that produce earthquakes. In 1992 alone, 86 earthquakes worldwide exceeded magnitude 6.5 on the Richter scale, and many of them caused extensive damage.

The world's earthquakes and volcanoes are not randomly scattered over the Earth's surface. Most of them are concentrated along the edges of certain continents (for example, the western margins of the Americas), along island chains (for example, Japan and the Aleutians), or along oceanic ridge crests (for example, the Mid Atlantic Ridge). Although geologists have long known this, it is only in the past 30 years that a concept has emerged to satisfactorily link these observations. The concept, called *plate tectonics*, is now widely accepted and has revolutionized the earth sciences.

Earth is a dynamic planet. Its outermost shell (the *lithosphere*) is a mosaic of a dozen or so large, rigid slabs of rock (called *lithospheric* or *tectonic plates*) that move relative to one another at speeds measured in centimeters per year—or about the same rate as our fingernails grow. The plates average about 80 kilometers (km) thick and are composed of the Earth's relatively thin surface rind (the *crust*) and the topmost 60-75 km of its 2,900 km thick *mantle*. The lithosphere is generally thicker under the continents than under the oceans.

The plates move very slowly on top of a flowing layer of hotter, softer mantle (the *asthenosphere*) several hundred kilometers thick. 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 can be imagined as the sluggish movement in a pot of thick soup boiling on a stove, and this movement transports the plates horizontally on the surface. Where the plates grind against each other, stress builds up and is relieved intermittently through earthquakes when rocks break along *faults*. Near plate boundaries, molten rock (*magma*) rises to the surface from as deep as tens of kilometers and erupts to form volcanoes.

The geologic processes associated with plate movements are concentrated in the narrow boundary zones between the shifting plates. This explains why most of our restless planet's earthquakes and volcanoes are found along or near plate boundaries. Nevertheless, some very active volcanic areas and large earthquakes also occur in the plate interiors.

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DISTRIBUTION OF VOLCANOES AND EARTHQUAKES

Divergent Plate Boundaries

The process of adjacent plates moving away from each other is best seen at the oceanic spreading ridges. These submarine features are impressive mountain ranges that are locally just as rugged and high as any above sea level, and they can be traced for tens of thousands of kilometers. Oceanic spreading ridges can be swells (broad domes) up to 1,000 km across, and some crests are marked by a central trough or rift valley where plates are separating. New ocean floor is produced along the spreading ridges as magma from the Earth's mantle rises into their crests (axes) to form new oceanic crust. This adds about 15-20 cubic kilometers of new oceanic crust each year. About an equal volume of old crust is lost each year along convergent plate boundaries so that the overall size of the Earth stays the same.

Almost all of the world's divergent plate boundaries, and the abundant volcanism along them, lie beneath the oceans. An exception is Iceland, where the ocean ridge is exposed on land, defined by zones of active volcanoes marking the spreading boundary between the North American and Eurasian plates. An estimated three quarters of all the lava erupted on Earth each year pours out along the oceanic spreading ridges.

Earthquake activity along the oceanic spreading ridges is neither as strong, nor as deep, as at convergent plate boundary zones. The reason is that the younger, hotter lithosphere is very thin and weak, and stresses cannot build up enough to cause large earthquakes.

Pulling apart of the lithosphere may also occur on a smaller scale within a plate, creating zones of localized divergence, as shown, for example, by the rift valleys of East Africa. Here, narrow blocks of crust have been dropped down by faulting, and the rift is widened by magma injected from below the valley floor. Volcanoes such as Kilimanjaro are the visible result of this process, and shallow earthquakes occur along the edges of the rift valleys. The East African rift valleys may eventually develop into a young ocean basin, such as the Red Sea to the north.

Convergent Plate Boundaries

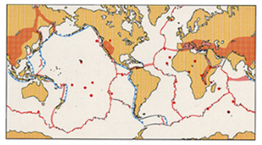
Most convergent plate boundaries are called subduction zones because one of the plates moves down, or is subducted, beneath the other. Often a deep trench forms on the ocean floor where the subducting plate begins its descent. Earthquakes are common in the subduction zone, particularly within the sinking lithospheric slab, thereby producing an inclined zone of earthquakes that dips into the Earth's upper mantle typically at angles of 40-60° from the horizontal. Earthquakes can occur at any depth within the sinking slab, from shallow (0-60 km) to as great as 700 km. Over three quarters of the world's earthquakes take place at convergent plate boundaries.

As the subducted lithosphere moves deeper into the hot mantle, its fluids are "sweated out" and rise, triggering partial melting within the overlying mantle. The new magma is less dense than the surrounding rock and ascends buoyantly, some of it erupts on the Earth's surface to form a line of volcanoes. Such volcanoes typically are steep sided cones called stratovolcanoes that erupt explosively. Nearly four-fifths of the Earth's historically active volcanoes are found near convergent plate boundaries.

An excellent example of a convergent boundary is that between the Nazca plate and the South American plate. The South American plate has been deformed and thickened to form the Andes. The downgoing Nazca plate forms the deep Peru-Chile trench and continues eastward beneath South America (as shown on the map by the deeper earthquakes to the east of the shallow ones). Magma, released by partial melting above the sinking Nazca plate, rises to form many volcanoes along the Andes, the backbone of the South American continent. Where the plate descends at a very shallow angle, as shown by the deep earthquakes unusually far from the trench (for example, in northern Peru and central Chile), partial melting is inhibited and no active volcanoes are present.

At other convergent plate boundaries, such as the Aleutian trench in Alaska, subduction results in a curved chain of submarine volcanoes or volcanic islands (called an *island arc*) behind the oceanic trench. Extensive island arc-trench systems also exist in much of the western Pacific. Several of these subduction zones also show localized divergence behind the arc, known as back arc spreading (for example, the Marianas Bonin arc).

Convergence may also force two continents together, as illustrated by the boundary between the Indian and Eurasian plates. Continental lithosphere is not as dense as oceanic lithosphere and resists subduction into the Earth's interior. The collision of India with Asia has doubled the thickness of continental crust in that region and produced the highest elevations on Earth in the Himalayas and Tibetan Plateau. Continent to continent convergence produces shallow and inter- [illegible]



Divergent plate boundaries—Where new crust is generated as the plates pull away from each other.

Convergent plate boundaries—Where crust is consumed in the Earth's interior as one plate dives under another.

Transform plate boundaries—Where crust is neither produced nor destroyed as plates slide horizontally past each other.

Plate boundary zones—Broad belts in which deformation is diffuse and boundaries are not well defined.

Selected prominent hotspots

The map shows a broad belt of abundant earthquake activity in the Himalayas, extending across central Asia to the Caucasus Mountains and on to the Mediterranean Sea. In this geologically complex region, much of the activity occurs between smaller plate fragments called microplates.

Convergent and divergent plate margins are natural complements. New crust is formed at the spreading ridges and is then rafted away to either side of the ridges. Old parts of the lithosphere, generally far away from the spreading ridges, are eventually consumed by subduction in a natural "recycling" process; consequently no oceanic crust is older than about 200 million years. As the subducting plate sinks deeper into the hot mantle, it softens to a state incapable of producing earthquakes by brittle fracture. It ultimately loses its identity altogether and merges into the deeper mobile mantle that convectively flows back toward the spreading ridges.

Transform Plate Boundaries

Plates slide horizontally past one another along transform boundaries. A well known example is the San Andreas fault, California. In places, the friction between the plates is so great that tremendous rock stresses can build up before being intermittently relieved by large earthquakes (for example, San Francisco, 1906). Transform boundaries typically produce shallow earthquakes and accompanying ground faulting, rather than volcanic activity. Many transform faults horizontally offset the divergent plate boundaries. The oceanic *fracture zones* formed in this way are outlined by shallow earthquakes where the segments are offset and produce the step like plate margins so prominent on the map. Some fracture zones are enormous ocean floor valleys that are hundreds of kilometers long and up to 8 km deep.

Volcanoes in Plate Interiors

Some active volcanoes, such as those making up the island of Hawaii, are located nearly 3,000 km from the nearest plate boundary. These Hawaiian volcanoes are above sea level summits at the southeastern end of a vast submarine volcanic mountain chain. This chain formed during the last 70 million years by the continuous northerly (and then northwesterly) [illegible]

called a hotspot. These features are thought by many geologists to be caused by long, thin convection plumes rising through the mantle. In the overlying plate, partial melting produces new magma that collects into blobs that rise and ultimately erupt to form a new volcano on the sea floor. During perhaps a million years and countless eruptions, the submarine volcano may grow large enough to emerge above sea level as an island volcano. Such midplate oceanic lavas are more fluid than those building stratovolcanoes along convergent plate boundaries; they usually erupt nonexplosively and form gently sloping shield volcanoes such as Hawaii's Mauna Loa. Continued northwestward movement of the Pacific plate eventually carries each volcano away from the underlying hotspot. Then, severed from its feeding magma source, the volcano ultimately dies. Even as a new volcano grows over the hotspot, the forces of erosion slowly wear a volcanic island down; it then gradually sinks below sea level and forms a flat topped seamount.

Active volcanoes in Hawaii, like Kilauea and Mauna Loa and the nearby offshore (submarine) new volcano called Loihi, currently lie above the Hawaiian hotspot. In many thousands of years, Loihi may grow above sea level to become the next island in the Hawaiian chain.

Intraplate volcanism also occurs in continental interiors. For example, the spectacular geothermal system at Yellowstone National Park, Wyoming, is the product of volcanic activity over a hotspot in the mantle below.

Earthquakes in Plate Interiors

Earthquakes in plate interiors are far less common than those near plate margins, but they can be devastating. Most lithosphere in midplate regions is geologically old and stiff, allowing very high stress levels to build up before rupturing in a large earthquake. Intraplate earthquakes greater than magnitude 7.5 have occurred in the central and eastern United States (Missouri in 1811-12 and South Carolina in 1886) and in Asia.

PREPARATION OF THE MAP

Base Map

The base map is derived from an unpublished revision of a computer generated, color coded, shaded relief map of the world originally prepared in 1986 by the National Geophysical Data Center, National Oceanic and Atmospheric Administration.

The topography is based on digital land and sea floor elevations taken from a worldwide gridded database that has a grid spacing of 5 minutes of latitude by 5 minutes of longitude. These data were then computer plotted on a Mercator map projection, according to a raster format system (rows and columns of picture elements or pixels) and shaded as if the topographic surfaces were illuminated at a sun elevation of 20° above the western horizon. Each pixel represents one 5-minute data rectangle, and color tones show the ranges of elevation and ocean depth; at the equator, the pixels are about 9 km (5 nautical miles) on edge.

Shorelines shown as black lines on the map are the actual boundaries between land and water on the Earth's surface. However, these shorelines do not always match the color-coded computer boundaries as, for example, the inland lakes and seas where color coding does not reflect water, but elevation above sea level. Ocean shorelines may also fail to match the blue-green color boundary because the digital elevations used for color coding represent averages over 5 minute square areas. The computer does not detect the precise land water boundary from these averaged elevations.

Mercator map projection is used, both for its familiarity and for the user's ease of transferring information from other Mercator maps. This projection exaggerates the relative size of high latitude areas, and we have omitted coverage above 72° N and below 70° S. This restriction in coverage excludes only 1% of the world's Holocene volcanoes, less than 1% of its 1960-90 [illegible]

VOLCANOES—(from the Global Volcanism Program, Smithsonian Institution, Washington, D.C.)

- Erupted A.D. 1900 through 1993
- Erupted A.D. 0 to A.D. 1900
- Holocene eruptions (within past 10,000 years), B.C. and undated A.D. eruptions
- Uncertain Holocene activity and fumarolic activity

IMPACT CRATERS—(from R.A.F. Grieve)

- Crater—Geologic age span: 1,000 years to 2,000 million years

PLATE TECTONICS

Divergent (spreading) and transform boundaries.—Red line marks spreading centers where most of the world's volcanism takes place; thickness of line indicates divergence rate, in four velocity ranges. Red number is speed in millimeters per year from DeMets and others (1990). The four spreading rates are: less than 30 mm/year, 30-60 mm/year, 60-90 mm/year and more than 90 mm/year. Thin black line, dashed where uncertain, marks the plate boundary whether spreading center or transform fault.

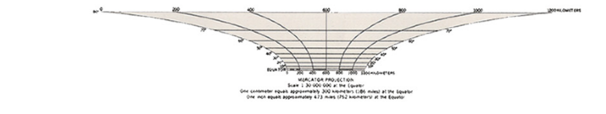
Plate motion (after Gripp and Gordon, 1990).—Length of arrow is proportional to the plate motion in millimeters per year at that location, calculated relative to hotspots that are assumed to be fixed in the mantle below the plates.

EARTHQUAKES—(from the National Earthquake Information Center, U.S. Geological Survey, Denver, Colorado) Magnitude for each event is the largest estimate available on file.

Magnitude = 4.0-5.4 (1960-1990)
- 0-60 km in depth
- > 60 km in depth

Magnitude = 5.5-6.9 (1960-1990)
- 0-60 km in depth
- > 60 km in depth

Magnitude > 7.0 (1897-1990)
- 0-60 km in depth
- > 60 km in depth



THIS DYNAMIC PLANET

WORLD MAP OF VOLCANOES, EARTHQUAKES, IMPACT CRATERS, AND PLATE TECTONICS

Compiled by

Tom Simkin[1], John D. Unger[2], Robert I. Tilling[2], Peter R. Vogt[3], and Henry Spall[2]

[1]Smithsonian Institution, [2]U.S. Geological Survey, [3]U.S. Naval Research Laboratory

Cartography by James E. Queen, Will R. Stettner, and Paul Mathieux

Oceanic Plate Boundaries Mapped from Outer Space

Most of the world's plate boundaries are covered by oceans. One of the best ways of mapping these remote, submerged boundaries is by using satellites to measure the shape of the Earth. In doing this, scientists use the concept of a geoid—a hypothetical surface around the entire globe determined by the Earth's gravity. The geoid approximates the ocean surface and, beneath continental areas, can be visualized as the extension of sea level underground. However, the geoid departs measurably from the smooth ellipsoidal shape assumed for the Earth. Influenced by local gravitational forces, the geoid is warped upward where there is extra rock mass below the ocean floor—for example, above oceanic spreading ridges—or warped downward where there is less rock mass, such as above a deep trench. The amount of this ocean "bumpiness," which can be as great as a meter vertically over tens of kilometers, has been mapped precisely by the GEOSAT satellite. Pulses of microwave radar energy are emitted by the satellite and reflected from the ocean surface. The round trip travel times of these reflected pulses were measured with great accuracy and, when combined with precise knowledge of the satellite's orbit, yielded the detailed shape of the ocean geoid. This in turn revealed the topography of the ocean floor below. These satellite based, indirect measurements of submarine topography reveal the rift valley along the crest of many oceanic ridges, as well as fracture zones, and thus make possible the precise location of submarine divergent plate and transform boundaries. These locations are published here for the first time. Where spreading is too fast to develop an axial rift valley, a small topographic (and geoid) high marks the spreading axis. Some boundaries, not identifiable from geoid data, were mapped using ship based surveys and other sources.

Size of an Earthquake

The most common measure of earthquake "size" is based on the actual amount of seismic vibration energy released and is called earthquake magnitude. It is determined by seismic wave characteristics, principally amplitude or half the height of the seismic wave recorded by seismographs at varying distances from the earthquake. The concept of earthquake magnitude was introduced in 1932 by the noted seismologist Charles F. Richter.

The Richter scale is logarithmic. A magnitude 6 earthquake releases approximately 30 times more energy than a magnitude 5 earthquake. Because Richter chose magnitude 0 arbitrarily, an earthquake smaller than magnitude −1 (minus one, or the energy released by a 1 kilogram brick dropped from approximately 200 m) can be recorded by highly sensitive seismographs located close to its source. In general, a magnitude 3 earthquake is about the smallest that can be felt by humans. Studies worldwide show that small magnitude earthquakes occur much more frequently than large ones. For example, about 6,000 earthquakes of magnitude 4 occur each year, on average, but earthquakes of magnitude 8 occur only about once a year.

Even though the Richter scale has no upper or lower limits, magnitudes as great as 9 have not been recorded historically on Earth. Such large earthquakes are not probable because rocks are not strong enough to build up the required stresses; they are likely to rupture at lower stress levels and produce a lower magnitude earthquake.

Selection of Earthquake Epicenters

The earthquakes plotted on the map are from a CD ROM database published by the National Earthquake Information Center. All earthquakes of magnitude 7.0 and larger that occurred between 1897 and 1990 were identified from the published catalogs. Prior to 1960, the distribution of seismograph stations around the world was not sufficiently dense or uniform to assure detection of all events in the magnitude range 4.0-6.9. However, earthquakes in this range after 1960 total more than 130,000, and plotting all of them would have obliterated the target earth- [illegible]

All events in the magnitude range 5.5-6.9 were plotted, but for the huge number in the magnitude range 4.0-5.4, the following scheme was used. The entire Earth surface was divided into a grid of 1/2° × 1/2° "bins", and earthquakes were selected for plotting only if a larger event had not already been plotted in that same "bin". By this scheme, only 22,540 events in the magnitude range 4.0-6.9 are plotted on the map. Characterization of the maximum earthquakes in any area remains accurate. (Included in the earthquake files are certain nuclear explosions that worldwide seismographs do not distinguish from earthquakes.)

IMPACT CRATERS

Cratering by impact of extraterrestrial comets or asteroids (bolides) has been a significant process on the rocky moons and planets of our solar system. Impact cratering was particularly important during the first 500 million years of the Earth's history. Although many small meteorites land on Earth every year, the arrival of larger extraterrestrial fragments forming giant impact craters is (fortunately) very infrequent. Evidence for large prehistoric impacts includes not only crater shape, but also mineralogic and structural changes caused by high impact shocks. Approximately 140 terrestrial craters have so far been discovered, and they range in age from a thousand years to 2 thousand million years. Their diameters can reach 300 km, and even larger craters may have been eroded away or covered by younger rocks. One of the best known and preserved is 1.2 km wide Meteor Crater, Arizona, which was formed about 50,000 years ago. Impact cratering this small might occur somewhere on Earth every 10,000 years on average, whereas a 100 km diameter crater might be produced once every 50 million years.

Since 1980, most scientists—after lively debate—have come to accept the hypothesis that one or more high energy bolide impacts occurred about 65 million years ago and were largely responsible for the abrupt changes in the fossil record, including the extinction of dinosaurs, between the Cretaceous and Tertiary Periods of geologic time. The resulting crater of one of these impacts is thought to be the now-buried 300 km wide Chicxulub structure in the Yucatan Peninsula, Mexico. Such impacts would have had huge energy releases, dwarfing the world's largest historical earthquake (Chile, 1960, Richter magnitude 8.3). The energy released by the Chicxulub impact would be equivalent to magnitude 13 or possibly even higher.

EARTH DYNAMICS THROUGH GEOLOGIC TIME

Earth history has been dominated by the opening and the closing of ocean basins in complex interwoven cycles. This map shows oceans in various stages of opening—East Africa (embryonic), Red Sea (young), Atlantic (mature)—as well as closing—Mediterranean (dying) and Himalayas (dead). The earthquakes and volcanoes that mark this slow tectonic movement are clearly shown, as are craters of the extraterrestrial impacts that can punctuate the Earth's history by catastrophic change. These continuing movements mask or obliterate traces of earlier events and make the older chapters of Earth's 4,500 million year history increasingly difficult to read. The recent activity shown on this map provides a snapshot of earth history, helping to clarify how our present planetary surface came to be, and even what it may become.

ACKNOWLEDGMENTS

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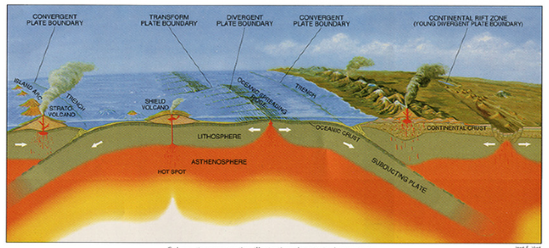

Schematic cross section illustrating plate-tectonic processes

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