

ENCYCLOPEDIA ARTICLE

Earthquake

The sudden movement of the Earth caused by the abrupt release of accumulated strain along a fault in the interior. The released energy passes through the Earth as seismic waves (low-frequency sound waves), which cause the shaking. Seismic waves continue to travel through the Earth after the fault motion has stopped. Recordings of earthquakes, called seismograms, illustrate that such motion is recorded all over the Earth for hours, and even days, after an earthquake.

Characteristics

Earthquakes vary immensely in size, from tiny events that can be detected only with the most sensitive seismographs, to great earthquakes that can cause extensive damage over widespread areas. Although thousands of earthquakes occur every day, and have for billions of years, a truly great earthquake occurs somewhere in the world only once every year. When a great earthquake occurs near a highly populated region, tremendous destruction can occur within a few seconds. In 1976, 600,000 people were killed in Tangshan, China, by a single earthquake. The city of Lisbon, one of the principal capitals of that day, was utterly destroyed, with high loss of life, in 1755. In the twentieth century such cities as Tokyo and San Francisco have been leveled by earthquakes. In these more modern cases, much of the damage was not due to the shaking of the earthquake itself, but was caused by fires originating in the gas and electrical lines which interweave modern cities, and by damage to fire-fighting capability which rendered the cities helpless to fight the conflagrations.

Cause

The locations of earthquakes which occurred between 1957 and 2000 are shown on the map in **Fig. 1**. The map shows that earthquakes are not distributed randomly over the globe but tend to occur in narrow, continuous belts of activity. Approximately 90% of all earthquakes occur in these belts, which define the boundaries of the Earth's plates. The plates are in continuous motion with respect to one another at rates on the order of centimeters per year; this plate motion is responsible for most geological activity.

Seismicity of the Earth from 1957 to 2000; depths to 700 km (435 mi). Earthquakes are plotted as circles; the plate boundaries are black. (After E. R. Engdahl et al., *Global teleseismic earthquake relocation with improved travel times and procedures for depth determination*, *Bull. Seis. Soc. Amer.*, 88:722–743, 1998; and A. Villaseñor et al., *Toward a comprehensive catalog of global historical seismicity*, *Eos*, 78:581, 583, 588, *American Geophysical Union*, 1997)

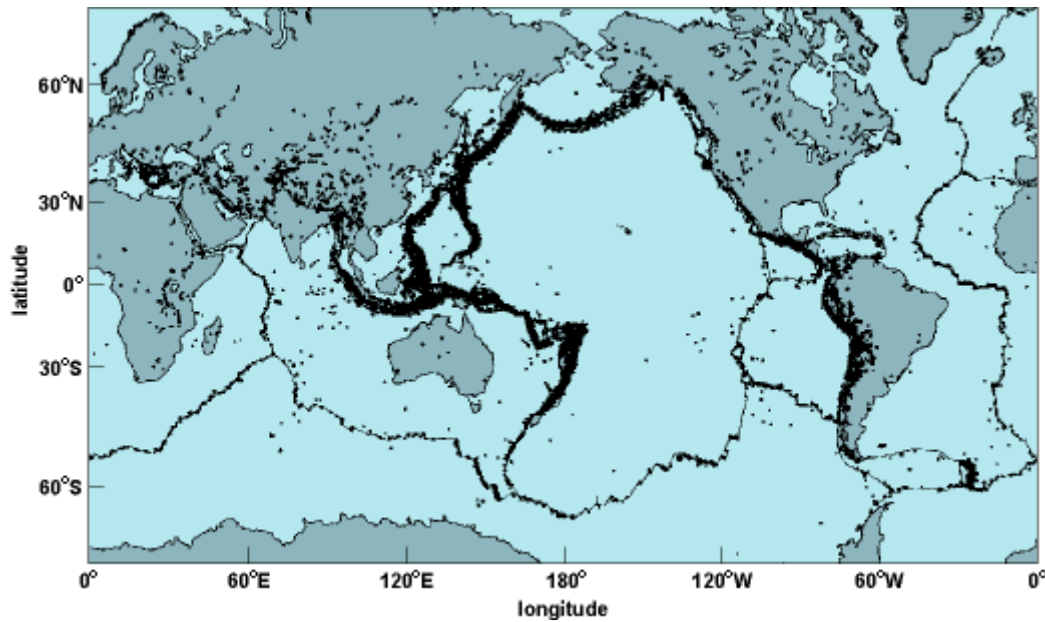
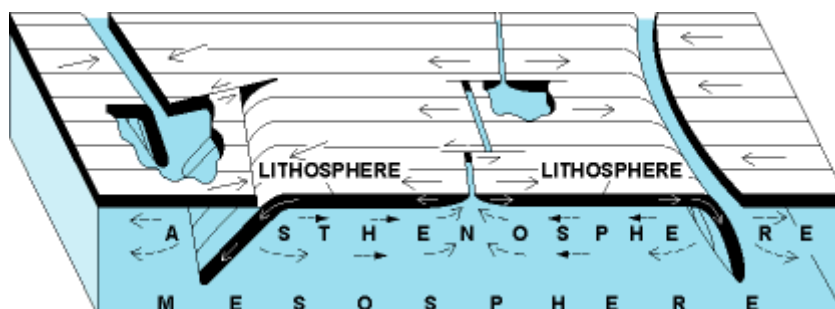


Plate motion occurs because the outer cold, hard skin of the Earth, the lithosphere, overlies a hotter, soft layer known as the asthenosphere. Heat from decay of radioactive minerals in the Earth's interior sets the asthenosphere into thermal convection. This convection has broken the lithosphere into plates which move about in response to the convective motion in a manner shown schematically in **Fig. 2**. The plates move apart at oceanic ridges. Magma wells up in the void created by this motion and solidifies to form new sea floor. This process, in which new sea floor is continually created at oceanic ridges, is called sea-floor spreading. Since new lithosphere is continually being created at the oceanic ridges by sea-floor spreading, a like amount of lithosphere must be destroyed somewhere. This occurs at the oceanic trenches, where plates converge and the oceanic lithosphere is thrust back down into the asthenosphere and remelted. The melting of the lithosphere in this way supplies the magma for the volcanic arcs which occur behind the trenches. Where two continents collide, however, the greater buoyancy of the less dense continental material prevents the lithosphere from being underthrust, and the lithosphere buckles under the force of the collision, forming great mountain ranges such as the Alps and Himalayas. Where the relative motion of the plates is parallel to their common boundary, slip occurs along great faults which form that boundary, such as the San Andreas fault in California. See also: Asthenosphere; Earth, heat flow in; Lithosphere; Magma; Volcanology

Movement of the lithosphere over the more fluid asthenosphere. In the center, the lithosphere spreads away from the oceanic ridges. At the edges of the diagram, it descends again into the asthenosphere at the trenches. (After B. Isacks, Oliver, and L. R. Sykes, *Seismology and the new global tectonics*, *J. Geophys. Res.*, 73:5855-5899, American Geophysical Union, 1968)



According to the theory of plate tectonics, the motion of the plates is very similar to the movement of ice floes in arctic waters. Where floes diverge, leads form and water wells up, freezing to the floes and producing

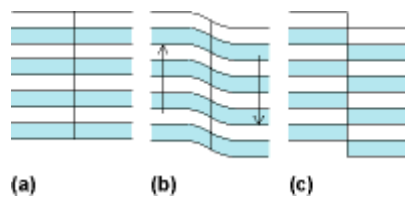
new floe ice. The formation of pressure ridges where floes converge is analogous to the development of mountain ranges where plates converge. See also: Orogeny; Plate tectonics

Stick-slip friction and elastic rebound

As the plates move past each other, little of the motion at their boundaries occurs by continuous slippage; most of the motion occurs in a series of rapid jerks. Each jerk is an earthquake. This happens because, under the pressure and temperature conditions of the shallow part of the Earth's lithosphere, the frictional sliding of rock exhibits a property known as stick-slip, in which frictional sliding occurs in a series of jerky movements, interspersed with periods of no motion—or sticking. In the geologic time frame, then, the lithospheric plates chatter at their boundaries, and at any one place the time between chatters may be hundreds of years.

The periods between major earthquakes is thus one during which strain slowly builds up near the plate boundary in response to the continuous movement of the plates. The strain is ultimately released by an earthquake when the frictional strength of the plate boundary is exceeded. This pattern of strain buildup and release was discovered by H. F. Reid in his study of the 1906 San Francisco earthquake. During that earthquake, a 250-mi-long (400-km) portion of the San Andreas fault, from Cape Mendocino to the town of Gilroy, south of San Francisco, slipped an average of 12 ft (3.6 m). Subsequently, the triangulation network in the San Francisco Bay area was resurveyed; it was found that the west side of the fault had moved northward with respect to the east side, but that these motions died out at distances of 20 mi (32 km) or more from the fault. Reid had noticed, however, that measurements made about 40 years prior to the 1906 earthquake had shown that points far to the west of the fault were moving northward at a slow rate. From these clues, he deduced his theory of elastic rebound, illustrated schematically in **Fig. 3**. The figure is a map view, the vertical line representing the fault separating two moving plates. The unstrained rocks in Fig. 3a are distorted by the slow movement of the plates in Fig. 3b. Slippage in an earthquake, returning the rocks to an unstrained state, occurs as in Fig. 3c. See also: Fault and fault structures

Schematic of elastic rebound theory. (a) Unstrained rocks (b) are distorted by relative movement between the two plates, causing strains within the fault zone that finally become so great that (c) the rocks break and rebound to a new unstrained position. (After C. R. Allen, *The San Andreas Fault, Eng. Sci. Mag., Calif. Inst. Technol., pp. 1–5, May 1957*)



Classification

Most great earthquakes occur on the boundaries between lithospheric plates and arise directly from the motions between the plates. Although these may be called plate boundary earthquakes, there are many earthquakes, sometimes of substantial size, that cannot be related so simply to the movements of the plates.

Near many plate boundaries, earthquakes are not restricted to the plate boundary itself, but occur over a broad zone—often several hundred miles wide—adjacent to the plate boundary. These earthquakes, which may be called plate boundary–related earthquakes, do not reflect the plate motions directly, but are secondarily caused by the stresses set up at the plate boundary. In Japan, for example, the plate boundaries are in the deep ocean trenches offshore of the Japanese islands, and that is where the great plate boundary earthquakes occur. Many smaller events occur scattered throughout the Japanese islands, caused by the overall compression of the whole region. Although these small events are energetically minor when compared

to the great offshore earthquakes, they are often more destructive, owing to their greater proximity to population centers.

Although most earthquakes occur on or near plate boundaries, some also occur, although infrequently, within plates. These earthquakes, which are not related to plate boundaries, are called intraplate earthquakes, and can sometimes be quite destructive. The immediate cause of intraplate earthquakes is not understood. Some of them can be quite large. Three of the largest earthquakes known to have occurred in the United States were part of a sequence of intraplate earthquakes which took place in the Mississippi Valley, near New Madrid, Missouri, in 1811 and 1812. Another intraplate earthquake, in 1886, caused moderate damage to Charleston, South Carolina.

In addition to the tectonic types of earthquakes described above, some earthquakes are directly associated with volcanic activity. These volcanic earthquakes result from the motion of underground magma that leads to volcanic eruptions.

Sequences

Earthquakes often occur in well-defined sequences in time. Tectonic earthquakes are often preceded, by a few days to weeks, by several smaller shocks (foreshocks), and are nearly always followed by large numbers of aftershocks. Foreshocks and aftershocks are usually much smaller than the main shock. Volcanic earthquakes often occur in flurries of activity, with no discernible main shock. This type of sequence is called a swarm.

Size

Earthquakes range enormously in size, from tremors in which slippage of a few tenths of an inch occurs on a few feet of fault, to the greatest events, which may involve a rupture many hundreds of miles long, with tens of feet of slip. Accelerations exceeding 1 *g* (acceleration due to gravity) can occur during an earthquake. The velocity at which the two sides of the fault move during an earthquake is only 1–10 mi/h (10–100 cm/s), but the rupture front spreads along the fault at a velocity of nearly 5000 mi/h (3 km/s). The earthquake's primary damage is due to the generated seismic waves, or sound waves which travel through the Earth, excited by the rapid movement of the earthquake. The energy radiated as seismic waves during a large earthquake can be as great as 10^{12} cal (4.19×10^{12} joules), and the power emitted during the few hundred seconds of movement as great as a billion megawatts.

The size of an earthquake is given by its moment: average slip times the fault area that slipped times the elastic constant of the Earth. The units of seismic moment are dyne-centimeters. An older measure of earthquake size is magnitude, which is proportional to the logarithm of moment. Magnitude 2.0 is about the smallest tremor that can be felt. Most destructive earthquakes are greater than magnitude 6; the largest shock known was the 1960 Chile earthquake, with a moment of 10^{30} dyne-centimeters (10^{23} newton-meters) or magnitude 9.5. It involved a fault 600 mi (1000 km) long slipping 30 ft (10 m). The magnitude scale is logarithmic, so that a magnitude 7 shock is about 30 times more energetic than one of magnitude 6, and 30×30 , or 900 times, more energetic than one of magnitude 5. Because of this great increase in size with magnitude, only the largest events (greater than magnitude 8) significantly contribute to plate movements. The smaller events occur much more often but are almost incidental to the process.

The intensity of an earthquake is a measure of the severity of shaking and its attendant damage at a point on the surface of the Earth. The same earthquake may therefore have different intensities at different places. The intensity usually decreases away from the epicenter (the point on the surface directly above the onset of the earthquake), but its value depends on many factors and generally increases with moment. Intensity is usually higher in areas with thick alluvial cover or landfill than in areas of shallow soil or bare rock. Poor

building construction leads to high intensity ratings because the damage to structures is high. Intensity is therefore more a measure of the earthquake's effect on humans than an innate property of the earthquake.

Effects

Many different effects are produced by earthquake shaking. Although the fault motion that produced the earthquake is sometimes observed at the surface, often other earth movements, such as landslides, are triggered by earthquakes. On rare occasions the ground has been observed to undulate in a wavelike manner, and cracks and fissures often form in soil. The flow of springs and rivers may be altered, and the compression of aquifers sometimes causes water to spout from the ground in fountains. Undersea earthquakes often generate very long-wavelength water waves, which are sometimes called tidal waves but are more properly called seismic sea waves, or tsunamis. These waves, almost imperceptible in the open ocean, increase in height as they approach a coast and often inflict great damage to coastal cities and ports.

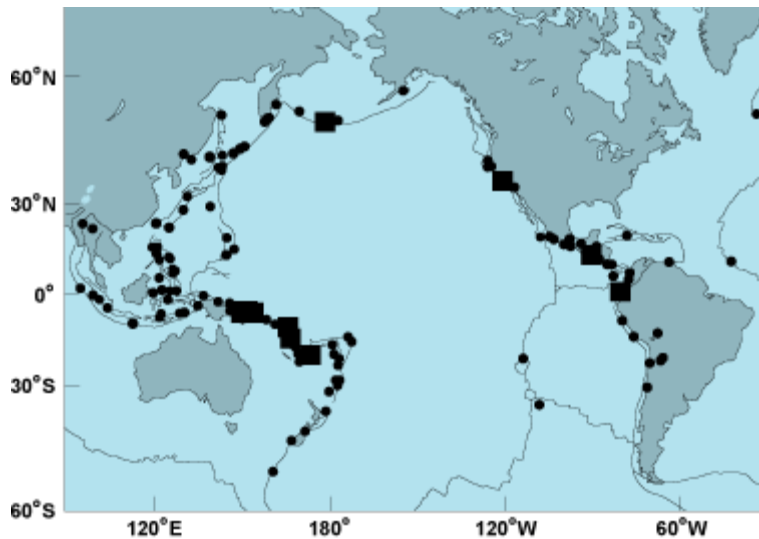
See also: Landslide; Tsunami

Prediction

Earthquake prediction research has been going on for nearly a century. A successful prediction, specifying the time, location, and magnitude of an earthquake, would save lives and billions of dollars in housing and infrastructure costs. Unfortunately, successful earthquake predictions are extremely rare. There are two basic categories of earthquake predictions: forecasts (months to years in advance) and short-term predictions (hours or days in advance). Forecasts are based a variety of research, including the history of earthquakes in a specific region, the identification of fault characteristics (including length, depth, and segmentation), and the identification of strain accumulation. Data from these studies are used to provide rough estimates of earthquake sizes and recurrence intervals.

An example of an earthquake forecast is the identification of seismic gaps, portions of the plate boundaries that have not ruptured in a major earthquake for a long time. These regions are most likely to experience great earthquakes in the future. **Figure 4** shows seismic gaps for the circum-Pacific region and indicates which gaps were most likely to experience a large or great earthquake in 1989–1999. Large earthquakes did occur in several of the likeliest gaps, but many large earthquakes occurred in less likely gaps as well. Earthquake probability estimates are another example of forecasting. Geologic, geodetic, and seismic information are combined to estimate the frequencies of damaging earthquakes in a specific region. Recent regional earthquake probability estimate studies have resulted in forecasts of an 80–90% probability of a magnitude 7 or larger earthquake in the southern California region before 2024, and a 70% probability of a magnitude 6.7 or larger earthquake in the San Francisco Bay region before 2030.

Major seismic gaps, western Pacific. The plate boundaries are shown in black. Black squares mark the locations of seismic gaps with a 50% or greater chance of being filled by a large earthquake between 1989 and 1999. Black dots are magnitude 7.0 or larger earthquakes that occurred between 1989 and 1999. (After S. P. Nishenko, *Pure Appl. Geophys.*, 135:169–259, 1991)



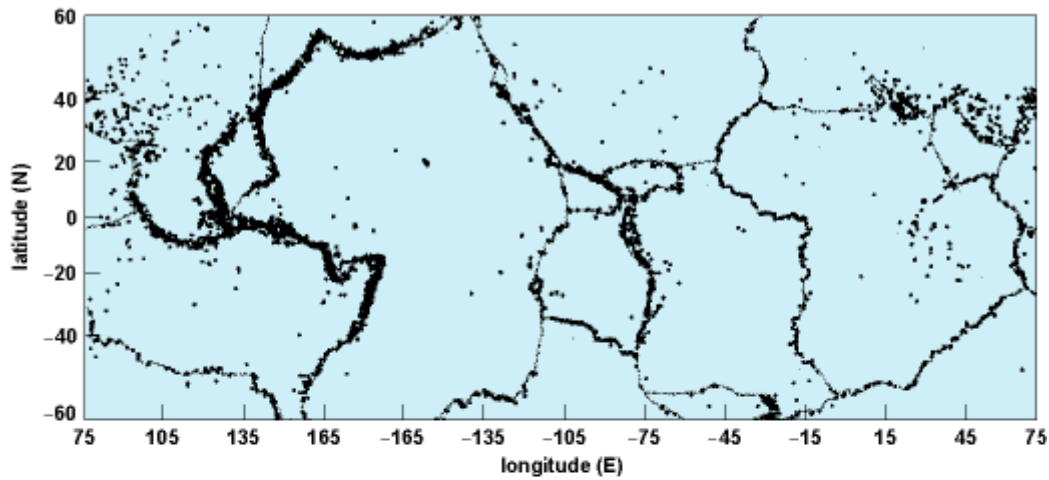
Short-term earthquake prediction is still entirely in the realm of ongoing research, and no method is known to be reliable. Evidence is emerging that short-term prediction may be inherently impossible due to the complex and chaotic nature of the earthquake process.

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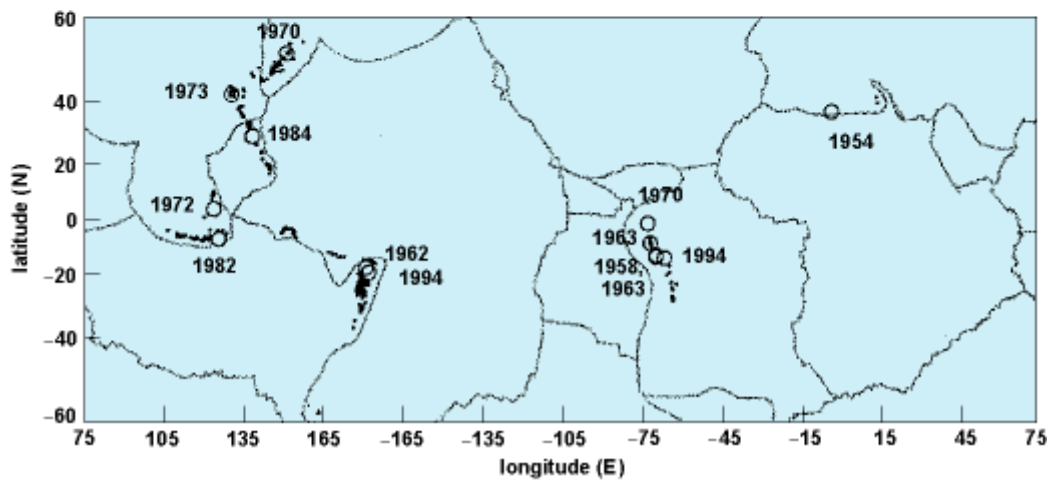
Deep Earthquakes

Most earthquakes occur at depths shallower than about 50 km (30 mi) [Fig. 5a] and are usually found near plate boundaries. A few percent of all shocks occur at depths of 300–700 km (183–427 mi), depths that correspond to earth pressures of 100,000–250,000 atm ($1\text{--}2.5 \times 10^{10}$ Pa; Fig. 5b and Fig. 6). That the mantle can suddenly rupture rather than flow plastically at such conditions has elicited wonder since deep earthquakes were first discovered in the 1920s. Modern insight into these phenomena has come from scientific advances of plate tectonics, seismic tomography, and the mineral physics of the deep mantle based on very high pressure experiments on mantle minerals.

Map showing the global distribution of shallow and deep earthquakes. (a) Earthquakes shallower than 40 km (25 mi). (b) Earthquakes deeper than 300 km (186 mi; open circles with dates indicate the locations of the 13 largest recorded deep shocks, including the 1994 Bolivian event).

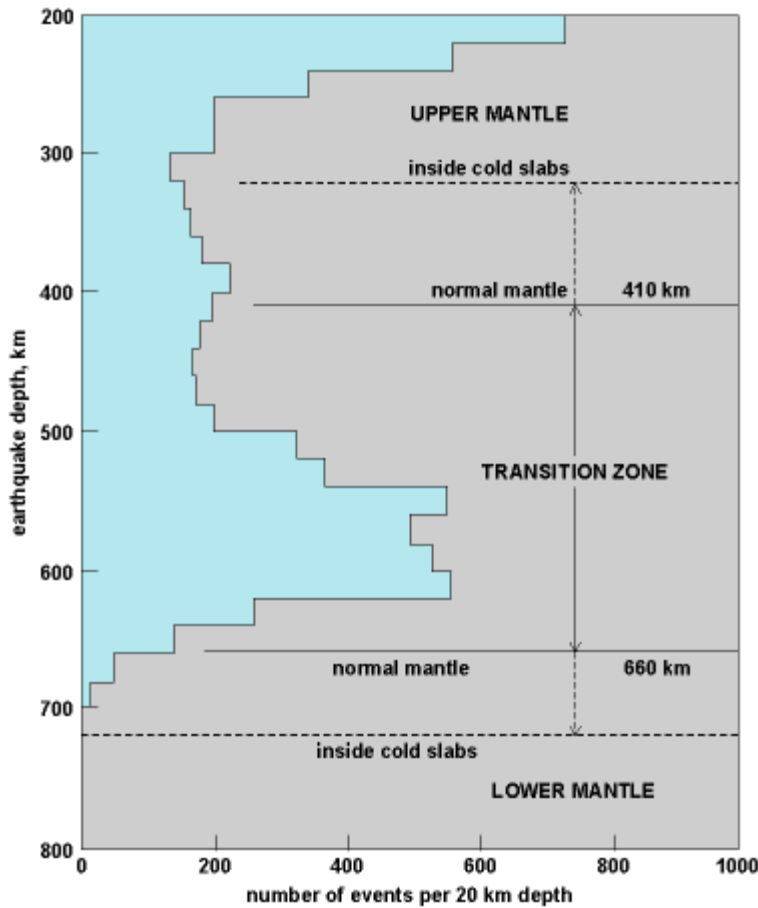


(a)

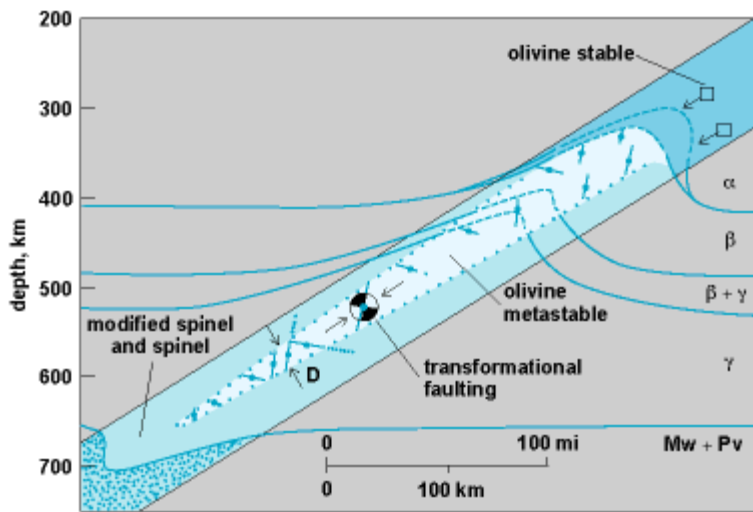


(b)

Depth histogram of earthquakes compared to the mineralogical structure of the mantle. (a) Depth histogram of well-located earthquakes (1964–1991) in relationship to seismic-wave speed discontinuities caused by mineralogical changes in normal mantle and in cold slabs. (b) Hypothetical mineralogical structure of very cold slabs and normal mantle, emphasizing the phase changes associated with the olivine component $[(\text{Mg,Fe})_2\text{SiO}_4]$ of the mantle [α (olivine), β (modified spinel) and γ (spinel)]; Mw + Pv are magnesiowüstite and perovskite, the higher-pressure minerals dominating the lower mantle. Transformational faulting is a shear instability that can occur in metastable olivine under stress and can produce deep earthquakes.



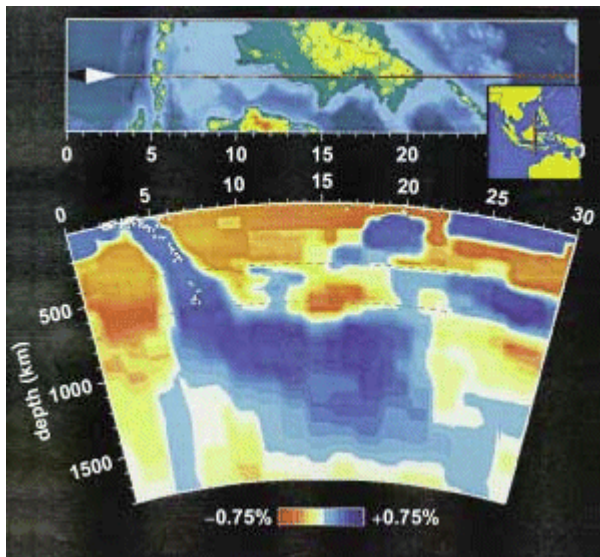
(a)



(b)

Most, if not all, deep earthquakes occur in inclined belts inside slabs, the cold, dense, and strong lithospheric plates that dive deeply into the Earth's mantle in places where plates are converging. Seismic waves have been used to image variations in the seismic wave speeds in the Earth. These anomalies in seismic tomographic images reflect differences in temperature, mineralogy, or composition. As expected, deep earthquakes occur in the high-wave-speed anomalies that mark cold slabs, anomalies that have been traced to depths as great as 2000 0km (1220 mi) or more (**Fig. 7**).

Tomographic image of the Australian plate subducting beneath Indonesia and associated slab earthquakes. The broken lines mark the mantle transition zone at depths of 410–660 km (250–403 mi); the upper and lower mantles are above and below this depth interval. Note that the compressional wave-speed anomaly of the slab extends deeply into the lower mantle, whereas slab earthquakes cease near 660 km (410 mi). (*Image courtesy of Dr. Wim Spakman, University of Utrecht*)



Curiously, earthquakes occur no deeper than 650–700 km (397–427 mi), far shallower than the maximum depths to which slabs descend. This abrupt shutoff and the gradual onset of the deep earthquake population at 300–350 km (183–214 mi) bracket approximately the transition zone of the mantle where seismic wave speeds abruptly increase (Fig. 6a). High-pressure experiments indicate that the mineralogy of the mantle changes at those depths and pressures from upper-mantle mineralogy (dominantly olivine and pyroxenes) to the minerals spinel, ilmenite, and majorite in the transition zone and, in turn, to the lower-mantle perovskite and oxide minerals. Slab mantle penetrating through the transition zone is expected to transform to these denser minerals.

Most deep earthquakes occur in the depth interval of the transition zone where upper-mantle slab minerals are reconstructed to their denser structural forms. Attention has therefore been drawn to the possibility that deep earthquakes are somehow caused by the mineralogical transformation of slabs as they descend into and through this region. Early speculation was that deep earthquakes represent rapid implosions that might occur when slab minerals transform suddenly to their denser, high-pressure forms. The patterns of seismic waves that radiate from deep earthquake sources indicate, however, that such disturbances represent slip on a fault, as do shallow earthquakes. If a connection exists between deep earthquakes and mantle phase changes, the underlying process must facilitate failure by faulting.

A clue to the nature of this possible connection comes from the observation that deep earthquakes do not occur in all slabs, only in those that are very cold because they are descending at very fast rates. Low slab temperatures are important because such conditions favor the metastable persistence of upper-mantle minerals in the coldest interiors of slabs as they descend into the transition zone (Fig. 6b). Laboratory studies show that some minerals deformed under metastable conditions will rupture by an unusual shear instability in which the mineral is transformed to denser minerals in the shear zone. This shear instability, called transformational faulting, is not inhibited by high pressures and hence is an attractive candidate for the faulting mechanism of deep earthquakes. According to this theory, deep earthquakes do not occur in the lower mantle because low-density upper-mantle slab rocks are too buoyant to sink into the lower mantle.

An extraordinary demonstration of the potential scale of deep seismic faulting was demonstrated by the great deep earthquake that occurred at a depth of about 640 km (390 mi) beneath the Amazonian rainforest of Bolivia on June 9, 1994. The ground motions of this magnitude 8.2 shock, the largest deep event on record, were felt by people in places as far north as Toronto and Seattle, corresponding to surface distances from the earthquake focus exceeding 8000 km (4880 mi). Theoretical analysis of the seismograms written by this earthquake indicate that deep rupture occurred on a horizontal fault over an area of about 1600–2500 km² (618–965 mi²) with a rupture duration of about 40–50 s and a shear offset of about 10–15 m (33–49 ft). This great, deep rupture occurred in the Nazca plate subducting beneath the South American plate, and was so energetic that it excited Earth's free oscillation modes and the planet rang like a low-frequency bell for many weeks after the earthquake. The global occurrence of such earthquakes is the deepest direct expression of Earth's thermal convection system. See also: Earth, convection in

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Additional Readings

- U.S. Geological Survey; Earthquakes in the United States
- Surfing the Internet for Earthquake Data

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