Earthquakes

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Definitions

An *earthquake* is the vibration of the Earth produced by an abrupt release of energy.

Most commonly, an earthquake is the result of slippage along a *fault* in the Earth’s crust.

A *fault* is a fracture in the crust on which there has been appreciable displacement.

The energy is released in all directions from its source known as the *focus*.

The *epicenter* of an earthquake is the point on the Earth’s surface directly above the focus.
I. Faults

*Hanging wall* — rock surface immediately above the fault surface.

*Footwall* — rock surface immediately below the fault surface.

There are several types of faults depending upon the geometry of the fault:

1. Dip-slip faults
   - normal
   - reverse
   - thrust
2. Strike-slip faults
3. Oblique slip faults

Detailed view of a normal fault. White strip running from upper left to lower right corner of picture is material dragged along fault plane. The well-bedded clay and silt in the lower left part of the picture have been abruptly truncated by the fault. Right side of picture has moved to the right and downward. Shovel provides scale.
Strike and Dip

Geologists have developed a convenient way to portray the orientation of planar surfaces such as faults in the Earth on maps.

*Strike* is the compass direction of the line produced by the intersection of an inclined fault with a horizontal plane.

*Dip* is the angle of inclination of the surface of the fault measured from a horizontal plane.
Dip Slip Faults

*Dip slip faults* are faults where the movement is parallel to the dip of the fault surface or plane. There are two main types of dip slip faults:

- *normal faults*
- *reverse faults*

In *normal faults*, the *hanging wall* block moves down relative to the *footwall* block.

*Normal faults* accommodate or are caused by extension of the crust — the Basin and Range province (E. California and Nevada) is caused by crustal extension and normal faults.
Dip Slip Faults
In *reverse faults*, the *hanging wall* block moves up relative to the *footwall* block.

*Reverse faults* accommodate shortening (compression) of the crust — compressional forces that form these faults generally produce folds in association with them.
Dip Slip Faults

*Thrust faults* are reverse faults where the angle of dip is $<45^\circ$. 

**USGS IRIS**
Strike-Slip Faults

In *strike slip faults*, the displacement (movement) is horizontal and parallel to the strike of the fault trace.

Right-lateral strike-slip faults have a sense of movement that the crustal block on the opposite of the fault has moved to the right as you face the fault (ex. San Andreas fault system).
Strike-Slip Faults

In *left-lateral* strike-slip faults, the movement is such that the block on the opposite side of the fault appears to have moved to the left as you face the fault.

The Great Glen fault (Scotland) is an example of a left lateral fault.
Strike-Slip Faults

A *transform fault* is a type of *strike-slip* fault where the motion is between two large crustal (tectonic) plates (ex. San Andreas fault system). Large *strike-slip* fault systems commonly consist of roughly parallel branches that define a fault zone up to several kilometers wide.
It is easy to see offset features when there has been *strike-slip* displacement at the Earth's surface.

In this photograph, the fence line near Point Reyes, CA was displaced approximately 8.5 feet by the 1906 San Francisco earthquake.

The dashed line indicates the fault trace and the sense of motion is *right-lateral*.
Other offset features such as stream channels indicate *strike-slip* motion.

In this photograph, the Wallace Creek on the Carrizo Plain (central California) has been displaced (*right-lateral*).

Displaced streams are common in the East Bay Hills adjacent to the Hayward fault such as at the Hayward Memorial Park.
During *strike-slip* motion along the San Andreas fault, rocks are crushed and are more easily eroded. This commonly results in linear valleys or troughs that mark the location of the fault.

This photograph shows a linear valley (or rift) caused by the San Andreas on the Carrizo Plain in central California.

In the Bay Area, the linear valley that the Warren freeway (Highway 13) runs through is a rift valley caused by the Hayward fault.

Imagine the damage to the Warren freeway if a surface rupture occurred along the Hayward fault.
Oblique-Slip Faults

Strike-slip and dip-slip faults represent end-member models of movement along faults. Some faults may exhibit both strike-slip and dip-slip motion and are classified as oblique-slip faults.

Most faults actually exhibit some degree of oblique-slip motion.
Although the Hayward fault is classified as a strike-slip fault, a small degree of dip-slip motion has created a scarp on the western edge of the East Bay Hills where the block to the west has moved down relative to the east.
As tectonic forces deform rocks on both sides of a fault, the rocks bend and store elastic energy. Eventually the frictional resistance is overcome (exceed shear strength of rocks) and slippage occurs. The built-up strain is released and the deformed rocks "snap back." A earthquake results from vibrations as the rock snaps back into shape - elastic rebound.
Most earthquakes are caused by the rapid release of elastic energy.

These images show the rupture surface (thrust fault) from the Chi-chi earthquake in Taiwan (1999).
Fault Creep

Some faults (including the San Andreas and Hayward faults) exhibit slow gradual displacement known as fault creep.

The displaced curb on D Street in downtown Hayward occurs along a trace of the Hayward fault. Note that the displacement is right-lateral.

Displaced curbs such as this can be seen on the east side of Mission Blvd along cross streets. The creep rate in Hayward is approximately 5 mm/year.
Fault Creep

Five creepmeters are maintained by the USGS to monitor fault creep on the Hayward fault. Fault creep is generally not as catastrophic as earthquakes, however, structures that straddle a fault such as buildings and bridges may be sheared (ripped apart) by these forces. The old city hall in Hayward is an example of a building that has been destroyed (condemned) by fault creep. Creep rates in Fremont average about 7.8 mm/year. Creep rates elsewhere on the fault are close to the ~5 mm/year.
Foreshocks and Aftershocks

Small earthquakes, known as foreshocks, may precede a major earthquake by hours, days, or years. These foreshocks are actively investigated as a means of predicting major earthquakes.

After a major earthquake, adjustments may be made along a fault resulting in the generation of many smaller earthquakes known as aftershocks.

Aftershocks are generally weaker but may destroy buildings damaged during the main shock.

After the Loma Prieta earthquake (magnitude 7.1), a magnitude 5.2 aftershock occurred within 2.5 minutes. There were thousands of aftershocks; 20 aftershocks with a magnitude greater than 4.0 occurred within one week of the main shock.
III. Seismology

Seismology is the study of earthquakes. Seismographs are instruments that detect and record earthquakes. The principle behind the seismograph is that inertia tends to keep the suspended mass motionless while the recording surface vibrates with the bedrock. Thus the seismograph measures the displacement or movement of the ground as seismic waves pass through the station.

Typical seismographs consist of rotating drums with recording paper. Most modern seismographs now record data digitally and are available in near real time on the internet.
Hundreds of seismographs are deployed in national and international networks to record earthquakes.

This extensive network permits us to determine the location of an earthquake and also to accurately measure the amount of energy released (magnitude).
Seismic Waves

How does seismic energy propagate through the Earth?

There are 2 types of seismic waves:

• **Body waves** travel through the Earth’s interior and provide useful information about the earthquake and the interior structure of the Earth.

• **Surface waves** move along the surface of the Earth. They tend to be the most destructive.

There are two types of body waves:

**P-waves** - primary waves - compress and extend material in the direction of wave travel.

**S-waves** - secondary waves move the material in a direction that is normal to the direction of wave travel.
P-waves travel ~6 km/sec. They are compressional waves and particle motion is in the travel direction.

S-waves travel in the crust ~3.6 km/sec (slower than p-waves). They propagate through the Earth by displacing particles perpendicular to the direction of travel.

P-waves travel ~1.7x faster than S-waves and arrive at a recording station first. The time delay between the arrival of the P- and S-waves can be used to determine the distance to the earthquake.
Seismograms are records obtained from seismographs. They provide a lot of information about the earthquake and the portion of the Earth that the seismic energy has moved through.

Note that in this example, the S-wave arrives at this seismograph station ~500 seconds after the arrival of the P-wave.

The greater the difference between the arrival of the P- and S-waves (SP interval), the more distant the earthquake from the recording station.
This travel-time graph is used to determine the distance to the epicenter of an earthquake. It shows the travel times for P and S waves. In addition, it shows the time lag between the arrival of the P and S waves (S-P).

In the previous seismogram, the difference in arrival time between the P and S waves was ~36 seconds. That would correspond to a distance from the recording station of ~340 km.

This type of analysis can be done for a single earthquake from a large number of seismic recording stations.
The distances to the epicenter of the Loma Prieta earthquake from three different stations were determined from seismograms from Eureka, CA, Elko and Las Vegas, NV.

On the map, we may draw circles around each seismograph station that represent the distance to the epicenter.

The epicenter is at the intersection of the three circles - it requires at least three distant seismic recording stations to "triangulate" the location of the epicenter.
IV. Earthquakes and Plate Tectonics

This plot shows the epicenters of large earthquakes from 1977-92 with magnitude >5.5. Most occur along narrow belts that are coincident with plate boundaries.

Note that most earthquakes occur around the edge of the Pacific Ocean. Included in this zone of earthquakes are numerous volcano chains.

The earthquakes are color-coded for depth:
black = shallow
green = intermediate
red = deep
The theory of plate tectonics states that the crust of the Earth is composed of a strong rigid layer that is broken into 7 major (and many smaller) plates. Earthquakes occur along these plate boundaries where they move relative to one another.

There are three distinct types of plate boundaries:

1. divergent
2. convergent
3. transform
This map shows the distribution of earthquakes in the Pacific basin.

Each dot represents the epicenter of individual earthquakes and are color-coded for the depth of the focus. Note the range of earthquake depths in subduction systems on the western margin of the basin, west coast of S. America and the Aleutian Islands.

Earthquakes at mid-ocean ridges are relatively shallow.
This map shows the distribution of earthquakes in California and Nevada.

Each dot represents the epicenter of individual earthquakes and are color-coded for the depth of the focus. Note that earthquakes in this region occur at relatively shallow depth in the crust.

The zone of earthquakes along the coast of California are due to the San Andreas fault system.

The zone of earthquakes in eastern California is due to thrust faulting in the Sierra Nevada.
V. Earthquake Intensity and Magnitude

The severity of an earthquake is expressed in terms of the intensity and magnitude.

The **intensity** is based on the observed effects of the earthquake — it is an assessment of the damage caused by an earthquake at a specific location. Thus the intensity of an earthquake depends upon the strength of the earthquake, but also on the distance from the epicenter — it varies from place to place with respect to the earthquake's epicenter.

The modified Mercalli intensity scale is composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction. It does not have a mathematical basis but is arbitrary and based on observed effects.

The levels of the Mercalli scale are given on the next page.
The following is an abbreviated description of the 12 levels of Modified Mercalli intensity.

I. Not felt except by a very few under especially favorable conditions.

II. Felt only by a few persons at rest, especially on upper floors of buildings.

III. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.

IV. Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

VII. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

VIII. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.
The *magnitude* of an earthquake is related to the amount of energy released during a seismic event.

The Richter scale is used to describe earthquake *magnitude*. Earthquakes with magnitudes less than ~2.0 are not commonly felt by people. Although there is no upper limit to the Richter scale, the largest earthquakes have magnitudes of ~9. The energy released by an earthquake of this size is equal to the detonation of 1 billion tons of TNT.

The Richter scale is not used to express damage like the Mercalli scale.
The Richter magnitude is determined from the maximum amplitude of displacement measured on seismogram at a known distance from the epicenter.

The Richter scale is logarithmic — an increase of 1 on the Richter scale corresponds to a ~ten-fold increase in the maximum amplitude (ground motion).

More importantly, each unit on the Richter scale is approximately equal to a 32-fold increase in released energy. Thus a M7.0 earthquake releases ~32 times more energy than a M6.0.