EARTHQUAKE MECHANICS

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Summary

The study of earthquakes is a very active field within the geosciences, which is partly due to their destructive nature and the subsequent need for understanding the processes that govern the occurrence and recurrence of earthquakes, as well as the ground motions resulting from earthquakes. Recent progress in seismic instrumentation has enabled us to obtain more detailed images of the earthquake process, whereas laboratory experiments have shed light on the behavior of friction on faults, both during slip events as well as between earthquakes. The inherent stick-slip character of earthquakes can be explained by relatively straightforward mechanical models, whether they are based on crack theory or rooted in frictional theory, both of which can be shown to be equivalent to some extent.

We can conceptually divide the earthquake process into several stages; the initiation stage, where a sudden drop of strength or friction on a crack surface leads to a rapid slip event, subsequent growth of the rupture area through stress concentrations at the fringes of the original crack and cessation of slip due to a complete release of the effective stress, and/or an increase of the strength or friction on the fault to allow for progressive stress buildup until the next earthquake. This entire process takes place within a larger framework where stresses on the fault continuously build up over long time scales due to global plate motions.

1. History—Earthquakes and Faults

Up to the end of the nineteenth century, the origins of earthquakes were poorly understood. Often, they were associated with underground volcanic activity, even in areas with no active volcanoes present, and not directly linked to faulting. In the cases where faults were observed, they were often regarded as secondary effects of the earthquake, not as the cause of the shaking. Like most of the natural sciences, the field developed rapidly in the late nineteenth century with several scientists, independently of each other, establishing the link between earthquakes and faults (e.g. Gilbert, Koto, Muller). These developments culminated in the seminal work of Reid (1910), who, after studying the geodetic data from the 1906 San Francisco earthquake, formulated the theory of seismic rebound and settled the argument about the origins of earthquakes definitively.

1.1. Distribution of Earthquakes

The majority of earthquakes occur in two major zones of tectonic activity (see Figure 1), the Circumpacific belt ("the Ring of Fire") which includes regions like the western coasts of North, Central and South America, New Zealand, Indonesia, the Philippines, Taiwan, Japan, Kamchatka and Aleutes; and the mountain belt that stretches from the Burma in the east to Gibraltar in the west (the "Tethyan" belt) and includes the Himalayas, Hindu Kush, Zagros mountains, the Alps as well as the Atlas mountain ranges. Another concentration of earthquakes can also be found along mid-ocean ridges.

Figure 1. The distribution of earthquakes around the world.

In terms of depth, earthquakes are concentrated in a very small volume of the Earth, viz. the Crust, which forms its outer "shell" with an average thickness of 30 km (out of a total radius of 6371 km). However, a smaller number of events occur down to depths of about 700 km (intermediate and deep earthquakes) in zones where crustal material sinks into the upper mantle. The theory of plate tectonics provides a general framework for the occurrence of earthquakes, since most of them occur along the boundaries between relatively rigid tectonic plates that move with respect to each other. The differential motion is taken up along the boundaries, through earthquakes as well as aseismic movements. The largest earthquakes occur along the so-called subduction zones, where oceanic crust dives under the continental crust, as is happening, for example, in South America, Alaska, Japan and Indonesia. The Chile earthquake of 1960, which had a magnitude of 9.5, ruptured along the subduction zone interface over a length of 1000 km, with vertical displacement of up to 6m (and even larger, submarine, horizontal displacements). Although the plates behave rigidly, stresses do build up within these plates so that earthquakes occur even away from the plate boundaries. These can still be very large and destructive as was demonstrated during the 1811 and 1812 New Madrid earthquakes in the United States and, more recently, the 2001 Gujarat earthquake in India.

On a much smaller scale, seismic events are also associated with volcanism, and human activities such as mining, oil extraction and nuclear test explosions. Although these events can have some significant localized consequences, we shall not discuss these specifically in this article.

2. Descriptions of Faults and Earthquakes

2.1. Geological Description

2.1.1. Geometry of faults

Faults (and earthquakes) are usually characterized by the sense of movement along the fault plane (see Figure 2). The two main groups are called strike-slip, where the adjacent blocks move sideways of each other (parallel to the fault), and dip-slip, where the blocks move either toward or away from each other. The two groups can each be further subdivided into two; the strike-slip into right-lateral and left-lateral, and the dip-slip into normal faults, with one block thrown down relative to the other, or else as a reverse, or thrust, fault, with one block sliding over the other. Earthquakes and faults can have a mixed character, containing elements of both strike-slip as well dip-slip faults, in which case we they are often referred to as oblique. The orientation of a fault is given by the strike of the fault, which is the azimuth of the intersection of the fault plane and the horizontal, and the dip of the fault plane relative to the horizontal plane. The displacement direction on this fault plane is called the rake angle, and is defined as the angle, measured in the fault plane, between the strike direction and the displacement direction.

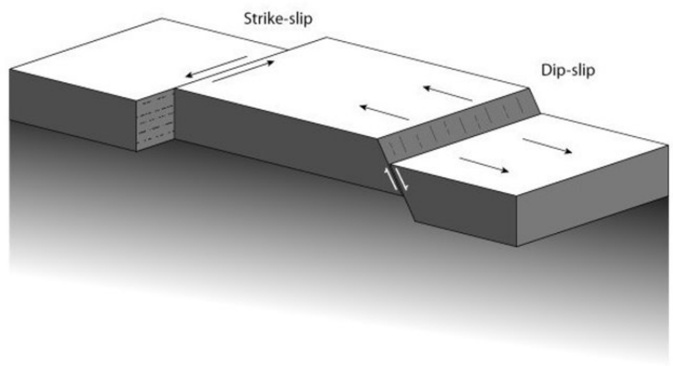

Figure 2. Diagram showing the two main types of faulting, strike-slip (on the left) and dip-slip (on the right).

Earthquake faults occur at scales ranging from microscopic to lengths of plate boundaries. The largest faults are the megathrusts, which are the boundary between over-riding continental crust and subducting oceanic crust, and these are generally located offshore. These faults can reach lengths of thousands of kilometers, although they rarely break in a single earthquake. Some of the largest on-land faults are the San Andreas fault in California and the Philippines fault which have lengths of hundreds of kilometers, but, like the megathrusts, they rarely if ever break in one earthquake.

At the surface, faults are often irregular showing changes in orientation, branching and step-overs. This complex morphology does not necessarily extend to great depths, although the major complexities do and these are related in some way to complexities of the earthquake rupture. The degree to which fault complexity influences the earthquake rupture is a very active field of research.

2.1.2. Depth dependent fault structure and rheology

For recent faults we can only study the surface exposure by direct observation, and this is not necessarily representative for the larger part of the fault, as it can extend to depths of 20 km or more. It is, however, possible to observe deeper parts of ancient (millions of years) fault systems, that have been uplifted by tectonic processes, in outcrops in the field. The structure of these fault zones is not uniform. Geologists have recognized very distinct characteristics, related to the original depth of the fault when it was active and these are directly related to the rheological properties of the crust and upper mantle. The structure, rheology, and composition of the Earth are strongly dependent on the pressure and temperature which both increase as a function of depth. In a simple crust, the top 15 to 20 km are in the brittle domain, sometimes referred to as schizosphere, where earthquakes occur. In the lower crust the effect of increased temperature and pressure lead to a more plastic deformation behavior, which means that the Earth behaves more as a viscous fluid than as a solid (see *Continental Crust*) so that shear stresses will immediately be dissipated by continuous deformation. This effect is amplified by the increase in normal stresses on a fault that lead to an increased frictional resistance. The character of the fault zone changes with depth accordingly, ranging from a soft fault gouge at the surface, to broken rock fragments (cataclasts) down to the mid-crustal depth (as can be deduced from the petrology of the surrounding rocks) to flow-like deformed rocks (mylonites) in the lower crust. The changes are gradual with mylonites existing side-by-side with cataclastic rocks in transition regions. Interspersed we also find small bands of glass-like material, called pseudo-tachelyte (named after volcanic glass, tachelyte), which is evidence for melting of the rocks and subsequent rapid cooling (quenching) to an amorphous glass state. This is consistent with stick-slip behaviour, where the slip occurs in a very short but intense event, with the sliding friction and sliding velocity large enough to generate enough heat to melt the rocks. Since the slip event is very short and localized the surrounding rocks remain relatively cold, so that the molten rock is cooled rapidly causing it to form glass instead of crystals.

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Biographical Sketch

Dr Hong Kie Thio, obtained his Ph.D. degree from Caltech in 1995, and joined the Pasadena office of URS (then Woodward Clyde) the same year. His main interest is in seismic source inversion studies using broadband waveform data and he has written papers on earthquakes in Southern California and the Mediterranean region, as well as rupture models of several recent large earthquakes using strong motion, teleseismic body and surface-wave and geodetic data. His other interests include earthquake locations in 3-D media and probabilistic seismic hazard analysis.