EARTHQUAKE, FOCAL MECHANISM

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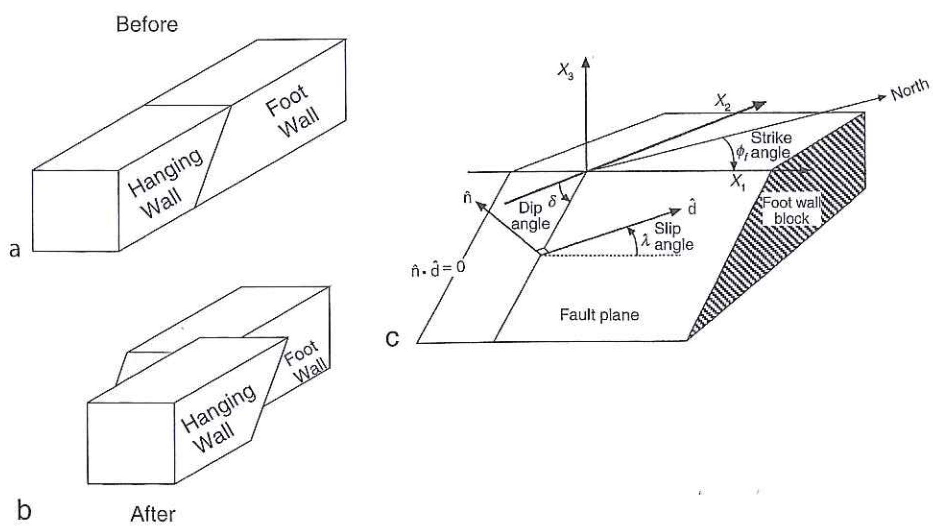
Definition

Focal mechanisms are geometrical or mathematical representations of the faulting during an earthquake. In very simple terms, the latter consists of the relative motions of two blocks of Earth called *walls* along a planar surface called *fault*. Figure 1 shows that the description of an earthquake rupture needs three angles. The *strike* angle ϕ is the azimuth (with respect to North) of the trace of the fault on a horizontal plane such as the Earth's surface; the *dip* angle δ characterizes the steepness of the fault, and the *rake* or *slip* angle λ, the direction of motion, within the fault plane and relative to the horizontal, of the hanging wall relative to the foot wall. A full description of the earthquake rupture requires an additional scalar, related



Earthquake, Focal Mechanism, Figure 1 (**a**) and (**b**) Before and after sketches of the displacement of fault blocks during an earthquake. The fault plane is shaded in (**b**). (**c**) Definition of the strike, dip, and slip angles, ϕ, δ, λ in the geometry of the rupture represented at left. The unit vector $\hat{\mathbf{d}}$ represents the direction of motion of the hanging wall (not represented to prevent clutter) with respect to the foot wall. (**c**: After Stein and Wysession, 2003.)

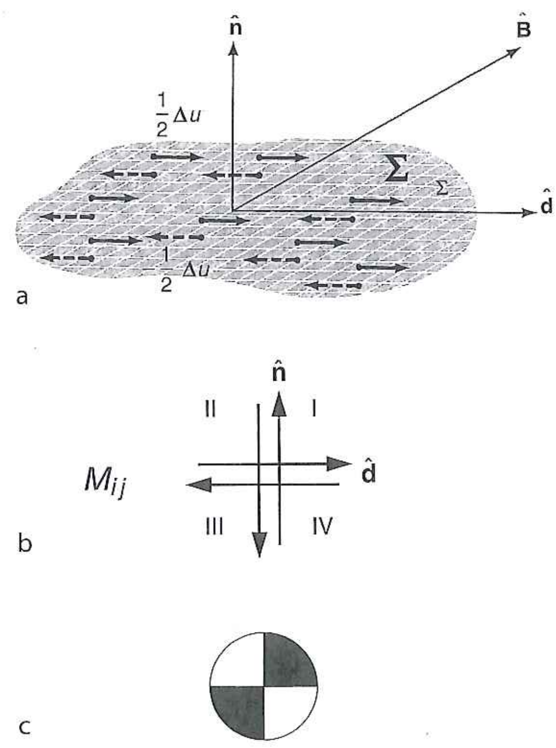
to the length of slip of the fault walls, and thus to the size or *magnitude* of the event.

Representation by a double-couple

As such, an earthquake source, described by three angles and a scalar, is a more complex mathematical entity than a simple vector (described by two angles and a scalar), and in particular cannot be represented physically by a single force. Vvedenskaya (1956), followed in the West by Knopoff and Gilbert (1959), introduced the concept of the double-couple, a system of forces shown on Figure 2 and consisting of two opposing torques of equal moment M_0; this system has no dynamic effect (translation or rotation) on a rigid body, but results in deformation of a medium of finite rigidity.

The representation theorem (e.g., Aki and Richards, 1980, pp. 38–41) considers an elastic medium of rigidity μ and states that a dislocation with slip Δu (in the direction $\hat{\mathbf{d}}$) along a fault of surface Σ cut into the medium (Figure 2a) will generate the same field of dynamic deformation (expressed as seismic waves) as a double-couple of moment $M_0 = \mu\Sigma\ \Delta u$, embedded in the medium in the absence of the cut, with the direction of forces and levers in Figure 2b along those of the slip, $\hat{\mathbf{d}}$, and of the normal to the fault plane, $\hat{\mathbf{n}}$.

The double-couple shown in Figure 2b separates the space around it into four quadrants containing respectively the heads and tails of the arrows. They are delineated by the fault plane and the plane normal to the slip $\hat{\mathbf{d}}$. In quadrants I and III, the seismic motion will be "*anaseismic,*" or away from the source, while in II and IV, it will be "*kataseismic*" or toward the source. The quadrants are accordingly shaded black and white in Figure 2c. Note that in Figure 2b and c, the source is



Earthquake, Focal Mechanism, Figure 2 (**a**) Seismic slip along a fault (represented as the hatched area of surface Σ). The total slip Δu is the difference between the displacements of the top wall (shown as *solid arrows*) and of the bottom wall (*dashed arrows*). (**b**) "Double-couple" system of forces, equivalent, in the unruptured medium, to the dislocation shown in (**a**). (**c**) "Beachball" representation of the quadrants defined by the orientation of the double-couple. (**a**: After Aki and Richards, 1980.)

approximated as a *point* in space, hence the concept of a "point-source double-couple."

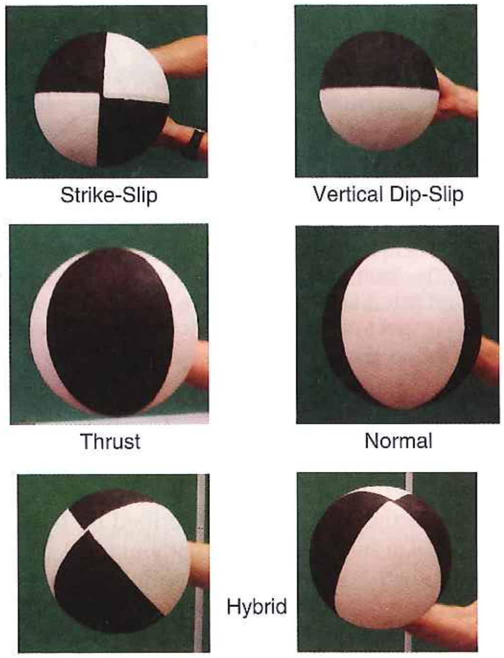
Focal mechanisms from P-wave first motions

Under the high-frequency approximation of geometrical optics, a most remarkable property of P waves is the conservation of the ana- or kataseismic character along the entire seismic ray, all the way to a receiving seismic station at the Earth's surface, where an anaseismic wave results in an initial *upward* motion of the ground, while a kataseismic one gives a *downward* first motion.

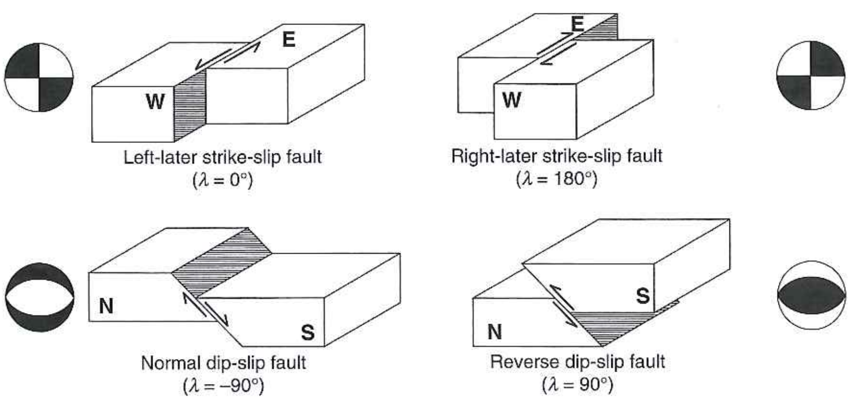
This property has been used extensively to obtain earthquake focal mechanisms by gathering first-motion P-wave data at large datasets of local and distant stations and backtracking this information along the relevant rays into a mapping of the focal sphere at the source. This amounts to resolving the orientation in space of the diagram on Figure 2c, known traditionally as a "beachball." Because of the difficulty of representing a full sphere on a planar figure (long known to world cartographers), and thanks to the symmetry of the beachball, it is convenient and sufficient to represent only a stereographic projection of the *lower focal hemisphere* separated at the horizontal plane and involving rays leaving down into the deep Earth, and eventually emerging at large distances. This constitutes the standard representation of earthquake focal mechanisms. Figure 3 illustrates examples of the most common types of mechanisms.

Note that a change of focal mechanism results in a mere *solid rotation* in space of the beachball pattern, but does not change its nature (Figure 4).

A common feature of the double-couple concept and of its beachball representation is their high level of symmetry. The two planes defining the quadrants on Figure 2b are conceptually interchangeable and as a result, there exists an inherent indeterminacy between two possible physical solutions obtained from any field of seismic data generated by a point source double-couple. For example, a left-lateral strike-slip earthquake on a vertical fault striking North–South is seismically indistinguishable from a right-lateral one on a fault striking East–West. This property, rooted in the symmetry of the double-couple, applies to all seismic waves, including P and S waves, surface waves, and the free oscillations of the Earth. The indeterminacy can be lifted only by considering a source extended in space, as opposed to a point source. In practice, this is done either by using field methods to recognize the orientation of the fault through its expression on the



Earthquake, Focal Mechanism, Figure 4 A basketball has been divided into four quadrants alternately painted black and white. By rotating the basketball in space, one can obtain a representation of all possible focal orientations of the double-couple shown in Figure 2b.This experiment demonstrates that earthquake focal geometries differ only by a solid rotation in space.



Earthquake, Focal Mechanism, Figure 3 Examples of focal geometries with corresponding beachball patterns. (Adapted from Stein and Wysession, 2003.)

ground, or by mapping the aftershocks of the event which are expected to occur along the direction of faulting, or by considering the so-called source-finiteness effects in the seismograms, which result from the interference of the elementary sources, distributed both in time and space, as the rupture propagates over the faulting area. In all cases, note again that the fault can no longer be represented as a point source.

Stress release

In another interpretation of focal mechanisms, one can expand the double-couple as a two-dimensional deviatoric and symmetric tensor

$$M_{ij} = M_0\left(\hat{d}_i\hat{n}_j + \hat{n}_i\hat{d}_j\right) \quad (1)$$

where $\hat{\mathbf{d}}$ and $\hat{\mathbf{n}}$ are the unit vectors along the direction of slip, and perpendicular to the fault, respectively. These components and the principal directions of the moment tensor are directly related to those of the stresses released during the earthquake.

In particular, the bisector $\mathbf{T} = \frac{1}{\sqrt{2}}(\hat{\mathbf{d}} + \hat{\mathbf{n}})$ represents the axis of maximum tension and the direction of maximum positive amplitude of P waves; it plots at the center of the shaded quadrants on the beachball. The direction $\mathbf{P} = \frac{1}{\sqrt{2}}(\hat{\mathbf{d}} - \hat{\mathbf{n}})$ is the axis of maximum compression (often and improperly called "pressure axis") and that of maximum negative amplitude of P waves; it plots at the center of the open quadrants. The direction $\mathbf{B} = \hat{\mathbf{d}} \times \hat{\mathbf{n}} = \mathbf{T} \times \mathbf{P}$ is the hinge of the fault planes; it is a direction where both P and S amplitudes vanish. For a given beachball, the **T, P, B** axes are independent of the choice between the two possible fault planes.

The interpretation of focal mechanisms in terms of stress release is particularly suited to the study of intraplate earthquakes, which express the release of stresses accumulated inside the plates by tectonic forces, while interplate events, which are controlled by the relative displacements of two of the Earth's plates at a common boundary, are more readily interpreted in terms of a slip vector on a fault plane.

Fundamental results

The most important application of focal mechanisms was the verification of the fundamental concepts of continental drift, seafloor spreading, and plate tectonics, in the mid-1960s. These ideas were derived using the spatial distribution of earthquake epicenters, but without the knowledge of the geometries of their ruptures. The latter could then be used as an independent verification of the concepts, following the development of the beachball model, and the deployment of the World-Wide Standardized Seismograph Network in the early 1960s. Sykes (1967) and Isacks et al. (1968) achieved a remarkable endorsement of the mechanisms predicted by plate motions (normal faulting expressing extension at the mid-oceanic ridges, underthrusting expressing convergence at the subduction zones), and most spectacularly, verified the polarity of strike-slip faulting at the oceanic transform faults, thus upholding the concept proposed by Wilson (1965).

Focal mechanisms inside subducting slabs were compiled by Isacks and Molnar (1971), who documented a universal mechanism of down-dip compression for events deeper than 450 km, expressing the difficulty of penetration by the slab of the lower mantle at the bottom of the transition zone. By contrast, a wide diversity of mechanisms is found in the upper parts of the slabs, where local parameters such as rate and steepness of subduction, as well as possible bending stresses, control the stress field accumulated inside the slab during the subduction process.

A most remarkable aspect of the focal mechanisms of deep earthquakes is the fact that, without exception, they can be modeled by a double-couple (e.g., using its beachball representation), even though the concept of brittle rupture should not apply at the relevant pressure and temperature conditions inside the slabs. In particular, modern analysis of major deep earthquakes (Kawakatsu, 1991; Okal, 1996) has ruled out the possibility of an isotropic (implosive) source even as a mere component of their mechanism, as initially envisioned by Bridgman (1945) and proposed by Gilbert and Dziewonski (1975). Deep events represent faulting on a planar dislocation in the framework of Figure 1, and differ from their shallow counterparts only in their usually higher level of stress drop (Antolik et al., 1999), but not in the geometrical or mechanical nature of their process. This observation supports the hypothesis that deep earthquakes may be induced by transformational faulting in volumes of metastable olivine persisting inside the slabs at greater depths than predicted by equilibrium thermodynamics (Kirby et al., 1996).

Modern focal solutions: inversion of the moment tensor

The double-couple used to represent a seismic source can be used, through its components given by Equation 1, as a forcing term in the wave equations expressing the fundamental law of dynamics (a variation of "$\mathbf{F} = m\,\mathbf{a}$"), to compute simulations of the Earth's response in space and time to the seismic disturbance. These are known as *synthetic seismograms.*

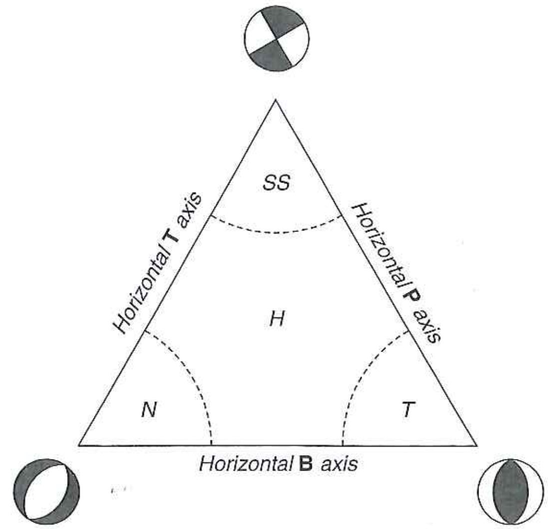
Conversely, and since the 1970s, inversion techniques have been used to derive the individual components of earthquake moment tensors directly from the waveforms of their recorded seismograms. Essentially, a best-fitting algorithm is used to express a large dataset of observed seismograms as a linear combination of synthetic seismograms computed for each individual component of the moment tensor. In addition, and for sufficiently large datasets, the inversion can resolve the best location in space of the source, and its result is known as a "centroid moment tensor" or CMT. These techniques, which can be applied on body waves, surface waves or normal modes, as well as on regional phases in the near field, can be carried out automatically on digital data, and eliminate the occasional difficulty of picking a first motion polarity under noisy or emergent conditions. They have replaced the compilation of *P*-wave first motions as the primary source of earthquake focal mechanisms.

In particular, the Global CMT (*ex*–Harvard CMT) project, described initially by Dziewonski et al. (1981), has now inverted more than 30,000 earthquake sources since 1976, through a uniform, comprehensive procedure, into a catalog that has become the backbone of most modern seismotectonic studies.

Evaluation tools for double-couple solutions

Because of the relative complexity of the double-couple source that cannot be represented by a vector, a number of applications have been developed to illustrate their properties in a user-friendly representation. Among them, Frohlich and Apperson (1992) have proposed to plot focal mechanisms in a ternary diagram whose apices are the "*pure*" mechanisms corresponding to vertical stress axes (**B**, strike-slip; **T**, thrust; or **P**, normal); using barycentric coordinates within the triangle, the position of the mechanism indicates at a glance the nature of faulting (Figure 5). Note that it remains independent of the azimuth ϕ of the fault strike.

In order to help compare different earthquakes, Kagan (1991) has offered an algorithm to quantify the proximity of two focal solutions given by their angles (ϕ_1, δ_1, λ_1) and (ϕ_2, δ_2, λ_2). It computes the angle ω of the minimum solid rotation bringing one of the beachballs onto the other. Because of their symmetry, the maximum value of ω is 120°.



Earthquake, Focal Mechanism, Figure 5 Ternary representation of focal mechanisms (Frohlich and Apperson, 1992). This approach uses barycentric coordinates with respect to end members with one vertical principal axis. Mechanisms close to apices are either predominantly strike-slip (*SS*), thrust (*T*) or normal (*N*). Hybrid mechanisms (*H*) plot in the center of the diagram. By contrast, the sides of the diagram represent geometries with one horizontal axis. This representation is useful when studying trends among large families of mechanisms, such as intraplate earthquakes, irrespective of their particular strike angles.

Non-double-couple solutions

The double-couple is a four-dimensional mathematical entity which constitutes a subset (featuring a zero-eigenvalue) but not a sub-vector space, of the five-dimensional vector space of deviatoric (i.e., zero-trace), symmetric second-order tensors. Consequently, linear inversions are carried out in the full five-dimensional space. The quality of fit of the inverted solution to a double-couple is assessed through a so-called Compensated Linear Vector Dipole (CLVD) parameter ε, expressing the ratio of the intermediate eigenvalue of the moment tensor to its largest one (in absolute value). In principle, ε could range from -0.5 to 0.5, and should be zero for a perfect double-couple. The average value of $|\varepsilon|$ for the whole CMT catalog is 0.12, which constitutes a good verification of the concept of the double-couple, especially since it falls to 0.08 for earthquakes with moments $M_0 \geq 10^{26}$ dyn cm. Occasionally, larger values of $|\varepsilon|$ (which can reach 0.4) indicate a deviation from the model of a double-couple, which may result from a number of scenarios. For example, earthquakes with complex ruptures consisting of multiple events with differing geometries will feature an overall deviatoric moment tensor, which however cannot be described in terms of a lone double-couple. A recent example is the Samoa event of 29 September 2009 ($M_0 \approx 1.8 \times 10^{28}$ dyn cm; $\varepsilon = 0.37$), which was modeled as a main outer rise normal faulting event triggering a smaller underthrusting shock on the nearby interplate contact (Li et al., 2009).

Other examples of non-double-couple solutions would include dyke injections during volcanic events (e.g., Tori-Shima Volcano, 13 June 1984; $\varepsilon = 0.33$; Kanamori et al., 1993), rupture on non-planar faults, again in a volcanic environment (Ekström, 1994), and certain cryoseismic events believed to involve calving at the front of glaciers (e.g., 15 August 2008, $\varepsilon = 0.33$; Nettles and Ekström, 2009).

Conclusion

Focal mechanisms provide a mathematical or illustrative representation of the geometry of the rupture process during an earthquake. Their compilation forms the basis of our interpretation of earthquakes in the framework of global tectonics.

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Cross-references

Earthquakes, Source Theory
Earthquake Rupture: Inverse Problem