Earthquakes with Non–Double-Couple Mechanisms

Cliff Frohlich

Seismological observations confirm that the pattern of seismic waves from some earthquakes cannot be produced by slip along a planar fault surface. More than one physical mechanism is required to explain the observed varieties of these non–double-couple earthquakes. The simplest explanation is that some earthquakes are complex, with stress released on two or more suitably oriented, nonparallel fault surfaces. However, some shallow earthquakes in volcanic and geothermal areas require other explanations. Current research focuses on whether fault complexity explains most observed non–double-couple earthquakes and to what extent ordinary earthquakes have non–double-couple components.

When an earthquake happens, what happens? The generally accepted explanation is that tectonic processes build up differential stresses within some region; when these stresses reach levels that approach the shear strength of rock, sudden slip occurs along a planar fault surface oriented approximately midway between the maximum and minimum stress axes. This fault slip relieves the shear stress and radiates elastic waves, recorded as earthquake waves at distant seismograph stations. Historically, such a mechanism has been called a double couple because the far-field radiation pattern is equivalent to that produced by the application of a pair of force couples at the moment of stress release (*1*).

However, occasionally there are reports of earthquakes with non–double-couple (NDC) mechanisms, for example, with peculiar radiation patterns that cannot be produced by slip along a simple planar fault (*2–4*). Recently observations of NDC mechanisms have become impossible to dismiss because of progress in two areas affecting the determination of earthquake mechanisms. First, the global network of seismographs now includes more than 100 broadband digital stations that routinely provide high-quality observations of both regional and teleseismic earthquakes. Second, scientists at Harvard University (*5*) and the U.S. Geological Survey (USGS) (*6*) now regularly interpret these data and report earthquake mechanisms expressed as seismic moment tensors, a parameterization that includes, but is not limited to, double couples.

The existence of NDC earthquake mechanisms has several significant implications for earth scientists: (i) It implies that there are inadequacies in our conceptual model of an earthquake fault as a planar or simple curved surface along which slip occurs. NDC mechanisms require more complex models, with failure occurring along multiple faults, on fractal surfaces, or within regions having a finite volume. (ii) NDC mechanisms may provide information about the mechanical conditions near the earthquake focus. For example, they might be more common if there were physical inhomogeneities or phase transitions in the near-source region; they might be more common in recently faulted material than along more mature, well-developed faults. (iii) The occurrence of NDC mechanisms affects the interpretation of earthquake catalogs to infer regional stress directions. Some of the apparent variability in stress directions inferred from previous studies of earthquakes may come about because NDC mechanisms have been misinterpreted as double couples.

In this article, I summarize the current understanding of NDC earthquake mechanisms. As background, I first explain the utility of the moment tensor representation of the earthquake mechanism and then review the observations confirming that some earthquakes do possess NDC mechanisms. I then review various explanations for NDC mechanisms and mention some outstanding problems that require more research.

The Moment Tensor

Seismologists generally use a symmetric tensor of rank 3, the seismic moment tensor **M**, to describe the overall pattern of elastic radiation from an earthquake (*7, 8*). A tensor rather than a scalar is necessary because the earthquake induces both longitudinal motions directed toward the focal region (P waves) and transverse motions directed perpendicular to it (S waves) and because the amplitudes of these motions are nonuniform around the focal region (Table 1). When an earthquake occurs, if certain assumptions hold, **M** is proportional to the strain ε released seismically (*9*), which in turn depends on the regional stress σ responsible for the earthquake activity (*10*).

If this strain release occurs as slip on an ordinary planar fault, it generates a double couple (Fig. 1). In this case, **M** has a simple form, with one zero eigenvalue and two eigenvalues of equal absolute value but opposite sign (*11*). For double couples, the size of these nonzero eigenvalues is an excellent measure of the intrinsic size of the earthquake and is called the scalar seismic moment M_0 (*12*). Because the sum of the three eigenvalues is zero, such a mechanism is said to be deviatoric.

The moment-tensor formulation also describes NDC earthquakes (Fig. 2). A possible type of NDC is the isotropic source, such as an explosion or an implosion. A purely isotropic source produces only longitudinal motions that have the same amplitude in all directions. For a purely isotropic source, the three eigenvalues of **M** are equal and their sum is nonzero. However, the most reliable investigations of natural earthquakes have found that the isotropic component is small—less than 10% of the value of the deviatoric component (*13*). Because this value is comparable to the systematic uncertainties in the determination of individual elements of **M**, investigators usually constrain the isotropic component of **M** to be zero when determining the value of **M** for earthquakes. Moreover, to reduce indeterminacy in reported values for **M**, both Harvard and the USGS arbitrarily impose this condition when they prepare catalogs of moment tensors.

Deviatoric NDC mechanisms are also possible, such as the compensated linear vector dipole (CLVD) (*14*). In this mechanism, motion toward (or away from) the focal region along a polar axis compensates

Table 1. Examples of symmetric tensors of rank 3 commonly used in physics and geology. Tensors express the relation between two non-parallel vectors, $\mathbf{v}_1$ and $\mathbf{v}_2$, such that $\mathbf{v}_2 = \mathbf{T}\mathbf{v}_1$.

$\mathbf{v}_2$	$\mathbf{v}_1$	Tensor name	Usual symbol
Angular momentum	Angular velocity	Moment of inertia	**I**
Force/area acting on plane	Unit vector perpendicular to plane	Stress tensor	σ
Deformation	Unit direction vector	Strain tensor	ε
Seismic amplitude	Unit direction vector along ray	Moment tensor	**M**

The author is with the Institute for Geophysics, University of Texas at Austin, 8701 North Mopac Boulevard, Austin, TX 78759, USA.

for motion away from (or toward) the focal region in an equatorial band (Fig. 2). If motion along the polar axis is toward the focus and represents compressional shortening (for example, Fig. 2), the axis is called a P axis and the CLVD is called a polar P type mechanism. Alternatively, if the polar axis represents extensional motion, it is a T axis and a polar T type. For a deviatoric moment tensor **M** that is neither a pure double couple nor a pure CLVD, a simple measure of the deviation from a double couple is the ratio f_{clvd} of the two eigenvalues of **M** having the smallest and largest absolute value, respectively. A pure CLVD has two equal eigenvalues having the same sign and a third eigenvalue of opposite sign but twice as large, so that f_{clvd} is 0.5. In contrast, a pure double couple has one zero eigenvalue, so that f_{clvd} is zero (*15*).

Observations of NDC Earthquakes

All methods to determine earthquake source mechanisms compare specific features of seismograms with features predicted by a model. The features analyzed include the following: (i) first motions of body wave phases recorded at stations surrounding the earthquake focus, (ii) amplitudes of the first cycle or largest cycle of body wave phases at stations surrounding the earthquake focus, and (iii) full waveforms of body or surface waves at one or more seismograph stations.

First motions. The use of first motions relies on the observation that different types of source mechanisms produce a different pattern of P- and S-wave motions at stations surrounding the earthquake focus. That is, isotropic sources produce P motions away from (or toward) the focus at all recording stations, double couples produce P motions both toward and away from the focus in a quadrantal pattern, and CLVD mechanisms produce a polar or zonal pattern (Fig. 2). Thus, in principle one can determine the type of mechanism if one can identify enough phases and determine at what direction they left the focal region. In practice, this method is complicated by two difficulties: (i) Often the stations cover only a small part of the focal sphere; and (ii) the direction of the first motion is sometimes unclear, either because of noise, instrumental polarity errors, or because the phase left the focus along a direction with low amplitudes.

Although most first motion studies find that the vast majority of well-recorded earthquakes have first motion patterns consistent with a double couple (*16*), in a few cases the motions appear to support an NDC, especially for earthquakes on normal faults at mid-ocean ridges (*2, 17, 18*). However, intensive analysis of these and similar mechanisms strongly suggests that they are ordinary double-couple events. In Fig. 3, for example, the first motions for one earthquake on the northern mid-Atlantic ridge are all compressions, suggesting an isotropic source, and for another earthquake the nodal planes separating quadrantal first motions subtend an angle of about 55°, rather than the 90° expected for a double couple. Yet, analysis of surface wave data (*19*) and the ray tracing of near source structure (*20*) demonstrated that both events were double couples, with the apparent NDC sources caused by the shallow focal depth and by the incorrect modeling of the velocity structure beneath the mid-ocean ridge axis. Such systematic ambiguities afflict all or most reported NDC mechanisms determined from teleseismic first motion data. Thus, none of the first motion investigations demonstrate the existence of NDC mechanisms for earthquakes with magnitudes greater than about 5.5.

In a few areas there are local seismic networks with sufficient azimuthal coverage and number of stations to determine first motion mechanisms for much smaller earthquakes. The most convincing first motion evidence for NDC has come from volcanic and geothermal areas near Iceland (*21*). There, 40 to 50% of the well-recorded earthquakes had NDC mechanisms, all with magnitudes between about −2 and +1 and a preponderance of compressional first motions, consistent with the opening of vertical tensile cracks (*22*). There are also reports of small events whose motions apparently represent the collapse or closing of cracks, both in geothermal areas (*23, 24*) and in mines (*25*).

Amplitudes. A second method to determine mechanisms is to compare amplitudes of the first or largest cycle of body wave phases with predictions for some family of models. For example, Randall and Knopoff (*3*) applied such a method to five deep and intermediate focus earthquakes occurring in 1964 and 1965. They found that isotropic components were as large as 10% of the scalar moment and CLVD components were 18 to 98%. Similarly, Fitch and colleagues (*26*) found the isotropic component to be about 9% and the CLVD component to be about 19% for a deep Bonin earthquake. More recently, Pearce and others (*27*) have applied a method of this type to numerous events to determine the range of mechanisms consistent with amplitude data. Generally, they find this range includes double couples as well as mechanisms with significant isotropic or CLVD components.

The advantage of using amplitude information rather than first motions alone is that amplitude methods are influenced less

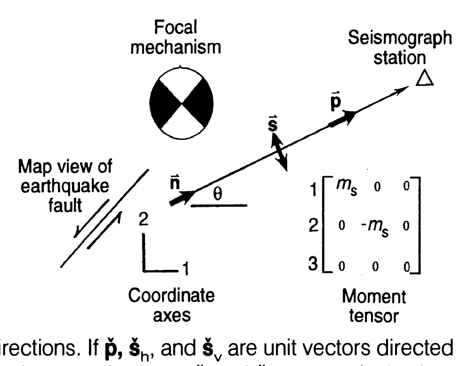


Fig. 1. Representations of earthquake mechanisms and explanation of the moment tensor. An earthquake that causes horizontal motion along a vertical fault (left) radiates both compressional (P) and shear (S) waves along direction $\check{\mathbf{n}}$, toward the seismograph station (right). A "beachball" focal mechanism is a diagram of an imaginary sphere surrounding the earthquake focus with away-from focus and toward-focus P motions colored black and white, respectively. A moment tensor **M** is 3 by 3 matrix (lower right), giving the relative amplitude of P and S waves as they leave the focus in different directions. If $\check{\mathbf{p}}$, $\check{\mathbf{s}}_h$, and $\check{\mathbf{s}}_v$ are unit vectors directed parallel to $\check{\mathbf{n}}$, perpendicular to $\check{\mathbf{n}}$ and horizontal, and perpendicular to $\check{\mathbf{n}}$ and $\check{\mathbf{s}}_h$, respectively, then the observed amplitudes of seismic waves are proportional to the scalar moment M_0, with directional variations in amplitude for P waves, horizontally polarized S waves, and vertically polarized S waves depending on the products $\check{\mathbf{p}}\mathbf{M}\check{\mathbf{n}}$, $\check{\mathbf{s}}_h\mathbf{M}\check{\mathbf{n}}$, and $\check{\mathbf{s}}_v\mathbf{M}\check{\mathbf{n}}$, respectively. The exact values of the amplitude also depend on the distance from the quake to the station and on Earth structure (*30*).

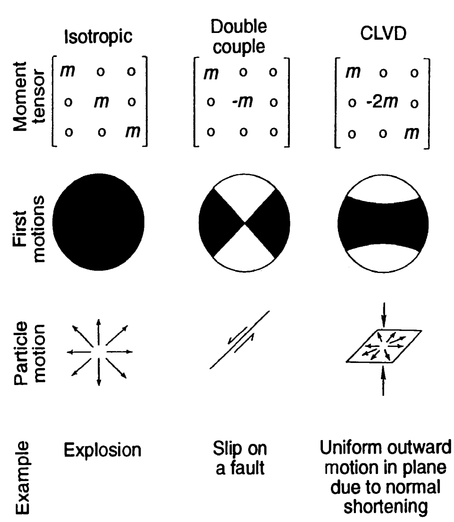


Fig. 2. Three types of earthquake mechanisms representable by a moment tensor. For an isotropic source such as an explosion or implosion, the sum of the eigenvalues of **M** [that is, Tr(**M**)] is nonzero. For a double-couple source with quadrantal first motions such as caused by planar fault slip, Tr(**M**) is zero and the determinant of **M** [det(**M**)] is also zero. The compensated linear vector dipole (CLVD) is an NDC mechanism with opposite motions along polar and equatorial regions of the focal sphere; for a CLVD, Tr(**M**) is zero but det(**M**) is nonzero (*30*).

by small amplitude arrivals near nodal planes. However, in practice amplitude inversions seem to be fraught with systematic errors, probably because amplitude is affected by much besides the earthquake mechanism, including attenuation, lateral heterogeneity of along-path mantle velocity structure, variation in near-station crustal properties, and fine adjustments of the seismograph station response. Thus, these methods do not convincingly demonstrate the existence of NDC mechanisms (*28*), except possibly for small events in volcanic regions and in mines (*23, 29*).

Full waveforms. The most abundant evidence supporting the existence of NDC mechanisms comes from the comparison of synthetically generated seismograms and long-period (f < 0.025 Hz) recordings of earthquakes. In the Harvard catalog, moment tensors have been routinely determined for all earthquakes occurring since 1977 with magnitudes (M_w) of about 5.5 or greater, or about 800 events per year (*5*). Of the more than 10,000 moment tensors in the catalog, 20% have CLVD components of 40% or more (Fig. 4), and the median value of the NDC component is 20% (*30*). Among the best determined 1149 moment tensors in the catalog, 283 possessed NDC components that were 40% or larger, with an uncertainty of 20% or less (*31*). For deep and intermediate focus earthquakes, the incidence of well-determined NDC mechanisms is higher than for shallow earthquakes (*31*). The analysis of real and synthetic data compared with the use of frequency domain inversion methods gives significant proportions of NDC mechanisms (*32, 33*). For example, in the USGS routine determinations, about 7% of earthquakes have NDC components of 40% or more (*34, 35*).

Numerous subsequent investigations of individual earthquakes have demonstrated that some do indeed possess NDC mechanisms. That is, they possess predominantly CLVD mechanisms as determined from long-period inversions, and the CLVD components observed cannot be attributed to systematic errors in the inversion process (Fig. 5). In some studies, data from modern broad-band digital seismographs have been used that provide information at frequencies from less than 0.005 Hz to more than 1 Hz. When long-period waveform inversion finds an NDC mechanism, the shorter period data often indicate that the event consists of two or more subevents separated in time by 5 to 10 s (*35–38*). Sometimes these subevents have differing double-couple mechanisms that add together to form a CLVD.

Finally, the detailed analysis of individual well-recorded earthquakes demonstrates that some clearly have NDC mechanisms. For example, the 13 June 1984 Tori Shima earthquake is especially peculiar (*39*). It generated no Love waves, which would be produced if it had been a double couple. Its reported body wave magnitude, m_b, is 5.5, indicating that it was relatively small, yet it generated a 58-cm tsunami 500 km from the focus, as would be expected for an event with magnitude M_w of about 7.2.

Two extensively studied earthquake sequences are of historical significance, although their mechanisms remain controversial, because they stimulated intensive research on methods to resolve NDC mechanisms, possible systematic errors that might produce spurious NDC mechanisms, and physical mechanisms that might cause NDC earthquakes. The first is the 31 July 1970 Colombia earthquake (m_B = 7.5, depth = 653 km), the largest deep earthquake recorded during the 20th century. Gilbert and Dziewonski (*4*) suggested that this earthquake possessed an isotropic precursor and a CLVD component about four times larger than the double-couple component; however, other studies (*40*) disputed this result. Skepticism is reasonable because there is difficulty in obtaining good on-scale recordings for such a large earthquake and because, when it occurred, methods to retrieve moment tensors were in their infancy.

The second intensively studied event is the Mammoth Lakes, California, earthquake sequence of May 1980. This sequence included four events with magnitudes greater than 6 and was well recorded at both regional and teleseismic stations. Although several investigators favored a CLVD for the 25 May event because of both first motion data (*41*) and full waveform inversion (*42, 43*), others found that one or more double couples fit the long-period waveforms equally well (*44*) or that the discrepancies might be attributed to systematic problems in the inversion method (*45*). The contemporary interpretation that best explains the observations is that the event consisted of two or more subevents occurring a few seconds apart, which together produced an NDC mechanism, as determined from long-period observations (*43, 44*).

Causes of NDC Mechanisms

What mechanism is responsible for persistent observations of NDC earthquakes? If landslides and impacts of extraterrestrial objects are excluded (*8*), the proposed mechanisms can be defined in two possible ways: (i) The observed NDC components are spurious, caused by systematic errors in

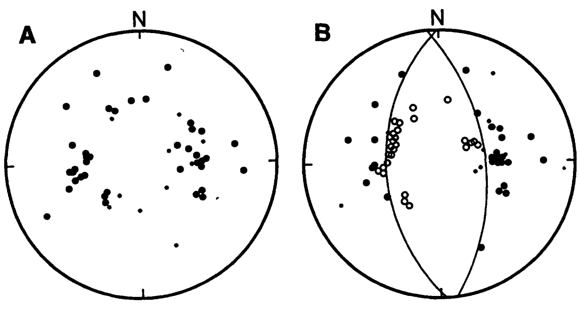


Fig. 3. P wave first motions apparently suggesting NDC mechanisms for earthquakes occurring near Iceland on (**A**) 24 April 1970 and (**B**) 3 April 1972 (*18*). Filled circles are compressional (motion away from focal region) first motions, and open circles are dilatational first motions (motion toward focus). The all-compressional first motions for the earthquake in (A) apparently confirm an isotropic source component. However, Trehu and colleagues (*19*) demonstrated instead that the extreme shallowness of the focus masks dilatational first motions. For the event in (B), the nonorthogonal nodal planes (lines on the diagram separating open and filled circles) also suggest an NDC mechanism, but instead are caused by inadequate assumptions about the velocity in the focal region (*20*). The first motions are plotted on a lower hemisphere surrounding the focal region, with greater distances from the center representing greater deviations from vertical for rays leaving the focus, and the azimuth corresponding to the azimuth of the observing seismograph station relative to the focus. Thus, rays leaving the focus vertically plot in the center and rays leaving horizontally plot on the edges.

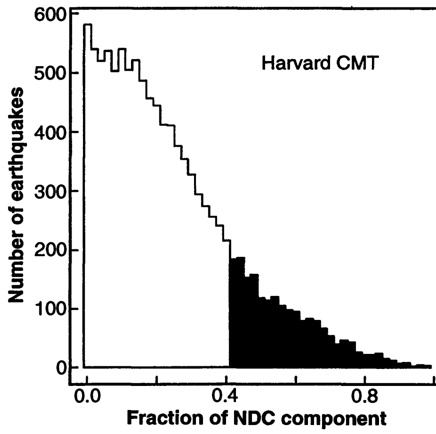


Fig. 4. Distribution of the NDC component of earthquakes in the Harvard catalog. Data are from events occurring between January 1977 and March 1993. The NDC fraction plotted on the horizontal axis is $2f_{clvd}$; that is, twice the ratio of the moment tensor eigenvalues having the smallest and largest absolute value. The value plotted on the vertical axis is the number of reported earthquakes in bins of width 0.02. Earthquakes with 40% or greater NDC component (colored black on histogram) constitute about 20% of all reported earthquakes.

the process of determining the mechanism, or (ii) the observed NDC mechanisms are real and caused by physical processes occurring within the Earth.

Systematic errors. Most systematic errors arise because there are inadequacies in the model used to process the observations or to determine synthetics for comparison with the data. Perhaps the most straightforward errors occur when there are unmodeled velocity irregularities near the focal region. For example, the nonperpendicular nodal planes observable in Fig. 3 are attributable (*20*) to unmodeled velocity structure near the mid-ocean ridge—rays leaving the focus are more strongly bent in the Earth than in the model, so that the focal plot of first motions is incorrect. Similarly, the absence of observable dilatational first motions for the focal sphere at right in Fig. 3 occurred because the shallowness of the focus allowed phases leaving the focal region and traveling upward to reflect and effectively cancel the initial half cycle of downgoing phases (*19*). Spurious NDC components may arise from a double couple that occurs near a discontinuity in velocity if the process to determine mechanism incorrectly places the focus on the wrong side of the discontinuity (*15, 46*). Finally, inhomogeneities in the velocity structure near the focus may permit the occurrence of reflected or trapped phases that follow the initial arrival and that will be mismodeled as subevents (*47*).

For shallow focus earthquakes, there are two additional sources of error. (i) There usually are observations available only from the lower part of the focal sphere; that is, there are no stations providing information about the source from rays leaving the focus horizontally and upward. (ii) Two of the six independent components of the moment tensor **M** approach zero as the depth of focus approaches the surface (*10*). In practice, this relation tends to make inversions to determine moment tensors unstable, especially if long-period observations such as surface waves are used in the determination of these tensors. Systematic errors of this kind may be responsible for reports that the NDC component of earthquakes differs for large and small events (*48–50*).

For deeper earthquakes, a well-organized structure such as a subducting plate can systematically affect amplitudes or waveforms so that a pure double couple will appear to have a CLVD component. However, modeling demonstrates that if the data are collected from a reasonable number of directions covering the focal sphere, then the spurious CLVD component will have a magnitude similar to that of the velocity anomaly. Thus, if the subducting slab is 10% faster than the surrounding mantle or if there is directional anisotropy of 10%, then the spurious CLVD component will be smaller than 10 to 20% of the total moment (*15, 46, 51, 52*). However, it is possible to obtain even larger spurious NDC components if station coverage around the focal sphere is poor (*52, 53*).

Similarly, waveform inversions may find spurious NDC mechanisms if the seismograms are noisy or if the data possess arrivals of unknown origin (*54*). As before, simulations with synthetic data show that if the station coverage is adequate, the contribution of the NDC component is generally approximately equal to the root-mean-square proportion of noise in the data (*55*).

Physical processes. If NDC mechanisms are real, what might cause them? One suggestion is that they are implosions associated with mineralogical phase transitions within the crust and mantle (*56–58*). However, for reliable earthquake observations, the double-couple components are always much larger than the reported isotropic components (*13*), and even known nuclear explosions produce radiation patterns with substantial double-couple components (*59*). Thus, even if phase transitions are a factor in earthquake occurrence, they must always occur in an environment that releases considerable shear stress. This condition could exist either (i) because the phase transitions are a precursory phenomenon occurring too slowly to release substantial elastic radiation, with the earthquakes representing the adjustment of nearby material to volume changes associated with the transition (*4, 57*), or (ii) because the phase transitions are shear stress–dependent, and so in a region approaching failure they occur first in a small volume region along the plane of maximum shear stress (*58*). If actual earthquakes do possess a small isotropic component, then both the Harvard and USGS inversion methods would instead find a mechanism with a small CLVD component (*7*), because both assume that the mechanism is deviatoric.

A second possible physical mechanism to explain NDC earthquakes is that they represent the opening and closing of tensile cracks (*60*). These cracks may open either because of the action of magma or groundwater or because of contraction caused by cooling. Unless there is a source of high-pressure fluid to open the cracks, this mechanism is only plausible for relatively shallow earthquakes because overburden pressures do not allow cracks to open except at depths of a few kilometers or less (*61*). Tensile crack formation is the most plausible explanation for the peculiar small earthquakes observed in Iceland (*21, 22, 24*) and Japan (*23*), and possibly for the Mammoth Lakes (*41–43*) and Tori Shima (*39*) earthquakes as well.

The third and perhaps most attractive explanation for NDC mechanisms is that they represent complex earthquakes with two or more subevents separated in space and in time occurring on suitably oriented, nonparallel faults (Fig. 6). This explanation is appealing because there is abundant evidence that many earthquakes consist of subevents (*36, 37, 62*) and that even simple, well-developed fault zones possess offshoots and adjacent regions where there is evidence for failure on surfaces not parallel to the main fault (*63*). Moreover, several NDC earthquakes possess suitably oriented, double-couple subevents (*36, 37, 42, 43*).

Although approximately 20% of the earthquakes in the Harvard catalog have mechanisms that are 40% or more NDC (Fig. 4), it is unknown whether most contain subevents.

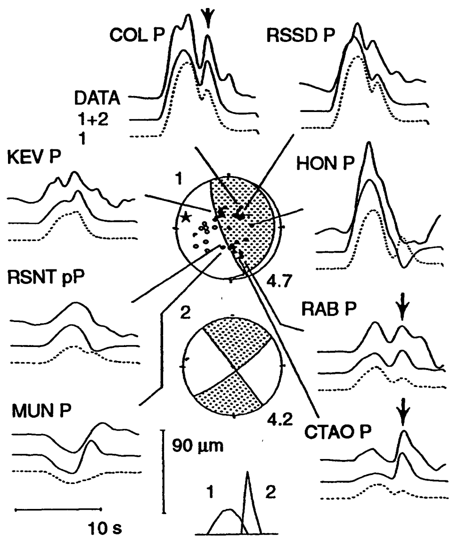


Fig. 5. Evidence that subevents with different mechanisms are responsible for NDC mechanisms. The figure presents observed and synthetic broad-band seismograms for the NDC earthquake occurring on 1 January 1984 at 386 km depth beneath Japan. At each station, the upper solid waveform is the P or pP displacement seismogram. The middle waveform is a synthetic calculated on the assumption of two subevents with disparate mechanisms 1 and 2 shown in the center. The lower waveform is a synthetic calculated on the assumption that the two subevents have the same focal mechanism. The subevent interpretation is essential to an explanation of the large amplitudes of the second subevent at stations to the south and north (see arrows). Initial up and down motions for long-period records are plotted as open and closed circles, respectively, on focal sphere 1, and the star symbol represents the relative location of the second subevent with respect to the location of the initial rupture. The abbreviations for stations are as follows: MUN, Mundaring, Australia; RSNT, Yellowknife, Canada; KEV, Kevo, Finland; COL, College Outpost, Alaska; RSSD, Black Hills, South Dakota; HON, Honolulu, Hawaii; RAB, Rabaul, New Guinea; and CTAO, Charters Towers, Australia (*36*).

However, of well-determined NDC earthquakes occurring along oceanic ridge transforms, along shallow subduction zones, and within Wadati-Benioff zones, about 70% had the proper polarity (polar T or polar P) and orientation (horizontal or vertical) to be made up of subevents produced by the most prevalent stress systems in these tectonic regimes (*31, 38, 64*) (Fig. 7). For example, NDC earthquakes along oceanic ridge-transform systems are generally horizontal, polar T

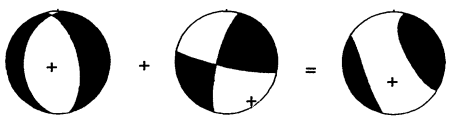
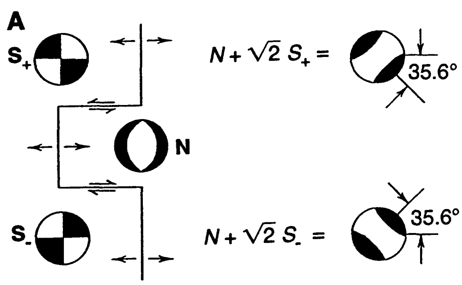


Fig. 6. Two double-couple subevents of the same size but different orientations together can produce a CLVD. For the 25 May 1980 Mammoth Lake earthquake, Ekstrom and Dziewonski (*43*) found a normal faulting subevent with a scalar moment of 1.5 × 10^{18} N·m (left) and a strike-elip subevent with a moment of 1.4 × 10^{18} N·m occurring 7 s later (center). In long-period seismograms, they appear as a mechanism with a 61% NDC component and a scalar moment of 2.2 × 10^{18} N·m (right).

earthquakes, explainable as sums of ordinary ridge-normal and transform strike-slip events (*48*). All these observations are consistent with the subevent hypothesis. However, this hypothesis cannot explain all observed NDC mechanisms. For example, for the 13 June 1984 Tori Shima earthquake, the multiple subevent hypothesis would require subevents too small to explain the observed tsunami (*39*).

A final suggestion is that CLVD earthquakes might be caused by slip along curved fault surfaces (*49, 65*). This relation is true only in a limited sense, because any slip pattern generated by a rotation about an axis produces a pure double couple. To obtain a CLVD on a curved fault, one must have a nonsymmetric pattern of slip (*65*). A more plausible model is that the deformation is so complex that it effectively occurs as a loss of rigidity within a volume rather than as slip along a fault plane (*14*), or that the slip pattern and fault surface have a complicated fractal geometry (*66*). However, observations indicate that the summing of moment tensors for groups of earthquakes occurring along plate boundaries nearly always produces a sum tensor that has a fractional NDC component smaller than the median NDC component for the individual earthquakes (*30*). Thus, if fractal faulting is responsible for NDC mechanisms, then the scaling appropriate for individual earthquake ruptures does not extend to dimensions as large as entire plate boundaries.



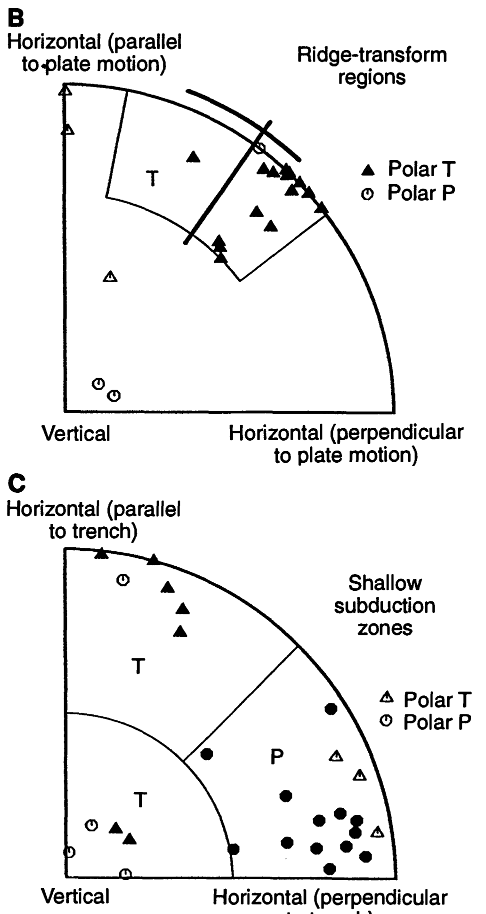


Fig. 7. Orientations of shallow CLVD mechanisms generally agree with predictions of the subevent model. In oceanic ridge-transform regions (**A**), the model predicts that strike-slip (S_+ and S_-) double couples along transforms combine with normal (N) double couples to form CLVD sources with horizontal polar T axes oriented 35.6° from the direction of plate motion. Observations plotted in (**B**) indicate that 70% of mechanisms agree with the model (filled triangles in box labeled "T"), while 30% are in disagreement (open symbols). In shallow subduction zones (**C**) an analogous model predicts that polar P mechanisms are horizontal and perpendicular to trench (sector labeled "P"), while polar T mechanisms are vertical or parallel to trench (sectors labeled "T"). Here, 74% of the mechanisms are in agreement with the model (filled symbols). Pie diagrams represent a quarter hemisphere, with vertical polar axes of the CLVD mechanism plotted at lower left, and horizontal polar axes along the curved edge of the plot, perpendicular to plate motion or trench at lower right and parallel to plate motion or trench at upper left. Triangles represent polar T mechanisms, and circles represent polar P mechanisms. Data are Harvard centroid moment tensors with well-determined CLVD mechanisms from earthquakes occurring along tectonically simple ridge-transform and shallow subduction zone regions (*31*).

Conclusions

The description of earthquake mechanisms in terms of moment tensors has coincided with major advances in an understanding of the causes and observable variety of earthquake mechanisms. With the observations now available, it is no longer possible to dismiss all reported NDC mechanisms as artifacts of the process to determine mechanism. Some small, near-surface earthquakes clearly have isotropic components, but for larger and deeper events, if isotropic components exist they are probably less than 10% of the total moment. NDC earthquakes with CLVD components clearly do exist; although they are somewhat more common among deep and intermediate earthquakes, they occur in a variety of shallow tectonic environments as well.

The most important unresolved questions are: (i) Do most reported earthquakes with large CLVD components possess demonstrable complexity; that is, do they possess two or more suitably oriented double-couple subevents? (ii) What mechanism is primarily responsible for the approximately 20% CLVD component observed for typical earthquakes in the Harvard catalog? This component could either be an important clue that earthquake fault zones are not planar but intrinsically complex or that the observed CLVD component is simply an artifact of systematic errors in the process of determining earthquake mechanisms. (iii) Are NDC earthquakes indicative of unusual mechanical, rheological, or tectonic conditions near the earthquake focus?

REFERENCES AND NOTES

1. B. V. Kostrov and S. Das, *Principles of Earthquake Source Mechanics* (Cambridge Univ. Press, Cambridge, 1988).
2. L. R. Sykes, *J. Geophys. Res.* 72, 2131 (1967).
3. M. J. Randall and L. Knopoff, *ibid.* 75, 4965 (1970).
4. F. Gilbert and A. M. Dziewonski, *Philos. Trans. R. Soc. London Ser. A* **278**, 187 (1975).
5. The Harvard University catalog includes moment tensors for about 800 earthquakes each year, beginning with earthquakes occurring in 1977. The inversion procedure compares digital seismograms low-pass filtered at about 0.025 mHz with synthetics constructed by the superimposition of 5000 normal modes of the Earth. Harvard performs the final inversion in the time domain and constrains the moment tensor to be deviatoric [A. M. Dziewonski and J. H. Woodhouse, in *Earthquakes: Observation, Theory and Interpretation*, H. Kanamori and E. Boschi, Eds. (North-Holland,

Amsterdam, Netherlands, 1983), pp. 45–137].

6. The USGS catalog includes moment tensors for selected earthquakes occurring since 1982. The USGS constructs body-wave synthetics with the Wentzel, Kramers, Brillouin, and Jeffreys (WKBJ) method, performs the inversion in the time domain, and constrains the moment tensor to be deviatoric [S. A. Sipkin, *Phys. Earth Planet. Inter.* **30**, 242 (1982)].
7. It has been demonstrated that a 3 by 3 symmetric moment tensor **M** is sufficient to describe the far-field, low-frequency elastic radiation from sources whenever the net force and net torque applied to generate the source are zero [M. J. Randall, *Bull. Seismol. Soc. Am.* **61**, 1321 (1971); F. Gilbert, *Geophys. J. R. Astron. Soc.* **22**, 223 (1971)]. This is always true for sources originating beneath the Earth's surface.
8. In rare cases, landslides or impacts of extraterrestrial objects may apply forces to the Earth's surface, producing seismic radiation patterns not describable by a moment tensor [A. Benmenahem, *Phys. Earth Planet. Inter.* **11**, 1 (1975); H. Kawakatsu, *J. Geophys. Res.* **94**, 12363 (1989)].
9. The moment-tensor formulation of earthquake mechanisms is also useful because within any volume V in the Earth there is a simple relation between the total moment $\Sigma \mathbf{M}$ of earthquakes occurring within V and the tensor ε describing strain relieved by earthquake activity; that is,
$$\Sigma M = \varepsilon/(2\mu V)$$
where μ is the rigidity of the material within V [V. V. Kostrov, *Izv. Acad. Sci. USSR Phys. Solid Earth, Engl. Transl.* **1**, 23 (1974)]. When the earthquakes occur as slip along a fault zone having surface area A,
$$\Sigma M = \mu A S$$
where ΣM_o is the sum of scalar seismic moment of events in V, and S is the average slip along the fault zone (*30*). At plate boundaries over sufficiently long times, the rate of slip dS/dt is the seismically released part of the motion across the faults forming the boundary. Thus, these relations allow the comparison of slip caused by earthquake activity to the total motion along plate boundaries or the comparison of moment release to more general models of deformation within a specific geographic region.
10. In a perfectly elastic, unfractured material, the stress σ would be proportional to the strain ε, and so $\sigma \sim \varepsilon \sim \mathbf{M}$. Thus, seismologists often use the P and T axes of **M** as crude indicators of maximum and minimum stress. Near a free surface like that of the Earth, the fact that some components of stress, σ, approach zero means that corresponding components of ε and **M** must approach zero as well.
11. Thus, in analogy to the stress tensor σ, the double-couple mechanism is like the deviatoric stress, whereas the isotropic source is like the hydrostatic stress.
12. More generally, if m_{ij} are the components of a 3 by 3 moment tensor **M**, then the scalar moment $M_o = (\Sigma m_{ij}^2/2)^{1/2}$.
13. H. Kawakatsu, *Nature* **351**, 50 (1991).
14. L. Knopoff and M. J. Randall, *J. Geophys. Res.* **75**, 4957 (1970).
15. Any moment tensor **M** can be decomposed into three components: one a purely isotropic component, $\mathbf{M}_I$; one a pure double couple, $\mathbf{M}_{DC}$; and one a pure CLVD, $\mathbf{M}_{CLVD}$. If A, B, and C are the eigenvalues of **M**, then the eigenvalues of $\mathbf{M}_I$ are just $(A + B + C)/3$. Suppose a, b, and c are the remaining differences (that is, $a = A - (A + B + C)/3$ and suppose $|b| < |c| < |a|$. Then, $\mathbf{M}_{DC}$ has eigenvalues $(a - c)/2$, 0, and $-(a - c)/2$, and $\mathbf{M}_{CLVD}$ has eigenvalues $-b/2$, b, and $-b/2$ [R. A. Strelitz, *Geophys. J. Int.* **99**, 811 (1989)].
16. B. L. Isacks and P. Molnar, *Rev. Geophys. Space Phys.* **9**, 103 (1971).
17. W. Thatcher and J. N. Brune, *Geophys. J. R. Astron. Soc.* **22**, 473 (1971).
18. P. Einarsson, *Tectonophysics* **55**, 127 (1979).
19. A. M. Trehu, J. L. Nabelek, S. C. Solomon, *J. Geophys. Res.* **86**, 1701 (1981). These workers demonstrated that the surface waves were consistent with a double couple and showed that the compressional first motions over much of the focal sphere were artifacts caused because the focal depth was extremely shallow. Interference from upgoing rays reflected at the surface affected downgoing rays with dilatational motions, so that the observed motions were compressional.
20. S. C. Solomon and B. R. Julian, *Geophys. J. R. Astron. Soc.* **38**, 265 (1974).
21. F. W. Klein, P. Einarsson, M. Wyss, *J. Geophys. Res.* **82**, 865 (1977); G. Foulger and R. E. Long, *Nature* **310**, 43 (1984); G. R. Foulger, *J. Geophys. Res.* **93**, 13493 (1988); *ibid.*, p. 13507.
22. G. R. Foulger and B. R. Julian, *Bull. Seismol. Soc. Am.* **83**, 38 (1993).
23. H. S. Shimizu, S. Ueki, J. Koyama, *Tectonophysics* **144**, 287 (1987).
24. G. R. Foulger, R. E. Long, P. Einarsson, A. Bjornsson, *Nature* **337**, 640 (1989).
25. S. J. Gibowicz, H.-P. Harjes, J. Schafer, *Bull. Seismol. Soc. Am.* **80**, 88 (1990); S. J. Gibowicz, R. P. Young, S. Talebi, D. J. Rawlence, *ibid.* **81**, 1157 (1991); M. C. Stickney and K. F. Sprenke, *J. Geophys. Res.* **98**, 6523 (1993).
26. T. J. Fitch, D. W. McCowan, M. W. Shields, *J. Geophys. Res.* **85**, 3817 (1980).
27. R. M. Rogers and R. G. Pearce, *Phys. Earth Planet. Inter.* **47**, 93 (1987); I. G. Stimpson and R. G. Pearce, *ibid.*, p. 107; R. G. Pearce and R. M. Rogers, *J. Geophys. Res.* **94**, 775 (1989); R. M. Rogers and R. G. Pearce, *ibid.* **97**, 14083 (1992).
28. R. A. Strelitz, *Geophys. J. R. Astron. Soc.* **52**, 359 (1978).
29. J. Sileny, *Pure Appl. Geophys.* **129**, 309 (1989).
30. C. Frohlich and K. D. Apperson, *Tectonics* **11**, 279 (1992).
31. C. Frohlich, in preparation.
32. P. G. Silver and T. H. Jordan, *Geophys. J. R. Astron. Soc.* **70**, 755 (1982); *J. Geophys. Res.* **88**, 3273 (1983).
33. M. A. Riedesel, thesis, University of California, San Diego (1985).
34. S. A. Sipkin, *Bull. Seismol. Soc. Am.* **76**, 1515 (1986); ______ and R. E. Needham, *Phys. Earth Planet. Inter.* **57**, 233 (1989).
35. S. A. Sipkin, *Phys. Earth Planet. Inter.* **47**, 67 (1987).
36. K. Kuge and H. Kawakatsu, *Geophys. Res. Lett.* **17**, 227 (1990).
37. ______, *Geophys. J. Int.* **111**, 589 (1992).
38. ______, *Phys. Earth Planet. Inter.* **75**, 243 (1993).
39. K. Satake and H. Kanamori, *J. Geophys. Res.* **96**, 19933 (1991); H. Kanamori, G. Ekstrom, A. Dziewonski, J. S. Barker, S. A. Sipkin, *ibid.* **98**, 6511 (1993).
40. E. A. Okal and R. J. Geller, *Phys. Earth Planet. Inter.* **18**, 176 (1979).
41. B. R. Julian, *Nature* **303**, 323 (1983).
42. ______ and S. A. Sipkin, *J. Geophys. Res.* **90**, 11155 (1985); S. A. Sipkin, *ibid.* **91**, 531 (1986).
43. G. Ekstrom and A. M. Dziewonski, *Bull. Seismol. Soc. Am.* **75**, 23 (1985).
44. J. W. Given, T. C. Wallace, H. Kanamori, *ibid.* **72**, 1093 (1982); T. C. Wallace, *J. Geophys. Res.* **90**, 11171 (1985); ______, J. Given, H. Kanamori, *Geophys. Res. Lett.* **9**, 1131 (1982).
45. J. S. Barker and C. A. Langston, *Geophys. J. R. Astron. Soc.* **68**, 777 (1982); *Bull. Seismol. Soc. Am.* **73**, 419 (1983).
46. J. H. Woodhouse, *Geophys. Res. Lett.* **8**, 1129 (1981).
47. Recently, it has been shown by the construction of synthetic seismograms that the bathymetry and upper-mantle structure near subduction zones may cause phases to arrive up to 20 s after the initial P arrival at some stations [T. Okamoto, *Geophys. J. Int.* **112**, 471 (1993)].
48. H. Kawakatsu, *Geophys. Res. Lett.* **18**, 1103 (1991).
49. A. Kubas and S. A. Sipkin, *ibid.* **14**, 339 (1987).
50. K. Kuge and T. Lay, *ibid.* **21**, 9 (1994).
51. I. Kawasaki and T. Tanimoto, *Bull. Seismol. Soc. Am.* **71**, 37 (1981); I. Kawasaki, *Geophys. J. R. Astron. Soc.* **71**, 395 (1982); T. Tada and K. Shimazaki, *Bull. Seismol. Soc. Am.*, in press.
52. C. A. Langston and W. A. Arnold, *Geophys. Res. Lett.* **9**, 1290 (1982).
53. D. J. Doornbos, *J. Geophys. Res.* **90**, 5466 (1985); D. W. Vasco and L. R. Johnson, *Geophys. J. Int.* **97**, 1 (1989); D. W. Vasco, *Bull. Seismol. Soc. Am.* **80**, 354 (1990).
54. C. K. Saikia and R. B. Herrmann, *Bull. Seismol. Soc. Am.* **76**, 709 (1986).
55. K. Satake, *ibid.* **75**, 1657 (1985); M. L. Jost and R. B. Herrmann, *Seismol. Res. Lett.* **60**, 37 (1989).
56. J. D. Bernal, *Observatory* **59**, 265 (1936); P. W. Bridgeman, *Am. J. Sci.* **243A**, 90 (1945); F. F. Evison, *Bull. Seismol. Soc. Am.* **53**, 873 (1963).
57. H. Benioff, *Science* **143**, 1399 (1964).
58. S. H. Kirby, *J. Geophys. Res.* **92**, 13789 (1987); ______, W. B. Durham, L. A. Stern, *Science* **252**, 216 (1991).
59. T. Lay, T. C. Wallace, D. V. Helmberger, *Bull. Seismol. Soc. Am.* **74**, 819 (1984).
60. M. Ishimoto, *Bull. Earthquake Res. Inst. Tokyo Univ.* **10**, 453 (1932); G. R. Robson, K. G. Barr, L. C. Luna, *Nature* **218**, 28 (1968).
61. For ordinary materials, the overburden stress at a depth of 3 km is on the order of the strength of rock [H. Jeffreys, *The Earth* (Cambridge Univ. Press, Cambridge, ed. 6, 1976), pp. 16–18].
62. M. Kikuchi and Y. Fukao, *Tectonophysics* **144**, 231 (1987); G. L. Choy and J. Boatwright, *Bull. Seismol. Soc. Am.* **71**, 691 (1981); G. L. Choy and E. R. Engdahl, *Phys. Earth Planet. Inter.* **47**, 80 (1987); R. J. Willemann and C. Frohlich, *J. Geophys. Res.* **92**, 13927 (1987).
63. A. J. Michael, *J. Geophys. Res.* **94**, 5615 (1989).
64. D. Giardini, in *Earthquakes: Observation, Theory and Interpretation*, H. Kanamori and E. Boschi, Eds. (North-Holland, Amsterdam, Netherlands, 1983), pp. 345–383; A. M. Dziewonski and J. H. Woodhouse, *J. Geophys. Res.* **88**, 3247 (1983).
65. C. Frohlich, M. A. Riedesel, K. D. Apperson, *Geophys. Res. Lett.* **16**, 523 (1989); C. Frohlich, *J. Geophys. Res.* **95**, 6861 (1990).
66. K. Kuge and T. Lay, *J. Geophys. Res.*, in press.

67. I thank T. Lay, S. Sipkin, and L.-S. Zhao for comments that improved an earlier draft of this manuscript. Supported by research grants from the NSF and the U.S. Air Force.