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CURRENT PROBLEMS IN RESEARCH

Earthquake Mechanisms

Seismograms give clues to possible mechanisms that convert potential into kinetic energy at the source.

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The seismographic record of an earthquake consists of a succession of vibrations divided into groups of varying appearance. Seismologists began careful study of seismograms about 1880 and throughout the years have succeeded in explaining many of these wave groups. The first waves to arrive are of the longitudinal type: the earth particles vibrate back and forth along the rays perpendicular to the wave front. The wave is one of compression and rarefaction. A later group is a transverse or shear wave. The particles vibrate at right angles to their paths. The longitudinal waves were early named *P* (primary); the transverse waves, *S* (secondary). It has been shown that these waves penetrate into the earth's interior, returning to the surface by refraction, since their speeds generally increase with depth in the earth.

That *P* waves are strictly longitudinal as they record at the earth's surface or that *S* waves are strictly transverse is not borne out by observation. Theoretically, in an "ideal" medium they should be, but the earth is not "ideal," particularly in the outer crust. However, the direction of the first motion in *P* is quite consistently either toward or away from the epicenter, depending on whether the first crest is a rarefaction or a compression.

The problem of identifying the first impulse in the *S* group is more difficult than the problem for *P*, since *S* begins while *P* motion is still in progress. Also the motion in *S* is rarely strictly transverse.

Seismography is a new science. In 1905 Omori and Imamura in Japan were studying the direction of earth motion during the passage of the various groups of seismic waves and becoming convinced that *P* waves were longitudinal waves. In 1909 Prince Galitzin in Russia was able to establish definitely that this was the case and that sometimes *P* began with a compression and sometimes with a rarefaction. Omori (*1*) noted that the *P* waves from certain regions always began with a first compression at Tokyo, whereas for other regions the *P* waves began with a rarefaction.

Labozetta (*2*), studying an Italian earthquake with seismograms from Italian stations, found that he could draw a straight line through the epicenter separating the region where the first *P* was a compression from that where it was a rarefaction. Shida in 1917 (*3*), working with Japanese seismograms, found that in some cases he could separate the regions of first compressions from those of first rarefactions by drawing two straight lines (nodal lines) through the epicenter at right angles to each other. This quadrant distribution is now known to be quite common.

Somville (*4*) plotted on a map of the world many epicenters of earthquakes recorded at the Uccle Observatory. He plotted them as black or red depending on whether *P* began, on the Uccle seismograms, as a rarefaction or a compression. There was a definite geographic correlation; for example, shocks in the western United States always send rarefactions first to Belgium. It was clear that similar tectonic processes are going on throughout fairly large regions of the earth's surface.

The Elastic Rebound Theory

After the California earthquake of 1906, Harry Fielding Reid, in 1909 (see *5*), proposed the elastic rebound theory of the cause of earthquakes. This great earthquake was accompanied by a fracture of the earth's crust for a length of 270 miles along what has since been called the San Andreas fault. The displacement was almost purely horizontal. The westerly, coastal side moved northerly relative to the inland side. The maximum relative displacement was 21 feet at the head of Tomales Bay; the displacement died off toward either end of the break, which extended from Upper Mattole, in Humboldt County on the north, to San Juan Bautista in San Benito County to the south. Comparing results of triangulation surveys across the San Andreas fault made by the United States Coast and Geodetic Survey during a long period of years before 1906 and just after 1906, Reid concluded that the coastal part of California had been slowly drifting northward relative to the inland part, causing a slow accumulation of strain across the fault. This strain finally became so great that the fault broke to relieve it. The surveys indicated that the large strains were highly localized near the fault, being

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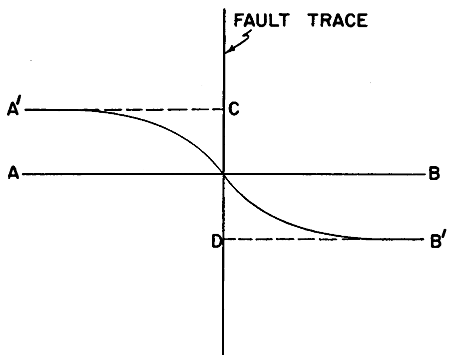

Fig. 1. Elastic rebound theory. *AB*, a line across a fault trace before strain; *A'B'*, same line after strain has accumulated; *A'C* and *B'D*, position of the line after the fault breaks.

appreciable only in a zone about 10 miles wide. A straight line drawn across the fault before strain is a curved line after strain but is reduced to two straight segments by the fault break (Fig. 1).

This earthquake has been considered the "type earthquake" by American geologists, and we have presumed that practically all earthquakes have a similar mechanism even though it is rare that the fault breaks through to the surface. On the other hand, many of our foreign colleagues consider the 1906 earthquake a freak, to be disregarded in the formation of causal mechanism theories. Faulting is considered, by many of them, to be the result of shaking.

Source of Seismic Waves

In considering the faulting phenomenon (Fig. 2) we think of it in two parts: the fling or mass movement of a whole strained region at the time of release of strain and the grating along the fault surface. Reid was very careful to say that the seismic waves came from the fault surface and not from the mass movement of the fling, which he says could not give rise to vibrations. Surely the multitudinous waves of varying frequency call for the interruption of the fling by fault friction. Housner (*6*) has elaborated on the effects of friction at the fault surface which breaks first at one point, developing increased stresses at a neighboring point which then breaks.

Knopoff and Gilbert (*7*) have developed the theory for first motions by allowing a fault to break as a step function which begins at one point on the fault and tears to either end. The results at a distance are step functions. They speak of theirs as the "result due to release of strain." They show their results to be the same as for a double couple applied at the origin.

The early theories all took for the source suddenly applied forces at a point or small cavity or area. The question arises as to whether the release of strain would send out waves without recourse to friction at the fault; whether mass fling is important as a wave source; whether the general uniformity of the direction of first motion in *P* as a function of azimuth from the source is as consistent with frictional effects along the fault as it is with fling as a source.

Many Japanese seismologists have proposed for the seismic source an impulsive movement of magma at depth. Why such a movement should occur is not clear, except perhaps in regions of volcanic activity. (With only a few exceptions, the earthquakes which have accompanied volcanic activity have been small—have been felt over only a tiny area and have not been recorded on distant seismographs.)

Most of the theory developed considers various systems of forces applied suddenly to a limited portion of an infinite homogeneous isotropic elastic body and the effect of these forces at

Fig. 2. Faulting in Nevada in 1954 (Fairview Peak earthquake). [Karl Steinbrugge]

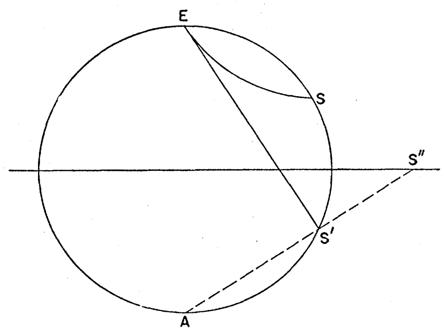

Fig. 3. A transform. The seismographic station at S is plotted at S'. S' is then projected onto the "equatorial plane" at S''.

distances that are large compared to the dimensions of the source (see *8*). Types of sources considered have been uniform pressure, single force, couple with moment, two couples at right angles without resultant moment, double forces without moment, and so on.

The theories indicate and observation confirms that the direction of first motion is preserved in the travel of the waves.

For each of the theoretical force systems there is computed the direction of the first pulse at a distance for P and S waves as a function of the direction of the observer from the source. Since the speeds of these body waves increase with depth in the earth, a transform is necessary to apply the theory to the observation. Such a transform was developed by Byerly (*9*). In it the curved seismic rays are straightened, and the transform effectively replaces the earth by a uniform sphere. Each recording seismographic station is plotted at the point on the globe where a straight ray which left the origin at the same angle as that of the curved ray recorded at the station would have emerged (see Fig 3).

The stereographic projection of the new station position is then plotted, the pole of projection being the anticenter (180 degrees from the epicenter). On this projection each station is marked to indicate whether the first motion of P is a compression or a rarefaction. One then seeks to draw on the projection two circles through the epicenter such that they separate regions of compressions from regions of rarefactions. Such circles represent circles on the surface of the sphere. The circles on the sphere define nodal planes through the source along which no longitudinal waves should be observable; on one side the first P would be compression, on the other, rarefaction.

If the source is a single couple with moment corresponding to the fling on two sides of a fault, one of these planes will include the fault plane. It will be a nodal plane because at large distances from the source the contributions to P of the two sides of the couple will cancel each other by destructive interference. The other nodal plane, called the auxiliary plane, will be perpendicular to the fault and to the two arms of the couple. It will be nodal because the forces at the source have no longitudinal component in this plane.

From the radii and the positions of the two circles on the stereographic projection, the dip and strike of the two nodal planes can be determined.

Which of the nodal planes corresponds to the fault remains ambiguous, for the quadrant distribution of compressions and rarefactions is symmetrical.

To remove this ambiguity, recourse to the S-wave motion is necessary, but this is difficult. The S wave is considered in two parts: SV is the component of S which is in the vertical plane, and SH, the component in the horizontal plane. While the fault plane is a nodal plane for both SV and SH (because of interference at large distances), SV and SH have different auxiliary nodes.

We now define the pole of motion of the couple acting along the fault as that point on the sphere where the downward-pointing member of the couple extended cuts the surface of the sphere.

SH has as a second node the vertical plane passing through the source and the pole of motion. The second node of SV is an elliptic cone with vertex at the source. It passes through the anticenter and the pole of motion and cuts the earth's surface in a circle. Since both of these auxiliary S nodes cut the surface of the sphere in circles through the anticenter (the pole of projection), they project as straight lines on the plane of projection (equatorial to the epicenter).

So if one can determine from seismograms the first crest of S motion and separate it into SV and SH components, he can add to the station projection on the equatorial plane the directions of SH and SV motions and then attempt the construction of nodal lines for each. This will resolve the ambiguity left by P, in which either of the two nodal planes might be the fault. This is for the source a single couple.

If the source is a double couple without moment the situation is altered. The pattern of S distribution is also ambiguous, as is that of P.

If the matter of observation of the first S motion were clear-cut, the distinction between a double couple and a single couple could be made.

As it stands, we have two groups,

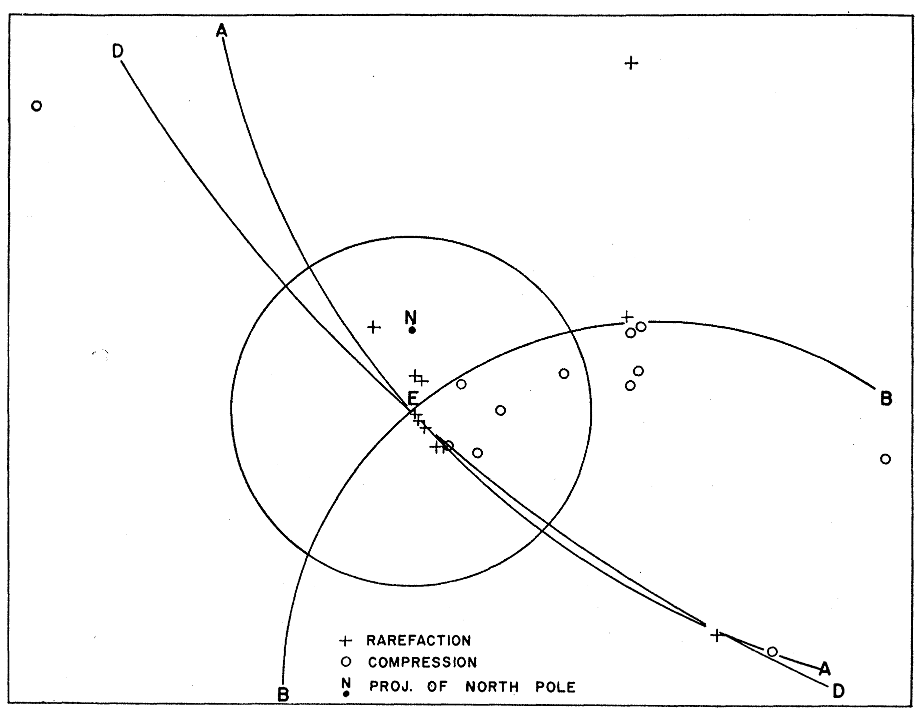

Fig. 4. The stereographic projection. *AD* and *DA*, two possible fault plane projections; *BB*, the auxiliary plane [earthquake of 6 July 1934 on the San Andreas fault off the coast of northern California (the first fault plane solution)].

one which finds a single couple (with moment) most satisfactory and one which finds the double couple (without moment) most satisfactory. The first group is ably represented by Keylis-Borok (*10*) in the U.S.S.R. He has made use of *S* observations not only in relation to first motion but also in studying the ratios of the amplitudes of *P*, *SV*, and *SH*, which are also diagnostic. Keylis-Borok is quite critical of those who maintain that the nature of stress precludes a single couple with moment. He points out that the static stress field may have been produced by a number of different force systems and that its release will not necessarily produce a double couple in which the forces are of equal magnitude or act at the same time. In North America in the past the single couple has generally been favored by those working with seismograms, although Knopoff *et al.* have deemed the double couple required by theory. In Japan Honda (*11*) has found that the double couple fits his observations better.

The double couple without moment is equivalent to a compression in one direction and an extension of like magnitude at right angles to it. Honda indeed concludes from his studies the directions of these strains, not using the fault concept. For even *S* does not distinguish between the fault and auxiliary planes if the source is a double couple.

Ritsema (*12*), studying many earthquakes in southeast Asia, found the single couple with moment slightly more satisfactory than the double couple. He points out the difficulty facing seismologists in mass studies of this sort. The investigator cannot ask for copies of seismograms of 100 earthquakes from 100 stations. He asks for directions of first motions and is dependent on the identifications made by a wide variety of seismologists and technicians. Some hesitate to make identifications at all unless the record is crystal clear. Others pick the wave almost at random. Again, seismographs operate all the time, frequently with non-technical supervision. Seismologists well know of the gremlins who delight in switching the wires on the poles of the galvanometer, thus reversing the earlier interpretation of first motion.

A more simple source is a single force acting at the origin, although from a geophysical point of view it may be more difficult to understand. All of the theory starts with such a force and then combines it with others.

Stauder (*13*) studied three Kamchatka aftershocks whose focal depths were between 40 and 60 kilometers. He used the directions of first motion of *P* and *S* as well as the angle of polarization of *S* (the angle between *S* and the vertical plane of propagation). He found that a force represented by a single arrow best explained the distribution. These arrows were nearly vertical, pointing down. Stauder had copies of the original records and picked his own beginnings. Studying four other earthquakes, Stauder found that for three of them the evidence supported a single couple. The fourth would perhaps allow a double couple.

One difficulty in the past has been that often many *P*-wave observations have been used to get two nodal planes and then very few *S* waves have been used to distinguish the two planes. More seismograms need to be studied for the nature of *S*.

Press *et al.* (*14*) have made some pertinent model studies. They applied a couple to a Plexiglas plate. The pattern recorded was that predicted by the theory for a single couple. But when they cut a slit in the plate and applied the same couple across the slit, the nodes of *S* were displaced 25 to 30 degrees to the right and left from the ends of the "fault." They suggest that this anomalous behavior of *S* may be due to the setting up of *S* at the ends of the slit by Rayleigh waves propagating on the slit's surface.

The earliest method of stereographic projection used to determine nodal surfaces is that described above. Other methods have been developed. In the U.S.S.R. the pole of projection is either the top or the bottom of a "focal sphere" drawn with the focus of the earthquake as its center (Fig. 4). The Wulff net is used. Scheidegger (*15*) has described the projections used and has suggested others.

Nature of Faulting from Fault Plane Analyses

Scheidegger (*16*) has analyzed the nature of the faulting deduced from fault plane studies from 179 earthquakes. These analyses were made by many investigators. The strike of a fault is its direction measured in a horizontal plane—if it breaks to the surface, the direction of its surface trace. Its dip is the angle the plane makes with the horizontal plane. If the motion on the fault is primarily in the direction of the strike, the faulting is called transcurrent or strike-slip. If the motion is primarily in the direction of the dip, the faulting is called dip-slip.

Of the 179 shocks listed by Scheidegger, about three-quarters were nearer strike-slip than dip-slip. This greater frequency of transcurrent faulting had been pointed out much earlier by Hodgson (*17*).

This has been surprising to many structural geologists. In reconstructing geologic history it is dip-slip faulting, it is vertical movement, which must be called upon to explain the varying physiography of the past. Horizontal movements of considerable magnitude would not leave so definite a geologic record. One is led to wonder if horizontal movements were as common in the past as today.

Summary

Theory going back to Stokes and Love indicates that a sudden force applied to a part of an infinite homogeneous elastic medium sends out waves of longitudinal and transverse types. The directional character of at least the beginnings of these waves is preserved at a distance. This character depends on the nature of the force system applied at the source. It is widely agreed that the energy released as seismic waves was gradually stored as potential energy of strain before the shock. The moot question is just how this strain energy is transformed into the kinetic energy of wave motion.

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