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Earthquake Source Mechanisms

Although progress has been made in the understanding of earthquakes, many problems remain.

Hugo Benioff

Modern ideas on the mechanism of earthquakes began with the elastic rebound theory of H. F. Reid, which he developed on the occasion of the great San Francisco earthquake of 18 April 1906. According to him, the immediate source of an earthquake is a sudden release of elastic strain energy accumulated in the rock mass surrounding a preexisting fracture in the earth's crust, known as a fault. In Fig. 1, the heavy lines represent the intersection of a vertical fault with the surface of the earth. Suppose that, after an earthquake has occurred, parallel lines are drawn on the ground, as shown at *A*. After a sufficient interval of time, measured in years or centuries, the blocks on either side of the fault are displaced relative to each other. Owing to friction and cementing, the fault surfaces remain locked together, and consequently the blocks become distorted or strained in the vicinity of the fault, as indicated by the curved parallel lines at *B*. As the blocks continue to move there comes a time when at some point the stress exceeds the restraints and the fault surfaces suddenly slip or rebound, as shown at *C*. The sudden slip at this point increases the existing stress at adjacent points on the fault, indicated in Fig. 1 by crowding of the lines in the direction of slip and separation of them in the reverse direction. The augmented stress is sufficient to cause these points to slip also, with the result that the slip or break is propagated along the fault. The sudden flings, in opposite directions, of the two fault lips thus generate seismic waves which propagate outward throughout the earth as body waves and around the earth as surface waves. If the slip is horizontal, as illustrated in Fig. 1, the fault is designated a strike-slip or transcurrent fault. The San Andreas fault of California [see cover and legend (p. 1371)] is a typical strike-slip fault. If the slip is vertical or perpendicular to the line formed by the intersection of the fault with the horizontal surface, the fault is known as a dip-slip fault. Combinations of dip-slip and strike-slip faulting also occur. Figure 2 is a photograph of the scarp formed during the Nevada earthquake of 16 December 1954 on a predominantly dip-slip fault.

The observed relative slip displacement varies from a few centimeters, in a very small earthquake, up to some 14.5 meters, observed on the dip-slip fault of the great Yakutat, Alaska, earthquakes of September 1899. The duration of slip at any one point is not accurately known but is estimated to vary from a fraction of a second, in the smallest earthquakes, to about 10 seconds in the largest. The horizontal extent of the break also varies with the size of the earthquake, from a few meters in the smallest up to 1000 kilometers in the largest. The longest directly observed break was that on the northern segment of the San Andreas fault in the San Francisco earthquake of 1906, in which the trace was visible on the ground for a distance of 330 kilometers, from San Juan Bautista northward to Point Arena, where it extended under the ocean at least an additional 150 kilometers. The majority of the great earthquakes of the world occur on faults extending along the margins of the circum-Pacific continents. Most of these faults intersect the surface offshore, and consequently the extents of their breaks cannot be observed directly. They can be determined indirectly from the lengths of the distribution patterns of aftershocks parallel to the fault and by a method developed by Ben-Menahem (*1*) that depends upon the spectra of Rayleigh and Love waves, which travel around the surface rather than through the earth. In the great Chilean earthquake of 20 May 1960, both methods indicated a length of break of about 1000 kilometers. Ben-Menahem's method also permits calculation of the horizontal speed of rupture propagation, which is found to be about 3 to 4 kilometers per second for strike-slip faulting and somewhat less for dip-slip faulting. Strike-slip faulting proceeds faster because it is propagated from point to point by compressional stresses, whereas dip-slip faulting is maintained by the smaller shearing stresses. The total duration of the earthquake at the source is equal to the length of rupture divided by the speed of rupture propagation. In the largest earthquakes, with 1000 kilometers of faulting, the duration of the source is thus $1000/3.5 =$ 286 seconds, approximately. The rate of accumulation of elastic strain is known for only one fault, the San Andreas fault, and even in this case the determination is only approximate. By comparing data from geodetic triangulation surveys of the strain zone made at intervals of 10 to 25 years, Whitten found that the two opposed fault blocks are moving relative to each

The author is professor of seismology in the Seismological Laboratory of the California Institute of Technology, Pasadena.

other at a rate of about 5 centimeters per year. If this rate is constant and if each break of the fault occurs at the same value of strain, earthquakes on any given segment should repeat at intervals given by the maximum relative slip divided by the rate of strain accumulation, or $630/5 = 125$ years, approximately. A slip rate such as this of some 5 meters per century represents a very rapid movement, geologically speaking, and should result in a large total accumulated slip, in view of the age of the fault. The differential effects of weathering and other geological processes, however, have made it very difficult, if not impossible, to find definite evidence of displaced mating structures on the two sides of the fault. Estimates of the total accumulated slip have varied from 15 kilometers or so up to 550 kilometers. The latter figure is more likely correct.

Earthquakes are classified as shallow, intermediate, or deep, depending upon their focal depths. The focus or hypocenter is the point within the earth where movement is initiated. The shallow shocks range down to about 60 kilometers, the intermediate, from 60 to 150 kilometers, and the deep, from 150 to 700 kilometers. No earthquakes with foci deeper than about 720 kilometers have been observed. Although focal depths can be determined with fair accuracy, the actual vertical extent of slip is not known even approximately for any earthquake. It is generally assumed, without convincing proof, that the break in shallow earthquakes does not extend below the Mohorovičić seismic-wave-velocity discontinuity, which is about 35 kilometers below the surface in continents and 11 kilometers under the oceans. The Mohorovičić discontinuity is generally deeper under mountains, and this accounts for some shallow earthquakes' having focal depths greater than 35 kilometers. The vertical extent of faulting in intermediate earthquakes is unknown. On the other hand, as discussed later, the available evidence for deep earthquakes indicates that the source is very small, possibly a kilometer or less in total extent in any direction.

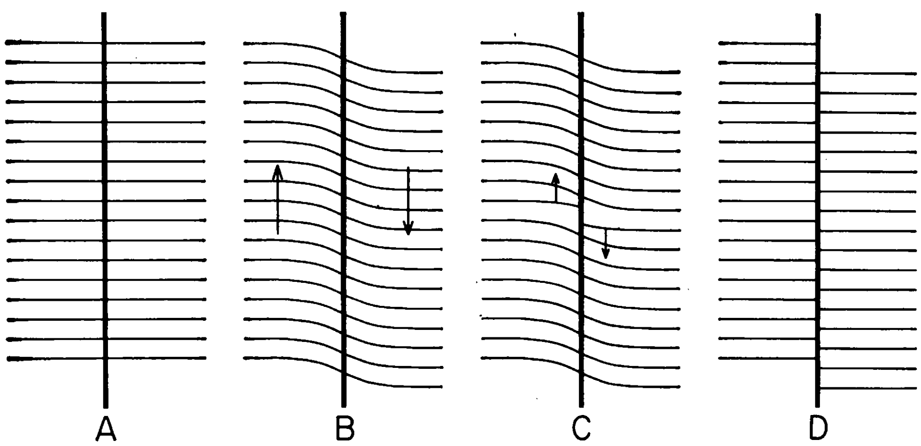

Fig. 1. Sketch illustrating Reid's elastic-rebound earthquake source mechanism.

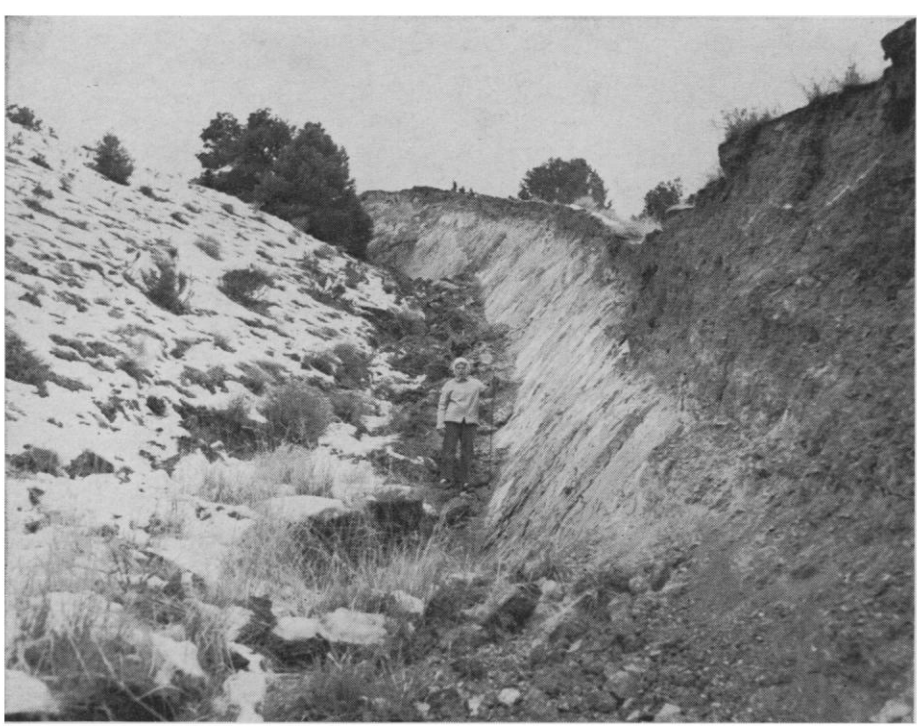
Fig. 2. Fault scarp of the Fairview, Nevada, earthquake of 16 December 1954. The photographer was facing south.

Source Mechanism Derived from Seismic Waves

Since the great majority of earthquake sources are either too remote or too deep to be observed directly, it has been necessary to find ways to determine source characteristics from observations of seismic wave motions. In one method, observed world patterns of direction of initial wave motion are compared with theoretical patterns calculated for assumed simple-force models. The first arrival is always a compressional body wave, designated P wave by seismologists. H. Nakano (*2*) made the first theoretical calculations of radiation wave patterns. He assumed, among other sources, one in the form of a single couple applied within the earth at the focus, as illustrated by the arrows in Fig. 3*A*. The calculated pattern of P-wave, initial movements for such a source, designated P_1 in Fig. 4, has a quadrantal distribution in which, for two diagonal quadrants, all initial movements are away from the source (compressions) and, for the other two, all initial movements are toward the source (dilatations). P. Byerly devised a method for deriving the orientation and direction of movement of an assumed elastic-rebound fault source from comparisons of observed initial P motions with those calculated for the single-couple model. The method was further developed by J. Hodgson (*3*) and applied by him, and later by other workers, to determine the fault-plane characteristics of a large number of earthquakes. Most of these early solutions yielded reasonable results, and for a while the elastic-rebound hypothesis appeared to be a satisfactory model for all earthquakes.

Owing to the rectangular symmetry of the four-lobed radiation pattern for the initial P-wave movement, a fault-plane solution based on this pattern alone does not distinguish between the fault plane and a plane perpendicular to it, known as the auxiliary plane. To resolve this ambiguity it is necessary to make use of the radiation pattern for initial S waves. Any disturbance within an elastic solid produces shear (or S) waves in addition to the compressional P waves. These travel along the same paths as P waves, but at lower speeds. Moreover, the particle motion in a shear wave is perpendicular to the direction of propagation, whereas that in the P wave is parallel to the direction of propagation. The radiation pattern (Fig. 4, S_I) for the initial S-wave movements around the single-dipole source has two lobes rather than four, and consequently it provides the means for distinguishing between the fault plane and the auxiliary plane. In attempting to use S waves for this purpose, a number of workers discovered that many, if not most, earthquakes exhibit four-lobed S-wave patterns similar to the P-wave patterns except that the former are rotated 45 degrees (Fig. 5, S_{II}). To account for the four-lobed S-wave pattern, H. Honda proposed a second simple theoretical source in the form of two oppositely poled couples oriented at right angles to each other, which he designated a type-II source (Fig. 5, II*a*). The single-couple source was designated type I. The radiation patterns for initial P-wave motion are identical in the type-II and the single-couple models. The type-II model can be represented in the equivalent form of two opposing colinear compressions oriented perpendicularly to two opposing colinear tensions, as at II*b* in Fig. 5. Since the type-I model, which was supposed to represent a simple faulting source, failed to represent many earthquakes, the validity of the elastic rebound theory of Reid has been questioned by many seismologists.

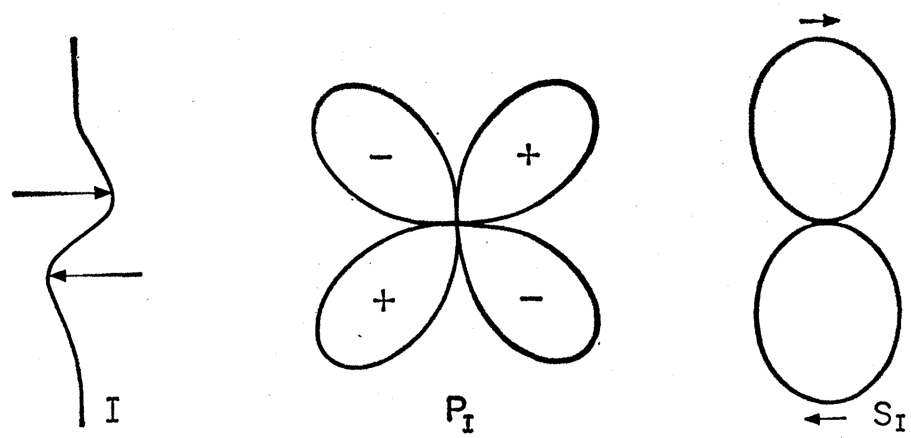

Fig. 4. Radiation patterns of initial motion for a type-I source. *I*, Source; P_I, P-wave pattern; S_I, S-wave pattern.

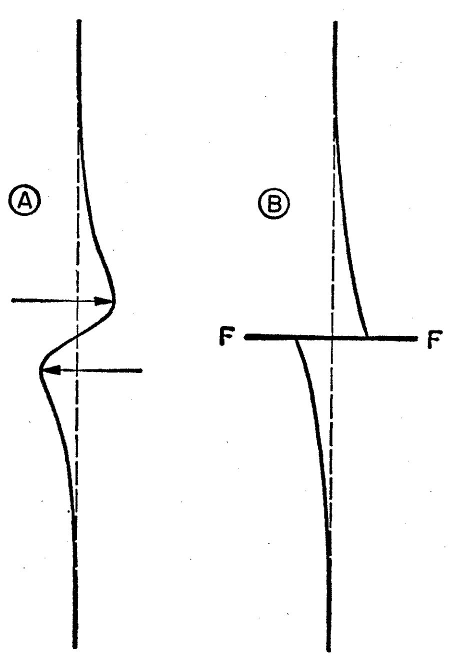

Fig. 3. Earthquake source mechanisms. *A*, Type-I single couple; *B*, elastic rebound source.

Elastic Rebound Mechanism as a Type-II Source

The apparent incompatibility of the type-II source with the elastic rebound mechanism arose from the oversimplification of the mathematical model. Referring back to Fig. 3, we find that the model at *A* differs from the Reid mechanism at *B* in that it lacks the fault break. Let us examine the model *B* to determine whether or not its radiation pattern can be qualitatively inferred from simple mechanical considerations. In Fig. 6, let XY represent a segment of a fault. Let us assume that the strain is confined in a narrow zone on either side of the fault, as observed in the San Francisco earthquake of 1906 and in other earthquakes, and let us represent a section of the zone at a time just after an earthquake has occurred by the rectangle $ABDC$. At a later time the blocks on either side of the fault will have moved, so that A will be displaced to A_1, B to B_1, C to C_1, and D to D_1. According to Reid's assumptions, the points at X and Y will not be displaced. The strain-zone section originally chosen as a rectangle has now become a parallelogram, and the original diagonals XB and CY have been stretched to the length XB_1 and C_1Y, while the diagonals AY and XD have been compressed to the lengths A_1Y and XD_1. When the stress at the fault exceeds the cohesive strength, the lips slip, and the upper lip points X and Y ("upper" in Fig. 6, that is) move suddenly to X_2 and Y_2, respectively, while the lower points X and Y move suddenly to X_1 and Y_1, respectively. The parallelograms A_1B_1XY and XYC_1D_1 become squares again—$A_1B_1X_2Y_2$ and $X_1Y_1C_1D_1$, respectively. During this sudden change of shape from parallelogram to square, the points A_1, B_1, C_1, and D_1 remain fixed. Thus, the long diagonal XB_1 is compressed to its original length X_2B_1 (the diagonal of the square) by movement of its end at X to X_2. This produces a compression outward at B_1, as shown by the arrow. Likewise, the short diagonal A_1Y is lengthened by movement of Y to Y_2, and this results in a tensional force directed inward, as shown by the arrow at A_1. In like manner outward compressions and inward tensions appear at C_1 and D_1, respectively. Owing to the exaggerated angle of shear A_1XY in the drawing, the parallel forces at B_1 and C_1 and at A_1 and D_1 are not colinear. In the actual case this angle is of the order of 5×10^{-4} radian in the largest earthquakes, so their departure from colinearity is negligible. Figure 6 represents a single segment of the active fault. As faulting proceeds, additional elements react successively in similar manner along the fault to the end point or points. To an observer studying the initial P and S wave movements from a location outside the strain zone, the earthquake origin thus appears as a moving type-II source which, at large distances, cannot be readily distinguished from a stationary point source. Recently J. H. Pfluke and B. F. Howell, Jr. (*4*), observed the four-lobed pattern of initial S waves in an experiment with an ultrasonic model, using a mechanical source which approximated natural fault action.

Now that the type-II radiation pattern of initial motion is found to be consistent with the Reid theory, a new problem has arisen. What is the nature of the source in those earthquakes which present a type-I pattern? The only suggestion offered so far is one made to me by K. Aki—that these are shallow dip-slip sources. In a dip-slip fault which intersects the surface, the strain pattern is greatly altered by the presence of the free surface, with a resulting modification of the configuration of compressions and tensions. It should be possible to verify this possibility by a study of known dip-slip earthquakes, but the necessary work has not yet been done.

Deep Earthquake Mechanisms

After the general acceptance in 1930 of the fact that earthquakes occur at depths greatly exceeding the thickness of the crust, in which originally all earthquakes were assumed to take place, it was observed that these deep shocks produced P-wave patterns similar to those of shallow earthquakes. Consequently it was concluded by many that they, too, are generated by elastic rebound mechanisms. However, a difficulty with this assumption arose as a result of the large frictional forces developed between slipping fault surfaces at such great depths. At a depth of 600 kilometers, the hydrostatic pressure resulting from the rock overburden amounts to some 2×10^{11} dynes per square centimeter. The frictional stress necessary to slip two solid fault surfaces pressed together with such a high pressure is about 10^{11} dynes per square centimeter, which is greater by some two orders of magnitude than the shearing strength of known rocks. The fault rocks would shatter before sufficient stresses could be built up to produce slip.

Several suggestions have been made as to possible ways in which slip might occur at lower stresses. These include (i) sudden crushing of the fault rock at the fault, so that movement would be permitted by a sort of reduced rolling friction of the particles, and (ii) liquifaction of the surfaces, with consequent low fluid frictional forces. A recent observation of two deep South American earthquakes has provided strong if not convincing evidence for a different kind of mechanism of origin for deep earthquakes (*5*). The epicenters of these shocks were identical, within the errors of measurement, and were located 600 kilometers from the strain-seismograph installation at Ñaña, Peru, operated jointly by the California Institute of Technology and the Instituto Geofisico de Huancayo. The foci were also identical and were approximately 600 kilometers below the surface. A line from the focal point to the seismograph thus made an angle of 45 degrees with the vertical. The Ñaña seismograph is designed to respond to the ultralong-period seismic movements associated with the free vibrations of the earth; of these vibrations, that of lowest frequency has a period of 54.7 minutes. The response of this instrument thus differs radically from the shorter-period characteristics of the more common pendulum seismographs, and it is able to reveal information which hitherto has been missing. Recordings from this seismograph of the two deep earthquakes exhibited a wave shape which differs radically from the form produced by a faulting source and, instead, corresponds very closely with the form calculated by C. Pekeris (*6*) for a single vertical force applied suddenly at depth and continuing thereafter indefinitely—a buried vertical step. Figure 7 shows (at left) the observed strain seismogram of the

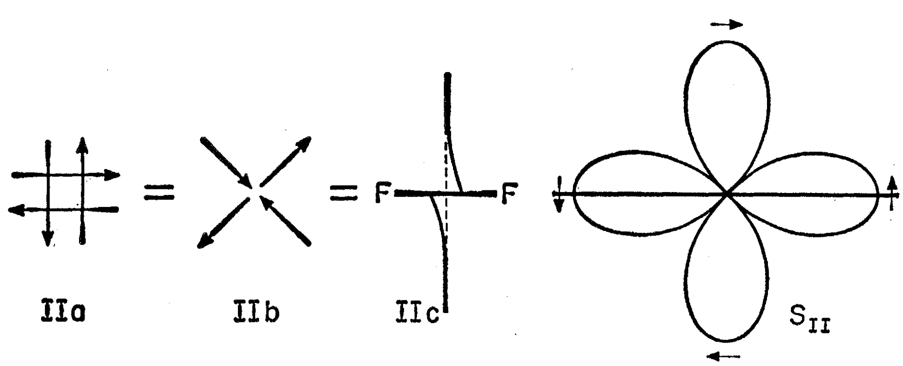

Fig. 5. Type-II source. II*a*, Double-couple model; II*b*, equivalent-force model; II*c*, actual fault source; S_{II}, radiation pattern of S-wave initial motion.

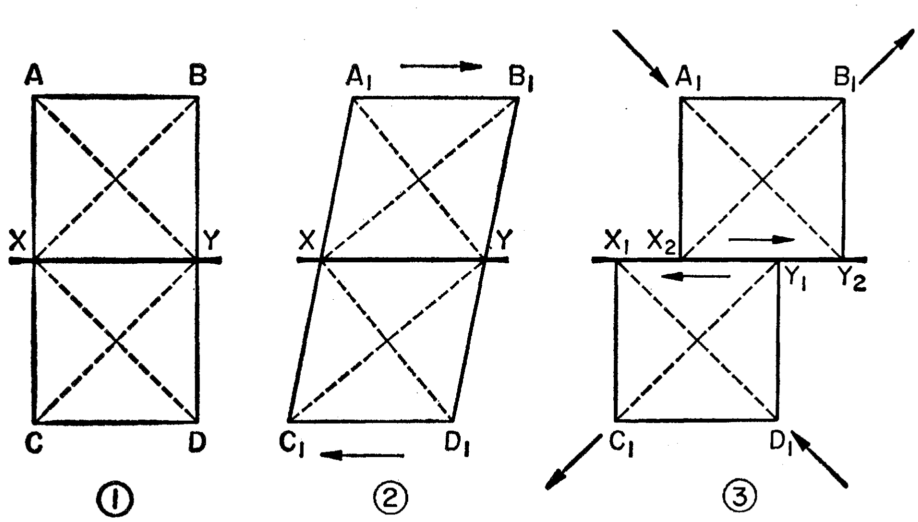

Fig. 6. Diagrams showing how the elastic rebound mechanism produces a type-II radiation pattern of initial wave movements.

earthquake of 19 August 1961 and (at right) the wave form predicted by Pekeris. In searching for a physically possible mechanism capable of applying a step force at depth, as envisaged by Pekeris, I can think only of sudden collapse of a small volume of rock at the focus, such as might be caused by a change of state. In Fig. 8, let the dashed lines represent a small volume which contracts to the size indicated by the shaded square. Owing to the weight of the overburden, the void is filled immediately by a downward motion of the rock mass, as indicated at *B*. For long-period waves at least, such a source is equivalent to a downward step. It may well be that for a source situated as this one is, at or near the inclined surface of a physical discontinuity between the continental and oceanic rocks, the downward motion of the contracting rock mass may be accompanied by faulting at its periphery. The faulting would be evident in the observed four-lobed initial radiation pattern for the short-period waves, while the gross movement shows up only in the record of long-period strain. These are the first observations in which the gross movement could be detected, and it will take further study to learn if these South American shocks are typical of all deep earthquakes. The hydrostatic pressure at a depth of 600 kilometers in the earth is approximately $P = 2 \times 10^{11}$ dyne/cm^2. The energy available from a volume contraction ΔV is $P\Delta V$. The energy of the earthquake of Fig. 7 was about 10^{23} ergs. Thus, $P\Delta V = 10^{23}$ erg. If the fractional change in volume $\Delta V/V$ is assumed to be 0.03, a not unreasonable figure, $V = 33\ \Delta V = 1.6 \times 10^{-2}$ km^3. This is equivalent to a sphere of 0.3-kilometer diameter. The size of the source for these earthquakes may thus be exceedingly small as compared with that for the equivalent shallow earthquake.

Strain-Generating Mechanisms

The preceding paragraphs have been concerned with the immediate sources of earthquakes—the mechanisms by which energy stored in the rock as elastic strain is converted into seismic waves. There remains the problem of the nature of the mechanisms which generate the elastic strains—the secular causes of earthquakes. In the case of the two Peruvian deep earthquakes described earlier, the problem is relatively simple if the collapse hypothesis is accepted. The strain stored in the rock at the focus is produced by hydrostatic pressure from the weight of the overlying rock. The sudden volume contraction serves as a means of immediately releasing a portion of the strain energy in the form of seismic waves. As soon as the cavity is filled, the elastic energy lost in waves is replenished by a general downward movement of the overlying rock, with consequent reestablishment of the original level of hydrostatic pressure. This movement also serves to generate the long-period seismic waves. The secular source for these shocks was therefore gravitational potential energy.

The problem of the origin of strains which generate the great shallow earthquakes is more difficult. Figure 9 is a world map of the epicenters of all great earthquakes (magnitude $\geq$ 8) that occurred from 1904 to 1954. It shows that these earthquakes are not randomly distributed over the earth but, instead, are confined to two rather well defined regions. The region with the larger number embraces the margins of the circum-Pacific continents; the other is a band extending westward from Southern Asia to Portugal. The majority of great earthquakes around the circum-Pacific arc are generated on long strike-slip faults lying parallel to the coasts, and, except for the San Andreas segment, all meet the earth's surface under the ocean a few kilometers offshore. Most of these faults for which data are available, including the South American, San Andreas, Canadian, Alaskan, Aleutian, Kamchatka, and New Zealand segments, are dextral (*7*). The known sinistral faults are the Taiwan and Philippine segments. In each of these great faults, which extend to several thousand kilometers in length, the oceanic and continental sides are moving horizontally relative to each other at the rate of a few

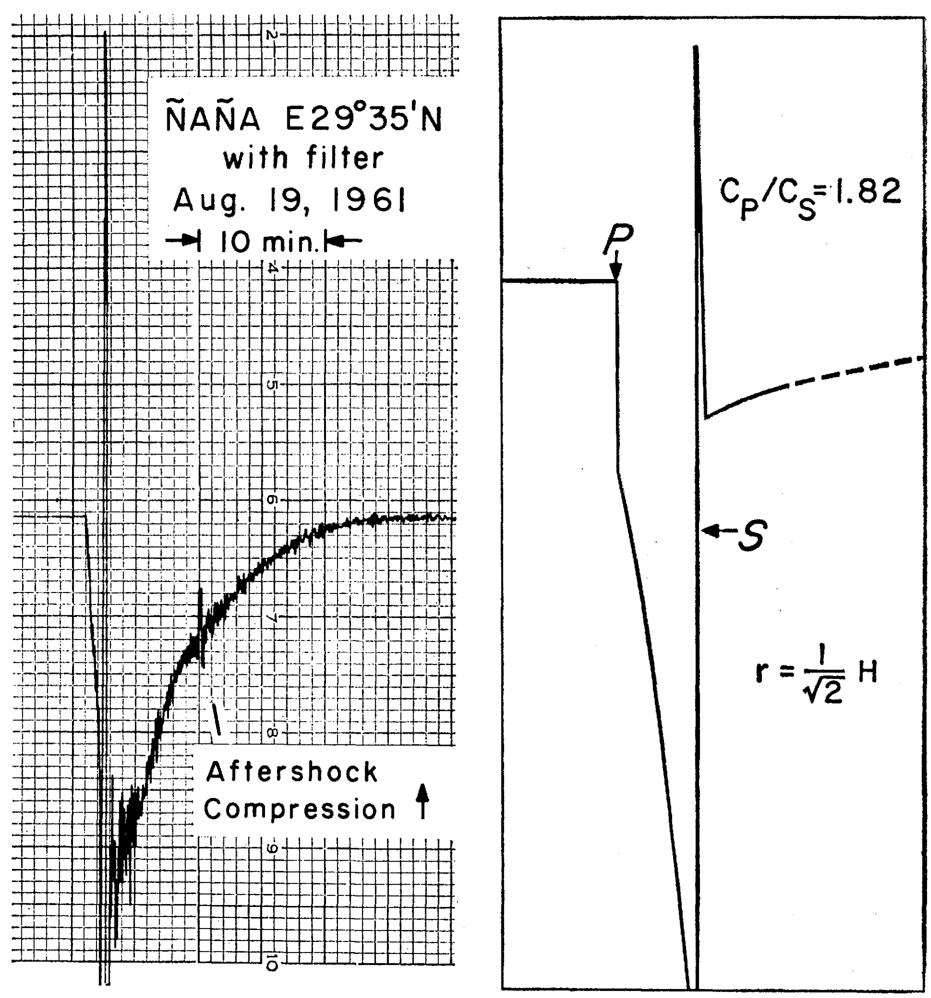

Fig. 7. (Left) Strain seismogram of the Peruvian earthquake, 600 kilometers deep, of 19 August 1961. (Right) Plot of the horizonal ground strain derived from ground displacement, calculated theoretically by C. Pekeris for a source having the form of a downward-step force applied at a point within the earth.

centimeters per year, and thus strain is accumulated, presumably at a constant rate, to be released intermittently in the form of earthquakes. There is good evidence that the circum-Pacific arc divides just south of Japan, with one branch going southwest through Taiwan and the Philippines and the other going southeast along the Bonin and Mariana islands to the Tonga Islands and New Zealand. If the latter branch is taken as the true continuation of the arc, all of the segments of the arc for which data are available exhibit dextral fault movements. Thus, in a substantial portion of the circum-Pacific arc the surrounding continents appear to be rotating clockwise relative to the oceanic rocks. However, in view of the nearly 90-degree cusps in the arc at junctions of the Aleutian segment with the Kamchatka-Kurile and Canadian segments and the nearly radial strike of the Tonga-Kermadec-New Zealand segment, such a rigid relative rotation meets with insuperable geometric difficulties. If continuity from one segment to the next is assumed, the only way the movements can be reconciled with the geometry of the arc is by plastic deformation or flow of the continental margins or of the adjacent oceanic masses, or of both. It would seem that, in the present state of geophysical knowledge, we cannot now describe with reasonable accuracy the overall strike-slip movements of the circum-Pacific system. With this uncertainty about the motions, a greater difficulty arises when we attempt to propose a satisfactory driving force. It has been suggested that the strike-slip prime-mover force is derived from horizontal velocity gradients in vertical mantle convection cells oriented with their planes of motion parallel to the margins and generated by the difference in temperature between the hot core of the earth and the cooler crust. Recent theoretical studies by Knopoff (*8*) and by Elsasser (*9*) indicate that convection of this kind cannot occur, because of the increase in viscosity with depth, resulting from the inequality of the effects of pressure and temperature. Knopoff (*10*) proposed shallow convection cells rotating essentially in horizontal planes and maintained by differences in temperature at equal depths between the oceanic and continental rocks. There are difficulties associated with this hypothesis, and the details have not yet been worked out. It appears, therefore, not only that the description of the overall movement of the great strike-slip earthquake-generating faults is inadequate but also that we are without a generally accepted theory to account for the driving forces.

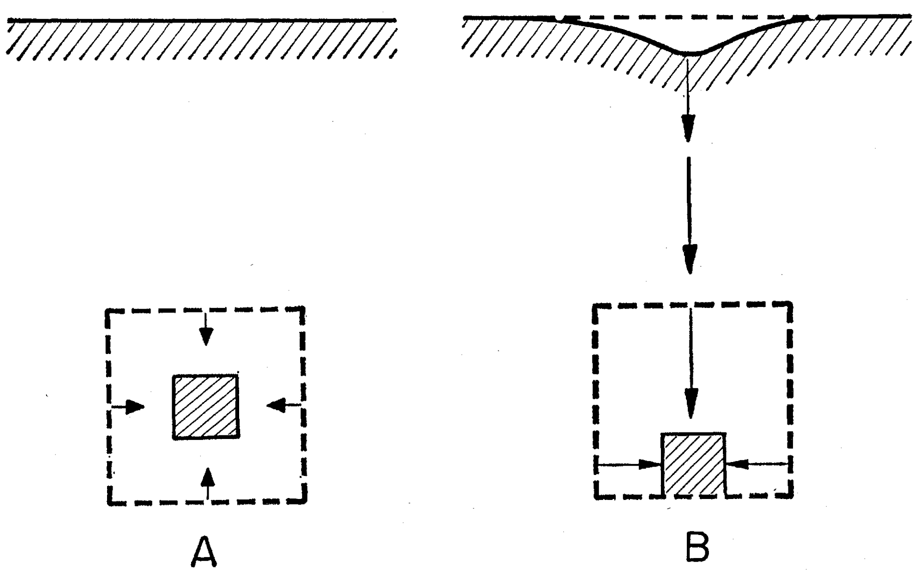

Fig. 8. Proposed source mechanism for the Peruvian deep earthquakes of 19 and 31 August 1961.

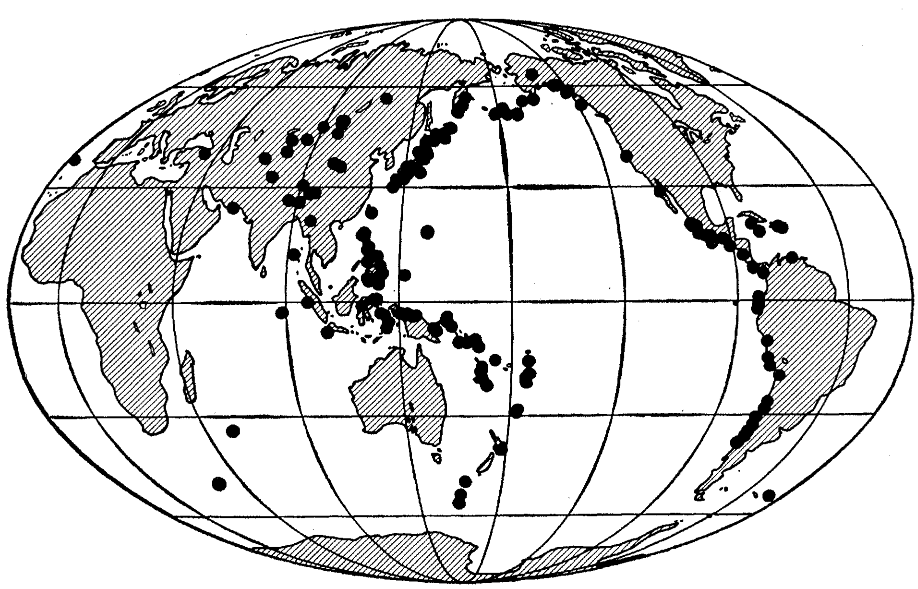
Fig. 9. Distribution of the epicenters of great earthquakes (magnitude ≥ 8) from 1904 through 1954. [After Gutenberg and Richter]

In general, the shallow dip-slip earthquakes are associated with orogenesis—the growth and decay of mountains. In California and Nevada all of the large dip-slip earthquakes recorded since reliable records have been available were generated by fault movements having polarities such that the existing relief was increased. In other segments, some earthquakes have been observed in which the slip decreased the relief. The origin of the dip-slip stresses is thus related to the problem of the origin of the mountain-building stresses. Throughout the circum-Pacific arc the mountain ranges form part of the general marginal-structure pattern illustrated in Fig. 10, which represents the Kurile-Kamchatka segment. The map shows the locations of the earthquake epicenters, the associated line of volcanoes, and the oceanic trench. At the right the earthquake foci are projected on a vertical section to scale, to show their distribution in depth. In addition, two sections are drawn with exaggerated vertical scale to show the character of the relief. The foci of intermediate and deep earthquakes lie within a fairly narrow zone which marks the area of contact between continent and ocean. This zone dips under the continent at an angle of about 30 degrees, to a depth of about 150 kilometers, where it steepens to 60 degrees and continues at that angle to the maximum depth of 720 kilometers. On the continental side of the earthquake zone the land rises abruptly to form the mountain range, while on the seaward side the surface drops sharply to a depth of some 8 kilometers at the bottom of the long narrow trench. Some of the other segments of the arc differ from the Kurile-Kamchatka segment of Fig. 10, mostly in minor ways. In the Mexico-Central America and the Aleutian segments the deep earthquakes are missing. The segment from Baja California to Alaska is the most atypical. In this the intermediate and deep earthquakes are missing, and so is the trench. Moreover, the principal strike-slip fault is on land. The characteristic configuration of the continental margin has led to a number of hypotheses as to its origin. In one it is assumed that the continental and oceanic masses are driven together by isotropic convection cells of the mantle, rotating in the vertical plane and oriented perpendicular to the coast, with consequent distortion of the crust and overriding of the light continental rocks over the denser oceanic rocks (*11*). This hypothesis meets with the same difficulty that was mentioned earlier for convection cells of the mantle oriented parallel to the coast. Recently Elsasser (*9*) has proposed shallow, greatly flattened anisotropic cells, rotating in the vertical plane and moving just below the crust and normal to the coast. With such cells the difficulty of the high viscosity at depth would be avoided. In another hypothesis it is assumed that the circum-Pacific continents are drifting oceanward as rigid bodies over the mantle—an extension of Wegener's original hypothesis of continental drift (*12*). In the oldest hypothesis applicable to the dip-slip earthquakes it is assumed that the earth was once hotter than it now is, that the outer layer cooled first to form the crust, and that subsequent cooling and consequent contraction of the mantle produces buckling of the crust. This hypothesis has fallen into disrepute as a result of the now generally held opinion that the earth began as a cold body and has been becoming warmer rather than colder, owing to radioactivity of the rocks. In another hypothesis, proposed to explain the sloping oceanic-continental contact and the associated trench and mountain range, it is assumed that the stresses and subsequent movements arise from the difference in density between the lighter, continental rocks and the adjacent heavier, oceanic rocks (*13*). This difference in density results in a difference in hydrostatic pressure between the two masses, which increases with depth. This in turn produces a horizontal stress, also increasing with depth and directed toward the continental boundary. In a qualitative way, at least, this hypothesis accounts for the sloping contact, for the downward movement of the trench, for the adjacent continental uplift, and presumably for some of the dip-slip earthquakes. In these, if the oceanic side goes down during slip, the relief-generating process is in progress, whereas a downward slip of the continental side indicates a return to equilibrium. In another hypothesis it is assumed that mountains grow by accretion at their roots through physical or chemical differentiation from the denser rock of the surrounding mantle. Faults are formed at the boundary between the growing mountain and the surrounding rock, and these are the sources of dip-slip earthquakes. Since the mountains float in buoyant equilibrium with the substratum, weathering tends to continue their upward movement even after accretion from below has ceased to act. Hence, on this hypothesis, earthquakes occurring on a dip-slip mountain fault having a slip direction that increases the relief, as in California and Nevada, may be evidence for growth of the mountain from below or for wearing away at the summit, or for both.

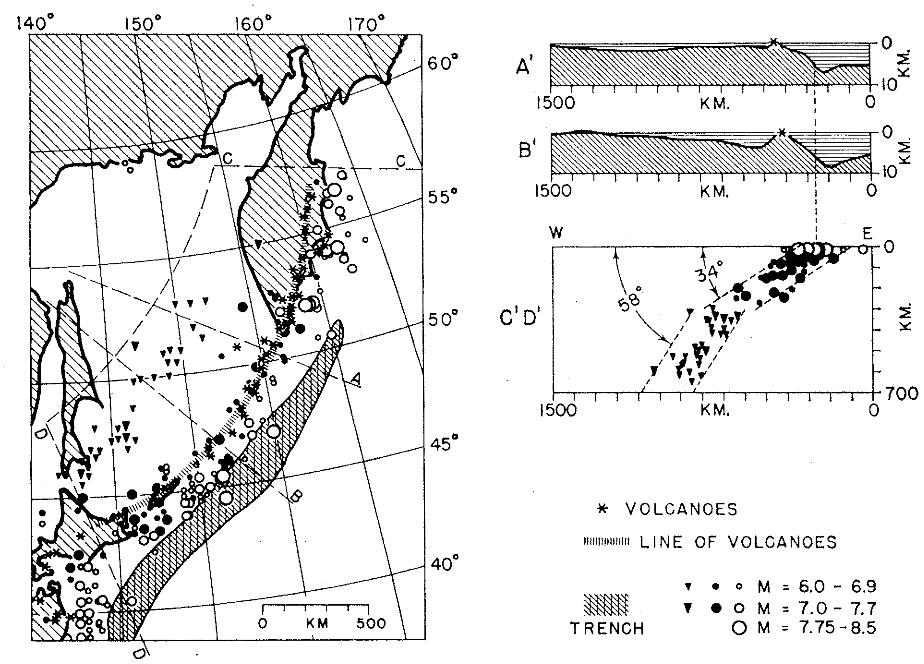

Fig. 10. Map and sections of the Kurile-Kamchatka segment of the circum-Pacific arc, showing earthquake epicenters, projected foci, and magnitudes.

Since most earthquakes exhibit double-couple patterns of radiation distribution, a number of geophysicists have assumed that the configuration of equivalent perpendicularly crossed compression and dilatation stresses (Fig. 5, II*b*) represent the regional stress pattern as well as the source pattern, and thus they have attempted to represent regional stresses by plotting the type-II*b* patterns on epicenter maps. It seems to me that this is not a valid procedure. The double-couple source and its equivalent crossed stresses are transient patterns generated during the initiation of fault slip at the focus and are characteristic of a fault source. They do not necessarily, and probably do not at all, represent the regional secular stress pattern. Any regional patterns that produce a shearing strain at the fault will result in the same radiation pattern during slip.

Summary

The elastic rebound theory of Reid provides a satisfactory model for the immediate source mechanism of shallow earthquakes and probably of earthquakes of intermediate depth. Deep earthquakes appear to involve volume collapse, either with or without associated faulting effects. Our knowledge of the origin of secular strains which provide the elastic rebound energy is incomplete. Strike-slip and dip-slip faults very probably involve different strain-generating mechanisms. No mechanism proposed to date for generating either strike-slip or dip-slip strains has achieved general acceptance.

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The Bearing of Philosophy on the History of Science

Philosophical mastery of the special theory of relativity is required for unraveling its history.

In what precise ways is philosophy instrumental in illuminating the *genesis* of the conceptual innovations wrought by a particular physical theory? In a book published in 1963 and in some papers which have appeared since 1961, I have used the unraveling of the history of the special theory of relativity to argue concretely that philosophy does have far-reaching relevance to the attainment of the following cardinal objectives of the historian of science: (i) the very posing of well-conceived, searching historical questions and (ii) the avoidance of serious historical blunders of certain kinds, and their discernment as such when they have been committed by those lacking the requisite philosophical mastery (*1*, chap. 12; *2*). Specifically, I maintained in the context of the special theory of relativity that there is a symbiosis of the philosophy and the history of science as follows: no historically correct, let alone illuminating account of the development of that theory can be furnished without a prior rigorous comprehension of the philosophical conceptions underlying it and distinguishing it from its ancestors. At the same time, I recognized that the history of the theory, in its turn, may indeed contribute to the philosophical analysis of the theory by disclosing the vicissitudes in Einstein's own philosophical outlook.

I now return to the theme of these earlier publications in order to develop it anew. And I do so for the following reasons: (i) I can now supply explicit and specific support for my thesis from Einstein himself, in the form of source materials. The materials in question were either published in 1963 or were previously unknown both to me and presumably to nearly all interested people. (ii) I have had second thoughts on my earlier logical *and* historical assessment of the charge that the *aether-theoretic* Lorentz-Fitzgerald contraction hypothesis and the aether-theoretic Lorentz-Larmor time-dilation hypothesis were severally and collectively *ad hoc*. My revised assessment of the charges against these auxiliary hypotheses is prompted by recognition of the need for making previously neglected distinctions between quite different senses in which a collateral hypothesis can have the logical status of being *ad hoc*. If this revised analysis is sound, it will have quite *general* relevance to the philosophy and history of science.

The source materials which have induced me to provide a fresh treatment of some facets of my earlier theme consist of two reports of interviews with Einstein in which he was asked to recall in as much detail as possible the thought processes which led him to propound the special theory of relativity. The first of these came to light in January 1963 with the publication of R. S. Shankland's "Conversations with Albert Einstein," which constitutes a record of what Einstein recalled during 1950 to 1954 concerning the genesis of the theory (*3*). The second report, which I ran across quite recently, is an account by the Gestalt psychologist Max Wertheimer of conversations he had with Einstein starting in 1916 concerning "The thinking that led to the theory of relativity" (*4, 5*).

I welcome the opportunity of this address here in Cleveland as a fitting occasion for a further philosophical glance at the history of the special theory of relativity. For it was in this city that Michelson, Morley, and Miller carried out interferometric investigations which figured prominently in the history of the debate on the theory. Cleveland was also the site at which in 1888 Michelson gave his vice presidential address on optical research to the physics section of the AAAS. It is an irony of history that in that address of 1888 Michelson saw fit *not* to mention the now celebrated null result

Dr. Grünbaum is Andrew Mellon professor of philosophy and director of the Center for Philosophy of Science at the University of Pittsburgh. This article is the revised text of his vice-presidential address to the History and Philosophy of Science section (L) of the AAAS, delivered 29 December 1963 during the Cleveland meeting.