OROGENESIS AND DEEP CRUSTAL STRUCTURE—ADDITIONAL EVIDENCE FROM SEISMOLOGY

BY HUGO BENIOFF

ABSTRACT

Seismic evidence indicates that the principal orogenic structure responsible for each of the great linear and curvilinear mountain ranges and oceanic trenches is a complex reverse fault. A study of eight regions in which orogenic activity is in progress reveals that these great faults occur in two basic types, here designated oceanic and marginal. Oceanic faults, situated within the oceanic domain, extend from the surface to depths of 550 to 700 km. They exhibit an average dip of 61°. Their elastic strain-rebound characteristics show that these faults are composed of two separate mechanical units—a shallow component extending from the ocean bottom to a depth of roughly 60 km, and a deeper component extending to the 700 km crustal boundary. The marginal faults situated along the continental margins occur in dual and triple forms. The dual faults comprise a shallow member extending from the surface to a depth of approximately 60 km and an intermediate member extending to a depth of 200 to 300 km. The average dip is 33°. The marginal triple form is similar to the dual down to the 300 km level. At this depth the dip changes abruptly to 60° to form a third component extending down to the 650± km crustal boundary. The elastic strain-rebound characteristics of the marginal faults indicate that the components of these structures also move as separate units, although in South America the two lower elements exhibit some evidence for mechanical coupling. In the continental domain the 300 km level thus represents a tectonic discontinuity not as yet revealed by seismic wave-propagation studies but which is apparently the lower boundary of the continents. Since the oceanic faults and the deep components of the marginal faults have the same average dip (61°) it may be assumed that both are fractures in a single, continuous mechanical structure subject to a single stress system. The different average dip (33°) of the marginal intermediate fault components suggests that they occur in a structure mechanically distinct from the deep oceanic and continental layer and that they are activated by a different stress system. A hypothesis offered for the origin of the volcanoes associated with the faults assumes that the source of volcanic energy is heat produced in the fault rocks by the inelastic components of the repeated to-and-fro strains involved in the generation of the sequences of earthquakes and aftershocks.

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1 Except for the paragraph on the origin of volcanoes and a few minor deletions and additions, this paper was read under the title, Evidence from seismology on the nature of orogeny, at the Panel on Orogeny of the Cordilleran Section meeting of the Geological Society of America, Tucson, Arizona, April 11-12, 1952.
INTRODUCTION

The physical science of seismology is based almost entirely on observations made with seismographs and clocks. The principal observed data refer to the origin times of earthquakes, the depths and geographic distribution of their foci, and the amplitudes, frequencies, and propagation characteristics of seismic waves. In the past, seismic contributions to the problem of orogenesis included chiefly information as to locations of regions of tectonic activity and evidence for crustal structure exhibited by the speeds and transmission discontinuities of seismic waves. Publication of the monumental catalog of earthquakes by Gutenberg and Richter (1950) has made it possible to augment these early contributions with knowledge derived from magnitudes, time sequences, and accurate hypocentral locations. Thus an investigation (Benioff, 1949) of the elastic strain-rebound characteristics and related spatial distributions of foci of the seismic sequences of South America and the Tonga-Kermadec region indicated that the orogenic features associated with these two structures represent surface expressions of great faults extending 650 km in depth and up to 4500 km in length. These preliminary findings were thus at variance with those older concepts in which orogenesis is considered a result of sinking and subsequent rising of weakened portions of a thin (35 km ±) crust floating on a viscous or plastic substratum. In the present discussion, studies of an additional number of orogenically active regions are presented. These include the Sunda arc, the Kurile-Kamchatka segment, Mexico and Central America, the New Hebrides, the Philippines, the Bonin-Honshu segment, the Aleutian arc, as well as revisions of the South American and Tonga-Kermadec presentations. Magnitudes, origin times, depths, and geographic locations of the earthquakes and the locations of active volcanoes are taken from Gutenberg and Richter (1950).

REGIONAL SEISMIC SEQUENCES—OBSERVATIONS

South America

A revised map with composite profiles of the South American earthquake sequences is shown in Figure 1. Epicenters and foci of shallow, intermediate, and deep earthquakes are represented by circles, circular dots, and triangular dots respectively. Active volcanoes are represented by stars. The linear distribution of volcanoes exhibited here is characteristic of all the sequences represented in this study except the Philippines. The oceanic trench.
lying approximately parallel to the line of volcanoes is also characteristic. In constructing the composite profiles of these sequences and of the following ones, the plotted horizontal layer to a depth of approximately 650 km. In the figure, D' and E' are vertically exaggerated profiles taken along the lines D and E of the map to show the spatial relations of the

positions of foci represent their perpendicular distances from the volcano lines taken as reference co-ordinates. The region has been divided as shown into northern and southern sections AB and BC, for geometric simplicity of the projections A'B' and B'C'. The complex South American orogenic fault is a good example of the type which occurs along the margins of continents. Moreover, as the author has pointed out (Benioff, 1949), the strain-rebound characteristics and the distribution of foci indicate that this fault structure is made up of three components having three distinctly different types of tectonic movements. The first component involves the shallow layer of the crust above what may possibly be the Mohorovičić discontinuity. Near the fault this layer is assumed to extend to a depth of approximately 60 km. The second component defines an intermediate layer extending from the bottom of the shallow layer to a depth of 250-300 km. The third component extends from the lower surface of the intermediate oceanic trench, the mountain range, and the line of volcanoes (indicated by the star).

In the composite sections A'B' and B'C', the vertical and horizontal scales are equal. In the northern (Peru-Ecuador) segment, A'B', the intermediate component extends to a depth of approximately 250 km with a dip of 22°. In the southern segment (Chile), B'C', the dip is 23°. Unlike other sequences of this type, South America has no shocks with depths between 300 and 550 km so that the dip of the lower component is not accurately defined. Assuming that there is no horizontal displacement between the intermediate component and the deep component, the fault-zone lines can be extended upward to intersect the intermediate-zone lines as shown, in which case the angles of dip of the deep components of the two segments are 47° and 58° respectively.

**Kurile-Kamchatka Segment**

Figure 2 shows the orogenic elements of the Kurile-Kamchatka segment. The composite
profile C'D' represents the portion of the map bounded by CC and DD. A' and B' are vertically exaggerated profiles taken along the lines A and B. The Kurile-Kamchatka segment is thus a marginal orogenic fault complex with three components similar to the South American structure. The intermediate component extends to a depth of 300 km and dips under the continent at an angle of 34°. The deep component, with a dip of 58°, appears to have undergone a horizontal displacement of approximately 100 km westward (toward the continent) relative to the intermediate component as indicated by failure of the parallel dashed fault-zone lines to intersect at the 300-km level.

**Bonin-Honshu Segment**

The region of the Bonin-Honshu segment is shown in Figure 3. The composite profile B'C' represents the portion of the map bounded by BBCC. A' is a vertically exaggerated profile taken along the line A of the map. This orogenic complex is actually a part of the Kurile-Kamchatka-Japan structure, but has been separated here to avoid interpretation difficulties arising from distortion of the shallow low earthquake activity in this Bonin-Honshu segment, the large horizontal displacements between its two lower components, and its reverse curvature all strongly suggest that the whole fault complex from northern Kamchatka to the southern portion of the Bonin-Honshu segment was once continuous and convex toward the Pacific over its whole extent, as indicated on the left in Figure 4. The present form appears to be a result of an approximately 90-degree counterclockwise bending about a vertical axis in Manchuria, of the two lower components of the original arc relative to the original shallow component now forming the Nansei Shoto branch, as shown on the map on the right in Figure 4. Consequently, in the present Bonin-Honshu segment the shallow component is missing, and the intermediate component extends from the surface to a depth of 400 km. It is thus the deepest continental structure observed in this study. The fault dips westward under the continent at 38°. The deep component is displaced horizontally.
eastward, away from the continent, some 200 km relative to the intermediate component. This displacement, and the 75-degree dip, the largest of any studied to date, suggest that the forces which originally reversed the curvature of the Bonin-Honshu segment also twisted the deep component fault surface about a horizontal axis, as indicated on the right in Figure 4. It appears therefore that the common component of the couples, responsible for the bend and the twist, acted horizontally eastward along the lower boundary of the lower layer.

**Sunda Arc**

Figure 5 shows the region of the Sunda arc. The portion of the map represented in the composite profile B'C' is that bounded by the dashed lines BBCC. This structure is also a triple marginal fault. The intermediate component dips northward under the continent at an angle of 35°. It has a maximum depth of approximately 300 km. The dip of the deep component is 61°. It has been displaced horizontally approximately 200 km southward (away from the continent) relative to the
intermediate component, as indicated by the dashed lines in $B'C'$. 

**Mexico and Central America**

Figure 6 shows the dual marginal Acapulco-Guatemala fault complex. The intermediate component extends (under the continent) to a depth of only 220 km with a dip of 39°. The shocks northwest of the boundary BB are shallow and presumably represent horizontal movements on the shallow clockwise transcurrent San Andreas fault system. There is no evidence for the existence of a deep component in this region.

**Aleutian Arc**

Figure 7 refers to the Aleutian arc, also a marginal dual fault. The composite profile $B'C'$ shows only those features bounded by the dashed lines BBCC of the map. The intermediate component dips northward 28° and extends to a depth of 175 km, thus forming the shallowest continental structure treated in this study, with the possible exception of the Philippines.

**New Hebrides Region**

Figure 8 shows the region of the New Hebrides fault. This orogenic structure is also a
marginal fault principally of the dual type, although the occurrence of two shocks at the 350-km level suggests the possibility of a deeper component of small activity. The intermediate component extends to a depth of 300 km and dips northeast 42°.

**Tonga-Kermadec Region**

A revised map and composite profile of the Tonga-Kermadec fault complex is shown in Figure 9. In the earlier paper (Benioff, 1949) the author assumed that the structure consisted of a single continuous fault. However, the existence of two lines of volcanoes and the asymmetrical distribution of epicenters are better explained with two faults, even though the strain-rebound characteristics indicate that the two are actuated by a single stress system. The composite profile A'B' represents the map area AABB associated with the Tonga segment. The vertically exaggerated profile C' is taken along the line C of the map. The composite profile D'E' represents the area DDEE of the map, associated with the Kermadec segment. The latter extends well into
the region of North Island of New Zealand. The Tonga-Kermadec structure is the principal representative of the oceanic form of orogenic fault complex. The elastic strain-rebound characteristics of these faults (Benioff, 1949) and their composite profiles show that they are of dual type with shallow components extending to a depth of approximately 70 km. The deep component of the Tonga fault dips 59° NW. and extends from 70 km to 650 km in depth. The deep component of the Kermadec fault dips approximately 64° NW. and extends to a depth of 550 km.

**Philippine Islands**

The region of the Philippine Islands (Fig. 10) is the most disturbed area in this series. The volcanoes exhibit no well-defined line. The projection line B'C' was constructed with the reference line OX drawn approximately parallel to the strike of the trench. The structure is
considered here an oceanic fault complex, although the concentration of foci in the depth range 70–150 km may represent an intermediate component of corresponding thickness and the mechanism of orogenesis found in the earlier investigation of the Tonga and South American sequences. Thus it appears that in those great linear and curvilinear tectonic structures, now

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| OCEANIC FAULTS            |
| FAULT                      | DEPTH RANGE, KM | DIP |
| MINDANAO                  | 70 - 700        | 60° |
| TONGA                     | 70 - 650        | 58° |
| KERMADEC                  | 70 - 550        | 64° |
| AVERAGE DIP               | 61°             |     |

having a dip westward of approximately 36°. If this is the correct interpretation, the fault is a marginal one of triple type. The deep component extends to a depth of 700 km with a dip of roughly 60°.

**Summary of Fault Measurements**

Depth ranges and dips of the orogenic fault components for each of the regions studied are assembled in Table 1. In the marginal faults the average values of the dips for the intermediate and lowest components are 33° and 60° respectively. In the oceanic faults the average dip of the lower component is 61°. The observational precision (approximately ±50 km in any direction) is not high enough to permit any conclusions regarding the dip of the shallow components nor to differentiate between dip slip and strike slip faulting in their movements.

**Implications Concerning Crustal Structure and Orogeny**

**Principal Orogenic Mechanism, Reverse Fault**

This extended study of tectonically active regions supplements the conclusions regarding seismically active, the principal orogenic mechanism involves a complex reverse fault extending to a depth which varies from 175 km to 720 km depending upon the region.

**Shallow and Intermediate Crustal Structure Indicated by Faults**

The principal features of the faults and the crustal structure which they define are shown in the generalized section of the crust in Figure 11. The continental marginal structure is indicated on the right, and the oceanic type is shown on the left. The shallow continental layer A, above the Mohorovičić discontinuity M, is approximately 35 km thick as determined by many investigators from wave-propagation studies. It is assumed here to be the same as the layer defined by the shallow earthquake sequences. The strain-rebound characteristics studied so far indicate that, in the vicinity of the faults, shocks belonging to the shallow sequences occur down to a depth of approximately 60 or 70 km in accordance with the classification of shallow, Gutenberg and Richter (1950). Accordingly, in the figure the shallow layer is shown thickened to this extent.
in the vicinity of the fault. Presumably this thickening is a result of drag and plastic flow of the strained fault lip. Thus, in part at least, the roots of mountains may be expressions of the oceanic structures the fault extends all the way from this level to the 60-km discontinuity, and presumably to the surface, with a constant average dip of approximately $61^\circ$. Since the

![Diagram showing oceanic and continental crustal sections with fault types](image)

**Figure 11.** Generalized Oceanic and Continental Deep Crustal Sections with Orogenic Fault Types

this fault-generated distortion. In the triple marginal faults the discontinuity in angle of dip at 300 km ±, and the marked dissimilarity between the strain-rebound characteristics of the shocks occurring in the fault components above and below this level, are interpreted as evidence for an additional tectonic discontinuity between B and C, as shown in the figure. In the dual structures the lower fault component C is either absent or inactive. The intermediate component with the 32-degree dip occurs in marginal structures, but not in oceanic structures; consequently, the layer B defined by this component is here assumed to be a part of the continental structure. If this assumption is correct, the continents extend downward to an average depth of 280 km, with 175 km and 400 km extreme values.

**Deep Crustal Structure Indicated by Faults**

In the triple marginal structures the fault dip increases suddenly at the lower boundary of the intermediate component to an average value of approximately $60^\circ$ and continues down with this value to the 700 ± km level, below which earthquakes do not occur. In dips of the oceanic faults and the deep components of the continental faults are essentially equal, it is assumed that both types are fractures in a single continuous medium (Fig. 11, C) subject to a single stress system. The measured seismic wave speeds near the upper boundaries of the continental layer B and the oceanic layer C are very nearly equal (8.2 ± km/sec for compressional waves). This suggests that they may be identical in composition. Bullard (1952), on the other hand, cites evidence to the contrary. However, whether or not they are of identical composition, the layers are separated by a tectonic discontinuity and are subject to different stress systems.

**Rigidity in Deep Layer**

Since earthquakes occur down to depths of 550–720 km in both marginal and oceanic faults, it must be assumed that at these depths the crustal rocks can maintain elastic shearing strains of sufficient duration to accumulate the necessary strain energy to generate earthquakes. Moreover, the strain-rebound characteristics of the deep sequence of South America provide evidence for accumulation of elastic
strain without creep or flow over a period of 53.5 years at a depth of 550–650 km (Benioff, 1949). The Tonga deep sequence exhibited elastic (recoverable) creep without flow over a period of 15 years down to a depth of 650 km (Benioff, 1949). Thus, for time intervals at least of the order of a decade, the earth’s crust in the vicinity of the orogenic faults is a rigid solid down to the 700 ± km level. Accordingly, this depth limit is here taken as the lower boundary of the solid crust. For geologically long time intervals the crust may, of course, behave as a viscous or plastic substance at these (and shallower) depths. The question as to whether or not the crustal structure, defined in this manner by orogenic faults, extends over the whole earth to regions not now seismically active, is one which cannot be answered by studies of this kind alone. In this connection, Birch’s (1951) discovery, derived from calculations of the rate of change of the bulk modulus with pressure, of a substantial departure from physical or chemical homogeneity in the depth range 200–800 km may be additional evidence for the discontinuities and structures derived from these studies.

**Orogenic Fault-generating Stresses**

The intermediate components are reverse faults which dip under the continents at an average angle of 33°. This value falls within the range calculated and observed by Hubbert (1951) for faults produced by stress patterns in which the greatest principal stress is a hori-

\[
\sigma_3 > \sigma_2 > \sigma_1 < \frac{\sigma_1 + \sigma_3}{2}
\]

\[
\sigma_2 > \frac{\sigma_1 + \sigma_3}{2}
\]

**Figure 12.**—Stress relations indicated by fault dips

If \( \sigma_2 \) is less than the average of \( \sigma_1 \) and \( \sigma_3 \), the angle of dip is less than 45°. If \( \sigma_2 \) is greater than the average of the other two, the angle of dip...
is greater than 45°. On this basis it would appear that both the 33-degree and 61-degree faults are produced by stress patterns in which the greatest principal stress is a horizontal compression oriented effectively at right angles to the orogenic axis. The continental margins are thus moving relatively toward the adjacent oceanic domains. In the 33-degree intermediate continental faults the horizontal intermediate stress $\sigma_2$ is nearer in value to the vertical stress $\sigma_1$ than to the horizontal stress $\sigma_3$. On the other hand, in the 60-degree oceanic faults and the deep components of the continental faults, $\sigma_2$ is closer in value to $\sigma_3$. In other words, the horizontal stress pattern is more nearly symmetrical in the deep layer than in the intermediate layer.

**Direction of Slip**

The direction of slip assumed for all the faults in which the underside moves down is dictated by the geometry of the trenches and adjacent uplifts. It refers to the fault-generating conditions only. There is no reason to believe that these original conditions necessarily remain unaltered in time, and consequently, once the fault structure has been formed, subsequent stress patterns may change. Later movements may thus involve horizontal slip or even reversals of slip direction. Such alterations may be temporary or permanent. In the latter case, the trench eventually disappears. Perhaps this has been the history of the Pacific coast of North America between Alaska and Lower California and of the Himalayan-Indian arc. A reverse slip may thus be the evidence for decline in the life of an orogenic fault. Instances of reversed slip have been observed by Ritsema (1952, thesis, Univ. Utrecht) for two deep shocks in the Sunda and Philippine regions respectively, and by Koning (1942) for one shock of the Sunda arc. However, the method employed by these authors for measuring the strike and direction of slip is of questionable reliability. It depends upon correct determination from seismograms of the displacement direction of the initial ground motion for each of a rather large number of seismograph stations. Particularly in deep earthquakes, the initial wave motion is nearly always made up of relatively high-frequency components for which most seismographs have inadequate magnification. Moreover, for those critically situated stations to which the initial waves travel in or near the plane of faulting, the direction of initial displacement is either indeterminate or else too small in relation to the ground unrest to be reliably recorded by an instrument situated outside the epicentral region. Evidence that the results of this method should be accepted with caution is provided by calculations reported by J. H. Hodgson (1952) using a modified form which, nevertheless, depends solely on correct observations of the initial displacements. In an application to the Ancash, Peru, earthquake of November 10, 1946, the method indicated that the faulting was of the transcurrent type, whereas observations on the ground reported by Silgado (1951) showed clearly that the faulting was of the dip-slip type in accordance with the known tectonic character of the region.

In a recent paper, H. Honda and A. Matsuoka (1952) have studied the direction of motion of some 145 intermediate and deep earthquakes of Japan using observations of a large number of Japanese stations. Since these stations are all in or near the epicentral region of the shocks, the reliability of first-motion determinations is relatively high. Their results indicate clearly that for these shocks the dip of the faults and the direction of slip are in substantial agreement with the assumptions and findings of the present investigation.

**Relationship Between Shallow Oceanic and Intermediate Marginal Layers**

The continental surface layer of 35 km thickness in which the shallow marginal components occur is generally reduced to approximately 5 km under the oceans insofar as the evidence from wave-propagation studies indicates. On the other hand, the strain-rebound characteristics of the Tonga-Kermadec sequences show that shallow earthquakes occur to a depth of 60 or 70 km in the oceanic structures. Hence, in the vicinity of the oceanic faults we must assume some sort of shallow discontinuity having approximately the same depth as the shallow discontinuity of the continents. Such a discontinuity is therefore shown on the left in Figure 11.
Figure 13.—Elastic strain-rebound characteristic, Tonga-Kermadec deep earthquake sequence for focal depths 70–680 km

Figure 14.—Elastic strain-rebound characteristic, New Hebrides shallow earthquake sequence h < 70 km

As indicated in Figure 11, it is assumed that in general the intermediate layer B terminates at the fault. There is some evidence from the strain-rebound characteristics, however, for the conclusion that in the New Hebrides-Tonga region the intermediate continental layer extends across the intermediate fault to become the shallow layer of the Tonga-Kermadec oceanic fault. The elastic strain-rebound characteristic of the Tonga-Kermadec deep
components is shown in Figure 13. That for the shallow component of the New Hebrides fault is shown in Figure 14. It is obvious that these two curves are dissimilar and that they must be derived from movements of two distinct mechanical structures. On the other hand, the characteristics of the Tonga-Kermadec shallow sequence and the New Hebrides intermediate sequence (Fig. 15) are strikingly similar, except for a time delay of approximately 2000 days of the former relative to the latter, and both are unlike either the New Hebrides shallow characteristic or the Tonga deep characteristic. It appears, therefore, that the Tonga shallow-fault component and the New Hebrides intermediate component are fractures in a single mechanical structure subject to a single stress system. The situation can best be understood by reference.
to Figure 16 in which the left portion is a map and section of the New Hebrides-Tonga region. On the right, the four rebound characteristics are roughly sketched with coinciding time co-
ordinates. Counting from the bottom, the first curve—the Tonga deep characteristic—refers to the component D in the section E-E'. The second curve, which is of the Tonga shallow component, refers to the component C of the
section. Since these two curves are so very dis-
similar, movements in the two involved com-
ponents are unrelated, and consequently a discontinuity must be drawn between C and D.
The third curve is the New Hebrides inter-
mediate characteristic. It refers to the com-
ponent B in the figure. Since the curves for B and C are so nearly alike we must assume that these two components are members of a single stress system, and consequently the inter-
mediate layer at B is shown continuous with the shallow layer at C. Since the rebound characteristic of the shallow New Hebrides component A (the fourth curve on the right) is unlike that of the deeper component below it, a discontinuity must be drawn between the two. The structure deduced here for the Tonga-
New Hebrides region may represent a special configura-
tion of this part of the earth only and may not be valid for other regions in which the structure outlined in Figure 11 must be con-
sidered representative.

Orogenesis and Volcanoes

One of the most remarkable features of the
orogenic faults discussed in this paper is the
linear array of volcanoes lying parallel to the
fault strike on the uplifted block. Indeed the
line of volcanoes has served as the principal
reference co-ordinate for drafting the composite
profiles. Volcanoes are clearly one of the
manifestations of orogeny. In an attempt to
explain this close relationship the writer is
offering a hypothesis of the origin of the vol-
canoes which at least will direct thinking toward
this interesting problem. By referring to the
composite profiles shown in Figures 1–9 it
will be noted that in general the volcano line
coincides with the highest elevation of the
overhanging fault block and thus appears to
be situated along the line of maximum bending
of the block. In recent studies the writer
(Benioff, 1951) found evidence that the after-
shock sequences which follow significant
earthquakes are generated by elastic after
working or creep recovery of the fault rock.
During the interval between principal earth-
quakes, strains accumulate in the rocks. A
portion of this strain is purely elastic, and a
portion is time-dependent. When the fault
slips to produce the principal earthquake, the
purely elastic strain only is involved. The time-
dependent or creep strain can be released only
relatively slowly in accordance with the creep-
recovery characteristics of the rocks. It is this
time-dependent elastic recovery which produces
the aftershocks. However, only a small portion
of the energy stored in the creep-elastic ele-
ment can be converted into seismic waves in
aftershocks. The main portion is liberated as
heat. A rough calculation of the energy liberated
as heat in a number of aftershock sequences
shows that it averages approximately half
the amount of the energy liberated as seismic
waves in the principal shock. In the orogenic
faults on which earthquakes occur repeatedly,
the fault rock undergoes a cycle of alternate
strain and relief for each earthquake. This
repeated to-and-fro bending generates heat in
much the same way that quick bending of a
wire warms it. The thermal time constant of
the great rock masses below the surface is so
long that heat generated by these cycles of
strain escapes very slowly and consequently
accumulates over long intervals of time. If the
rock being heated has components with differ-
ent melting points, there comes a time when
one or more will melt. The region of most
intense heat generation should coincide with
the regions of most intense bending—the
highest elevations of the overhanging block
and the lowest depths of the neighboring
trenches. The low incidence of volcanoes in
the trenches may be ascribable to a higher
melting point induced by the increased pressure
and to the fact that the trench (in the form of a
syncline) is not so effective a structure for
concentration of the molten rock as the com-
plementary anticline of the uplifted block on
the upper side of the fault.

A rough idea of the magnitude of energy
released, say per year, by the aftershock se-
quences in a region on one side of the fault can be obtained by taking one fourth of the energy released in the same time by seismic waves in the principal earthquakes. Thus, in the case of South America, the shallow and intermediate earthquake sequences each liberate approximately $4 \times 10^{23}$ ergs per year. Thus roughly $10^{24}$ ergs per year is being released in the fault blocks. The writer has no knowledge of the amount of energy per year required to maintain the South American system of volcanoes, and consequently it is not possible to say whether or not the energy requirements are met on this hypothesis. Moreover there must be a large time lag between the liberation of heat in the depths and its appearance in the form of volcanic output. Thus the present rate of volcanic energy release should be equated to a phase of seismic-heat generation which occurred long ago, rather than to the present rate.

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