SEISMOLOGICAL EVIDENCE FOR SELECTIVITY IN SLIP PLANES UNDER DOWN-DIP EXTENSION OR COMPRESSION

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RESUMEN

Un análisis reciente de temblores múltiples sugiere que hay una selectividad en los planos de falla en las zonas sísmicas bajo condiciones de extensión o compresión. Las soluciones de planos de falla no distinguen entre el plano de falla y el plano auxiliar. El análisis de un temblor múltiple permite resolver esta ambigüedad. Se presentan los resultados resumidos del análisis de más de veinte temblores múltiples profundos, en cuanto a la relación mutua de las pendientes entre los planos de falla y sus planos auxiliares. Los planos de falla tienden a tener pendientes más cercanas a la vertical que los auxiliares, sea que predomine la compresión o la extensión en la dirección de subducción. Las fuerzas exteriores que se ejercen desde arriba o desde abajo de la placa litosférica pueden causar extensión o compresión, pero no pueden determinar una selectividad en los planos de falla. La explicación más sencilla de tal selectividad es la idea de un hundimiento gravitacional de la litósfera. Esta explicación se basa en el hecho que todo desplazamiento de falla implica un trabajo en contra de la gravedad. Posiblemente pueda existir una selectividad similar para los temblores litosféricos someros debajo de las trincheras.

ABSTRACT

A selectivity in slip planes under down-dip extension or compression in seismic zones is suggested from recent analyses of multiplets. A fault plane solution cannot distinguish the slip plane from the auxiliary plane. Analysis of a multiplet can remove this ambiguity. The results of the analyses of more than twenty deep multiplets are synthesized in reference to the mutual relationship in dip angle between the slip planes and their auxiliary planes. The slip planes tend to dip more steeply than their auxiliary planes in seismic zones where either down-dip extension or compression is predominant. The external forces applied below and above the sinking slab of lithosphere could cause either extension or compression but cannot produce such a selectivity in slip planes. The idea of gravitational sinking of the lithosphere provides the simplest explanation for this selectivity. The explanation is based on the fact that faulting must do some work against gravity. A similar selectivity may exist for shallow lithospheric earthquakes beneath trenches.

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INTRODUCTION

Usually we call earthquakes that occur within the oceanic lithosphere: lithospheric earthquakes. If the stress which causes lithospheric earthquakes is generated by the same mechanism that drives the movements of lithospheric plates, the source mechanism of these earthquakes may furnish one of the best clues to the driving mechanism of plate tectonics. Perhaps the most typical lithospheric earthquakes are deep and intermediate-depth earthquakes. Isacks and Molnar (1969, 1971) used focal mechanism data of deep and intermediate-depth shocks to suggest that at intermediate depths the lithosphere sinks into the asthenosphere under its own weight and at great depths it encounters stronger or denser material. The present paper attempts to support these ideas of gravitational sinking of the lithosphere by presenting some new evidence obtained from the studies of source mechanism of lithospheric earthquakes.

SHEAR FAULTING MODEL

It is generally known that the radiation pattern of P and S waves is explained by a model of double couple force system. The double couple model is often regarded as corresponding to the occurrence of shear faulting but other explanations are possible. For example, the radiation patterns of double couple type are expected from a volumetric source with a sudden change in shear modulus caused by a phase transition (Knopoff and Randall, 1970).

Perhaps the most convincing results for supporting the shear faulting model have been obtained from the analyses of deep multiplets which include more than two shocks with very short time and space intervals. The deep Western Brazil earthquake of 1963 is one of the best examples for such multiplets. This earthquake is a triplet containing three events closely related in time and space to each other and was followed by a large aftershock (Fukao, 1972). Fig. 1 shows a long –and a short– period seismogram of this earthquake. On the long-period record it is clearly seen that the P wave seismogram contains three distinct P phases P_1, P_2 and P_3 corresponding to the first, the second and the third event of the triplet. On the short-period record only the first arrival (P_1 phase) can be identified. On the other hand, the first arrival of the aftershock can be read more accurately on the short-period record than on the long-period record. By reading the differences in arrival times between the first event and the subsequent events, we can determine the spatial and temporal relation between any of the four shocks including the aftershock. In Fig. 2 the orientation of the second and the third shocks and the aftershock referred to the first shock are plotted on the focal sphere of the first shock in a stereographic projection. The fault plane solution of the first shock is superimposed. Two solid lines represent the easterly and the westerly dipping nodal planes for P waves. This figure clearly shows that the second and third shocks and the aftershock are located on the easterly dipping nodal plane within the uncertainty of the analysis (see Chandra, 1973; Fukao, 1973).

If a multiple shock occurs in the form of shear faulting, the events constituting the multiplet are likely to share the same slip plane. The events subsequent to the first event are therefore expected to concentrate on one of the P wave nodal planes. There would be no such tendency for a volumetric source model such as a phase transition model. For this reason I believe that the Western Brazil earthquake of 1963 occurred in the form of shear faulting, and that the slip plane was the easterly dipping nodal plane rather than the westerly dipping nodal plane. More than twenty multiplets have been investigated by the same method and nearly all the results support the shear faulting model (Oike, 1969, 1971; Fukao, 1972; Chandra, 1970, 1973).

SELECTIVITY IN SLIP PLANES

We now synthesize the results of the analyses of the multiplets. The multiplets are classified into three groups according to the nature of their seismic zone. The first type of multiplets are those at intermediate depths where extensional stresses parallel to the dip of the zone are predominant. Seven events occurred in such regions, including Peru-Chile, Kuril, Mindanao, New Britain, Solomon Islands and Hindu Kush. The second type of multiplets are those at great depths, where compressional stresses parallel to the dip of the zone are prevalent. The seismic activity is continuous to depths of 500-700 km in such zones. Eight events occurred in such regions, including North Honshu, Izu-Bonin and Tonga. The third type of multiplets are those between depths of about 500 to 650 km above which there is a marked gap in seismic activity. The focal mechanisms are characterized by nearly vertical compressional axes. Eight events occurred in such regions, including Peru-Chile, New Hebrides and Sunda. Table 1 gives the pertinent information on all twenty-three multiplets.

The top illustrations in Fig. 3 show the orientations of the axes of the stress as given by the fault plane solutions for each type of multiplets. Symbols P, T and B represent the compressional axis, the tensional axis and the null axis respectively, all plotted on the lower hemisphere of an equal area projection. The data for each seismic zone are plotted relative to the strike of the zone. The dips of the zones are indicated by the solid and the dashed lines. The dashed lines are used where the orientations of the zones are estimated from the fault plane solutions (Isacks and Molnar, 1971). The dip of the zones varies within a wide range from region to region for the first type of multiplets. The zones dip at an angle of 30 to 45° for the second type of multiplets and nearly vertically for the third type of multiplets. The plots clearly show down-dip extension for the first type of multiplets, and down-dip compression for the second and the third types of multiplets.

A fault plane solution cannot determine which of the two nodal planes is the slip plane. The analyses of the multiplets resolved this ambiguity and distinguished the slip planes from their auxiliary planes. We now consider the mutual relationship in dip angle between the slip planes and their auxiliary planes. Two cases arise in this context, as illustrated in Fig. 4. In Case A, the slip plane dips more steeply than the auxiliary plane. In case B, the slip plane dips less steeply than the auxiliary plane. In Fig. 4 the left-hand drawings refer to the first type of multiplets and the right hand to the second and third types of multiplets. We are interested in which case is more predominant, Case A or B, for each type of multiplets.

The bottom figures in Fig. 3 illustrate the orientations of the poles of the nodal planes. A fault-plane solution gives two mutually orthogonal nodal planes whose poles are indicated by an open and a filled circle. The open circle represents the more steeply dipping nodal plane. The filled circle represents the less steeply dipping nodal plane. For Case A, the slip plane is the steeper nodal plane rather than the more gently dipping nodal plane, and is marked by a cross on the open circle. For Case B, the slip plane is the more gently dipping nodal plane, and is marked by a cross on the filled circle. In Fig. 3 crosses are far more predominantly associated with open circles than with filled circles. In other words, Case A is much more prevalent than Case B for each type of multiplets. Table 2 lists the number of multiplets belonging to Case A and B respectively. Predominance of Case A over Case B, originally noted by Oike (1971) for the first type of multiplets, is again obvious. It is strongly suggested that the slip planes tend to dip more steeply than their auxiliary planes either under down-dip extension or compression.

INTERPRETATION

Deep and intermediate-depth earthquakes occur in the form of shear faulting inside the slab in response to extensional or compressional stresses aligned parallel to the slab (Isacks and Molnar, 1969, 1971). In view of the symmetry either of the two slip planes which are mutually conjugate with respect to the axis of extension or compression seems to be equally possible. The actual slip plane, however, tends to be selected from these two possible slip planes so that the slip plane dips more steeply than the auxiliary plane. Since the two possible slip planes are roughly orthogonal (Isacks and Molnar, 1969, 1971), this seleectivity may be replaced by the following selectivity: though we could imagine two possible slip planes under down-dip extension or compression, the more steeply dipping one tends to be the actual slip plane.

Such a tendency would not be expected, if extension or compression were the result of forces applied at both ends of the slab. The idea of gravitational sinkin of the lithosphere provides a key to understanding this tendency. The sinking slab of lithosphere, more dense than the surrounding mantle, possesses excess mass. Gravitational forces act on this excess mass. From an energy standpoint the preferred among the two possible slip planes should be the one along which virtual sliding will do less work against the gravitational field.

The idea is schematically shown in Fig. 5. At intermediate depths the gravitational forces acting on the excess mass in the slab are mainly supported by resisting forces applied above the sinking portion. The cause of this resistance might be either friction between the oceanic and continental lithospheres or the buoyant effect due to depression of the slab below its local equilibrium level (Jacob, 1970). The slab is under extension. Such extension would produce two possible slip planes, one of which must be steeper than the other. Virtual sliding along this steeper slip plane does less work against gravity than along the other possible slip plane. This is simply because the downward-directed gravitational forces are supported from above (see Fig. 5). At great depths the excess load within the slab is mainly supported from below, by resisting forces applied to the lower parts of the slab. This resistance may arise from an increase in strength or density of the surrounding mantle. The slab is under compression. Such compression may produce two possible slip planes. Virtual sliding along the steeper slip plane again does less work against gravity than along the other possible slip plane (see Fig. 5). In either down-dip extension or compression, the simple energy considerations favor the more steeply dipping of the two possible slip planes.

In some regions such as North Honshu, Izu-Bonin and Tonga, the slab appears to be continuous from the surface to geat depths. In such regions the slab might be pushed from the suboceanic plate on the surface. This pushing could cause down-dip compression but cannot produce selectivity in slip planes. I therefore believe that pushing from the suboceanic plate cannot be the primary cause of compression prevailing in the sinking slab.

If the friction between the oceanic lithosphere and the continent is not significantly large, the sinking lithosphere gravitationally pulls the suboceanic plate left on the surface (Kanamori, 1971b). The suboceanic plate is thereby placed under extension at least to some degree towards the seaward side of the trench. This extension may produce shallow lithospheric earthquakes of normal faulting type. Perhaps the great Sanriku earthquake of 1933 and the large Rat Island earthquake of March 30, 1965 were of this type (Kanamori, 1971a; Abe, 1972a). They represented normal faulting and occurred beneath the Japan trench and the Aleutian trench respectively. Fig. 6 shows the planar distribution of the aftershocks of the Rat Island earthquake (Abe, 1972a). The aftershock zone marks the slip plane of this earthquake. The slip plane dips towards the continental side of the Aleutian trench. The slip plane of the Sanriku earthquake dips towards the continental side of the Japan trench (Kanamori, 1971). In either case the slip plane dips towards the continental side of the trench and the sinking portion of the lithosphere slipped down with respect to the suboceanic plate left on the surface as shown by the left illustration in Fig. 7. This coincidence may not be a matter of chance. If the slip plane dips towards the seaward side of the trench, the sinking portion must slide up along it (see Fig. 7). This is obviously unfavorable from the energy standpoint. Slip planes dipping towards the continental side are more preferable. This selectivity should exist if the extension within the suboceanic plate is the result of gravitational pull of the sinking portion. Besides the gravitational pull, a simple bending of the lithosphere could produce extension beneath trenches. If this were the primary cause of extension, however, the slip planes dipping towards the continental side and those dipping towards the seaward side would be equally likely. At present the data are limited to only two earthquakes but they are at least consistent with the interpretation that gravitational pull is the primary cause of extension beneath trenches.

IMPLICATIONS OF SEISMIC ACTIVITY IN SOUTH AMERICA

Fig. 8 shows the depth profile of the seismic activity across the Peru trench. At intermediate depths the seismic zone is slablike and dips gently beneath the South American continent. Between depths of 200 and 500 km there is a remarkable gap in seismic activity. Deep shocks concentrate around depths of 600 km. Down-dip extension parallel to the seismic zone is predominant at intermediate depths and nearly vertical compression is prevalent at great depths (Isacks and Molnar, 1971). Fig. 9 shows a model explaining these seismological features. The gap in seismic activity is explained by a detachment of the sinking lithosphere (Isacks and Molnar, 1969, 1971; Fukao, 1972). The Nazca plate underthrusts the South American continent. The Peru earthquake of 1966 represents thrust faulting and manifests this tectonic movement (Abe, 1972b). Since the descending slab is more dense than the surrounding mantle, extension prevails in it. Although one may imagine two mutually conjugate slip planes for this extension, the steeper one tends to be the actual slip plane of an intermediate-depth earthquake. The large Peru earthquake of 1970 represents normal faulting (Abe, 1972b) and may be regarded as the shallowest event of this type as illustrated in Fig. 9. This earthquake produced a large crack within the oceanic lithosphere. If such internal cracks are developed to a large extent along the coastal line of South America, the sinking portion of the lithosphere may be mechanically decoupled, to some extent, from the suboceanic plate left of the surface. If this is the case, the effect of the gravitational pull from the sinking portion may not extend to the whole Nazca plate. In fact, the focal mechanism of a shock in the middle of the Nazca plate suggests that the Nazca plate is now being compressed in the direction of plate motion (Mendiguren, 1971).

CONCLUSIONS

Focal mechanism data suggests that deep and intermediate depth earthquakes occur in response to extensional or compressional stresses parallel to the inclined seismic zone (Isacks and Molnar, 1969, 1971). This down-dip extension or compression may produce two planes of weakness which are mutually conjugate with respect to the axis of extension or compression. The actual slip plane should be selected from these two planes. The selectivity that we found is such that the more steeply dipping plane reather than the less steeper one tends to be the actual slip plane. This result is based on a compilation of results of the analyses of deep multiplets. Among twenty-three multiplets only two shocks are incompatible with this selectivity. However, the evidence may be still insufficient to regard this as a general rule.

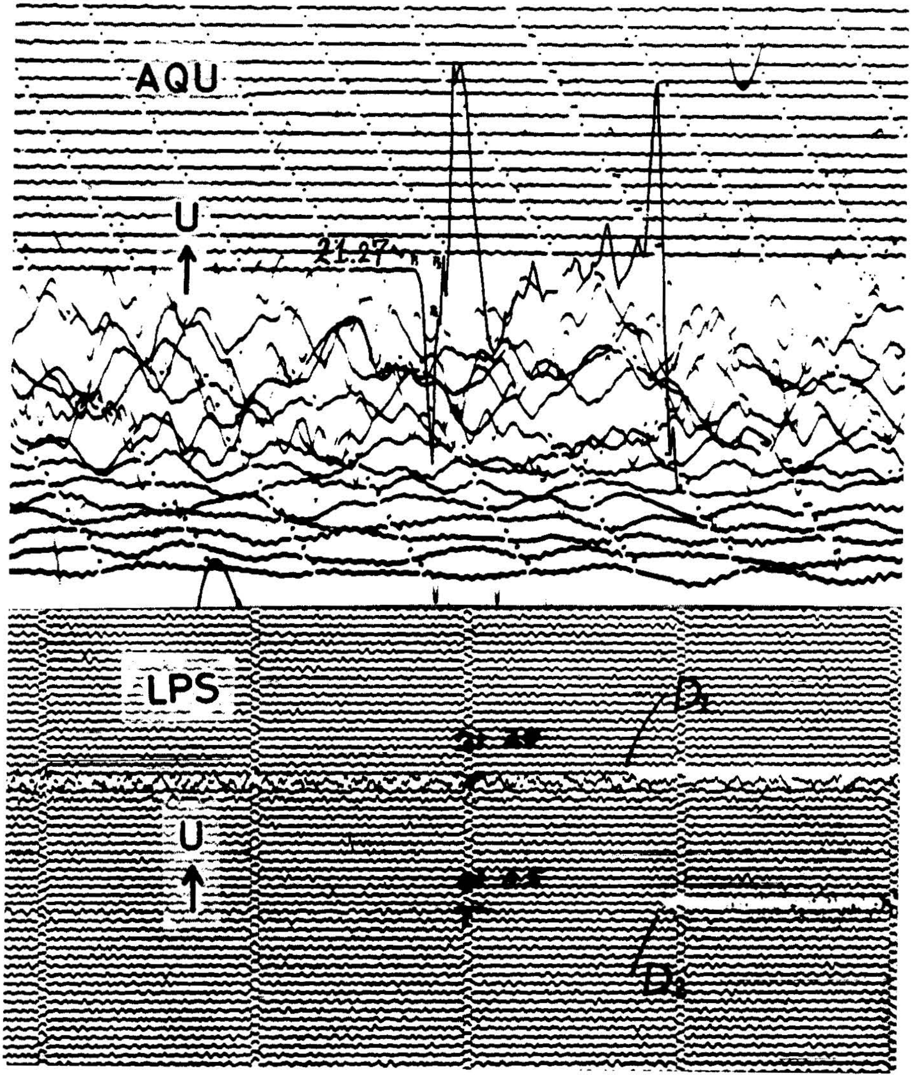

Figure 1. Top: Long-period record of the vertical component at L'Aquila in Italy. Bottom: Short-period record of the vertical component at La Palma in El Salvador.

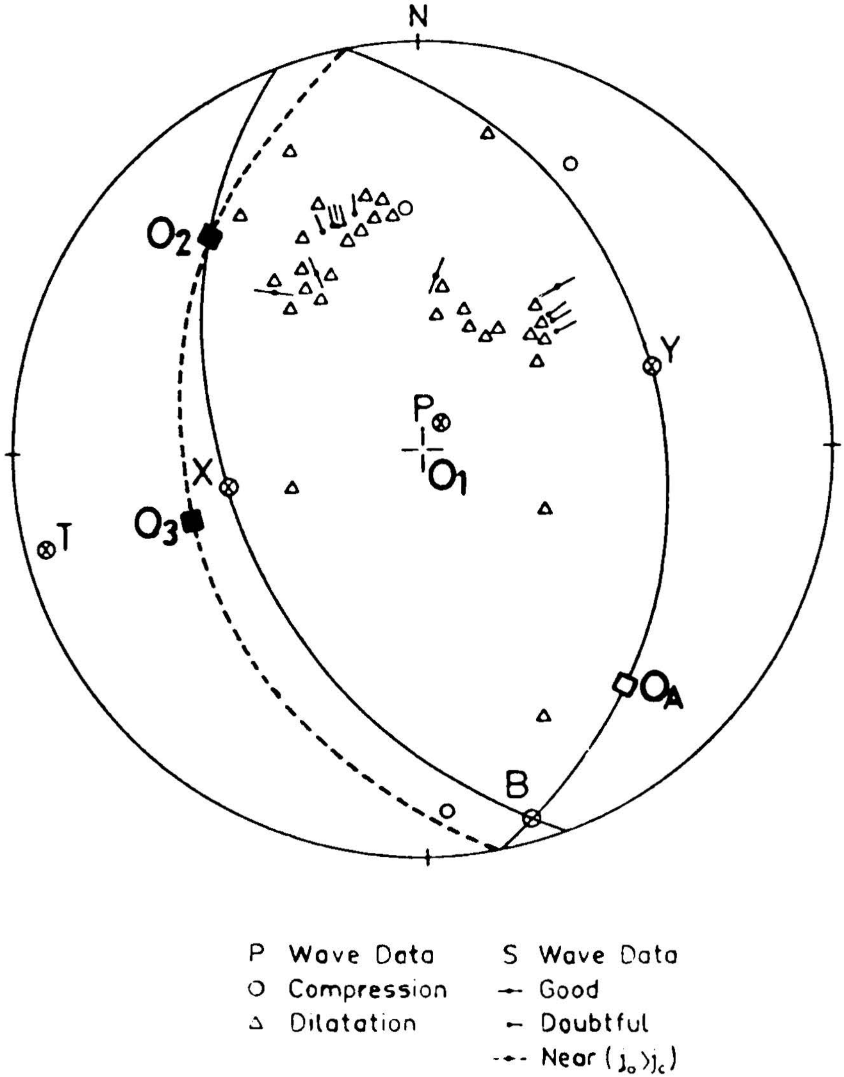

Figure 2. Fault plane solution of the first shock on an equal-area projection. Two solid curves represent the two nodal planes of the lower hemisphere of the focal sphere. The dotted curve represents the easterly dipping nodal plane of the upper hemisphere: The orientations of the second and the third shocks (0_2 and 0_3) relative to the first shock are plotted on the upper hemisphere. The orientation of the aftershock (0_A) relative to the first shock is plotted on the lower hemisphere.

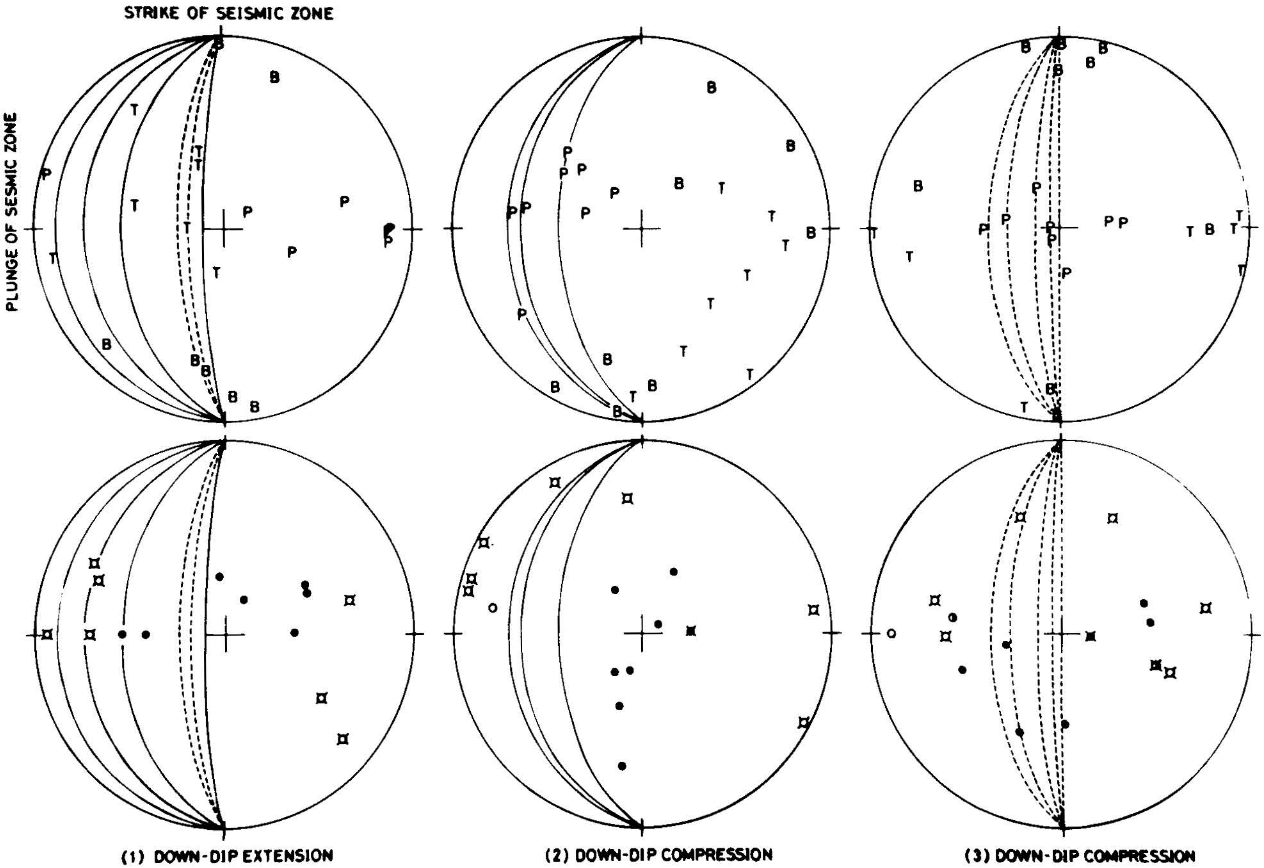

Figure 3. Top: Orientations of the axes of stress as given by the fault plane solutions. The left, middle and right illustrations for the first, second and third types of multiplets. Symboles P, T and B represent the compressional axis, the tensional axis, and the null axis. The data for each seismic zone are plotted relative to the strike of the xone. The dips of the zones are indicated by the solid and the dashed lines. Bottom: Orientations of the poles of the slip planes and their auxiliary planes. If a slip plane dips more steeply than the auxiliary plane, their poles are indicated by an open circle with a cross on it and a filled circle without the cross respectively. If a slip plane dips less steeply than the auxiliary plane, their poles are indicated by a filled circle with a cross on it and an open circle without the cross respectively.

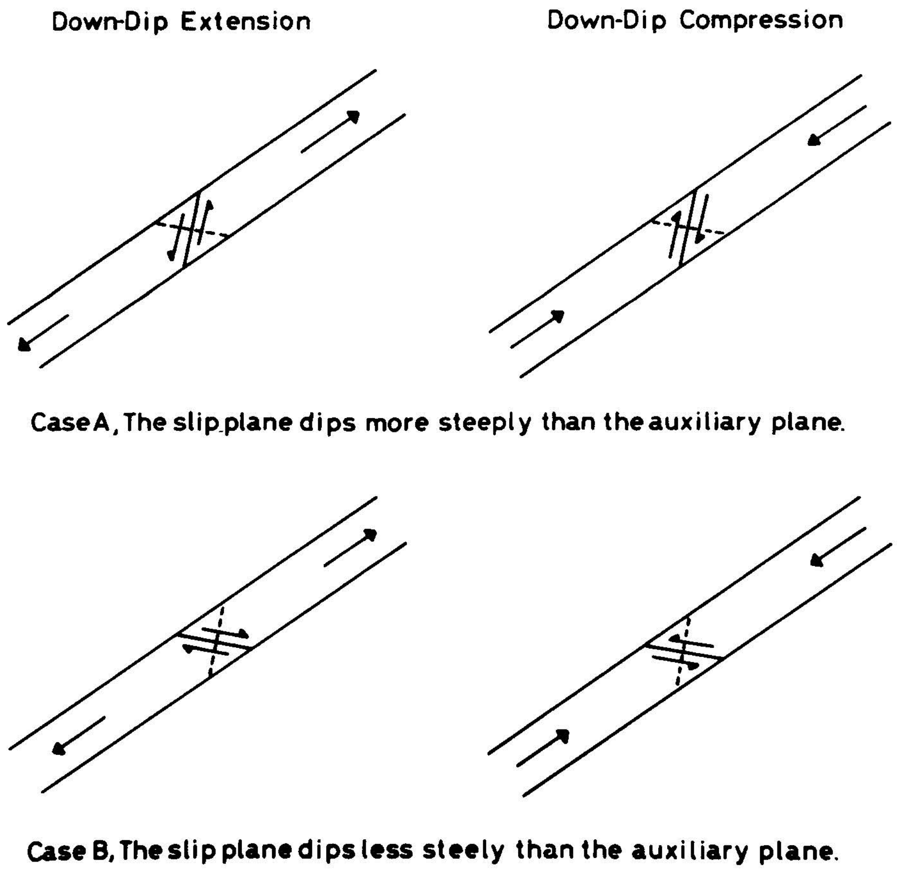

Figure 4. Relation in dip angle between a slip plane and the auxiliary plane.

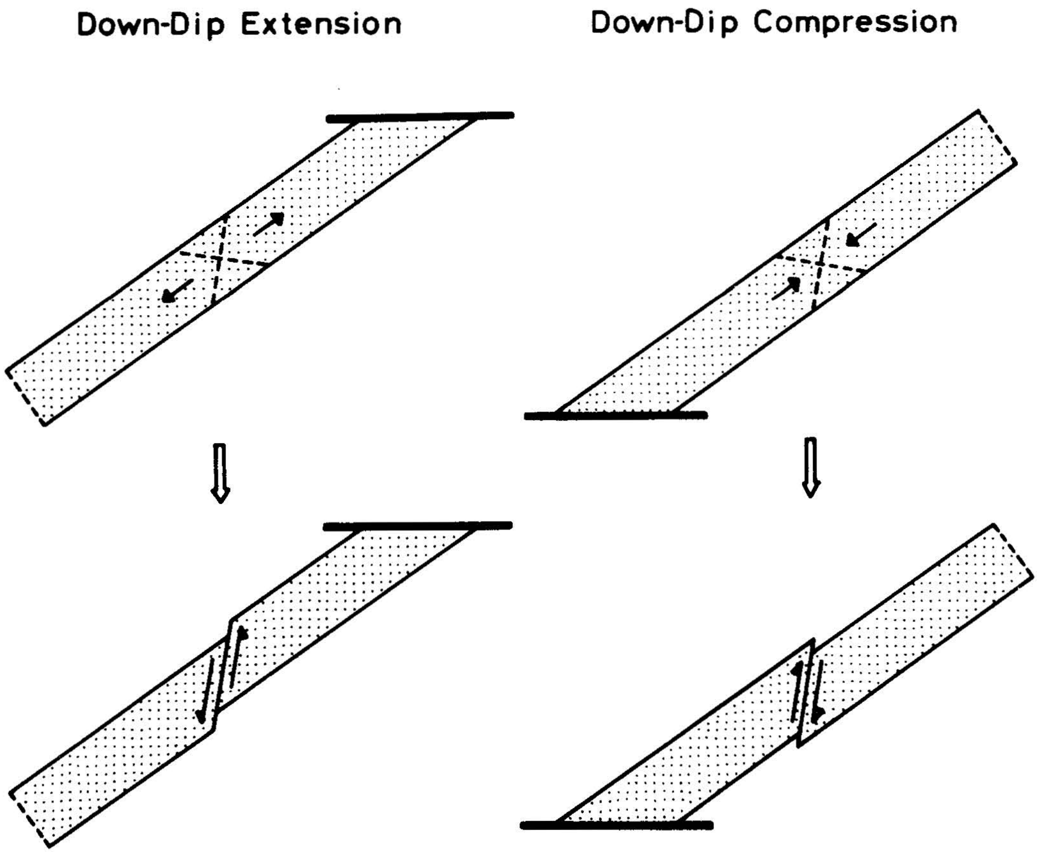

Figure 5. An explanation for predominance of Case A. Left: The sinking slab, more dense than the surrounding mantle, is supported from above so that down-dip extension prevails in the slab. Right: The slab is supported from below so that down-dip compression prevails in it. Down-dip extension or compression may produce two mutually conjugate weak planes in the slab as shown by the dotted lines in the top figures. Gravity favors the steeper plane of these two as illustrated in the bottom figures.

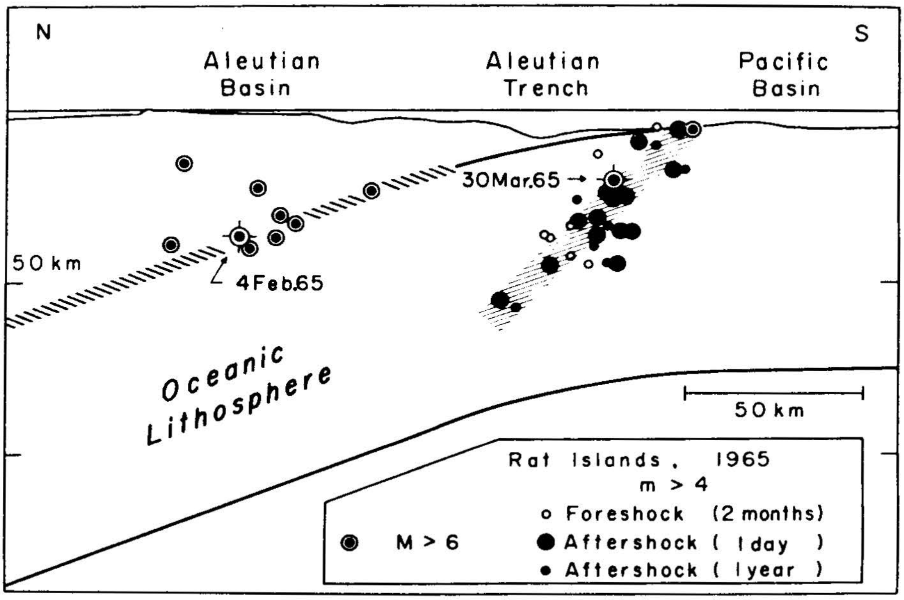

Figure 6. Depth profile of the aftershocks of the Rat Island earthquake of March 30, 1965. The aftershock zone marks the slip plane of this earthquake. (after Abe, 1972a.)

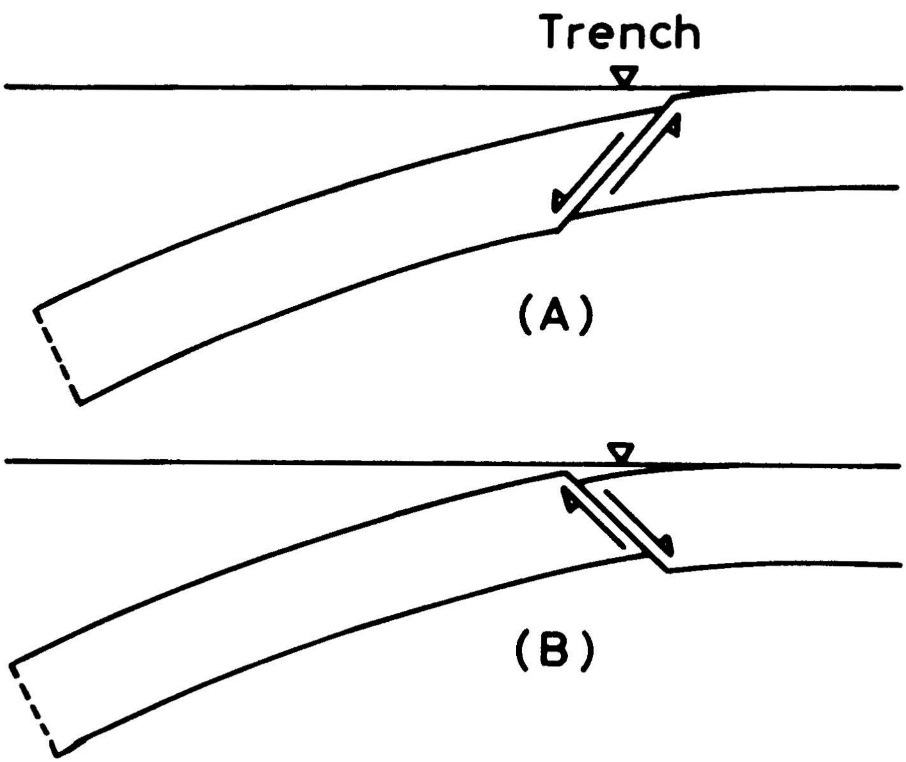

Figure 7. Two possible slip planes for lithospheric earthquakes of normal fault type beneath a trench.

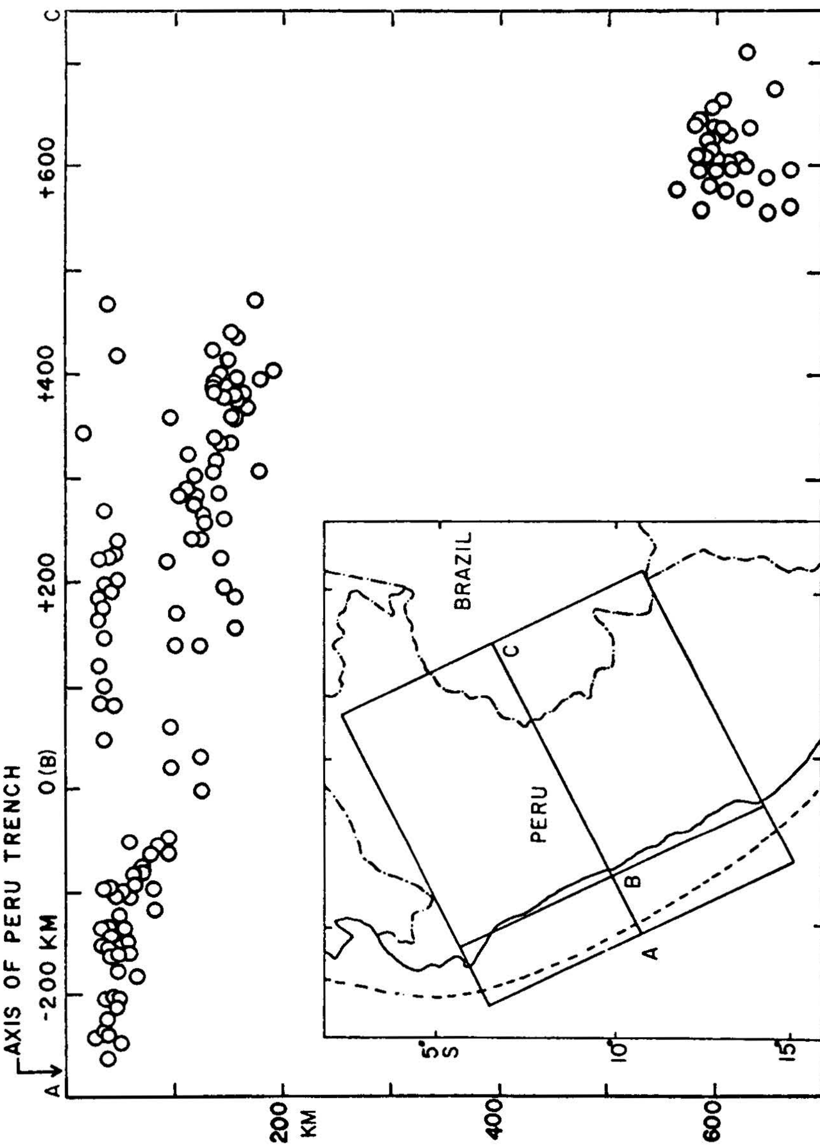

Figure 8. Vertical section through Peru including events within the area shown in the inset. The events are those with magnitude greater than about 5 reported in the Preliminary Determination of Epicentre (1961-1967). (After Isacks and Molnar, 1971.)

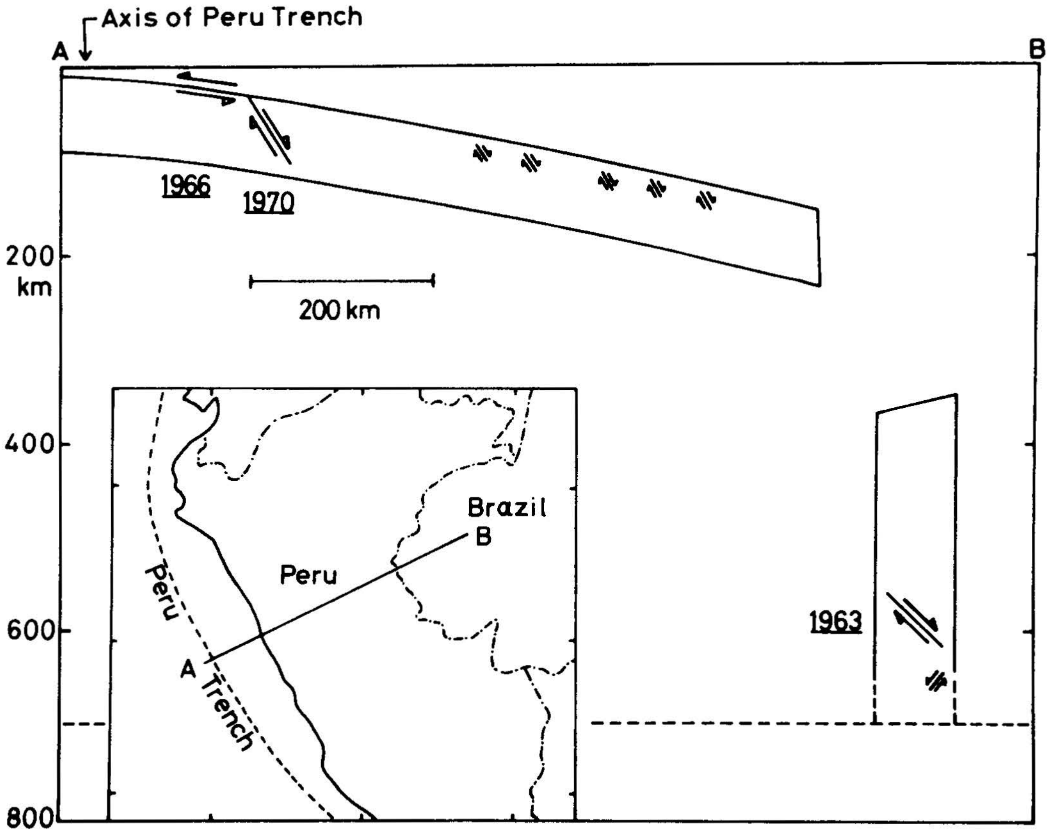

Figure 9. Schematic figure showing selectivities in slip planes for earthquakes in the Peru-western Brazil region. The dashed line at a depth of about 700 km represents a possible discontinuous increase in strength or density across it. Typical tectonic movements in this region may be represented by the three large earthquakes which occurred in 1963, 1966 and 1970 (see the text).

Table 1, Orientations of the slip planes and the auxiliary planes for deep and intermediate-depth earthquakes

No.	Type	Region	Mo.	Day	Yr.	Epicenter Lat. (degrees)	Epicenter Long. (degrees)	Depth km	Pole of Slip Plane Trend	Pole of Slip Plane Plunge	Pole of Aux. Plane Trend	Pole of Aux. Plane Plunge
1	1	Solomon	Jan	7	1968	5.1S	153.9E	118	261	40	048	45
2	1	New Britain	Nov	14	1967	5.4S	147.1E	201	033	24	154	50
3	1	Peru-Chile	May	1	1966	8.5S	74.3W	165	286	19	148	66
4	1	Peru-Chile	Dec	27	1967	21.2S	68.3W	135	239	33	073	56
5	1	Kuril	Dec	1	1967	49.5N	154.4E	136	310	08	069	74
6	1	Mindanao	Feb	3	1966	0.1N	123.5E	131	333	29	104	51
7	1	Hindu Kush	Mar	14	1965	36.4N	70.7E	205	035	30	215	60
8	2	Tonga	May	22	1965	21.1S	178.5W	538	018	30	224	58
9	2	Tonga	Mar	17	1966	21.1S	179.2W	626	110	70	304	20
10	2	Tonga	Oct	2	1967	21.0S	178.8W	604	354	10	226	74
11	2	Tonga	Oct	9	1967	21.1S	179.4W	654	324	04	087	82
12	2	Tonga	Oct	12	1967	21.1S	179.2W	636	312	06	052	60
13	2	Tonga	Dec	28	1964	22.1S	179.6W	577	143	04	243	70
14	2	North Honshu	Mar	31	1969	38.3N	134.6E	417	308	05	214	22
15	2	Izu-Bonin	Apr	12	1965	30.2N	138.7E	425	067	10	313	69
16	3	New Hebrides	Nov	4	1968	14.2S	172.0E	585	106	32	250	52
17	3	Peru-Chile	Nov	9	1963	8.8S	71.7W	576	263	48	074	42*,**
18	3	Peru-Chile	Nov	28	1964	7.9S	71.3W	650	064	39	238	52
19	3	Peru-Chile	Aug	15	1963	13.8S	69.3W	593	098	37	322	44**
20	3	Peru-Chile	Dec	9	1964	27.5S	63.2W	578	261	78	081	12
21	3	Sunda	Feb	3	1967	5.6S	110.5E	569	228	40	010	44
22	3	Sunda	Mar	24	1967	6.0S	112.4E	600	199	24	019	66
23	3	Sunda	Jun	22	1966	7.2S	124.6E	507	084	35	238	52

See Isacks and Molnar (1971) and Oike (1971) for the references for the fault plane solutions.

*, The solution could be a pure 45^{o} dip slip fault with the strike azimuth of 170^{o} as obtained by Teng (1966).

**, Multiplets No.17 and No.19 were investigated by Fukao (1972) and Chandra (1970, 1973) respectively. The others were studied by Oike (1969, 1971).

Table 2, Numbers of multiplets for Cases A and B

	Case A	Case B	*
Type 1	7	0	0
Type 2	7	1	0
Type 3	6	1	1

*, for nearly pure 45° dip slip

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