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Tectonical Implications of the Izu–Bonin–Mariana Arc from Composite Mechanism Solutions

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Abstract: Earthquake generating stress fields around the Izu-Bonin-Mariana arc are investigated in detail. Region-by-region analysis of composite mechanism solutions, obtained from superposition of *P*-wave initial motions, is performed in connection with the plate tectonics theory. Composite mechanism solutions at shallow depths near the trench are well explained by the interaction of the Pacific plate and the Philippine Sea plate. Solutions in the Philippine Sea plate show the strike-slip faulting with the tension axis (T-axis) in the direction of east and west. This implies that the stresses in the Philippine Sea plate are not directly induced by the movement of the Pacific plate. The regularity that the pressure axis is parallel to the direction of the local dip of seismic zone at intermediate and deep depths is confirmed only for the Izu-Bonin region where the seismic zone takes a simple, plane-like form. In the Mariana region where the shape of seismic zone is not simple but concaved eastward, the mechanism solutions that suggest tearing of the descending plate are found at intermediate depths. The orientation of T-axis in this region seems to have some correlation with contortion of the descending plate.

1. Introduction

Two typical types of focal mechanisms were found by Stauder (1968) for shallow earthquakes in the Aleutian island arc: The seismically active zone at the inner margin of the oceanic trench is characterized by thrust faulting, which is considered to represent the relative motion of two converging plates of lithosphere. Earthquakes on the outer wall of the trench, where the oceanic plate begins to flex as it dips under the island arc, is characterized by normal faulting. The mechanisms of interaction between plates and of the flexure of a plate have been discussed by means of focal mechanisms of large earthquakes near the trench (Kanamori, 1970a, b, 1971a, b; Katsumata and Sykes, 1969; Fitch, 1972).

The focal mechanisms of deep and intermediate focus earthquakes were studied by Isacks and Molnar (1971) from the standpoint of new global tectonics. Their discussions were focused mainly on the relation between stress fields within lithospheric slabs and the orientations of principal axes of stresses. Based on the theory of a finite moving source, the source process of intermediate and deep focus earthquakes has recently been studied by means of wave-form analyses (*e.g.*, Mikumo, 1969, 1971a, b; Fukao, 1970, 1972; Koyama, 1975). From their results, shear faulting in the source

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region is considered to be an appropriate source model for intermediate and deep focus earthquakes at least as a first approximation.

In order to understand the driving and deforming mechanisms of plate, it is required to investigate focal mechanisms of earthquakes. Since there are few large earthquakes for which *P*- and *S*-wave data are obtained at widely distributed observation stations, an analysis of composite mechanism solution of small earthquakes is of great importance (Ritsema, 1955; Aki, 1966). Oike (1971) investigated the earthquake generating stress fields at intermediate and deep depths of all the seismically active belts in the world by using the Aki's method (1966). His results are consistent in a statistical sense with those of Isacks and Molnar (1971).

Topographic and geophysical features at the western margin of the Pacific plate are characterized by island arcs, deep sea troughs, volcanic chains, and high-level seismic activities. Koyama *et al.* (1973) have shown the stress pattern in the northeastern Japan arc. Their analysis of deriving the regional stress fields is based on the method of composite mechanism solutions originally introduced by Ritsema (1955) and on the revised Aki's method. Recently Horiuchi *et al.* (1975) have investigated the stress field in the Kuril-Kamchatka arc by the method of composite mechanism solution.

In the present study earthquake generating stress fields in the Izu-Bonin-Mariana arc are studied. The deep seismic zone of this region is more complex in topographic feature than those of the northeastern Japan region and of the Kuril-Kamchatka region. A discussion will also be made on the relationship between the stress field and the shape of the deep seismic zone.

2. Method of Analysis

About a thousand earthquakes are analyzed which occurred around the Izu-Bonin-Mariana arc during the period from January, 1964 to March, 1969. Data pertinent to hypocentral coordinates during the period from 1964 to 1967 are supplied by Katsumata and Sykes (1969) and those during the later period are taken from the bulletins of the International Seismological Centre (I.S.C.). Epicentral locations of the earthquakes are illustrated in Fig. 1.

First, the seismic zone is divided into nine regions from A to I whose boundaries are represented by dotted lines in Fig. 1. The hypocenters of earthquakes included in a region are projected on a vertical section, which is indicated by each solid line-segment from A-A′ to I-I′ in Fig. 1 and nearly perpendicular to the local strike of the trench axis. Projected hypocenters on each vertical section are denoted by solid circles in Figures from 2 to 10. Next, earthquakes which are projected closely to one another on a vertical section are taken as one group. *P*-wave initial motions from earthquakes in a group are superposed on a focal sphere. If the distribution of *P*-motions for a group is similar to those for its adjacent groups, all of the groups are put into one.

After this careful grouping of seismic regions, the composite mechanism solution for each group is obtained by the method of Horiuchi *et al.* (1972). Using the weighting

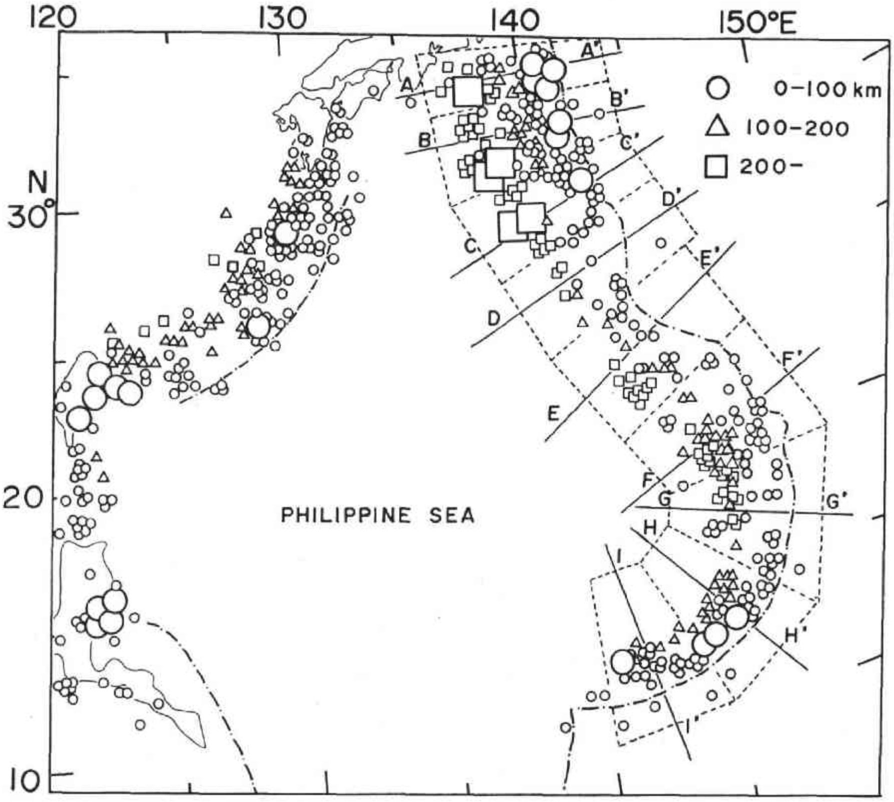

Fig. 1. Seismicity map around the Izu-Bonin-Mariana arc.
Solid lines of A-A' to I-I' indicate the strikes of vertical sections onto which the hypocenters of earthquakes enclosed by dotted lines are projected in Figs. 2 to 10. Chained lines indicate the trenches. Large and small symbols of circle, triangle and square imply 10 earthquakes and 1 earthquake, respectively.

function W_i introduced by Wickens and Hodgson (1967), the accuracy of the solution is indicated by SCORE defined as

$$\mathrm{SCORE} = 50\,\{1+(\Sigma W_i \cdot \mathrm{sgn}\, R_i \cdot \mathrm{sgn}\, S_i)/\Sigma W_i\}\ ,$$

$$W_i = |S_i(1-|S_i|/2)+0.3\,\mathrm{sgn}\, S_i|\ ,$$

where R_i and S_i are the observed and theoretical amplitudes of P-wave initial motion. The theoretical amplitude S_i is so normalized that its maximum value takes unity. If the SCORE of the best fit solution for a group is lower than 65.0 or the number of P-wave observations is less than 15, the use of the solution for the group is abandoned. The best fit solution for each group is illustrated in Figures from 2 to 10, and their point source parameters are tabulated in Table 1.

3. Composite Mechanism Solutions

(i) *Izu-Bonin region*

Around the Izu-Bonin arc (regions from A to D), the local strike of the trench is

Table 1. Composite mechanism solutions

	P-axis		T-axis		B-axis		SCORE	N_t	N_e
	Tr	Inc	Tr	Inc	Tr	Inc			
A— 1	65	72	128	144	166	60	82.3	299	53
A— 2	317	82	38	139	54	50	71.1	55	16
A— 3	136	81	215	138	234	50	77.1	241	58
A— 4	355	107	84	86	342	17	74.9	151	38
A— 5	121	130	263	133	193	70	84.4	208	33
A— 6	100	135	100	45	10	90	85.1	275	42
B— 1	1	114	92	93	8	24	67.0	76	24
B— 2	237	72	288	152	334	70	69.1	91	26
B— 3	187	90	277	106	216	16	67.0	156	51
B— 4	140	120	232	94	150	30	75.3	216	57
B— 5	141	129	254	117	189	50	82.2	110	21
B— 6	86	146	108	58	11	80	82.0	132	27
B— 7	72	142	196	113	119	62	78.8	345	75
B— 8	44	127	144	104	71	40	81.3	164	31
B— 9	76	126	161	83	61	37	77.8	292	71
C— 1	10	110	100	89	7	20	75.0	83	19
C— 2	52	69	80	157	146	80	78.4	146	34
C— 3	26	75	90	149	124	63	86.6	86	12
C— 4	336	100	82	148	60	60	84.1	134	21
C— 5	260	172	260	82	170	90	85.3	55	8
C— 6	97	156	325	107	230	107	80.5	386	76
C— 7	90	121	188	104	118	34	87.5	190	26
C— 8	74	126	188	120	126	50	84.6	140	22
D— 1	227	112	1	149	309	70	66.7	64	20
D— 2	255	89	343	150	345	60	88.6	43	5
D— 3	158	128	224	62	108	50	88.5	253	29
E— 1	83	118	173	91	84	28	72.9	192	50
E— 2	345	85	68	142	79	53	70.4	240	69
E— 3	123	76	181	155	219	70	81.0	229	44
F— 1	178	108	272	102	215	22	84.3	334	51
F— 2	305	104	34	85	283	15	82.9	33	6
F— 3	162	80	246	118	270	30	67.5	137	42
F— 4	323	101	64	135	43	48	81.2	131	25
F— 5	7	110	97	90	7	20	69.8	65	20
F— 6	12	95	102	92	38	5	84.6	25	3
F— 7	217	164	358	103	270	80	76.2	187	45
F— 8	222	70	299	123	338	40	81.5	56	10
F— 9	129	144	245	107	165	60	81.3	144	27
F—10	193	111	291	110	240	30	80.3	55	11
G— 1	280	102	25	141	1	53	68.8	192	64
G— 2	279	137	24	104	306	50	82.8	114	20
H— 1	290	134	110	136	20	90	77.0	64	14
H— 2	292	88	10	170	23	80	74.9	196	50
H— 3	50	143	95	62	353	68	69.1	132	38
H— 4	169	84	249	150	262	60	69.5	146	44
H— 5	155	115	248	97	172	26	73.5	93	22
I — 1	101	84	176	159	193	70	81.9	236	44
I — 2	18	69	94	122	135	40	67.1	157	48
I — 3	49	139	132	83	36	50	68.4	480	146
I — 4	146	93	239	140	234	50	76.7	73	18

P-, T- and B-axes; pressure, tension and null axes, respectively.
Tr; trend of an axis measured clockwise from the north.

(to be continued)

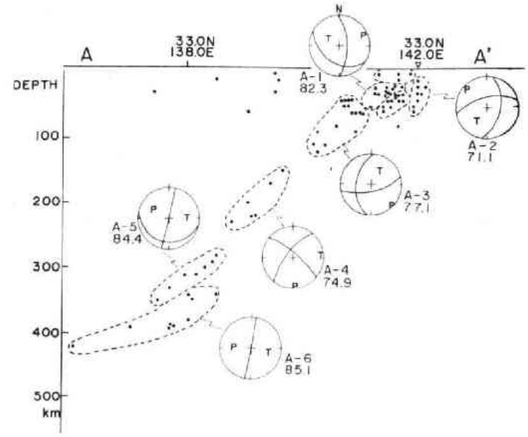

Fig. 2. Composite mechanism solutions on the vertical section along A-A′. Solid circles show the locations of earthquakes projected onto this section. Mechanism solutions for groups of earthquakes enclosed by dashed curves are exhibited with their SCORE on the lower half of the focal sphere by the equal area projection. The locations of pressure and tension axes for the best fit solution are indicated by letters P and T, respectively, in the mechanism diagram. The horizontal position of the trench axis is shown by a triangle. The same convention will be used in Figs. 3 to 10 as well.

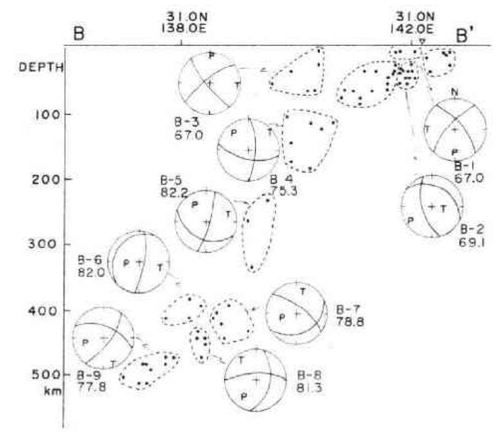

Fig. 3. Composite mechanism solutions on the vertical section along B-B′.

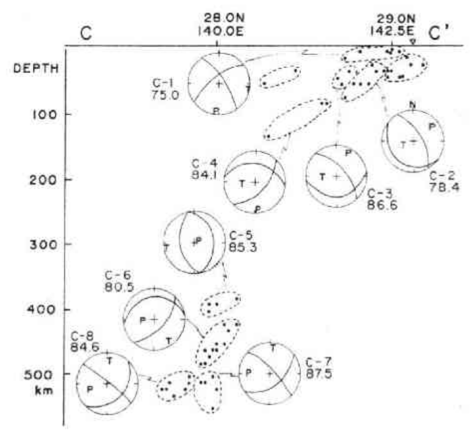

Fig. 4. Composite mechanism solutions on the vertical section along C-C′.

almost parallel to the island chain and is nearly straight line running from north to south. Most of shallow earthquakes are located between the trench and the island chain, and the high seismic activity is concentrated near the trench. The vertical sections of these regions are shown in Figures from 2 to 5. The three-dimensional variation in topographic feature of the seismic zone is significant at depths deeper

(continued)

Inc; inclination angle of an axis measured from the downward vertical.

N_t; total number of observational data of P-wave initial motions used in deriving a solution.

N_e; number of observational data inconsistent with the radiation pattern expected theoretically for the best fit solution.

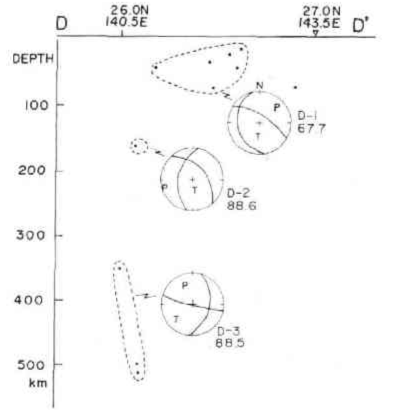

Fig. 5. Composite mechanism solutions on the vertical section along D-D′.

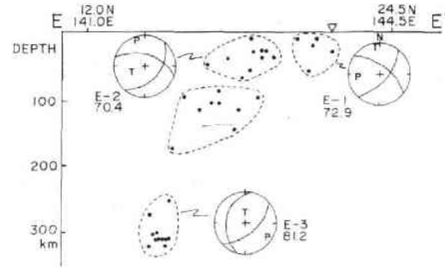

Fig. 6. Composite mechanism solutions on the vertical section along E-E′.

than 200 km, though the seismic zone is nearly planar at shallower depths. The dip angle of the seismic zone below about 200 km becomes larger as the seismic zone goes down to the south.

At shallow depths two principal types of composite mechanism solutions are found in these regions. One is the reverse faulting which is seen for groups located along the seismic zone. The other is the strike-slip faulting for groups of very shallow earthquakes (B–1, B–3 and C–1). For the latter type of the mechanism solution, the pressure axis (P-axis) is horizontal in the direction from north to south. This trend of the P-axis is apparently different from that for the groups of the former type. The groups of the strike-slip faulting (especially group B–3) are located in the Philippine Sea plate.

All of the mechanism solutions at deep depths are of down-dip compression type which is characterized by the P-axis parallel to the local dip of the seismic zone. However, the orientations of the tension axes (T-axes) in the solutions are different from one another. One of two typical orientations of the T-axis is seen on the focal sphere for the group A–5, for example, where the T-axis is nearly normal to the seismic zone. The other is for the group B–9 where the T-axis is approximately horizontal and parallel to the local strike of the seismic zone.

(ii) *Mariana region*

The trench is concaved eastward around the Mariana arc (regions from E to I) as seen in Fig. 1. The topographic feature of the seismic zone is greatly different from that around the Izu-Bonin arc, considering the projection of hypocenters on the vertical sections from E-E′ to I-I′. The deep seismic zone is rather broad on the sections H-H′ and I-I′, probably because the sections are not taken in parallel to the local dip direction of the seismic zone. The seismic zone is nearly vertical below the depth of 200 km at the central Mariana (regions F and G), while it does not reach to 200

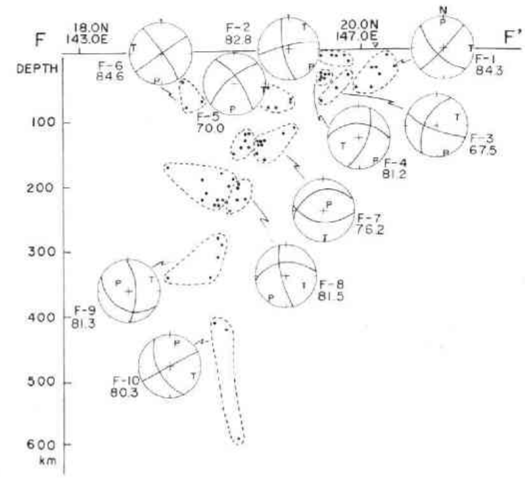

Fig. 7. Composite mechanism solutions on the vertical section along F-F′.

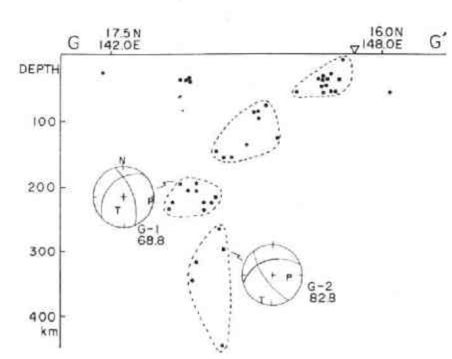

Fig. 8. Composite mechanism solutions on the vertical section along G-G′.

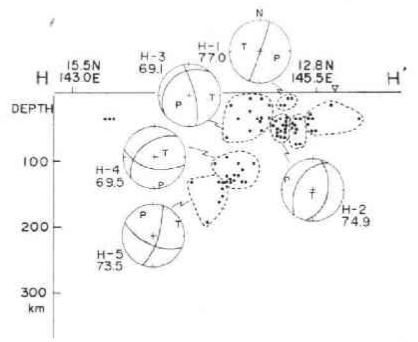

Fig. 9. Composite mechanism solutions on the vertical section along H-H′.

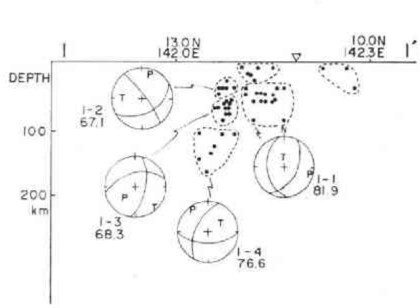

Fig. 10. Composite mechanism solutions on the vertical section along I-I′.

km at the southern Mariana (regions H and I).

At shallow depths both the mechanism solutions of reverse faulting and strike-slip faulting are seen in regions E and F. Among groups having solutions of strike-slip faulting, the group F–6 consists of earthquakes that occurred apparently in the Philippine Sea plate, while E–1 and F–1 consist of those located beneath the trench where the two plates, the Philippine Sea plate and the Pacific plate, are interacting with each other. The groups of shallow earthquakes in region G have no mechanism solution whose SCORE is higher than 65.0. At shallow depths in regions H and I, the reverse faulting is predominant. However, the mechanism solution for the group H–3 is somewhat peculiar and the orientations of P- and T-axes are in contrast with those for the group H–1 that is adjacent to the H–3.

At intermediate and deep depths mechanism solutions for groups E–3 and G–1 are of down-dip extension type which is characterized by the T-axis parallel to the local dip of the seismic zone. The solutions for groups other than the E–3 and G–1 show neither down-dip compression nor down-dip extension type but have comparatively large strike-slip components. Around the Mariana arc the topographic profile of the seismic zone is not so simple compared with that around the Izu-Bonin arc. The complexity of the profile may be reflected on the composite mechanism solutions.

4. Tectonical Implications from Composite Mechanism Solutions

Composite mechanism solutions obtained in the preceding sections are briefly summarized as follows:

(1) Solutions of reverse faulting with P-axis mainly in the direction of east and west are found at shallow depths near the trench throughout the Izu-Bonin region and in some parts of the Mariana region.

(2) Solutions of strike-slip faulting with P-axis in the direction of north and south are found at shallow depths for groups of earthquakes that are located in the Philippine Sea plate.

(3) Solutions of strike-slip faulting, which have characteristics different from those of (2), are found at shallow depths near the trench in the Mariana region.

(4) Solutions of down-dip compression type are found at deep depths in the Izu-Bonin region.

(5) Solutions of down-dip extension type are found at intermediate and deep depths in the Mariana region.

(6) Solutions, which show neither down-dip compression type nor down-dip extension type but have a significant amount of strike-slip component, are found at intermediate and deep depths in the Mariana region.

The mechanism solutions of large earthquakes in the region discussed here have been interpreted by Katsumata and Sykes (1969) and by Fitch (1972) in connection with the movement of the plates. Since the large earthquakes whose mechanism solutions are obtained from the *P*-wave initial motions of individual earthquakes occur mostly near the boundary of the plate, their discussions are limited to the interactions at shallow depths between the Pacific and the Philippine Sea plates. In the present study, however, the earthquake generating stress fields have been obtained in more detail than those of their studies.

The pressure axis in the direction of east and west at shallow depths stated in (1) indicates the existence of thrusting force between the Pacific plate and the Philippine Sea plate. This may further be regarded as a manifestation of the underthrusting of the Pacific plate beneath the Philippine Sea plate, if we take the nodal plane dipping toward the island arc to be the fault plane. The solutions of the strike-slip faulting near the trench stated in (3) imply the existence of the relative horizontal-motion between the Pacific and the Philippine Sea plates. The interpretations given above for the earthquake generating stress fields are similar to those by Katsumata and Sykes (1969) and by Fitch (1972).

The solutions mentioned in (2) give an interpretation about the stress fields in the Philippine Sea plate. The P-axes are all in the direction of north and south, and

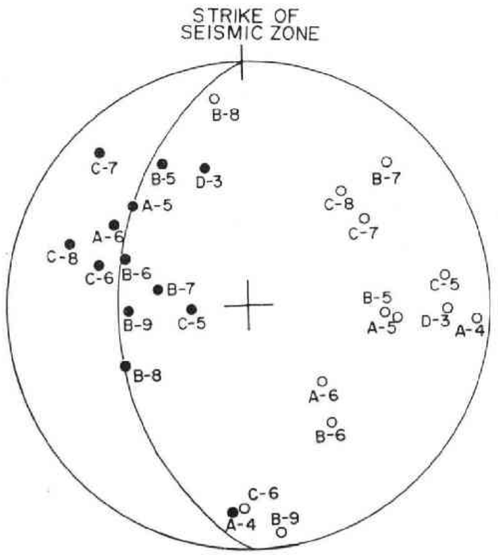

Fig. 11 (a). Relative orientations of P- and T-axes in the Izu-Bonin region (regions from A to D as shown in Fig. 1). Intersection of the reduced seismic plane with the surface of conceptual sphere is indicated by a solid curve by using the equal area projection of the lower hemisphere. Solid and open circles, respectively, represent the locations of P- and T-axes relative to the seismic plane.

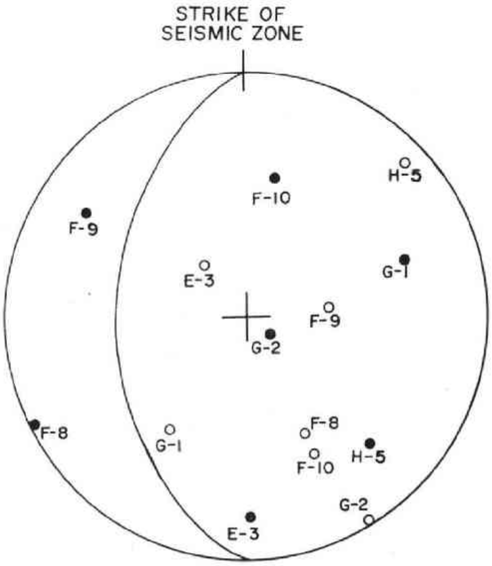

Fig. 11 (b). Relative orientations of P- and T-axes in the Mariana region (regions from E to I as shown in Fig. 1). The same convention is used as in Fig. 11(a).

the T-axes in the direction of east and west. These trends of the P- and T-axes are inconsistent with the idea that the stresses of the interior of the Philippine Sea plate are induced mainly by the pressure of the Pacific plate moving toward the west or the northwest. In the case of stress fields in the northeastern Japan, Koyama *et al.* (1973) obtained, from composite mechanism solution, P-axes generally parallel to the motion direction of the Pacific plate against the northeastern Japan arc. This parallelism suggests that there is a direct relationship between the motion of the Pacific plate and the stress fields in the northeastern Japan arc. On the other hand, in the present case there exists no direct effect of the motion of the Pacific plate on the stress field in the Philippine Sea plate. It is possible to consider that the extensional stress in the direction of east and west results from the descending motion of the Philippine Sea plate at the western margin beneath the Ryukyu trench.

We now discuss stress fields at intermediate and deep depths. Three typical composite mechanism solutions are taken up in the items from (4) to (6). The regularity in orientation of P- and T-axes relative to the local dip of the seismic zone can be seen more clearly in Figs. 11(a) and (b). In the figures the local dip direction and dip angle of the seismic zone are taken, for convenience sake, to be $-90°$ and $45°$, respectively, and the orientations of P- and T-axes are shown relatively to this reduced seismic plane. Here, the local dip direction and dip angle of the seismic zone at the focal region for each composite mechanism solution are estimated from the profile of the seismic zone projected on the vertical sections.

Fig. 11(a) shows the P- and T-axes in solutions for the Izu-Bonin region (regions from A to D), where the seismic zone is planar in comparison with that in the Mariana region. From this it is evident that the P-axes are all parallel to the local dip of the seismic zone. This regularity of the P-axis for intermediate and deep earthquakes has already been pointed out by Isacks *et al.* (1968), Isacks and Molnar (1971), and Oike (1971).

On the other hand, the orientations of the T-axes do not show any apparent correlation with the local dip of the seismic zone. Comparing the local profiles of the seismic zone with one another among the neighbouring vertical sections from A-A′ to D-D′ (cf. Figs. 2 to 5), it is seen that the seismic zone is more contorted at large depths than at relatively shallow depths. It can be recognized from Fig. 11(a) that the T-axes for groups at relatively large depths (for example, B-8, B-9, and C-6, in particular) are parallel to the local strike of the seismic zone and, consequently, the B-axes (null axes) are perpendicular to the seismic zone. On the contrary, the T-axes for groups at relatively shallow depths (for exmaple, A–5, B–5, and C–5) are perpendicular to the seismic zone. Isacks *et al.* (1968) have noted on the irregularity of T-axis that the difference between the intermediate and the least principal stresses is less than the difference between the greatest and the intermediate principal stresses, and that the stress state may be quite variable owing to contortion of the slab. The present result suggests that the orientation of T-axis is regulated by the spacial rate of contortion of the descending plate.

As shown in Fig. 11(b), the tendency in orientation of the principal axis of stress in the Mariana region is quite different from that in the Izu-Bonin region, and the P-axis has no regular tendency. As stated in (5) and in the preceding section, the T-axis for the group G–1 is nearly parallel to the local dip of the seismic zone. The region G is situated at the middle of the Mariana arc and the seismic zone is almost vertical below about 200 km. The result for the orientation of T-axis suggests that the descending plate is in a state of extension at depths approximately from 200 km to 300 km.

The complex feature in topography of the seismic zone is reflected on the complexity of the stress field in the Mariana region. From the mechanism solutions obtained for the groups F–8 and H–5 at depths of about 200 km, it is apparent that the orientations of P- and T-axes are opposite in these two cases. If we take nodal planes whose strikes are nearly in the direction of east and west as the fault planes for both the solutions, the solution for F–8 shows the left lateral movement and that for H–5 does the right lateral. These motion directions are consistent with the topographic feature of the seismic zone that the deeper part of the region G is pushed out eastward. This suggests that tearing of the plate occurs in the regions of F–8 and H–5.

Isacks and Molnar (1971) introduced the concept of tearing of a plate in order to explain the deformation of a descending plate at the triple junction of plates where three plates are converging. They showed an example; the Pacific plate is tearing off the Boso peninsula, and one of the torn parts is down-going beneath the northeastern Japan arc and the other beneath the Philippine Sea plate. It is suggested from the present result that tearing of a plate takes place not only at shallow depths near a triple junction but also at intermediate depths where the seismic zone is considerably deformed. Considering the solution of down-dip extension type for G–1, it should further be noted that the gravitational force may play an important role in deforming the down-going plate of lithosphere in the Mariana region.

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