J. Phys. Earth, **28**, 17–43, 1980

TECTONICS OF THE KYUSHU-RYUKYU ARC AS EVIDENCED FROM SEISMICITY AND FOCAL MECHANISM OF SHALLOW TO INTERMEDIATE-DEPTH EARTHQUAKES

Kiyoji SHIONO,* Takeshi MIKUMO,** and Yuzo ISHIKAWA**

**Department of Geosciences, Faculty of Science, Osaka City University, Osaka, Japan*
***Disaster Prevention Research Institute, Kyoto University, Uji, Japan*

(Received July 23, 1979; Revised October 24, 1979)

Tectonic features of the Kyushu-Ryukyu arc have been investigated in detail, on the basis of seismicity and focal mechanism of shallow to intermediate-depth earthquakes with magnitudes around and greater than 5.0.

All shallow earthquakes in the Hyuga-nada region east of Kyushu are characterized by low-angled thrust faulting, which may be directly related to the underthrusting of the Philippine Sea plate beneath southwest Japan. Their frequent occurrence, dissected fault regions and somewhat large stress drop, in comparison with great earthquakes along the Nankai trough, may be attributed either to local stress concentration due to the contortion of the subducting plate resulting from southwestward warping of the trough, or to heterogeneous structure extending northward from the Kyushu-Palau ridge.

The shape of the Wadati-Benioff zone and the stress state within the descending lithosphere show marked differences between the northern and southern Ryukyu arcs bounded by the Tokara channel; the dip of the zone at depths below 100 km reaches 70° in the northern arc, while it decreases to 40–50° in the southern section. Focal mechanisms of intermediate-depth earthquakes show down-dip tension and down-dip compression within the northern and southern parts of the lithosphere, respectively. Two interpretations may be possible of the above differential subduction, both of which are attributed to the difference in shear resistance to the subduction; one is due to a difference in the convergence plate velocities, and the other to that in the physical properties such as viscosity and density in the surrounding mantle in relation to volcanism. For lower resistance, the lithosphere will sink rather smoothly into the asthenosphere, which is dragged down by a gravitational pull with high dip angles and will be in a tensional state, whereas the subducting lithosphere will be subjected to compressional stress and have low dip angles if it receives higher resistance.

1. *Introduction*

The Kyushu-Ryukyu arc, facing the Philippine Sea plate, has many typical features of an island arc: the Ryukyu trench, non-volcanic frontal arc, active volcanoes, a back-arc basin (the Okinawa trough) and a well developed Wadati-Benioff seismic zone (KONISHI, 1963, 1965; KATSUMATA and SYKES, 1969; WAGEMAN *et al.*, 1970; KARIG, 1973; HONZA, 1977; NAKAGAWA, 1977a, b; KIZAKI, 1978a, b). KONISHI (1963, 1965) first pointed out that two major left-lateral strike-slip faults, now represented by the Tokara channel and the Miyako depression, make a cut to the zonal pre-Miocene tectonic belts along the Ryukyu islands. Recently, extended geological surveys have also revealed geological and structural contrasts between the north-central and south Ryukyus bordered by the Miyako depression (HONZA, 1977; KIZAKI, 1978a, b), which suggest that the two sections of the arc with different origins have differently shifted southwestward particularly from the Middle Miocene to the Plio-Pleistocene (see Fig. 1; KIZAKI, 1978b). Geologically, the Ryukyu arc has usually been divided into the north, central and south parts by

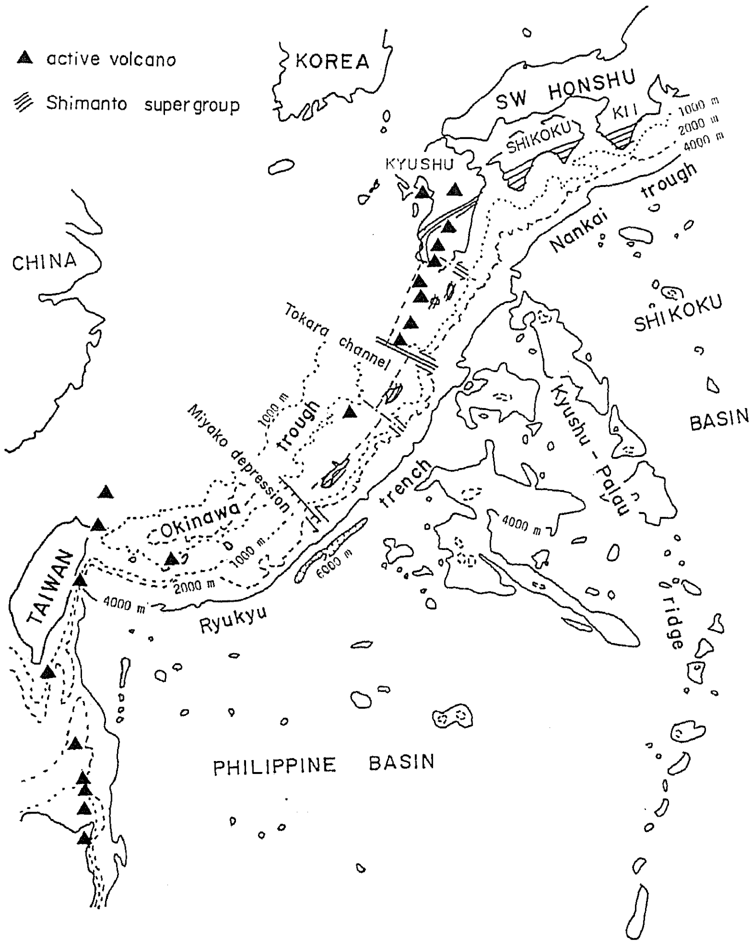


Fig. 1. Index map around the Kyushu-Ryukyu arc, which includes bathymetry, active volcanoes (triangles), strike-slip faults and distribution of Shimanto supergroup. After KIZAKI (1978 b).

the above two strike-slip faults.

The Philippine Sea plate descending under the Kyushu-Ryukyu arc has been characterized by their relatively low dip angles of 35°–45° and by the stress state of down-dip compression (KATSUMATA and SYKES, 1969; ISACKS and MOLNAR, 1971; OIKE, 1971). However, seismicity all over the arc including Kyushu has not yet been fully discussed at the same level of accuracy, and some intermediate-depth earthquakes indicating down-dip tension have also been reported in the northern region (ICHIKAWA, 1971; MIKUMO, 1971; NISHIMURA, 1973; SHIONO, 1977). The main purpose of the present study is to reveal the general tectonic features of the Kyushu-Ryukyu arc, and also to see if there is any difference in seismicity and focal mechanism between the north, central and south sections of the arc. In this paper, we use reliable ISC (International Seismological Centre) hypocenters, and determine fault plane solutions.

The Kyushu-Ryukyu arc continues to the Southwest Honshu arc in the north and to the Taiwan-Philippine arc in the south. The Southwest Honshu arc lacks the typical features of island arcs (e.g. SUGIMURA and UYEDA, 1973; SUGIMURA, 1978), suggesting the possibility of a more recent subduction of the Philippine Sea plate (KANAMORI, 1972; SUGIMURA, 1972, 1978; SHIONO, 1977), while complex tectonics around the junction between the Ryukyu and Taiwan-Philippine arcs has been suggested from geological and seismological evidence (e.g. WU, 1970, 1978b; SUDO, 1972; KARIG, 1973; SENO and KURITA, 1978). Since we are mainly concerned here with the Kyushu-Ryukyu arc, the relation to the outside regions will not be discussed here. The present study, however, will pay special attention to Hyuga-nada earthquakes in comparison with great earthquakes along the Nankai trough, and try to explain some of the differences in their nature and tectonic implications.

2. *Seismicity along the Kyushu-Ryukyu Arc*

2.1 Epicentral distribution of selected ISC hypocenters

KATSUMATA and SYKES (1969) have relocated earthquakes along the Ryukyu arc south of Kyushu during the 7-years' interval from 1961 to 1967, and described some features of seismicity: (1) there exists a seismicity gap between 24° and 25°N and between 126° and 128°E as a likely site of future major earthquakes, (2) intermediate-depth earthquakes are confined within a thin zone about 50 km thick that dips northwestward at angles about 35° to 45°, and the dip of the zone decreases at shallower depths, and (3) intra-plate shallow earthquakes are active under the zone with historically active volcanism in the northern part but is inactive in the southern part with no reported volcanism.

Japan Meteorological Agency (JMA) has also provided locations of hypocenters in the Kyushu region, but it is difficult to discuss seismicity all over the Kyushu-Ryukyu arc at the same level of accuracy by combining the above two sources of data. For this reason, we select reliable hypocenters from ISC Monthly

Bulletin for the 12 years from 1964 to 1975, according to the following standards: (1) all earthquakes with magnitudes equal to or greater than 5.0 are used without qualification and (2) earthquakes with magnitudes less than 5.0 are used only when hypocenters are determined by using arrival times at more than 50 stations and probable errors of focal depth determination are less than 5 km or when focal depths are determined by *pP-P* time intervals. As *pP-P* time intervals provide useful data for the determination of focal depths, the depths inferred from the time intervals are used here whenever they are listed. For earthquakes under oceanic regions, however, we have corrected the focal depths for the effects of sea water with a low velocity by using YOSHII's formula (1978),

$$h_{mod}=h_{ISC}(pP\text{-}P)-3.67\,W\,,$$

where h_{mod}, $h_{ISC}(pP\text{-}P)$ and W give the modified focal depth, the listed *pP-P* depth and water depth in km, respectively.

Figure 2 shows the epicentral distribution of the selected ISC hypocenters. Two major features of shallow seismicity can be noticed from Fig. 2 together with the seismicity maps presented by KATSUMATA and SYKES (1969), UTSU (1977), YOSHII (1978) and others. First, shallow earthquakes spread out toward the Ryukyu trench in the region south of Kyushu. This is in contrast to seismicity around the Nankai trough which is an eastern continuation of the Ryukyu trench, where seismicity has been very low except around the period of the 1944 Tonankai and the 1946 Nankaido earthquakes. Second, a seismicity gap, which has been noticed by KATSUMATA and SYKES (1969) in the region between 24° and 25°N and

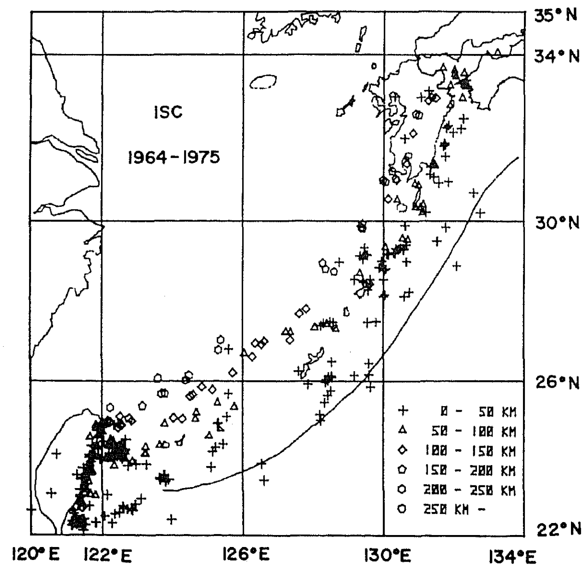


Fig. 2. Distribution of selected ISC hypocenters. Different symbols indicate depth ranges of foci as shown in the lower-right side.

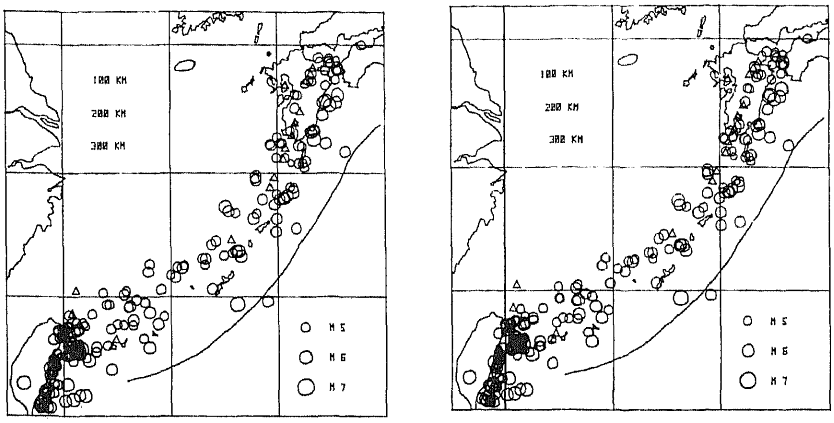


Fig. 3. Stereographic expression of selected ISC hypocenters. For earthquakes shallower than 50 km, only shocks with magnitudes greater than 5.0 are plotted.

between 126° and 128°E, still continues to exist even up to the present.

Figure 3 presents stereographically the distribution of the selected ISC hypocenters, from which we can obtain a better understanding of the distribution of intermediate-depth earthquakes. It is apparent that the dip of the Wadati-Benioff zone is not constant throughout the Kyushu-Ryukyu arc, but the deeper portion of the zone dips steeply in the northern part of the arc. This interesting feature can be noticed more clearly in the vertical section normal to the arc as will be mentioned in the following section.

2.2 Distribution of ISC hypocenters in vertical sections normal and parallel to the Kyushu-Ryukyu arc

In order to see the detailed hypocenter distribution in two vertical sections, normal and parallel to the Kyushu-Ryukyu arc, the radius of the arc and the center of curvature are calculated on the basis of a 150 km iso-depth contour of intermediate-depth earthquakes, which is approximated by epicentral coordinates of the selected ISC hypocenters with focal depths ranging from 125 km to 175 km. The relation among the radius of curvature, coordinates of the center and data coordinates can be expressed by,

$$\cos \varDelta = \sin \varphi \sin \varphi_i + \cos \varphi \cos \varphi_i \cos (\lambda - \lambda_i)\,,$$

where $\varDelta$ is the radius of curvature, λ, φ, λ_i and φ_i are the longitude and geocentric latitude of the center and of the i-th data point, respectively. Least square solutions for all the data points provide,

$$\varDelta = 12.4 \pm 0.8°$$

$$\lambda = 116.7 \pm 0.8°\text{E}$$

$$\varphi' = 36.1 \pm 0.5°\text{N (geographic latitude).}$$

The obtained radius of curvature of the Kyushu-Ryukyu arc appears somewhat smaller than the previously estimated values of 20° by AOKI (1974) and of 14° by TOVISH and SCHUBERT (1978), which have been estimated from the locations of the Ryukyu trench and the volcanic front, respectively. The curvature of the trench gives only a rough estimate of the arc, because the trench tends to migrate due to accretion along the inner wall of the trench (KARIG *et al.*, 1976; JACOBS *et al.*, 1977; TOVISH and SCHUBERT, 1978), and also the back-arc opening of the Okinawa trough might have caused a seaward drift of the trench. On the other hand, the curvature of the volcanic front might also give a measure for that of the descending lithosphere. However, since there are only two volcanoes in the arc south of the Tokara channel, it is difficult to trace the volcanic front throughout the arc (see Fig. 1). For this reason, the curvature of 150 km iso-depth contour adopted here may be considered as giving the most reliable estimate, partly because the contour represents directly the descending lithosphere and partly because the deeper portion of the descending lithosphere would not have seriously changed its position before and after the migration of the trench (KARIG *et al.*, 1976).

In Fig. 4, all the selected ISC hypocenters are projected in the vertical section normal to the Kyushu-Ryukyu arc and through the center of the curvature, separately for the northern (a) and southern (b) arcs. The northern and southern sections are bounded here by a line S55°E. This line nearly crosses the Tokara channel, where there is a left-lateral strike-slip fault which is presumed to have shifted the pre-Miocene tectonic belts along the Ryukyu arc (KONISHI, 1963, 1965; KIZAKI, 1978 a, b).

It is apparent in Fig. 4 that there is a significant difference in the shape of the Wadati-Benioff zone between the two sections. In the northern section, intermediate-depth earthquakes are confined within a thin zone that bends sharply at depths around 100 km and dips steeply at high angles of about 70° in the lower portion. Similar bending of the Wadati-Benioff zone has been recognized in many island arcs at depths around 100–150 km (KARIG *et al.*, 1976; ENGDAHL, 1977; JACOBS *et al.*, 1977; ISACKS and BARAZANGI, 1977). It is also an interesting feature that seismicity is very low around the 100 km-bend.

In the southern section, the Wadati-Benioff zone does not bend so sharply as in the northern one, and dips at low angles of about 40°–50° even in the lower portion. Although this segment of the arc has been geologically divided into the central and south Ryukyus by the strike-slip fault in the Miyako depression, there is no serious difference in the shape of the seismic zone between them. KATSUMATA and SYKES (1969) have found low dip angles of the zone of about 35°–45° around Amami-Oshima and Miyako-jima, which almost correspond to the central and south Ryukyu arcs, respectively. Their results are consistent with those of the present study. It is also interesting that shallow seismicity around the trench is high.

In Fig. 4 are also plotted the locations of active volcanoes. The volcanoes appear close to the 100–150 km iso-depth contours of earthquakes in the northern

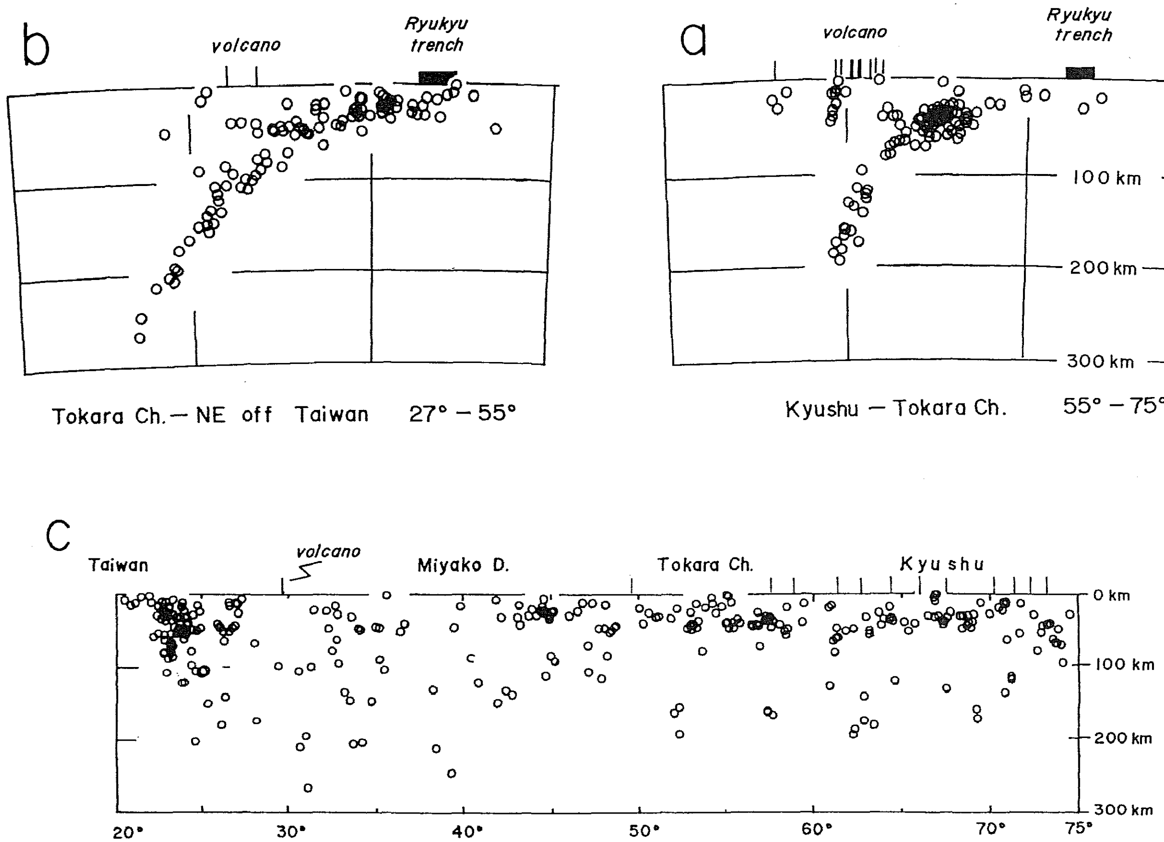


Fig. 4. Distribution of selected ISC hypocenters projected on the vertical planes normal to the Kyushu-Ryukyu arc (a and b) and parallel to the arc (c). The northern (a) and southern (b) sections are bounded by the Tokara channel (the azimuth S 55°E). Numerals show the azimuths measured from the south.

section but two active volcanoes in the southern section are located at shallower iso-depth contours. This slightly outward departure of the two southern volcanoes may be due to the seaward drift of the island arc accompanied by the opening of the Okinawa trough.

All the selected ISC hypocenters are plotted on the vertical plane parallel to the arc in Fig. 4c which is a view looking toward the center of curvature and projected horizontally at a radius $\Delta=12.4°$. Focal depths of the deepest earthquakes appear to increase steeply from Iyonada to central Kyushu, but only gradually from southern Kyushu to southmost of the Ryukyu arc. A zone of relatively low seismicity appears at depths around 100 km under the region from Kyushu to south of the Tokara channel. Above the zone, shallow seismicity are very high, whereas earthquakes tend to cluster below the zone. This feature is in contrast to that in the southern part, where earthquakes seem to occur uniformly, especially south of the Miyako depression. This contrast may be correlated to the difference in volcanism, in the dip of the Wadati-Benioff zone and also in the focal mechanism of the intermediate-depth earthquakes to be discussed later.

3. Focal Mechanisms of Earthquakes in the Kyushu-Ryukyu Region

3.1 Determination of fault plane solutions

Although several authors have presented fault plane solutions in this region (KATSUMATA and SYKES, 1969; ICHIKAWA, 1971; MIKUMO, 1971; FITCH, 1972; NISHIMURA, 1973; YAMASHINA and MURAI, 1975; SHIONO, 1977), the number of the solutions is not large enough to fully understand the nature of the descending Philippine Sea plate, which is the main concern in the present study. For this reason, fault plane solutions are investigated here for 37 major earthquakes that occurred along the Kyushu-Ryukyu arc mainly after 1960. Ten solutions out of them are referred to the previous authors and twenty-seven solutions are newly determined. Details of the solutions are given in the Appendix, and the results are shown in Figs. 5, 7, 8, and 9.

3.2 Solutions for shallow earthquakes

Figure 5 shows the fault plane solutions for earthquakes shallower than about 60 km (shocks Nos. 1–21), in which the directions of slip vectors, the P- or T-axes are given, according to the types of the solutions. Different marks indicating their epicenters show the difference in the locations of earthquakes: open, double and filled circles show earthquakes that occurred at the interface between two plates (inter-plate earthquakes), within the continental Asian plate (intra-plate ones) and within the descending oceanic plate, respectively. Simplified mechanism diagrams given there indicate dilatational (open) and compressional (shaded) quadrants, together with the location of the axes, projected onto the lower hemisphere of the Wulff grid.

Fault plane solutions for nine earthquakes in Hyuga-nada (shocks Nos. 1–9)

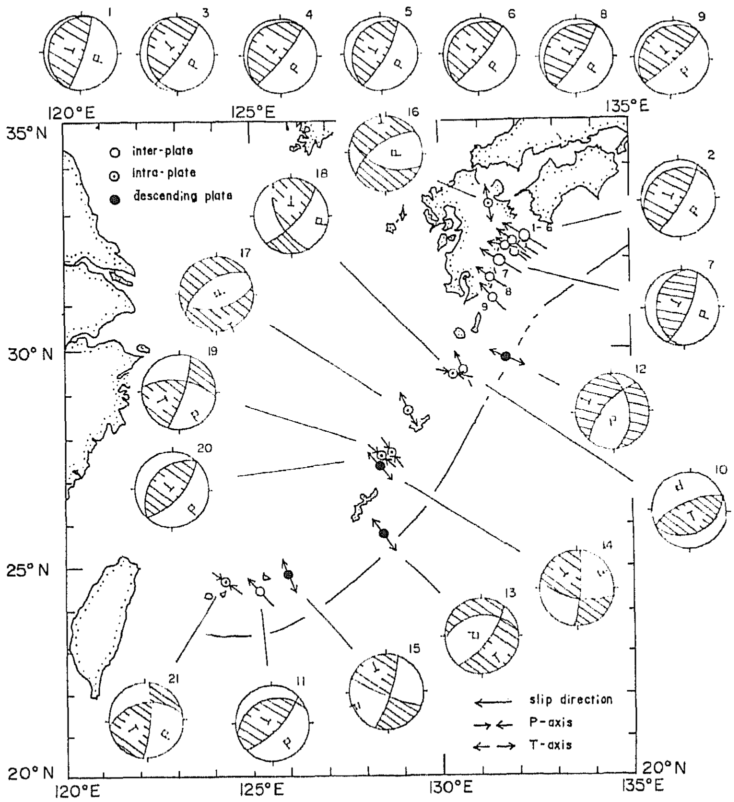


Fig. 5. Fault plane solutions for earthquakes shallower than about 60 km (shocks Nos. 1–21). Directions of slip vectors, the P- or T-axes are given to classify the types of solutions. Different marks indicating epicenters show the difference in the locations of earthquakes as given in the upper-left side. Simplified mechanism diagrams are also given. Numerals are the same as those in Table 3.

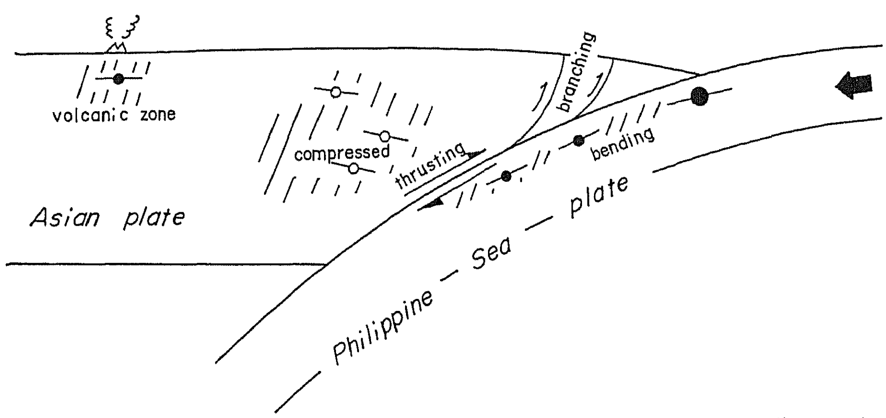


Fig. 6. Schematical illustration explaining the spatial relation among shallow earthquakes and their focal mechanisms.

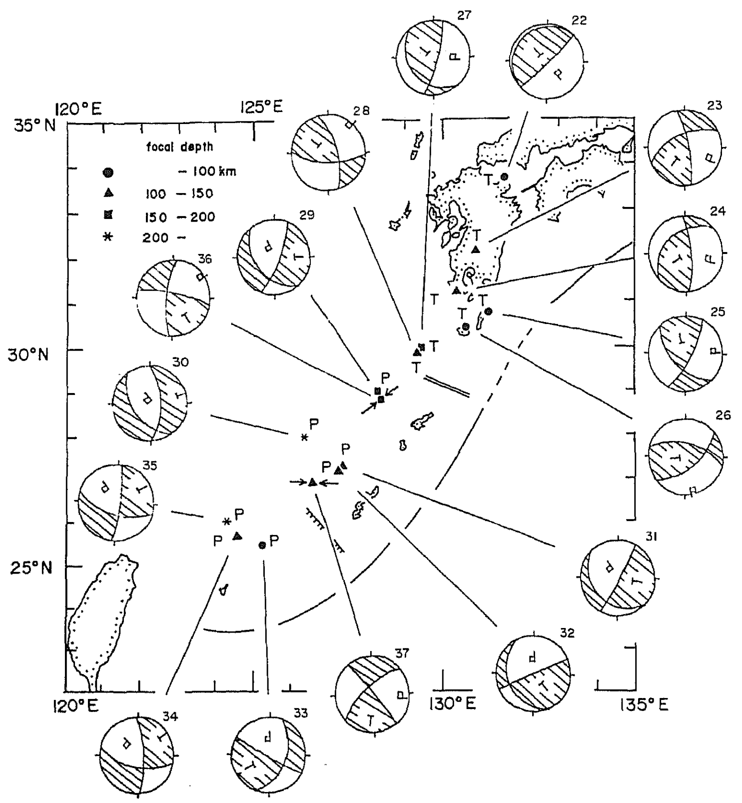


Fig. 7. Fault plane solutions for earthquakes deeper than about 60 km (shocks Nos. 22–37). Focal depths of these earthquakes are shown by different symbols as given in the upper-left side. Earthquakes labeled by T and P have focal mechanisms of down-dip tension and compression, respectively. Arrows indicate the directions of the P-axes for shocks Nos. 36 and 37. Simplified mechanism diagrams are also given in the same manner as in Fig. 5.

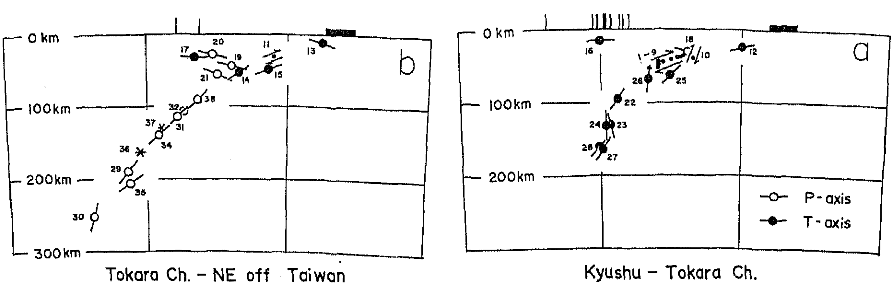
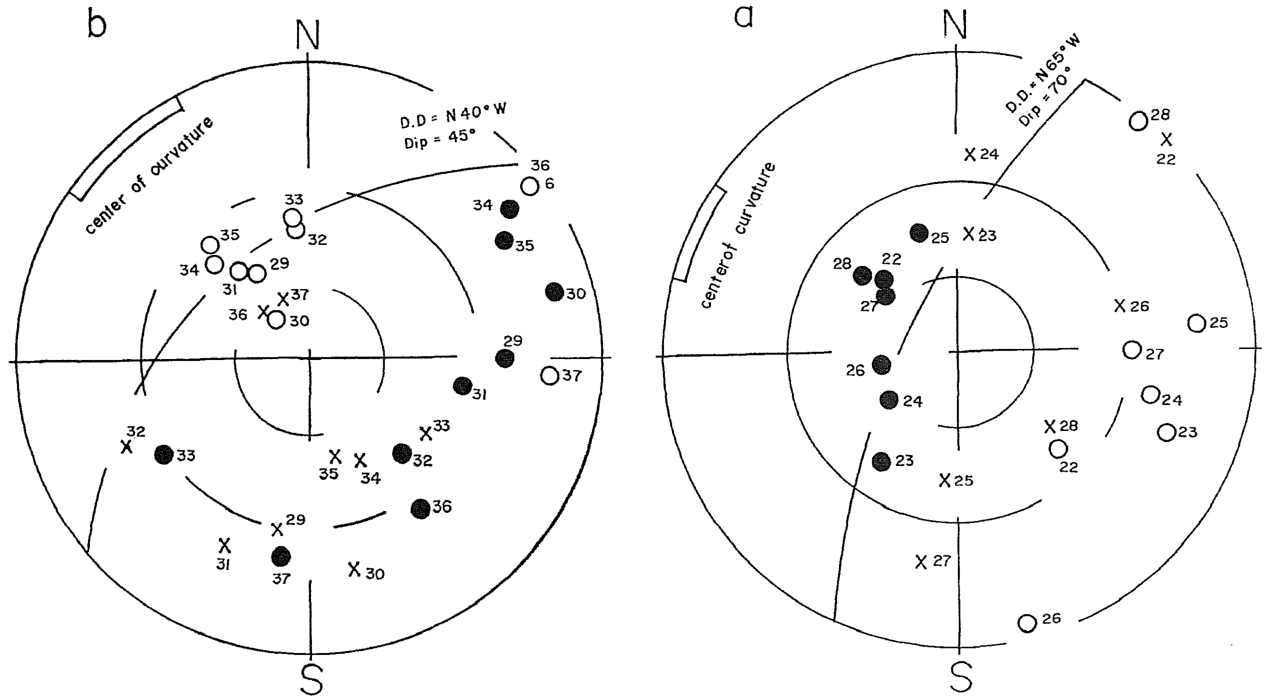


Fig. 8. Distribution of slip vectors (arrows), the P- (open circles) and T- (closed circles) axes in the vertical sections normal to the Kyushu-Ryukyu arc. Numerals are the same as in Table 3. (a): the northern arc north of the Tokara channel and (b): the southern arc south of the channel.



No. 29-37 Tokara Ch. - NE off Taiwan

No. 22-28 Kyushu - Tokara Ch.

Fig. 9. Distribution of the P- (open circles), T- (closed circles) and B- (cross marks) axes on the lower hemisphere of the Wulff grid. (a): the northern arc (shocks Nos. 22–28) and (b): the southern arc (shocks Nos. 29–37). For the reference, planes with dip direction (D.D.)=N 65°W and dip=70° and with D.D.=N 40°W and dip=45°, which approximate the Wadati-Benioff zones, are given in (a) and (b), respectively. Directions of the center of curvature are also given. Numerals are the same as in Table 3.

and one earthquake in the southern Ryukyu arc (shock No. 11) indicate, consistently, a thrusting with slip directions of the oceanic block oriented northwestward. KATSUMATA and SYKES (1969) and FITCH (1972) also mentioned that thrusting earthquakes occur in Hyuga-nada and in the southern Ryukyu arc. All these earthquakes are interpreted as the result of elastic rebounds of the continental plate margin that has been dragged down by the subducting oceanic plate. This interpretation is supported also by the fact that their slip directions are roughly parallel to the direction of relative motion between the Asian and the Philippine Sea plates. SENO (1977) located the pole of the relative motion at a point northeast of Hokkaido, Japan (longitude=150.54±5.4°E, latitude=45.5±3.7°N with the rate of rotation=1.20±0.12 deg/Ma), while FITCH (1972) concluded that the pole near Alaska is preferred. Although these estimated poles differ significantly, there is no serious difference in the direction of the relative motion near the Kyushu-Ryukyu arc. SENO (1977) suggested, however, that the consuming rate varies seriously from Hyuga-nada (4.4 mc/yr) to the southmost Ryukyu arc (6.5 cm/yr), because the distances from the pole are short.

Earthquake No. 10 has a fault plane solution indicating reverse faulting. The slip direction of the oceanic block appears more or less parallel to that of the above thrusting earthquakes if the steeply northwestward-dipping plane can be taken as the fault plane. Figure 8 shows that this earthquake took place nearer to the trench side than the thrusting earthquakes. This suggests that the earthquake may have been caused by faulting which branches off rather steeply from the main fault plane between the oceanic and continental plates, similar to the case of the Patton Bay fault at the time of the 1964 Alaskan earthquake (see PLAFKER, 1972 and Fig. 6). However, this interpretation is only tentative, because we cannot rule out a possibility that the earthquake might have occurred in the underthrusting oceanic plate.

Two normal faulting earthquakes (shocks Nos. 12 and 13) occurred near the Ryukyu trench. These earthquakes are located in the area where shallow earthquakes spread out toward the trench as mentioned in the foregoing section (see Fig. 2), and where the strike of the trench becomes nearly normal to the direction of relative motion between the two plates. The T-axes are roughly normal to the strike of the trench axis. The spatial relation between hypocenters of the above inter-plate earthquakes and normal faulting ones is represented in the vertical section normal to the Kyushu-Ryukyu arc (Fig. 8). The fact that normal faulting earthquakes occur outside of the zone of inter-plate earthquakes can be commonly observed in well developed subduction zones; for examples northeastern Japan (YOSHII, 1978), Kurile (STAUDER and MUALCHIN, 1976), Aleutian (STAUDER, 1968, 1972), Central American (DEAN and DRAKE, 1978), Chilean (STAUDER, 1973), New Hebrides (PASCAL *et al.*, 1978) and Bonin arcs (KATSUMATA and SYKES, 1969; FITCH, 1972). As already suggested by FITCH (1972), these features support the familiar interpretation that the two normal faulting earthquakes occurred due to the tensile stress generated in the upper side of the oceanic plate when it bends downward to underthrust beneath the continental plate margin.

The present study provides an interesting nature of other types of shallow earthquakes which occurred around the interface between the continental plate margin and the underthrusting oceanic plate. Earthquakes Nos. 14 and 15 that occurred just below the interface indicate strike-slip faulting with northwestward dipping T-axes. Since the T-axes are parallel to those of the normal faulting earthquakes Nos. 12 and 13 near the trench, these earthquakes may be interpreted to have occurred under tensile stress due to bending of the upper portion of the oceanic plate, as in the case of shocks Nos. 12 and 13 (see Fig. 8).

On the other hand, shocks Nos. 18, 19, 20, and 21 which appear to have occurred slightly above the oceanic plate have southeastward dipping P-axes. This suggests that these four earthquakes may have been caused within the continental plate margin by a nearly horizontal compressional force due to the downgoing plate.

Two other normal faulting earthquakes Nos. 16 and 17 appear to have taken place under the volcanic front. These earthquakes may be interpreted as having been caused by some tensile stress working under the volcanic region (YAMASHINA and MURAI, 1975; YAMASHINA and MITSUNAMI, 1977), although KARIG (1973) has considered shock No. 17 as evidence suggesting that the Okinawa trough is still extending.

The features discussed above for shallow earthquakes are summarized, as a schematical illustration, in Fig. 6.

3.3 Solution for intermediate-depth earthquakes

Figure 7 shows the fault plane solutions for earthquakes deeper than about 60 km (shocks Nos. 22–37). Focal depths of these earthquakes are shown by different symbols, as given in the upper-left corner of the figure. It is noticed that there is a significant difference in the fault plane solutions for earthquakes that occurred north and south of the Tokara channel. The distributions of the P- and T-axes are given separately in Fig. 9 for these earthquakes in the northern (a) and southern (b) regions.

The solutions for seven earthquakes Nos. 22 to 28, which occurred in the region north of the Tokara channel, indicate the T-axes roughly parallel to the dip of the Wadati-Benioff zone, i.e. down-dip tension as shown in Figs. 7, 8, and 9. The nature of down-dip tension is consistent with the classical two-dimensional model presented by ISACKS and MOLNAR (1971); down-dip tension appears at intermediate-depths of the Wadati-Benioff zone due to a gravitational pull. However, the T-axes of shocks Nos. 23 and 24 somewhat deflect from the general trend, and all the axes seem to scatter over a somewhat wide range (see Figs. 8 and 9). This feature might be attributed to local stress concentration due to some internal deformation of the subducting plate, although the details must be left unsolved until the local structure of the Wadati-Benioff zone or the descending plate is made clear.

On the other hand, seven of the nine earthquakes (shocks Nos. 29–35), which occurred in the region south of the Tokara channel, indicate the P-axes nearly parallel to the dip of the Wadati-Benioff zone, i.e. down-dip compression (see Figs. 7, 8, and 9). KATSUMATA and SYKES (1969) have sampled two earthquakes which are here referred to as shocks Nos. 29 and 31, characterizing the Ryukyu arc as a zone of down-dip compression. ISACKS and MOLNAR (1971) also reported the Ryukyu arc as one example which cannot be correlated to their simple down-dip tension model. It is interesting to note, however, that the zones of down-dip tension and compression seem to be separated sharply around the Tokara channel, where the dip of the Wadati-Benioff zone also changes sharply from high angles around 70° in the north to low angles around 40°–50° in the south. This contrast in the focal mechanism and seismicity will be discussed later with relation to other geophysical and geological features.

Fault plane solutions of earthquakes Nos. 36 and 37 have the P-axes parallel to the arc as shown by two arrows in Fig. 7. The P-, B- and T-axes of the two earthquakes are oriented in the direction corresponding to the T-, P- and B-axes of the above earthquakes with down-dip compression, respectively. These features might be explained by excessive compressive stress working in the direction parallel to the arc, which is locally added to the general stress of down-dip compression along the dip of the Wadati-Benioff zone. It should be noted here that these exceptional earthquakes appear only at depths of about 150 km in the central Ryukyu arc between the Tokara channel and the Miyako depression. The additional compressive stress might be caused by some internal deformation of the descending plate, but their details are not well known at this moment.

4. *Discussion*

4.1 Transition from great earthquakes along the Nankai trough to Hyuga-nada earthquakes

There have been recurrences of great earthquakes such as the Nankaido earthquake of 1946 at 100–200 years' interval along the Nankai trough (e.g. ANDO, 1975), which is an eastern continuation of the Kyushu-Ryukyu region now in consideration. All these earthquakes seem to be characterized by thrust faulting on a low-angled, northwestward-dipping fault plane over an extensive area with the dimension of 150 km × 100 km (FITCH and SCHOLZ, 1971; KANAMORI, 1972; ANDO, 1975). The fault region sometimes extended to off coast of the western Shikoku region (ANDO, 1975). The estimated fault displacements exceed several meters, but the average stress drop is of the order of only 30 bars (e.g. KANAMORI, 1972).

As described in the foregoing section, earthquakes in the Hyuga-nada region also indicate thrusting mechanism with the slip directions almost similar to that of the Nankaido earthquake. The occurrence of these earthquakes with magnitudes

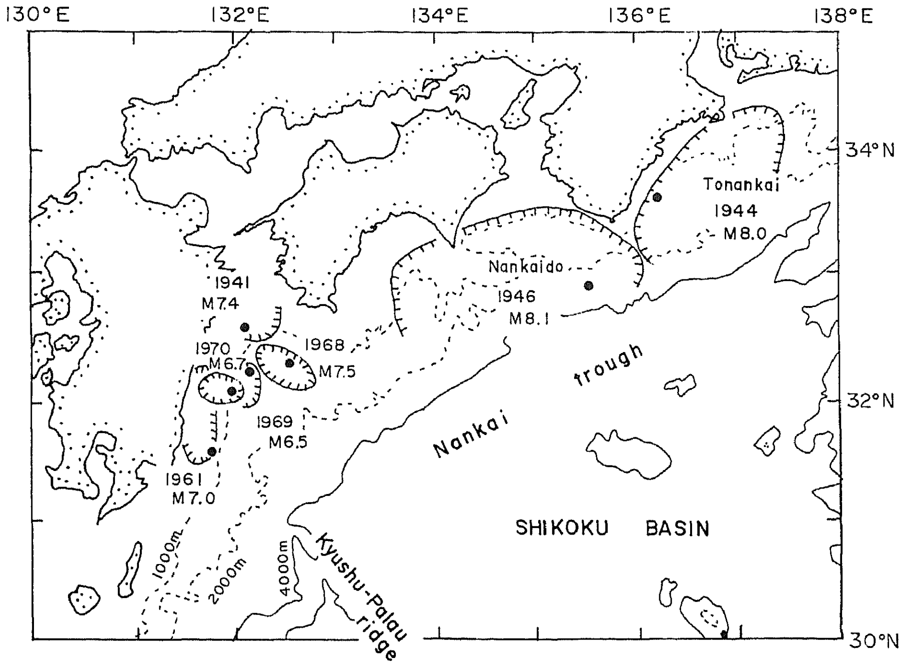


Fig. 10. Tsunami source areas of great earthquakes along the Nankai trough and major Hyuga-nada earthquakes. After HATORI (1969, 1971, 1974).

Table 1. Source parameters of two Hyuga-nada earthquakes of 1968 and 1970.

	1968	1970
Magnitude	7.5	6.7
Fault plane		
dip angle	17°	10°
dip direction	N 63° W	N 55° W
slip direction+	N 63° W	N 55° W
Fault length (km)	56	31
Fault width (km)	32	24
Seismic moment (dyne·cm)	1.8×10^{27}	4.1×10^{26}
Average fault displacement (m)	1.6	1.0
Stress drop (bars)	60	50

+ lower-side block.

greater than 6.5 seems more frequent in this region, which was at about 10–20 years' interval, and their fault areas were considerably smaller but were distributed in a wide region east of Kyushu (see Fig. 10). The fault parameters for two recent Hyuga-nada earthquakes of 1968 and 1970 have been estimated from spatial distribution of aftershocks, tsunami source area, seismic waveforms and amplitudes observed at several stations in the near- and far-fields and coseismic tectonic crustal movements (SHIONO *et al.*, 1976). The results are given in Table 1. Since the extent of aftershock region of the earthquakes is not so well defined (JMA, 1972; Kimura, 1975 personal communication), the estimated fault area is mainly based on the tsunami source region inferred from tidal records (HATORI, 1969, 1971; AIDA, 1974). It is to be mentioned that the estimated stress drop during the two Hyuga-nada earthquakes reaches about 60 bars, which is about twice that for the Nankaido earthquake.

Now we discuss some possible reasons for the more frequent occurrence of smaller divided fault regions and somewhat larger stress drop of the Hyuga-nada earthquakes, in comparison with the Nankai trough earthquakes. One possible reason for the above phenomena would be local stress concentration in the Hyuga-nada region, which may arise from abrupt southwestward warping of the Nankai trough just south of Hyuga-nada (see Fig. 1). This warping could yield a bending of the subducting plate, which produces tensional stress just above it, and may be one possible source of normal faulting earthquakes along a hinge line through the Bungo-channel–Iyonada regions (see SHIONO and MIKUMO, 1975). Somecontortion could also be generated just on the southwestern side of the hinge line in the plate sinking towards the Kyushu region. If this is the case, the subduction would be more or less resisted by the contortion, and excessive local stress would be added to this portion. This could be one of likely explanations.

Another possible explanation is based on structural heterogeneities on the upper thrusting interface of the descending plate. The Kyushu-Palau ridge including aseismic seamounts and other uplifted regions extends northwestwards and appears to reach the Nankai trough (see Fig. 1), and there is a possibility that it goes further down under the Hyuga-nada basin. In this case, the upper interface of the subducting Philippine Sea plate could have a heterogeneous structure there, and would not yield very large thrusting earthquakes as suggested by KELLEHER and McCANN (1976). On the other hand, the interface under an extensive region off coast of Shikoku—the Kii peninsula appears less heterogeneous in view of the relatively flat sea bottom of the Shikoku basin (see Fig. 1). It is possible that the more heterogeneous interface would often break into smaller-size fault planes under the increasing tectonic stress due to the subduction of the Philippine Sea plate. This interpretation might also account for the somewhat large stress drop during the Hyuga-nada earthquakes if the shear strengths are not uniformly distributed over the fault region (MIKUMO and MIYATAKE, 1979).

The appreciable difference in the properties of earthquakes from the Nankai trough to Hyuga-nada may be explained in either or both of the above two ways.

4.2 Differential subduction of the Philippine Sea plate along the Kyushu-Ryukyu arc

It has been shown in the foregoing sections that the downgoing Wadati-Benioff zone dips steeply at high angles reaching 70° in the northern Kyushu-Ryukyu arc north of the Tokara channel, while the dip decreases to 40°–50° south of it. The sharp difference might suggest that the northern segment of the descending Philippine Sea plate tears apart from the southern segment along a vertical latent hinge fault under the Tokara channel, although no earthquakes with focal mechanism indicating hinge-faulting have been detected there. It seems also significant that the pre-Miocene tectonic belts in the southern arc has apparently shifted left-laterally with respect to the northern arc by about 100 km towards the trench axis (KONISHI, 1963, 1965; KIZAKI, 1978 a, b). The stress state within the deeper portion of the subducting lithosphere, which has been inferred from the focal mechanism of intermediate-depth earthquakes, also indicates a clear difference; down-dip tension in the northern arc and down-dip compression in the southern arc. The difference appears to be bounded by the Tokara channel. These features are summarized in Table 2.

The variation in the dip of the Wadati-Benioff zone under island arcs in relation to the curvature of the arc and the convergence velocity of the subducting lithosphere have been discussed by many geophysicists (e.g. FRANK, 1968; LUYENDYK, 1970; STROBACH, 1973; AOKI, 1974; DEFAZIO, 1974; TOVISH and SCHUBERT, 1978; UYEDA and KANAMORI, 1977; WU, 1978a). Some of the authors found that the dip and the velocity are more or less related, and among them, an inverse relationship between the two parameters has been proposed by LUYENDYK (1970), although there is some objection to this interpretation (TOVISH and SCHUBERT, 1978). If it is the case for the subduction zone under the Kyushu-Ryukyu arc, the difference in the dip of earthquake zone bounded by the Tokara channel might be attributed to the difference in the convergence velocity between north and south of the channel. Actually, some variations in the convergence velocity from Hyuga-nada to the southmost Ryukyu arc have been noted (SENO, 1977, see Table 2), although the velocity does not change sharply between the north and south of the Tokara channel.

Now we attempt to present two possible interpretations of the difference in the dip and stress state within the descending lithosphere, with some inference

Table 2. Comparison between the northern and southern segments of the Kyushu-Ryukyu arc.

	Northern segment of the Kyushu-Ryukyu arc (north of the Tokara channel)	Southern segment of the Kyushu-Ryukyu arc (south of the Tokara channel)
Wadati-Benioff zone	bends sharply at depths about 100 km, high dip angle (about 70°)	gradually increase in dip angle with depth, low dip angle (about 40°–50°)
Focal mechanism of intermediate-depth earthquakes	down-dip tension	down-dip compression
Volcanism	very high activity	very low activity
Rate of plate convergence after SENO (1977)	4.4–5.4 cm/yr	5.4–6.5 cm/yr

to the previous work described above. One explanation is based on the standpoint that the convergence velocity would play a dominant rôle. The other standpoint is to take into consideration the rôle of the physical properties such as viscosity and density in the surrounding mantle, in relation to volcanism. In both cases we consider shear resistance to the subduction of the lithosphere, which may be governed by the plate velocity and/or viscosity.

If we take the first interpretation, the lithosphere sinking with a lower velocity in the northern arc receives a somewhat smaller resistance, and hence will be rather smoothly dragged down by a gravitational pull into the asthenosphere with a high angle. The stress state within the lithosphere will therefore be tensional. In the southern arc, on the other hand, the subducting lithosphere will be plunged down by the northwestward advancing oceanic plate with a faster velocity, in addition to the gravitational pull, and hence will sink with a lower dip angle. The higher plate velocity causes more resistance to the subduction, and will yield a down-dip compressional stress within the lithosphere.

The second interpretation is mainly based on volcanic activity. Along the Kyushu-Ryukyu arc north of the Tokara channel, there are a number of active volcanoes, suggesting that high temperature magmas are formed in the upper mantle above 200 km. This implies the existence of low viscosity material above the subducting plate, which is also suggested by the existence of a low-Q zone for long-period P waves (MIKAMI and HIRAHARA, 1979). Viscous resistance to the subduction received from the surrounding mantle will be somewhat weaker, and the plate will sink rather smoothly by the gravitational pull, yielding tensional stress within it, as in the case of lower plate velocity. In the southern section, however, there are only two volcanoes. This suggests that thermal activity in the upper mantle there above the plate would be generally lower than that in the northern arc, and hence that the material would have a larger viscosity. The density contrast between the surrounding mantle and the plate would also be smaller. These situations would increase the resistance to the subducting plate and hence produce compressional stress as in the case of higher plate velocity.

There is some evidence for high heat flow near the southern Ryukyu (WATANABE *et al.*, 1970; YASUI *et al.*, 1970), but this might be due to a thin crust in the marginal sea, which still retains high temperatures. Volcanic activity in these regions, as well as the back-arc opening (e.g. UYEDA, 1977) of the Okinawa trough and outward drift of the southern Ryukyu arc (e.g. KARIG, 1973), may be closely related to the history of the subduction of the Philippine Sea plate, but a more detailed discussion on this subject is beyond the scope of our paper.

5. *Concluding Remarks*

In the present paper, we have investigated tectonic features of the Kyushu-Ryukyu arc on the basis of seismicity and focal mechanism of both shallow and intermediate-depth earthquakes, in order to reveal more clearly the nature of the subducting Philippine Sea plate.

The most remarkable finding is the differential subduction evidenced by clear differences in the dip of the Wadati-Benioff zone and the stress state within the descending plate between the northern and southern arcs bounded by the Tokara channel; high-angle dip and down-dip tension in the north, and relatively low-angle dip and down-dip compression in the south. We have presented two possible interpretations, both of which are attributed to the difference in shear resistance to the subduction; one is the difference in the convergence plate velocity and the other is that in the physical properties of the material in the surrounding mantle. We feel, at this moment, that it is hard to descriminate which is more probable before further evidence is obtained.

We have also discussed some features of shallow thrust-earthquakes in the Hyuga-nada region east of Kyushu, in terms of their frequent occurrence, smaller fault regions and larger stress drop, in comparison with great earthquakes along the Nankai trough. These phenomena might be explained by local stress concentration due to the warping of the Nankai trough, and/or by heterogeneous structure of the interface between the continental and oceanic plates under the Hyuga-nada region due to the subduction of the Kyushu-Palau ridge.

We would like to express our sincere appreciation to the staff members of the Abuyama Seismological Observatory of Kyoto University who kindly permitted us to copy ISC Bulletins. We also wish to thank the staff members of the Disaster Prevention Research Institute of Kyoto University and of Department of Geosciences, Faculty of Science of Osaka City University for their stimulating discussions. Computations involved were made at the Data Processing Center of Kyoto University, the Computer Center of Osaka City University and at the Information Processing Center of Disaster Prevention Research Institute, Kyoto University, and also by YHP 9830 Personal Computer at the laboratory of Osaka City University.

APPENDIX

Focal coordinates and parameters of fault plane solutions for 37 earthquakes discussed in the present study are listed in Table 3. Twenty-seven solutions are newly determined here and are indicated by an asterisk, and others are referred to the authors listed in the column Ref. of Table 3.

Focal coordinates are taken from ISC Monthly Bulletin. When the focal depths inferred from *pP-P* time intervals are listed, they are used after correction for the effect of sea water depth.

Fault plane solutions are determined on the basis of P-wave first motion reported in JMA Monthly Seismological Bulletin and ISC Monthly Bulletin. For the three Hyuga-nada earthquakes of 1968, 1969, and 1970 (shocks Nos. 2, 4, and 5), P-wave first motions are directly read from WWSSN long-period seismograms. To calculate emergent angles of seismic rays leaving from the focus, Ichikawa-Mochizuki's tables (ICHIKAWA and MOCHIZUKI, 1971) are used for stations within epicentral distances of 2,000 km, and those of PHO and BEHE (1972)

Table 3. Dates, focal coordinates and focal mechanism parameters of shocks Nos. 1–37.

No.	Date	Coordinate (ISC)			Pole X		Pole Y		B-axis		P-axis		T-axis		M	Ref.†††
		Long.	Lat.	Depth†	Az.	Pl.	Az.	Pl.	Az.	Pl.	Az.	Pl.	Az.	Pl.		
1	Oct. 3, 1963	131.78°E	32.78°N	33 km	287°	8°	107°	82°	17°	0°	107°	37°	287°	53°	6.3	*
2	Apr. 1, 1968	132.28	32.48	32	302	12	158	76	34	8	129	33	292	56	7.5	*
3	Apr. 1, 1968	132.21	32.24	26	306	8	80	78	215	8	119	36	316	53	6.3	*
4	Apr. 21, 1969	131.98	32.15	32	309	8	129	82	39	0	129	37	309	53	6.5	*
5	July 25, 1970	131.78	32.26	46	300	16	120	74	30	0	120	29	300	61	6.7	*
6	July 26, 1970	131.83	32.31	41	308	10	128	80	38	0	128	35	308	55	6.1	*
7	Feb. 26, 1961	131.56	31.84	50	295	20	96	69	203	6	110	25	306	64	7.0	Sh
8	Nov. 27, 1961	131.33	31.56	46	304	12	135	78	34	2	126	33	301	57	6.0	*
9	Sep. 17, 1969	131.43	31.43	36	315	10	135	80	45	0	135	35	315	55	6.1	*
10	Sep. 2, 1972	130.64	29.41	40	335	64	155	26	65	0	335	19	155	71	6.1	*
11	July 10, 1966	125.21	24.30	25	315	22	161	66			142	22	297	65	5.7	KS
12	July 18, 1961	131.73	29.74	23	265	52	133	28	29	24	177	62	294	13	6.6	*
13	Aug. 3, 1968	128.4	25.6	19††	309	24	174	58	48	20	274	64	145	18	6.5	Fi
14	Apr. 13, 1967	128.66	27.32	50	275	12	12	30	166	57	57	12	320	30	5.9	*
15	June 20, 1976	125.99	24.79	50	23	10	290	14	147	73	246	3	337	17	5.8	*
16	Apr. 20, 1975	131.3	33.2	15††	20	40	144	34	259	31	86	58	351	4		YM
17	Dec. 31, 1969	129.1	28.5	30††	145	44	346	44	246	10	58	80	155	0	5.8	Fi
18	Mar. 23, 1973	130.41	29.30	33	62	40	312	22	201	42	101	11	359	46	5.9	*
19	Oct. 26, 1972	128.57	27.48	46	288	14	187	35	36	51	144	14	243	36	6.0	*
20	Nov. 12, 1968	128.48	27.50	51	311	30	131	60	41	0	131	14	311	75	5.6	Fi
21	Mar. 11, 1958	124.29°E	24.62°N	65	277	12	173	50	16	38	126	23	240	43	7	*
22	May 7, 1969	131.68	33.68	95	135	84	315	6	45	0	135	39	315	51	5.2	Sh
23	Nov. 28, 1967	130.84	32.13	129	259	16	155	40	6	46	112	15	215	41	5.3	Sh
24	Mar. 4, 1960	130.39	31.15	130	139	60	266	19	4	22	104	22	234	58	6.5	Sh
25	Aug. 17, 1963	131.18	30.74	62	296	20	44	40	186	43	84	12	342	44	5.9	*
26	July 8, 1960	130.64	30.47	65	320	35	194	40	74	31	166	3	261	59	6.1	*

27	May 14, 1968	129.39	29.93	164	50	67	285	14	190	18	90	29	308	55	5.9	Mi
28	Mar. 23, 1970	129.39	29.82	162	3	30	255	29	130	46	39	1	309	44	5.7	Mi
29	Sep. 21, 1965	128.23	28.96	194	50	55	292	18	192	29	329	52	90	22	6.0	KS
30	Oct. 12, 1958	126.31	27.89	256	55	50	270	34	168	18	321	70	75	8	6.8	*
31	Jan. 6, 1964	127.36	27.23	91	45	69	298	7	205	20	321	48	100	35	5.8	KS
32	May 26, 1959	127.37	27.11	108	335	0	65	70	245	20	354	42	136	42	6.6	*
33	Nov. 16, 1965	125.27	25.45	87	28	6	290	50	123	39	353	38	238	28	5.6	*
34	Sep. 11, 1973	124.58	25.65	144	12	35	268	20	154	48	315	40	53	10	5.7	*
35	Jan. 2, 1974	124.38	26.02	207	15	35	275	14	167	52	319	35	59	14	5.5	*
36	Mar. 19, 1969	128.34	28.81	163	191	15	95	20	315	65	52	3	144	25	5.6	*
37	June 15, 1968	126.65	26.93	132	232	6	140	24	335	65	94	12	189	21	5.6	*

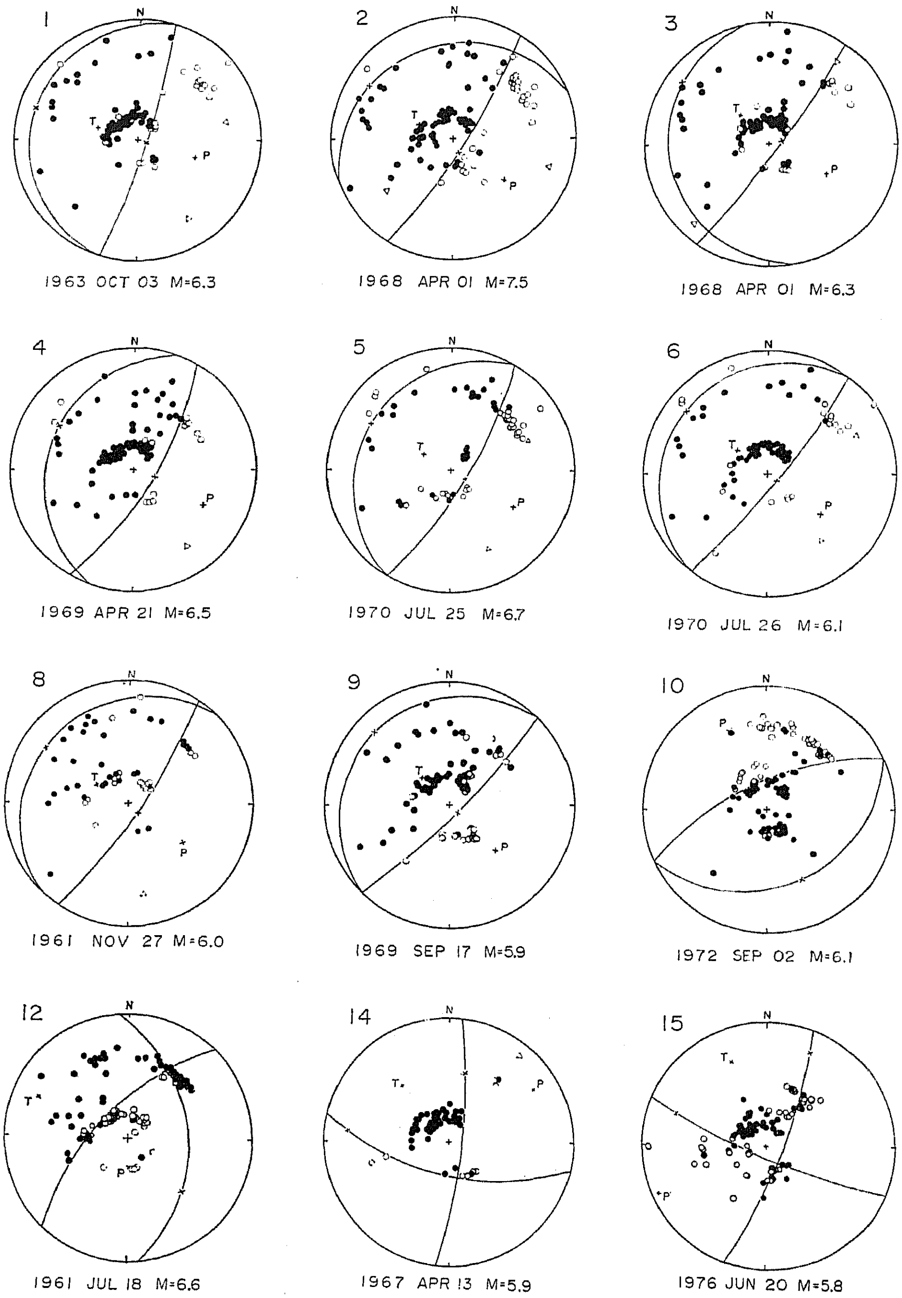
† focal depths inferred from *pP-P* time intervals and corrected for the effect of water

†† focal depths reported in the referred paper

††† Reference; *: new solution, Sh, SHIONO (1977); Mi, MIKUMO (1971); KS, KATSUMATA and SYKES (1969); Fi, FITCH (1972); YM, YAMASHINA and MURAI (1975).

Poles X and Y represent the poles of nodal planes; Az, azimuth of the axis measured clockwise from the north; Pl, plunge of the axis measured downward from the horizon; *M*, magnitude.

are used for farther stations. Because the former tables are based on the average crustal structure appropriate to Japan islands, the calculated angles for near stations may have a slight bias, but no corrections have been applied in the present



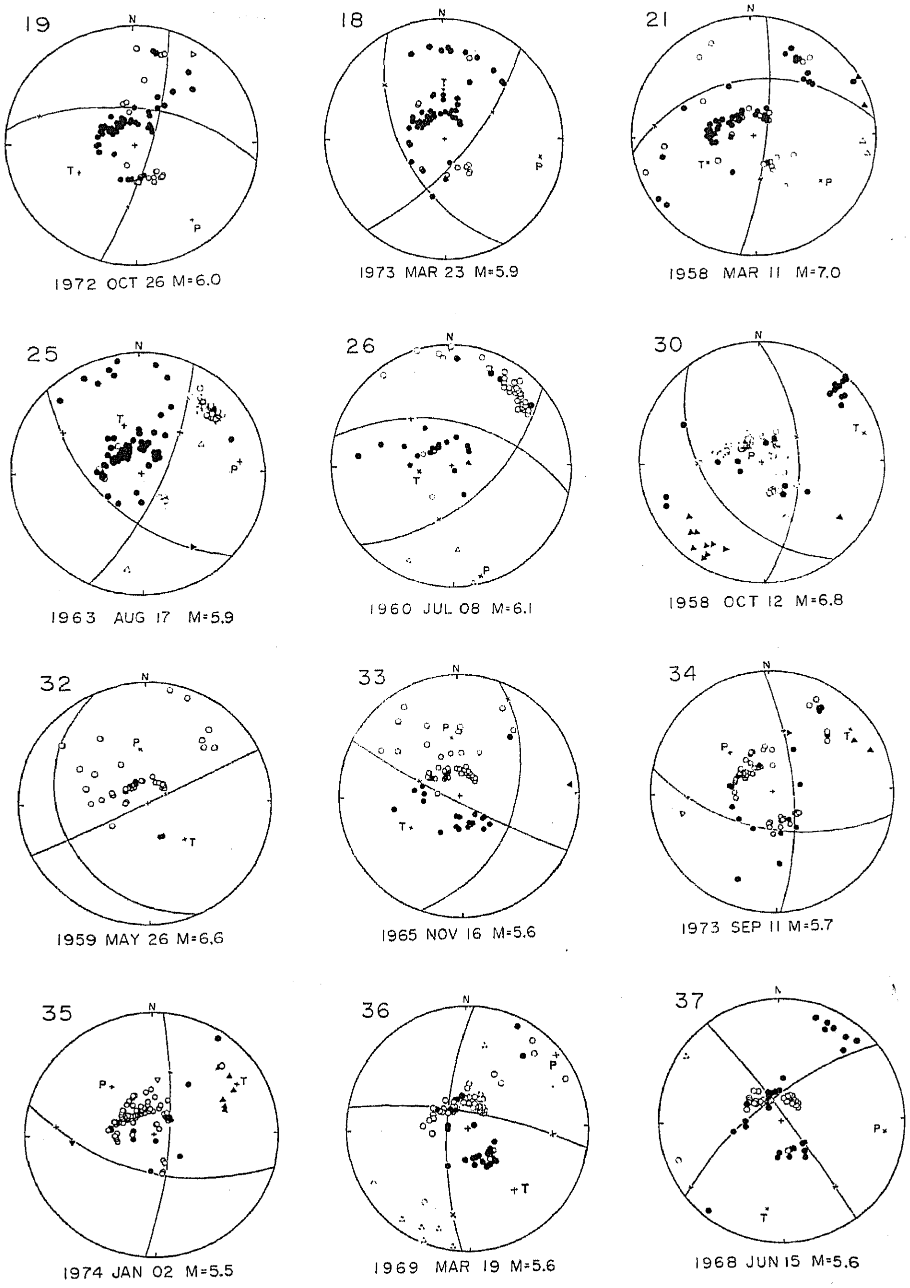


Fig. 11. Mechanism diagrams newly determined in the present study. Symbols and projection are explained in the text.

study. Another possible bias from the lateral heterogeneity of the upper mantle structure due to the presence of the descending plate (e.g. TOKSOZ *et al.*, 1971; TOKSOZ *et al.*, 1973; ENGDAHL *et al.*, 1977; HIRAHARA, 1977) has also been ignored here.

The mechanism diagrams are presented in Fig. 11, in order to show the quality and consistency of data. The diagram shows the distribution of P-wave first motions, two nodal planes and the poles, and the P-, T-, and B-axes projected on the lower hemisphere of the Wulff grid.

REFERENCES

AIDA, I., Numerical computation of a tsunami based on a fault origin model of an earthquake, *Zisin*, **27**, 141–154, 1974 (in Japanese).

ANDO, M., Source mechanisms and tectonic significance of historical earthquakes along the Nankai trough, Japan, *Tectonophysics*, **27**, 119–140, 1975.

AOKI, H., Pressure effects on the deformation of slab descending below island arcs, *Zisin*, **27**, 110–119, 1974 (in Japanese).

DEAN, B. W. and C. L. DRAKE, Focal mechanism solutions and tectonics of the Middle America arc, *J. Geol.*, **86**, 111–128, 1978.

DEFAZIO, T. L., Island-arc and underthrust-plate geometry, *Tectonophysics*, **23**, 149–154, 1974.

ENGDAHL, E. R., Seismicity and plate subduction in the central Aleutians, ed. M. Talwani and W. C. Pitman III, in *Island Arcs. Deep Sea Trenches and Back-Arc Basins*, pp. 259–271, Maurice Ewing Series 1, A.G.U., Washington, 1977.

ENGDAHL, E. R., N. H. SLEEP, and M. T. LIN, Plate effects in north Pacific subduction zones, *Tectonophysics*, **37**, 95–116, 1977.

FITCH, T. J., Plate convergence, transcurrent faults, and internal deformation adjacent to southeast Asia and western Pacific, *J. Geophys. Res.*, 77, 4432–4460, 1972.

FITCH, T. J. and C. H. SCHOLZ, Mechanism of underthrusting in southwest Japan: A model of convergent plate interaction, *J. Geophys. Res.*, **76**, 7260–7292, 1971.

FRANK, F. G., Curvature of island arc, *Nature*, **220**, 363, 1968.

HATORI, T., A study of the wave sources of the Hiuga-nada tsunamis, *Bull. Earthq. Res. Inst.*, **47**, 55–63, 1969.

HATORI, T., The magnitude of tsunamis generated in Hiuga-nada during the years, 1926–1970, *Zisin*, **24**, 95–106, 1971 (in Japanese).

HATORI, T., Sources of large tsunamis in southwest Japan, *Zisin*, **27**, 10–24, 1974 (in Japanese).

HIRAHARA, K., A large-scale three-dimensional seismic structure under the Japan islands and the Sea of Japan, *J. Phys. Earth*, **25**, 393–417, 1977.

HONZA, E., An island arc activity in the Ryukyu arc and its difference in the northern and southern part of the arc, *Kaiyo-Kagaku* (monthly published by Kaiyo-shyuppan, Tokyo), **9**(9), 31–35, 1977 (in Japanese).

ICHIKAWA, M., Reanalyses of mechanism of earthquakes which occurred in and near Japan, and statistical studies on the nodal plane solutions obtained, 1926–1968, *Geophys. Mag.*, **35**, 207–274, 1971.

ICHIKAWA, M. and E. MOCHIZUKI, Travel time tables for local earthquakes in and near Japan, *Pap. Met. Geophys.*, **22**, 229–290, 1971.

ISACKS, B. L. and M. BARAZANGI, Geometry of Benioff zones: Lateral segmentation and downward bending of the subducted lithosphere, ed. M. Talwani and W. C. Pitman III, in *Island Arcs, Deep Sea Trenches and Back-Arc Basins*, pp. 99–114, Maurice Ewing Series 1, A.G.U., Washington, 1977.

ISACKS, B. L. and P. MOLNAR, Distribution of stress in the descending lithosphere from a global survey of focal-mechanism solutions of mantle earthquakes, *Rev. Geophys. Space Phys.*, **9**, 103–174, 1971.

JACOBS, K. H., K. NAKAMURA, and J. N. DAVIES, Trench-volcano gap along the Alaska-Aleutian arc: Facts, and speculations on the role of terrigeous sediments for subduction, ed. M. Talwani and W. C. Pitman III, in *Island Arc, Deep Sea Trenches and Back-Arc Basins*, pp. 243–258, Maurice Ewing Series 1, A.G.U., Washington, 1977.

JMA (THE JAPAN METEOROLOGICAL AGENCY), Regional catalogue of earthquakes in and near Japan (1961–1970), *The Seismological Bulletin of the Japanese Meteorological Agency*, Suppl. **4**, 61, 1972.

KANAMORI, H., Tectonic implication of the 1944 Tonankai and the 1946 Nankaido earthquakes, *Phys. Earth Planet. Inter.*, **5**, 129–139, 1972.

KARIG, D. E., Plate convergence between the Philippine and the Ryukyu island, *Mar. Geol.*, **14**, 153–168, 1973.

KARIG, D. E., J. G. CALDWELL, and E. M. PARMENTIER, Effects of accretion on the geometry of the descending lithosphere, *J. Geophys. Res.*, **81**, 6281–6291, 1976.

KATSUMATA, M. and L. R. SYKES, Seismicity and tectonics of the western Pacific: Izu-Mariana-Caroline and Ryukyu-Taiwan regions, *J. Geophys. Res.*, **74**, 5923–5948, 1969.

KELLEHER, J. and W. MCCANN, Buoyant zones, great earthquakes, and unstable boundaries of subduction, *J. Geophys. Res.*, **81**, 4885–4896, 1976.

KIZAKI, K., Problems on the tectonics of the Ryukyu island arc, *Geological Studies of the Ryukyu Island*, **3**, 1–9, 1978 a (in Japanese).

KIZAKI, K., Tectonics of the Ryukyu island arc, *J. Phys. Earth*, **26**, Suppl. s301–s307, 1978 b.

KONISHI, K., Pre-Miocene basement complex of Okinawa, and the tectonic belts of the Ryukyu islands, *Sci. Rep. Kanazawa Univ.*, **9**, 169–188, 1963.

KONISHI, K., Geotectonic framework of the Ryukyu islands (Nansei-shoto), *Bull. Geol. Soc. Japan*, **71**, 437–457, 1965 (in Japanese).

LUYENDYK, B. P., Dips of downgoing plates beneath island arcs, *Geol. Soc. Am. Bull.*, **81**, 3411–3416, 1970.

MIKAMI, N. and K. HIRAHARA, Global distribution of Q as derived from long-period P waves, *Progr. & Abstr. Seismol. Soc. Japan*, No. 2, B43, 1979.

MIKUMO, T., Source process of deep and intermediate earthquakes as inferred from long-period P and S waveforms. 2. Deep-focus and intermediate earthquakes around Japan, *J. Phys. Earth*, **19**, 303–320, 1971.

MIKUMO, T. and T. MIYATAKE, Earthquake sequence on a frictional fault model with non-uniform strengths and relaxation times, *Geophys. J. R. Astron. Soc.*, **59**, 497–522, 1979.

NAKAGAWA, H., Geology of the Ryukyu islands—Late Cenozoic development—, *Kaiyo-Kagaku* (monthly published by Kaiyo-shyuppan, Tokyo), **9**(9), 7–13, 1977 a (in Japanese).

NAKAGAWA, H., Problems of Cenozoic history of the Ryukyu islands, *Geological Studies of the Ryukyu Island*, **2**, 1–9, 1977 b (in Japanese).

NISHIMURA, K., Characteristic features of focal mechanism in and near Kyushu island (1), *Contr. Geophys., Kyoto Univ.*, **13**, 181–198, 1973.

OIKE, K., On the nature of the occurrence of intermediate and deep earthquakes. 1. The world wide distribution of the earthquake generating stress, *Bull. Disas. Prev. Res. Inst., Kyoto Univ.*, **20**, Part 3, No. 177, 145–182, 1971.

PASCAL, G., B. L. ISACKS, and M. BARAZANGI, Precise relocation of earthquakes and seismotectonics of the New Hebrides island arc, *J. Geophys. Res.*, **83**, 4957–4973, 1978.

PHO, H. and L. BEHE, Extended distance and angles of incidence of P waves, *Bull. Seismol. Soc. Am.*, **62**, 885–902, 1972.

PLAFKER, G., Alaskan earthquake of 1964 and Chilean earthquake of 1960: Implication for arc tectonics, *J. Geophys. Res.*, 77, 901–925, 1972.

SENO, T., The instantaneous rotation vector of the Philippine Sea plate relative to the Eurasian plate, *Tectonophysics*, **42**, 209–226, 1977.

SENO, T. and K. KURITA, Focal mechanisms and tectonics in the Taiwan-Philippine region, *J. Phys. Earth*, **26**, Suppl. s249–s263, 1978.

SHIONO, K., Focal mechanism of major earthquakes in southwest Japan and their tectonic significance, *J. Phys. Earth*, **25**, 1–26, 1977.

SHIONO, K. and T. MIKUMO, Tectonic implications of subcrustal normal faulting earthquakes in the western Shikoku region, Japan, *J. Phys. Earth*, **23**, 257–278, 1975.

SHIONO, K., T. MIKUMO, and Y. ISHIKAWA, Focal mechanism of earthquake in Hyuga-nada and the Ryukyu arc and their tectonic implication, *Progr. & Abstr. Seismol. Soc. Japan*, No. 2, 71, 1976 (in Japanese).

STAUDER, W., Mechanism of the Rat island earthquake sequence of February 4, 1965, with relation to island arcs and sea-floor spreading, *J. Geophys. Res.*, **73**, 3847–3858, 1968.

STAUDER, W., Fault motion and spatially bounded character of earthquakes in Amchitka pass and the Delarof islands, *J. Geophys. Res.*, **77**, 2072–2080, 1972.

STAUDER, W., Mechanism and spatial distribution of Chilean earthquakes with relation to subduction of the oceanic plate, *J. Geophys. Res.*, **78**, 5033–5061, 1973.

STAUDER, W. and L. MUALCHIN, Fault motion in the larger earthquakes of the Kurile-Kamchatka arc and of the Kurile-Hokkaido corner, *J. Geophys. Res.*, **81**, 297–308, 1976.

STROBACH, K., Curvature of island arcs and plate tectonics, *Z. Geophys.*, **39**, 819–831, 1973.

SUDO, K., The focal process of the Taiwan-oki earthquake of March 12, 1966, *J. Phys. Earth*, **20**, 147–164, 1972.

SUGIMURA, A., Plate boundaries around Japan islands, *Kagaku*, **42**, 192–202, 1972 (in Japanese).

SUGIMURA, A., Major reliefs, volcanoes and earthquakes of island arcs, *Chikyu-Kagaku* (*Earth Science*: Iwanami, Tokyo), **10**, 159–181, 1978 (in Japanese).

SUGIMURA, A. and S. UYEDA, *Island Arcs—Japan and Its Environs*, 235 pp., Elsevier, Amsterdam, 1973.

TOKSOZ, M. N., J. W. MINEAR, and B. R. JULIAN, Temperature field and geophysical effects of a downgoing slab, *J. Geophys. Res.*, **76**, 1113–1138, 1971.

TOKSOZ, M. N., N. H. SLEEP, and A. T. SMITH, Evolution of the downgoing lithosphere and mechanisms of deep focus earthquakes, *Geophys. J. R. Astron. Soc.*, **35**, 285–310, 1973.

TOVISH, A. and G. SCHUBERT, Island arc curvature, velocity of convergence and angle of subduction, *Geophys. Res. Lett.*, **5**, 329–332, 1978.

UTSU, T., *Seismology*, Kyoritsu-Zensho p. 216, 286, Kyoritsu-Shyuppan, Tokyo, 1977 (in Japanese).

UYEDA, S., Some basic problems in the trench-back arc system, ed. M. Talwani and W. C. Pitman III, in *Island Arcs, Deep Sea Trenches and Back-Arc Basins*, pp. 1–14, Maurice Ewing Series 1, A.G.U., Washington, 1977.

UYEDA, S. and H. KANAMORI, Subduction of the oceanic plate and back-arc opening, *Kagaku*, **48**, 91–102, 1977 (in Japanese).

WAGEMAN, J. M., T. W. C. HILDE, and K. O. EMERY, Structural framework of the East China Sea and Yellow Sea, *Am. Assoc. Petrol. Geol. Bull.*, **54**, 1611–1643, 1970.

WATANABE, T., D. EPP, S. UYEDA, M. LANGSETH, and M. YASUI, Heat flow in the Philippine Sea, *Tectonophysics*, **10**, 205–224, 1970.

WU, F. T., Focal mechanisms and tectonics in the vicinity of Taiwan, *Bull. Seismol. Soc. Am.*, **60** 2045–2056, 1970.

WU, F. T., Benioff zones, absolute motions and inter arc basins, *J. Phys. Earth*, **26**, Suppl. s39–s54, 1978 a.

WU, F. T., Recent tectonics of Taiwan, *J. Phys. Earth*, **26**, Suppl. s265–s299, 1978 b.

YAMASHINA, K. and I. MURAI, On the focal mechanisms of the earthquakes in the central part of Oita prefecture and in the northern part of Aso of 1975, especially, the relation to the active fault system, *Bull. Earthq. Res. Inst.*, **50**, 245–302, 1975 (in Japanese).

YAMASHINA, K. and T. MITSUNAMI, Stress field in the Unzen volcanic area, *Kyushu*, *Japan*, *Kazan*, **22**, 13–25, 1977 (in Japanese).

YASUI, M., D. EPP, K. NAKAGAWA, and T. KISHI, Terrestrial heat flow in the seas round the Nansei Shoto (Ryukyu islands), *Tectonophysics*, **10**, 225–234, 1970.

YOSHII, T., Basic geophysical data around Japanese islands, *Kagaku*, **48**, 489–494, 1978 (in Japanese).