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SOURCE MECHANISMS OF SUBCRUSTAL AND UPPER MANTLE EARTHQUAKES AROUND THE NORTHEASTERN KYUSHU REGION, SOUTHWESTERN JAPAN, AND THEIR TECTONIC IMPLICATIONS

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The source mechanisms of subcrustal and upper mantle earthquakes with magnitudes from 6.0 to 6.8 that occurred around the northeastern Kyushu region have been closely investigated to clarify its tectonic features in relation to the subducting Philippine Sea plate with a laterally bending configuration.

Two subcrustal earthquakes that occurred in Suonada and the Bungo channel, which are located close to the leading edge of the subducting Philippine Sea plate, show the mechanism of normal faulting type. These events may have been generated by lateral bending of the oceanic plate. The Kunisaki peninsula earthquake of August 26, 1983 ($M=6.8$, $h=116$ km), which was the largest upper-mantle earthquake in this region, shows a reverse fault type mechanism. Comparisons between the observed and synthetic seismograms suggest that the southeastward dipping nodal plane may be the fault plane, and that the rupture propagated northwest-upwards. The seismic moment was estimated to be $M_0=1.13\times10^{26}$ dyn·cm. The focal mechanism of three upper mantle earthquakes inland of Kyushu, including the Kunisaki peninsula earthquake, suggests that they may have been caused under the stress regime of down-dip extension. The tensional stress working southwest-downwards at intermediate depths in the Suonada and inland Kyushu regions may be explained by the gravitational pull acting on the Philippine Sea plate subducting deeper southwestwards.

1. *Introduction*

In recent years the tectonics of southwestern Japan have been extensively studied in relation to the subduction of the Philippine Sea plate beneath this region. It has been found from the distribution of subcrustal earthquakes and the travel-time analysis that the configuration of the subducting Philippine Sea plate are quite complex (SHIONO, 1974; MIZOUE, 1977). HIRAHARA (1981) has revealed a more detailed three-dimensional seismic velocity structure of the subducting plate using an inversion technique. It was found from these investigations that the plate appears remarkably distorted beneath the eastern Shikoku

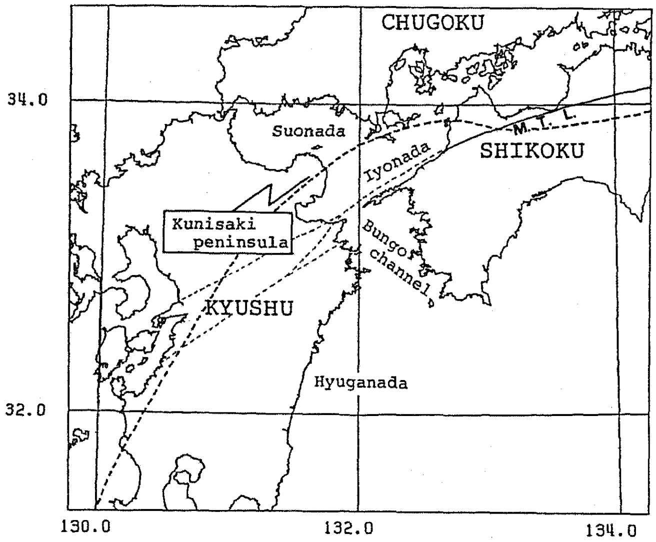


Fig. 1. Index map around the regions mentioned in the present study. A thick broken line indicates the approximate location of the leading edge of the Philippine Sea plate. Thin solid and broken lines indicate the Median Tectonic Line and its westward extension, respectively.

region, and the western Shikoku to the eastern Kyushu regions. The approximate location of the leading edge of the Philippine Sea plate beneath this region is shown by a thick broken line in Fig. 1.

On the other hand, SHIONO (1977) suggested that the stress state in southwestern Japan may be classified into three categories on the basis of the locations of hypocenters and focal mechanisms of crustal and upper mantle earthquakes taking place there. One is the northwestward compressional stress working at shallow depths along the Nankai trough and in the Hyuganada region, which is inferred from low-angled thrust faulting earthquakes. The stress state at subcrustal depths over an extensive region from the southern Chubu region to the Iyonada, northwestern Shikoku are characterized by systematic alignments of the tensional axis parallel to the leading edge of the subducting Philippine Sea plate (parallel extension). SHIONO (1977) and SHIONO *et al.* (1980) also found that the tensional axis dips westwards and is approximately parallel to the dip of an inclined seismic zone under the Kyushu Island and the northern Ryukyu arc. In the inland Kyushu region, on the other hand, tensile stress working in an N-S direction appear to prevail at a shallow crust, in view of the focal mechanism with normal faulting type of relatively large earthquakes in central Kyushu (YAMASHINA and MURAI, 1975). Recent geodetic triangulation surveys also indicate that extensional strains in the N-S direction dominate the region (TADA, 1983; GEOGRAPHICAL SURVEY INSTITUTE, 1984). HASHIMOTO (1982, 1984) attempted to model these complicated stress fields observed in southwestern Japan by applying a three-dimensional finite element method, and suggested that the extensional stress parallel to the leading edge of the plate may be caused either by the negative buoyancy acting on the distorted subducting plate, or by possible asthenospheric flows underneath the plate.

From these studies, it has been shown that local and even regional stress patterns may be closely related to the three-dimensional configuration and structure of the subducting Philippine Sea plate. Among them, the leading edge of the plate appears to play an important role in generating the complicated stress field,

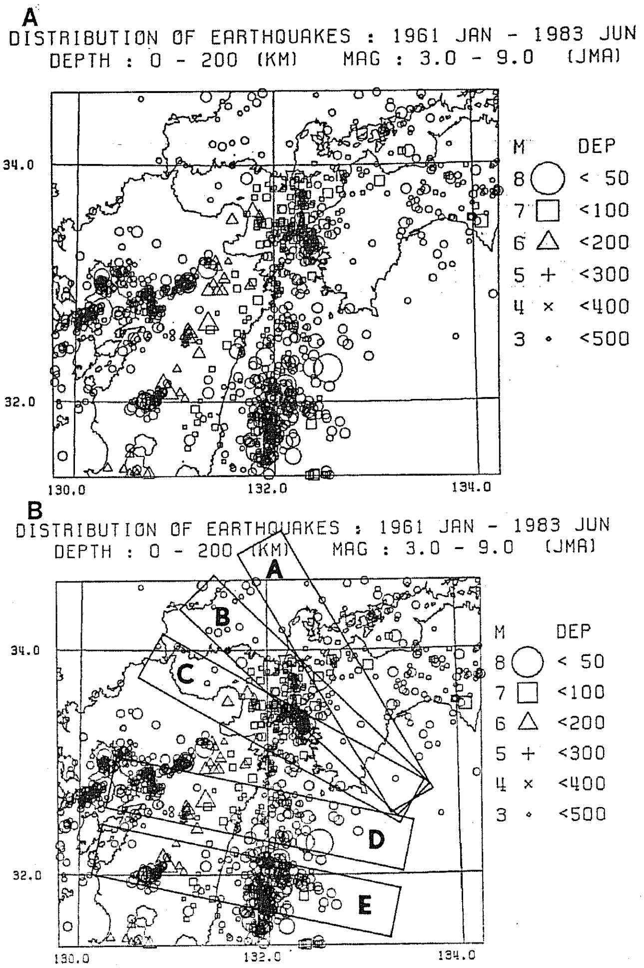
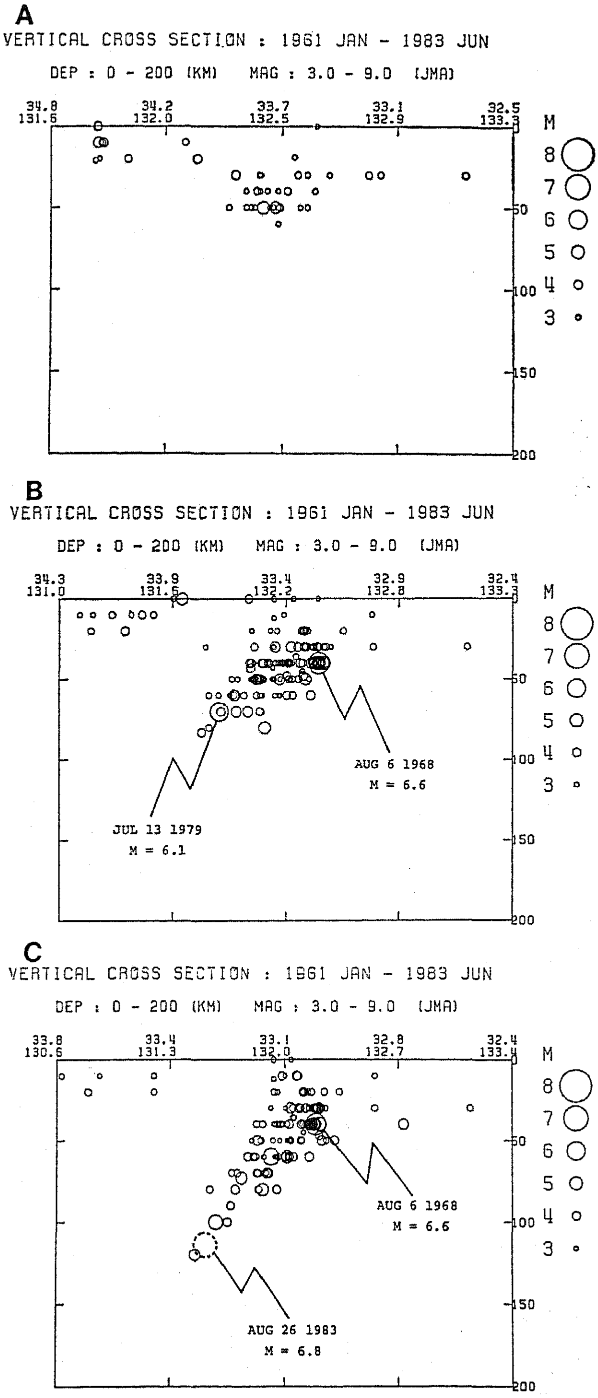


Fig. 2. A. Epicentral distribution of earthquakes in the western Shikoku to Kyushu regions during the period from January, 1961 to June, 1983, based on the Monthly Seismological Bulletin of JMA. Different symbols and sizes indicate their focal depths and magnitudes respectively. B. Index map for the distribution of earthquakes within five areas A–E.


A
VERTICAL CROSS SECTION : 1961 JAN - 1983 JUN
DEP : 0 - 200 (KM) MAG : 3.0 - 9.0 (JMA)
34.8 131.6
34.2 132.0
33.7 132.5
33.1 132.9
32.5 133.3
0
50
100
150
200
M
8
7
6
5
4
3
B
VERTICAL CROSS SECTION : 1961 JAN - 1983 JUN
DEP : 0 - 200 (KM) MAG : 3.0 - 9.0 (JMA)
34.3 131.0
33.9 131.6
33.4 132.2
32.9 132.8
32.4 133.3
0
50
100
150
200
AUG 6 1968
M = 6.6
JUL 13 1979
M = 6.1
M
8
7
6
5
4
3
C
VERTICAL CROSS SECTION : 1961 JAN - 1983 JUN
DEP : 0 - 200 (KM) MAG : 3.0 - 9.0 (JMA)
33.8 130.6
33.4 131.3
33.1 132.0
32.8 132.7
32.4 133.4
0
50
100
150
200
AUG 6 1968
M = 6.6
AUG 26 1983
M = 6.8
M
8
7
6
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4
3

Fig. 3.

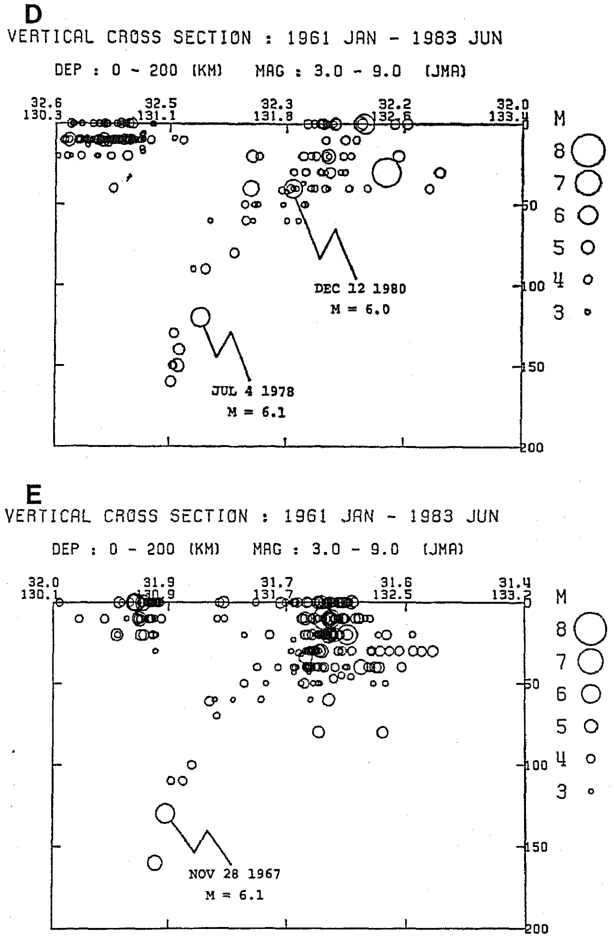


Fig. 3. A–E. Vertical cross sections, in which earthquakes in the area enclosed by rectangles in Fig. 2B are projected with no vertical exaggerations onto the vertical plane striking in the direction of the longer side of each rectangle. Focal depths of earthquakes have been determined every 10 km before 1982 and every 1 km after 1983.

particularly in the extreme northwest part of southwestern Japan covering the western Shikoku to northeastern Kyushu region, since this region is close to the corner of the laterally bending Philippine Sea plate. In fact, SHIONO and MIKUMO (1975) suggested that the Bungo channel earthquake of August 6, 1968 (M=6.6, h=45 km) was generated by the tensional stress working in an E-W direction, which may arise from internal deformations at the bottom of the continental lithosphere probably due to laterally bending of the oceanic plate or gravitational drag of the plate down- and northwestwards. The northeastern part of Kyushu, including the Suonada and Kunisaki peninsula, has been seismically rather inactive area, in contrast to the Bungo channel and Iyonada, and few detailed studies have been made so far on the earthquake source mechanism and its tectonics. In this region, however, two relatively large earthquakes occurred in the past five years; one was the Suonada earthquake of July 13, 1979 with a magnitude 6.1 (33.85°N, 132.05°E, h=70 km) and the latest one was the Kunisaki peninsula earthquake of August 26, 1983, northeastern Kyushu, with a magnitude of 6.8 (33.55°N, 131.61°E, h=116 km).

The purpose of the present paper is to make clear the stress regime in the region from Suonada to central Kyushu on the basis of the faulting mechanisms of the above two major earthquakes and several other subcrustal and upper mantle earthquakes with magnitudes greater than 6.0. Finally, we discuss tectonic implications of the obtained stress field in relation to the subducting Philippine Sea plate.

2. *Seismicity*

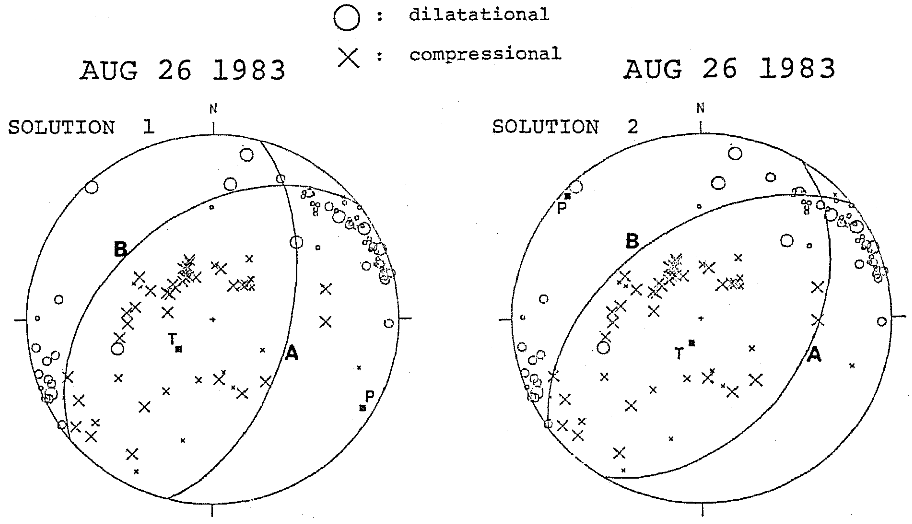
Epicentral distribution of earthquakes with magnitudes greater than 3 that occurred in the northern to central Kyushu region during the period from January 1961 to June 1983 is shown in Fig. 2A, which is based on the Seismological Bulletin of the JMA. Different symbols and sizes indicate their focal depths and magnitudes, respectively. The focal depths have been determined by JMA at every 10 km for the period before 1982, while their accuracy increased to every 1 km after 1983. It is immediately clear that shallow earthquakes are active in central Kyushu, indicating a clear lineation along a belt-like tectonic zone which is a westward extension of the Median Tectonic Line running through the northern Shikoku region. Very shallow earthquakes are also active in the Hyuganada region, while relatively deep shocks with depths ranging from 50 to 100 km are active in the Bungo channel-Iyonada region. The focal depths of these shocks become deeper from Hyuganada to inland Kyushu, which forms a westward dipping Wadati-Benioff zone. The deepest shocks are located at depths around 160 km.

For better understanding of seismic activity at different depths, all shocks in this region are grouped into five rectangle areas, regions A–E, as shown in Fig. 2B, and projected onto a vertical cross section striking in the direction of their longer side (Figs. 3A–E). These cross sections have been taken perpendicularly to iso-depth curves of subcrustal earthquakes suggested by MIZOUE (1977) and SHIONO (1977). It is obvious that the focal depths of the deepest earthquakes increase from the northern to southern region. It may also be seen that the dip of the Wadati-Benioff zone becomes abruptly steeper at depths around 50–70 km, particularly in sections C, D, and E, and that the seismicity at these depths is quite low, as have been pointed out by SHIONO *et al.* (1980). Figure 3C (cross section C) includes the hypocenter of the August 26, 1983 Kunisaki peninsula earthquake (M=6.8, h=116 km), with a dotted circle, while the Suonada earthquake of July 13, 1979 is included in Fig. 3B. It appears that these two events occurred at the deepest portion of the Wadati-Benioff zone beneath these regions.

Next, we will discuss the faulting mechanism of several subcrustal and upper mantle earthquakes with magnitudes 6.0–6.8 indicated by arrows in Figs. 3A–E.

3. *Faulting Process of the August 26, 1983 Kunisaki Peninsula Earthquake*

A relatively strong earthquake with a magnitude of 6.8 occurred under the Kunisaki peninsula in northeastern Kyushu (33.55°N, 31.61°E, h=116 km) on August 26, 1983. This was followed by only small numbers of aftershocks. This region has usually low seismicity, and these earthquakes occurred at the deepest portion of the Wadati-Benioff zone as described in the above section. The radiation pattern of P waves from this event is shown in Fig. 4, on the lower hemisphere of an equal area projection, where circles and crosses indicate dilatational and compressional initial motions, respectively, and large, medium and small symbols indicate impulsive, intermediate and emergent onsets, respectively. In this projection, we use the P-wave first motions recorded on the vertical com-



	PLANE-A	PLANE-B
dip direction	105°	320°
dip angle	56°	42°

	PLANE-A	PLANE-B
dip direction	123°	323°
dip angle	42°	50°

Fig. 4. Radiation pattern of P-wave first motions from the Kunisaki peninsula earthquake of August 26, 1983, and its fault plane solutions projected onto the lower hemisphere of equal area projection. Circles and crosses indicate dilatational and compressional waves respectively, and large, moderate and small symbols indicate impulsive, intermediate and emergent onsets, respectively. The P- and T-axes are also shown. There are two possible solutions, called solutions 1 and 2. A and B are two nodal planes.

ponent of long-period seismograms at WWSSN, DWWSSN, and Canadian Seismograph Network stations, and also JMA 59-type and 61-type seismograms at JMA stations. To calculate the emergent angle of seismic rays leaving from the focus, we use the JMA standard model as an average crust-mantle structure, which has the same profile as that of ICHIKAWA and MOCHIZUKI (1971) for depths less than 35 km and that of JEFFREYS (1939) for depths over 96 km. Since several inconsistent signs for nearby stations are included in the above projection, there could be two possible fault plane solutions as shown in Fig. 4, and we call them solutions 1 and 2. Solution 1 is similar to the solution given by DZIEWONSKI *et al.* (1984). For each solution, we denote the southeastward dipping nodal plane by plane A and the northwestward dipping one by plane B. In the present earthquake, however, we cannot identify the fault plane from these two nodal planes due to insufficient number of aftershocks observed.

Direct P, pP, and sP waves from the main shock have been clearly recorded on the long-period seismograms at a number of WWSSN stations. The vertical component seismogram at COP ($\Delta=77.2°$, $\varphi=329.5°$) is shown, as an example, at the top of Fig. 5. A very narrow pulse width of pP wave is a characteristic feature of the record at this station, and this is also the case for stations located at almost the same epicentral distances and azimuths as those for COP.

To elucidate the source process of the main shock, we compute synthetic seismograms for 13 stations at teleseismic distances, and then compare them with the corresponding records. The method of computing the synthetic seismograms is the same as in MIKUMO (1969), except that we calculated not only direct P waves, but also included pP and sP waves and then summed them with appropriate phase delays. The mantle transfer function, crustal response and instrumental response are all involved in this calculation. The mantle transfer function has been computed by the product of geometrical spreading and attenuation, with the JMA standard model as the velocity structure and Model 11 of MIKUMO and KURITA (1968) as the Q model. For the portion of sP waves which travel as S waves, we assumed two relations $V_P/V_S=\sqrt{3}$, and $Q_P/Q_S=9/4$.

The lack of sufficient number of aftershocks makes it difficult to specify the fault plane and to estimate the source dimension of the main shock event. For this reason, we assume a number of combinations of the source parameters rather arbitrarily in computing the synthetic seismogram, and then search for the best fit of the synthetics to the corresponding records to estimate their parameters.

We assume a finite moving dislocation source with unilateral faulting over a rectangular surface, as in MIKUMO (1969). The fault length L and width W are fixed as 10 km and 5 km, respectively, which are only crude estimates from the distribution of several aftershocks (SHIRAKI MICROEARTHQUAKE OBSERVATORY, 1984). The rupture front is assumed to propagate in the direction parallel to the fault length with a finite velocity V_R. We computed a number of synthetic seismograms with two possible fault plane solutions (solutions 1 and 2) for various rupture velocities, rise times, directions of rupture propagation, and source depths.

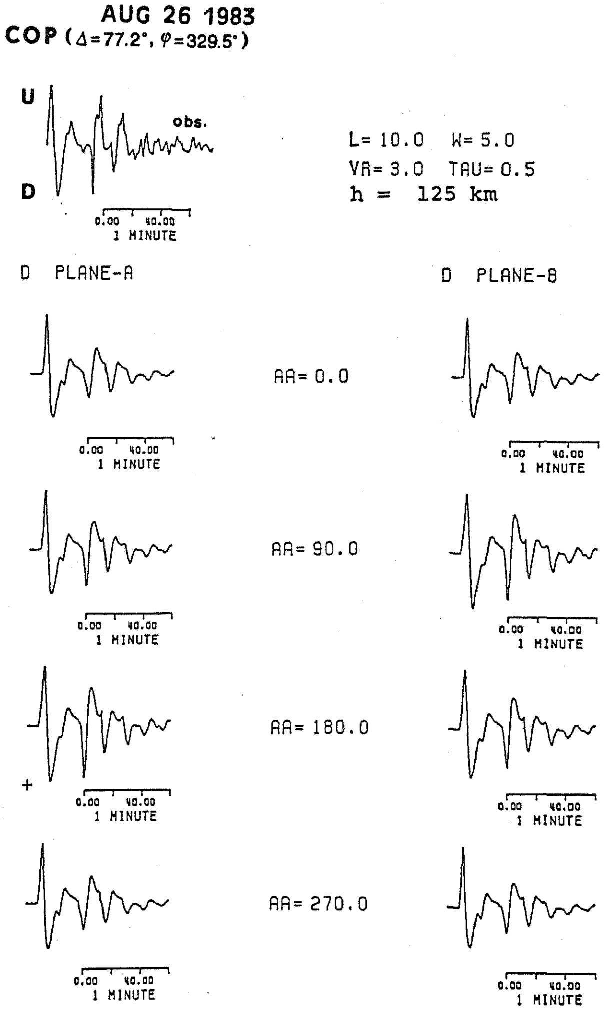


Fig. 5. Long-period seismogram (vertical component) of the August 26, 1983, Kunisaki peninsula earthquake recorded at COP ($\Delta=77.2°$, $\varphi=329.5°$) (uppermost trace) and the synthetic seismograms calculated with two possible fault planes and variously assumed directions of the rupture propagation (lower traces). Each trace is normalized to have the same maximum amplitude.

The results suggest that solution 1 could better explain the observed records than solution 2, and that an assumed source depth of 125 km may be suitable to explain the observed time interval between the onsets of direct P and pP waves, if we refer to the velocity model adopted here. From these results, we adopted solution 1 as an appropriate fault plane solution for the present earthquake. The next step is to estimate more closely the direction of rupture propagation on either of two nodal planes (planes A and B shown in Fig. 4) in solution 1 with a

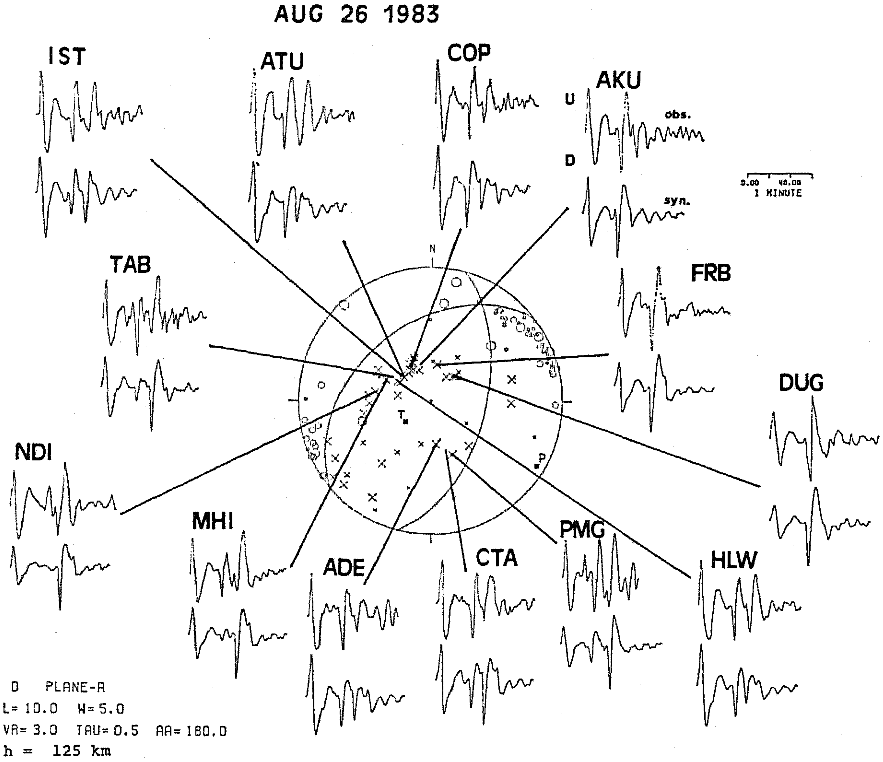


Fig. 6. Observed records (upper trace) from the August 26, 1983, Kunisaki peninsula earthquake (solution 1) and the synthesized seismograms (lower traces) at WWSSN and Canadian Seismograph Network stations at teleseismic distances. Each trace is normalized to have the same maximum amplitude.

fixed rupture velocity of 3.0 km/s and a rise time of 0.5 s, respectively. These results are shown in Fig. 5. All traces have been normalized to have the same maximum amplitude. Notation AA indicates the direction of the rupture propagation measured clockwise from the slip direction on the assumed fault plane, which is defined here as the direction of motion of the lower block relative to the upper block. From Fig. 5, it appears that the observed records can be best explained by the synthetic seismograms when AA is taken to be nearly 180° on plane A. Although there are some other possible solutions, for example, a solution with AA=90° on plane B, close examinations show that the relative amplitudes of direct P, pP, and sP waves and very sharp onsets of pP wave of the observed records favor the former solution. This means that the southeastward dipping nodal plane should be the fault plane, and that the rupture appears to have initiated at the deepest portion of the fault plane and propagated northwest-upwards. The strike of the presumed fault plane is nearly perpendicular to the moving direction of the Philippine Sea plate, and its dip obliquely encounters the

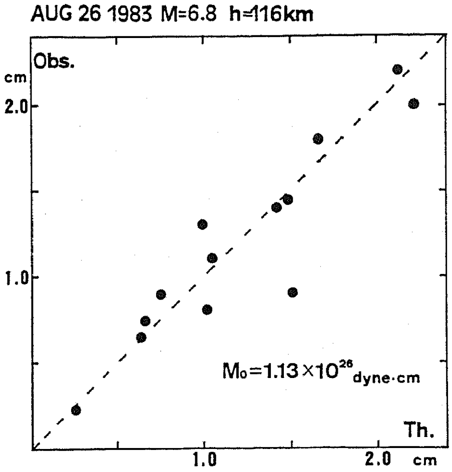


Fig. 7. Observed and calculated amplitudes of the first half-cycle of P waves. The seismic moment is found to be $M_0 = 1.13 \times 10^{26}$ dyn·cm.

inclination of the plate at this depth. This feature seems to suggest that a high-angled thrust faulting occurred within and near the upper boundary of the subducting plate in such a way that the end portion of the plate was pulled down by a down-dip tensional stress. Comparisons between the observed records (upper) at 12 WWSSN stations and one Canadian Seismograph Network station (FRB) and the corresponding synthetic seismograms (lower) computed with the estimated parameters are shown in Fig. 6. All traces have been normalized to have the same maximum amplitude. It may be seen that the synthetic waveforms at these stations agree reasonably well with the corresponding records, except for some cases (e.g., NDI).

To determine the seismic moment M_0 of this earthquake, the observed and computed amplitudes of the first half cycle of P waves are directly compared in Fig. 7. Although there exist some scattered plots from a mean straight line, this comparison yields the average seismic moment of 1.13×10^{26} dyn·cm. If we adopt the fault dimension of 10 km × 5 km as assumed above and rigidity of 0.68×10^{12} dyn/cm^2, the average fault displacement is estimated to be about 3.3 m, and the stress drop 325 bar using the formula by CHINNERY (1969). The estimated stress drop appears to be within a reasonable range, in view of the empirical relationship between the stress drop and focal depths of intermediate and deep-focus earthquakes (MIKUMO, 1971), although the present calculation depends on the assumed source dimension.

4. Focal Mechanism of Several Other Subcrustal and Upper Mantle Earthquakes

In addition to the 1983 Kunisaki peninsula earthquake, the focal mechanisms of four other earthquakes with magnitudes around 6.0 were determined here, using JMA data together with data from the Monthly Bulletin of the International Seismological Center (ISC). The focal coordinates have been taken from seismological catalogues of JMA. We again refer to the JMA standard model to estimate the emergent angle at source, as in the previous case. The focal mechanism solutions determined for the four earthquakes are shown on the lower hemisphere of an equal area projection in Fig. 8, and also listed in Table 1 together with the solutions for the other two earthquakes. Figure 9 shows the simplified mechanism diagrams of all the earthquakes treated in this paper. Solid and open

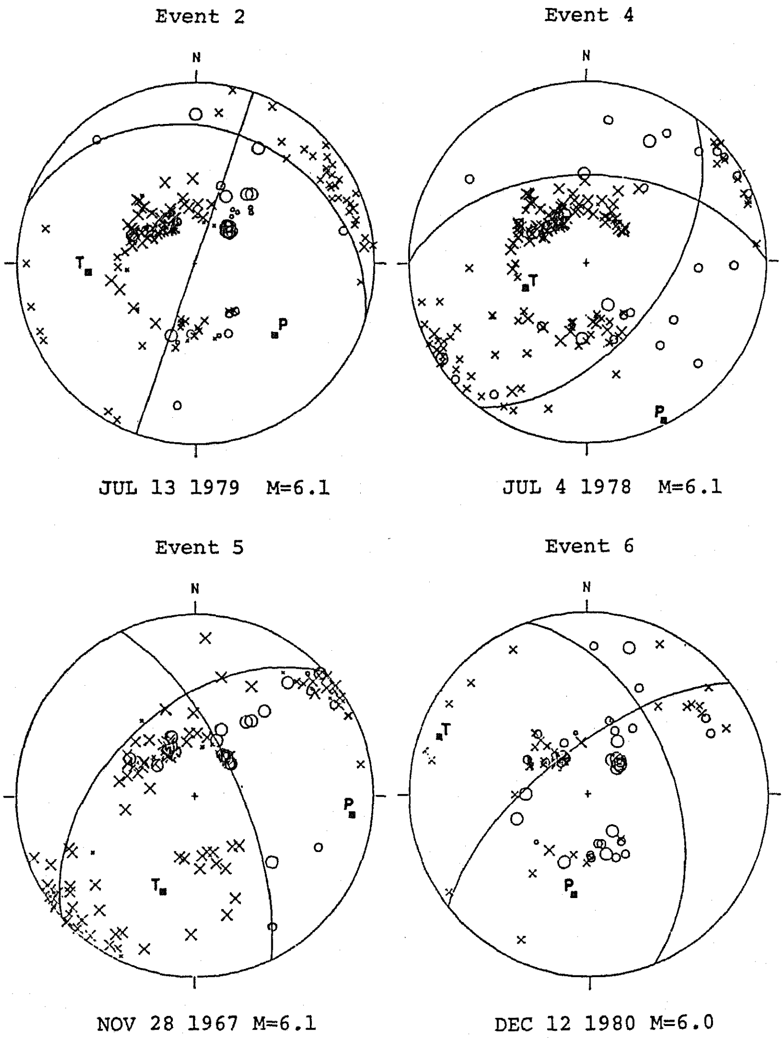


Fig. 8. Mechanism diagrams newly determined in the present study. Symbols and projection are explained in the text.

Table 1. Focal mechanism parameters of shocks Nos. 1–6.

No.	Date	Depth (km)	M	P-axis		T-axis		Plane 1		Plane 2		Ref.
				strike (°)	plunge (°)	strike (°)	plunge (°)	D.D. (°)	D.A. (°)	D.D. (°)	D.A. (°)	
1	Aug. 6 1968	40	6.6	147	55	273	22	55	32	293	70	SM
2	Jul. 13 1979	70	6.1	131	40	265	39	109	90	19	26	*
3	Aug. 26 1983	116	6.8	121	6	230	70	105	56	320	42	*
4	Jul. 4 1978	120	6.1	154	3	248	60	127	54	0	50	*
5	Nov. 28 1967	130	6.1	97	12	198	44	65	70	317	50	*
6	Dec. 12 1980	40	6.0	189	44	291	12	69	50	322	70	*

D.D., dip direction; D.A., dip angle; Reference: *, new solution; SM, SHIONO and MIKUMO (1975).

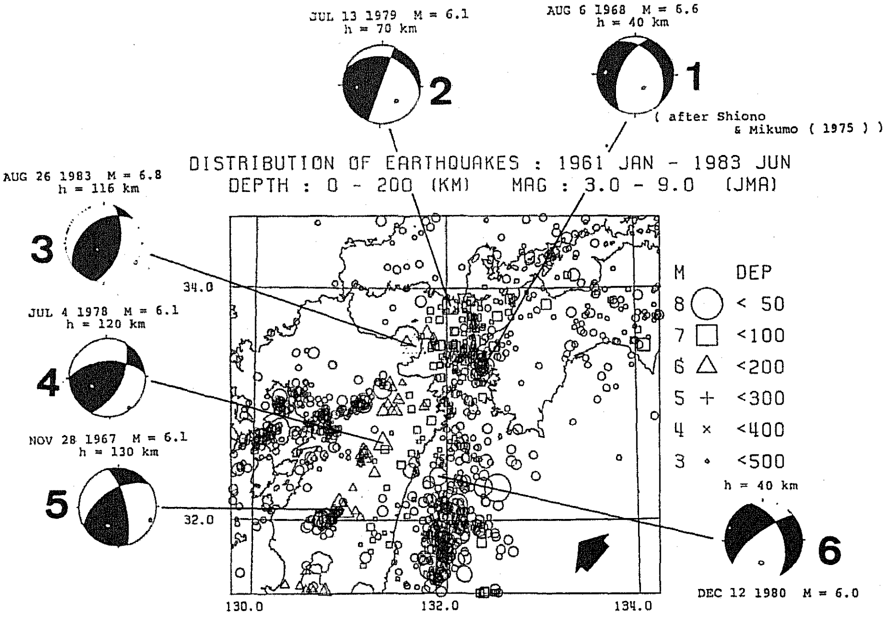


Fig. 9. Simplified mechanism diagrams (lower hemisphere) of subcrustal and upper-mantle earthquakes in the region concerned. Solid and open quadrants correspond to compressional and dilatational ones, respectively. Small circles in the solid and open quadrants indicate the position of T- and P-axes, respectively. A solid arrow shows the moving direction of the Philippine Sea plate relative to the Eurasian plate, which is N50°W (SENO, 1977).

quadrants in the diagram show compressional and dilatational ones, and small open circles in the solid and open quadrants indicate the locations of T- and P-axes, respectively. The focal mechanisms of the Kunisaki peninsula earthquake of August 26, 1983 (event 3) determined in the foregoing section, and of the Bungo channel earthquake of August 6, 1968 (event 1) determined by SHIONO and MIKUMO (1975), are also included. A solid arrow in the map indicates the direction of the motion of the Philippine Sea plate relative to the Eurasian plate in this region, which is N50°W (SENO, 1977).

Event 1, the 1968 earthquake ($M=6.6$, $h=40$ km) with a normal faulting mechanism (SHIONO and MIKUMO, 1975), took place in the Bungo channel located in the western Shikoku region. SHIONO (1974) and SHIONO and MIKUMO (1975) suggested that this earthquake occurred just above the interface between the continental and oceanic plates and that it was generated by internal deformations of the bottom of the continental lithosphere, due to lateral bending of the subducting plate. HIRAHARA's analysis (1981) using a three-dimensional inversion technique reveals a high velocity layer indicating the Philippine Sea plate subducting beneath the present region, as reproduced in Fig. 10. Profiles D and E in his paper roughly correspond to sections B and D in Fig. 2B, respectively.

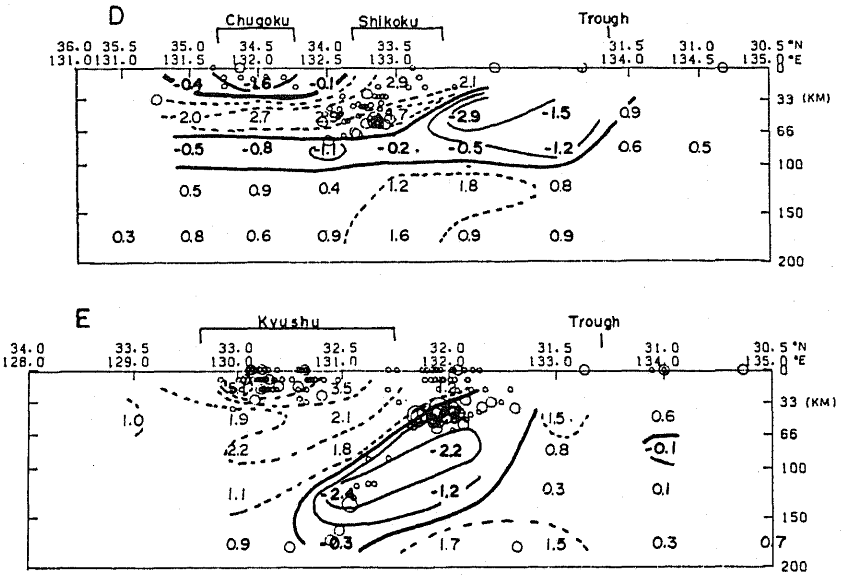


Fig. 10. Slowness perturbations and hypocenters of earthquakes by the ISC projected onto the vertical cross section along profiles D and E (after HIRAHARA, 1981), which correspond roughly to sections B and D in Fig. 2B, respectively.

His results also suggest that the 1968 earthquake occurred above the subducting plate. We refer to the three-dimensional seismic velocity structure in discussing the focal mechanism of events 2–6.

The Suonada earthquake (event 2 in Fig. 8; M=6.1, h=70 km) occurred northwest of the Bungo channel earthquake, as shown in Fig. 9, indicating a normal faulting mechanism. This event is included in section D in Fig. 10. In other words, it appears that this event also occurred just above the top portion of the laterally bending oceanic plate. Under the regions of Shikoku and between Shikoku and Chugoku, earthquakes take place within the continental Eurasian plate as discussed in HIRAHARA (1981). It may be reasonable to conclude that the Suonada earthquake occurred just above the interface between the subducting Philippine Sea plate and the continental Eurasian plate, and that this shock was also generated by the same mechanism as in the case of the Bungo channel earthquake.

Event 6 (M=6.0, h=40 km) occurred in the Hyuganada region, which is included in section E in Fig. 10. The vertical cross section shows that shallow seismicity is very active around the upper boundary of a high velocity zone. A number of large thrust-type earthquakes frequently take place seaward there due to the underthrusting of the Philippine Sea plate. Event 6 occurred landward of these earthquakes at a slightly deeper depth. It is not certain, however, whether event 6 occurred within or above the subducting Philippine Sea plate, although it is located around the interface between the continental and oceanic plates. This earthquake shows a normal fault type mechanism, which is entirely different from the low-angled, thrust-type earthquakes that occurred seaward in the Hyuganada region. In this region, the subducting oceanic plate does not laterally bend, but its dip appears to change quite sharply around depths of 50–70 km (Fig. 3D). For this reason, it is possible that this earthquake might have been generated by tensional stress working on the bottom of the continental lithosphere or the top of the oceanic lithosphere, in the direction parallel to the subduction of the Philippine Sea plate.

Events 4 and 5 occurred in section E in Fig. 10, which indicates that the two intermediate-depth earthquakes took place within the high velocity zone corresponding to the subducting plate. Event 3 (1983 Kunisaki peninsula earthquake) occurred in the same situation as events 4 and 5, as seen in the vertical cross section C (Fig. 3C). These three events, which occurred in northern Kyushu with intermediate depths (h=110–130 km), have high-angled thrust-type mechanisms, indicating that they were generated under the stress regime of down-dip extension caused by negative buoyancy acting on the deeper part of the downgoing slab (e.g., ISACKS and MOLNAR, 1971).

5. *Tectonic Features of the Northern to Central Kyushu Region*

Figure 9 shows that the P- and T-axes derived from subcrustal and upper mantle earthquakes in this region indicate some systematic features. These axes

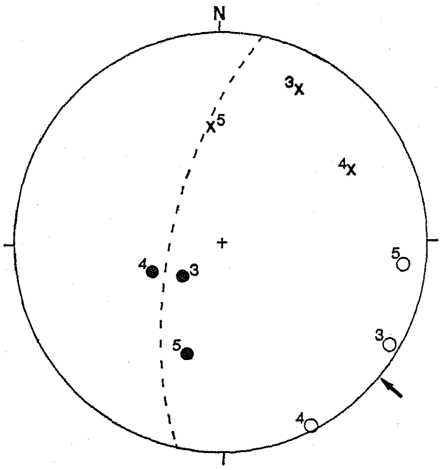


Fig. 11. Equal-area projection (lower hemisphere) of the P- (open circles), T- (solid circles), and B- (crosses) axes. Broken curve indicates the dip and strike of the Philippine Sea plate subducting deeper than 100 km beneath the Kyushu region, and an arrow indicates the direction of the motion of the Philippine Sea plate relative to the Eurasian plate.

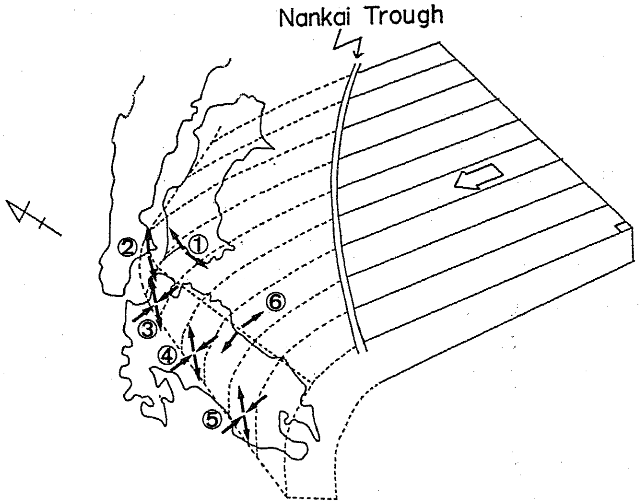


Fig. 12. A schematic illustration explaining the tectonic stress field beneath the Kyushu region, inferred from the faulting mechanisms of subcrustal and upper mantle earthquakes.

for events 3–5 are shown in Fig. 11. The stress patterns together with some features of the subducting Philippine Sea plate are schematically illustrated in Fig. 12. The T-axes for events 2–5 are systematically aligned southwest-downwards. These features imply that the subcrust and upper mantle beneath the northern to central Kyushu region are strongly subjected to tensional stress. It is evident from cross-sectional seismicity maps along profiles A–E given in Figs. 3A–E that the focal depths of the deepest earthquakes increase steeply from the northeast to southwest profile, as has been pointed out by SHIONO *et al.* (1980), indicating that the Philippine Sea plate is subducting deeper in southwestern Kyushu (about 150 km) than northeastern Kyushu (about 50 km). The difference in the penetration depth of the subducting oceanic plate will yield a southwest-downward pull due to negative buoyancy acting on the excess mass of the slab in the southwest region, and hence could explain the systematic alignment of the T-axes. Although event 2 appears to have taken place within the continental lithosphere, a strong coupling between the oceanic and continental lithospheres will produce this systematic pattern of the T-axes also for the event. On the other hand, the strikes of the P-axes for events 1–5 are almost parallel to the moving direction of the Philippine Sea plate relative to the Eurasian plate. The alignment might suggest that compressional stress in this region is dominated by the motion of the Philippine Sea plate. HASHIMOTO (1984) made a detailed finite element modeling study to explain the complex three-dimensional stress field beneath the Kyushu region, incorporating several possible loads such as slab pull and ridge push forces, asthenospheric flows, and positive buoyancies acting on a low-density crust, back-arc basin, and an aseismic ridge. One of his results clearly shows that the down-dip tensional stresses working in the deeper portion of the subducting Philippine Sea plate may be caused mainly by a slab pull force. This provides a reasonable explanation for the faulting mechanisms of events 3–5. It has also been shown in HASHIMOTO (1984) that a nearly horizontal tensile stress will be generated from possible asthenospheric flows in a gently-dipping portion of the subducting Philippine Sea plate in the direction parallel to that of the motion of the plate, particularly on the oceanic side of the eastern Kyushu region. This may be another possible explanation for the normal faulting mechanism of event 6, if this earthquake occurred within the oceanic plate. In this case, however, shear stresses are concentrated near the bending portion of the downgoing slab. This may not well explain the observed seismicity which takes place even below this portion. For this point, a different explanation would be required.

6. *Concluding Remarks*

In the present paper, we have investigated tectonic features of the northeastern Kyushu region on the basis of seismicity and source mechanism of subcrustal and upper mantle earthquakes there.

The August 26, 1983 Kunisaki peninsula earthquake was one of the deepest and largest upper mantle earthquakes in northeastern Kyushu with high-angled thrust type mechanism. Close comparisons between the observed and synthetic seismograms at a number of teleseismic stations indicate that the southeastward dipping nodal plane may be the fault plane and that the rupture may have propagated unilaterally northwest-upwards from the deepest portion of the fault plane. The seismic moment is estimated as $M_0=1.13\times 10^{26}$ dyn·cm, although some ambiguity remains.

Two subcrustal earthquakes, the 1968 Bungo channel and the 1979 Suonada earthquakes, indicate normal faulting type mechanisms. One possible interpretation is that these events may have been generated under the stress regime caused by internal deformations of the bottom of the continental lithosphere due to lateral bending of the subducting Philippine Sea plate. A subcrustal event in the Hyuganada region also indicates a normal faulting mechanism, but it may have been caused by tensile stress due to an abrupt increase in the dip angle of the subducting plate. Upper mantle earthquakes in the inland Kyushu region show a high-angled thrust type mechanism, indicating that they are subjected to the down-dip extension due to negative buoyancy acting on the deeper part of the downgoing slab.

The tensional axes for these events, including that of the Kunisaki peninsula earthquake, are systematically aligned southwest-downwards, presumably because the Philippine Sea plate is subducting deeper in the southwest region. The compressional axes for all events except the Hyuganada earthquake (event 6) are almost parallel to the moving direction of the Philippine Sea plate relative to the Eurasian plate.

Table 2. Summary of the tectonics of southwestern Japan inferred from the faulting mechanisms of the subcrustal and upper mantle earthquakes.

	Near the leading edge of the subducting Philippine Sea plate			Along a profile in sections D and E (Fig. 2B)		
Region	southern Chubu │ Iyonada	Bungo channel │ Suonada	Kunisaki peninsula │ southern Kyushu	Hyuganada	east coast of Kyushu	Kyushu inland
Seismicity	shallow (<50 km)	active in the continental lithosphere	deeper in the southern region (<160 km)	shallow (<50 km), active	rather inactive	intermediate depth (<160 km), active
Configuration of the Philippine Sea plate	shallow penetration	abrupt change in the strike of the subducting plate (ENE-WSW→ NNE-SSW)	deeper penetration in the southern region, thicker plate	low-angled subduction	abrupt change in the dip of the subducting plate	high-angled subduction
Stress field (faulting mechanism)	parallel extension (normal slip +strike slip)	nearly horizontal extension due to lateral bending of the subducting plate (normal-slip)	down-dip extension (high-angled thrusting)	nearly horizontally northwestward compression	nearly horizontal extension	down-dip extension
		T-axes have tendency to be aligned southwest-downwards.		(low-angled thrusting	(normal-slip)	(high-angled thrusting)

The essential features of seismicity, the configuration of the Philippine Sea plate, and the stress field derived from the focal mechanism of earthquakes in southwestern Japan are summarized in Table 2.

As discussed above, it thus appears that the faulting mechanisms of the subcrustal and upper mantle earthquakes in the Iyonada, Suonada, and Hyuganada regions and the inland of Kyushu may be explained qualitatively by the three-dimensional configuration and the motion of the subducting Philippine Sea plate. To investigate more detailed stress state in this region, it will be necessary to proceed with more precise hypocentral determination and analyses of the faulting mechanisms.

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The computations involved were made at the Data Processing Center of Kyoto University. We used the hypocentral data of JMA. in the data base "JISHIN" at the Data Processing Center of Kyoto University.

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