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SEISMOLOGICAL STUDY ON THE MEDIAN TECTONIC LINE OF SOUTHWEST JAPAN

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Abstract

Tectonic implications of crustal and subcrustal earthquakes in Southwest Japan are discussed in relation to the faulting activity along the Median Tectonic Line (MTL).

Activity of small crustal earthquakes is high around the active segment of the MTL, and the MTL forms, in a broad sense, a boundary between the seismically active area on the southern side and the aseismic area on the northern side. As these small earthquakes release only small fractions of accumulated strain energy, a quiet zone of historical earthquakes appearing around the active segment of the MTL should be recognized as a seismicity gap indicating a likely site of future large earthquakes.

The shape of the underthrusting slab of the Philippine Sea plate has been derived from distributions of subcrustal earthquakes, high velocity layer and high-Q zone and seems to be closely related to recent faulting activity along the MTL. Spatial relations show that (1) around the active segment of the MTL on the leading edge, the lower tip of the underthrusting slab still remains in the outer side of the MTL but (2) around the segments of low activity the leading edge extends to the inner side across the MTL. This is explained in terms of the decoupling of the outer continental block from the inner one along the MTL.

Introduction

Inland from the zone of convergence between the Asian and the Philippine Sea plates runs the Median Tectonic Line, simply referred as MTL in this paper, on which recent strike-slip movements in right-lateral sense have been proposed first by KANEKO (1966) and later surveyed in detail in Shikoku and the western Kii Peninsula (OKADA, 1968; 1970; 1973; 1980 in the present volume; HUZITA and OKUDA, 1973; OKADA and SANGAWA, 1976 etc.).

According to historical records for about 1,000 years, there have occurred no destructive earthquake directly indicating fault breaks along the MTL. This absence of earthquakes had prevented seismologists for many years from recognizing the potential danger and tectonic significance of the MTL. Geologists and geomorphologists have discovered recent high activity along the MTL since the latter half of 1960's and suggested that the absence of earthquakes might predict the potential danger of future earthquakes instead of safety.

Since the latter half of 1960's, microearthquake observations have been carried out widely in Southwest Japan by many universities, and defined the outline of seismic activity. Research on active faults, including the MTL, has indicated the tectonic significance of the distribution pattern of earthquakes, and led to detections of apparent spatial relations between active faults and zones of high seismicity. The spatial relation has been pointed out for the MTL in the western Kii Peninsula (KANAMORI and TSUMURA, 1971; HUZITA *et al.*, 1973) and in eastern Shikoku (SAWAMURA and KIMURA, 1971; KONOMI, 1976; OKANO *et al.*, 1978). Densely distributed microearthquake

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observation stations have enabled us to determine fault plane solutions of small earthquakes which represent the nature of regional tectonic stress around the MTL (SHIONO, 1970, 1973; KIMURA and OKANO, 1977 etc.).

On the other hand, investigations on the source mechanisms of the great earthquakes along the Nankai trough (FITCH and SCHOLZ, 1971; KANAMORI, 1972b; ANDO, 1975) and on subcrustal earthquakes distributed widely under the Outer Zone of Southwest Japan (SHIONO, 1970; 1973; 1974; 1977; KANAMORI and TSUMURA, 1971; MIZOUE, 1977 etc.) have outlined the present state of plate convergence along the Nankai trough in a framework of global tectonics.

These investigations have deepened our understanding of present-state tectonics around the MTL in both local and global sense. The purposes of this present paper are to summarize the natures of seismic activity and tectonic stress around the MTL and to present a simple model explaining the basic features of recent faulting activity along the MTL in terms of the underthrusting of the Philippine Sea plate.

Although the MTL has a complex history of faulting since its generation at least in the Late Mesozoic (see ICHIKAWA, 1980, in the present volume), the present paper pays special attention to the following two features as basic characteristics of recent activity;

1) Although the MTL as a geologic boundary extends for more than 800 km long from Chubu District to Kyushu separating Southwest Japan into the Inner and the Outer Zones, recent movements are confined within the central segment about 250 km long from the western Kii Peninsual to central Shikoku (see Fig. 1 and OKADA, 1980, in the present volume for example).

2) Recent movements yield an average rate of right-lateral slip about 5–10 mm/yr in central Shikoku (OKADA, 1970) and about 1–2.8 mm/yr in the western Kii Peninsula (OKADA and SANGAWA, 1976). Although the slip rate suggests that faulting along the active segment of the MTL is most active among active faults in Japan (see MATSUDA, 1975; 1976), it should be also noted that the rate is lower by about one order of magnitude than the convergence rate along the Nankai trough of 3.3–4.3 cm/yr proposed by SENO (1978).

Historical Earthquakes

Historical records on destructive earthquakes in Japan date back to A.D. 415 and have been compiled widely (MUSHA, 1951; Imperial Earthquake Investigation Committee, 1904 and 1973; USAMI, 1975). Fig. 1 shows epicenters compiled by USAMI (1978) for destructive earthquakes of magnitude 7.0 and greater. Earthquakes were not necessarily sampled uniformly in both space and time because of unequal distribution of culture and because of imcomplete collection of historical documents. This may be responsible for apparent low seismicity around Kyushu. However, it may be reasonable to consider that earthquakes of magnitudes 7.0 and greater were sampled correctly to some extent in Chugoku, Shikoku, Kinki and Chubu Districts for the last 1,000 years.

As Fig. 1 shows, the most clear feature is a series of great earthquakes of magnitude around 8.0 along the Nankai trough. The last two occurrences were the 1944 Tonankai and the 1946 Nankaido earthquakes, which have been studied in detail and interpreted to represent the underthrusting of the Philippine Sea plate (FITCH and SCHOLZ, 1971; KANAMORI, 1972; ANDO, 1975).

Many earthquakes have occurred inland,

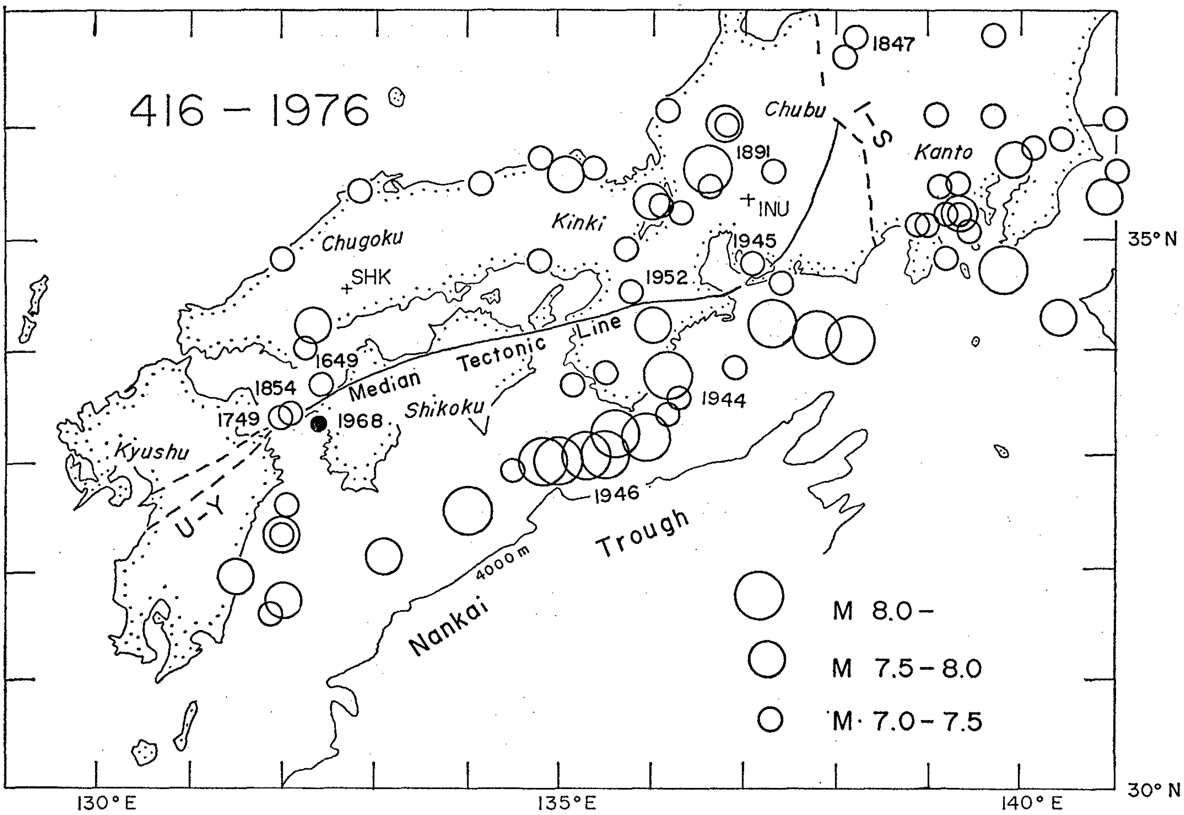

Fig. 1. Distribution of historical large earthquakes of magnitudes 7.0 and greater; After USAMI (1978). Numeral indicates the year of occurrence of the earthquake referred to in the text. The 1968 Bungo Channel earthquake of magnitude 6.6 is shown by a closed circle. The MTL is shown by a solid line. The MTL as a geological boundary, continues to the Utsuki-Yatsushiro line (U-Y) in Kyushu. I-S; Itoigawa-Shizuoka line. The Locations of the Shiraki and Inuyama Micro-earthquake Observatories are shown by cross marks labelled SHK and INU, respectively.

too. Among them, the 1891 Nobi (Mino-Owari) earthquake had the greatest magnitude of 8.4. Although the historical records before the beginning of academic seismology in 1880's reported the occurrence and the effects of destructive earthquakes in various manners, it is only two earthquakes such as the 1847 Zenkoji and the 1854 Iga-Ueno earthquakes that left momumental surface breaks and documents indicating directly the appearance of surface faults (see MATUSDA *et al.*, 1976). Since 1880's, extensive field surveys have been carried out around the source regions, but there have occurred no earthquakes that indicated faulting along the MTL.

We can see in Fig. 1 that five earthquakes occurred around the MTL in 1649, 1749, 1854, 1945 and 1952. However, the 1945 Mikawa earthquake has been considered to result from the thrusting of the Fukozu fault which runs in the north-south direction about 20 km north of the MTL (TSUYA, 1946; IIDA and SAKABE, 1972; ANDO, 1973). The 1952 Yoshino earthquake occurred at depth of 70 km, suggesting that the earthquake represented the subcrustal seismicity discussed later. Three earthquakes around Iyonada, west part of Seto Inland Sea, may be interpreted to represent the subcrustal earthquakes from an analogical inferrence of facts that (1) the 1968 Bungo Channel earthquake, which may be considered to belong to a series of destructive earthquakes in the region, occurred at depth of about 45 km (SHIONO and MIKUMO, 1975) and that (2) present seismicity is extremely low in the crust but active in subcrustal depths of 40–100 km (SHIONO and MASAOKA, 1978).

Even if the above five earthquakes are taken into consideration, it is apparent that a quiet zone of destructive earthquakes appears around the active segment of the MTL from the western Kii Peninsula to central Shikoku (see Fig. 1). SHIMAZAKI (1976) has calculated seismic energy released by historical earthquakes for the last four hundred years in Southwest Japan and has shown that energy greater than that of the 1891 Nobi earthquake seems to be stored in this seismicity gap.

Seismic Activity around MTL

1 Data

Microearthquake observation networks have been operated in the Kii Peninsula since 1964 by the Wakayama Microearthquake Observatory, Earthquake Research Institute of the University of Tokyo and, in central Shikoku since 1967 by the Kochi Earthquake Observatory of Kochi University, and in eastern Shikoku since 1975 by the Tokushima Microearthquake Observatory of Kyoto University. The observational results have been reported in a series of *Wakayama-Bisho-Jishin-Kansokusho-Kiho* (*Quaternary Report of Wakayama Microearthquake Observatory*), *Report of the Kochi Earthquake Observatory*, KONOMI (1976), OKANO *et al.* (1978) and others. The present writer additionally carried out temporary observations at Hashimoto HMT in the central Kii Peninsula (SHIONO, 1978 a,b) and at the Sada-Misaki Peninsula IYJ in western Shikoku (SHIONO and MASAOKA, 1978). The results of microearthquake observations are summarized in Figs. 2 and 3 in a simplified manner. As the figures represent seismicity only for short periods, details should be referred to the above reports.

2 Crustal earthquakes

Although no destructive historical earthquake occurred around the active segment of the MTL, activity of small and microearthquakes is high, especially in the western Kii Peninsula (see Figs. 2 and 3).

KANAMORI and TSUMURA (1971) first mentioned explicitly the fact that the MTL forms a boundary between seismically active area on the southern side and aseismic area on the northern side in the western Kii Peninsula. The feature can be clearly seen in Fig. 3a, which gives the hypocentral distribution in the vertical section. Extremely high activity of small earthquakes has been interpreted, independently, in terms of the existence of weak materials (KANAMORI and TSUMURA, 1971; KANAMORI, 1972a), local stress concentration around the corner bordered by the MTL and the presumed Kii thrust striking in the north-south direction (HUZITA *et al.*, 1973) and densely distributed small scale fault systems. (MIZOUE and NAKAMURA, 1975, 1976).

SAWAMURA and KIMURA(1971), KONOMI (1976) and OKANO *et al.*(1978) have shown the similar feature in eastern and central Shikoku. The contrast of seismicity between the northern and southern sides can be clearly recognized, although crustal earthquakes spread out over the whole area south of the MTL and are not so sharply bounded as in the case of the western Kii Peninsula (see Figs. 2a and 3b).

KISHIMOTO *et al.*(1977) have classified the spatial relation between seismically active area and active faults in Southwest Japan into four groups as follows;

(a) Linear alignment of earthquakes runs along the active fault (e.g. the Yamasaki, the Mitoke and the Atotsugawa faults).

(b) Linear alignment of earthquakes appears within the aftershock zone of a large

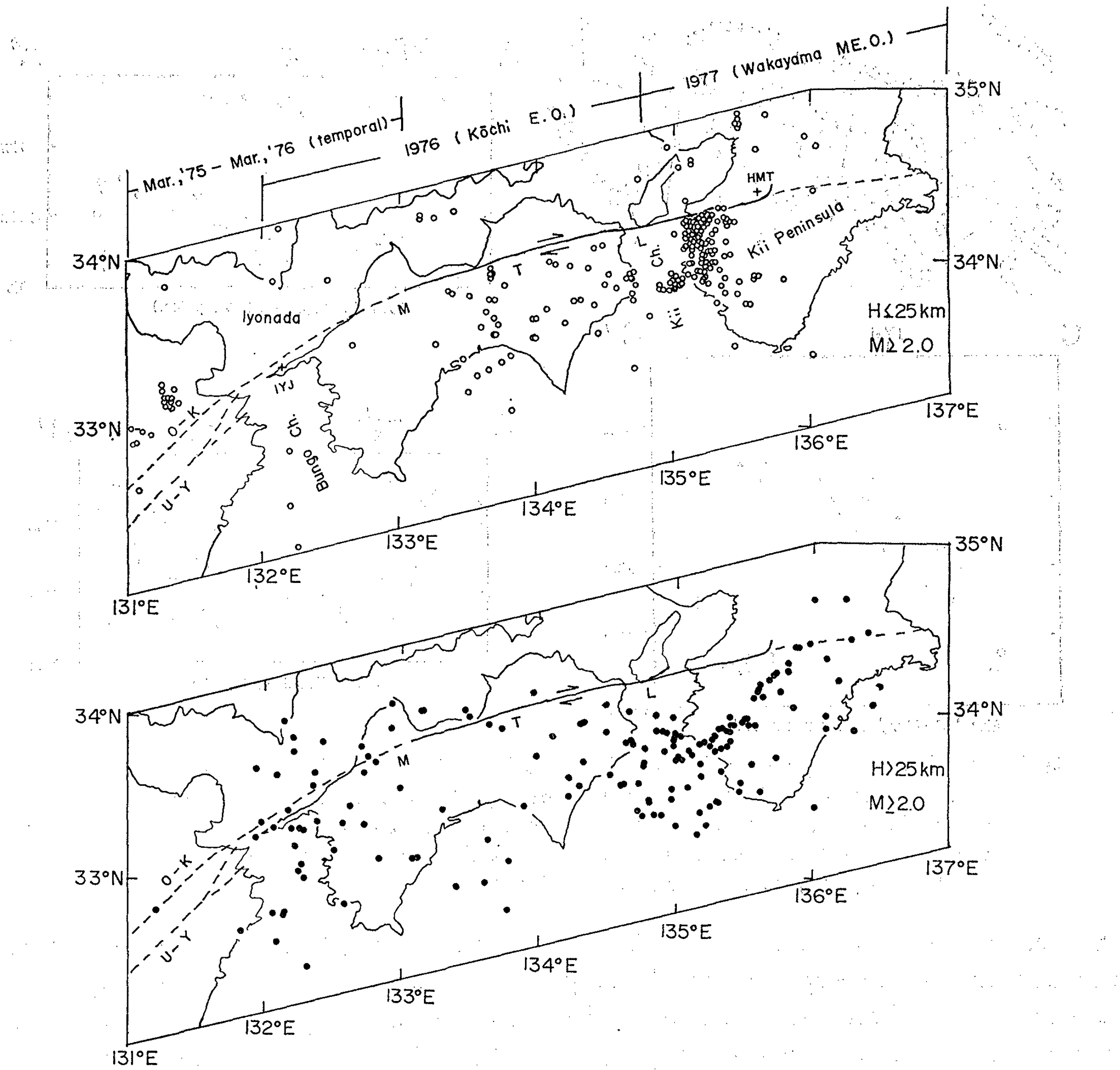

Fig. 2. Distribution of earthquakes with focal depths less than 25 km (above) and greater than 25 km (below) around the MTL. Focal coordinates of earthquakes which occurred around the Kii Peninsula, Shikoku and Iyonada are taken from the *Quaternary Report of Wakayama Microearthquake Observatory, the Report of the Kochi Earthquake Observatory* and SHIONO & MASAOKA (1978), respectively. Note that earthquakes which occurred in different periods are compiled as shown in the upper side of the figure. The MTL segments of high and low activity are shown by solid and broken lines, respectively. HMT and IYJ show locations of temporal microearthquake observation stations referred to in the text.

earthquake (e.g. the Yoshioka-Shikano fault of the 1943 Tottori earthquake, the Gomura fault of the 1927 North Tango earthquake and the Fukui earthquake fault of the 1948 Fukui earthquake).

(c) Active faults form a boundary between seismically active and aseismic areas (e.g. the Arima-Takatsuki Tectonic Line, the Hanaore-Katada fault, the Yanagase fault and possibly the Neodani fault).

(d) Others (e.g. the Atera fault without seismicity and the MTL of which relation to seismicity is unknown).

As mentioned above, it is clear that the active segment of the MTL forms a boundary between the seismically active area on

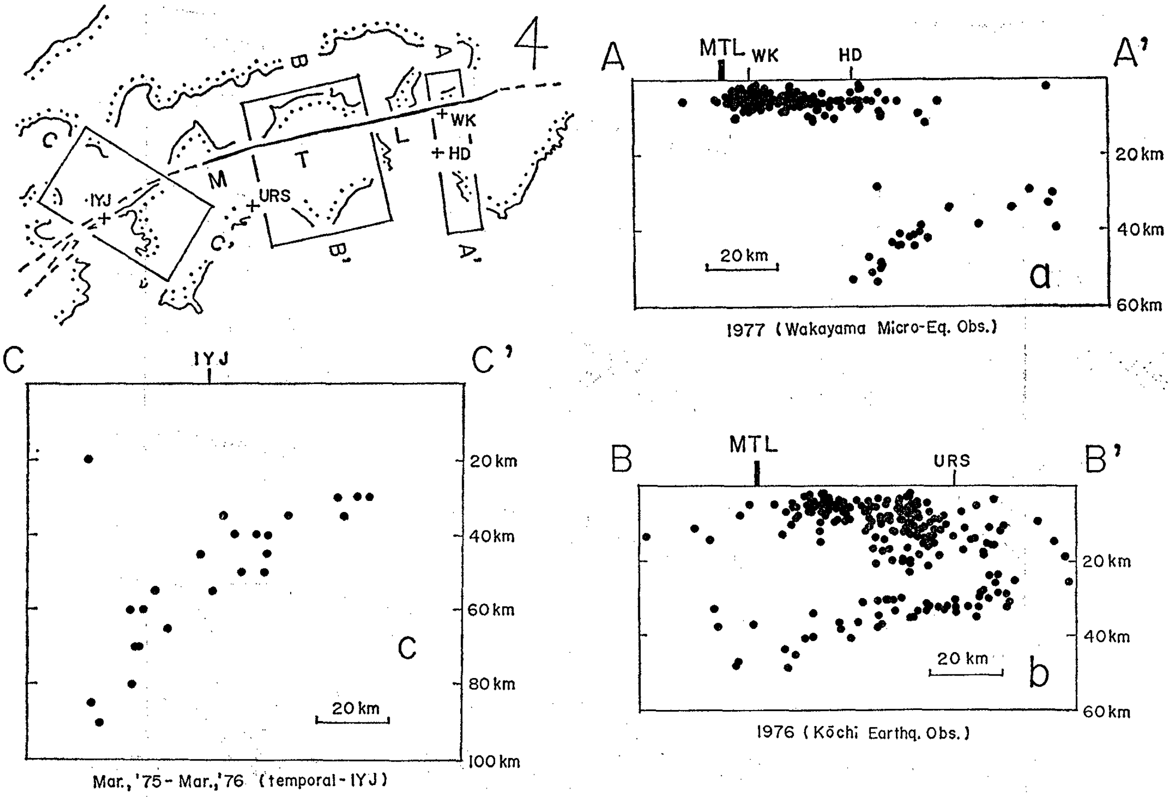

Fig. 3. Distribution of hypocenters in vertical sections for earthquakes which occurred in the area enclosed by solid lines in the figure of upper left side. (a) the western Kii Peninsula (section A-A'), (b) eastern Shikoku (section B-B') and (c) Iyonada (section C-C'). Data sources are as same as in the case of Fig. 2, but earthquakes with magintudes less than 2.0 are included. Sections A-A' and B-B' are nearly normal to the strike of the MTL.

the southern side and aseismic area in the northern side when we ignore low seismicity around the northern Kii Channel. The relation may be classified into a group (c) of KISHIMOTO *et al.*(1977)'s classification, as long as the active segment is concerned.

On the other hand, seismicity is very low around the low active segments of the MTL such as in the central and eastern Kii Peninsula and in western Shikoku. Low seismicity in the central Kii Peninsula has been supported by NAKAMURA and KOIZUMI (1975) and SHIONO (1978a,b). Frequency distribution of S-P times observed at HMT suggests low seismicity within distances of 20 km from HMT (see Fig. 4a). Low seismicity of crustal earthquakes around Iyonada and Bungo Channel has also been supported by a temporary observation at IYJ (SHIONO and MASAOKA, 1978). Low seismicity within distances of 40 km from IYJ is apparent in Fig. 4b which gives frequency distribution of S-P times observed at IYJ and in Fig. 3c which gives the hypocenter distribution in a vertical section.

In conclusion, the feature of seismic activity around the MTL is simply summarized as follows;

1. Around the active segment of the MTL from the western Kii Peninsula to central Shikoku, the MTL forms, in a broad sense, a boundary between the seismically active area on the southern side and the asiemic area on the northern side.
2. Around the segments of low faulting activity, crustal seismicity is very low. This feature of small earthquakes con-

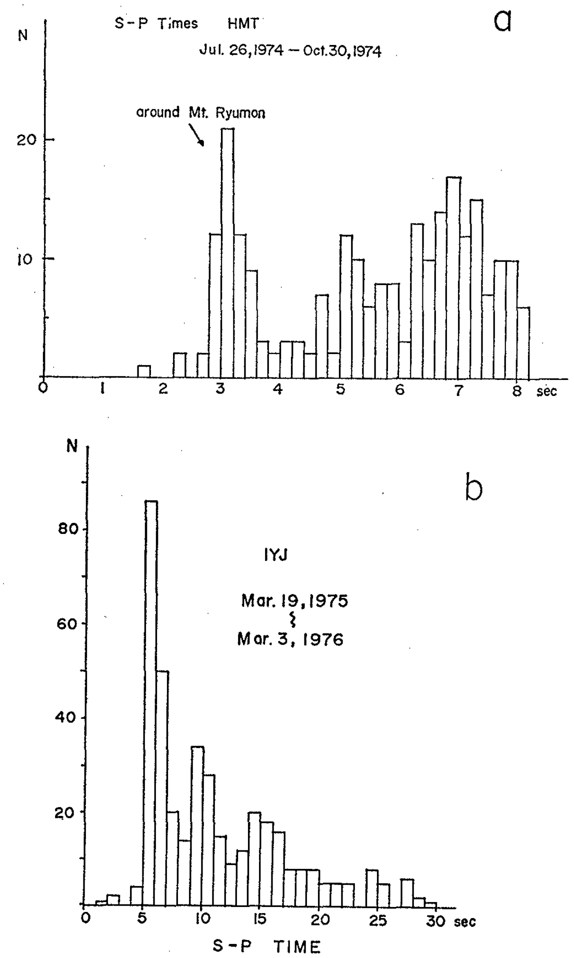

Fig. 4. Frequency distribution of S-P times observed at HMT (a) and at IYJ (b). Note that earthquakes with S-P times less than 3 sec at HMT and less than 5 sec at IYJ are almost absent. Peaks around 3-4 sec in (a) and around 5–6 sec in (b) correspond to crustal seismicity around the east side of Wakayama City and to subcrustal seismicity beneath IYJ, respectively. Locations of stations HMT and IYJ are given in Fig. 2.

trasts with that of destructive earthquakes as shown in Fig. 1, which suggests that a quiet zone of destructive earthquakes appears around the active segment of the MTL. However the activity of small earthquakes could release only small portions of tectonic strain accumulated around the active segment of the MTL, because most of these earthquakes have magnitudes smaller than 5.0. According to the *Regional Catalogue of Earthquakes in and near Japan* (1961–1970) published by the Japan Meteorological Agnecy (1972), only three crustal earthquakes had magnitudes equal to or greater than 5.0 (two of M5.0 and one of M5.2) in the region of longitudes 133–136° E by latitudes 33–35° N for ten years from 1961 to 1970. Nakamura (1976) determined the locations of the hypocenters and magnitudes for the earthquakes which were reported as "Felt" by Wakayama Meteorological Observatory for eleven years from 1965 to 1975, by using data from Wakayama Microearthquake Observatory and its satellite stations. The earthquakes of magnitudes 4.8, 5.1 and 5.3 were greatest among the crustal earthquakes that occurred around Wakayama. *The report of the Kochi Earthquake Observatory* shows that three earthquakes of magnitudes 4.0, 4.1 and 4.2 were greatest among crustal earthquakes that occurred in the whole area of Shikoku for ten years from 1967 to 1976. This suggests that it may be hardly acceptable even for earthquakes of magnitude 5.0 to occur once a year around the active segment of the MTL. Even if it were the case, the total for 1,000 years would be less than one tenth of seismic energy which will be released by an earthquake of magnitude 8.0 which has been usually considered by Matsuda (1975), Shimazaki (1977) and others to occur owing to faulting along the active segment of the MTL.

Therefore, it is impossible to consider that the quiet zone of destructive earthquakes would appear, because the accumulated strain has been released fragmentally by the activity of these small crustal earthquakes. The observational fact that tectonic creep has not yet found on the active fault trace along the MTL (Okada, 1973) also denies this possibility. Okada (1973; 1978), Matsuda (1975), Shimazaki (1977) and others have repeatedly given warning of this danger, so the quiet zone should thus be recognized as a seismicity gap indicating a likely site of future large earthquakes.

3 Subcrustal earthquakes

Fig. 5 shows the distribution of hypocenters with depths ranging from 40 to 250 km which were determined by the Japan Meteorological Agency during the period from 1961 to 1970. This indicates high activity of subcrustal earthquakes around Iyonada, the Kii Channel and southern Chubu District. Including the intermittent zones of relatively low activities, the earthquakes form a narrow belt of seismicity with focal depths shallower than 100 km. This active belt with a convex notch around the Kii Channel strikes approximately parallel to the axis of the Nankai trough, and changes its general trend southwestward under Kyushu with an increase in the depth of its lower rim down to about 200 km, and continues to the Benioff zone developed under the Ryukyu arc (see Katsumata and Sykes, 1969; Shiono *et al.*, 1979). Routine and temporary microearthquake observations have revealed the details of this activity.

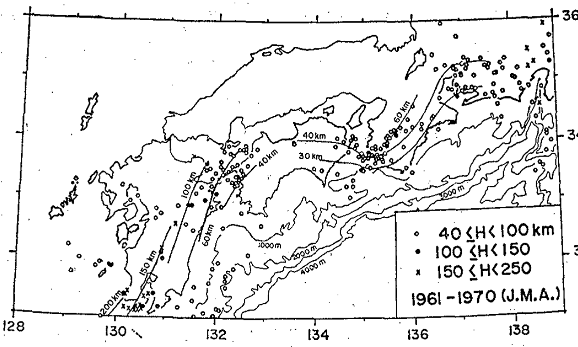

Fig. 5. Epicentral distribution of subcrustal earthquakes with focal depths greater than 40 km given by the Japan Meteorological Agency (1972) for years 1961–1970. Symbols indicating epicenters show depth ranges of hypocenters as given in the inset. Contours represent average depths of hypocenters modified from Mizoue (1977).

As Fig. 3 shows, the subcrustal earthquakes are spatially separated from crustal ones, and tend to occur around planes dipping north- or northwestward (see Kanamori and Tsumura, 1971; Nakamura *et al.*, 1974; Okano *et al.*, 1978; Shiono and Masaoka, 1978 etc.). Contours in Fig. 5 gives average depths of hypocenters modified from Mizoue (1977) who has presented the depth contour of the activity by referring to the results of microearthquake observations.

In spatial relation to the MTL, the following features are apparent in Figs. 2b and 5;

1. Around the active segment of the MTL, subcrustal earthquakes occur only on the southern side of the MTL.
2. Around the low active segments of the MTL, the earthquakes extend northward across the MTL.

The contrast is remarkable especially within the Kii Peninsula. The features will be discussed later with relation to the underthrusting slab of the Philippine Sea plate.

Tectonic Stress around MTL

1 Data

The direction of the tectonic stress can be estimated to some extent in the seismic region from the analyses of radiation patterns of seismic waves i.e. fault plane solutions. Geodetic measurements and *in situ* stress mesurements also provide data on tectonic stress. Figs. 6 and 7 summarize the results of fault plane solution surveys for major and small earthquakes, respectively, on the basis of data provided by many seismologists including the writer (see Shiono, 1973, 1977). Strictly speaking, the P- and T-axes which are defined as the centers of quadrants of dilatational and compressional initial P-motions in the fault plane solution, respectively, may deflect in some degree from the axes of tectonic stress because of the effects of local stress concentration, the

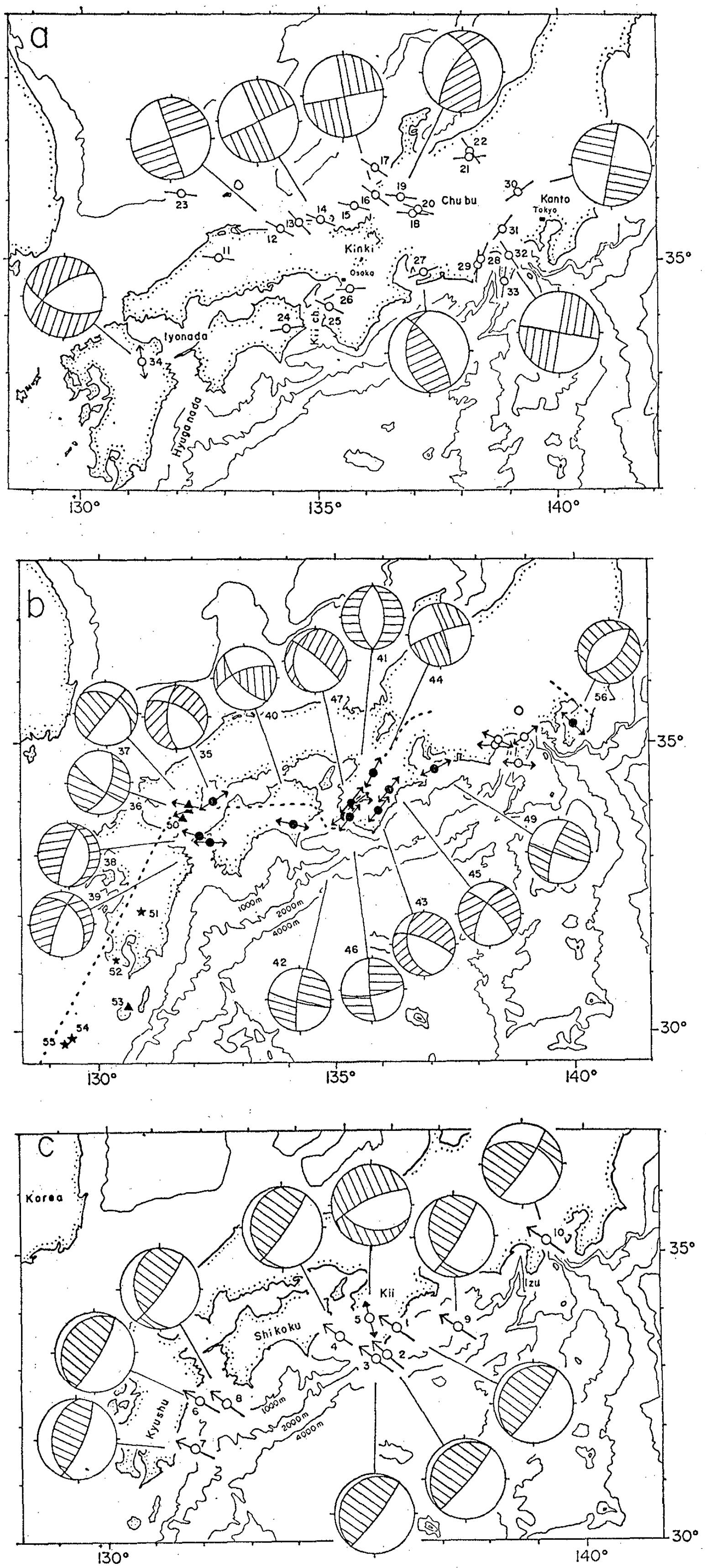

Fig. 6. Results of fault plane solution surveys for major earthquakes in Southwest Japan compiled from various references (see SHIONO, 1977). Simplified mechanism diagrams represent lower hemispheres projected in Wulff's grid. The open and shaded quadrants of the diagrams show dilatational and compressional ones whose centers are defined as the P- and T-aexs, respectively. (a) Crustal earthquakes. Distribution of the P-axis is given. The T-axis is given, exceptionally, for a normal faulting earthquake No. 34. (b) Subcrustal earthquakes. The T-axis is given. Earth quakes around Izu Penninsula are also plotted although the focal depths are shallower than 30 km. The axes are not given for earthquakes Nos. 51–55 because the axes plunge at angles steeper than 45°. The dotted line gives the horizontal projection of the leading edge of the underthrusting Philippine Sea plate. (c) Earthquakes along the Nankai trough and in Hyuganada. Arrows give directions of slip vectors of the oceanic block. The T-axis is given, exceptionally, for a normal faulting earthquake No. 5.

internal friction of rock and pre-existing fault system (see NISHIDA *et al.*, 1974 for example). However, it has been usually accepted as a reasonable idea that the direction of the P- and T-axes approximately indicate the axes of regional tectonic stress as long as the average directions are concerned instead of the individual directions of the P- and T-axes.

2 Crustal stress

Fig. 6a suggests that the P-axes are nearly oriented in the east-west direction. The similar feature is more obvious for smaller earthquakes as shown in Fig. 7a. SHIONO (1970) has presented many fault plane solutions for small earthquakes in the western Kii Peninsula and has shown that the average direction of the P-axes lies horizontally in N 105° E. Composite radiation patterns of P-waves and fault plane solutions for small earthquakes in Shikoku suggest that the P-axes are roughly oriented in the east-west (SAWAMURA and KIMURA, 1971; SHIONO, 1973; KIMURA and OKANO, 1977).

Another interesting feature of fault plane solutions for crustal earthquakes around the Kii Peninsula and Shikoku is that the types of fault plane solutions indicate strike slip faulting, reverse faulting and combination of both types without component of normal faulting (see SHIONO 1970; 1973; 1977; MIZOUE and NAKAMURA, 1976). This implies that this type of tectonic stress may be compressive and not extensive.

On the other hand, NAKANE (1973) has calculated the distribution of long-term crustal strain without the effects of large earthquakes on the basis of data from first-order retriangulation surveys. The axes of maximum contraction are oriented in the northwest-southeast around the Kii Peninsula and Shikoku. The results of *in situ* stress measurement carried out at Okuyoshino in the central Kii Peninsula has suggested that the axis of maximum compressive stress lies in the northwest-southeast, consisting with the result of NAKANE (1973) (ITO *et al.*, 1976).

These evidence consistently suggest that the tectonic compressive stress now acts in the direction ranging from the east-west to the northwest-southeast around the MTL. This stress state is consistent with right-lateral strike-slip faulting along the MTL.

3 Stress in subcrustal depths

Figs. 6b and 7b indicate that subcrustal earthquakes occur in a significantly different situation from the case of crustal ones. As Figs. 7b and 8 show, the inclination angles of the P-axes vary in a wide range, and the axes do not cluster around any characteristic direction, but are distributed weakly around a plane striking northwestward. The P-axes of small earthquakes are also oriented roughly in the direction ranging from the north-south to the northwest-southeast, but the inclination angles vary over a considerably wide range and many axes dip steeply over 45° (see Fig. 7b).

On the other hand, it is apparent in Figs. 6b and 8 that the T-axes are nearly horizontal with the azimuths ranging from east-west to the northeast-southwest and are roughly parallel to the axis of the Nankai trough. A similar feature has been noticed for small earthquakes in the western Kii Peninsula and in southern Chubu District (SHIONO, 1970; OOIDA and ITO, 1974).

Subcrustal earthquakes are characterized by another significant feature in that the component of normal faulting predominates. As the simplified mechanism diagrams in Fig. 6b show, the types of faulting are of strike-slip faulting, normal faulting and a combination of both types. The predominance of normal faulting component is remarkable, especially around Iyonada and the Kii Channel.

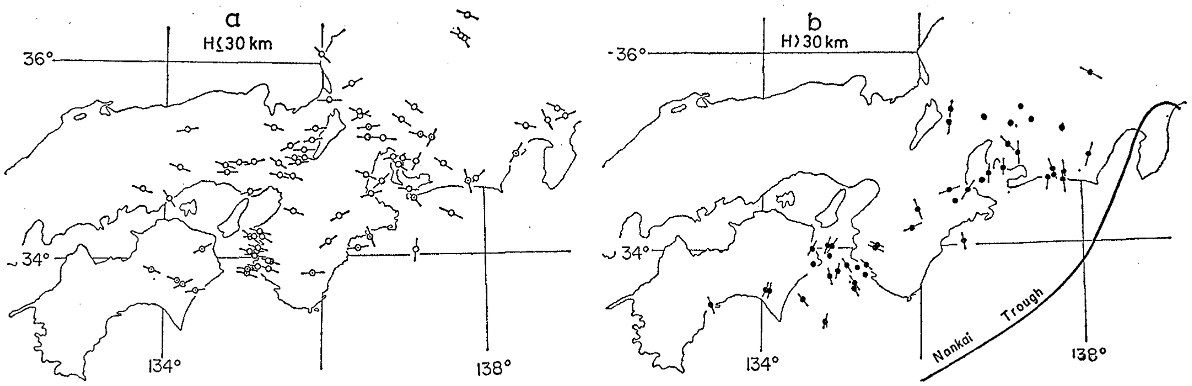

Fig. 7. Distribution of the P-axes for small crustal (a) and subcrustal (b) earthquakes, of which depth boundary is assumed to lie 25 km deep. The axes of earthquakes in the northern Kinki District, in the eastern Kinki and Chubu Districts, and in the western Kii Peninsula and Shikoku are taken from Nishida (1973), Ooida and Ito (1974) and Shiono (1973), respectively. The directions of the P-axes are not shown in the case that the axes plunge at angles steeper than 45° (circle without a bar).

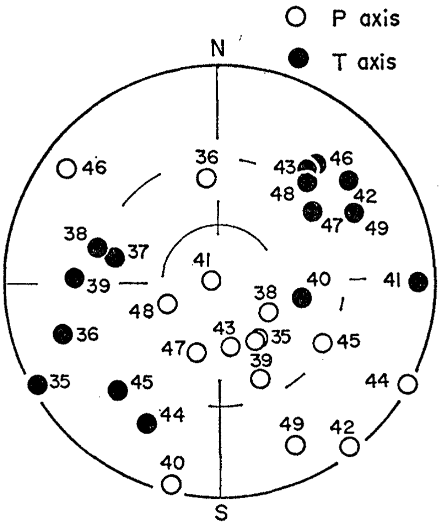

Fig. 8. Distributions of the P- and T-axes on the lower hemisphere projected on the Wulff's grid for major subcrustal earthquakes located in the regions from Iyonada to southern Chubu District. Index numbers correspond to those in Fig. 6.

Although Shiono and Mikumo (1975) and Shiono (1977) have discussed the tectonic origin of stress generating the earthquakes with special interest in systematic alignment of the T-axes, the features of subcrustal earthquakes may be explained also by another simple model as follows;

Assume a Cartesian coordinate with the vertical z-axis and the north or northwestward trending x-axis in a semi-infinite body with a surface at $z=0$. If both sides of the body normal to the x and y-axes are constrained, stress components in a static condition applied only by the effect of gravitational loading of materials below the surface $z=0$ can be expressed as;

$$\sigma_x = \sigma_z/(m-1)$$
$$\sigma_y = \sigma_z/(m-1)$$
$$\sigma_z = \int_0^z \rho(z)g(z)dz$$

where σ_x, σ_y, σ_z, m, $\rho(z)$ and $g(z)$ give x, y, z components of principal stress, poisson's number (1/poisson's ratio), density and gravitational accerelation, respectively. As long as the materials behave elastically at least to some extent, m is greater than 2.

When constant compressive stress σ is given in the x-direction, total stress becomes;

$$\sigma_x = \sigma_x/(m-1)+\sigma$$
$$\sigma_y = \sigma_z/(m-1)+\sigma/m$$
$$\sigma_z = \sigma_z.$$

As we consider the stress state in subcrustal depths, we may assume that the the loading σ_z becomes large enough to exceed σ_y or

$\sigma/(m-2)$. If so, σ_y is always identical to the minimum compressive stress σ_3. This explains the systematic alignment of the T-axes.

The maximum compressive stress σ_1 changes from σ_x to σ_z below the depth of $\sigma_z = (m-1)\sigma/(m-2)$. We can expect the occurrence of strike-slip and normal faulting earthquakes above and below the critical depth, respectively. If the critical depth lies around 40–50 km deep, we can expect the co-existence of both types of earthquakes and variety of inclination angles of the P-axes.

Thus, the basic features of subcrustal earthquakes can be at least tentatively explained by above simple model assuming only gravitational loading and uni-axial tectonic stress. This supports an idea that subcrustal earthquakes may be generated by tectonic stress acting in the direction ranging from the north-south to the northwest-southeast. It may be reasonable to consider that the tectonic stress originates from the underthrusting of the Philippine Sea plate because the direction is roughly parallel to the relative motion between the Asian and the Philippine Sea plates, as KANAMORI (1972b) first proposed.

Underthrusting of the Philippine Sea Plate

Underthrusting of the Philippine Sea plate has been presumed chiefly based on the following evidence;

1. Nature of great earthquakes along the Nankai trough
2. Existence of subcrustal earthquakes corresponding to the Benioff zone
3. Existence of high velocity and high-Q layer.

The shape of the underthrusting slab has been outlined on the basis of distribution of subcrustal earthquakes, travel time analyses and attenuation of seismic waves.

1 Great earthquakes along the Nankai trough

Great earthquakes with magnitude around 8.0 have repeatedly occurred along the Nankai trough (see Fig. 1). Source mechanisms of the 1944 Tonankai and the 1946 Nankaido earthquakes have convincingly suggested that the earthquakes arose from the elastic rebound of the continental margin forced down by the underthrusting Philippine Sea plate, similar to the case of great earthquakes along the trenches in other island arcs (FITCH and SCHOLZ, 1971; KANAMORI, 1972b; ANDO, 1975 etc.; see the mechanism diagrams of earthquakes Nos. 1 and 2 in Fig.5c). The underthrusting is also supported by fault plane solutions of smaller earthquakes along the Nankai trough and in Hyuganada consistently indicating low-angled thrusting (see Fig. 5c; KATSUMATA and SYKES, 1969; FITCH, 1972; SHIONO, 1977; SHIONO *et al.*, 1979).

2 Subcrustal earthquakes

The facts that (1) subcrustal earthquakes occur within a thin zone dipping north- or northwestward, (2) the activity continues to the well-developed Benioff zone under Kyushu and Ryukyu and (3) the earthquakes are generated by tectonic stress in the direction ranging from the north-south to the northwest-southeast convincingly support an idea that the subcrustal earthquakes represent the result of the interaction between the continental Asian plate and the underthrusting Philippine Sea plate around the interface, as pointed out first by KANAMORI (1972b) in the Kii Peninsula. According to this line of thinking, the absence of earthquakes deeper than 100 km suggests that the leading edge, or the lower tip, of the underthrusting slab still remains within the continental plate and does not penetrate deeply into the asthenosphere. This idea enables us to outline the shape of the underthrusting slab from the distribution of subcrustal earthquakes.

3 The high velocity layer and the high-Q zone

Generally, the underthrusting slab has been characterized as the layer with high velocity and high-Q chiefly because the temperature is lower in the slab than in the surrounding upper mantle. Existence of high velocity layer and high-Q zone under Southwest Japan has been confirmed by the analyses of travel times and the attenuation of seismic waves.

KANAMORI and TSUMURA (1971) have observed precursory seismic waves from seismograph readings at a station in the eastern Kii Peninsula for the earthquakes which occurred in the western Kii Peninsula and they suggested the existence of a high velocity layer beneath the Kii Peninsula. MIZOUE (1977) has identified the later seismic phase observed in the Kii Peninsula as a wave refracted from the plane dipping northwestward under the southern Kii Peninsula. OIKE and KIMURA (personal communication) have suggested that initial P-waves have a high apparent velocity of about 9 km/sec and the later phase arriving 1–3 sec later has a normal apparent velocity of about 8 km/sec in central Shikoku for earthquakes that occurred west of Shikoku (see SHIONO, 1974). SHIONO (1974) has shown the existence of high velocity layer under Shikoku and the absence of the layer under the northern Kii Channel, by using travel times of seismic waves generated by subcrustal earthquakes that occurred in the Bungo Channel, especially by using travel times of later phase with apparent velocity of about 4.6 km/sec which were interpreted as S-wave converted from P-wave at the edge of the high velocity layer eastern Shikoku.

IKAMI and ITO (1974) have ascertained the existence of a high-Q zone in the Outer Zone of Southwest Japan from the consideration of the observational fact that the seismic waves travelled from Southwest Japan to Inuyama Microearthquake Observatory (INU) in western Chubu District were less attenuated than those from other regions in and near Japan. This high-Q zone was conceived by the detectability of earthquake at INU, too.

Spatial extent of the high velocity layer and high-Q zone is approximately similar to that of subcrustal seismic activity. The high velocity layer and the high-Q zone can be interpreted as suggesting directly that the underthrusting slab exists under Southwest Japan.

4 Shape of the underthrusting slab of the Philippine Sea plate

The shape of the underthrusting slab of the Philippine Sea plate has been derived and shown in Figs. 9 and 10, chiefly on the distribution of subcrustal earthquakes and the high velocity layer (see SHIONO, 1974). IKAMI and ITO (1974) have inferred, independently, the location of the leading edge of the underthrusting slab is chiefly based on the spatial extent of the high-Q zone and subcrustal earthquakes. The results of both authors are, in general, similar.

The convex notch around the Kii Channel was supported by travel time analyses of the converted S-waves with an apparent velocity of about 4.6 km/sec (SHIONO, 1974). The leading edge may penetrate further inland around the border between Kinki and Chubu Districts, because earthquakes with depths and fault plane solutions similar to subcrustal earthquakes have been found around the region east of Lake Biwa (OOIDA and ITO, 1974, for example). It may be sure that the leading edge under eastern Shikoku remains in the southern side of the MTL because activity of subcrustal earth-

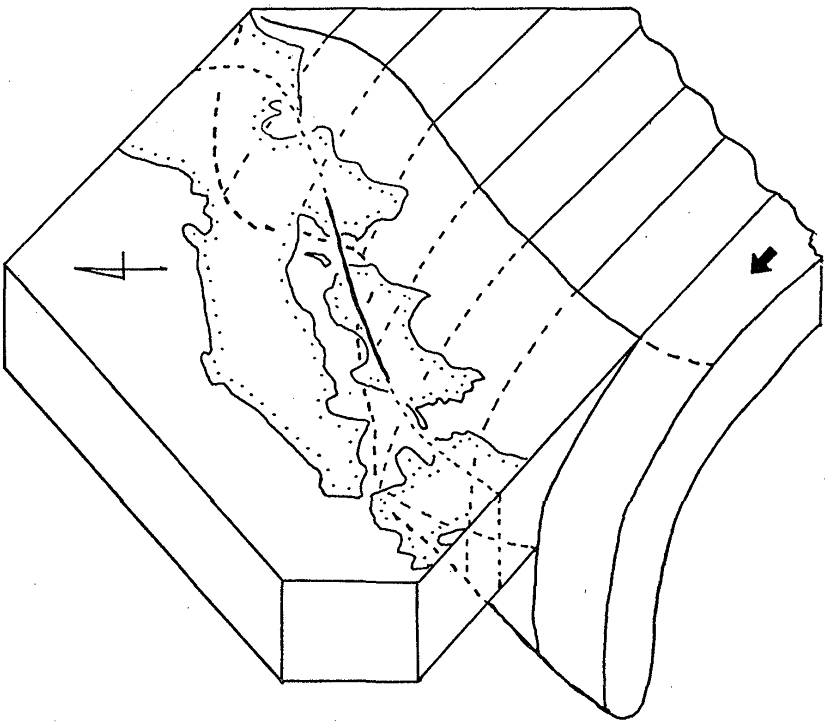

Fig. 9. Three-dimentional illustration representing the spatial relation among the continental margin, the underthrusting Philippine Sea plate and the MTL. The MTL segments of high and low activity are shown by solid and broken lines, respectively. The thick arrow represents the direction of relative motion of the Philippine Sea plate against the Asian Plate.

quakes are confined within the southern side (Okano *et al.*, 1978) and also because the high-Q zone exists only in the southern side of the MTL (Ikami and Ito, 1974). It is probably certain that the leading edge intersects somewhere under western Shikoku, as subcrustal earthquakes are active under Iyonada north of the MTL (see Figs. 2b and 5).

Discussion on Fault Movements along MTL

In the present section, we will discuss the nature of fault movements along the MTL on the basis of the decoulping hypothesis proposed by Fitch (1972).

1 Decupling hypothesis

Fitch (1972) proposed a model explaining strike-slip faulting in the region of oblique plate convergence i.e. decoupling hypothesis. When the oceanic plate converges obliquely to the plate margin, the horizontal shear is generated in the continental margin. If the vertical zone of weakness pre-exists with the strike parallel to the plate margin in the continental margin, horizontal shear concentrates in the pre-existing zone of weakness more effectively than on the inclined interface between the underthrusting and the continental plates. As the result, a portion of this horizontal shear is easily released by strike-slip movements along the vertical fault, and the remaining stress is released by thrusting along the interface. Fitch (1972) showed that this hypothesis is favored in many real situations such as in western Sunda and Philippines. Although he mentioned the MTL, too, it will be necessary to modify the hypothesis in order to explain relatively complex natures of recent fault movements along the MTL.

2 Application to MTL

Figs. 9 and 10 show a spatial relation between the MTL and the underthrusting slab of the Philippine Sea plate. The follwing relations are apparent;

1. Around the active segment of the MTL from the western Kii Peninsula to central Shikoku, the leading edge of the underthrusting slab still remains in the outer side of the MTL.
2. Around the segments of low activity in the regions east of the central Kii Peninsula and west of western Shikoku, the leading edge extends to the inner side of the MTL.

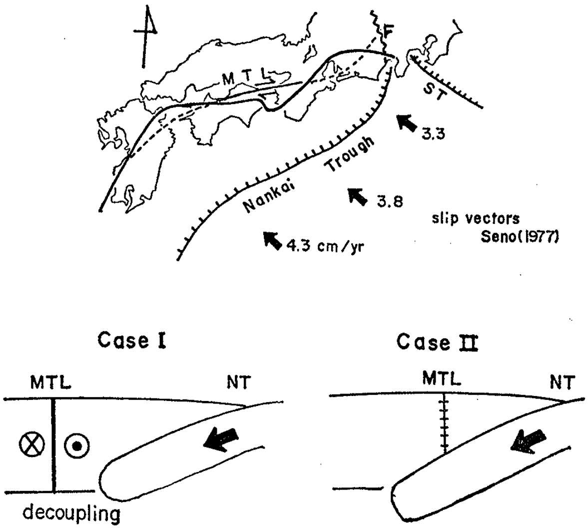

Fig. 10. Schematical diagrams showing the spatial relation between the underthrusting plate and the MTL. Upper; spatial relation between the horizontal projection of the leading edge of the underthrusting slab (a thick solid line) and the MTL. The MTL segments of high and low activity are given by solid and broken lines, respectively. Directions (arrows) and rates (numerals) of relative motion between the continental Asian and the oceanic Philippine Sea plates are taken from Seno (1977). Lower; idealized cross sections for case I where the leading edge remains in the outer bolck and for case II where the leading edge extends to the inner side across the MTL. Cases I and II correspond to high and low faulting activity along the MTL, respectively, because the outer continental block easily decouples from the inner one along the MTL as in case I, but hardly decouples in case II.

As the MTL has a complex displacement history that began at least in the Late Mesozoic (see Ichikawa, 1980), it may be reasonable to consider that wide sheared zone has been built up in depth so as to penetrate through the continental plate. Therefore, it is a reasonable assumption that the MTL can act as the pre-existing zone of weakness conductive to horizontal shear due to oblique convergence. Then, the contrast of faulting along the MTL as mentioned above can be explained as follows;

Case I. The leading edge does not reach the MTL but remains within the outer block; strike slip movements easily occur in the right-lateral sense in order to release horizontal shear due to oblique convergence because the outer block can be decoupled from the inner one along the MTL. Case II. The leading edge extends to the inner side across the MTL; strike slip movements hardly occur because the underthrusting slab is in contact with both the inner and outer blocks so that the outer block can not move independently from the inner one.

The idea may not be applicable to the MTL in Kyushu, because the MTL is nearly normal to the direction of plate convergence, and therefore, concentration of horizontal shear becomes too small to produce a large amount of strike-slip movements along the MTL. Low activity may be explained by low concentration of horizontal shear.

The above model suggests that the slip rate along the MTL may be considerably lower even in the active segment than the case of complete decoupling. Because the active segment accompanies on both sides in the segments of low activity where decoupling hardly occurs, the whole outer block cannot move freely as a rigid body, but only small portion of the horizontal shear can be released by an internal deformation of the outer block. This idea is consistent with the observational fact that the slip rate of recent strike-slip movement in central Shikoku (5–10 mm/yr; OKADA, 1970) and in the western Kii Peninsula (1–2.8 mm/yr; OKADA and SANGAWA, 1978) is lower by about one order of magnitude than the converging rate along the Nankai trough (3.3–4.3 cm/yr; SENO, 1977).

3 Additional remarks

In addition to the basic characteristics of recent movements along the MTL, the present model may be able to present a possible explanation to the two features as follows:

SANGAWA and OKADA (1977) found that faulting along the MTL in the central Kii Peninsula was active in the early Quaternary Period and became inactive in the late Quaternary Peroid. This termination of faulting activity may be explained by an idea that the active segment corresponding to Case I became inactive one corresponding to the Case II resulted from the progress of the leading edge of the underthrusting Philippine Sea plate.

The Butsuzo Tectonic Line which runs in about 50 km outside is a major tectonic line in Southwest Japan, nearly comparable with the MTL. Although the Butsuzo Tectonic Line may be considered to concentrate the horizontal shear as a pre-existing zone of weakness in the same manner as the MTL, recent activity there has not been remarkable. This contrast to the MTL may be explained by an idea that the situation always corresponds to Case II, because the Butsuzo Tectonic Line lies in much outer side.

The present model can explain to some extent some basic problems regarding the recent movements along the MTL on the basis of the shape of the underthrusting slab of the Philippine Sea plate. However, the above discussions are confined to recent ages when the presumed situation might not change significantly, say a few hundred thousand years. The model expects that fault movements would have spread over whole segment of the MTL when the Philippine Sea plate began to underthrust a few millions years ago. However, field evidence suggesting that movements were then active, have not been found along the MTL in the eastern Kii Peninsula except for SANGAWA and OKADA (1977)'s fragmental observation. Therefore, there still remain some problems on the efficiency of the present model for geologic past.

In order to progress discussion, it will be important to make clear the history of plate convergence from its initiation to the present.

1. Following two data may be significant. One is the irregular shape of the slab (see Fig. 10). The other is NAKANISHI's (1979) discovery of aseismic slab. He found a remarkable phase arriving 5–6 sec early beofre the ScS phase in seismographs at Shiraki Microearthquake Observatory (SHK), and identified it as a ScSp phase which were converted from ScS at the layer of velocity contrast about 50 km beneath the station SHK. He suggested a possibility that the underthrusting slab penetrates much more inland than that presumed in the present paper, although subcrustal earthquakes are completely absent there.

2. As above phenomena are hardly explained if we assume that the oceanic plate began to underthrust newly along the inactive margin, the following idea may be possible: The slab which had underthrusted at the previous cycle of the plate convergence stopped its movement, and was affected by thermal assimilation of surrounding upper mantle for some time, say less than ten

millions years since the cycle ceased, but did not completely assimilate with the upper mantle when the present cycle of plate convergence began.

3. The present slab consists of not only the newly underthrusting part but also the unassimilated old one and, therefore, the lower part has an irregular shape representing local variation in degree of thermal assimilation, suggesting that the spatial relation between the MTL and the underthrusting slab was already determined at the beginning. However, as this idea is very speculative and is not more than one of the possible explanations, the validity is open to future discussions.

Summary and Acknowledgements

The present paper discusses seismicity and tectonic stress in relation to the MTL based on data provided by many authors including the present writer, and later presents a simple model explaining some basic features of recent faulting activity along the MTL, based on the shape of the underthrusting slab of the Philippine Sea plate. The results are summarized as follows;

1. Historical records for about 1,000 years suggests that a seismicity gap of destructive earthquakes exists along the active segment of the MTL.

2. Observational facts that (1) tectonic creep has not yet been found along the active segment of the MTL and (2) magnitudes of crustal earthquakes around the active segment are small in spite of the high activity suggest that the seismicity gap of destructive earthquakes should be recognized as a likely site of future large earthquakes.

3. Active segment of the MTL forms, in a broad sense, a boundary between the seismically active area in the south and the aseismic area in the north.

4. Tectonic compressive stress now acts around the region of the active segment of the MTL in the direction ranging from the east-west to the northwest-southeast, consisting with the right-lateral strike-slip faulting.

5. Based on spatial distribution of subcrustal earthquakes, the high velocity layer and high-Q zone, the shape of the underthrusting slab is outlined under thewhole of Southwest Japan.

6. Spatial relations that (1) around the active segment of the MTL, the leading edge of the underthrusting slab still remains in the southern side of the MTL and (2) around the segments of low activity, the leading edge extends to the inner side across the MTL are explained in terms of decoupling of the outer block from the inner along the MTL.

This paper refers to the results by many seismologists and geologists. I am very grateful to the Wakayama Microearthquake Observatory, the Earthquake Research Institute of University of Tokyo and the Kochi Earthquake Observatory of Kochi University that kindly provided lists of hypocenter coordinates in the Kii Peninsula and Shikoku, respectively. I wish to thank Professor K. Huzita, Dr. Wadatsumi and collaborators of the laboratory for their suggestions from a geologic viewpoint. I would like to express my appreciation to Professors T. Mikumo and Y. Kishimoto and Dr. K. Oike helpful suggestions on a series of my investigations on subcrustal earthquakes in Southwest Japan. Calculations included were made at the Computer Center of Osaka City University and by the YHP 9830 Personal Computer at the laboratory.

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西南日本における中央構造線の地震学的研究

塩野清治

（要旨）

西南日本の地殻内地震及び地殻下地震のテクトニックな意味を，特に中央構造線（MTL）沿いの断層運動との関係において議論した．

MTL 沿いの断層運動の活発な部分（紀伊半島西部〜四国中部）では，地殻内における，小又は微小地震の活動が活発であり，MTL は，広い意味で，南側の地震活動域と北側の低活動域の間の境界となっている．これらの小地震によって解放される歪は，小規模なものであるため，MTL の断層運動が活発な部分のまわりに，過去1,000年の間に大地震が発生していない事実は，近い将来における大地震の発生を示す「地震の空白域」として，認識されるべきであろう．

地殻下地震の分布や地震波高速度層の分布から，high-Q zone の分布を参考しつつ，南海トラフからもぐりこんでいるフィリピン海プレートの形を推定した．その形は，MTL の断層運動と密接な関係があり，(1) 断層運動の活発な所では，もぐりこむプレートのの先端は，MTL の外側にある，(2) 断層運動が不活発な所では，プレートの先端は，MTL の下を横切って内側までのびているという見かけ上の位置関係がみられる．この関係は，MTL より外側の大陸プレートが MTL 沿いに，内側のプレートから decouple するか，又は，decouple しないかという関係におきかえて説明することができた．

和名

Arima-Takatsuki Tectonic Line	有馬-高槻構造線
Atera fault	阿寺断層
Atotsugawa fault	跡津川断層
Bungo Channel earthquake	豊後水道地震
Butsuzo Tectonic Line	仏像構造線
Fukozu fault	深溝断層
Fukui earthquake	福井地震
Hanaore-Katada fault	花折・堅田断層
Hashimoto	橋本
Iga-Ueno earthquake	伊賀上野地震
Inuyama Microearthquake Observatory	犬山微小地震観測所
Lake Biwa	琵琶湖
Kochi Earthquake Observatory	高知地震観測所
Mino-Owari	美濃・尾張
Mikawa earthquake	三河地震
Mitoke fault	三峠断層
Nankaido earthquake	南海道地震
Neodani fault	根尾谷断層
Nobi earthquake	濃尾地震
North Tango earthquake	北丹後地震
Okuyoshino	奥吉野
Sada-Misaki Peninsula	佐田岬半島
Shiraki Microearthquake Observatory	白木微小地震観測所
Tonankai earthquake	東南海地震
Tottori earthquake	鳥取地震
Wakayama-Bisho-Jishin-Kansokusho-Kiho	和歌山微小地震観測所季報
Wakayama Microearthquake Observatory	和歌山微小地震観測所
Yamasaki fault	山崎断層
Yanagase fault	柳瀬断層
Yoshino earthquake	吉野地震
Yoshioka-Shikano fault	吉岡・鹿野断層
Zenkoji earthquake	善光寺地震