Active Tectonics and Intraplate Paleoseismic Activities, Southwest Japan

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Abstract

In the first part of this paper, the author examined active structures of southwest Japan and pointed out that a westward movement of the forearc sliver caused by the oblique subduction of the Philippine Sea plate plays a very important role in the active tectonics of the Southwest Japan and Ryukyu arcs.

The Southwest Japan arc is divided into six major arc-parallel structural zones from characteristics of active structures. The Median Tectonic Line (MTL), one of the most active faults on land in Japan, is situated as the main boundary fault which separates the arc into two, namely forearc and backarc. The Shikoku zone (forearc ridge zone) on the south of MTL is characterized by broad mega-folds whose axes are almost perpendicular to MTL. These arc-parallel compressional structures are explained by that a westward translation rate changes along the forearc. This tectonic situation is caused by that obliquity of two plates decreases to the west because of the concave shape of the plate boundary. On the north of MTL exists the depressional zone which is named Seto'uchi or Seto Inland Sea. This 80 to 100 km wide depression is composed of en-echelon basins and ridges whose axes are oriented to NE-SW, about 30 to 40 degrees to MTL. The author named this zone as "Seto'uchi shear zone" (SSZ) because these structures are explained as a drag motion caused by a right-lateral strike slip faulting of MTL.

SSZ extends to the volcanic region of central Kyushu where E-W trending en echelon grabens and normal faults are intensively developed. The Unzen graben shows a typical pattern of normal faults around volcano in E-W compressional stress field. These en-echelon grabens are also understood as elemental structures in a dextral shear zone.

The tectonic framework of Southwest Japan arc is also applicable to the Ryukyu arc system. The southwestward migration of forearc sliver in the southern Ryukyu arc is apparently coupled with the development of en-echelon grabens in the backarc, Okinawa trough. The forearc is characterized by the development of normal faults perpendicular to arc. This forearc extension is explained by that migration rate increases in the south. In the northern Okinawa Trough active faults are very rare because of small migration rate of forearc sliver. This suggests that the major active tectonic framework of the Okinawa trough, that is, extensional right-lateral shear zone is not directly connected to the central Kyushu which belongs to the backarc of Southwest Japan arc.

Secondly, the author discussed historical earthquakes and their source faults in southwest Japan, and he pointed out that clustering and migration of earthquakes since the early 16th century are significant in the Kinki and Chubu districts. It was suggested that the 1596 Fushimi earthquake caused by the movement of the Arima-Takatsuki Tectonic Line and Rokko fault system from distribution of damaged area and some faulting evidences at the archeological excavation sites. The faults of the 1995 Hyogo-ken Nanbu earthquake, which probably did not move during the 1596 earthquake, is located in the southwestern segment of the above cited fault system. This estimation is proved by the recent intensive trench excavation surveys along the fault system. The 1995 faulting area is located in MTL seismic zone, one of four potential seismic zones designated by Tsukuda (1978). It is found that there is a long term seismic cycle of 1300 to 1600 years. During this long-term seismic cycle seismic area shifts significantly in active tectonic provinces. Seismic period of western SSZ comes little after the beginnig of that of Kinki district (eastern SSZ). According to the seismotectonic framework of dextral shear movement in southwest Japan and seismotectonic cycle, somewhere along MTL could be a potential seismic fault in the near future.

Key words: active fault, forearc sliver, oblique subduction, graben, strike-slip fault, arc-arc junction, Seto'uchi shear zone, Southwest Japan arc, Ryukyu arc, Philippine Sea plate, Eurasian plate, central Kyushu, Hyogo-ken nanbu earthquake, paleoseismology, Median Tectonic Line, Arima-Takatsuki Tectonic Line, Rokko fault system,

1. Introduction

For the purpose to understand a seismotectonic environment, it is essentially important to describe clearly an active tectonic framework which would be illustrated by accumulation of long-term deformation. An individual large seismic activity is a key factor to construct active structures as a major incremental strain step. The author discussed the development of active structures of southwest Japan (Fig. 1) in some papers (Tsukuda, 1992; 1993) and conclusively pointed out that a westward movement of forearc sliver driven by oblique subduction of the Philippine sea is a key feature for the active tectonics of southwest Japan (Fig. 2).

Oblique subduction is a very popular feature in convergent two plates. In the early period of plate tectonics, Fitch (1972) introduced an importance of oblique subduction in island arc tectonics and proposed a decoupling hypothesis of continental margins. He sited the Median Tectonic Line as an example of transcurrent fault as well as the Great Sumatran fault of Indonesia, the Philippine fault of Philippines and the Alpine fault of New Zealand. Matsuda and Ueda (1971) , and Kaizuka (1972;

1975) also found a very significant role of arc-parallel strike-slip fault which divides arc into two, forearc and backarc. Recently, tectonics of Japanese islands is being discussed with Eurasian plate movement (e.g. eastward movement of Amurian plate; Ishibashi, 1986; Kimura et al, 1986). It is however, concluded that effects of oblique subduction of Philippine Sea plate is much more substantial in southwest Japan (Tsukuda, 1992; 1993). Migration of forearc sliver caused by oblique subduction is a very common feature in modern subduction zones (Beck, 1983; Jarrard, 1986).

In this paper, again characteristics of active tectonics of southwest Japan will be discussed with newly obtained data with special reference to deformation of forearc sliver together with backarc shear. In addition, paleoseismic activity related to the active tectonics will be discussed based upon recent excavation surveys of active faults.

Active faults are well described as for their distribution in Japan except for submarine areas or some metropolitan areas covered with thick Quaternary deposits (Research Group for Active Faults of Japan, 1991). In the case of active structures of southwest Japan,. it seems, however, to be difficult to understand their development process because orientations and natures of active faults are not so simple. This paper will solve this question.

The author himself participated in several mapping projects in southwest Japan , for example, as 1 to 500,000 scale Neotectonic map series (Tsukuda et al, 1982; 1985; Yamazaki et al, 1984) and strip map series of active fault system (Tsukuda et al, 1993 and Mizuno et al, 1994) in southwest Japan. He also contributed to excavation surveys of active faults (e.g. Tsukuda and Yamazaki, 1984; Tsukuda, 1985a; 1989c; 1995a) and paleoseismological studies (Tsukuda, 1987; Sangawa *et al,* 1986a, 1986b). Discussions of this paper are based upon very original studies mentioned above and with his colleagues of Geological Survey of Japan.

2. Active tectonics of southwest Japan

2.1 Zonal arrangement of southwest Japan arc

The Southwest Japan arc can be divided into six arc-parallel zones from a view point of tectonic landforms and active faults distribution (Fig. 3). They are named as 1) Inner trench slope zone, 2) Forearc basin zone, 3) Forearc ridge zone (Shikoku zone), 4) Seto'uchi (shear) zone, 5) Chugoku zone, 6) San'in zone, from the Nankai trough on the south, respectively (Tsukuda, 1992).

Among them, active tectonic features of the forearc basin zone, Shikoku zone and Seto'uchi shear zone will be discussed as well as right-lateral shear motion of the Median Tectonic Line (MTL).

2.2 Activity of the Median Tectonic Line

The most significant active structure of Southwest Japan arc is the right-lateral strike-slip faulting of the Median Tectonic Line (MTL). Researches on MTL has progressed intensively and extensively during 1970's. With respect to the displacement history, Ichikawa (1980) recognized five stages since early Createceous. Roughly speaking, left-lateral displacement is predominant during Creataceous to Tertiary ages (Hara et al, 1980). To the contraty, right-lateral displacement is very significant during recent 1 million years. It can be said that dextral movement is a very recent feature in its long geologic history. Recent activity of MTL is first recognized by Kaneko (1966). He suggested some geomorphological features showing right-lateral strike slip displacement along the fault. After his works, Okada (1968, 1970,1971, 1973a, 1973b) continued to investigate extensively on the Quaternary faulting of MTL and summerized in Okada (1980). He concluded that

1) active segment of MTL is restricted from western Kii peninsula in the east to western Shikoku in the west for about 300 km long, 2) average dextral slip-rate of MTL is estimated to be about 5 to 5mm/year in central to eastern Shikoku, 3) total amount of right-lateral displacement in the Quaternary is estimated to be several kilometers at eastern Shikoku, 4) amount and direction of vertical displacement are different from place to place along the fault, and the maximum vertical displacement of 1.5 km is obtained at the Ishizuchi fault scarp. The beginning age of dextral slip of MTL is estimated about 0.5 to 1 Ma by Sangawa (1977, 1978) Okada and Sangawa (1978), and Hujita (1980). Although there are many discussions on its activity and slip sense since their original works, very active dextral motion of MTL is now widely accepted.

Shimamoto (1989) proposed a thin-skinned island arc lithosphere from crust strength. Fig. 4 illustrates using lower limits of microearthquake distribution (Regional Observation Center of Earthquake Prediction of Kyoto University, 1988; Okano et al, 1983; Okano and Kimura, 1988; Shiraki Microearthquake Observatory, 1990) based on Shimamoto's idea. It is reasonable that MTL is located at a thinnest part of lithosphere which is weaker than other parts.

Shiono (1980; 1992) modified Fitch (1972)'s decoupling hypothesis and pointed out the importance of leading edge position of subducting plate to explain that active portion of MTL at present is limited.

2.3 Forearc basins of southwest Japan

South of MTL, the forearc sliver is not a rigid plate and has characteristic deformed structures. It can be divided into two zones, namely the zone of forearc rise (Shikoku zone) and that of forearc basins. Both of them are characterized by folds and reverse faults oriented at high angle to MTL, although the making processes for those structures are significantly different from each other.

The forearc basin zone is composed of five major basins divided by reverse faults and folds (Awata and Sugiyama, 1989; Okamura et al, 1986; 1987) as shown in Fig. 5. These surface structures characterized by inverted L-shaped structural highs (Sugiyama, 1992; 1994) are explained to has been made by low angle oblique thrust faulting (Ando, 1975), as a coseismic rebound to the subducting plate. Each basin (structural unit) is fundamentally formed by the accumulation of coseismic deformations (Awata and Sugiyama, 1989; Sugiyama, 1992; 1994). These units indicate the segmentation of interplate seismogenic mega-thrust (A-B-C of Fig. 4). The Tonankai earthquake of 1944 was caused by the movement of C and D segments in Fig. 5. The Nankai earthquake of 1946 is A, B and Z segments. Maemoku (1988a,b) and Maemoku and Tsubono (1990) found that arc-parallel movement with intervals of 300 to 1500 years contributed the elevation of structural highs. This event considered to be made by faulting of N-S trending reverse faults along structural highs by Awata (1991) and Sugiyama (1992). They call this faulting event Genroku-type earthquake (Matsuda, 1978).

The northern end of this zone is located on the margin of forearc basins. N-S structural high axis like Muroto peninsula does not continue to the North (Fig. 6).

2.4 Deformation of the Shikoku zone

In the Shikoku zone, NNW-SSE trending structures are predominant like synclines of Kii-suido and Bungo-suido, Mt. Tsurugi anticline and Hijikawa monocline, which indicate an arc-parallel shortening (Fig. 6). This evidence, together with the right-lateral strike-slip motion of MTL, supports the hypothesis of westward movement of forearc sliver. The Shikoku zone can be recognized as a forearc ridge zone which is significantly compressed to the island arc direction(Fig. 8). It is a very rare case in forearc deformation, but this arc-parallel compression of forearc is a very rare example which is theoretically shown in MaCaffery (1992).

Hijikawa area in the west of Shikoku shows a monoclinal structure whose axis is drawn from the uplift-rate contours and studies of the late Quaternary terrace deformation along the Hijikawa river (Fig. 7; Tsukuda, 1992).

Satoh et al (1994) studied microearthquakes around the borders between Ehime, Kagawa and Tokushima prefectures along MTL and revealed very shallow hypocenter distribution less than 8 km. This earthquake swarm (S of Fig. 6) is in the west of Mt. Tsurugi anticline located in the flexure of westerly inclined fold (Fig. 8). This is the same situation as the Wakayama microearthquake swarm (Wakayama Microearthquake Observatory, 1992). Earthquakes of magnitude more than 4.0 clearly show thrust faulting with E-W P-axis (ditto).

The maximum compressional axis obtained from earthquake mechanism analyses is oriented to ENE-WSW (Kimura and Okano, 1992), almost parallel or slightly oblique to the zone. This maximum stress orientation is concordant to the folds development mentioned above. The zone continues to the east in the area of the Mikawa earthquake, of which maximum compression axis is oriented to ENE-WSW (Fig. 3; Ando, 1974)

2.5 Seto'uchi shear zone

The Seto' uchi longitudinal basin (Setonaikai or Seto inland sea) on the north of MTL has characteristic dextral shear structures. The Seto' uchi basin is divided into four major en-echelon basins, namely Osaka bay, Harima-nada, Hi'uchi-nada, Iyo-nada. The long axis of these basins (syncline axis) is oriented to NE-SW, at the angle of 30 to 40 degrees to MTL. The northwestern margin of basin is bounded by dextral reverse faults dipping to the northwest. These synclines and anticline with faults can be explained as structures in a right-lateral shear zone. The Fig. 9 summarizes the active structures of SSZ. These faults and folds are recognized as thrust shears (P-shear) and drag folds, respectively, in a shear zone (Wilcox et al, 1973; Skempton, 1966). This shear zone about 80-100 km wide is named as "Seto'uchi shear zone" (SSZ; Tsukuda, 1992).

We can see a typical structures of shear zone in Osaka bay and Harima-nada area which is located in the eastern end of SSZ (Fig. 10). Fig. 11 shows a strain ellipsoid together with faults of different orientations in right-lateral shear zone. Most of the northwestern marginal faults of Osaka bay belong to D-shear, P-shear and reverse fault, increasing the angle to shear zone, getting larger vertical component

The Osaka group surrounding Osaka bay is well surveyed and one of type Quaternary sediments in Japan (Huzita and Kasama, 1982; Huzita and Maeda, 1985; Mizuno et al, 1990; Mizuno, 1992). It is suggested that topography or landscape of this area has been made during the last 1 or 0.7 Ma by Sangawa (1986b). In other words, Osaka basin is made by the movement of northwestern marginal faults of Arima-Takatsuki Tectonic Line and Rokko fault system which caused 1596 Keicho-Fushimi earthquake and 1995 Hyogo-ken nanbu earthquake. The thickness of Osaka group reaches as much as 2000 m in front of the higher Rokko mountains. This Osaka bay is strongly affected by E-W compression, which may be a effect of the Pacific plate (Huzita, 1980; Kuwahara, 1985) which can be seen by the development of thrust faults of Uemachi fault and Ikoma fault in the east.

Other basins in the west of SSZ have very limited structural information. There are, however, some hints for tectonics, that is, right-lateral strike slip of Iwakuni fault system (Higashimoto, 1983; 1986, Tsukuda, 1985) of Yamaguchi prefecture , Koi fault in the west of Hiroshima city and Chojagahara fault to the north of Onomichi city.

SSZ extends to central Kyushu of volcanic region (Matsumoto, 1979) where E-W trending en echelon grabens and normal faults are intensively developed as shown in next section. Fig. 12 shows stress trajectories of maximum compression in and around SSZ, mainly obtained from seismological data (Shiono, 1980; Kimura and Okano, 1992) and active faults data (Research Group for Active Faults of Japan, 1991; Tsukuda et al, 1982; 1985). This shear motion is not able to see in geodetic surveys (Hashimoto, 1990).

2 .6 Right-lateral shear zone of central Kyushu

The central Kyushu is the western extension of Seto'uchi shear zone (Fig. 1 and Fig. 9; Tsukuda, 1992). There is no tectonic boundary between Setonaikai in the east and central Kyushu except for the volcanic front (Fig. 13). In this volcanic region, four major volcanogenic grabens are developed (Fig. 14). They are called, Unzen, Yufu-Tsurumi, Kuju-Haneyama and Aso grabens. A dextral shear deformation is very clear in central Kyushu although Tada (1984; 1985) proposed north-south rifting model (Hatanaka and Shimazaki, 1988; Fig. 15). Stress trajectories of maximum compression support this shear motion (Fig. 16). It is easily understood that hydrothermal activity and high pore pressure in a volcanic region are contributing to the development of normal faults. The Unzen graben shows a typical distribution of normal faults around volcano in E-W compressional stress field (Kaneko, 1973). Fig. 17a illustrates active faults of terrestrial (Chida, 1979, Tsutsumi, 1978) and submarine (Nakai et al, 1982; Geographical Institute of Japan, 1988) area s. Leaving from volcanic centers, normal faults tend to settle their orientation to E-W of regional maximum horizontal stress. This is very concordant with stress field from seismological analysis (Yamashina and Mikami, 1977). The length and width of this graben is 42 km and 12 km, respectively. This characteristic fault distribution coincide with the dike pattern of Spanish peaks (Ode, 1957). This pattern is quite different from rifting of Iceland and Okinawa trough. Fig. 17b shows a stress trajectories obtained from active faults. (Ohta (1972;1987) recognized Chijiwa caldera, but there is no evidence of active faults. The Unzen graben typically shows a fault distribution pattern of E-W compressional stress field, developed and modified by the volcanic activity (uplifting of magma) of Unzen volcanoes.

The general direction of grabens is oriented at the angle of 40-50 degrees to the trend of the shear zone. This means that there is no positive or negative zone-normal dilation in the shear zone (Ramsay and Huber, 1983).

Fig. 18a shows active fault distribution around Yufu and Tsurumi volcanoes. This graben area has been called as follows, Beppu-nishi (west) and Beppu-higashi(east) grabens by Chida (1979), Hayami grabens by Ikeda (1979)Beppu-bay and Yufuin grabens by Chida (1992). Tsukuda (1993) named this graben as Yufu-Tsurumi graben taken from names of volcanoes. This graben pattern is a little twisted compared with Unzen graben. This is the reason why eruption centers of Yufu-dake and Tsurumi-dake is a little shifted. Recently, Shimazaki et al (1986) and Nakata et al (1989) surveyed distribution and activity of submarine active faults in northern Beppu bay. In the southern margin of Beppu bay no active faults are found, but the author expects active faults there according to significant topographic relief (Fig. 19). The ratio of width to length of graben is 1:3 or 1:4. This is almost the same ratio as Unzen graben.

Kuju-Haneyama graben (Fig. 20) and Aso graben (Fig. 21) are also developed by the same manner, mentioned above (Tsukuda, 1993). Volcanic activities looks to be working as hydrofracturing for stress measurement.

The rifting model of the Central Kyushu proposed by Tada (1984,1985) is not supported by the study of active faults. Hashimoto and Jackson (1993) reviewed his analysis and did not support his results either. This orientation of grabens as well as fault pattern is completely different from that of the "extensional" Okinawa trough.

2.7 Development of tectonic landform of southwest Japan arc

In the east of Southwest Japan arc, the oblique subduction of the Philippine Sea plate is quite obvious (Seno, 1977; Seno et al, 1993), which gives the driving force of westward translation of forearc sliver (Fig. 13). In the west, it becomes not clear because the trench axis rotates counterclockwise. This means that there is no driving force for the westward translation. The gradient of translation rate along the forearc sliver to west can make the arc parallel compressional structures of Shikoku zone.

Fig. 22 shows generalized distribution of displacement across the Southwest Japan arc. This explains zonal arrangement of active structures. It is very interesting that a right-lateral shear is expected along the outer ridge between the inner trench slop and the forearc basin zone. Some kinds of extensional structure are expected between Shikoku zone and forearc sliver zone.

Fig. 23 illustrates the basin development in southwest Japan. It is very interesting that basins of different orientation, origin and structure are formed during the same period.

2 .8 Zonal arrangement of Ryukyu arc and Okinawa trough

In the middle and south of Okinawa trough, the development of en-echelon grabens is significant. Orientation and density of active normal faults in Okinawa trough are shown in rose diagram (Kato et al, 1988; Fig. 24). In the southern Okinawa trough, faults are oriented at low angle (15 degrees) to the zone of Okinawa trough. Sibuet et al (1987) and Ota and Kaizuka (1991) suggested that this en-echelon grabens are developed by the dextral shear in the Okinawa trough.

Fig. 25 shows several examples on orientation of normal faults in a shear zone. Data are obtained from Taupo-Rotorua depression (Cole, 1984: New Zealand Geological Survey, 1973), Fizroy trough in Australia (Smith, 1968) and Guatemara-Montagua fault zone (Plafker, 1976). According to the text book of Ramsay and Huber (1983), It is very clear that Okinawa trough belongs to extensional (positive dilational) shear zone.

The most remarkable active structure of forearc sliver of the Ryukyu arc is a development of transverse normal faults (Fig. 26) which is typically shown in Miyako island (Kawana and Pirazzoli, 1989). This structure indicates an arc-parallel extension. Many examples are reported concerning on forearc extension (Kimura, 1985; Kuramoto and Konishi, 1989; MaCaffery, 1992).

This interesting structural phenomena of forearc extension and backarc dextral shear can be explained by that the migration rate of southern part of the Ryukyu forearc is much higher than that of northern part because of a convex shape of Ryukyu arc-trench system. The structural contrast between forearc compression of Southwest Japan arc and forearc extension of Ryukyu arc depends on only shape of curvature of arcs.

2 .9 Junction between the southwest Japan arc and the Ryukyu arc

It is very significant that the movement of forearc sliver is very important in the tectonics of oblique subduction. Fig. 27 shows the speed of forearc sliver translation is coupled with backarc shear deformation. The oblique subduction of the Philippine Sea plate to the Eurasia plate plays a very important role in development of backarc shear zone. The arc-parallel translation rate changes as a function of the obliquity between the two plates. The higher migration rate of the forearc sliver in the southern Ryukyu arc is apparently coupled with the development of en-echelon grabens in the backarc, Okinawa trough. In the northern Okinawa trough active faults are quite rare (Kato et al, 1988) because of low migration of forearc sliver. This suggests that the major active tectonic framework of the Okinawa trough, that is, extensional right-lateral shear zone is not directly connected to the central Kyushu which belongs to the Southwest Japan arc.

3. Paleoseismicity of southwest Japan

In the latter half of this paper, paleoseismic activities in southwest Japan will be discussed together with active tectonics shown in the previous chapter. It is very important to develop some works in order to identify a source fault for a historical seismic event, because we may find precautional faults (Matsuda, 1980) on the basis of "characteristic earthquake model" (Schwartz and Coppersmith, 1984). Nakata et al (1990) showed us a very successful example of the Philippine earthquake of 1990. Each seismic event works as an incremental displacement for the on-going tectonics. Therefore, a long term (more than 1500 years) seismic activity which is especially possible in southwest Japan with long historical records, should show us a deformation process and time-space relationship of faulting in the area. This may also provide a clue to predict a future ocurrence of earthquakes in the active tectonic system in southwest Japan.

3.1 Migration of large earthquakes in central Japan

Historically in Japan, there were many large earthquakes which caused severe damages. Some of them are well recorded and documented (Table 1). Tsukuda (1987) examined historical earthquakes in the Kinki and the Chubu areas from the earthquake catalog by Usami (1975, 1987), and then discussed their source faults from some geologic evidences, and pointed out that clustering and eastward migration of earthquakes since the early 16th century are significant in the central Kinki area. It was concluded that the 1596 Fushimi earthquake caused by the movement of the Arima-Takatsuki tectonic line and Rokko fault system from distribution of damaged area and some faulting evidences at the archeological excavation sites. The faults of the 1995 Hyogo-ken nanbu earthquake, which probably did not move during the 1596 earthquake, is located in the southwestern margin of the above cited fault system. This estimation is being examined by the many trench excavation surveys after the earthquake to find faults with high possibility of movement. Tsukuda (1987) paper also forecasted that the future seismic activity would be concentrated outside of the past faulting area and this seems to be correct.

The trench excavation surveys have been conducted widely in Japan to identify paleoseismic events on faults. The author himself participated many excavation surveys in last 15 years and found recurrence intervals are long, more than 1500 years in southwest Japan. This is quite different from faults to the east of the Itoigawa-Shizuoka Tectonic Line, for example the Nagano active fault system (Tsukuda et al, 1995a), Itoigawa-Shizuoka Tectonic Line active fault system (Okumura et al, 1994), the Northern Izu fault system.

Kinki district

Sangawa (1986) investigated the detailed topography of the Konda-yama tumulus (burial mound, 430m long) in the eastern end of Osaka plain. This tumulus is said to have been built for the Emperor Ohjin in the forth or fifth century. He found that the tumulus deformed by the Konda fault of 4 km long, Vertical displacement is measured 1.8 m, which may represent an historic destructive event. He concluded that the event was the earthquake of 1510 because there was no other destructive earthquake reported in the eastern Osaka plain in our history. Magnitude for the earthquake is calculated to be 7.1 form the equation M - (log D+4.0) / 0.6 (Matsuda, 1975; 1977). D (in meter) is the surface displacement accompanying an earthquake. The long-term vertical slip rate (s) of 0.25-0.4 m / 1000 years for the Konda fault is obtained from terrace deformation analysis. The recurrence interval (R) is estimated at 5000 to 7500 years from the equation log R =0.6 M-(log S+4.0) (Matsuda, 1977). From the empirical basis of the relation between magnitude and surface fault length, surface faults of the earthquake of magnitude 7.1 extends at least 20 km. Therefore, it is very possible that the north-south trending eastern marginal fault system of the Osaka plain composed of the Konda fault and Ikoma fault, generated the earthquake of 1510.

The following large earthquake after the 1510 event in the Kinki area is 1596 (Keicho-Fushimi) earthquake. There were many discussions on the source fault for the 1596 earthquake. On the basis of hazard area illustrated by Usami (1987), it is suggested that the Arima-Takatsuki Tectonic Line fault system and Rokko fault system of the northwestern margin of Osaka basin is the source faults of the earthquake. Recently, in some archeological excavation sites found geologic evidences of faulting between 15 and 17 century layers. Trench excavation surveys on one segment of the Arima-Takatsuki fault performed in 1995 strongly suggests that the 1596 event was caused by the fault (Sangawa, 1995; personal communication).

The epicenter of 1662 earthquake (M=7.8) is located in Biwa lake (Usami, 1987). The western coast region of the lake suffered severe damage and it is reported that a significant area of the coast had been submerged into the lake, Sangawa and Tsukuda (1986b) investigated ancient picturesque maps for comparison with present topography. The detailed bathymetric map shows the ancient main road is now below the water. The tectonic depression from the earthquake was estimated at about 2-3 m. Fault scarplets near the coast that cut the terrace dated younger than 5700 years B.P. show 2.0-2.7 m of vertical displacement, the amount of which is comparable the depression. The submerged zone was recognized along the entire western coast of Biwa lake. The total length of surface rupture is expected to be more than 50 km for the earthquake magnitude of 7.8. Consequently, it is concluded that the 1662 event was caused by the movement of the western marginal fault system of Biwa lake, which is composed of en echelon faults and is closely related to the development of Biwa lake. Recent archeological excavations in Biwa lake indicated that the previous events were occurred in some time middle of Yayoi period (BC 0+-50) and in about 3000 years B.P. (Sangawa and Tsukuda, 1986).

After the 1662 earthquake, 158 years later, the Hikone earthquake of 1819 (M=7.4) occurred in central Kinki. The seismic intensity map for the earthquake (Usami, 1987) suggests that the marginal faults of the Suzuka mountains were activated although no geological evidences has not been found yet. The Iga-Ueno earthquake (M=7.6) occurred in 1854. Yokota et al (1976) found some surface evidences of surface ruptures of the earthquake along a segment of the Kizugawa fault system. Seismic intensity map of Usami(1987) suggests the Kuwana and Yokkaichi faults may be activated during the earthquake. Between 1819 and 1854 earthquakes the so-called Kyoto earthquake (M=6.5 +/- 0.2) occurred locally in the Kyoto city area. After this earthquake, 37 years later, the great Nobi earthquake of magnitude 8.0 occurred in the Chubu district, an adjoining seismic area.

Chubu district

The Atera fault system in the Chubu district is known as one of the most active fault in Japan. It dissects central Japan with a northwest-southeast strike and a length of about 70 km. This fault shows left-lateral slip with a vertical component of northeast side up. Lateral slip rate is estimated to be about 3-5 m / 1000 years (Sugiyama and Matsuda, 1965). Many excavation survey had been performed since 1981 (Tsukuda and Yamazaki (1984). The latest four events shows an average recurrence interval of 1700 years. The most recent event for the Atera fault is estimated to be the great earthquake of 1586 (so-called Tensho earthquake, M=7.9-8.1 by Usami, 1987), from following data,

(1) Usami(1987) located the epicenter in the northwest border of Gifu prefecture from a damage area distribution. (2) Dai-itokuji, a abandoned temple on the fault is reported to have been collapsed completely during the 1586 earthquake. En-echelon fractures still remain covered by thick forest near the temple. (3) There is a legend that the 1586 earthquake made a pond, which is a wet muddy rice field now which is explained to be a sag pond from a geomorphological view point. (4) Large scale land slides during the earthquake are found to the southeast of the fault system, recently (Matsushima, 1994 personal communications). (5) The

1586 event was supported by recent excavation surveys along the fault by Toda et al (1995).

Therefore, the recognition of the Atera fault as one of precaution faults by Matsuda (1981) is denied (Tsukuda et al, 1993). Sugiyama et al (1994) revealed that the Miboro fault system which is the northwest extension of the Atera fault system also displaced during the 1586 earthquake. This evidence suggests that faults of 1586 Tensho earthquake extends as long as 85 km in total.

After the Tensho earthquake, the Kaga earthquake of 1799 was caused by the movement of the trust fault (Morimoto fault) at Kanazawa city (Sangawa, 1986) in the northward extension of the Tensho rupture zone. The earthquake of 1858 (M=6.9) on the Atotsugawa fault (Matsuda, 1966; Research Group for Excavation of the Atotsugawa Fault, 1983) in the east of the northwest fault termination point of the Tent earthquake.

The Nobi earthquake of 1891 (M=8.0, Matsuda, 1974) occurred after these seismic area in the east. It seems that the occurrence of the Nobi earthquake is closely related to the earthquake migration in the Kinki and Chubu districts. Close to the both ends of the Nobi earthquake faults ruptured in 1945 (Fukozu fault, Mikawa earthquake) and 1948 (Fukui earthquake).

The 1925 Tajima earthquake, M=6.8 and the 1927 Kita-tango earthquake, M=7.3 occurred after more than 6000 years interval (Tsukuda et al, 1989a; 1989b; 1993) in the tectonic province of San'in zone (Fig. 3) northwest of central Kinki area, which had been active during 16 to 19 centuries. The 1872 Hamada earthquake (M=7.1) and the 1943 Tottori earthquake (M=7.2) occurred in this zone.

The time-space distribution of earthquakes and their faults since the 16 century is illustrated in Fig. 28. It is interpreted that most of faults in the core area of central Japan had been activated during the last 1300 years as discussed above. It is recognized by geological observations that an active fault causes "characteristic earthquakes" (Schwartz and Coppersmith, 1984) with a long recurrence interval. A seismic chain reaction or clustering can be seen in seismotectonic zones in intraplate Japan. With this view, Tsukuda(1987) designated four "potential seismic zones", which has almost same meaning as precaution fault of criterion 1 in Matsuda (1981). Potential seismic zones are characterized by low seismicity at present, no historic major earthquakes and tectonic significance. This will be discussed in the next section.

3.2 Intraplate paleoseismic activities of southwest Japan arc

According to recent progresses of paleoseismology, the author describes a long-term seismic behavior in southwest Japan for more than 2000 years. Some of the active faults in this area are at present being investigated and much more detailed studies are required. It is, however, hard to avoid pointing out the following features.

(1) Shifting of seismic active area or partitioning of activities is recognized in southwest Japan. Fig.29 shows the time-space distribution of paleoseismic activities obtained from the data set of Usami (1987; Table 1) and excavation surveys. The activity of central Kinki district has more than 1500 years interval. Shifting phenomena for seismic activity from central Kinki to both western Chubu

and Tango-San'in districts are recognized after c.a. 6th century, as happened similarly during 19th century.

Seismic area of Kinki from 16th to 19th century is located in the eastern end and extension of SSZ, where active faults are densely populated and show highly compressive structures, namely north-south trending reverse faults of Uemachi fault, Ikoma fault and western marginal faults of Biwa lake. The Kinki district may be seen as a "compressive bend" to the dextral shear zone of SSZ (Fig. 9).

In the west of Seto'uchi district, Beppu bay to Aki-nada area, two of seismic activity is recognized since the end of 16th century. The epicenter of November 4, 1596 (M=7.0) earthquake is located in Beppu bay. There is a legendary story that the pre-existing Uriu island was subsided under the sea during the earthquake, although no geological evidences are reported. This is presumably caused by the southern marginal fault of the Yufu-Tsurumi graben (Fig. 18 and 19). This earthquake was followed by the earthquakes of March 17, 1649 (M=7.0) and January 4, 1686 in the Iyo-nada area. The trend of activity seems to be related to the geological structure. After 179 years quiescence, the earthquake of December 26, 1854 (M=7.3-7.5) occurred at southern end of Iyo-nada. This earthquake was followed by the earthquakes of October 12, 1857 (M=7.3) and June 2, 1905 (M=6.7) at Aki-nada area. It is very interesting that these two series of active period and period of intermission coincides with the seismic pattern of Kinki district mentioned in the previous section.

(2) From historical earthquakes in central Japan, Tsukuda (1987) proposed four major potential seismic zones (Fig. 30) outside of previously active seismic zone (Fig. 28) as follows,

I. Median Tectonic Line (MTL) seismic zone:

The right-lateral slip rate and recurrence interval of MTL are estimated 5-10m

/1000 years (Okada, 1980) and 1500-2000 years, respectively. The most recent event of MTL is obtained as 5 to 8 century in the central to western segments in Shikoku (Yamazaki et al, 1993; Okada, 1993). Tsukuda(1996a) revealed by trench excavation surveys that no historic earthquakes since 16th century occurred along the Negoro fault of the Kinki segment of MTL. The most possible earthquake appeared in the catalog of Usami (1987) is the earthquake of 734, by that the Koyasan temple was reportedly damaged. Recently, in the eastern segment of Shikoku, the latest event was reported to be younger than 16 century (Okada, 1993).

II. Itoigawa-Shizuoka Tectonic Line seismic zone:

ISTL is a major tectonic boundary together with MTL in Japan. In general, this tectonic line composed of left-lateral strike slip faults with some amount of vertical component. The most recent event along ISTL is estimated at 841 AD At Gofukuji fault (Okumura et al, 1994), 1700 to 2500 years B.P. at Okaya site (Research Group for the Okaya fault, 1984), and 1000 to 1400 years B.P. at Fujimi site (Miyoshi and Research group for the Itoigawa-Shizuoka tectonic Line, 1984) by excavation surveys in central segments of this zone. The recurrence interval, slip-rate and average slip for single event is estimated to be shorter than 1000 years, 9.4+-4.5 mm (since c.a. 6000 years B.C. and 7.5 +-1.5 m, respectively (Okumura et al, 1994).

III. Central Japan Alps (CJA) seismic zone:

CJA is characterized by thrust faults on both flanks of central Japan Alps mountains. Inadani fault system belongs to this seismic zone. There is no reliable information on paleoseismic activity in the zone.

IV. Noto peninsula (NP) seismic zone:

NP seismic zone is characterized by very short dip-slip faults with low seismicity. There is no reliable information on paleoseismic activity in the zone yet.

This was partly proved by the hazardous Hyogoken-nanbu earthquake of 1995. The 1596 Fushimi earthquake was determined to have been produced from the Arima-Takatsuki Tectonic Line and Rokko fault system from distribution of damaged area and some faulting evidences at the archeological excavation sites. Their own characteristic earthquake is very different from the faults of the 1995 earthquake. The faults of the 1995 Kobe earthquake, which probably did not moved during the 1596 earthquake, is located in the western margin of the above cited fault system. The surface faults area is clearly located in the seismic zone of MTL cited above. Faults of Hyogoken-nanbu earthquake and their rupturing process are discussed in the next section.

Two phenomena mentioned above indicate a long-term seismotectonic cycle (Tsukuda, 1989b) of c.a. 1300 to 1600 years, and are stongly suggesting the movement of MTL in the near future.

4. Faults of the 1995 Hyogo-ken nanbu (Kobe) earthquake

The 1995 Hyogo-ken nanbu (Kobe) earthquake (M=7.2) caused severe damages in Kobe area. Death toll reached more than 6000. After the earthquake, there are many arguments on existence of faults in the Kobe area. The author maintained his opinion that no faults moved in the urban area from geological and seismological view points. Terrible hazards downtown Kobe area may be caused by faulting directivity and/or focusing and amplification of ground motion caused by subsurface structures. On the faults and their rupturing process, Tsukuda (1995) concluded as follows,

The right-lateral strike slip fault of the earthquake is composed of three major segments, namely NE-SW trending Nojima fault (10 km) at northern Awaji island, E-

W trending Takaiso fault (6 km) at the Akashi strait and NE-SW trending Suma fault (9 km) at western Kobe, which extends about 25 km long in total. The Nojima fault displaced as much as 2.1m right laterally at the central part (Awata et al, 1995). Fig. shows active faults distribution obtained from Izaki and Kaneko (1960). The Takaiso fault close to which the epicenter is located, played a major role in faulting process from the view point of active tectonics of the Seto'uchi inland sea which is a right-lateral shear zone (SSZ; Tsukuda, 1992). But, the details are still unknown because of heavy traffic and high flow rate of sea water in the strait. Fig. 32 shows that Takaiso fault has a same orientation as the Arima-Takatsuki Tectonic Line which is a major fault in SSZ as well as MTL. The right-lateral displacement of the Takaiso fault is estimated about 1.3m from GPS measurements between two piers of the Akashi strait bridge under construction (Yamagata, 1995 personal communications). High activity of the Takaiso fault is suggested by that the submarine channel of the Akashi strait is significantly displaced in the right lateral motion across the Takaiso fault.

No reliable observations of surface breaks were reported along the Suma fault, although geodetic measurements by Hashimoto et al (1995) suggest a movement of deeper part of the fault. No surface rupture were not reported either along the foot of Rokko mountains to the east along the Suwayama fault and Uzugamori fault, where damages are limited.

The sigmoidal geometric pattern of three fault segments mentioned above makes two major compressional bends (barriers) which seems to be the locations of earthquake nucleation. Early phase of aftershocks, three to four hours right after the main shock show the rupture was terminated at somewhere central Kobe where a extensional bend and jog is recognized. Regional GPS measurements (Yoshida et al, 1995; Hashimoto et al, 1995) also indicate abrupt decrease of displacements around the same area. It is concluded that fault ruptured at the compressional bend between the Takaiso and the Nojima faults at the initial moment and propagated to another compressional barrier in the east between the Takaiso and Suma faults, which is the second break point. Then the rupture was terminated at extensional bends between Suma, Nagata and Suwayama faults. In the south of the Nojima fault recognized is a releasing bend where is the place of fault termination. Fault ruptures were terminated releasing bends in both ends. This faulting pattern is shown in Fig. 33 and is very similar to recent earthquakes generalized as “A rupture starts from a compressional barrier and stops at an extensional barrier” by Tsukuda (1991).

This fault rupturing process is consistent with the result of Kikuchi (1995) obtained from distant seismographs. Direction of his initial bilateral fault break may be the average direction of two faults, Takaiso and Nojima faults.

This 1995 event, as terrible as it was, was not "the big one" for the area. It did not contribute the mountain building of Rokko mountains and depression of Osaka bay described as “Rokko movement” by Huzita, 1968; Huzita and Kasama, 1982). From paleoseismological studies mentioned in the previous chapter, we may say that the 1596 Keicho-Fushimi earthquake was the main event which caused much hazardous damages around the bay area (Usami, 1987; Sangawa, 1993). Recent on-going trenching studies after the earthquake are proving this conclusions.

V. Discussions

Fig. 34 shows a timing of great earthquakes of Nankai trough and earthquakes inland. From the figure, we can read without hesitation that inland earthquakes are crowded on and in front of the lines of Nankai trough earthquake as pointed out several seismologists. The Hyogo-ken nanbu earthquake may be one of the examples before the great earthquake of Nankai trough. It is quite possible to expect that some other large earthquakes inland may occur in the near future. MTL is one of the candidates for future earthquake generator as discussed in previous section. It is very important to recognize the 100 years seismic cycle together with a long-term seismotectonic cycle of 1300 to 1600 years for earthquake prediction Reseaches.

Recently two volcanoes in central Kyushu, namely Unzen and Kuju volcanoes which belong to the Seto'uchi shear zone become very active. This might be related to the strain release of right-lateral shear. It is reported that the most recent eruption of the Kuju volcano has occurred after the 1700 years quiescence and its recurrence intervals are estimated to be about 1000 to 2000 years.

The author strongly suggests that it is very important to analyze quantitatively the deformation process of SSZ for long-term earthquake prediction in southwest Japan

VI. Conclusions

The author discussed active tectonic features of the Southwest Japan and Ryukyu arcs, and also paleoseismic activities of the area, and made following conclusions:

1. The Oblique subduction of the Philippine Sea plate plays a very important role in the active tectonics of Southwest Japan arc.
2. Tectonic contrast between the forearc rise zone named as the Shikoku zone and the backarc depression named as the Seto'uchi shear zone, separated by the right-lateral strike slip fault, the Median Tectonic Line is totally explained by the westward movement of the forearc sliver of the Southwest Japan arc caused by oblique subduction of the Philippine Sea plate.
3. It is recognized that a significant arc-parallel shortening in the Shikoku zone

which is made by an existence of gradient in an arc-parallel translation rate from east to west as a function of the obliquity between the two plates.

4. The Seto'uchi shear zone of Seto Inland sea is composed of four major basins which are bounded by NE-SW trending and NW dipping reverse fault with right-lateral shear component.
5. The Seto'uchi shear zone continues to the central Kyushu volcanic region. where en-echelon volcanotectonic grabens are developed. Characteristic fault pattern are typically shown in the Unzen graben.
6. Development of active faults of the Okinawa islands and the Okinawa trough is also controlled by the southwestward extensional translation of forearc sliver.
7. Arc-parallel compression and extension of forearc slivers are recognized in the Southwest Japan arc and the Okinawa arc, and they mainly depend on concave or convex shapes of island arcs or plate boundaries.
8. A shifting pattern of seismic area in southwest Japan is found during the last 2000 years. This is thought to be closely related to the right-lateral shear tectonics which has some long-term seismic cycle for about 1300 to 1600 years.
9. Ruptures of the 1995 Hyogo-ken nanbu earthquake started from compressionalbarrier and stopped at extensional barriers, as seen commonly in Tsukuda (1991).
10. Faults of the 1995 Hyogo-ken nanbu earthquake belongs to MTL seismic zone, one of four potential seismic zones. It is suggested that MTL might be a potential fault for the future movement.

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Figures and tables

Figure. 1 Active structures in the Southwest Japan arc.
Solid arrow indicates the direction of the forearc translation. A shear zone named as Seto'uchi shear zone is shaded on the north of the Median Tectonic Line (MTL).

Figure 2 Oblique subduction of the Philippine sea plate and westward forearc migration of the Southwest Japan arc.
Active tectonic features of the Seto'uchi shear zone and the forearc sliver are very different each other.

Figure 3 Arc-parallel zonal arrangement of Southwest Japan arc.
Each zone has its own characteristic features of active structures.

Figure 4 Generalized profile of Southwest Japan arc.
Micro-earthquakes are observed in the area of gray color which is recognized as an island arc lithosphere.

Figure 5 Separated forearc basins of Southwest Japan arc (from Awata & Sugiyama, 1989)
Z: Hyuga basin, A: Tosa b., B: Muroto b., C1: Shima b., C2: Kumano b,. D: Enshu b., a: Ashizuri promontory, m: Muroto p., s: Shionomisaki p., d: Daiozaki p., o: Omaezaki p..

Figure 6 Tectonic structures of the Shikoku zone.
Contours indicate the average uplift rate during last 1Ma (Omori, 1990).
K: Kii-suido syncline, T: Mt. Tsurugi anticline, M: Muroto anticline, H: Hijikawa monocline, A: Ashizuri anticline, B: Bungo-suido syncline, S: the microearthquake swarm in shallow crust west of Mt. Tsurugi.
N-S or NNW-SSE structures suggest arc-parallel compression.

Figure 7 Westward tilting along the Hijikawa river, western Shikoku.
a: Alluvium along the Hijikawa river, b: tilting area c: direction of tilting.

Figure 8 Generalized profile of the Shikoku zone
Microseismic activity is significant in shaded areas.

Figure 9 East-west compression area of Kinki and Chubu in the east of the Seto'uchi shear zone.

Figure 10 Active tectonic structures in the east of the Seto'uchi shear zone.
I: Ikoma faults, U: Uemachi fault, R: Rokko faults, O: Osaka-wan fault.

Figure 11 Orientation of elemental structures expected in a right-lateral shear zone.

Figure 12 σ1 stress trajectory derived from earthquakes and active faults. Dotted area indicates the Seto'uchi shear zone.

Figure 13 Development of en-echelon folds in non-volcanic region and grabens in volcanic region, in the right-lateral shear zone, Southwest Japan.

Figure 14 En-echelon grabens in the central Kyushu.
Dotted area indicates the right-lateral shear zone (Seto'uchi shear zone).
YT:Yuhu-Tsurumi graben, KH:Kuju graben, As:Aso graben, Uz:Unzen graben.

Figure 15 The displacement field related to the baseline modified from Hatanaka & Shimazaki (1988). Direction of the displacement in the northern Kyushu is almost parallel to the shear zone.
M.T.L.: Median Tectonic Line.

Figure 16 σ1 stress trajectory derived from earthquakes and active faults. Dotted area indicates the Seto'uchi shear zone of central Kyushu.

Figure 17 a: Active normal faults of the Unzen graben.
See Fig. 14 for the location of this figure. Notice that normal faults are not arranged in parallel. It is inferred to be made by E-W oriented compressional stress condition.
b: Orientation of maximum horizontal stress in the Unzen area.
Diameter of the circle is about 25 km.

Figure 18 a: Active normal faults in the Yufu-Tsurumi graben.
Y: Mt. Yufu, T: Mt.Tsurumi, A-A': profile line of Fig. 14
b: Orientation of maximum horizontal stress in the area.
Diameter of the circle is about 25 km.

Figure 19 Profile along the line A-A' of Fig. 18 a. showing normal faults in the Beppu bay.

Figure 20 Active normal faults in the Kuju–Haneyama grabens
Am: Mt. Amagoi, Ni: Mt. Noine, Ke: Mt. Kuenohira, Hn: Mt. Haneyama, Wi: Mt. Waita, Km: Mt. Kameishi.

Figure 21 Active faults of the Aso graben

Figure 22 Displacement distribution across zones of Southwest Japan arc.

Figure 23 Development active tectonic basins of southwest Japan.
These basins are formed the same tectonic regime, that is, oblique subduction of the Philippine sea plate.

Figure 24 Orientation of active faults in the Okinawa trough, modified from Kato et al (1988).
a: angle between faults and the trough direction.

Figure 25 Orientation of normal faults to a shear zone.
a: angle between the trend of shear zone and normal faults. Solid bars indicate the range of a in each shear zone.

Figure 26 Active faults characteristics of the forearc and backarc from the Southwest Japan arc to the Ryukyu arc. The explanation of the figure is in the text.

Figure 27 Southwestward translation of the forearc sliver accompanied with the right-lateral shear of backarc caused by the oblique subduction of the Philippine Sea plate. The development of en-echelon grabens in the backarc is closely related to the migration of forearc sliver. Double open triangles indicate a relatively higher translation rate than single ones. Solid arrows indicate the direction of relative convergence between the Philippine sea plate and the Eurasian plate.

Figure 28 Faults of historical intraplate large earthquakes (M>6.5) since the 16th century.
Starting from the 1510 Settsu earthquake, earthquakes migrated to the central Kinki district. After the 1854 Iga-Ueno earthquake, seismicity become very high outside of the central Kinki. (Modified from Tsukuda, 1987)

Figure 29 Time-space diagram of paleoseismic activities in southwest Japan showing a partitioning of activity.
Shaded areas indicate periods of high seismicity estimated from trench excavation surveys and archeological surveys. B: Biwako area, K: Kobe area. Details of earthquakes are shown in Table 1.

Figure 30 Major potential seismic zones surrounding the core of central Japan which had been active during the past 500 yrs. (from Tsukuda,1987).
MTL:Median Tectonic Line seismic zone; CJA: Central Japan S.Z.; ISTL: Itoigawa-Shizuoka Tectonic Line S.Z.; NP: Noto peninsula S.Z..

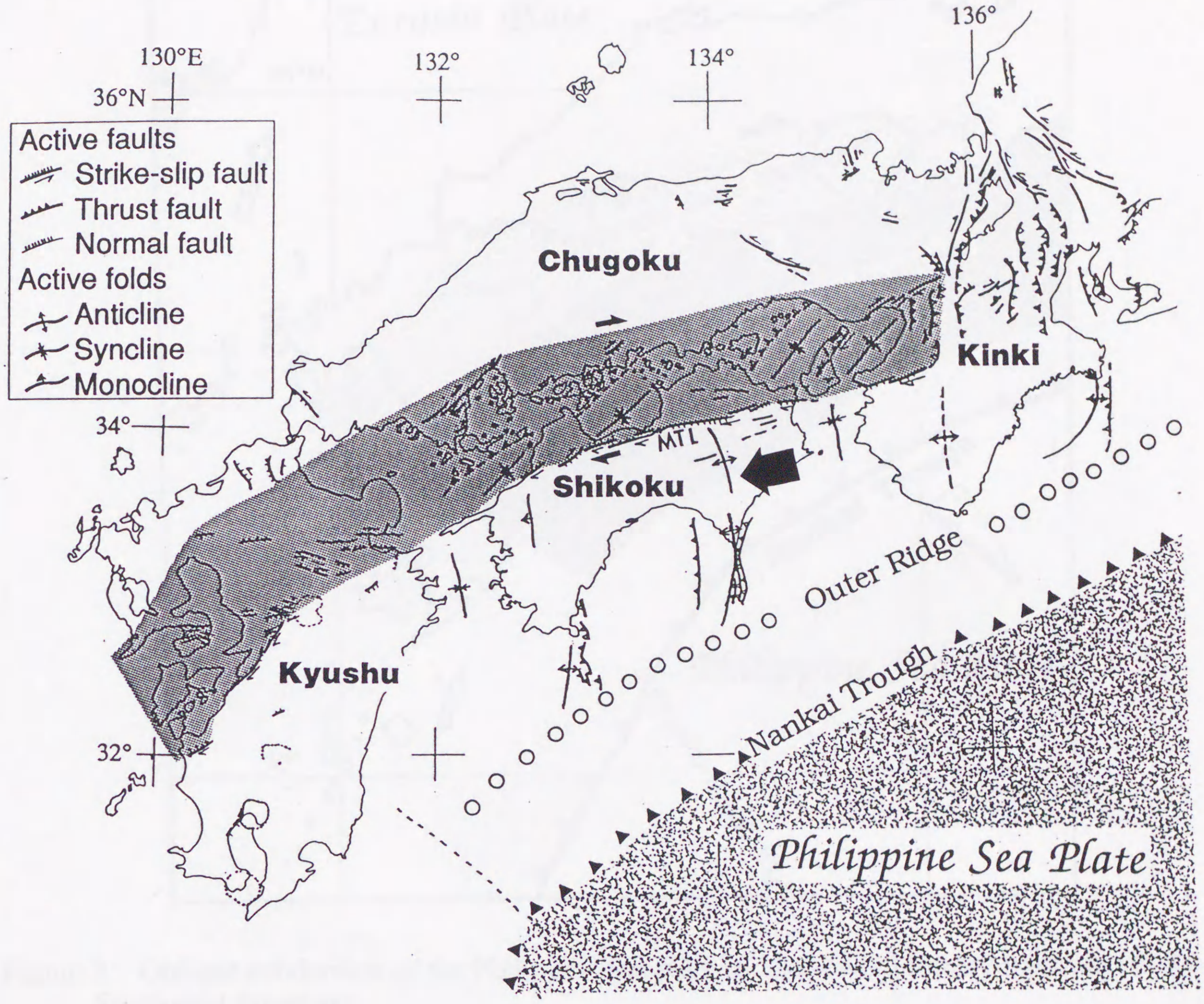
Figure 31 Fault distribution and submarine topography in the Akashi strait.
1A, 2P, 3P, 4A: Anchorage and pier of the Akashi strait bridge under construction

Figure 32 Active faults of the Arima-Takatsuki Tectonic Line and the Rokko fault system.
Faults of the 1995 Hyogo-ken Nanbu earthquake is located in the western margin of the fault system which is the source of 1596 Fushimi earthquake.

Figure 33 Estimated fault rupturing process of the Hyogo-ken Nanbu earthquake from the view point of the fault geometry.
The initial break started from the compressional bend(1) between the Nojima fault and the Takaiso fault. Ruptures were propagated bilaterally , then the second break started from the compressional barrier(2) in the east. Finally ruptures were terminated in the extensional bends(3) or jogs in the east and south.

Figure 34 Relation between inland historic earthquakes of southwest Japan and great earthquakes along the Nankai trough since the 16 century.
Vertical dashed lines indicate the timing of great plate boundary earthquakes along the Nankai trough.

Table 1 Historic earthquakes greater than or equal to M6.5 during the past 1300 years. The original source is mainly obtained from Usami (1987).



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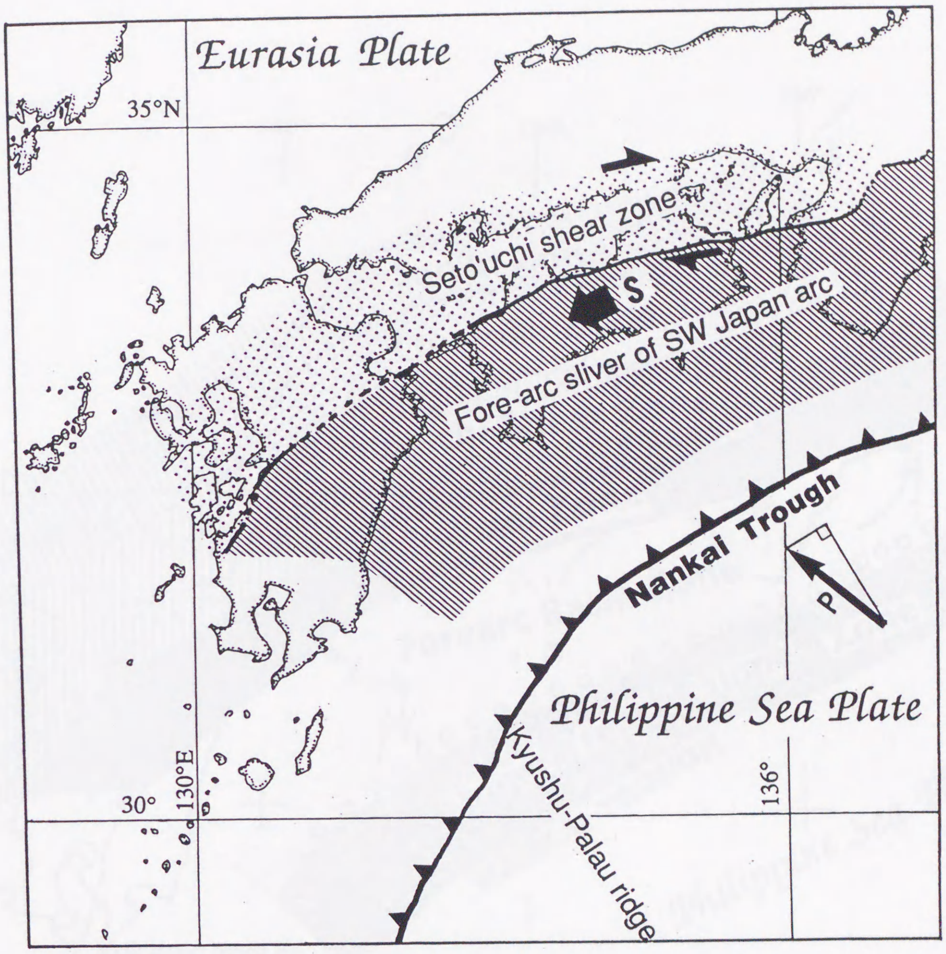

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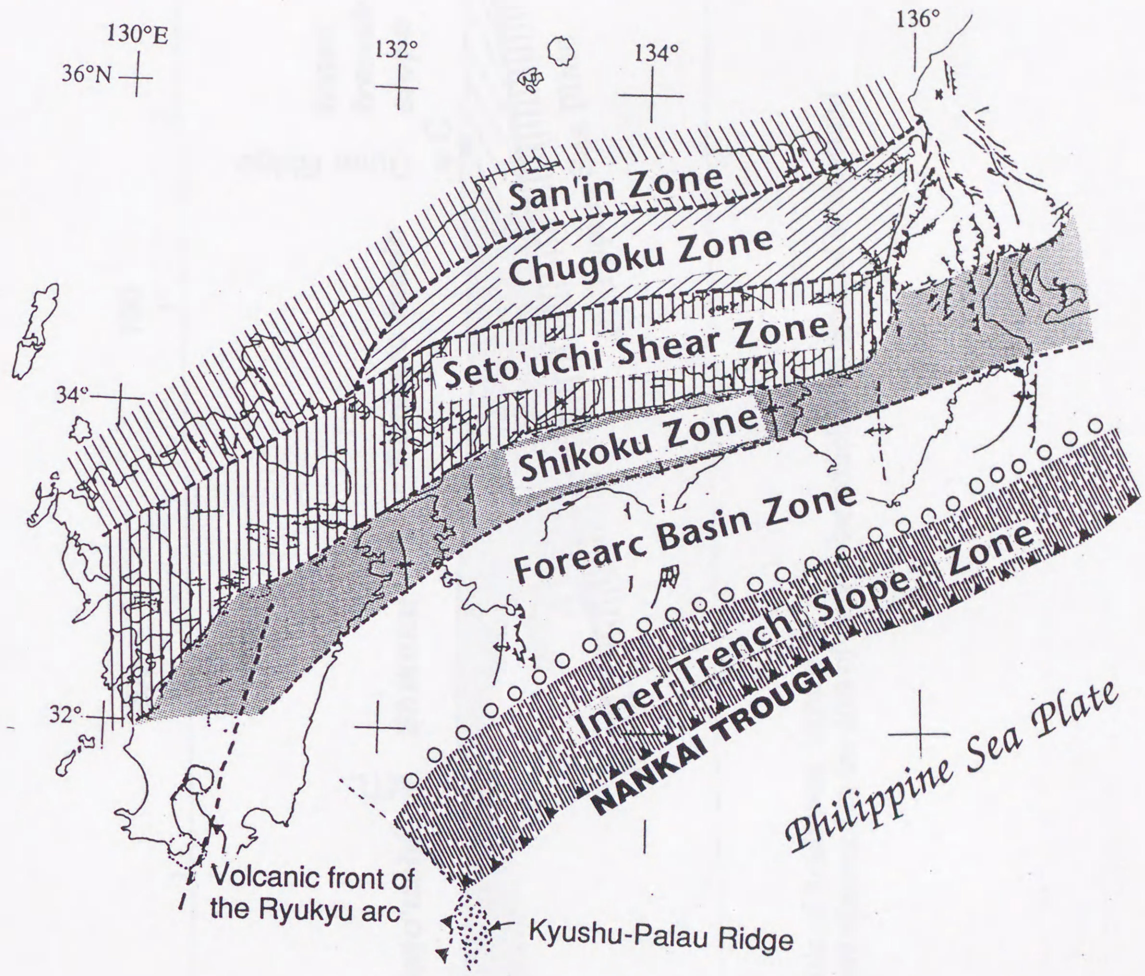
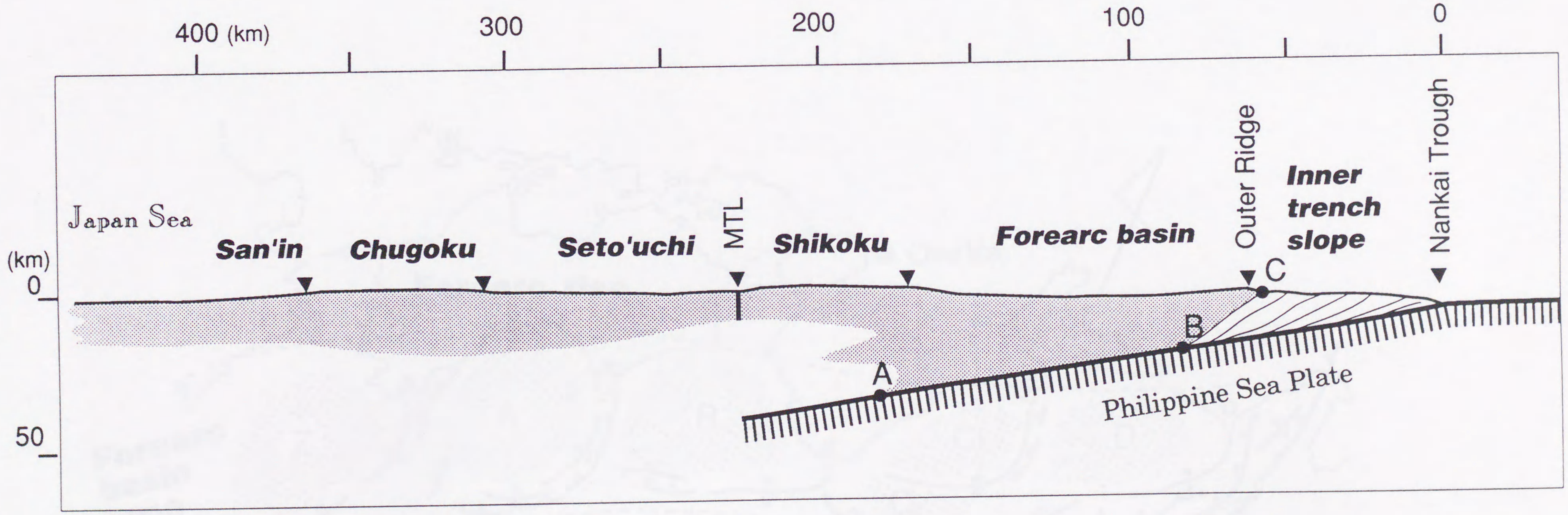


Figure 3 Arc-parallel zonal arrangement of Southwest Japan arc.
Each zone has its own characteristic features of active structures.



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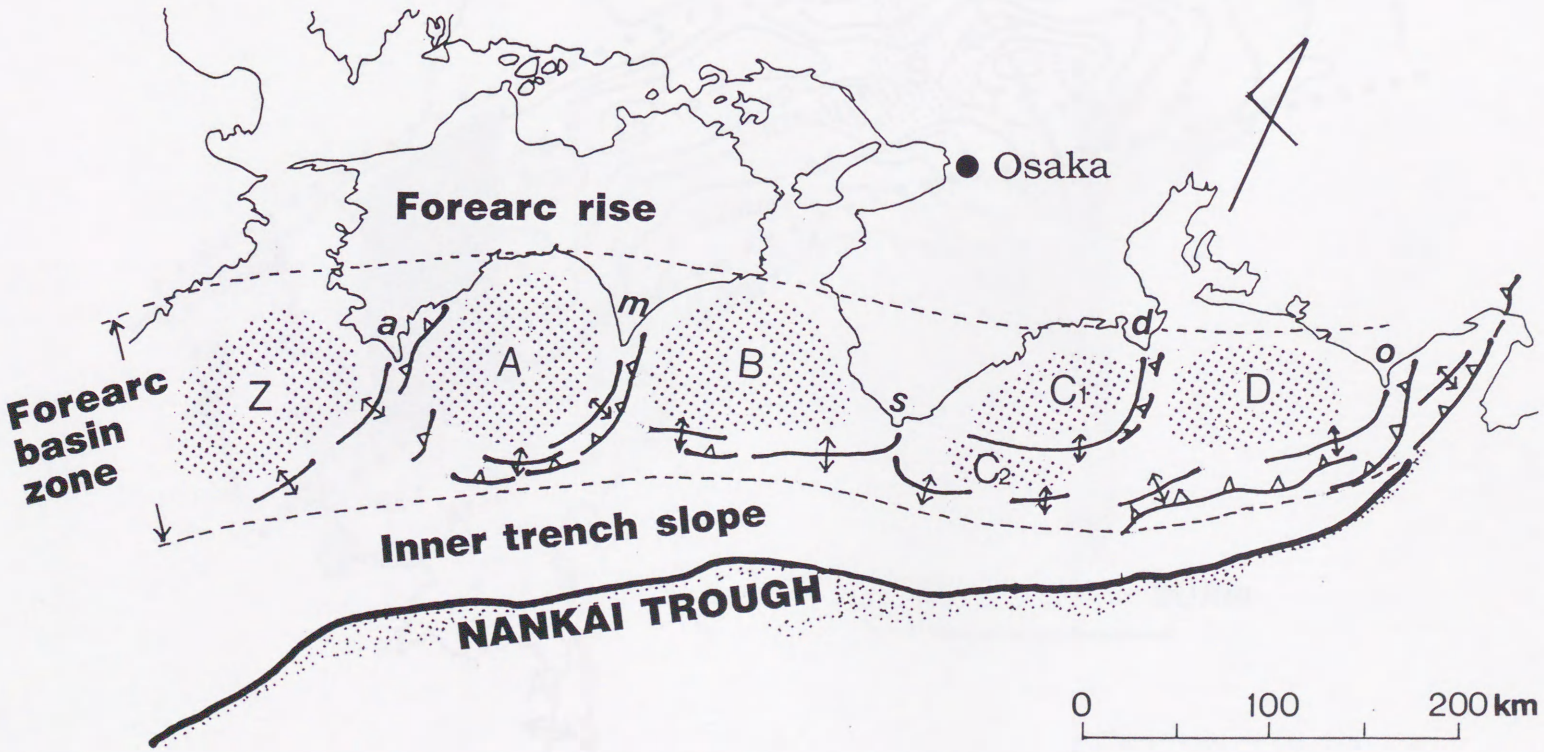
Micro-earthquakes are observed in the area of gray color which is recognized as an island arc lithosphere.



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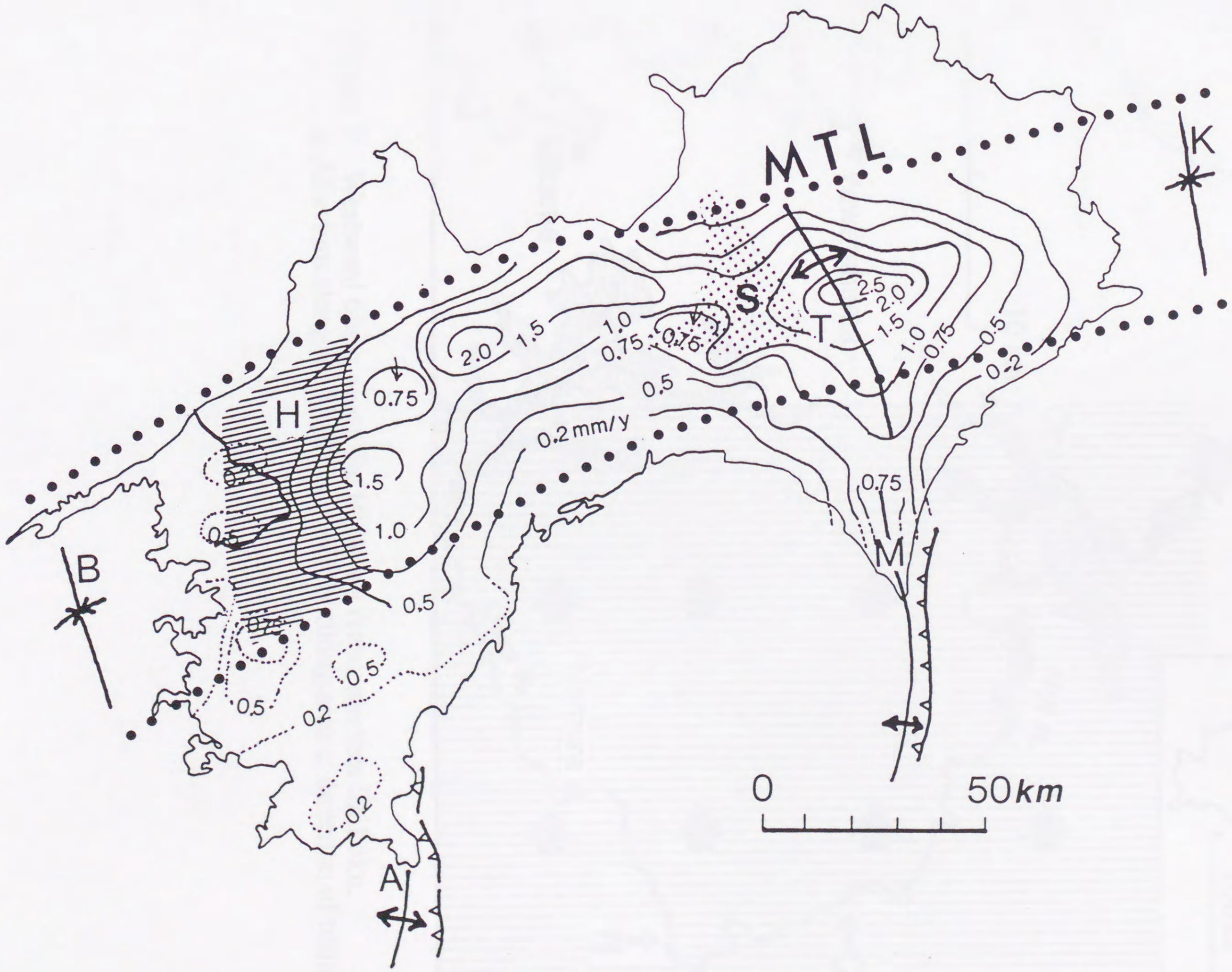

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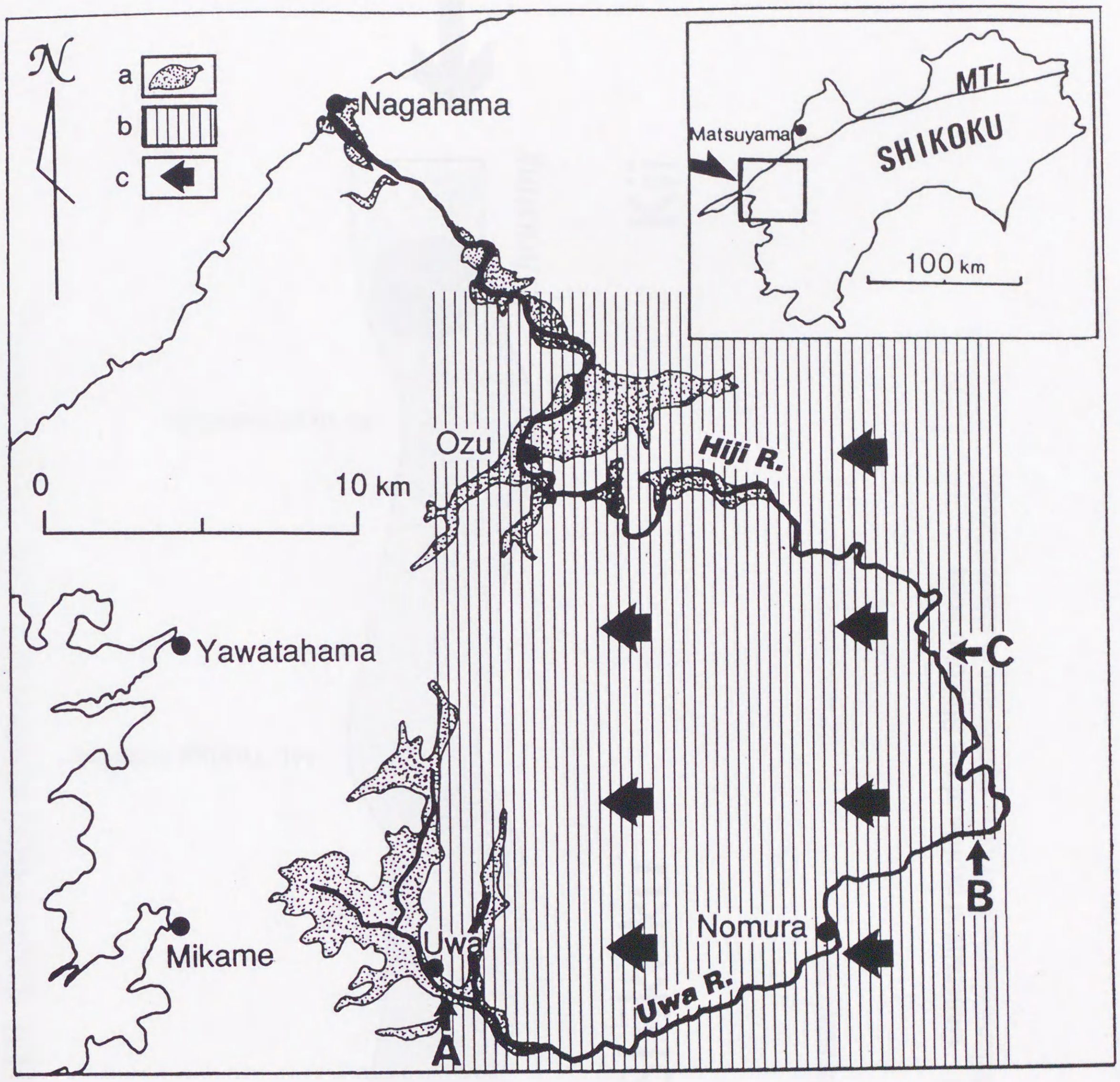

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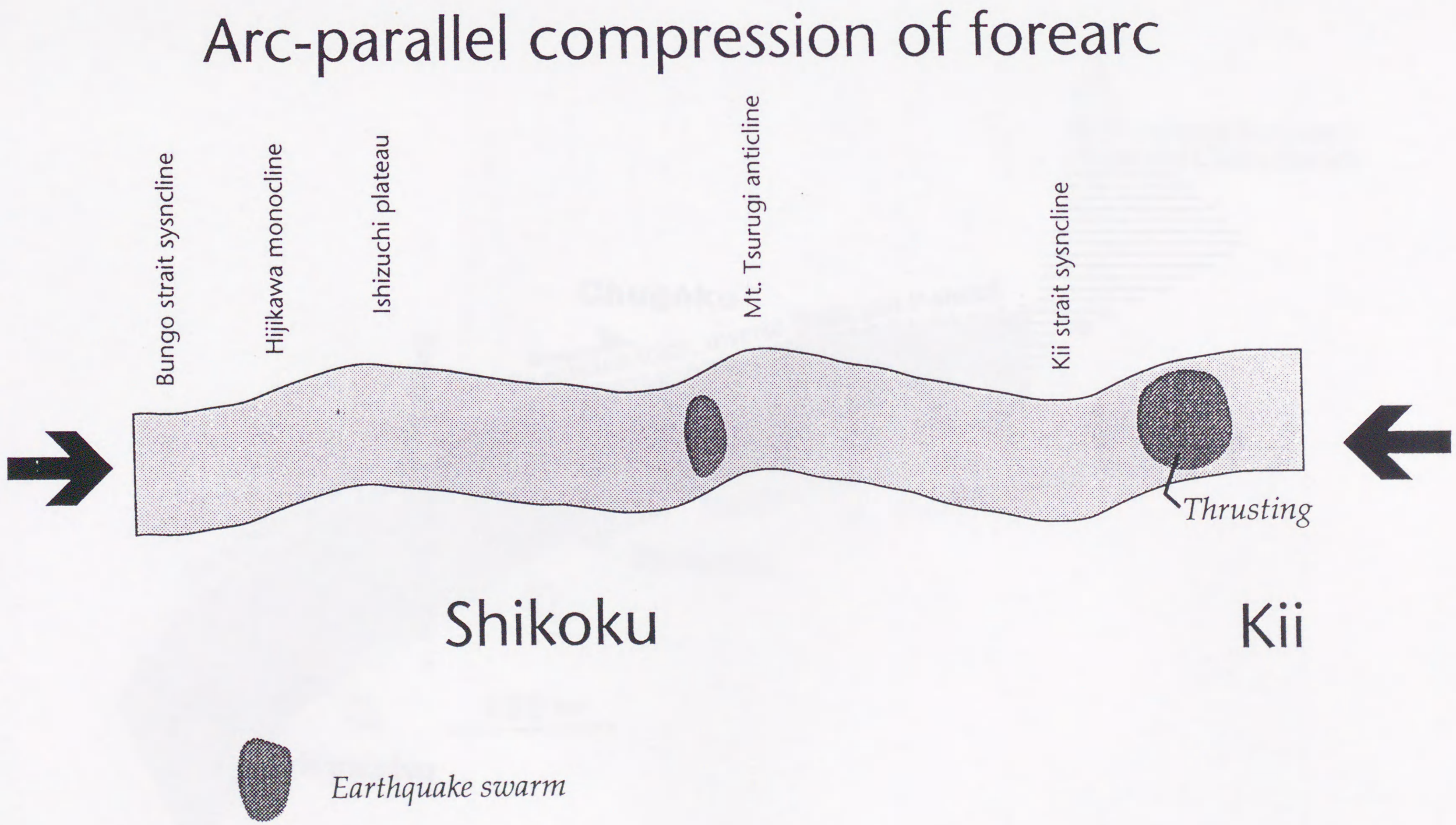

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Microseismic activity is significant in shaded areas.

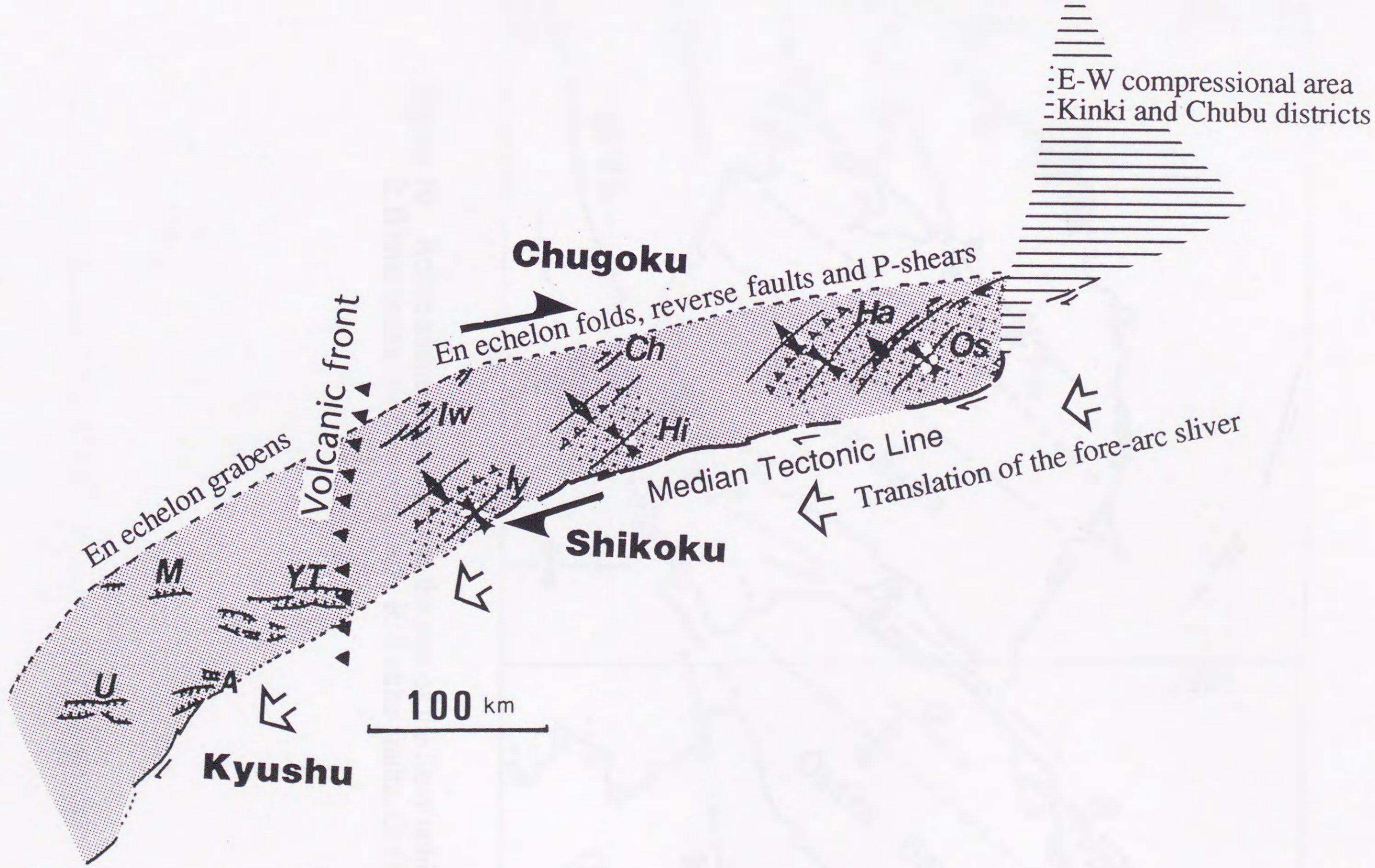


Figure 9 East-west compression area of Kinki and Chubu in the east of the Seto'uchi shear zone.

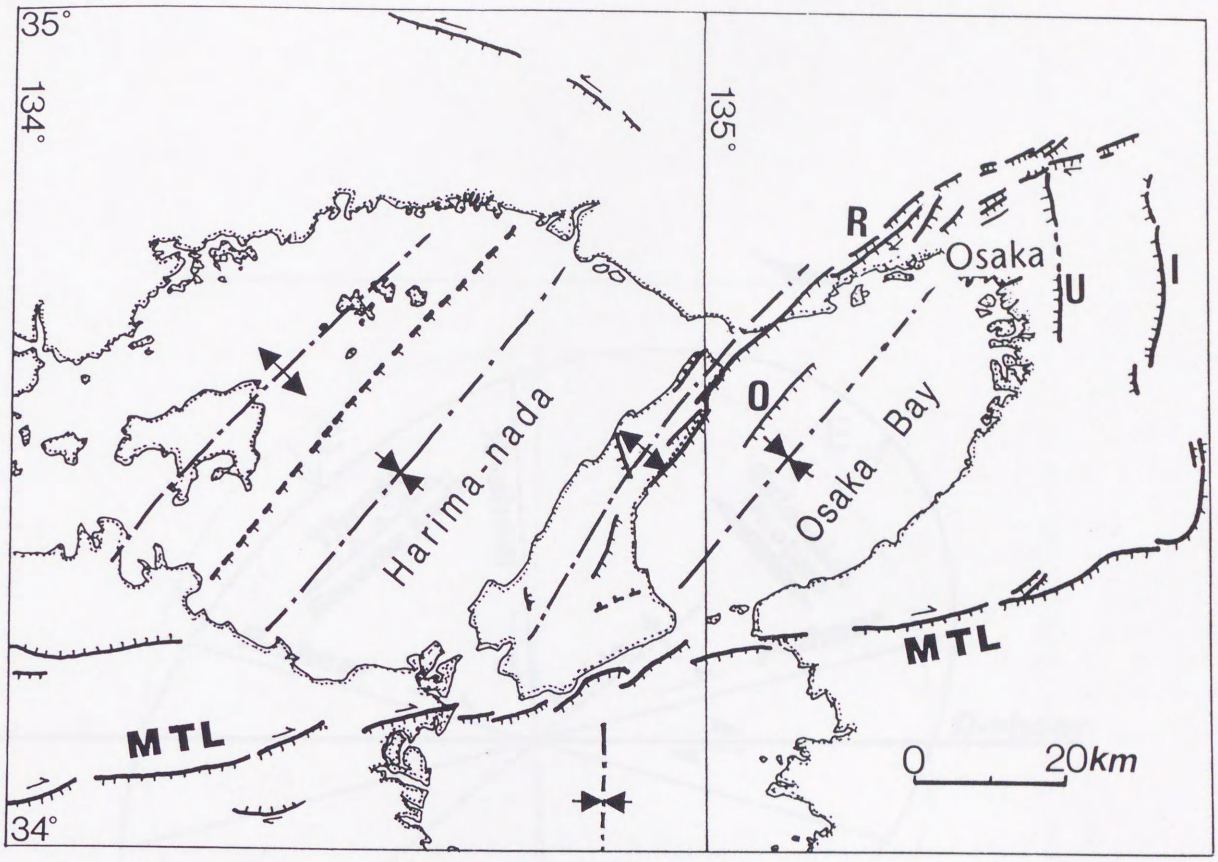


Figure 10 Active tectonic structures in the east of the Seto'uchi shear zone.
I: Ikoma faults, U: Uemachi fault, R: Rokko faults, O: Osaka-wan fault.

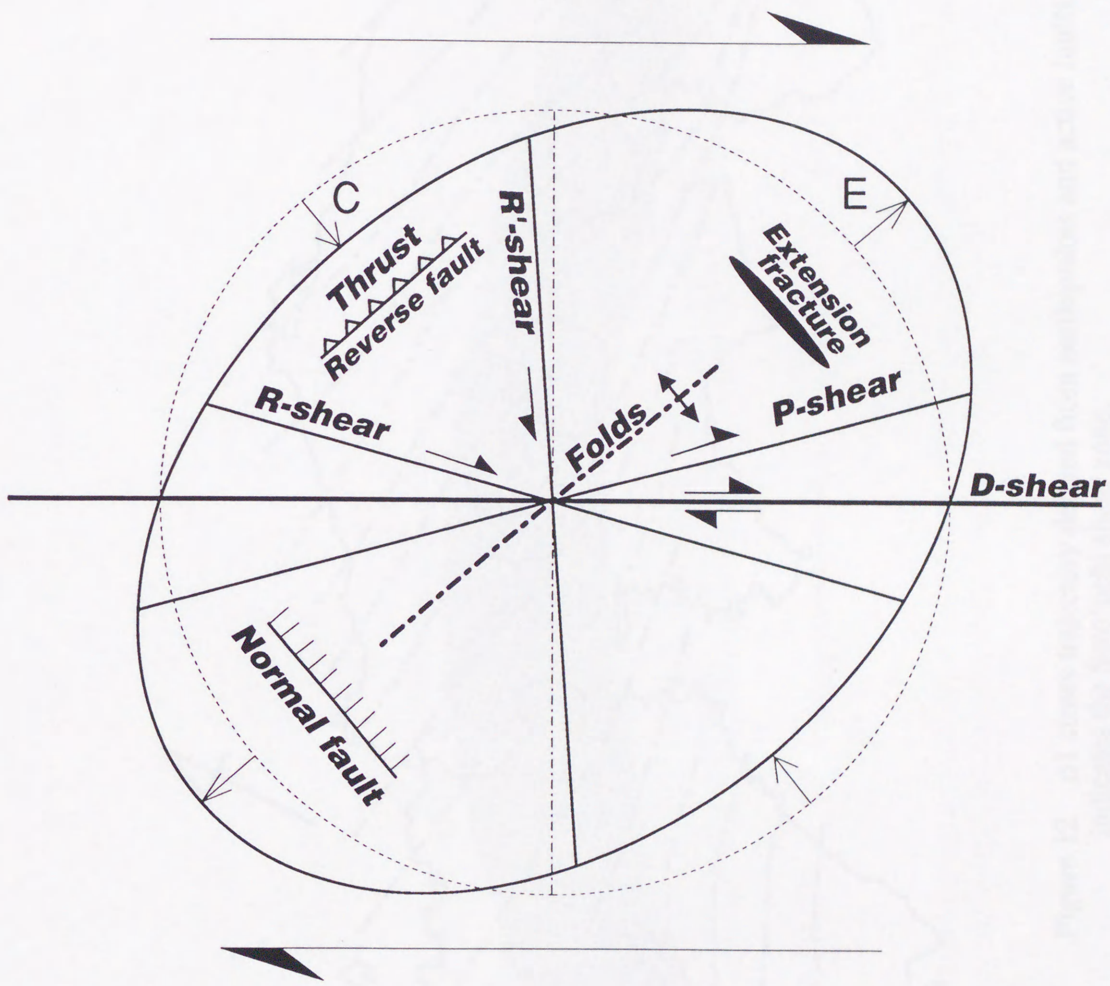


Figure 11 Orientation of elemental structures expected in a right-lateral shear zone.

Figure 12 $\sigma 1$ stress trajectory derived from earthquakes and active faults. Dotted area indicates the Seto'uchi shear zone.

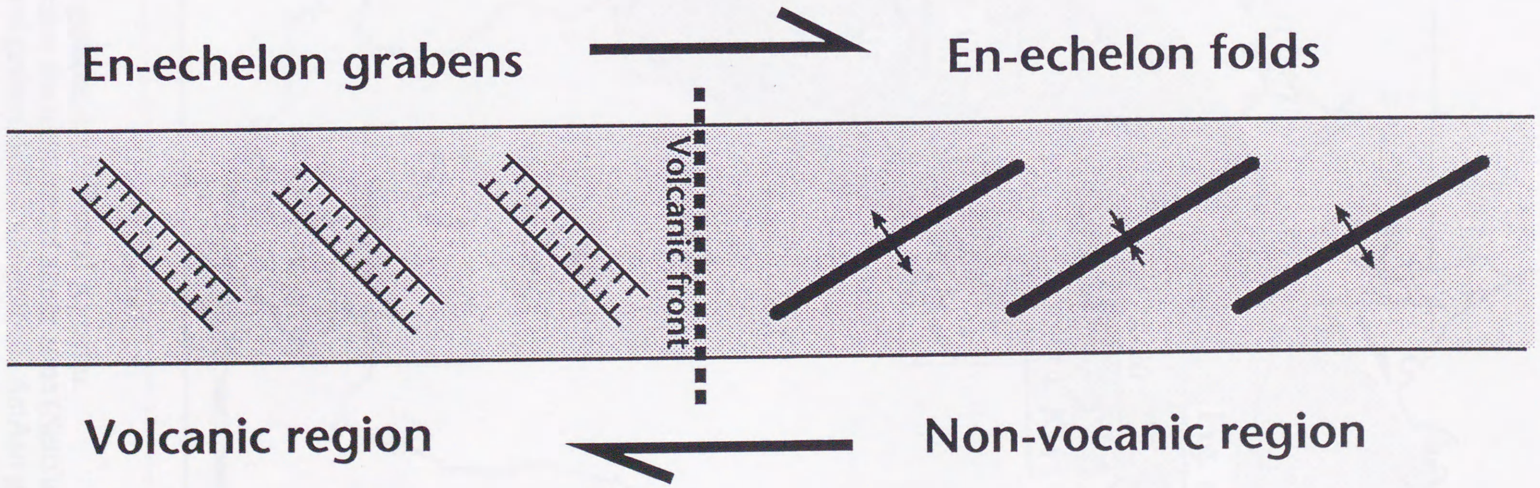


Figure 13 Development of en-echelon folds in non-volcanic region and grabens in volcanic region, in the right-lateral shear zone, Southwest Japan.

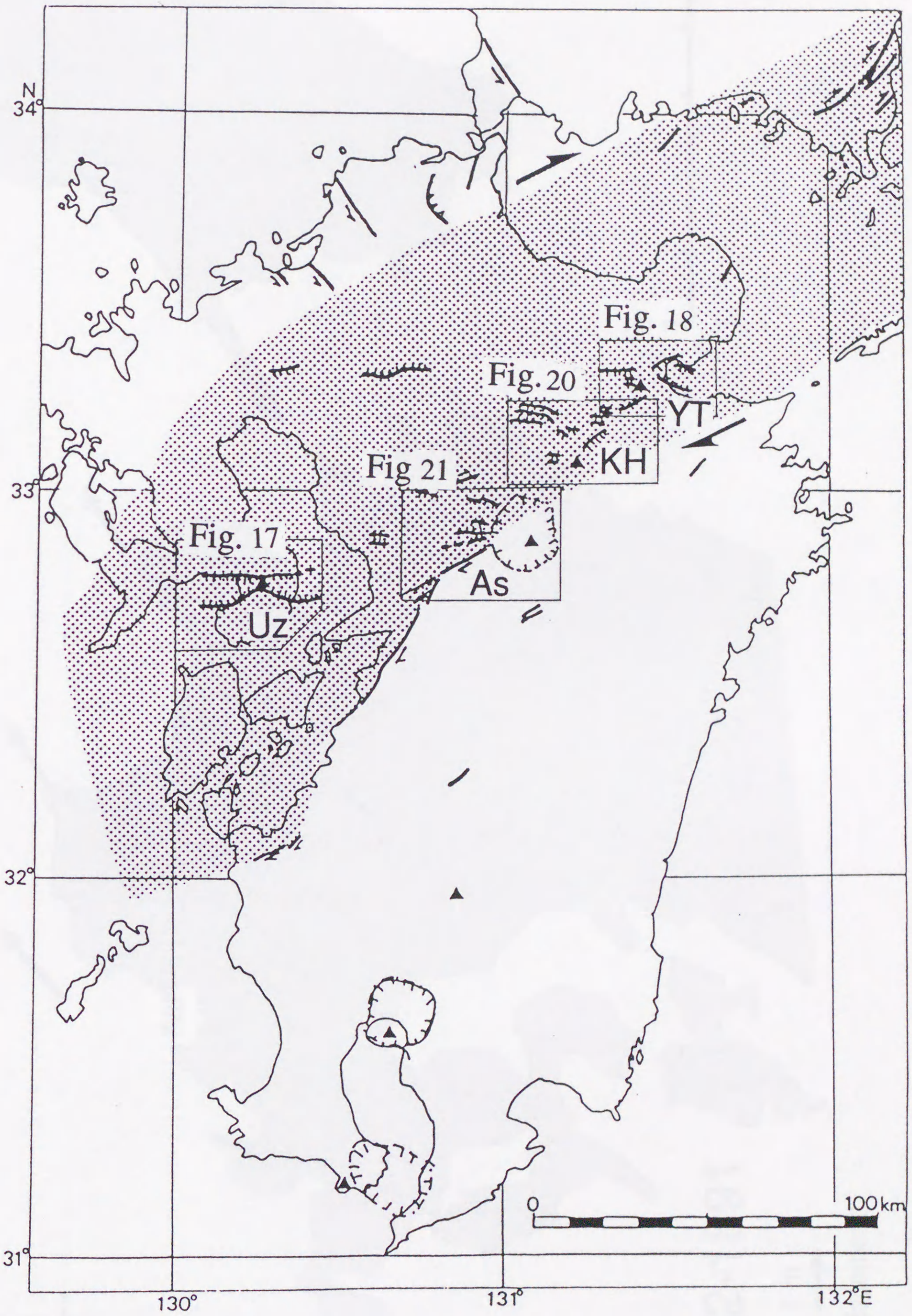


Figure 14 En-echelon grabens in the central Kyushu.
Dotted area indicates the right-lateral shear zone (Seto'uchi shear zone).
YT:Yuhu-Tsurumi graben, KH:Kuju graben, As:Aso graben, Uz:Unzen graben.

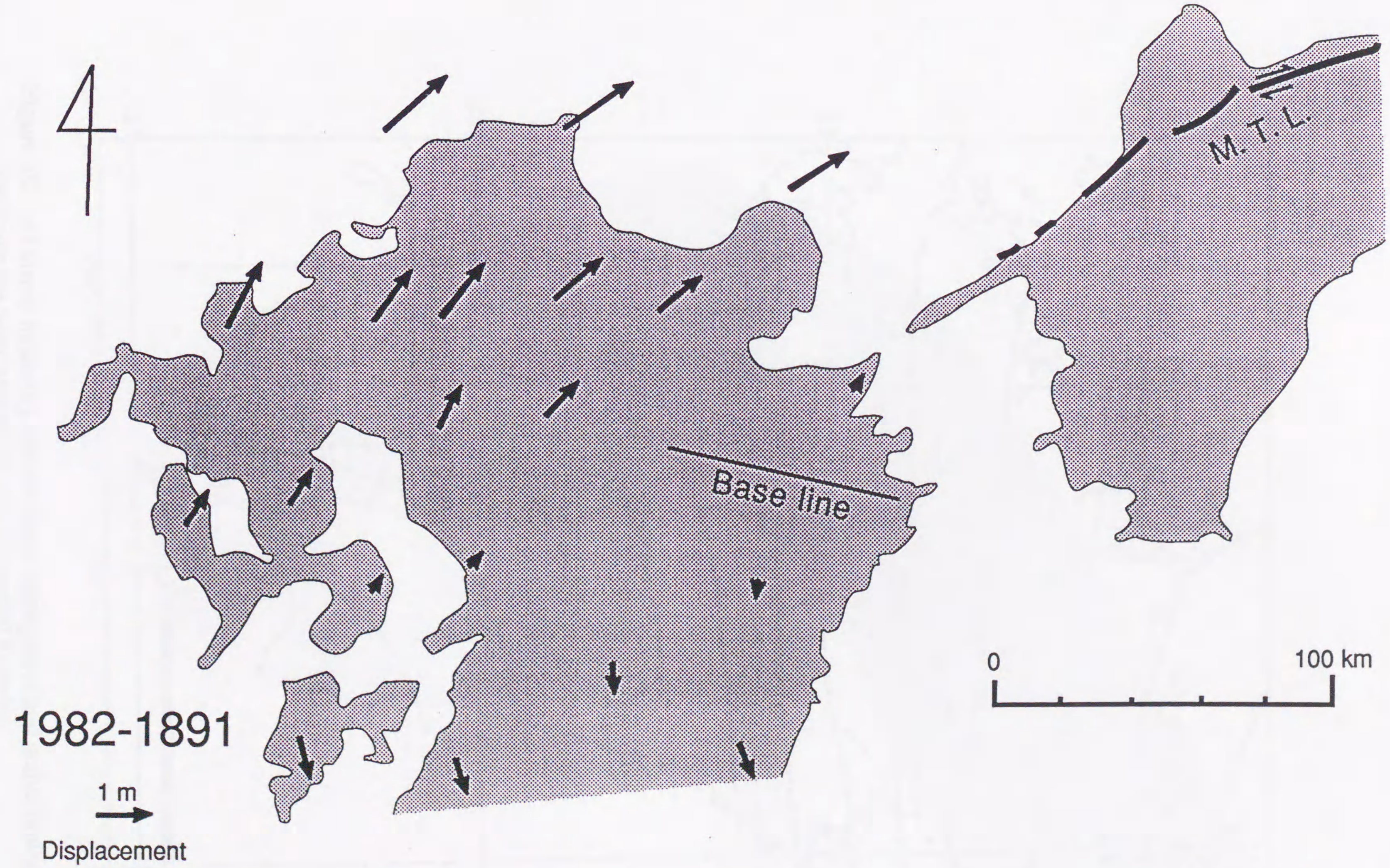


Figure 15 The displacement field related to the baseline modified from Hatanaka & Shimazaki (1988). Direction of the displacement in the northern Kyushu is almost parallel to the shear zone.
M.T.L.: Median Tectonic Line.

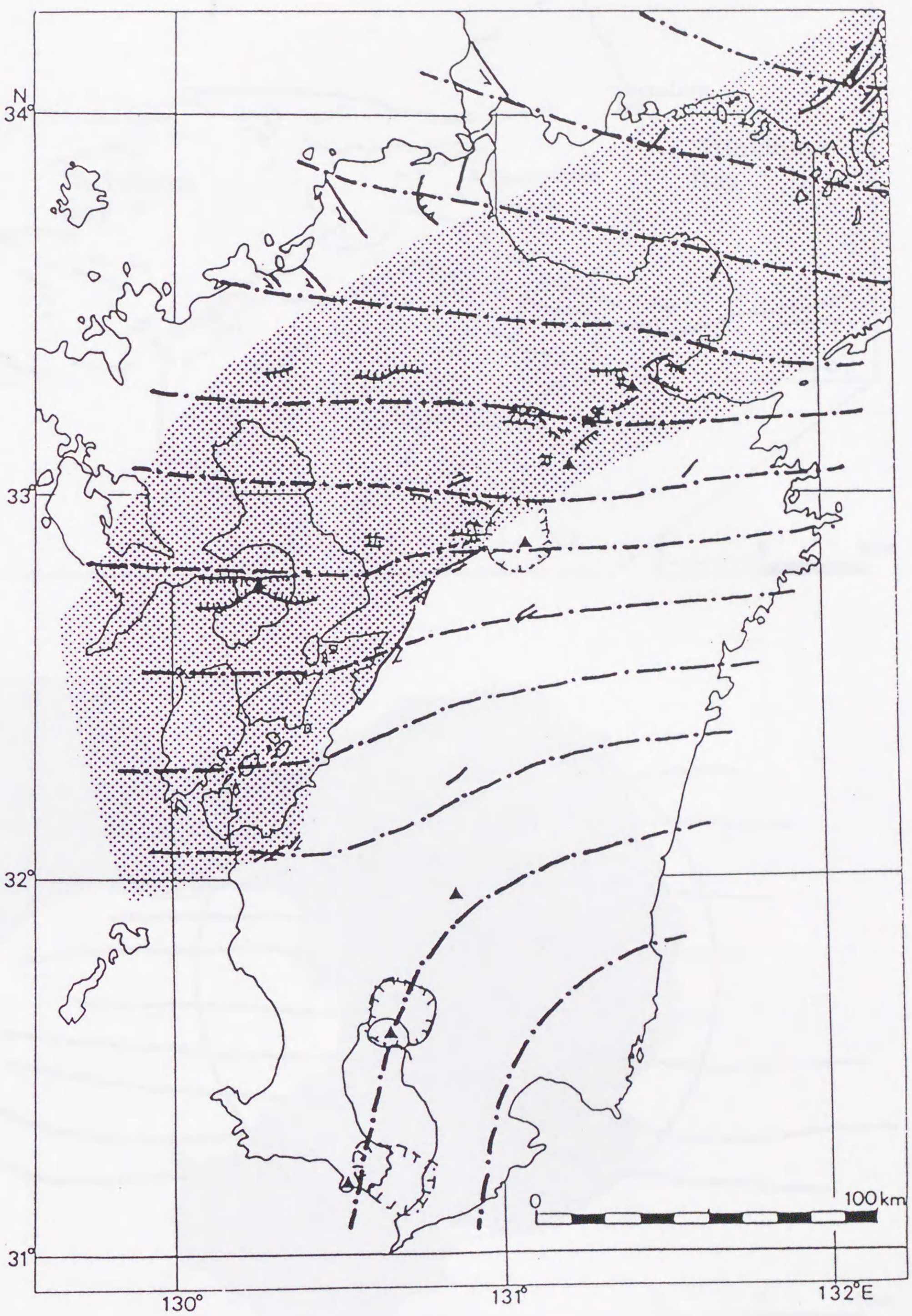
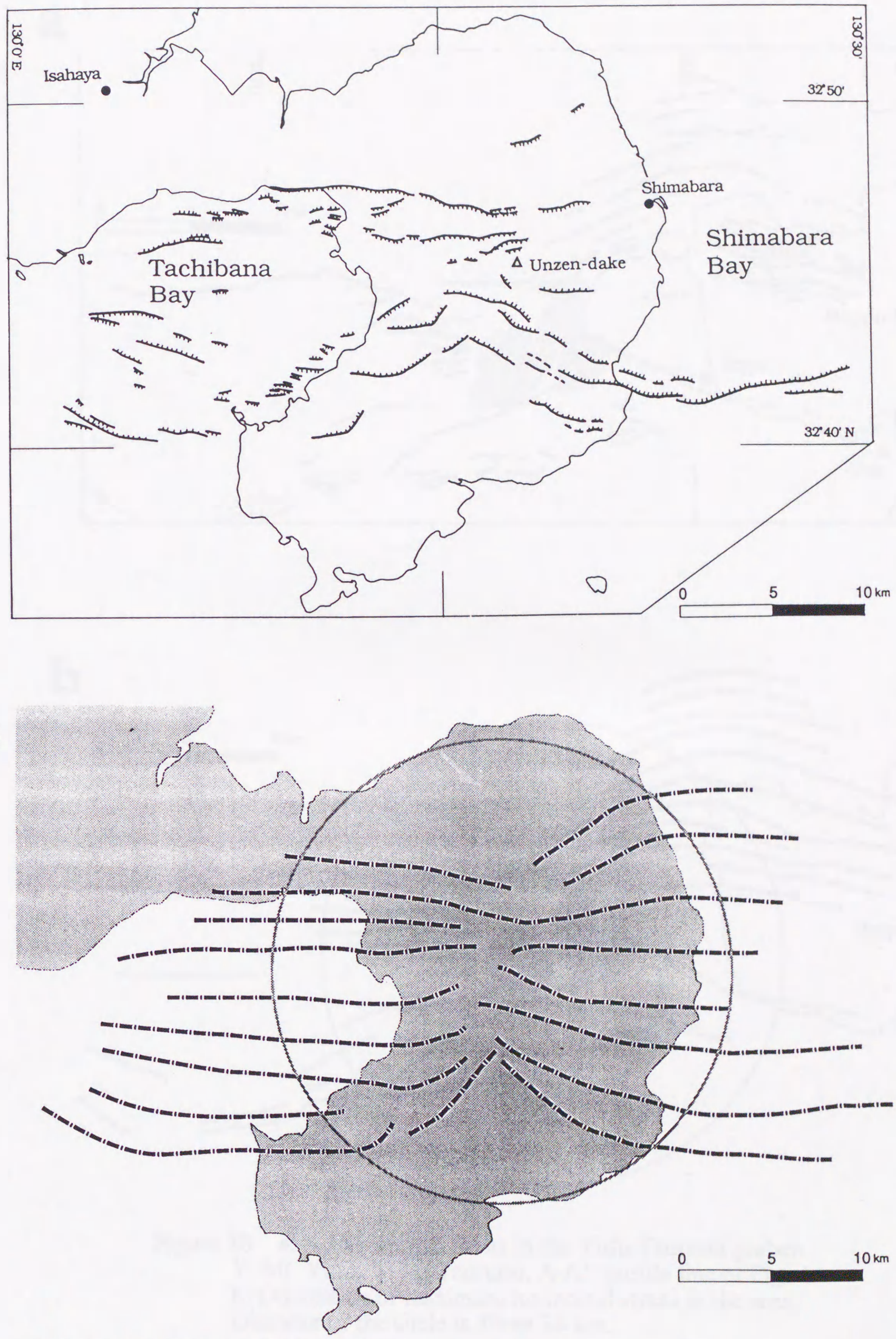


Figure 16 σ1 stress trajectory derived from earthquakes and active faults. Dotted area indicates the Seto'uchi shear zone of central Kyushu.

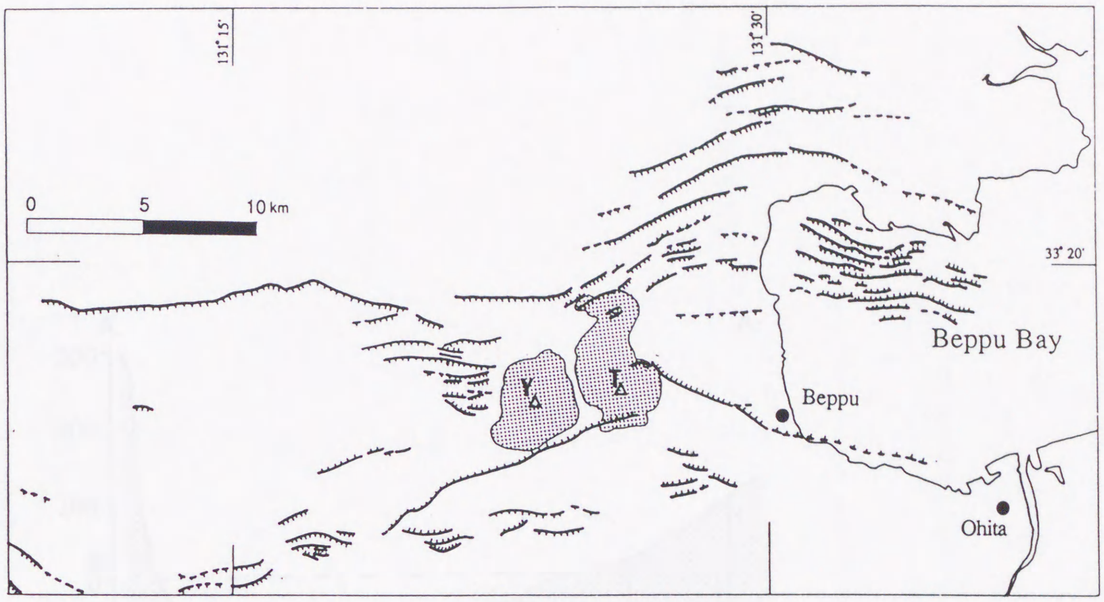
a



b

Figure 17 a: Active normal faults of the Unzen graben.
See Fig. 14 for the location of this figure. Notice that normal faults are not arranged in parallel. It is inferred to be made by E-W oriented compressional stress condition.
b: Orientation of maximum horizontal stress in the Unzen area.
Diameter of the circle is about 25 km.

a



b

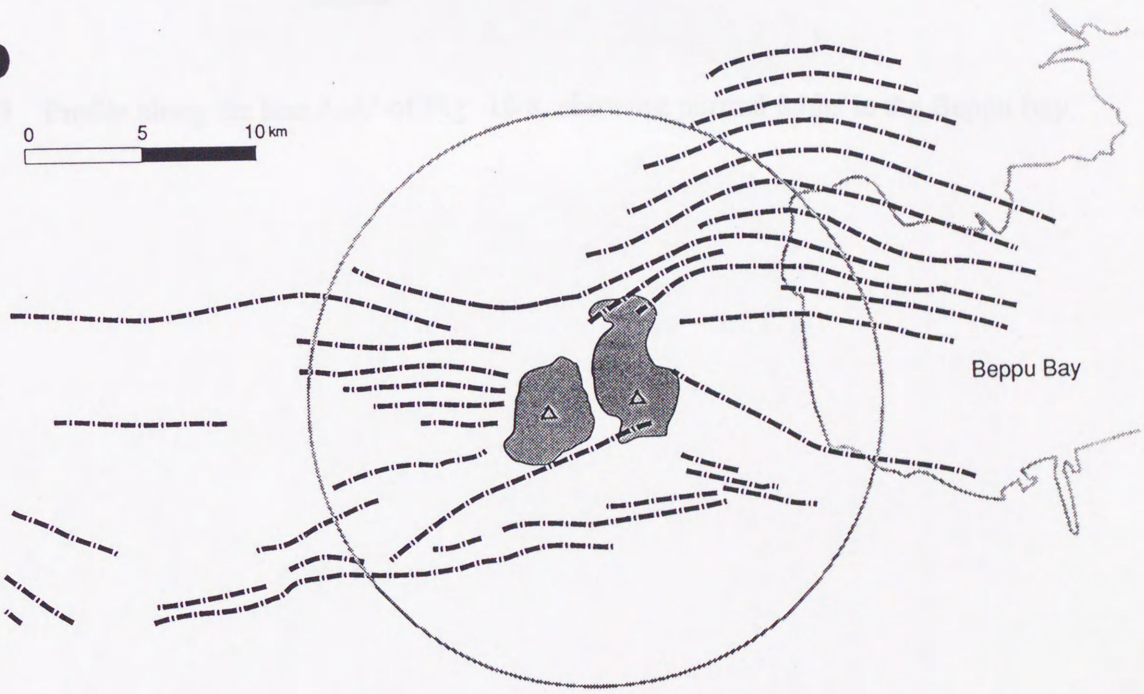


Figure 18 a: Active normal faults in the Yufu-Tsurumi graben.
Y: Mt. Yufu, T: Mt.Tsurumi, A-A': profile line of Fig. 14
b: Orientation of maximum horizontal stress in the area.
Diameter of the circle is about 25 km.

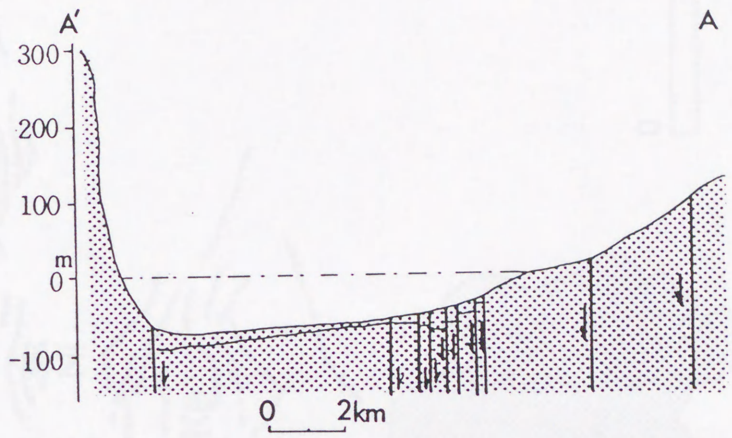


Figure 19 Profile along the line A-A' of Fig. 18 a. showing normal faults in the Beppu bay.

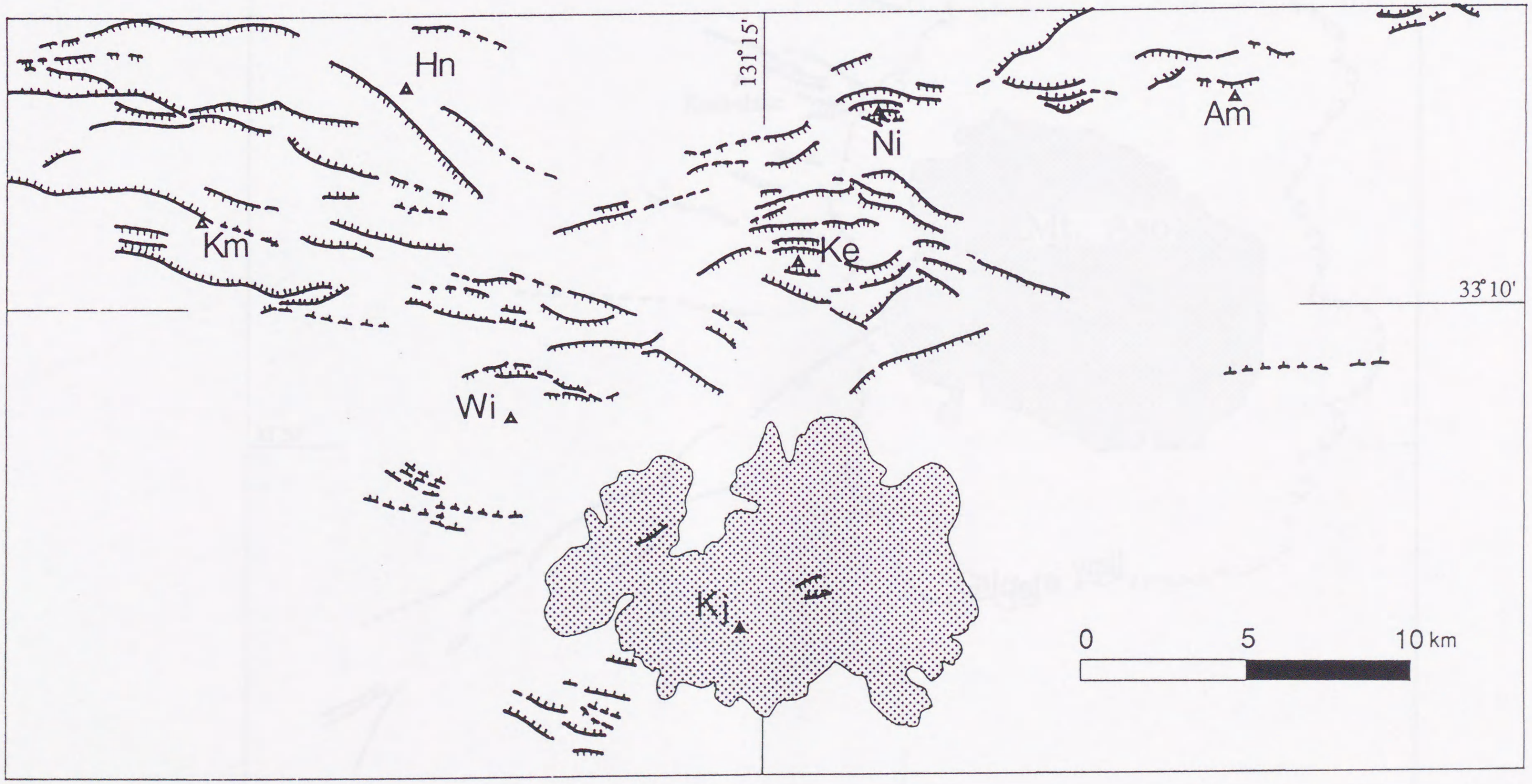


Figure 20 Active normal faults in the Kuju–Haneyama grabens
Am: Mt. Amagoi, Ni: Mt. Noine, Ke: Mt. Kuenohira, Hn: Mt. Haneyama, Wi: Mt. Waita,
Km: Mt. Kameishi.

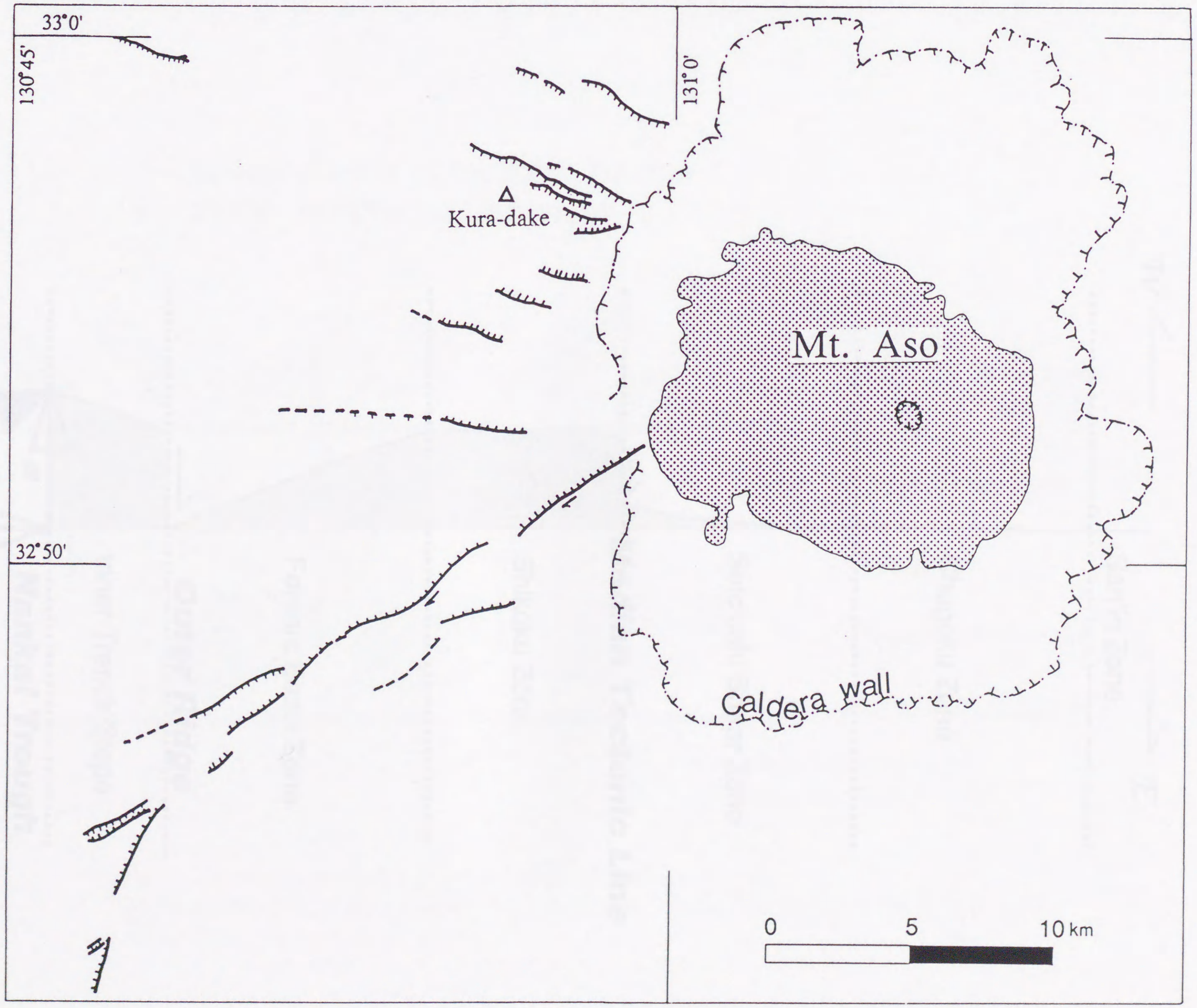


Figure 21 Active faults of the Aso graben

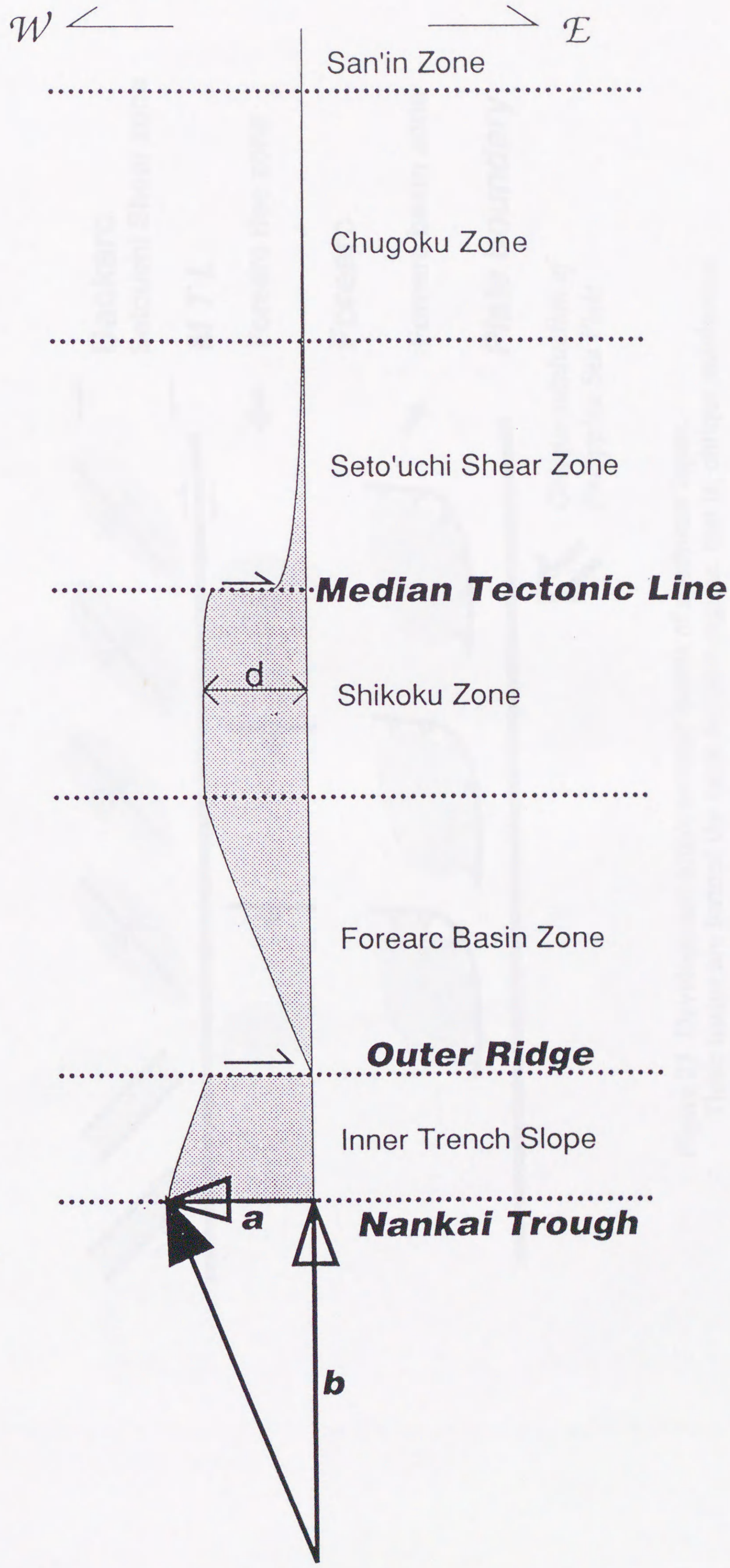


Figure 22 Displacement distribution across zones of Southwest Japan arc.

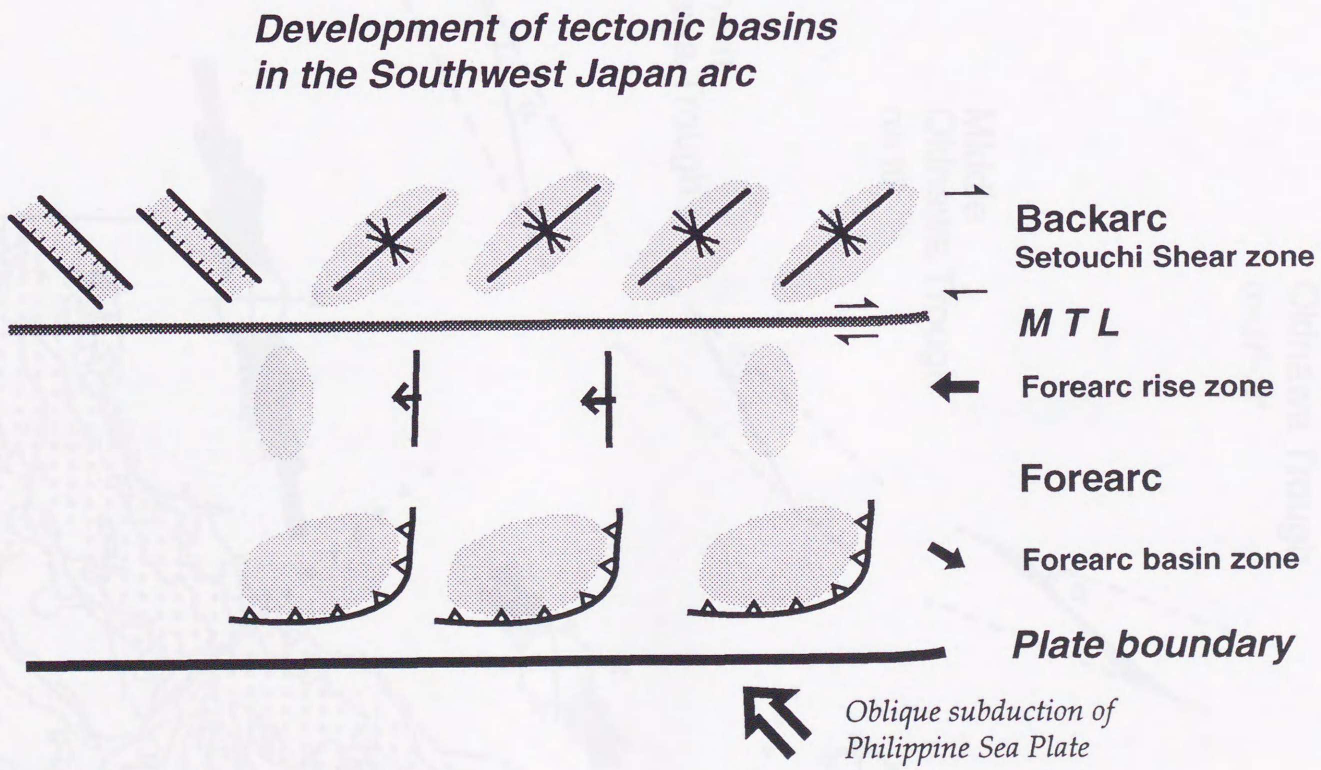


Figure 23 Development active tectonic basins of southwest Japan.
These basins are formed the same tectonic regime, that is, oblique subduction of the Philippine sea plate.

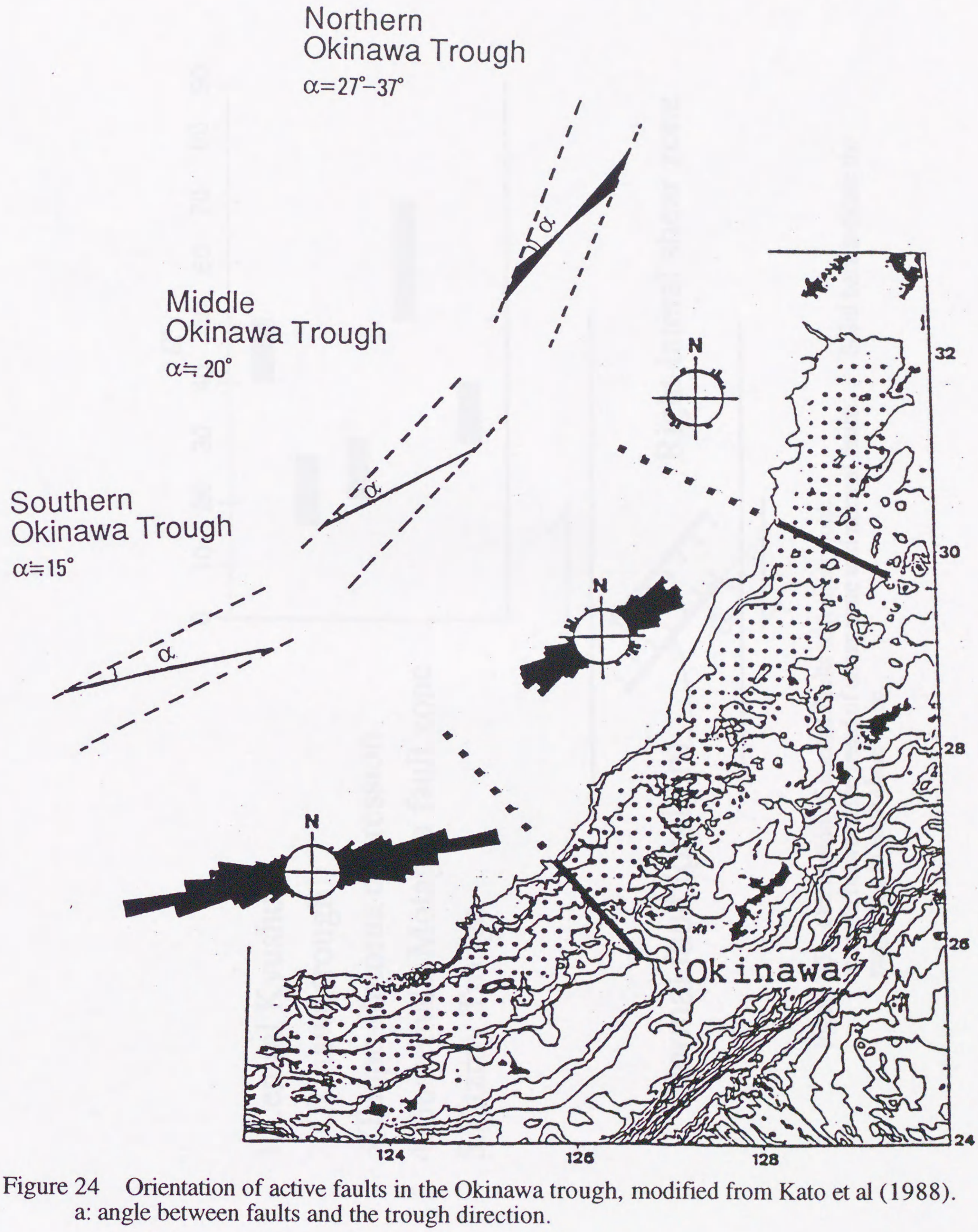


Figure 24 Orientation of active faults in the Okinawa trough, modified from Kato et al (1988).
a: angle between faults and the trough direction.

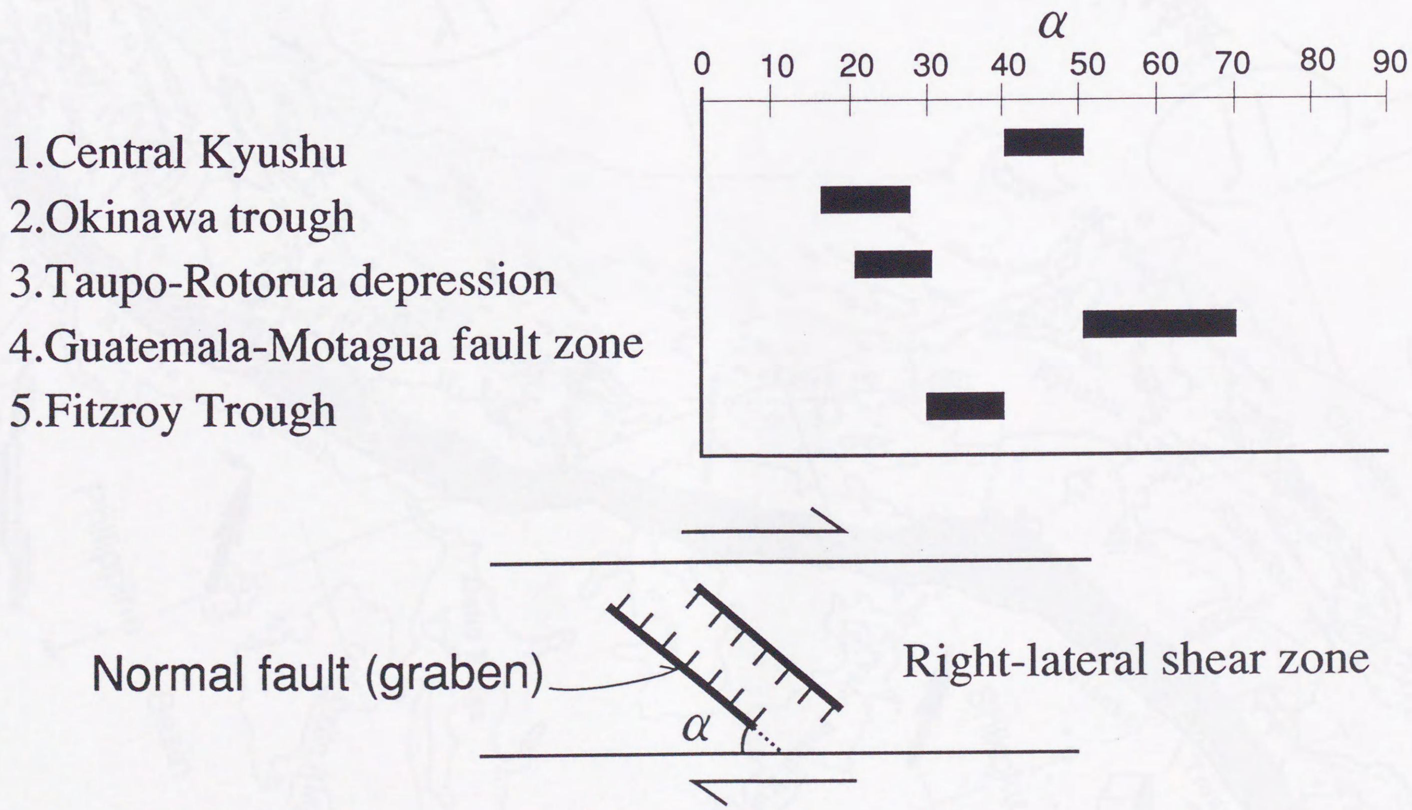


Figure 25 Orientation of normal faults to a shear zone.
a: angle between the trend of shear zone and normal faults. Solid bars indicate the range of a in each shear zone.

Figure 26 Active faults characteristics of the forearc and backarc from the Southwest Japan arc to the Ryukyu arc. The explanation of the figure is in the text.

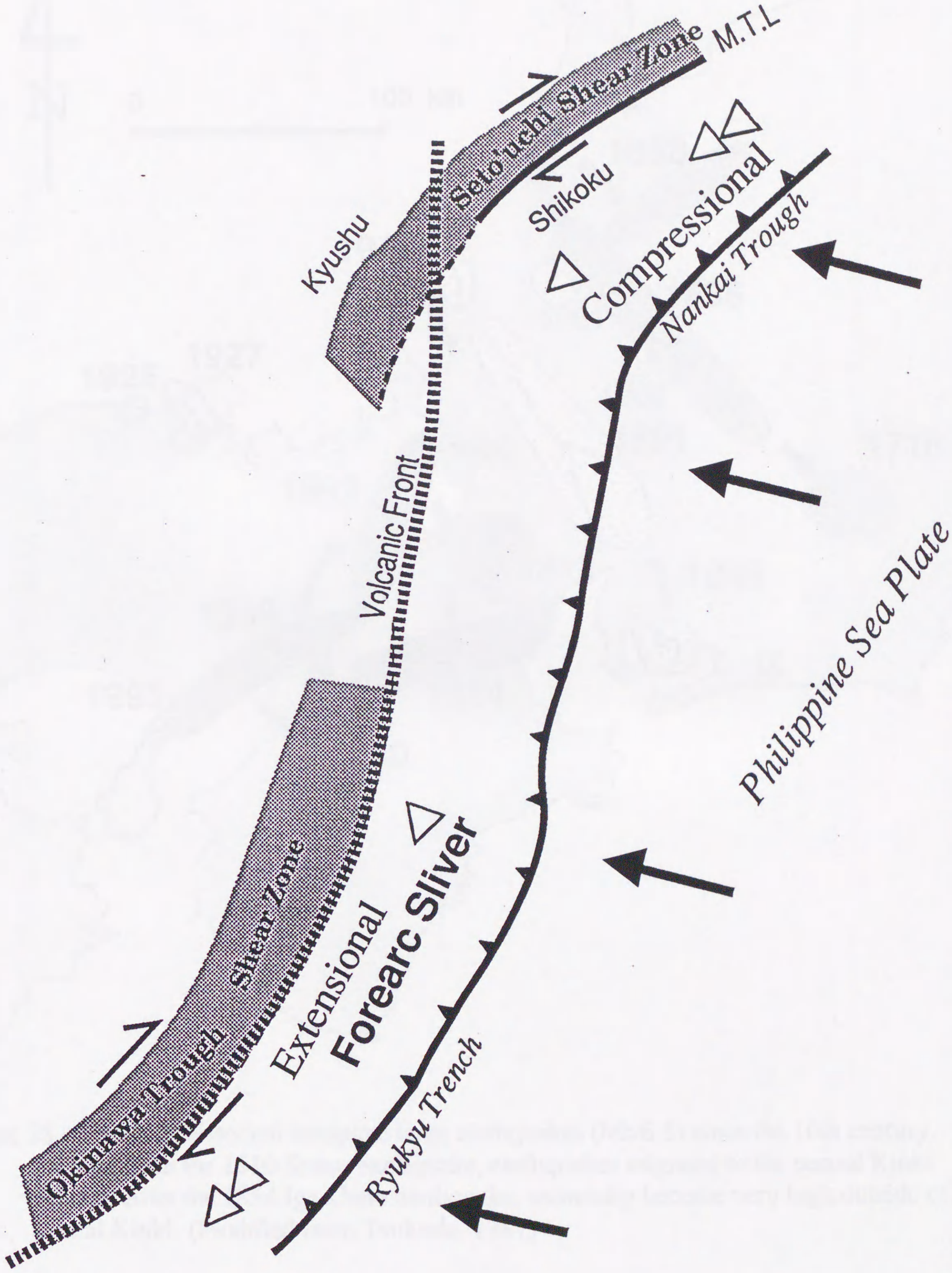


Figure 27 Southwestward translation of the forearc sliver accompanied with the right-lateral shear of backarc caused by the oblique subduction of the Philippine Sea plate. The development of en-echelon grabens in the backarc is closely related to the migration of forearc sliver. Double open triangles indicate a relatively higher translation rate than single ones. Solid arrows indicate the direction of relative convergence between the Philippine sea plate and the Eurasian plate.

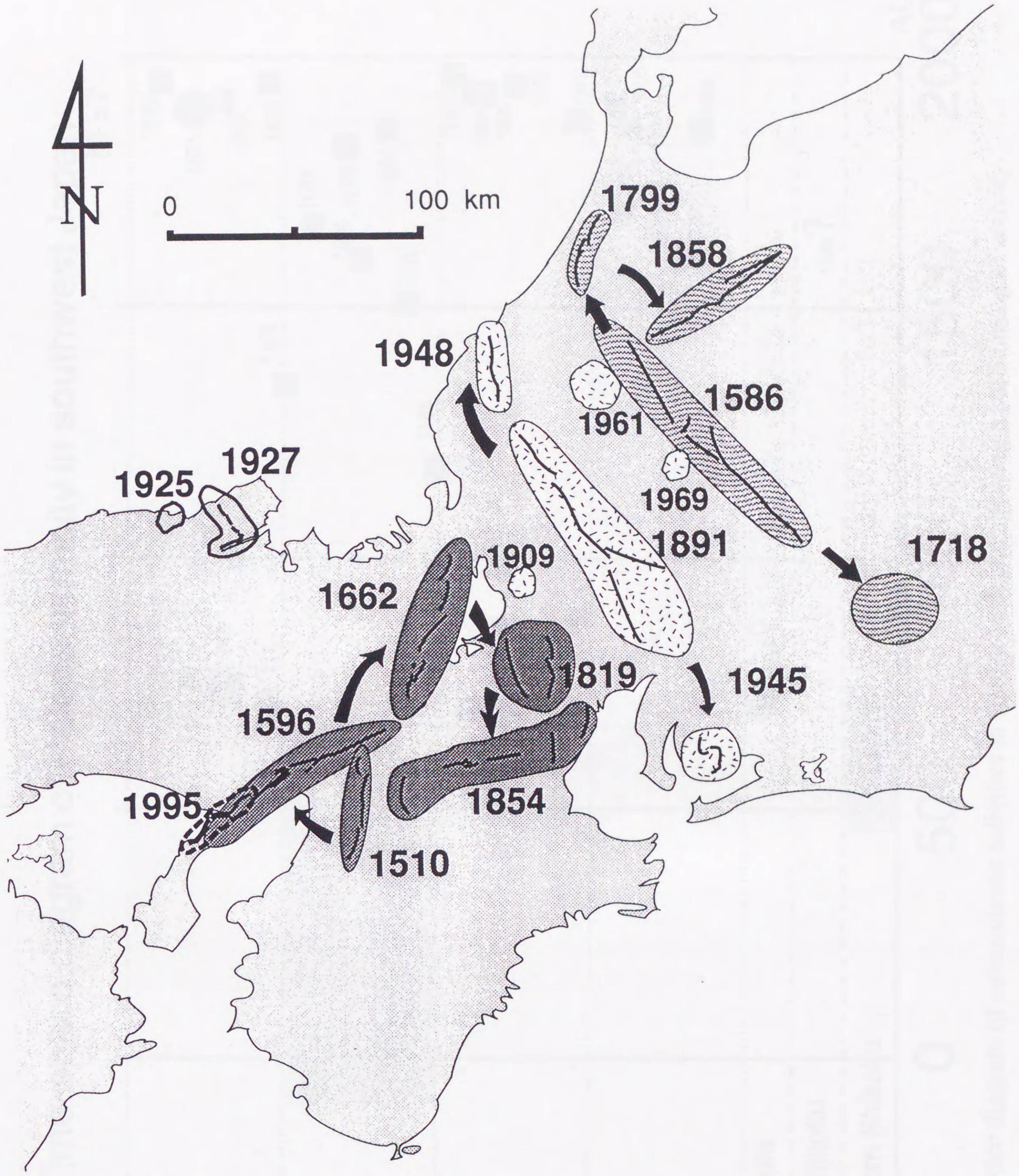


Figure 28 Faults of historical intraplate large earthquakes (M>6.5) since the 16th century. Starting from the 1510 Settsu earthquake, earthquakes migrated to the central Kinki district. After the 1854 Iga-Ueno earthquake, seismicity become very high outside of the central Kinki. (Modified from Tsukuda, 1987)

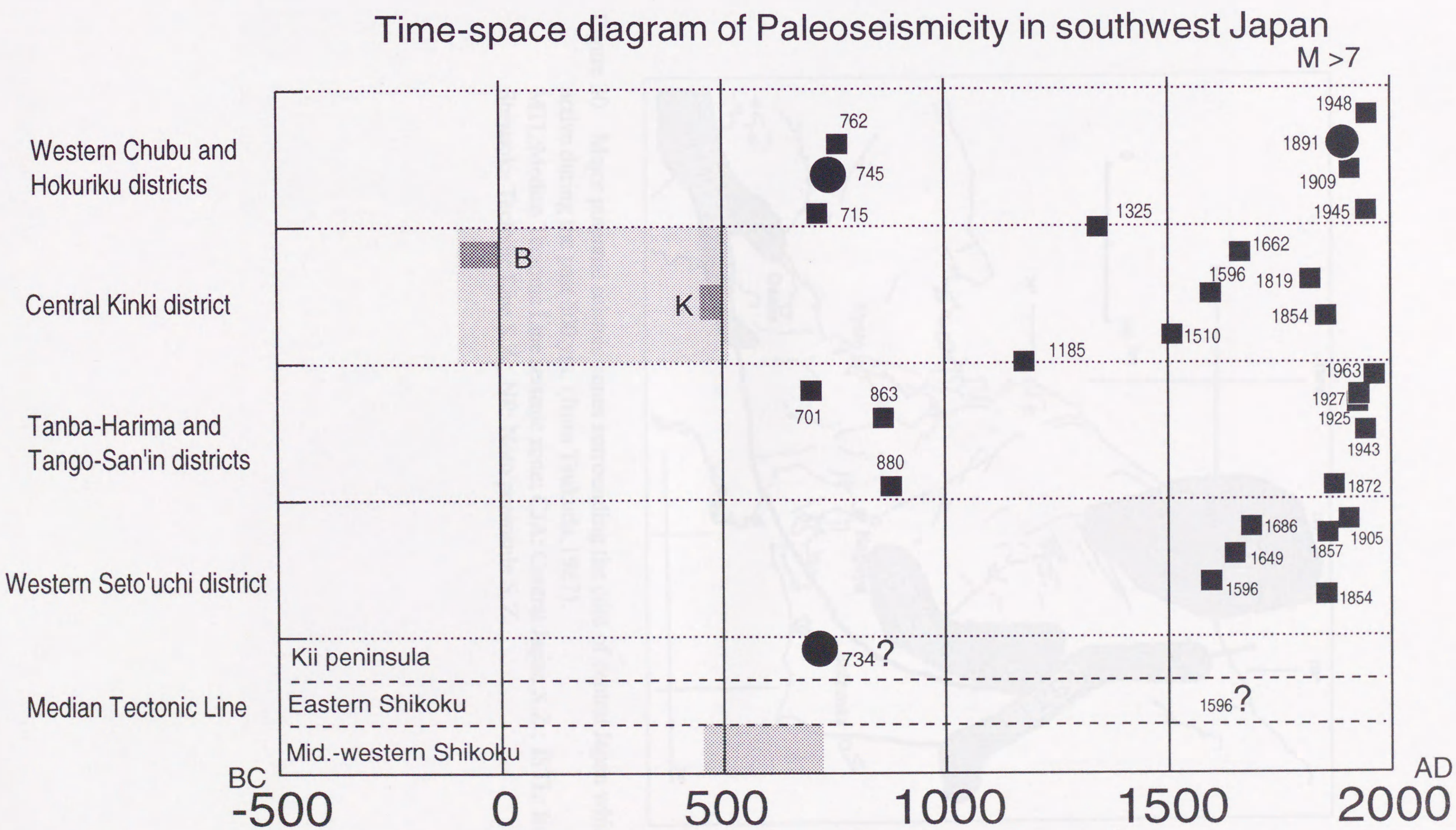


Figure 29 Time-space diagram of paleoseismic activities in southwest Japan showing a partitioning of activity. Shaded areas indicate periods of high seismicity estimated from trench excavation surveys and archeological surveys. B: Biwako area, K: Kobe area. Details of earthquakes are shown in Table 1.

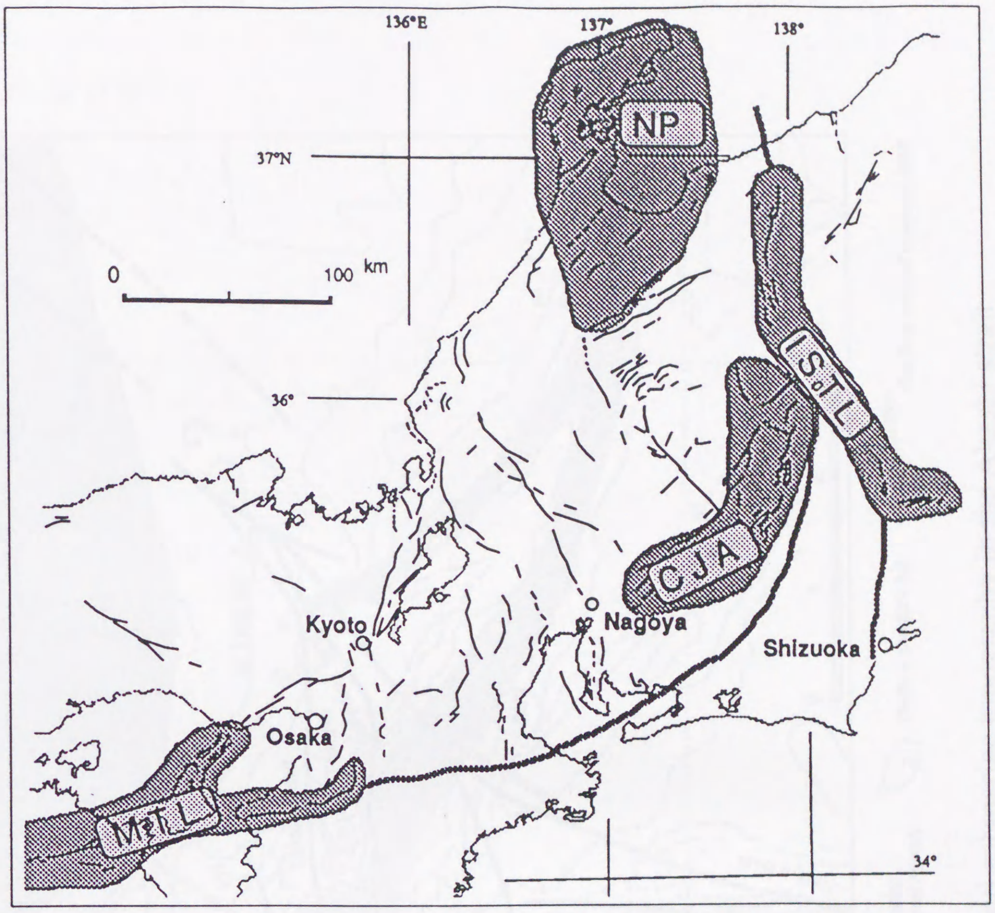


Figure 30 Major potential seismic zones surrounding the core of central Japan which had been active during the past 500 yrs. (from Tsukuda,1987).
MTL:Median Tectonic Line seismic zone; CJA: Central Japan S.Z.; ISTL: Itoigawa-Shizuoka Tectonic Line S.Z.; NP: Noto peninsula S.Z..

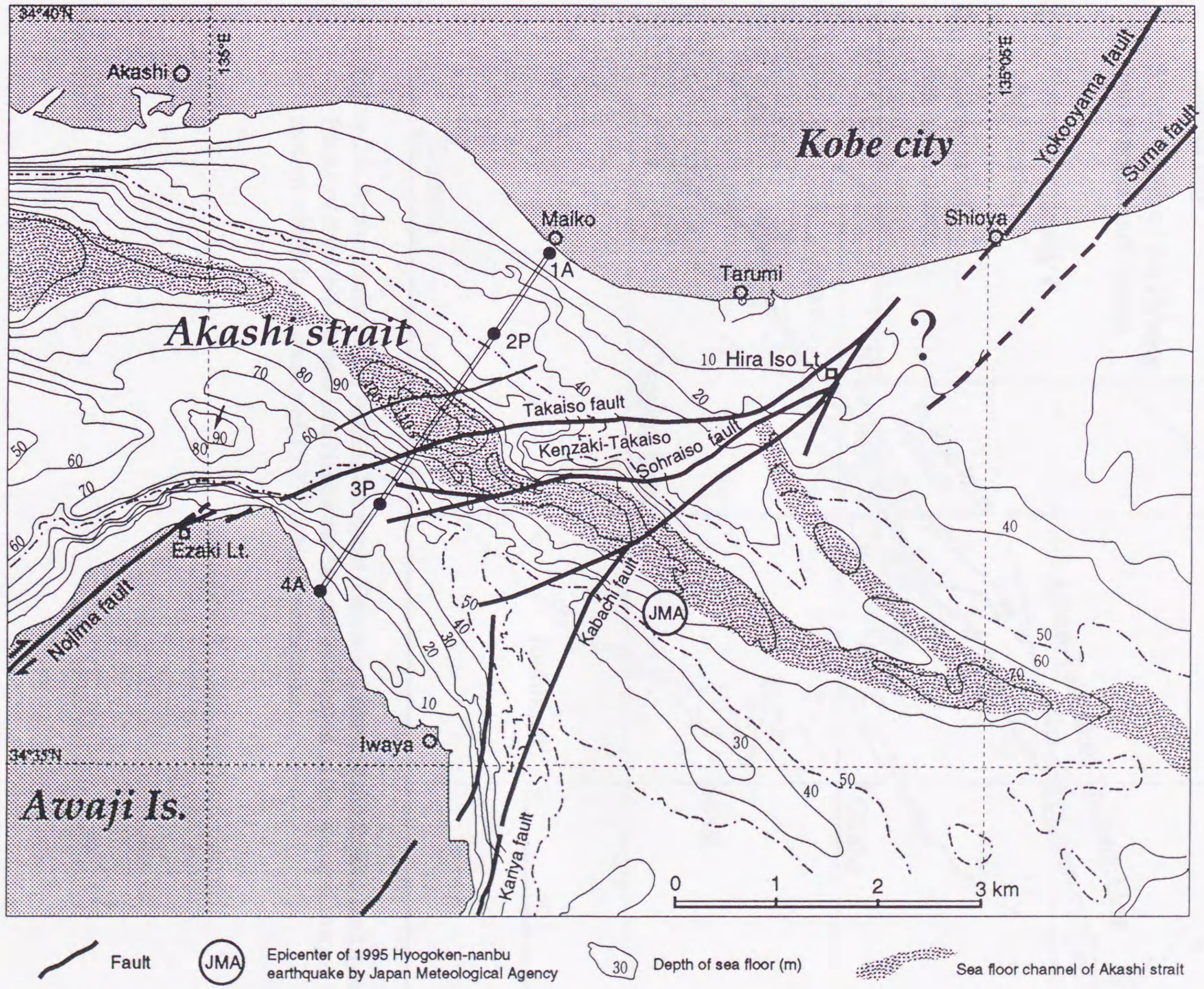


Figure 31 Fault distribution and submarine topography in the Akashi strait.
1A, 2P, 3P, 4A: Anchorage and pier of the Akashi strait bridge under construction

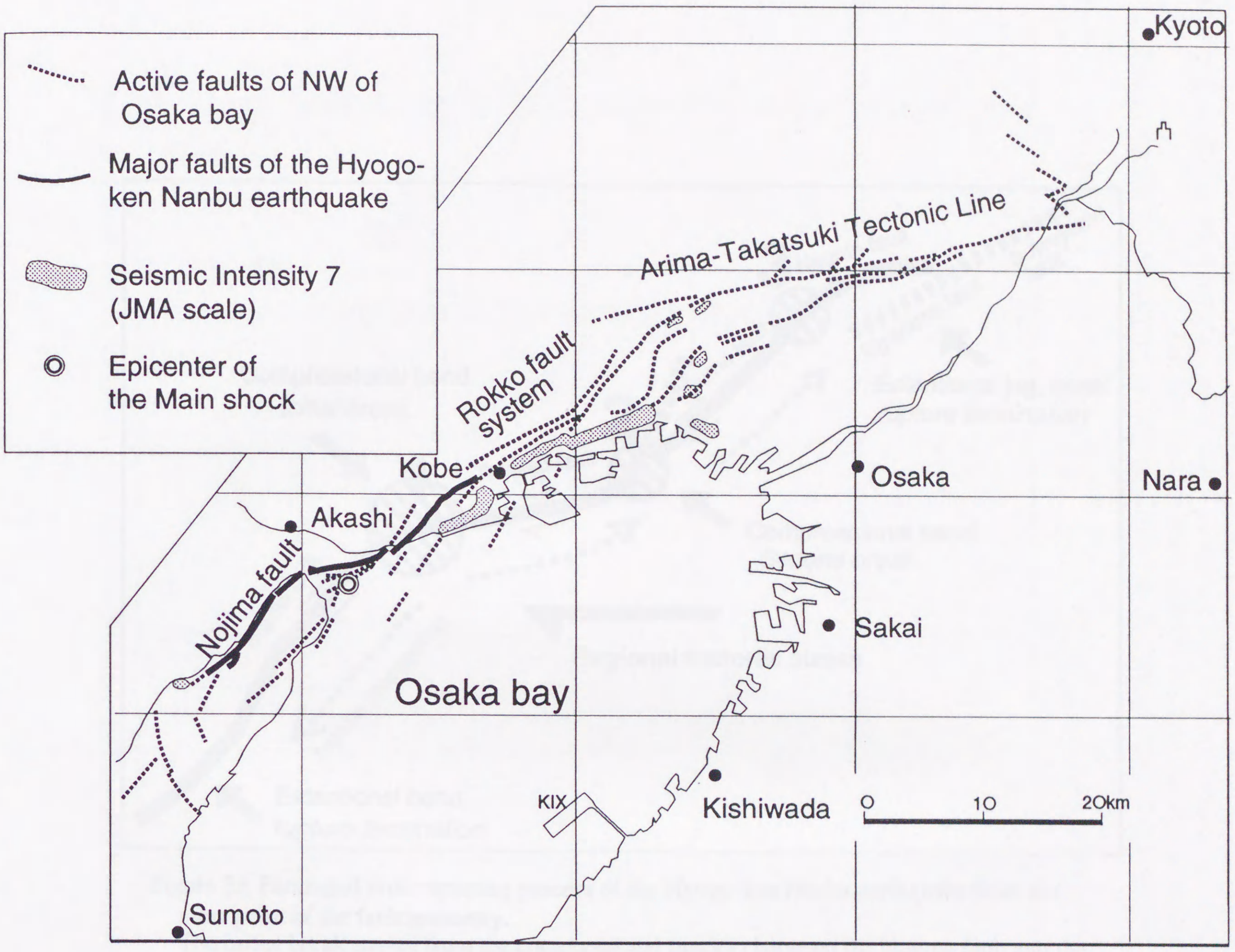


Figure 32 Active faults of the Arima-Takatsuki Tectonic Line and the Rokko fault system. Faults of the 1995 Hyogo-ken Nanbu earthquake is located in the western margin of the fault system which is the source of 1596 Fushimi earthquake.

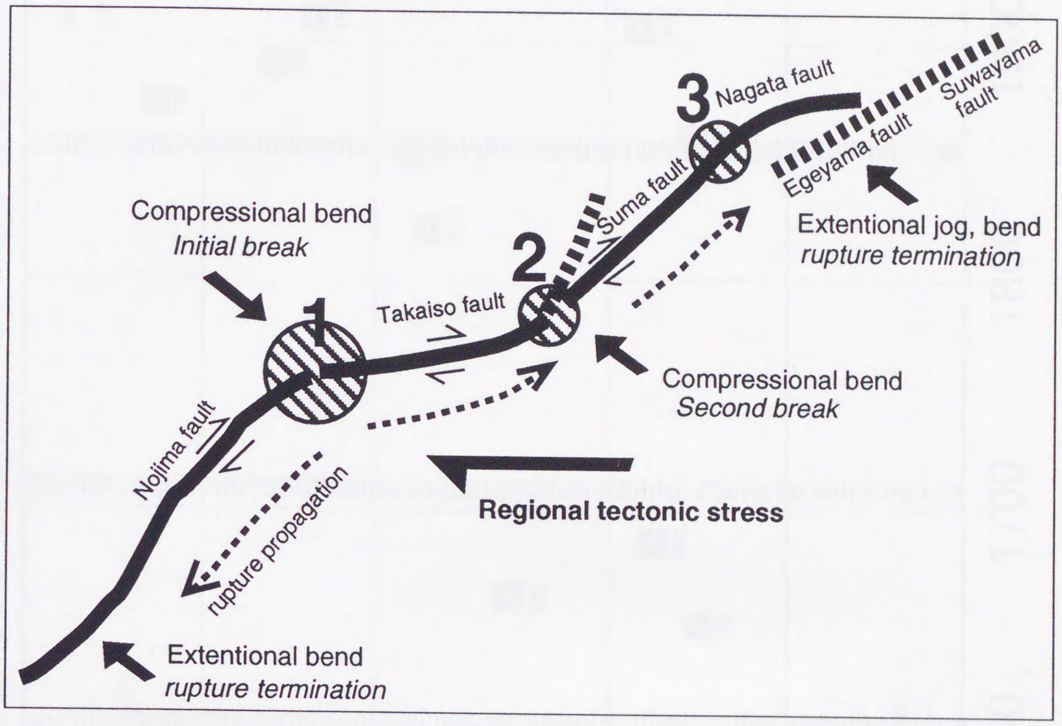


Figure 33 Estimated fault rupturing process of the Hyogo-ken Nanbu earthquake from the view point of the fault geometry.
The initial break started from the compressional bend(1) between the Nojima fault and the Takaiso fault. Ruptures were propagated bilaterally , then the second break (2)started from the compressional barrier in the east. Finally ruptures were terminated in the extensional bends (3)or jogs in the east and south.

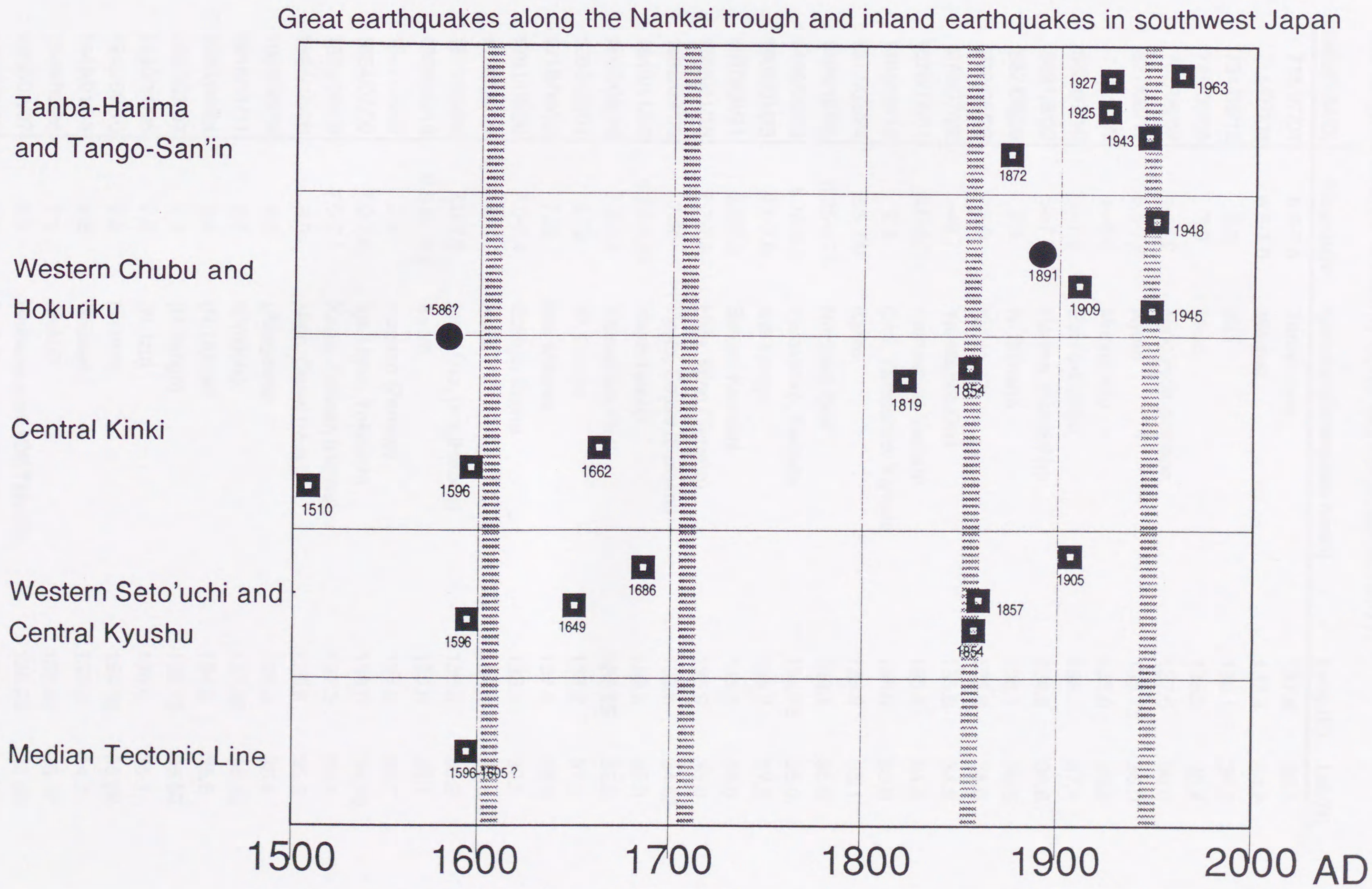


Figure 33 Relation between inland historic earthquakes of southwest Japan and great earthquakes along the Nankai trough since the 16 century.
Vertical dashed lines indicate the timing of great plate boundary earthquakes along the Nankai trough.

Table 1

Historic earthquakes greater than or equal to M6.5 during the past 1300 years

The original source is mainly obtained fromUsami(1987).

Date(Y/M/D)	Magnitude	Location(Earthquake name)	Long.(E)	Lat.(N)
715/07/04	6.5-7.5	Tenryu river	137.8	35.1
715/07/05	6.5-7.0	Mikawa	137.4	34.8
734/05/18	7.0	Kii	136.1	34.3
745/06/05	7.9	Mino	136.5	35.4
762/06/09	>=7.0	Mino,Hida,Shinano	137.5	36.0
827/08/11	6.5-7.0	Kyoto	135.75	35.0
841/?/?	>=6.5	Matsumoto	138.0	36.2
863/07/10	>=7.0	Ecchu-Echigo	138.1	37.1
868/08/03	>=7.0	Harima, Yamashiro	134.8	34.8
887/08/26	7.4	N. Shinano	138.1	36.6
938/05/22	7.0	Kyoto, Kii	135.8	35.0
976/07/22	>=6.7	Yamashiro,Omi	135.8	34.9
1070/12/01	6.0-6.5	Yamashiro, Yamato	135.8	34.8
1185/08/13	7.4	Omi, Yamashiro, Yamato	135.8	35.0
1317/02/24	6.5-7.0	Kyoto	135.8	35.1
1325/12/05	6.25-6.75	Northern Omi	136.1	35.6
1449/05/13	5.75-6.5	Yamashiro, Yamato	135.75	35.0
1502/01/28	6.5-7.0	SW Echigo	138.2	37.2
1510/09/21	6.5/7.0	Settsu, Kawachi	135.6	34.6
1586/01/18	7.7-7.9	Hida, Mino (Tensho)	136.9	36.0
1596/09/05	7.25	Kyoto, Settsu (Fushimi)	135.6	34.65
1640/11/23	6.25-6.75	Kaga-Taiseiji	136.2	36.3
1662/06/16	7.3-7.5	Yamashiro, Omi	135.95	35.2
1666/02/01	6.75	W. Echigo	138.2	37.1
1718/08/22	7.25	Ina, Mikawa	137.9	35.3
1751/05/20	7.0-7.4	Echigo, Ecchu	138.1	37.1
1799/06/29	6.5	Kaga	136.6	36.6
1819/08/02	7.0-7.5	Ise, Mino, 0mi (Hikone)	136.3	35.2
1830/08/19	6.5 +/- 0.2	Kyoto	135.6	35.1
1847/05/08	7.4	Nagano (Zenkoji)	138.2	36.7
1854/07/09	7.0-7.5	Iga-Ueno, Yokkaichi	136.0	34.75
1858/04/09	7.0-7.1	Kaga, Echizen (Hietsu)	137.2	36.4
1891/10/28	8.0	Mino, Owari (Nobi)	136.6	35.6
1909/08/14	6.8	(Anegawa)	136.3	35.4
1918/11/11	6.5	(Omachi)	137.88	36.45
1925/05/24	6.8	(N.Tajima)	134.8	35.6
1927/03/07	7.3	(N.Tango)	135.15	35.53
1930/11/26	7.3	(N. Izu)	139.0	35.1
1943/09/10	7.2	(Tottori)	134.08	35.52
1945/01/13	6.8	(Mikawa)	137.0	34.7
1948/06/28	7.1	(Fukui)	136.20	36.17
1952/03/07	6.5	Ishikawa pref. (Off Taiseiji)	136.20	36.48
1961/08/19	7.0	E. Fukui pref. (Kita-Mino)	136.46	36.01
1963/03/27	6.9	Wakasa bay (Off Echizenmisaki)	135.77	35.78
1966/08/03-	6.4	(Matsushiro)	138.2	36.5
1969/09/09	6.6	(C. Gifu pref)	137.04	35.47
1974/05/09	6.9	(Off. Izu Pen.)	138.48	34.34
1978/01/14	7.0	(Off. Izu-Oshima)	139.15	34.46
1984/09/14	6.8	(W. Nagano pref)	137.56	35.82
1995/01/17	7.2	(S. Hyogo pref.)	135.03	34.36

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