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Active right-lateral strike-slip fault zone along the southern margin of the Japan Sea

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Abstract

We describe an active right-lateral strike-slip fault zone along the southern margin of the Japan Sea, named the Southern Japan Sea Fault Zone (SJSFZ). Onshore segments of the fault zone are delineated on the basis of aerial photograph interpretations and field observations of tectonic geomorphic features, whereas the offshore parts are interpreted from single-/multichannel seismic data combined with borehole information. In an effort to evaluate late Quaternary activity along the fault zone, four active segments separated by uplifting structures are identified in this study. The east–northeast-trending SJSFZ constitutes paired arc-parallel strike-slip faults together with the Median Tectonic Line (MTL), both of which have been activated by oblique subduction of the Philippine Sea plate during the Quaternary. They act as the boundaries of three neotectonic stress domains around the eastern margin of the Eurasian plate: the near-trench Outer zone and NW–SE compressive Inner zone of southwest Japan arc, and the southern Japan Sea deformed under E–W compression from south to north.

Keywords: Active fault zone; Strike-slip fault; Southwest Japan; Japan Sea

1. Introduction

Southwest Japan lies along the eastern margin of Eurasia, and is subject to active deformation as a result of the west–northwestward subduction of the Philippine Sea plate (Seno et al., 1993) and the westward convergence of the North American plate (Nakamura, 1983) during the Quaternary. Onshore deformational trend of the island arc has been studied by many researchers (e.g. Tsukuda, 1992; Itoh and Takemura, 1993), and distribution of active faults has been shown on maps with inventories by the Research Group for Active Faults of Japan (1980, 1991). As for the offshore areas around the island arc, however, neotectonic features have been poorly defined because of scarce high-resolution geomorphic information and uneven distribution of seismic profiling data.

Recently, Gutscher and Lallemand (1999) advocated an arc-parallel right-lateral fault zone, named the

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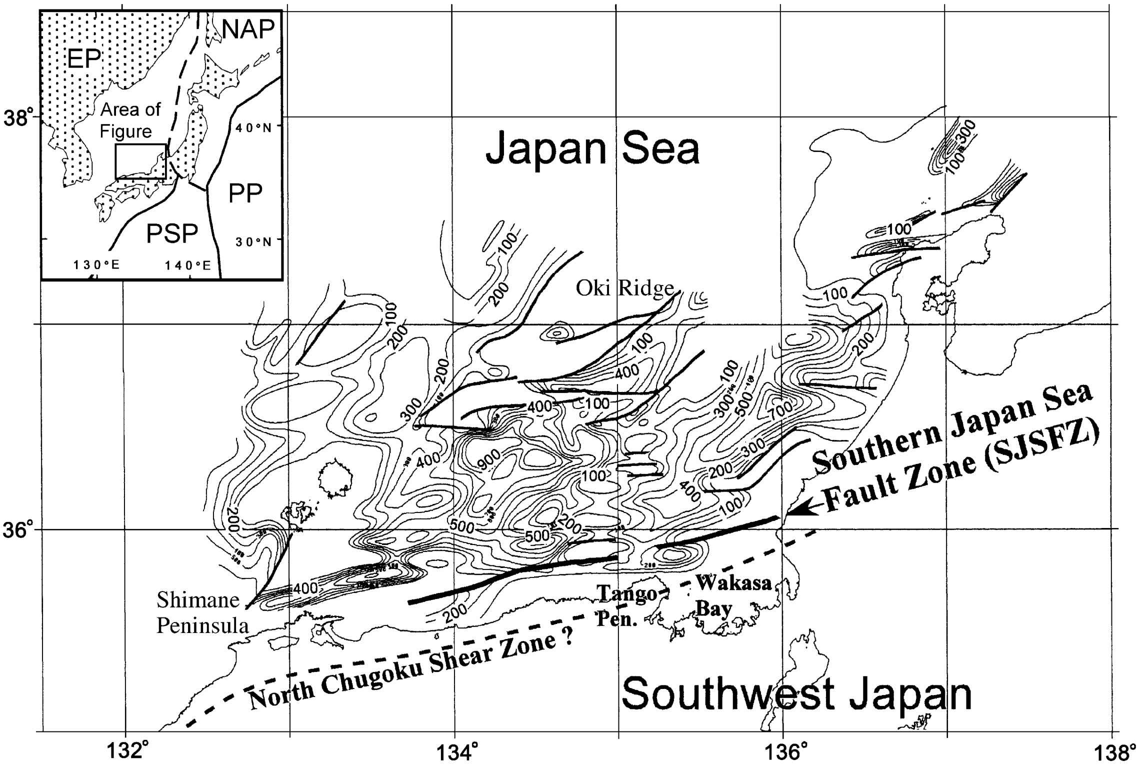

Fig. 1. Isopach contour (thin lines; in m) map of the Early Pliocene unit around the southern Japan Sea with faults (gray thick lines) (after Itoh and Arato, 1999). Black thick lines show a part of the Southern Japan Sea Fault Zone (SJSFZ), which was originally identified as a Pliocene fault. The North Chugoku Shear Zone (NCSZ), advocated by Gutscher and Lallemand (1999), is shown by a broken line. Inset shows plate tectonic regime. Abbreviations: EP, Eurasian plate; NAP, North American plate; PP, Pacific plate; PSP, Philippine Sea plate.

North Chugoku Shear Zone (NCSZ; Fig. 1), along the Japan Sea coast on the basis of strike-slip focal mechanisms for 15 earthquakes. Their hypothesis that the oblique subduction of a flat slab causes shear deformation even on the back-arc side is important to understand tectonic process on an active plate margin. However, there is no continuous trend of active faults corresponding to the NCSZ (Research Group for Active Faults of Japan, 1991), and the back-arc shear zone, if exist, should be identified through detailed geomorphic and geologic surveys.

In this paper, we describe active faults along the southern margin of the Japan Sea back-arc basin (Fig. 1) by combining onshore and offshore surveys on the basis of aerial photograph interpretations and seismic interpretations with borehole data, respectively. We define an arc-parallel right-lateral strike-slip fault zone, and name it the Southern Japan Sea Fault Zone (hereafter referred to as the SJSFZ). Recognition of the SJSFZ gives a clue to understand complicated stress regime around the eastern Eurasian margin. We also attempt to distinguish active and inactive segments of the fault zone, which is important for assessments of seismic hazard, on the basis of offshore structural trends delineated by extensive seismic/acoustic surveys.

2. Background: origin of the SJSFZ

The southern margin of the Japan Sea, which originated from back-arc rifting in the Early Miocene (Otofuji et al., 1985; Tamaki et al., 1992), was a site of intensive inversion event in the Late Miocene and Early Pliocene. Yamamoto (1993) described subsurface structural features along the back-arc margin

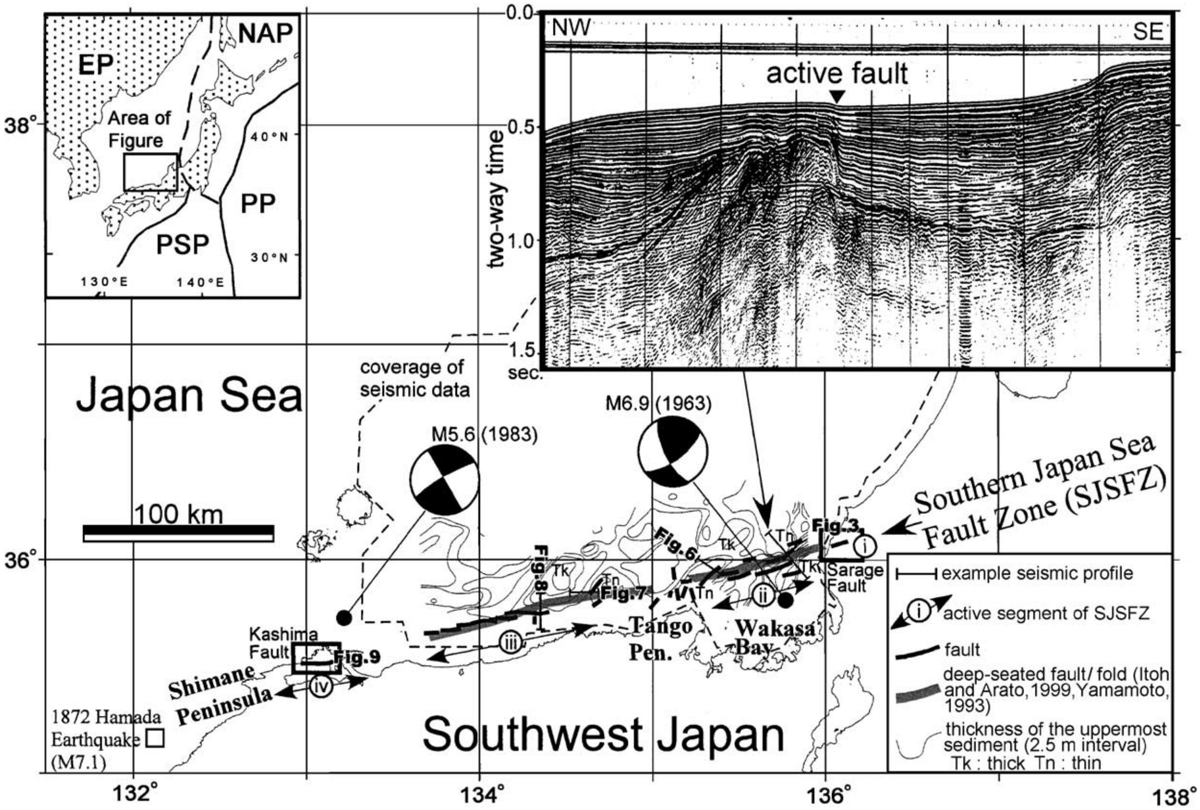

Fig. 2. A compilation of geological and geophysical data indicative of active deformation along the SJSFZ. Single-channel seismic profile is after Yamamoto et al. (2000). Focal mechanism for M6.9 (1963) earthquake is from Abe (1974); M5.6 (1983) earthquake is from Harvard CMT Catalog. Locations of Figs. 3 and 6–9 are shown. See caption of Fig. 1 for abbreviations of the plate tectonic inset.

based on single-channel seismic data, and regarded the SJSFZ as an east-trending arc-parallel fold zone (Fig. 2).

Deeper structures of the inversion zone were studied by Itoh and Nagasaki (1996) using multi-channel seismic, gravity and geomagnetic data. They compiled stratigraphic data from offshore exploration boreholes and concluded that the climax of the inversion event was around the end of Miocene time. The coeval onset of northward subduction of the Philippine Sea plate was thought to be a probable cause of the tectonic event. An average N–S shortening ratio for the back-arc shelf is ca. 0.94, and the crustal contraction resulted in closure of southwestern gateway of the Japan Sea during the Early Pliocene (Itoh et al., 1997). Itoh and Arato (1999) delineated wider area of subsurface structures of the back-arc shelf combining available seismic data sets. They described the SJSFZ as a deep-seated fault (Fig. 2) activated in the Pliocene. As shown in Fig. 1, the Early Pliocene strata show E–W elongate depocenters along the northern coast of southwest Japan, and the SJSFZ coincides with the southern margin of the inversion zone. In Section 3, we integrate previous works explained above with new evidences of active faulting, and clarify that the deep-seated offshore structure is a part of an arc-parallel trend of active strike-slip faults.

3. Active faulting along the SJSFZ

3.1. Methodology

The eastern and western parts of the SJSFZ are along the coastal areas of southwest Japan (Fig. 2).

Onshore segments of the fault zone are described on the basis of interpretation of aerial photographs and field observations of tectonic geomorphic features.

Offshore segments of the SJSFZ are described based primarily on geophysical data. Geological Survey of Japan (GSJ) conducted extensive acoustic profiling surveys in the Japan Sea. Extent of survey area is delineated by an enclosure in Fig. 2. Intervals of near-shore survey lines range from 3 to 6 km. Their interpretations of single-channel seismic data (Yamamoto et al., 1990, 1993, 2000) are compiled to delineate shallow faults (black solid lines in Fig. 2) along the SJSFZ, which was originally identified as a deeper structure on multichannel seismic profiles (gray bold lines in Fig. 2; Itoh and Arato, 1999).

Recent deformational pattern is documented by the thickness of the uppermost sediments (up to several tens of meters). The 3.5-kHz subbottom profiler records acquired by the GSJ (Ikehara et al., 1990; Ikehara, 1991; Katayama et al., 1993, 2000) delineate sediment thickness between sea floor and the first reflector (contours in Fig. 2), which was interpreted as the horizon of the widespread Aira-Tn tephra erupted at 24–25 ka (Ikeda et al., 1995).

As explained in the following sections, the SJSFZ has a predominant dextral strike-slip component of displacement. It is important to identify patterns of dip-slip motion along the fault zone for the definition of segments which rupture simultaneously during an earthquake (Nakata and Goto, 1998). In this paper, we utilize multichannel seismic records acquired by the Japan National Oil Corporation (JNOC) and an oil company together with borehole geological information. Uplifting blocks in offshore areas are identified as a bulge or truncated surface depending on the intensity of bottom-water current. Seismic profiles unravel internal deformation of a bank and growth fault morphology beneath a flat eroded surface.

3.2. Four active segments of the SJSFZ

Fig. 2 shows four active segments (i–iv) of the SJSFZ. In general, active fault segments are defined on the basis of geometric and structural features and coseismic behavior (Schwartz and Coppersmith, 1986; dePolo and Slemmons, 1990). Because paleoseismological data are scarce along the SJSFZ, we identify segments based primarily on geometric and structural features of the fault zone. Thus, the term "segment" in this paper is equivalent to "geometric segment" or "structural segment" of dePolo et al. (1991). It should also be noted that the density of geometric or structural data in offshore areas is much lower than that in onshore areas, thus, direct evidence of strike-slip motion is difficult to detect and an offshore "segment" may be composed of multiple geometric segments.

3.3. Segment i (Sarage fault)

On the eastern projection of the active submarine segments of the SJSFZ, an east–northeast-trending fault exists onshore northeast of Wakasa Bay (Fig. 2). This fault, called the Sarage fault by Research Group for Active Faults of Japan (1980), marks a topographic boundary between the Niu Mountains to the north and Fukui plain to the south (Fig. 3). The Sarage fault has been mapped as a probable active fault but its location and late Quaternary activity were poorly defined by previous studies (Research Group for Active Faults of Japan, 1980). We have mapped this fault in detail based on interpretation of 1:10,000 aerial photographs as well as field observations.

The Sarage fault extends from northwest of Hirao, Shimizu Town, eastward to Shimoichi, Fukui City for a distance of ~ 8 km (Fig. 4). The fault trends N60°E with a bend near Hasaka. The fault trace is characterized by a series of right-lateral stream offsets and hillside ridges along or slightly north of the range front of the Niu Mountains. The systematic deflection of streams as large as 200 m suggests that the late Quaternary movement on the Sarage fault is predominantly right-lateral strike-slip. The Sarage fault traverses Holocene alluvial fans at several localities but no distinct fault scarp is observed on those geomorphic surfaces.

About 1 km south of the western termination of the Sarage fault northwest of Hirao, there are two faults subparallel to the Sarage fault (Fig. 4). These faults offset a fluvial terrace, called D2 terrace by Nakagawa et al. (1995), with a vertical sense of slip up-on-the-south. The terrace is extensively dissected but the original depositional surface is preserved at an elevation 20–30 m higher than the modern stream channel. At an outcrop 2 km south of Hirao, the D2 terrace deposits are overlain directly by the Daisen–Kur-

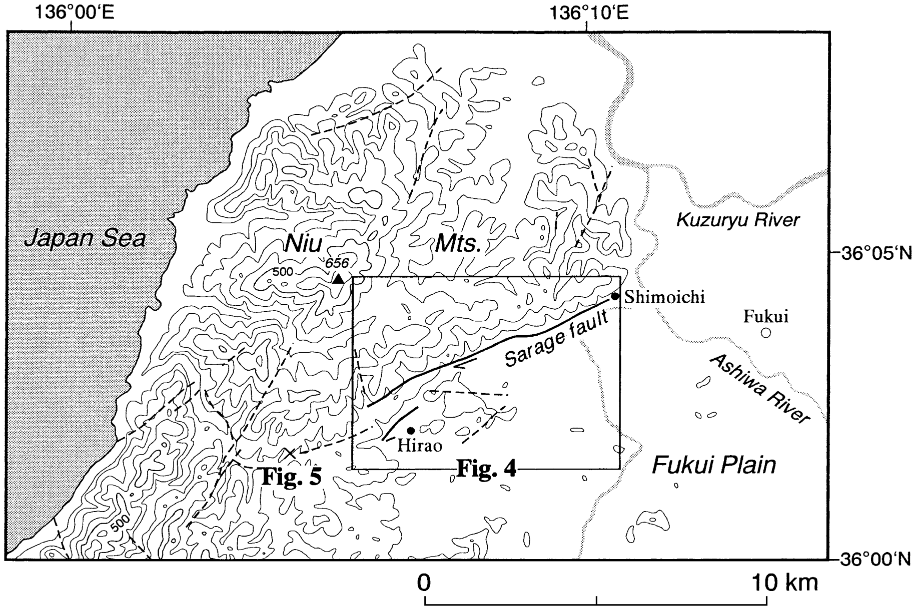

Fig. 3. Index map around the Sarage fault. Contour interval 100 m. Solid lines show active trace of the Sarage fault. Broken lines are inactive geologic faults after Miura et al. (1971). Locations for Figs. 4 and 5 are shown.

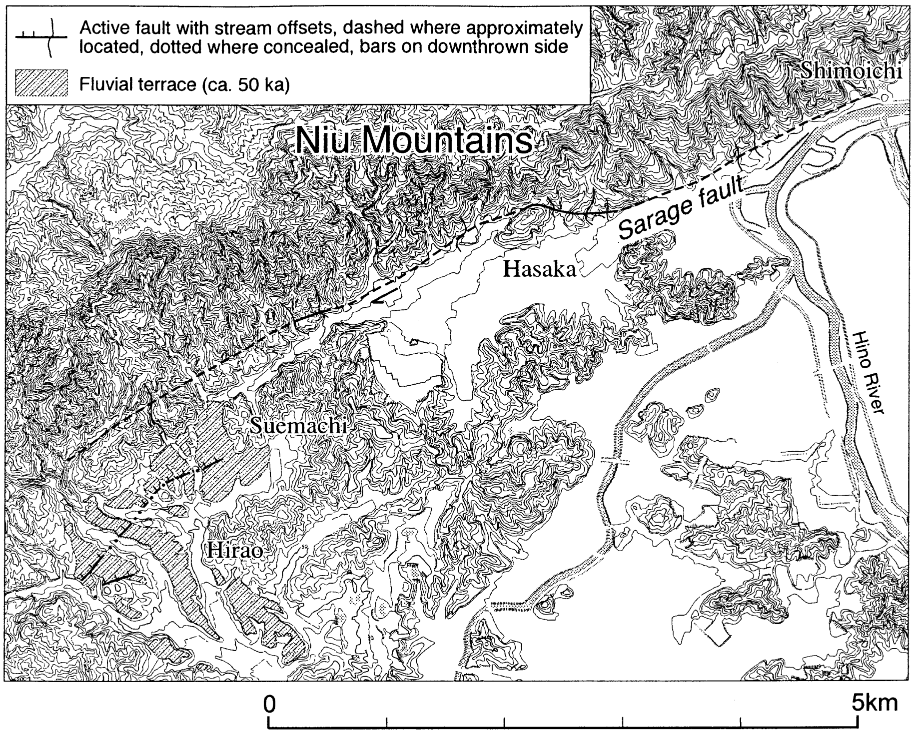

Fig. 4. Topographic map along the Sarage fault. Contour interval 10 m. Hatch pattern near Hirao shows terrace surface which is correlated to D2 terrace of Nakagawa et al. (1995).

ayoshi tephra erupted at about 50 ka (Machida and Arai, 1992). This constrains the age of D2 terrace at slightly older than 50 ka. The offset of D2 terrace surface at Suemachi was measured at 1.6 m, suggesting that an average vertical slip rate for the fault is < 0.03 mm/year. Because the fault at Suemachi is only 1.5 km long and 1 km away from the Sarage fault, it is likely that the fault moves together with the Sarage fault.

At Nishibessho, 3.5 km west of Hirao, a fault plane was exposed during excavation in winter of 2000–2001 (Fig. 5). Based on the location of the outcrop, a western extension of the Sarage fault appears to have been exposed (Fig. 3). The fault separates tuff breccia of the Ito Formation of early Miocene age to the north against fluvial deposits of the Shukudo Formation of middle Pleistocene age to the south. The fault plane dips steeply to the north with apparent sense of vertical movement up-on-the-north. No deformation of the ground surface was observed around this site. West of Hirao, the western continuation of the Sarage fault seems to have been active in the middle Quaternary but lacks evidence for late Quaternary movement.

Although being located on the eastern projection of the SJSFZ north of Wakasa Bay, the Sarage fault is not continuous from the coast line. Between the coastline and Hirao, no late Quaternary active fault is identified based on aerial photograph interpretation (Fig. 3). East of Shimoichi, the Sarage fault cannot be traced into the Fukui Plain. The eastern margin of the Fukui Plain is bounded by north-trending reverse faults, part of which ruptured during the 1948 Fukui earthquake (M7.1). East of the Fukui Plain, north-trending reverse faults develop predominantly and there is no east-trending right-lateral strike-slip fault which could be part of the SJSFZ.

3.4. Segment ii

A series of east-trending faults across Wakasa Bay are found on single-channel seismic profiles. Some of these faults offset the sea bottom with a vertical sense of slip up-on-the-north (inset profile of Fig. 2). Thickness of the uppermost sediments shows a pattern characteristic for right-lateral strike-slip faults; the north side is up along the eastern trace of Segment ii whereas the south side is up along the western trace. Focal mechanism for the Wakasa Bay earthquake (M6.9 in Fig. 2; Abe, 1974) is concordant with the strike-slip fault motion. Segment ii terminates westward at a northeast-trending fault (Figs. 2 and 6) that coincides with the eastern scarp of the Urashima Bank. Western flank of the bank, off the Tango

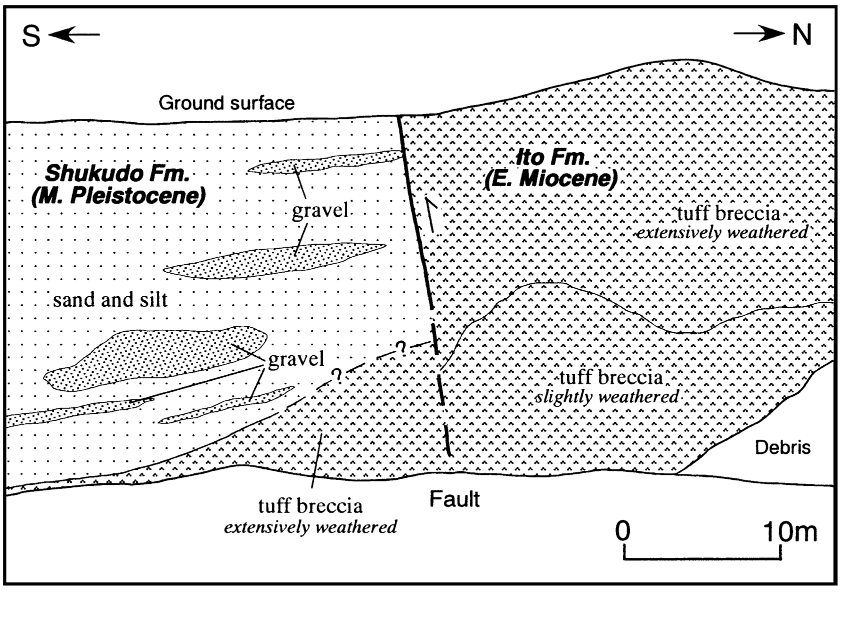

Fig. 5. Simplified log of fault outcrop at Nishibessho. View is to the west. See Fig. 3 for location.

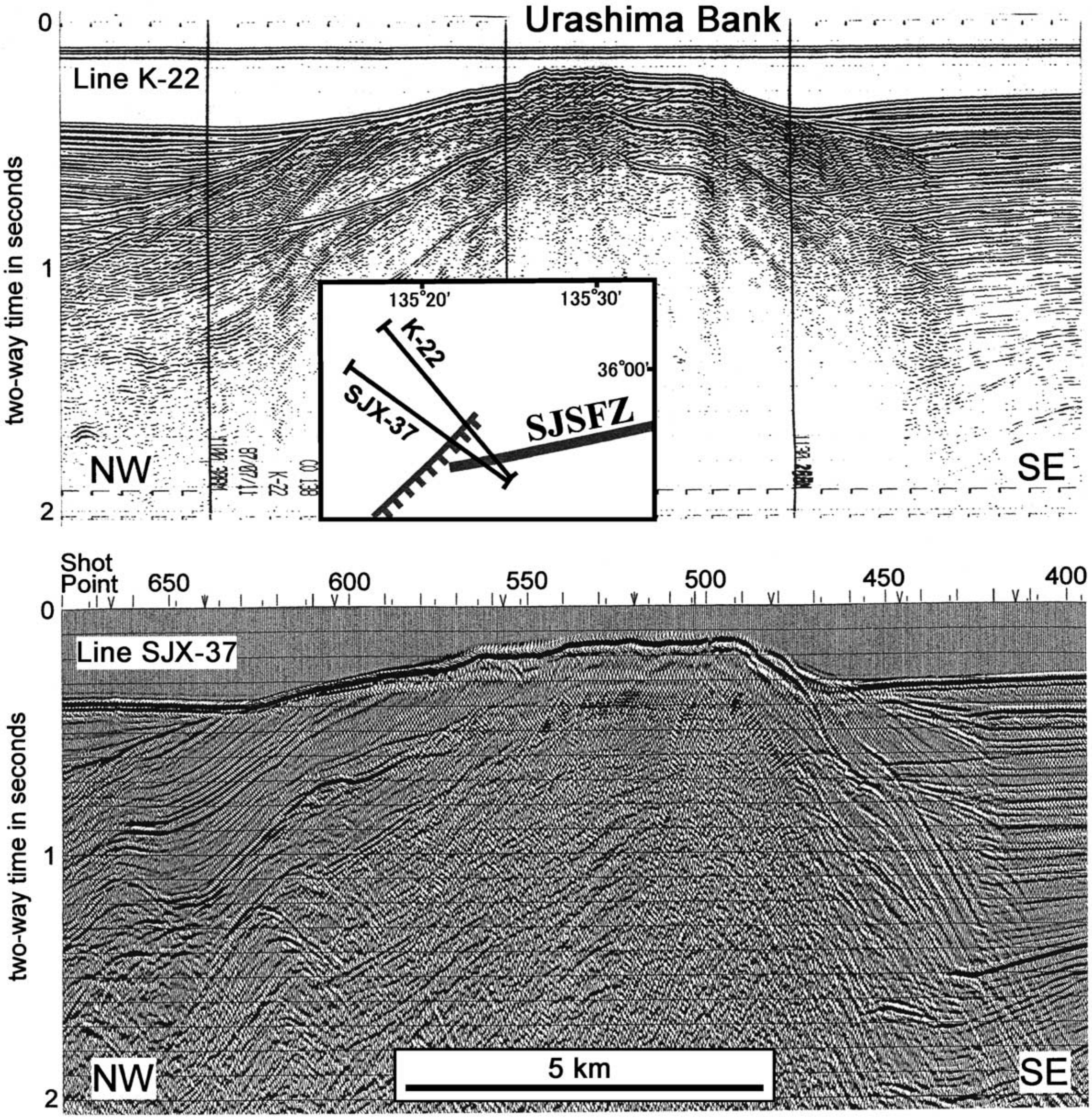

Fig. 6. NW–SE single- (upper) and multichannel (lower) seismic profiles in the same scale crossing the Urashima bank at the western end of active segment ii of the SJSFZ. See Fig. 2 for location.

Peninsula, is cut by short faults. Multichannel seismic profile in Fig. 6 indicates that the bank is not a preexisting basement high but an actively tilting block with internal deformation (around SP. 650 of Line SJX-37). The Urashima Bank may constitute northern part of a larger uplifting block, because the Tango Peninsula (Fig. 2) has been uplifted during the late Pleistocene, evidenced by raised marine platforms younger than marine isotope stage 5e (Okada and Togo, 2000).

3.5. Segment iii

Single-channel seismic data delineate faults aligned on the SJSFZ (Fig. 2). The faults show left-stepping en echelon pattern, suggesting a right-lateral motion along the SJSFZ. Shallow structural features diminish to the east, and the SJSFZ seems to have been inactive throughout the Pleistocene from 134°40′ E to 135°20′ E (north of the Tango Peninsula). Fig. 7 shows E–W seismic profiles around the eastern termination of the Segment iii. Multichannel seismic profile (Line SJX-128) and geological data of the MITI Kasumi-oki borehole (JNOC, 1990) demonstrate that a truncated anticline exists beneath flat sea bed, and the structure has developed throughout the Pleistocene above an active reverse fault. Thus, the concealed anticline appears to have grown in response to contraction at a termination of right-lateral strike-

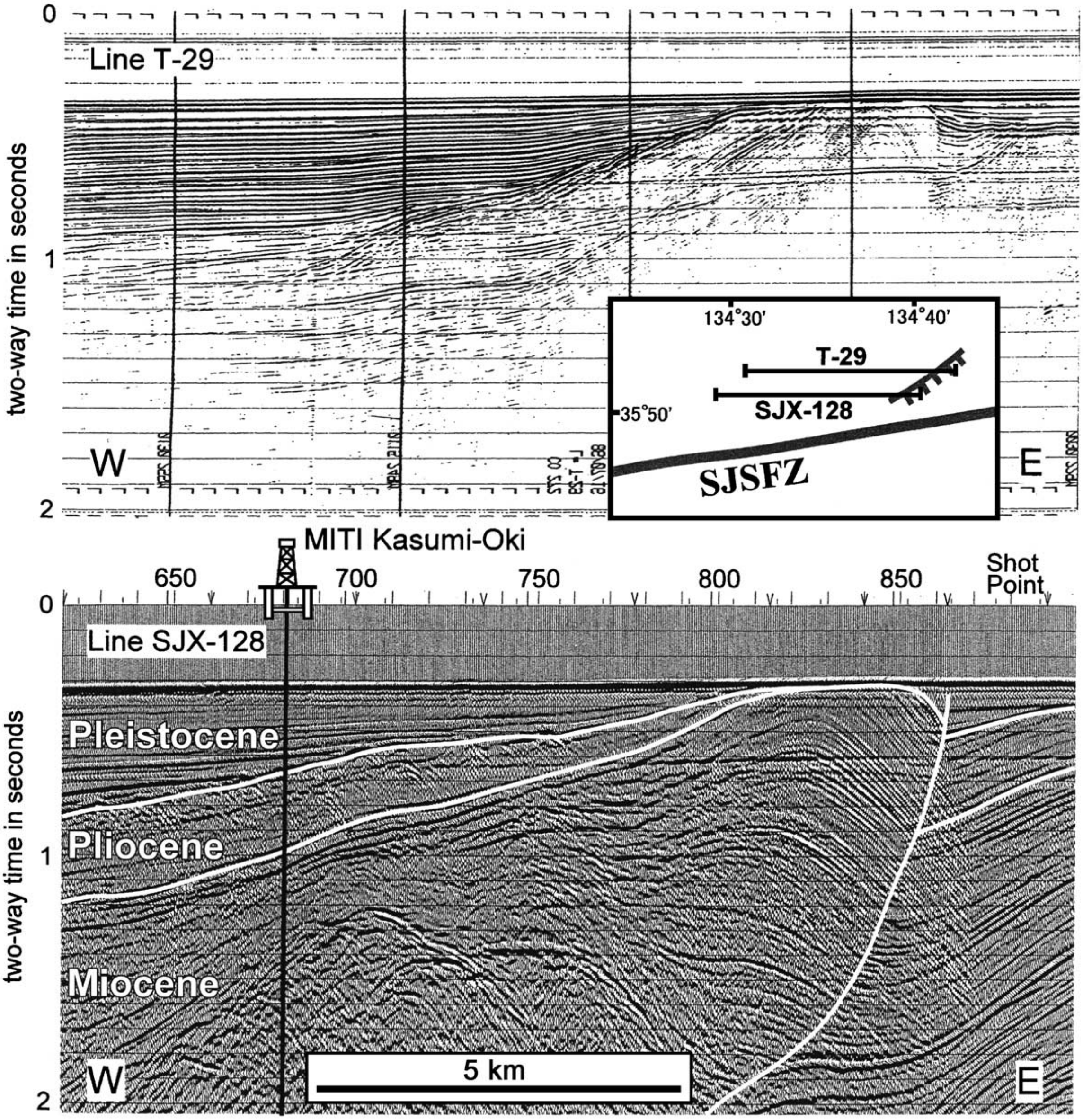

Fig. 7. E–W single- (upper) and multichannel (lower) seismic profiles in the same scale running near the eastern end of active segment iii of the SJSFZ. Subsurface unit boundaries are based on geological information of MITI Kasumi-oki well (JNOC, 1990). See Fig. 2 for location.

slip faults. An N–S seismic profile crossing central part of the Segment iii is presented in Fig. 8. Sea bed is deformed on an active fault, which is accompanied by a deep-seated fold identified by Yamamoto (1993). At present, we cannot determine the western termination of this segment because of absence of acoustic data around 133°30′ E (Fig. 2). Segments iii and iv may be continuous because an earthquake occurred in between (M5.6 in Fig. 2) has a pure dextral strike-slip focal mechanism.

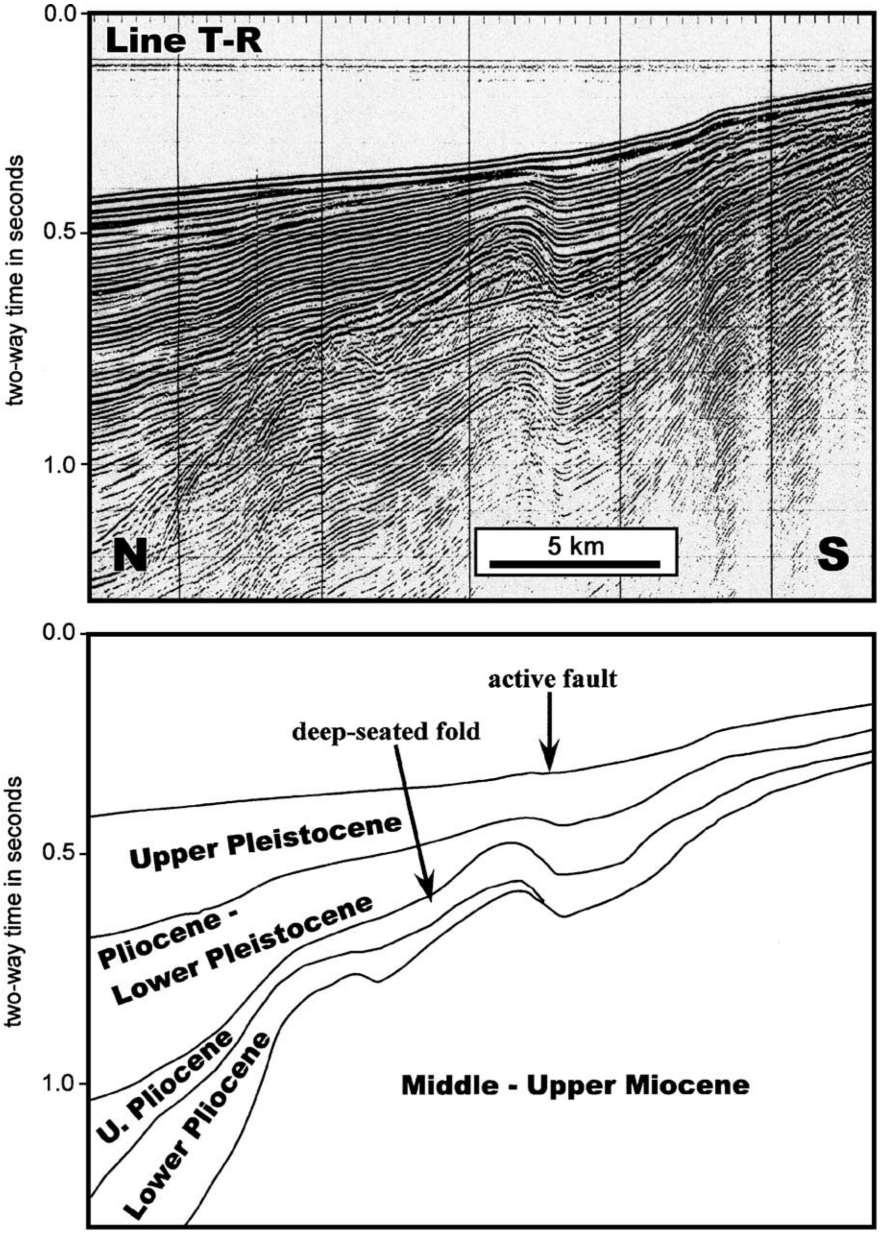

Fig. 8. N–S single-seismic profile (upper) crossing active segment iii of the SJSFZ. Its geologic interpretation (lower) is after Yamamoto et al. (1990). See Fig. 2 for location.

3.6. Segment iv (Kashima fault)

On the western extension of Segment iii offshore, the east-trending Kashima fault was mapped by Nakata and Goto (1998) for a distance of about 15 km in the Shimane Peninsula (Fig. 2). Systematic right-lateral offset of stream channels as much as 150 m suggests that the fault has been active in the late Quaternary (Fig. 9; Nakata and Goto, 1998). However, no fault scarp is identified along the Kashima fault because it traverses mostly across hilly terrain composed of Miocene strata. The Kashima fault appears to have reactivated the Shinji fault, a Miocene reverse fault which dips 60°–90°N. The Shinji fault and anticlinorium in the Shimane Peninsula were interpreted to have formed during middle to late Miocene time under an N–S compressional stress field (Kano and Yoshida, 1985). The eastern and western terminations of the Kashima fault are not known due to lack of high-resolution acoustic profiling data east and west of the Shimane Peninsula. The epicenter of the 1872 Hamada earthquake (M7.1) is located at about 80 km west–southwest of the Kashima fault based on distribution of structural damages and crustal deformation along the coast (Fig. 2; Usami, 1996). The earthquake is one of the largest historical earthquakes along Japan Sea side of southwest Japan and may be related to the movement of the SJSFZ. Therefore, SJSFZ seems to be an arc-parallel deformation zone throughout the back-arc margin of southwest Japan.

4. Discussion

4.1. A pair of transcurrent faults activated by Quaternary oblique subduction: MTL and SJSFZ

We have described the SJSFZ, an active right-lateral fault zone along the southern margin of the Japan Sea. There is another active right-lateral fault zone parallel to the southwest Japan arc, the Median Tectonic Line (MTL; Fig. 10). It is the most pronounced geological discontinuity since the late Mesozoic in southwest Japan dividing Inner zone (Paleozoic/Mesozoic terranes, low pressure–high temperature Ryoke metamorphic belt) to the north and the Outer zone (high pressure–low temperature Sambagawa metamorphic belt, Mesozoic/Cenozoic accretionary prism) to the south for over 1000 km (e.g. Hashimoto and Kanmera, 1991). The MTL has been reactivated related to oblique subduction of the Philippine Sea plate beneath the Eurasian plate at the Nankai trough (Fig. 10; Fitch, 1972). Because the

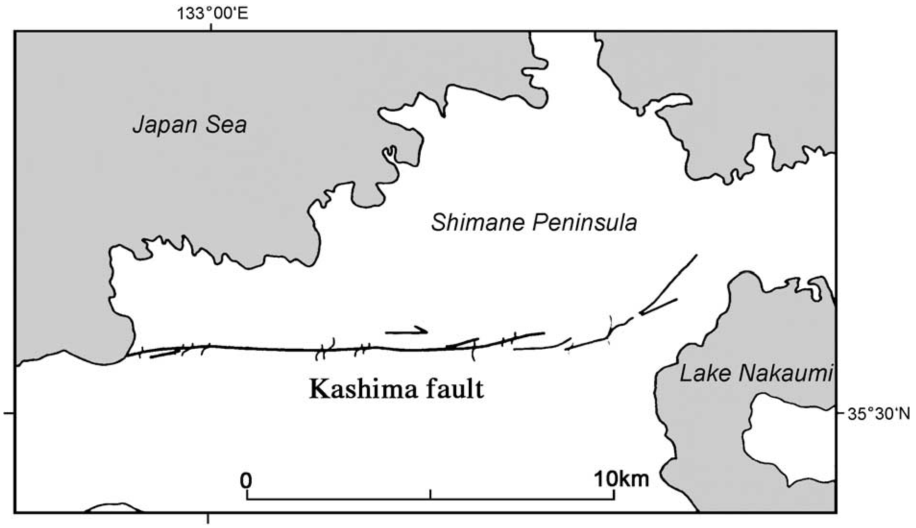

Fig. 9. Map showing active trace of the Kashima fault (thick lines) after Nakata and Goto (1998). Right-lateral offsets along the fault are shown by thin lines.

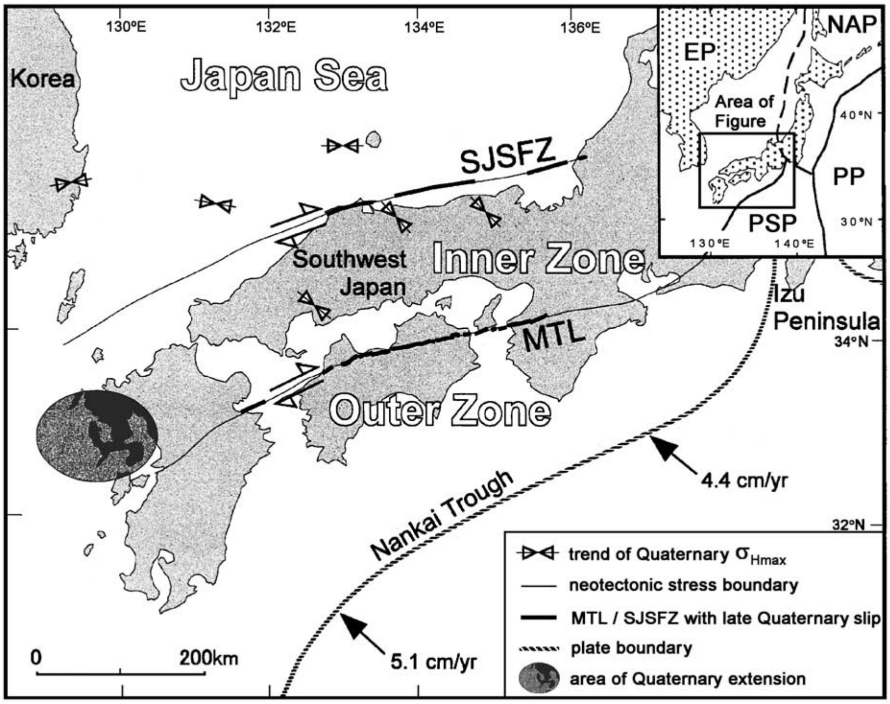

Fig. 10. Neotectonic stress domains bounded by the SJSFZ and Median Tectonic Line (MTL). Active segments of the MTL are after Tsutsumi and Okada (1996) and Itoh et al. (1998). $\sigma_{H_{max}}$ trend of the Japan Sea domain is based on active fault research in the Korean Peninsula (Okada et al., 1998) and seismic interpretation (Itoh and Arato, 1999). $\sigma_{H_{max}}$ trend of the Inner Zone domain is from elongate distribution of the Quaternary monogenetic volcanoes (Nakamura, 1975) and geomorphic trend formed by wrench deformation (Itoh and Takemura, 1993). Plate convergence vectors along the Nankai trough are calculated based on the work of Seno et al. (1993). See caption of Fig. 1 for abbreviations of the plate tectonic inset.

convergence vector of the Philippine Sea plate shifted counterclockwise at around 1–1.5 Ma (Nakamura et al., 1984, 1987), right-lateral slip rate of the MTL has probably accelerated during the Quaternary. As reviewed in Section 2, the SJSFZ was initiated as a rifted back-arc margin and developed as a part of inversion zone during the Neogene. This preexisting zone of weakness in the crust may have been reactivated as a right-lateral shear zone simultaneously with the Quaternary activity of the MTL. Thus, shear stress caused by oblique subduction of the Philippine Sea plate resulted in right-lateral slips along the paired arc-parallel fault zones, the MTL and SJSFZ, and westward translation of the Outer and Inner zones of southwest Japan relative to the Eurasian plate.

Gutscher and Lallemand (1999) insisted that their hypothetical back-arc shear zone (NCSZ) is more active than the MTL based on lack of recent earthquake events on the MTL. Activity level of a fault, however, should be evaluated on the basis of its slip rate or cumulative slip in a geologic timescale because motions of intraplate faults are quite intermittent, and many of them have recurrence interval longer than 1000 years. Right-lateral stream offset along the Segment i of the SJSFZ (as large as 200 m; see Section 3.3) is much smaller than that along the MTL (e.g. 1.5 km; Tsutsumi and Okada, 1996). Such difference may be related to attenuation of shear stress in the overriding continental lithosphere away from the oblique convergent plate margin. Much more detailed geological and paleoseismological information is necessary to estimate average Quaternary slip rate on the SJSFZ and compare with that on the MTL.

4.2. Neotectonic stress domains around the southern Japan Sea

Fig. 10 depicts neotectonic stress trend and stress domain boundaries around the southern Japan Sea and southwest Japan. The SJSFZ and its extension as the southern margin of the Neogene inversion zone separates the Japan Sea and Inner Zone domains. The active and inactive (geologically defined) MTL separates the Inner zone and Outer zone domains. Southern Japan Sea is under E–W compressive stress on the basis of active fault research in Korea (Okada et al., 1998) and offshore seismic interpretation (Itoh and Arato, 1999).

In contrast, the Inner zone of southwest Japan is under NW–SE compression, consistent with wrench deformation between parallel right-lateral faults (Itoh and Takemura, 1993). It is noteworthy that neotectonic stress inferred from the trend of Quaternary monogenetic volcanoes on the Japan Sea coast (Nakamura, 1975) is quite different from stress field in the southern Japan Sea, implying that a boundary of neotectonic stress domain exists along the Japan Sea coast. Stress trend in the western portion of the Inner zone is affected by complicated factors. Itoh et al. (1999) described subsurface structural features around the westernmost part of the Inner zone (shaded oval in Fig. 10) on the basis of geophysical and geological data. They clarified that the area is actively subsiding under a transtensional regime related to multifarious causes such as mantle upwelling (Nakada and Kamata, 1991) and wrench deformation (Tsukuda, 1993).

As for the Outer zone, Quaternary volcanoes as a stress indicator do not exist because it is located on the fore-arc side of volcanic front. There are very few active faults in the Outer zone between the MTL and fore-arc basins to the south (Research Group for Active Faults of Japan, 1991). Tsukuda (1992) regarded this zone to behave as a rigid sliver. Offshore (near-trench) part of the zone is intensively deformed and accommodates stresses provoked by oblique underthrusting of the Philippine Sea plate and continental fragments on the plate (Sugiyama, 1992; Yamazaki and Okamura, 1989). Thus, the stress trend within the Outer zone, acting as a buffer zone along the convergent margin, is too complex to be summarized and schematically shown in Fig. 10.

5. Summary

Integrated geophysical and geological study delineates an active right-lateral fault zone along the southern Japan Sea margin. We identified four active segments along the Southern Japan Sea Fault Zone (SJSFZ) on the basis of onshore geomorphic data and offshore acoustic/seismic data. The SJSFZ constitutes a paired arc-parallel faults with the Median Tectonic Line (MTL), both of which are reactivated by oblique subduction of the Philippine Sea plate beneath the Eurasian plate and regarded as boundaries of neotectonic stress domains around the southern Japan Sea and southwest Japan, namely, Japan Sea, Inner zone and Outer zone domains.

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