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Duplex Stress Regime in the North Fossa Magna, Central Japan

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Abstract

The seismogenic zone along the Japan Sea coast of the Japanese archipelago is a site of active convergences between Amur and Okhotsk plates, as demonstrated by frequent occurrences of historical earthquakes larger than magnitude M6.5. The geologic structure of the zone is commonly characterized by the Neogene thrust/fold belt on the intra-arc continental shelves of both Northeast and Southwest Honshu arcs. A widespread stress field with a northwesterly orientation of maximum principal stress axis is identified throughout the inner side of Honshu by seismotectonics and geodetic monitoring. As for the fault plane solutions of crustal earthquakes, thrust faulting dominates throughout the inner side of the Northeast Honshu arc, while paired fault provinces of thrust and strike-slip faulting are recognized along the inner Southwest Honshu arc. On the basis of a synchronism of seismicity between the Southwest Honshu arc and the Nankai Trough, strain partitioning might account for the strike-slip fault provinces due to oblique subduction of the Philippine Sea plate, as well as the collision of the Izu-Bonin arc with Southwest Honshu. As the easternmost portion of the Southwest Honshu arc is the overriding plate of the Philippine Sea Plate, a duplex stress regime of the northwest-southeast compression intercalated by north-south compression has been associated with the north Fossa Magna region.

Key words: tectonic stress field, active fault, Fossa Magna, fault history, central Japan

1. Introduction

The Japanese archipelago comprises five island-arc systems—the Kuril, Northeast Japan, Southwest Japan, Ryukyu, and Izu-Bonin arcs. The former two belong to the East Japan arc system and the latter two to the West Japan system (Fig. 1). Honshu, the largest island of the Japanese archipelago, was initiated by tectonic processes of rifting and back-arc spreading of the Japan Sea, which is similar to the other arcs in Japan. Central Honshu represents an arc-to-arc juncture of the East Japan and the West Japan arc systems, with dual collisions of Amur and Philippine Sea plates and Amur and Okhotsk plates. Such a superposed tectonic condition appears as a dense distribution of active strike-slip faults and intense crustal movements concentrated in central Honshu. The Neotectonic evolution of the Japan Sea and Honshu Arc (Hirooka *et al.* 1986; Ishikawa *et al.* 1989; Kano *et al.* 1991; Jolivet *et al.* 1994; Sneider 2003; Takeuchi 2004; Ohguchi *et al.* 2005; Yun *et al.* 2007) is summarized in a time table (Fig. 2, Fig. 3).

In the Northeast Honshu arc, strong E-W contractions along the eastern margin of the Japan Sea commenced at about 4 Ma (Ohtake *et al.*, 2002). Such tectonic events denote the onset of convergence along the nascent plate boundary between the Amur and Okhotsk plates (Nakamura, 1983; Kobayashi, 1983). In Southwest Honshu including the Fossa Magna region, development of N-S trending folds became remarkable instead of E-W trending folds (e.g. Takeuchi, 1981; 2004).

Because the arc-parallel thrust/fold belt comprises three different structural trends, development of the belt could not be attributed simply to horizontal shortening due to thin-skin tectonics, but is also attributed to strike-slip displacement and vertical block movement as basement-involved tectonics. In response to the Pliocene and later compression re-

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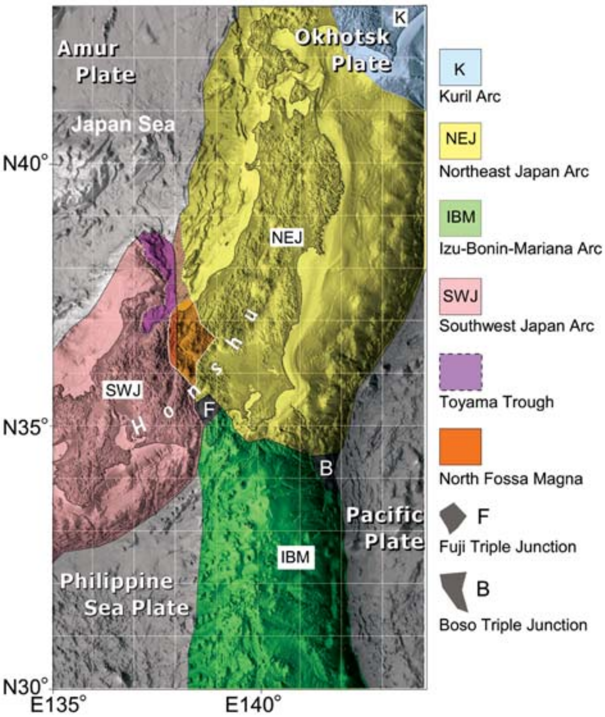

Fig. 1. Index Map of Triple Arc junction at and around central Japan (modified from Takeuchi (1991)

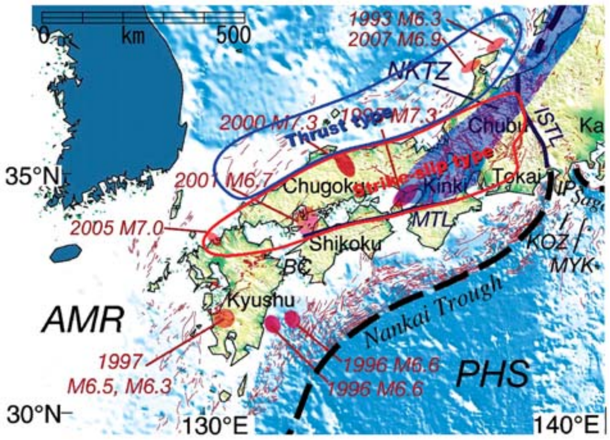

Fig. 2. Active-Fault Province in the inner belt and Niigata-Kobe tectonic zone. Base map after Sagiya (2004)

gime, the Miocene fault-block boundaries were reactivated to produce differential block movements demonstrated by both coastal plains and uplifted peneplain such as the Hida highland and the Chugoku peneplain. However, the present style of faulting did not start until the Izu/Honshu collision when the tectonic province of strike-slip faulting started to spread from central Japan into Southwest Honshu (1–0.3 Ma).

Recently, in central Honshu, the Noto Hantou earthquake (magnitude M_{JMA} 6.9 on the Richter scale; depth H=11 km) occurred under a shallow seabed west of the northern Noto Peninsula in 2007. Just 3.6 months after the Noto Hantou event, the 2007 Niigata Prefecture Chu'etsu-oki Earthquake (M_{JMA} 6.8 and H=15 km) was generated. The 2004 Chu'etsu earthquake occurred in the inland Chu'etsu region 2.5 years before the Noto event, and the 2005 West off Fukuoka Earthquake (M_{JMA} 7.0 and H=9 km) occurred in the westernmost Japan Sea. Therefore, attention is being paid to a genetic relation among these earthquakes because of their close relationship in time and space. These earthquakes may suggest a common cause of high seismicity along the Japan Sea coast of the Northeast and Southwest Honshu arcs. This paper reviews the Plio- and Pleistocene fault history of north-central Japan, and discusses the tectonics stress field associated with larger earthquakes in and around the North Fossa Magna.

2. The north fossa magna

2. 1. *Tectonic evolution of Honshu Arc*

As a triple arc-junction of Northeast and Southwest Honshu arcs and Izu-Bonin arc, the Fossa Magna region has steep mountain ranges, which include the Hida, Kiso, and Akaishi Mountains on the western side of the Itoigawa-Shizuoka Tectonic Line. There are many active faults in the central Honshu region at the boundary between mountains and basins. Geodetically, a largest crustal movement in the Japanese archipelago has been observed in central Honshu, and there is a pronounced contraction whose orientation of maximum strain axis generally ranges from east-west to northwest-southeast (Tada and Hashimoto, 1990; Tada, 1995). Adjacent to the Hida mountain ranges, the Hakuba basin has been developed by an active reverse fault—the Kamishiro fault—at the northern termination of the Itoigawa-Shizuoka Tectonic Line, bounding the western border of the North Fossa Magna region (Ikeda *et al.*, 2002). The most recent strong earthquake along the Kamishiro fault occurred in 1714 with a surface rupture having a north-south trend. According to Tsukuda (1994), the next event will soon be generated around Hakuba at a specific area of maximum concentration of tectonic strain in the Niigata-Kobe Tectonic Zone (NKTZ: Sagiya *et al.,* 2000).

The stress regime of strike-slip faulting occupies the basement as inferred from focal mechanism solutions for small events. One possible model for the deeper geologic structure presents high-angled block faults bounding tectonic provinces that originate from vertical weak zones in the deep seismogenic zone (Iio and Kobayashi, 2002; Takeuchi, 2004).

3. Fault history

3. 1. Geologic structure and tectonic history of the North Fossa Magna

The geologic structure and the tectonic history of the North Fossa Magna are summarized as follows (e.g. Takeuchi, 2004). Basically, the geologic structure of the North Fossa Magna is divided into two tectonic provinces—the Central Upheaval zone and the western Shin'etsu sedimentary basin. The Shin'etsu basin was initiated in the early Miocene by north-south trending rifting accompanied by subaqueous volcanic activity at the east adjacent area. After subsidence with the accumulation of mudstones of abyssal facies in the early Middle Miocene, east-west trending folds formed probably due to the collision of Izu-Bonin Arc. North-south trending normal faulting, however, restarted in the later Middle Miocene and continued up to the end of the Late Miocene. During the extensional period, granitic intrusion and related hydrothermal activities became dominant in the Central Upheaval zone.

The first appearance of strong compression tectonics was recognized by north-south trending folds unconformably covered by the bases of Pliocene volcanoes dated at 5.4 Ma. The next remarkable shortening with northeast-southwest trending folds commenced at about 4 Ma. Trough-fill turbidites accumulated in synclinal depressions on the footwall of thrusts (Takano *et al.,* 2005). This shortening, known as basin inversion from the rifted Sin'etsu basin to the Nishi-kubiki mountain, formed the Nagano basin at the side of the Central Upheaval due to northwestward tilting, although the west adjacent district, Hida, had been relatively stable until magmatic uplifting started there at around 3.5 Ma (Tamura, 2005).

3. 2. Reversals of tectonic stress fields of the North Fossa Magna

According to previous studies based on the dike method (Takeuchi, 1981; 1986), the regional tectonic stress field of the North Fossa Magna was associated with the following five epochs of vicissitude in the Neogene: (1) Early Miocene extensional regime with a maximum extensional stress-axis oriented along a north-south trend from about 17 Ma, (2) early Middle Miocene compressive disturbance around 14–12 Ma, (3) later Middle to Late Miocene extensional regime of the east-west extension, (4) early Pliocene east-west compression regime from about 6 Ma., and (5) late Pliocene and later regime of northwest-southeast compression. It seems significant that the changes in the stress field always anteceded the crustal response to form the resultant geologic structure (Takeuchi, 1977; 1999).

The Neotectonic evolution of the Japan Sea and Honshu Arc is summarized by a timetable (Fig. 3).

4. Present-day active tectonics

4. 1. Present-day deformation along the Japan margin of the Amur Plate

On the basis of the open data source offered by the International GNSS Service (IGS) for the period from 1997 to 2005, a systematically differential movement was recognized in spatial variations of the GPS horizontal velocity field, and the hypothesis of the Amur plate originally proposed by Zonenshain & Savostin (1981), including Japan Sea and Southwest Japan, was verified with the existence of the Amur plate and its plate tectonic significance as a sub-plate within the eastern Eurasia plate. The Amur plate is surrounded by broad deformation zones in the East Asian continent. Both Amur and South China plates show an eastward motion that differs from the Eurasia Plate depicted by Irkutsk and Lhasa.

Detailed monitoring of crustal movements in Japan using the GPS Earth Observation Network system (GEONET) managed by Geographical Survey Institute (GSI) of Japan, shows a horizontal velocity field relative to the proper Amur Plate, as inferred from averaged data during the period from April 1996 to July 1999, and displays the Niigata-Kobe tectonic zone of the geodetic strain concentration (NKTZ). This zone is traced from Sakhalin through west Hokkaido, northeast Honshu and southwest Honshu down to the central part of Kyushu Island, and is coincident with the Japan margin of Amur Plate (JMAP). During the 20^{th} century, five major

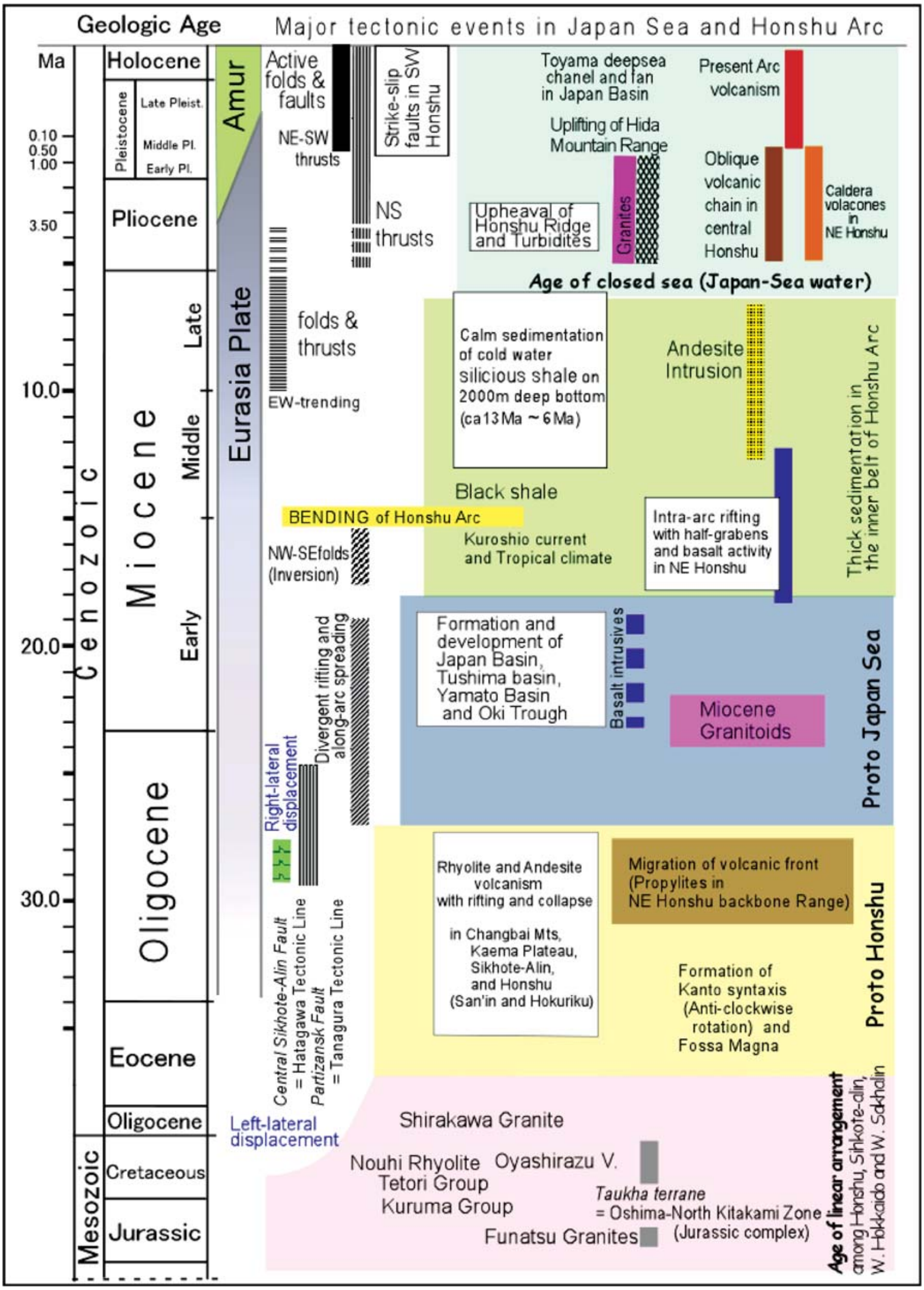

Fig. 3. Timetable for the Neotectonic evolution of Japan Sea and Honshu Arc. Data from National Astronomical Observatory of Japan (2006).

earthquakes occurred along the segment of the JMAP that comprises the boundary between the oceanic crust of Japan Basin and the continental blob of the Northeast Japan arc. Three larger earthquakes have occurred since 2003 in the NKTZ zone, which runs southward into the North Fossa Magna region and is the Paleogene arc suture between Northeast Honshu and Southwest Honshu.

4. 2. Seismic activity of Southwest Honshu Arc

The temporal distribution of historical earthquakes in southwest Honshu demonstrates an alternative sequence of quiet and active periods following major earthquakes along the Nankai Trough, where the Philippine Sea plate subducts obliquely under the Southwest Honshu arc. Crustal earthquakes greater than M6.5 occur soon before or after a major event along the Nankai Trough, when tectonic activity of the back arc side of the Southwest Honshu arc reaches a climax. This demonstrates synchronism between crustal seismicity and subduction of the Philippine Sea plate. At present, we are in a new active period just prior to the near-future Tounankai earthquake, with a 60–70% occurrence probability within the next 30 years (Headquarters for Earthquake Research Promotion, 2007).

Larger earthquakes of more than M6.5 tend to occur along the Neogene thrust/fold belt on continental shelves in the intra-arc belts of the Southwest and Northeast Honshu arcs. Major thrust earthquakes (M7.4–7.8) along the eastern margin of the Japan Sea west of Northeast Honshu arc demonstrate nascent subduction of the Amur plate beneath the Okhotsk plates. Thrust-type faulting in their focal mechanism dominates the continental shelf of Southwest Honshu including Noto and Shimane Peninsulas. While, a strike-slip fault province occupies the inland area of the inner belt of Southwest Honshu.

The 2007 Noto Hantou Earthquake was a thrust event along the coastal thrust/fold belt. The rupture was initiated from the base of the seismogenic zone at a depth of 11 km. The earthquake fault strikes a NE-SW trend and dips southeast according to the distribution of after-shocks. It is noteworthy that the geometry of the fault is not a single flat plane but is composed of a moderately inclined fault and an almost vertical fault at the lowermost part. Moreover, opposite dipping faults are recognized from after-shock distribution (Hiramatsu, 2007). The source mechanism is a reverse fault with a right-lateral slip, and the initial rupture was almost a pure strike-slip dislocation.

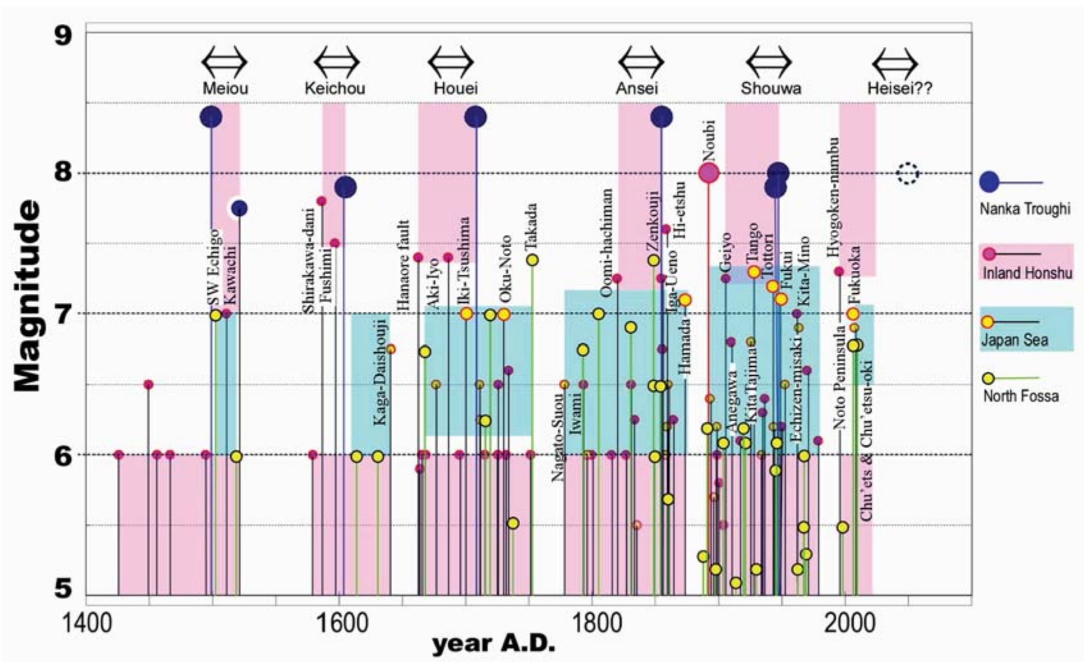

Fig. 4. Temporal distribution of larger historical earthquakes that occurred in the Southwest Honshu arc. Vertical axis represents magnitude on the Richter scale.

4. 3. Synchronism of historical earthquakes between Nankai Trough and back-arc sides of Southwest Honshu arc

Figure 4 shows a time series of historical earthquakes that occurred in the Southwest Honshu arc and in the North Fossa Magna region. Seismic events occurred in the Northeast Honshu arc east of the eastern margin of the Fossa Magna. The Yoneyama-Ogi uplift zone (Okamura *et al.,* 1994) and Nao'estsu-Chiba Tectonic Line (Kono, 2003) are excluded. Earthquakes greater than M6.5 generated within about 50 years before the giant event along the Nankai Trough, when seismic activity of the back arc side of Southwestern Japan Arc was also activated simultaneously, include the 1891 Noubi earthquake, which was the largest inland crustal earthquake to occur in Japan. Similarly, larger events in the North Fossa Magna region occurred contemporaneously with events at the Japan-Sea side of the Southwest Honshu arc, such as 1872 Hamada (M7.1), 1927 Tango (M7.3), 1943 Tottori (M7.2) earthquakes. The 1847 Zenkouji earthquake (M7.4) occurred seven years before the 1854 Ansei Toukai and Nankai earthquakes (M8.4). Consequently, on the basis of such a remarkable synchronism of seismicity between the Southwest Honshu arc and the Nankai Trough, mechanically the same cause is suggested to generate crustal events.

5. Discussion

(1) The oblique to longitudinal compression in the seismogenic stress field of the Southwest Honshu arc appeared within the Pleistocene significantly later than the strong shortening perpendicular to the Northeast Honshu arc (Takeuchi, 1991; 1999). The earliest contraction tectonics in the North Fossa Magana region commenced at the end of the Miocene, while the development of east-west trending fold belts had already started along the Japan Sea coast in the Southwest Honshu arc (Takeuchi, 1986; 1999). The thrust/fold belt on the continental shelf north of the Fossa Magna region formed since the middle Pliocene (4 Ma), as well as the inland region to the south, when the orientation of the maximum principal stress axis of compression changed from east-west to northwest-southeast (Niitsuma *et al.,* 2003). Such a difference in the timing of the first appearance of the present compression between the Northeast and Southwest Honshu arcs suggests different sources of tectonic force.

(2) Larger earthquakes of more than M6.5 tend to occur along the Neogene thrust/fold belt on continental shelves at the inner belts of the Southwest Honshu arc, as well as at the Niigata-Kobe strain concentration zone running from the Japan Sea coast of Northeast Honshu across the Itoigawa-Shizuoka Tectonic Line into the inland area of Southwest Honshu. Because of the geomorphologic setting across both Honshu arcs, it is difficult to explain the origin of the latter tectonic zone as a direct effect of the Philippine Sea plate. Based on a numerical experiment, Hyodo and Hirahara (2003) claimed that subduction of the Pacific plate might easily explain the origin of the strain distribution cutting across the major geologic structure. Nakajima and Hasegawa (2007) revealed a three-dimensional seismic velocity structure along NKTZ, whose crust and uppermost mantle show remarkable heterogeneity and segmentation due to the concentration of fluids derived from the Philippine Sea slab, and also fluids related to back-arc volcanism of the East Japan arcs. Although the East Japan arc system belongs to the subduction zone of the Pacific plate, the subducted slab of Philippine Sea plate is recognized beneath the south-central Fossa Magna region of the overriding Okhotsk plate. Consequently, synchronous seismic activity between the great interplate earthquakes along the Nankai Trough and concentration of larger events in the inner arc might be evidence that subduction of the Philippine Sea plate drives activity of the crustal seismogenic zone along the Japan margin of Amur plate. The effects of subduction of the Philippine Sea plate could also explain the paired fault provinces of thrust and strike-slip faulting recognized along the inner zone of Southwest Honshu arc on the overriding Amur plate. According to mechanical configuration (Seno *et al.,* 1996), both subduction of the Philippine Sea plate along the Nankai trough and collision of the Izu-Bonin arc with the South Fossa Magna region are the two forces required to explain the

origin of the strike-slip fault province in the inland area of Southwest Honshu.

(3) As for active tectonics at the inner side of the Southwest Honshu arc, strain partitioning could account for the parallel, zonal arrangement of active fault provinces, on the basis of the idea of an eastward motion of the Amur plate and oblique subduction of the Philippine Sea plate. Because the north Fossa Magna region is located at the easternmost portion of the Southwest Honshu arc as the overriding plate of the Philippine Sea Plate, a distribution map of source fault-planes solved from present-day crustal earthquakes (e.g. NIED, 2007) shows a duplex stress field where local north-south compression, sometimes intercalated with regional northwest-southeast compression, can be recognized in the North Fossa Magna region.

6. Conclusion

Seismic activity along the Japan Sea coast of Southwest and Northeast Honshu arcs was examined in relation to the active geologic structure, and is summarized as follows.

(1) Widespread stress field with a northwesterly orientation of maximum principal stress axis recognized throughout the inner side of Honshu by means of seismotectonics and geodetic monitoring. As regards fault plane solutions of crustal earthquakes, thrust faulting dominates throughout the inner side of the Northeast Honshu arc, while paired fault provinces of thrust and strike-slip faulting are recognized along the inner Southwest Honshu arc.

(2) Historical earthquakes larger than M6.5 demonstrate synchronism between crustal earthquakes in the inner belt of the Southwest Honshu arc and great interplate earthquakes along the Nankai Trough. Consequently, strain partitioning might account for the strike-slip fault provinces due to oblique subduction of the Philippine Sea plate, as well as the collision of Izu-Bonin arc with Southwest Honshu.

(3) With the easternmost portion of the Southwest Honshu arc being the overriding plate of the Philippine Sea Plate, a duplex stress field of northwest-southeast compression intercalated by north-south compression was recognized in the north Fossa Magna region.

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