Post-Opening Deformation History of the Japan Sea Backarc Basin : Tectonic Processes on an Active Margin Governed by the Mode of Plate Convergence

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Chapter 6

Post-Opening Deformation History of the Japan Sea Back-Arc Basin: Tectonic Processes on an Active Margin Governed by the Mode of Plate Convergence

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Additional information is available at the end of the chapter

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Abstract

Three-dimensional structure of the Japan Sea back-arc basin is investigated based on an extensive reflection seismic survey. The process of the Oligocene to early Miocene rifting is described in reference to a geologic database, and the most likely paleoreconstruction of rifted continental fragments is presented. The back-arc region has been subjected to intermittent post-opening deformation events, which the author regards as side effects of temporal shifts in the convergence mode of the Philippine Sea Plate (PSP). The southern shelf of the Japan Sea appears to have suffered North-South strong contraction for a short period of time during the latest Miocene. Resumed convergence of the PSP was responsible for the regional tectonic event because frequent igneous intrusions within the upper Miocene series upon the back-arc shelf, which was confirmed by a borehole stratigraphic study, are suggestive of revitalized arc volcanism linked to dehydration of the subducted slab. During the Quaternary period, confined structure in varied forms developed on the shelf, which is related to the dextral wrench deformation of southwest Japan and the eventual arc-parallel crustal breakup along the back-arc region. Simultaneous highly oblique subduction of the PSP provoked the prevailing shear stress and conspicuous neotectonic deformation.

Keywords: convergent margin, back-arc opening, back-arc basin, seismic survey, Japan Sea, Philippine Sea Plate, eastern Eurasia

1. Introduction

Back-arc opening specifically occurs on convergent plate margins of the globe. Since the phenomenon inevitably impacts geographical and environmental conditions, numerous researchers have pursued evolutionary processes of back-arc basins.

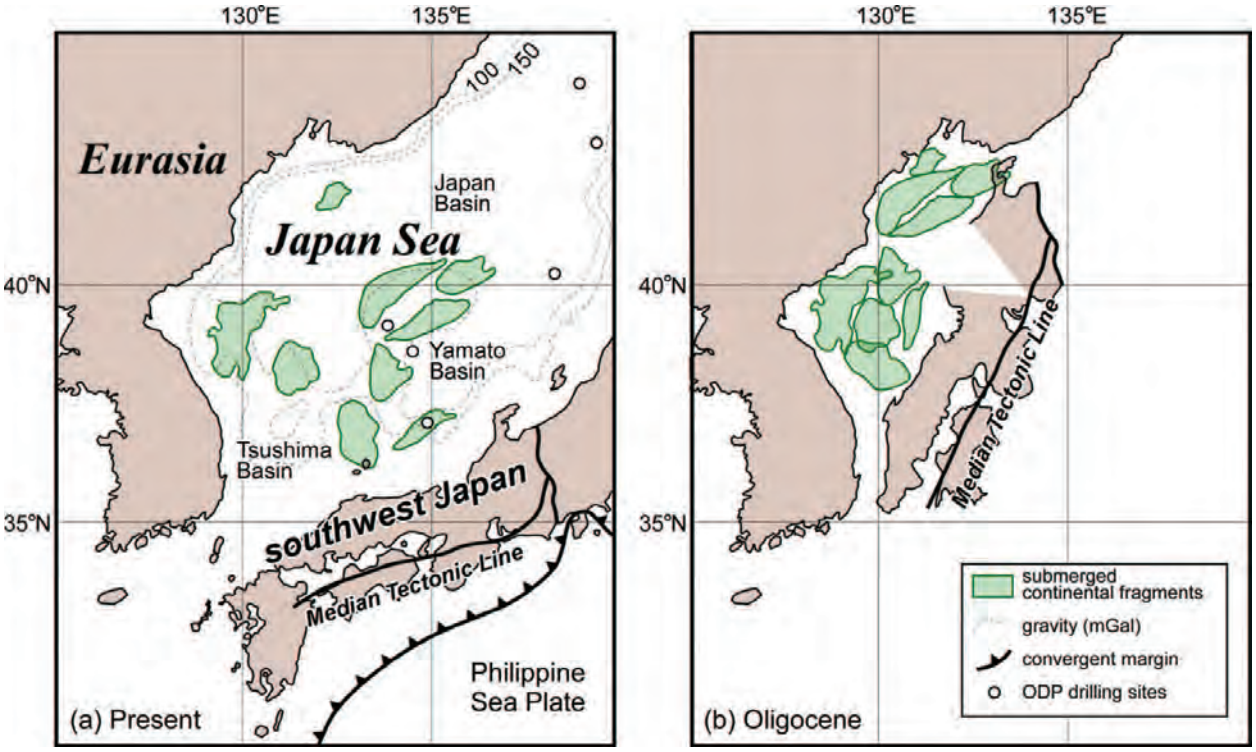

Figure 1. (a) Present configuration of southwest Japan and (b) its paleogeographic reconstruction before opening of the Japan Sea following [4]. Bending of the southwestern Japan arc caused by the middle Miocene collision event has been restored referring to paleomagnetic studies, expressed as the straightforward trend of the Median Tectonic Line.

The eastern Eurasian margin has been a site of vigorous basin formation related to long-standing convergence of major oceanic plates since the late Mesozoic [1]. The Japan Sea is located around mid-latitudes on the margin and is interpreted as a late Cenozoic back-arc basin based on the geological affinity between the Japanese Archipelago and the continental rim. In a series of pioneering paleomagnetic studies by Otofuji et al. (e.g., [2, 3]), a fan-shaped opening mode was advocated to explain the large rotation of the rifted block. **Figure 1** shows the most probable paleoreconstruction of the southern part of the Japan Sea [4], in which jigsaw fitting of subsea continental fragments is carefully taken into account.

In this chapter, the author focuses on the southwestern shelf of the back-arc basin. The three-dimensional architecture of the shelf is visualized by means of detailed seismic data, and its development process is described referring to stratigraphic data of deep boreholes. The spatio-temporal variety in the structural styles reflects intermittent changes in the converging sense of the Philippine Sea Plate (PSP). In other words, deformation records around the arc are a key to elucidating the transient motion of the marginal sea plate.

2. Geophysical survey

In 1989, the Ministry of International Trade and Industry (MITI) conducted an extensive offshore seismic campaign around the Japan Sea and the East China Sea (see **Figure 2**) by using the M/V

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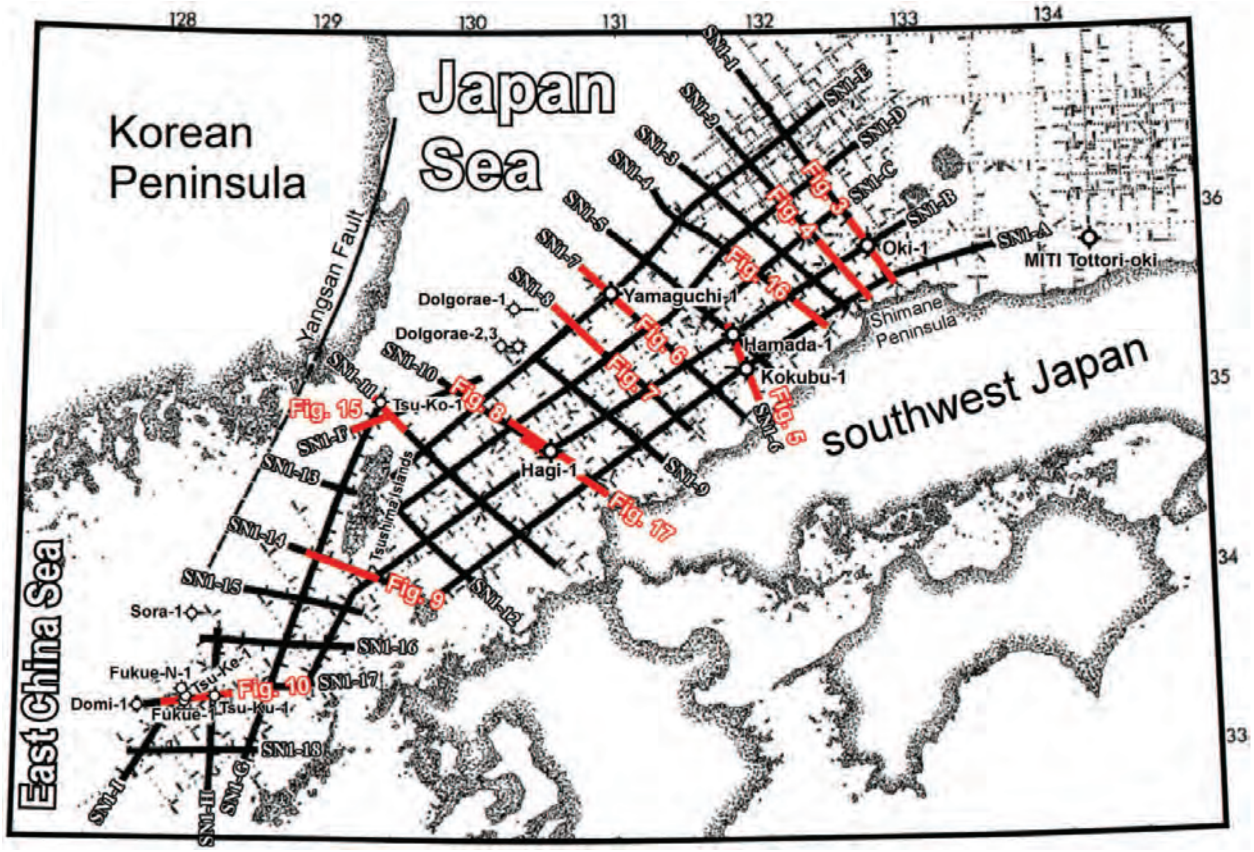

Figure 2. Index map showing geophysical survey tracks (dotted lines) around the southwestern shelf of the Japan Sea. The thick solid lines and larger open symbols are the seismic lines analyzed in the present study and key stratigraphic boreholes, respectively.

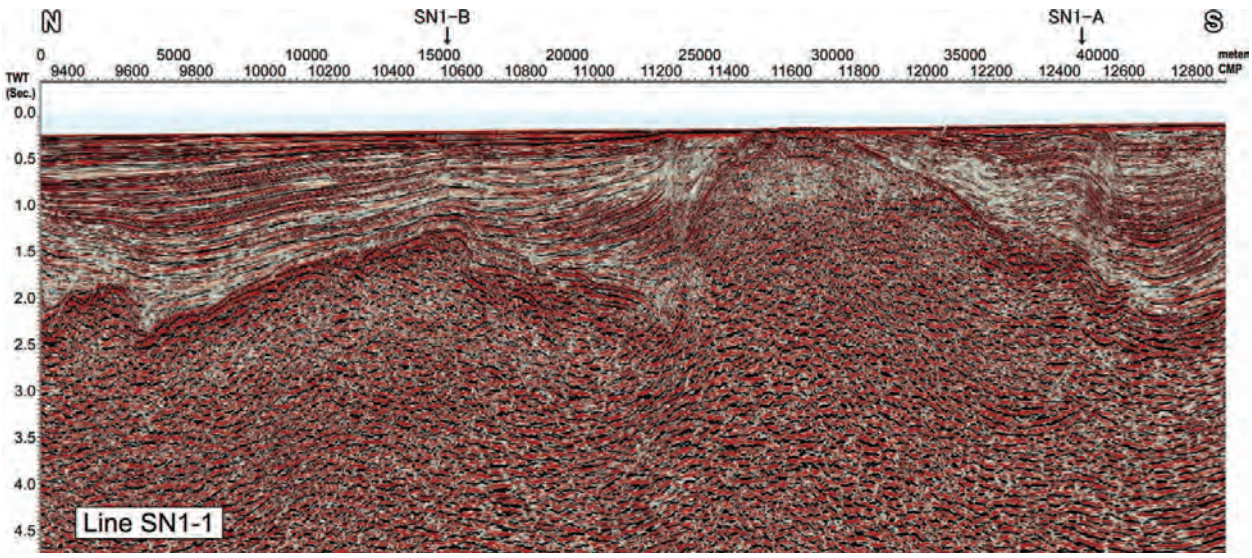

Figure 3. Reflection seismic profile (time migration; SN1-1) on the southwestern shelf of the Japan Sea. See **Figure 2** for line locations.

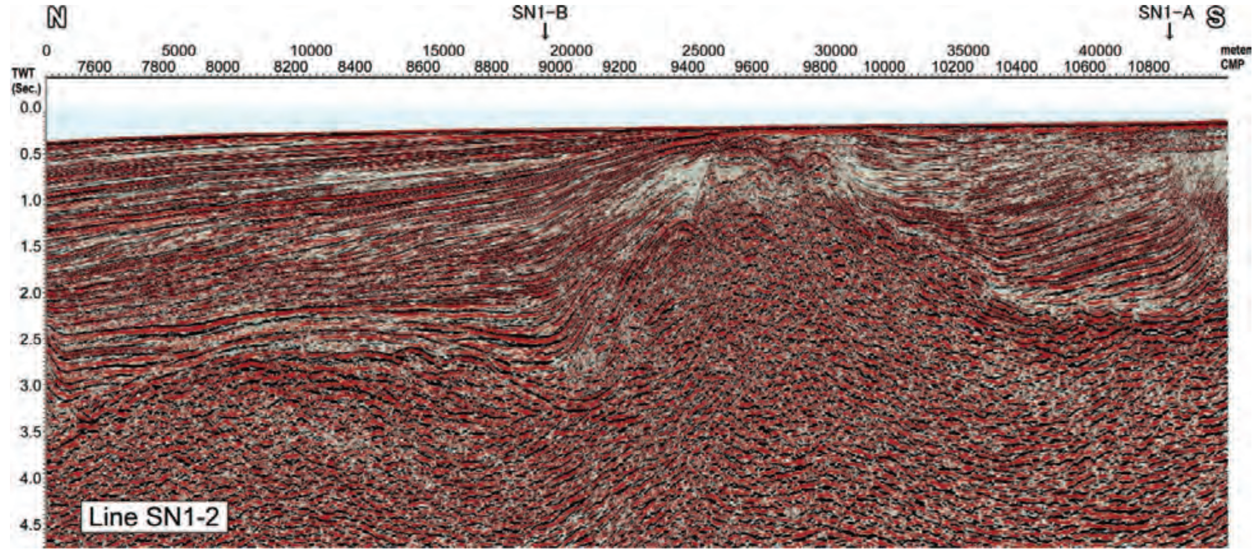

Figure 4. Reflection seismic profile (time migration; SN1-2) on the southwestern shelf of the Japan Sea. See **Figure 2** for line locations.

GECO MY. During the shooting of survey lines, 240 channels of hydrophones (12.5-m intervals) recorded the energy released from a tuned air-gun array (total: 78 l), which was shot at 25-m intervals. Raw field data were stacked and then subjected to a processing sequence for the enhancement of resolution. Regional seismic reflectors were traced throughout the study area and were correlated with the results of a previous seismic survey [5]. Basically, the back-arc shelf consists of an acoustic basement (pre-Neogene metamorphosed sedimentary complex and early Miocene volcaniclastics) and Neogene-Quaternary marine sediments. In the following section, we investigate the characteristic features of the seismic profiles.

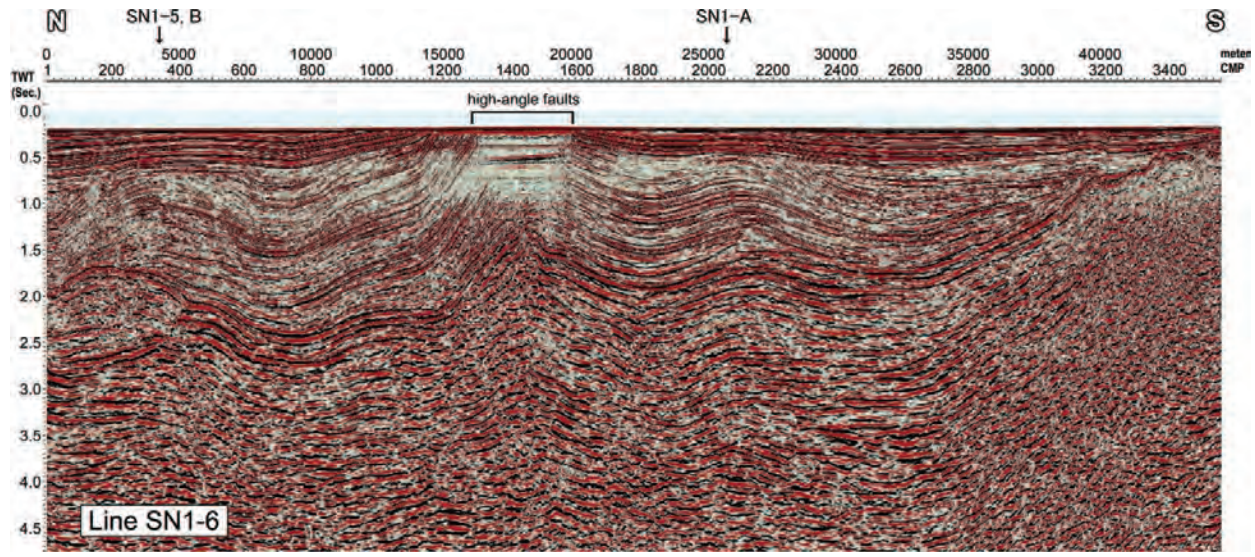

Figure 5. Reflection seismic profile (time migration; SN1-6) on the southwestern shelf of the Japan Sea. See **Figure 2** for line locations. The bracket indicates the recent high-angle faults discussed in the chapter.

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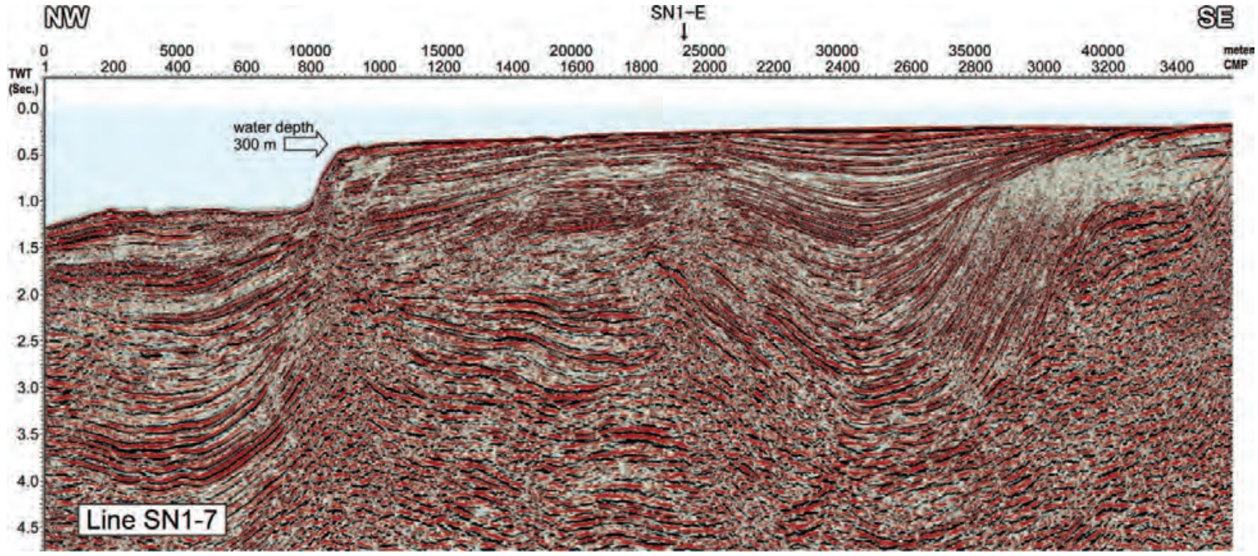

Figure 6. Reflection seismic profile (time migration; SN1-7) on the southwestern shelf of the Japan Sea. See **Figure 2** for line locations. The arrow indicates the location at which the water depth exceeds 300 m.

The morphology of the top of the acoustic basement is well preserved in the eastern part of the survey area. **Figure 3** (line SN1-1) shows the tilted blocks of the basement, which imply dominant normal faulting in the incipient stage of the back-arc rifting. On occasion, thinly layered younger sediments are tilted and dragged upon the fault scarps reflecting subsequent tectonic events (**Figure 4**; SN1-2).

The most remarkable and traceable event around the survey area is an unconformity in the upper portion of the sediment pile (**Figure 5**; SN1-6). The east-northeastward (namely arc-parallel) axis of the folds coincides with the latest Miocene deformation trend on land [6]. The strong contraction appears to almost reach the northern shelf break (**Figure 6**; SN1-7). As

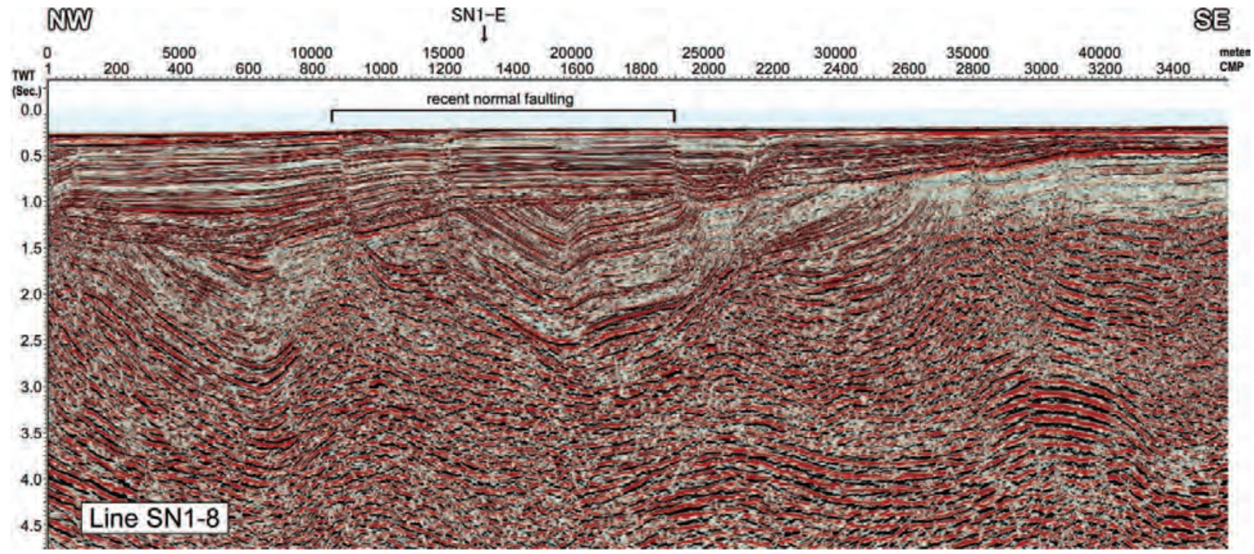

Figure 7. Reflection seismic profile (time migration; SN1-8) on the southwestern shelf of the Japan Sea. See **Figure 2** for line locations. The bracket indicates the range of recent normal faulting discussed in the text.

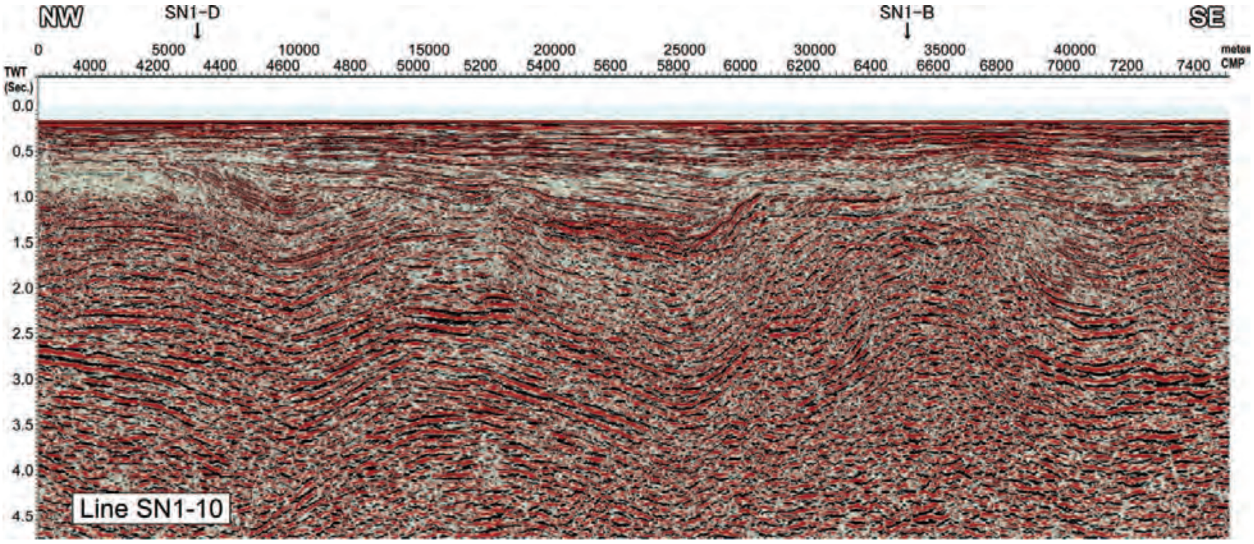

Figure 8. Reflection seismic profile (time migration; SN1-10) on the southwestern shelf of the Japan Sea. See **Figure 2** for line locations.

shown in **Figure 5**, undulation of the erosional surface and truncation near the surface are indicative of younger tectonic events.

We notice a change in the recent stress regime around the westernmost part of the shelf. **Figure 7** (line SN1-8) demonstrates that the latest Miocene unconformable boundary is cut by normal faults. Separation along these faults grows through the Plio-Pleistocene. The areal extent and neotectonic context of this intriguing feature is discussed in the following section.

Deformation trends around the westernmost shelf are partially obscured by strong discontinuous reflectors in shallow horizons (**Figure 8**; SN1-10). Such disturbances are spatially coincident

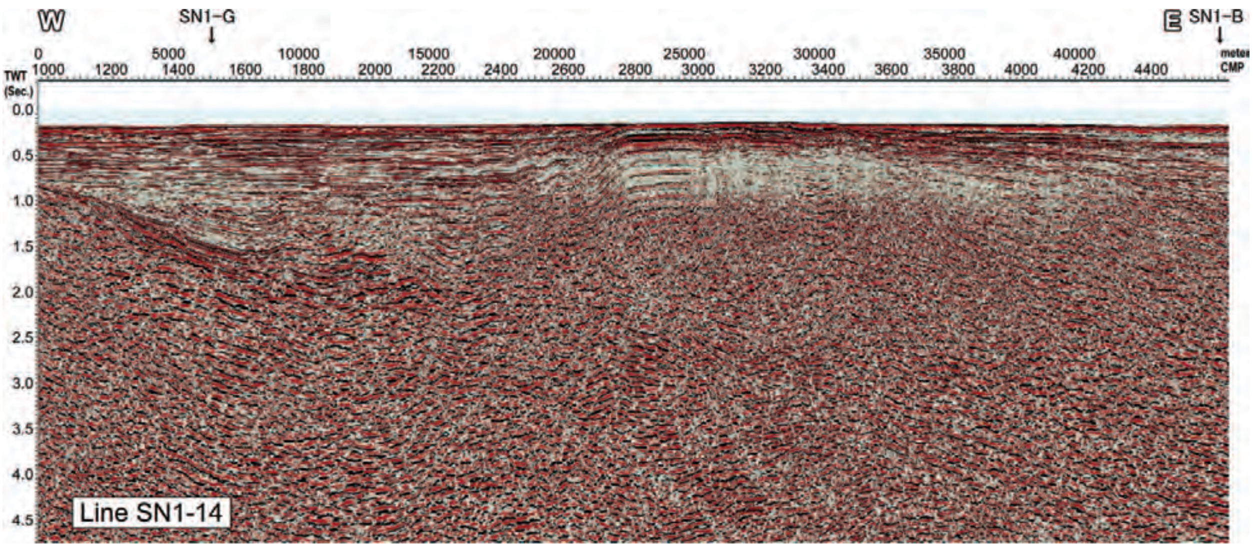

Figure 9. Reflection seismic profile (time migration; SN1-14) around the eastern end of the East China Sea. See **Figure 2** for line locations.

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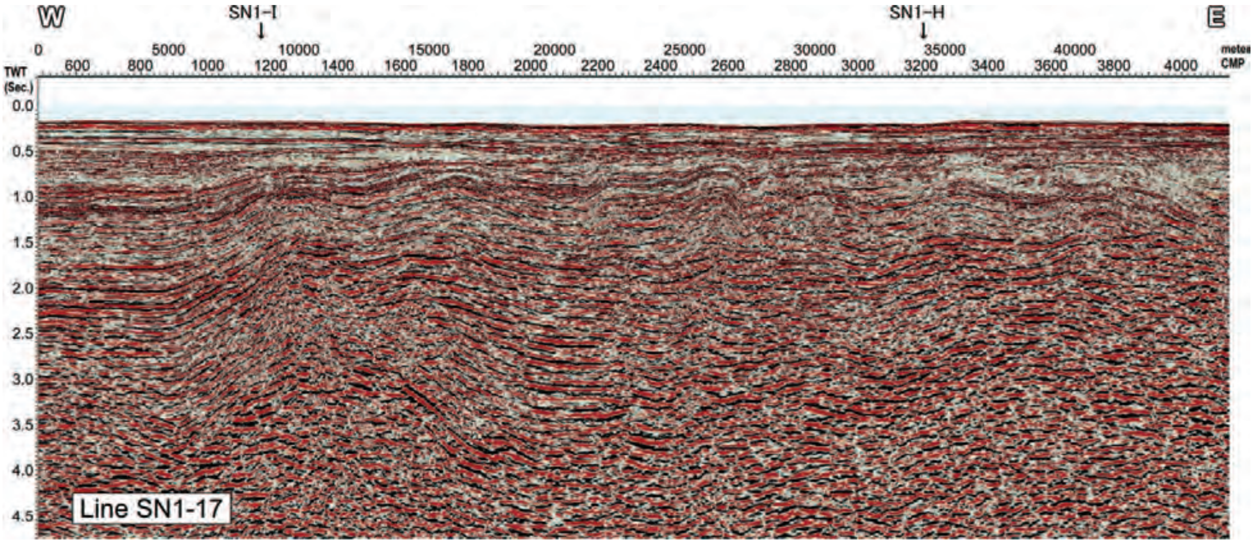

Figure 10. Reflection seismic profile (time migration; SN1-17) around the eastern end of the East China Sea. See **Figure 2** for line locations.

with sporadic geomagnetic anomalies [7]. Together with borehole lithology described in the next section, post-opening volcanic activities may be responsible for the phenomenon.

The regional contraction zone abruptly ends as the pivot of a folding fan to the west. Back-arc folds change their azimuth to counterclockwise and converge into the anticlinoria of Tsushima [7]. The islands along the Japan-Korea border are accompanied by a deep half-graben developed beneath an east-dipping thrust (**Figure 9**; SN1-14) and are regarded as the product of the highest level of transpressive stress around the end of the Miocene.

In contrast with the strong deformation on the Japan Sea shelf, the easternmost portion of the East China Sea is underlain by intact sediments in shallow horizons (**Figure 10**; SN1-17). Short-wavelength deeper undulations are bounded by high-angle ruptures.

3. Stratigraphy

For the purpose of oil exploration, five deep drilling surveys were performed in the study area. **Figure 11** shows their locations (columns 1–5) along with an auxiliary nearby borehole (column 6). Based on detailed stratigraphic assessments [5, 8], lithologic piles penetrated by these boreholes are divided into four units. In ascending order, the X Group corresponds to the acoustic basement and is collectively defined as a mixture of early Miocene nonmarine sediments and pyroclastic rocks and older granitic intrusives. The N Group rests unconformably on the basement and consists of early Miocene marine sediments with numerous tuff intercalations. Nonvolcanic monotonous sediments of the K Group yield foraminiferal assemblages correlated with Blow's [9] zone N14~N16 (late middle Miocene-early late Miocene) and are overlain by sandy clastics of the D Group, the basal part of which is assigned to zone N19 (early Pliocene) of [9]. Thus, the angular unconformity at the K/D boundary is identified to be

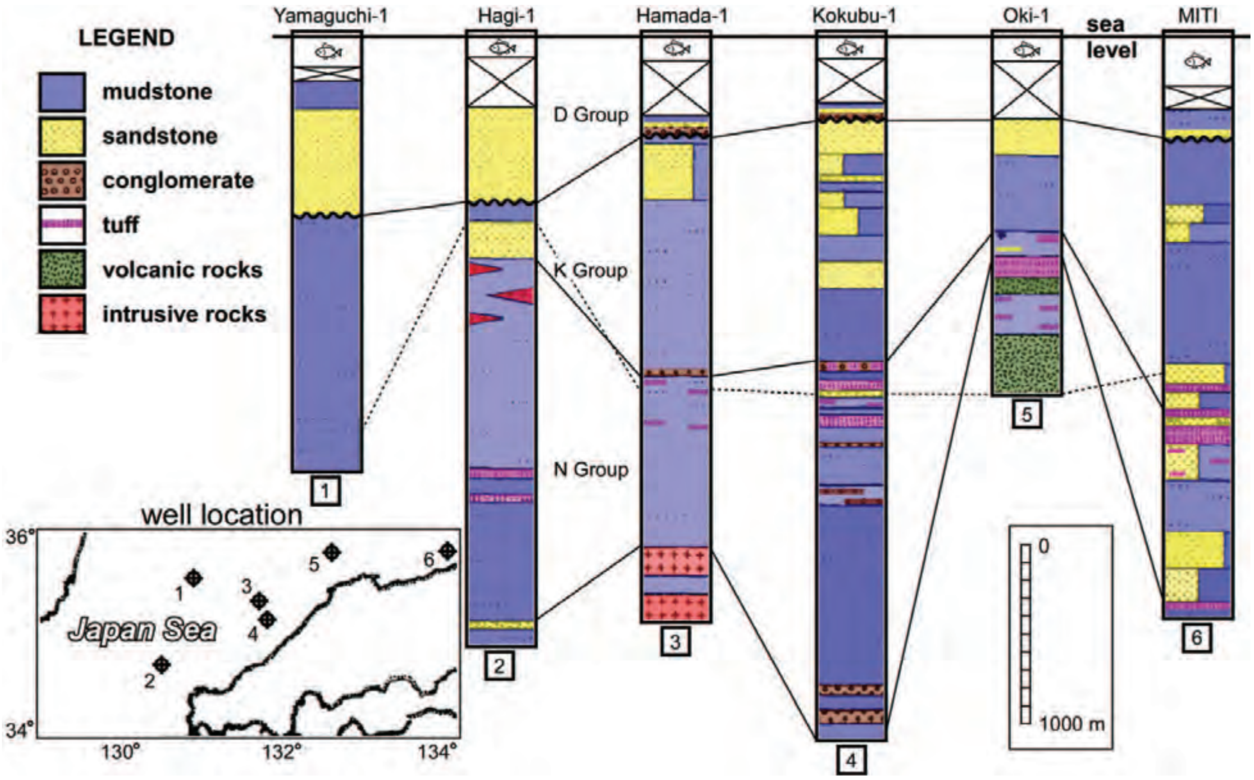

Figure 11. Stratigraphy of the offshore boreholes described by [5, 8]. Their localities are also shown in **Figure 2**. The solid and broken lines indicate unit boundaries and the 0.6% Ro (vitrinite reflectance) contour, respectively.

of the late Miocene, which is in good agreement with the formation age of a remarkable folded zone on land [6].

4. Discussion

After the abovementioned overview of the structural and stratigraphic characteristics of the southwestern Japan Sea shelf, we now discuss the evolutionary processes of the study area following the back-arc opening event. In this section, the author discusses structural features governed by a unique opening mode, regional inversion provoked by resumed underthrusting of the Philippine Sea Plate, and stress-strain concentration on the shelf under the influence of an emerging simple shear regime, in this order.

4.1. Back-arc opening governed by the divergent rift system

As mentioned earlier, the southern Japan Sea is unique, in that the oceanic basin is studded by a number of submerged highlands composed of massive continental crust. Therefore, in order to force the sea floor to spread, a radial rift system presumably developed on the eastern Eurasian margin from the Oligocene to early Miocene. The normal faults in **Figures 3** and **4** are relics of the prevalent extension. **Figure 12** shows a paleoreconstruction map in the early Miocene stage. As suggested by [4], such a divergent breakup is endorsed by the presence of the early Miocene rift-margin type volcanism along the normally faulted scarp. In comparison to the pre-rifting paleogeography in **Figure 1**, the separated southwest Japan block drifted

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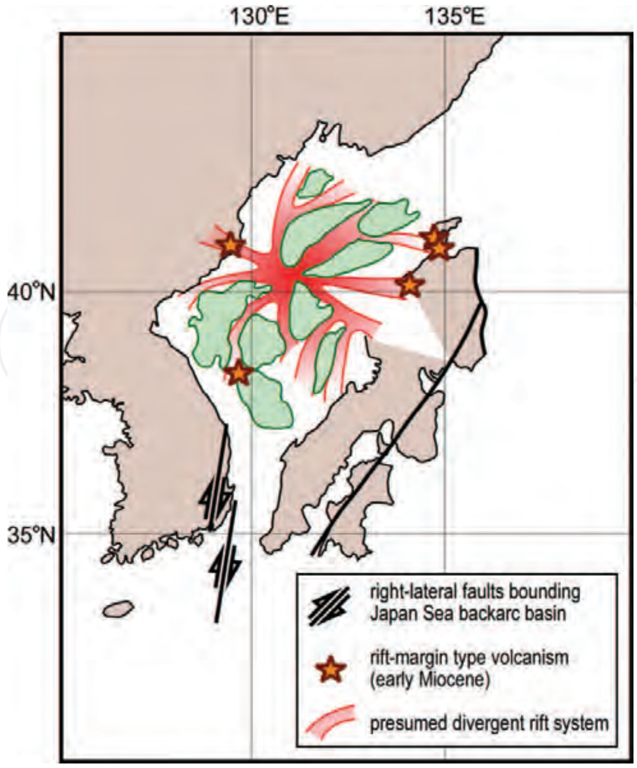

Figure 12. Paleoreconstruction map of the southern Japan Sea in the syn-rifting stage (early Miocene) modified from ref. [4].

southward and rotated clockwise as a result of differential effective spreading rates determined by rift geometry. Coeval development of N-S high-angle ruptures around the easternmost portion of the East China Sea (**Figure 10**) is interpreted as dextral faults to compensate for rapid spreading of the Japan Sea back-arc basin [10].

Another troublesome but highly intriguing problem is the plate configuration in the Pacific Northwest during the Japan Sea opening. **Figure 13** shows two paleogeographic reconstructions around the southern Japan Sea in the Neogene period. Based on the detailed geologic research of the Sundaland, Hall [11] adopted lingering expansion and rotational motion of the Philippine Sea Plate. On the other hand, Itoh et al. [12] advocated an earlier migration of the marginal sea plate. Their kinematic model is dependent on the collision of the easternmost tip of the clockwise-rotating southwest Japan against the Izu-Bonin arc along the eastern margin of the Philippine Sea Plate from 15 to 12 Ma [13].

The rotational processes of the marginal sea plate remain unsettled. Hall [11, 14] argued that the Philippine Sea Plate began to rotate clockwise at the earliest Miocene (ca. 24 Ma) with a relevant sinistral motion around north New Guinea. An incipient spreading center at that time is identified along the northeastern margin of the plate. Based on rapid crustal growth in southwest Japan, Kimura et al. [15] recently insisted that the plate swiftly rotated clockwise nearly simultaneously with the oceanward drift of the Japanese island arc driven by the Miocene Japan Sea opening. On the other hand, the significant rotation phase of the Philippine Sea Plate has been assigned before 25 Ma based on newly obtained paleomagnetic data from the northwestern part of the plate [16]. However, the present author believes that further geochronological information is necessary in order to clarify these processes.

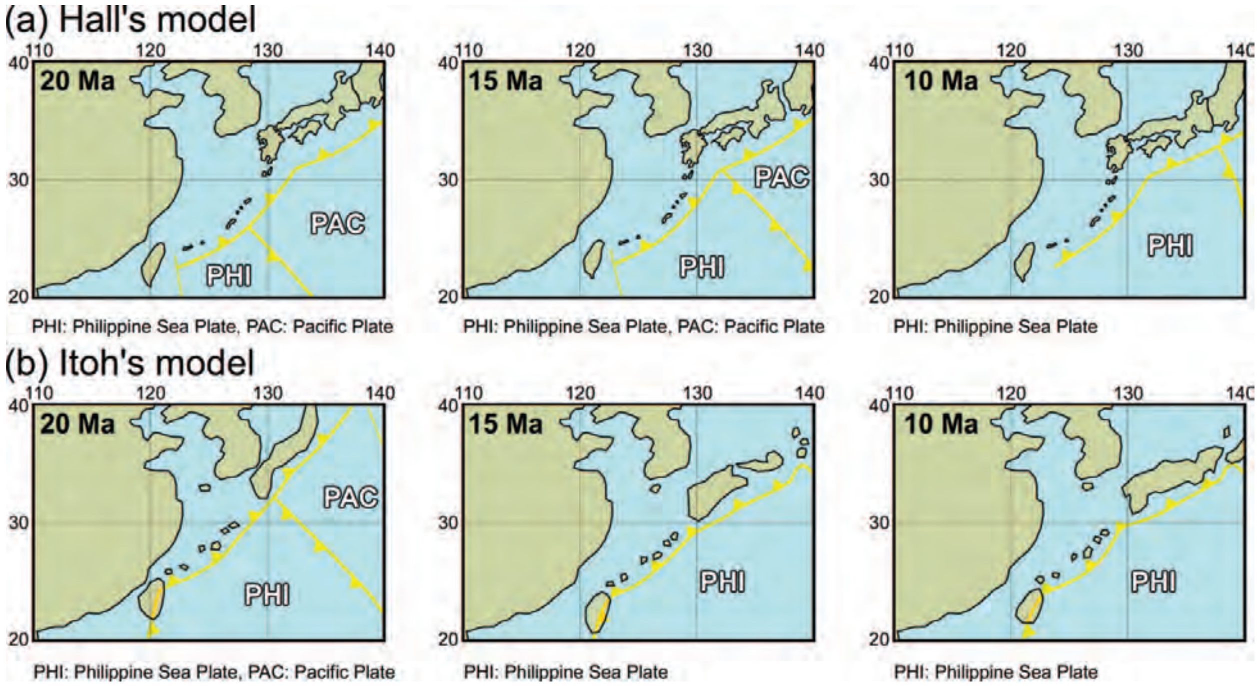

Figure 13. Comparison of two Neogene paleogeographic reconstruction models around the southern Japan Sea. (a: top) Model of lingering (delayed relative to the Japan Sea opening) migration of the Philippine Sea Plate [11]. (b: bottom) Model adopting earlier migration of the Philippine Sea Plate [12].

4.2. Extensive inversion: Structural contrast between forearc and back-arc regions

North-South strong contraction is the most notable post-opening event around the southern Japan Sea and southwest Japan. Although the amplitude of the folds tends to diminish toward the intra-arc region [7], arc-parallel gentle undulation was ubiquitous along the late Miocene convergent margin. Based on the spatiotemporal distribution of tectonic events related to contraction/extension found mainly in intra-/forearc areas, Itoh et al. [17] argued that compressive stress propagated progressively westward through the Plio-Pleistocene and attributed the change in the stress-strain state to the shift of the Euler pole of the subducting Philippine Sea Plate. Itoh [18] redefined their Quaternary epochs based on detailed structural analysis of an event sedimentary sequence. **Figure 14** shows a series of compiled illustrations depicting variable tectonic regimes around southwest Japan.

Compared to the transient history of southwest Japan, the back-arc shelf appears to have been uniformly deformed throughout its extent, considering the subsurface structures described by Itoh and Nagasaki [7], Itoh et al. [19], and the author of the present study (**Figures 5**, **6**, and **9**). The seismic characteristics at the bottom of the D Group do not exhibit clear time-transgressive terminations onto the K/D erosional surface. Thus, the Japan Sea back-arc region appears to have suffered synchronous deformation in a short period.

Nevertheless, it is plausible that resumed convergence of the Philippine Sea Plate was responsible for the regional contraction because frequent igneous intrusions within the upper part of the K Group (**Figures 8** and **11**) are suggestive of revitalized arc volcanism linked to dehydration of the subducted slab. Not only the change in relative motions of the marginal sea plate

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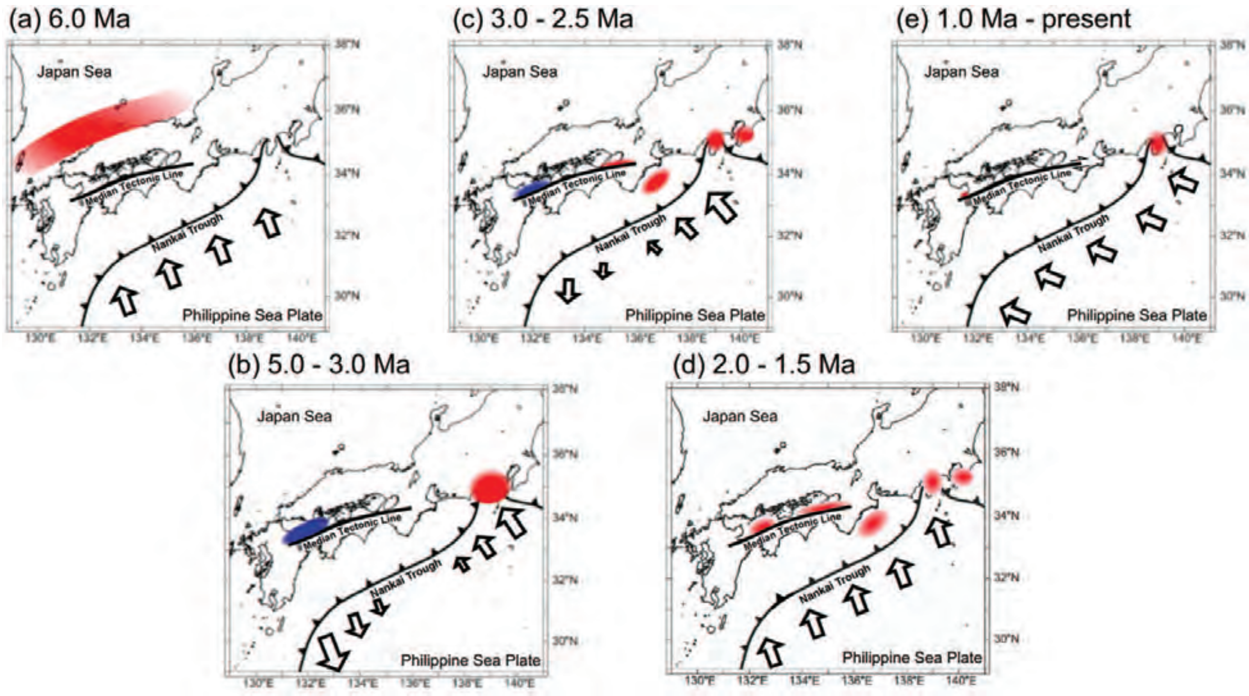

Figure 14. Spatiotempora distribution of stress-strain regimes in southwest Japan, the southern Japan Sea shelf, and a kinematic model of the Philippine Sea/Eurasian plate convergence since 6 Ma (a to e) compiled from [17, 18]. The red and blue areas represent areas of compressive (contractional) and tensile (extensional) stress (strain), respectively. Modes of the Philippine Sea Plate convergence are shown schematically by the length and azimuth of the arrows.

but also spatial variations in the coupling on the slab surface may be a key to understanding these complicated tectonic processes.

4.3. Confined deformation on the back-arc shelf: Emerging Quaternary back-arc break

Seismic data for the westernmost part of the back-arc shelf imply the emergence of an extensional regime during a recent period. The K/D interface as the product of an impulsive contraction is cut by normal faults, which have been active since the Pliocene (**Figure 7**). The shelf break partly reaches a depth of 300 m (**Figure 6**) and exceeds the limit of the eustatic sea-level fluctuation. **Figure 15** shows a conspicuous depression on the north side of the Tsushima Islands. As mentioned earlier, the border islands originated from a strong transpressive regime around the latest Miocene. However, the depression appears not to have been generated as a foreland basin related to the nearby reverse faulting that became dormant in the early Pliocene. Deformation of superficial sediments in the seismic profiles requires the subsea landforms to originate from neotectonic stress relief. Such a drastic shift from contraction to extension may be linked to an episodic change of the Philippine Sea Plate's motion in the Quaternary. Nakamura et al. [20] suggested that the plate changed its converging direction to be counter-clockwise at ca. 2–1 Ma, which inevitably enhanced the right-lateral wrench deformation of southwest Japan and the eventual arc-parallel crustal breakup, such as that at the Median Tectonic Line (MTL in **Figure 16**). Itoh et al. [21] found an embryotic right-lateral rupture along the Japan Sea margin (Southern Japan Sea Fault Zone; SJSFZ in **Figure 16**). The area of confined subsidence is coincident with a propagating tensile termination of the lateral fault

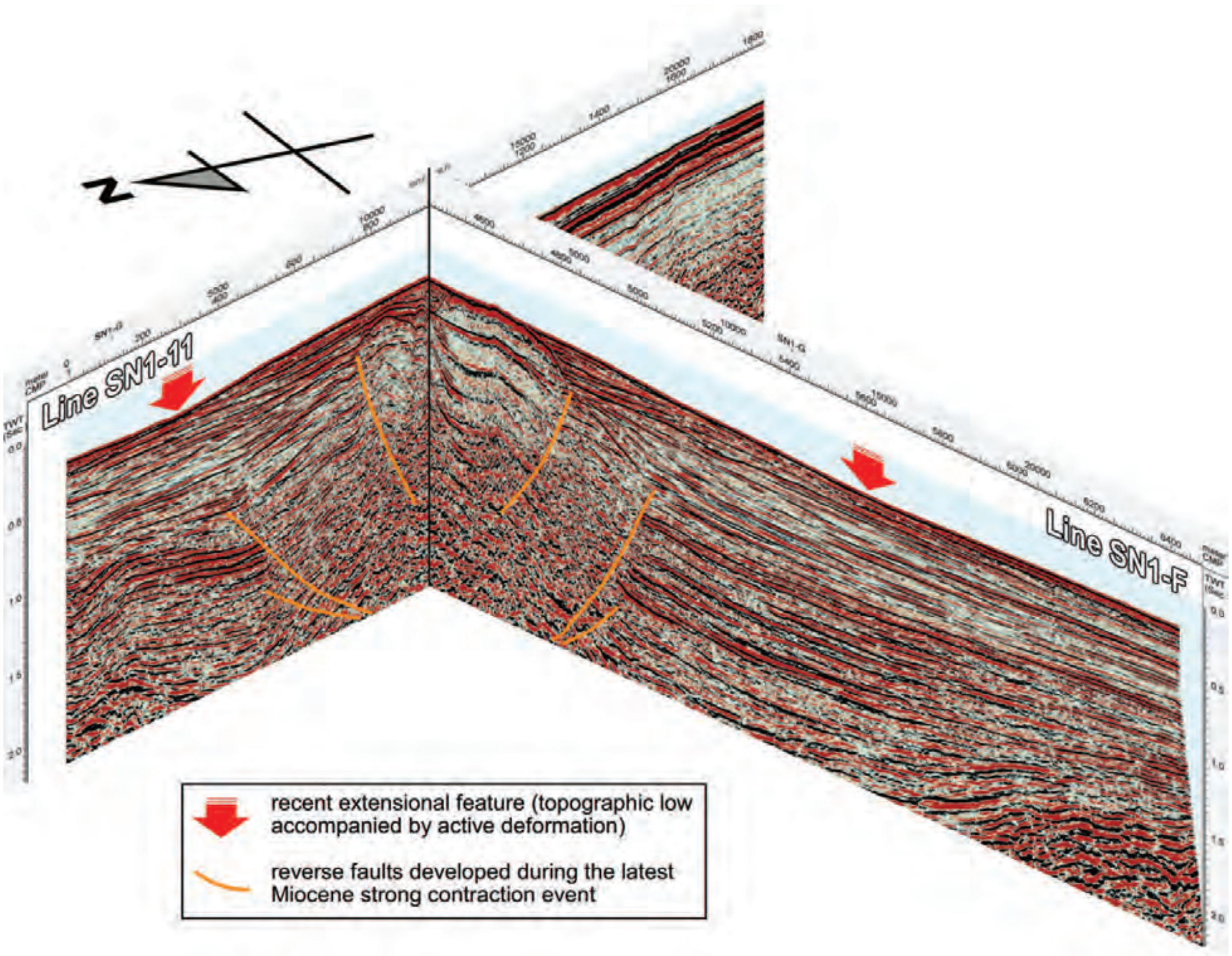

Figure 15. Confined recent depression north of the Tsushima Islands confirmed by seismic profiles. See **Figure 2** for line locations.

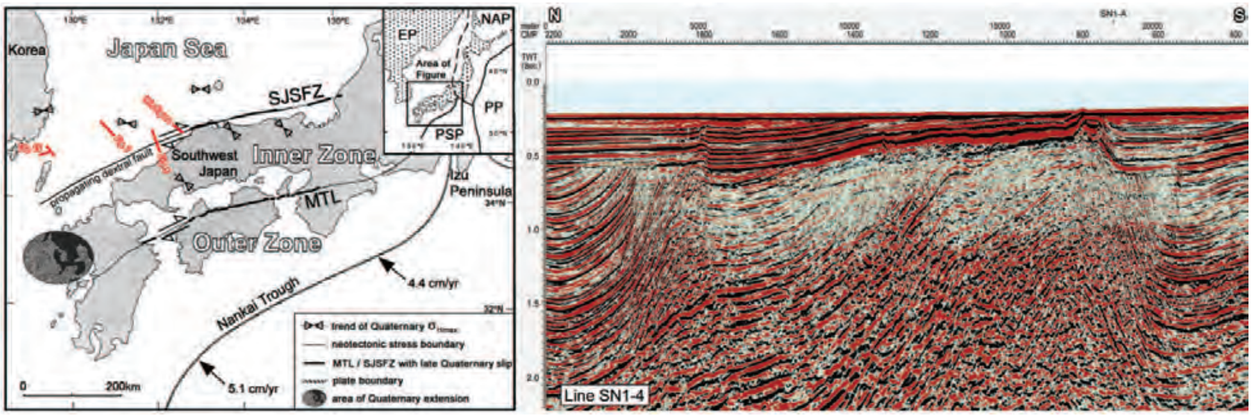

Figure 16. Neotectonic synthesis around the southwestern Japan arc together with a seismic section (time migration; SN1-4) showing high-angle faults along the trace of the Southern Japan Sea Fault Zone (SJSFZ). EP, NAP, PP, and PSP in the regional inset represent the Eurasian Plate, the North American Plate, the Pacific Plate, and the Philippine Sea Plate, respectively. The location of the seismic section is also shown in **Figure 2**.

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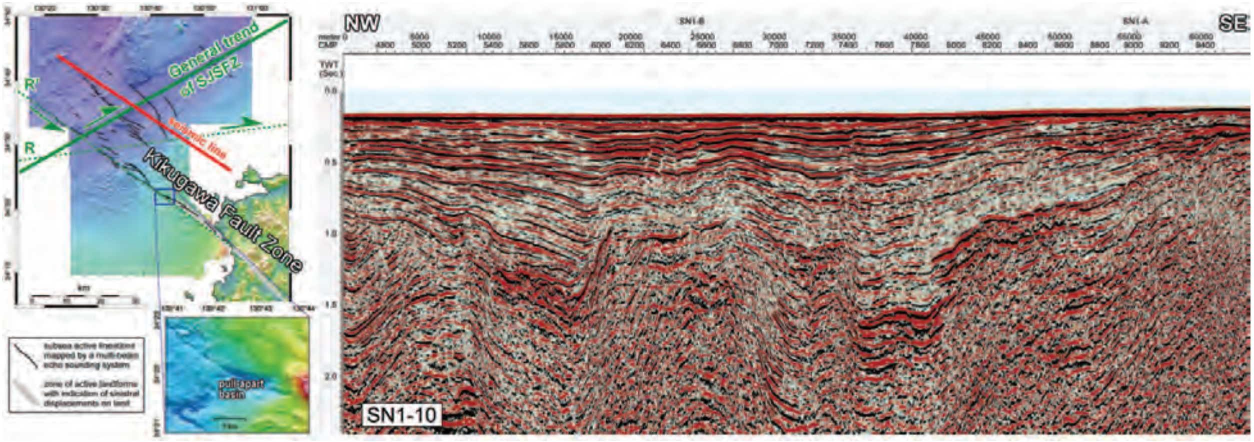

Figure 17. Subordinate shear deformation developed around the Southern Japan Sea Fault Zone (SJSFZ). Subsea topographic maps were compiled using a multibeam echo sounding system [25]. R and R' with their strike-slip senses (arrows) in the topographic index are the azimuths of the Riedel shear and the conjugate Riedel shear, respectively, provoked by recurrent dextral activities on the SJSFZ. The location of the seismic line (time migration; SN1-10) is also indicated in **Figure 2**.

[22], as shown in **Figure 16**. A closer look at the seismic records indicates high-angle faults cutting the sediment surface on the trace of the SJSFZ (see the seismic inset of **Figure 16** and the active horst in **Figure 5**, which is indicated by a bracket).

Figure 17 shows another side effect of the SJSFZ's activity. A northwest-trending sinistral rupture, called the Kikugawa Fault [23], extends to the back-arc shelf. The seismic and geologic investigation of the Kikugawa Fault [24] confirmed recurrent slips during the late Pleistocene. Recent sounding of subsea topography [25] delineated an active pull-apart sag on a releasing (i.e., leftward) bend of the rupture. The azimuth and slip sense of the active lineament agree with those of the conjugate Riedel shear provoked by the dextral motion on the arc-bisecting fault, as shown in the figure. The multichannel seismic record shown in **Figure 17**, acquired parallel to the Kikugawa Fault, is cut by several high-angle faults that can be interpreted as dextral Riedel shear adjacent to the SJSFZ.

Thus, the present research demonstrates that the change in the convergence modes of the Philippine Sea Plate triggered a series of episodic deformation around the rim of the overriding plate. The latest mode of highly oblique subduction promotes the development of extensive wrenching in fore-, intra-, and back-arc regions as well as the formation of a crustal sliver sandwiched between the MTL and SJSFZ. This mode also enhances the compartmentalization of the Japan Sea back-arc basin.

5. Conclusions

The present seismic study has fully described the following tectonic epochs of the Japan Sea back-arc basin.

1. The Oligo-Miocene back-arc opening of the southern Japan Sea was governed by a divergent rift system. The southwestern Japan block drifted southward and rotated clockwise as a result of differential effective spreading rates determined by the rift geometry.
2. The Japan Sea back-arc region appears to have synchronously suffered North-South strong contraction during a short period of the latest Miocene. Resumed convergence of the Philippine Sea Plate was responsible for the regional tectonic event because frequent igneous intrusions within the upper Miocene series on the shelf are suggestive of revitalized arc volcanism linked to dehydration of the subducted slab.
3. Confined and complicated deformation on the back-arc shelf during the Quaternary is related to the dextral wrench deformation of southwest Japan and the eventual arc-parallel crustal breakup along the back-arc region. Recent highly oblique subduction of the Philippine Sea Plate provoked the prevailing shear stress.

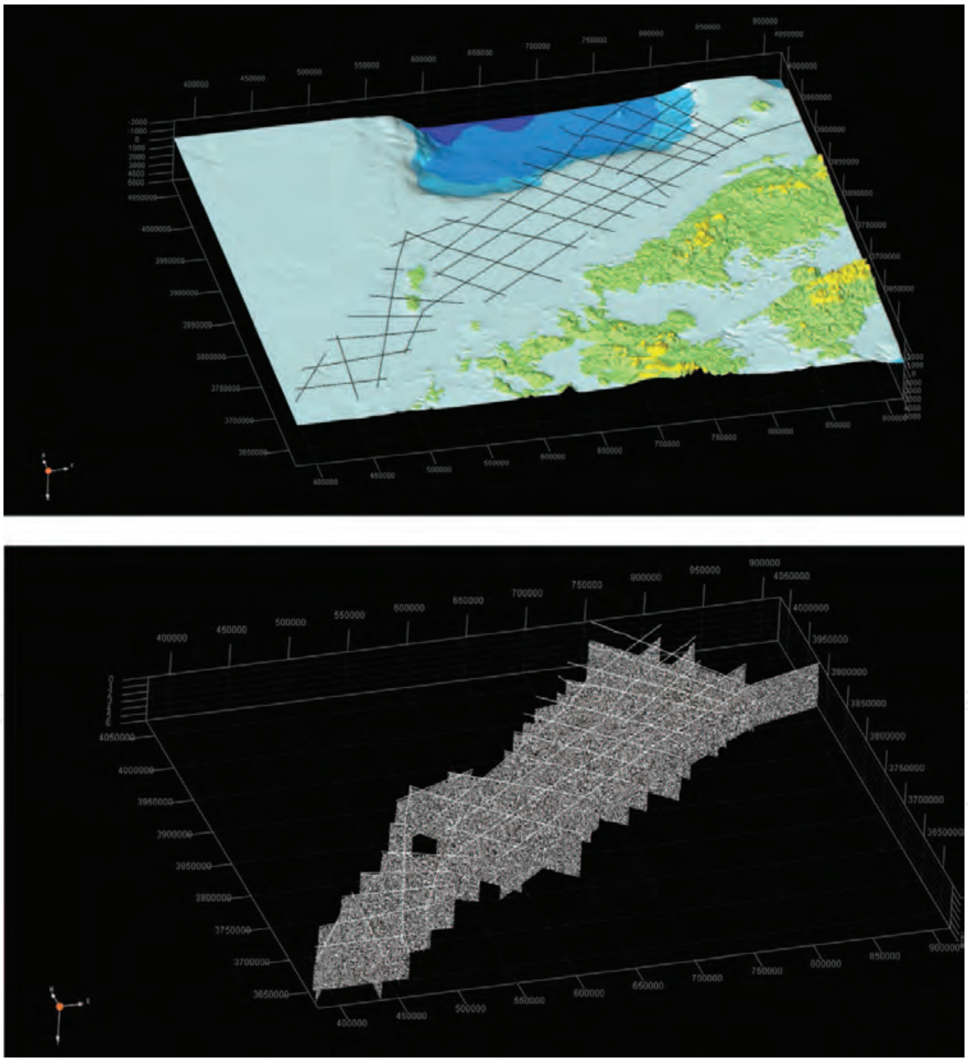

Figure 18. Bird's eye topographic vista (from southwest) around the southern Japan Sea (top) and the subsurface structural architecture (bottom). See **Figure 2** for seismic line locations. Although the total accommodations shown on the seismic data (bottom) of the northern and western back-arc of southwest Japan are in the same level, the present study integrating structural and stratigraphic knowledge has revealed that the shelf to the east of the Tsushima Islands was built up in a short period reflecting intensive post-opening deformation events since the Miocene.

The three-dimensional architecture around the southern Japan Sea has been visualized, as shown in **Figure 18**. A bird's eye view movie of the subsurface structure based on seismic interpretation and high-resolution original figures in this chapter are available from the Osaka Prefecture University Education and Research Archives (OPERA) (http://hdl.handle.net/10466/15505).

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