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Seismic evidence of divergent rifting and subsequent deformation in the southern Japan Sea, and a Cenozoic tectonic synthesis of the eastern Eurasian margin

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Abstract

Neogene rift system configuration for the back-arc of southwest Japan, southern rim of the Japan Sea, is argued on the basis of reflection seismic interpretation. Divergent rifting and subsequent contraction provoked by an arc–arc collisional event are manifested by the formation of faulted grabens and their inverted deformation, respectively. We identified the following four Cenozoic tectonic epochs as a decomposition process of the eastern Eurasian margin based on reliable paleomagnetic data: (1) Plate margin rearrangement on a regional left-lateral fault through southwest Japan and Sikhote Alin, which constituted a continuous geologic province before the early Tertiary differential motion; (2) Early Tertiary clockwise rotation (>20°) of the east Tan-Lu block relative to the North China block; (3) Oligocene to early Miocene divergent rifting and spreading of the Japan Sea, which divided southwest Japan from the east Tan-Lu block; (4) Middle Miocene bending and back-arc inversion of southwest Japan caused by collision with the Izu-Bonin arc. According to the estimation of relative motions during these events, a paleogeographic reconstruction is presented through Cenozoic time.

Keywords: Japan Sea; Southwest Japan; Sikhote Alin; Cenozoic; Rifting; Differential rotation; Paleomagnetism; Seismic interpretation; Tectonics

1. Introduction

The western half of the Japanese Islands (southwest Japan; Fig. 1) is understood as a rifted continental sliver. Around the island arc, drastic paleoenvironmental changes occurred throughout the Cenozoic in association with formation of rift basins, including the Japan Sea (Fig. 2) (Otofuji et al., 2003a). According to Otofuji et al. (1985), rotational motion of southwest Japan brought about by the Japan Sea back-arc opening proceeded in a rapid succession at around 15 Ma. However, an earlier origin of the Japan Sea (since 30 Ma) has been proposed on the basis of marine geophysical/geological surveys (Jolivet and Tamaki, 1992). It may be attributed to a rifting stage without vertical-axis rotation that cannot be detected by paleomagnetic analysis as indicated by Hayashida et al. (1991). In order to solve such a controversy, it is important to describe and establish the time sequence of complicated tectonic processes on the continental margin.

In this paper, the authors first present newly interpreted seismic data on the southern Japan Sea that give us an insight about the pattern of the extensive rifting, and post-opening deformation by an arc–arc collision event in the middle to late Miocene. Then, we evaluate paleomagnetic data (cf. Fig. 1, Table 1) since the Cretaceous in order to delineate tectonic domains along the plate margin, and to present the most probable Cenozoic paleogeographic reconstruction from inception to completion of the Eurasian rift basin formation accommodating differential rotation. We attempt to submit a chronicle of Cenozoic tectonic evolution on the convergent or near-transform plate boundary based on a multidisciplinary study around southwest Japan and its environs.

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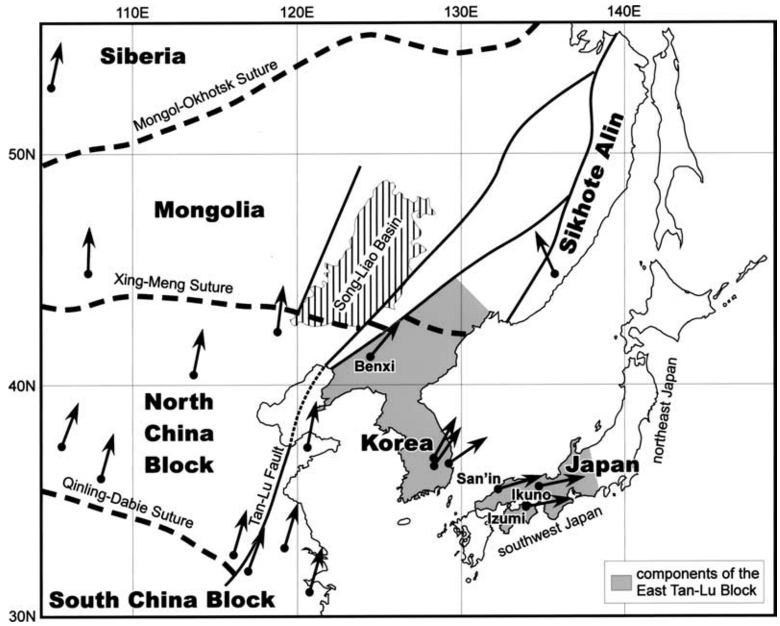

Fig. 1. A regional index map of the eastern Eurasian margin. Arrows are the Cretaceous paleomagnetic directions of eastern Asia (compiled after Lin et al., 2003; Otofuji et al., 2003a and Uno, 2002). Shaded areas once constituted a continuous and coherent rotational block at around the end of the Mesozoic.

2. Seismic study

2.1. Identification of seismic units/horizons

A reflection seismic survey was conducted by METI (Ministry of Economy, Trade and Industry, Japan) in 1973 off the northeastern coast of southwest Japan (Fig. 2(a)). We interpreted seismic profiles as long as 1400 km, covering an area of 10,000 km^2, and present the structural and sequence stratigraphic summary in Figs. 3 and 4. As some exploration boreholes have been drilled within the area (Itoh et al., 1994, 1997), seismic units/horizons can be assigned to geologic periods as listed in Table 2. This offshore basin is characterized by a rapid subsidence and thick accumulation of the Unit E, the lowermost part of the marine succession, during the late early Miocene. It is correlated with an adjacent onland transgressive sequence, the Yatsuo Group, interpreted as a syn-rift sedimentary unit (Hayakawa and Takemura, 1987). Therefore we first attempt to decipher the distribution of the unit and morphology of the incipient rift basin around the present Japan Sea coast.

2.2. Sedimentological and structural interpretations

Fig. 3 presents an isopach map of the early Miocene Unit E on the basis of seismic interpretation. Because the unit partly thickens toward the coastline, the transgressive Miocene sequences on the present southwest Japan seem to represent a marginal facies of a larger rift basin. It is notable that the transgressive unit has NW–SE elongated depocenters on the

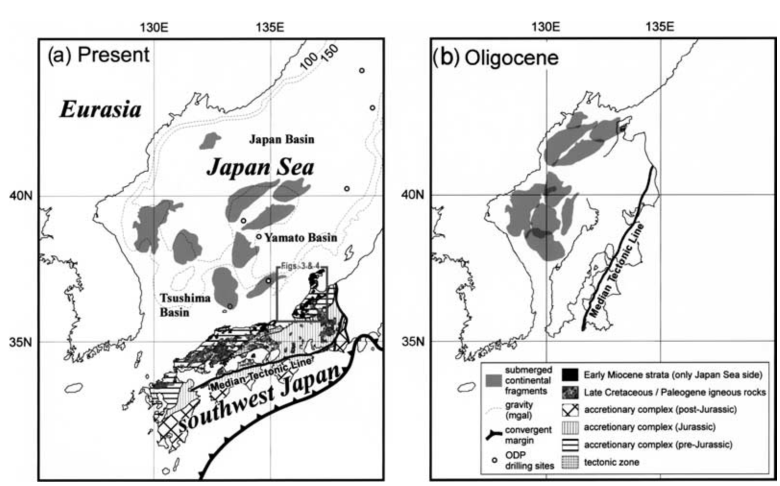

Fig. 2. Present configuration of southwest Japan (a) and its paleogeographic reconstruction before opening of the Japan Sea (b). Geologic units and boundaries of southwest Japan are after the Geological Survey of Japan (1996).

Table 1
Selected Cretaceous paleomagnetic data for southwest Japan and eastern Eurasia

Locality (area)	N (n)	Pole		A_{95} (°)	Rotation (°)	References
		Lat (°)	Long (°)			
Central part of southwest Japan						
(Ikuno)	(4)	24.1	208.0	8.5	64.5 ± 16.4	Uno (2002)
(Izumi)	(70)	25.0	203.0	6.0	65.9 ± 13.2	Kodama (1990)
(San'in)	(14)	28.0	210.0	9.8	60.0 ± 16.6	Otofuji and Matsuda (1987)
Korea	9	61.2	199.5	6.6	22.6 ± 16.5	Zhao et al. (1999)
Benxi	(7)	59.4	205.5	7.3	22.5 ± 10.2	Lin et al. (2003)
NCB	5	78.6	202.6	6.2	–	Gilder and Courtillot (1997)

N (n): number of the studies (sites); Lat: north latitude; Long: east longitude; A_{95}: radius of the circle of 95% confidence; NCB: North China Block. Rotation is evaluated by comparison between the observed declinations and the expected one from the NCB at the representative point of southwest Japan (35°N, 134°E).

northeastern flank of southwest Japan, which is nearly normal to the coast. The MITI Kanazawa-oki borehole penetrated a basaltic seamount erupted within one of the depocenters. Its chemical composition is suggestive of thinned lithosphere during deposition of Unit E (Itoh et al., 1994). Paleobathymetric data on the borehole imply that the basin rapidly subsided 1000 m simultaneously with the igneous activity (Itoh et al., 1997).

Although depositional trends of the younger units have been obscured by erosional portions as a result of the latest Miocene intensive contraction (Itoh and Arato, 1999), an onlap pattern map within the sedimentary basin (Fig. 4) indicates that the pre-existing NW–SE rifted depression had been buried by marine units throughout the Miocene. The intriguing morphological trend is also confirmed for the post-rifting stage of the Japan Sea.

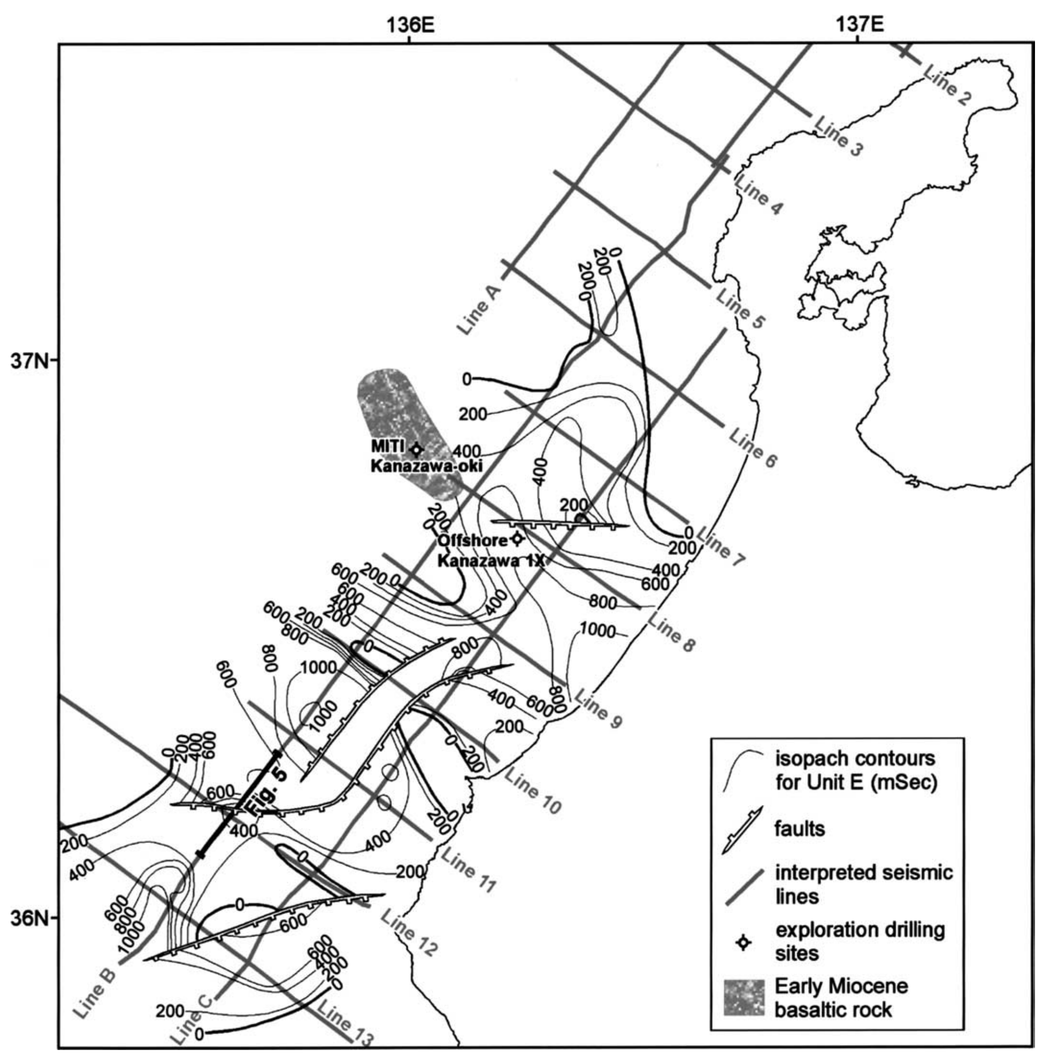

Fig. 3. An isopach map of the early Miocene seismic unit E (Itoh and Arato, 1999) on the northern slope of southwest Japan. See Fig. 2(a) for the mapped area. Distribution of the Early Miocene basaltic rock is after Itoh et al. (1994).

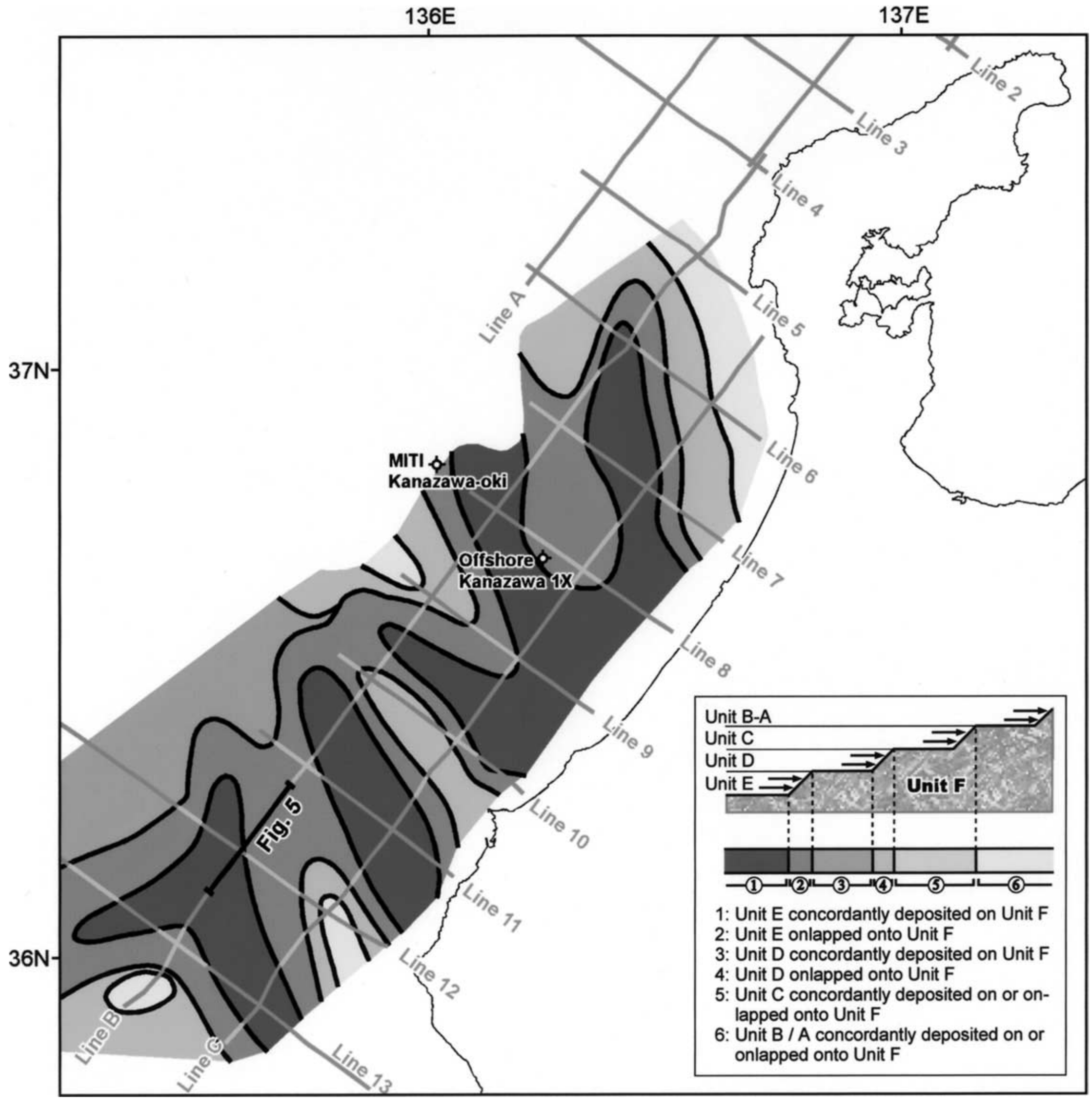

Fig. 4. A sedimentary onlap map of the seismic units to an acoustic basement (unit F; early Miocene (Itoh and Arato, 1999)) upon the northern slope of southwest Japan. See Fig. 2(a) for the mapped area.

Fig. 5 presents an NE–SW seismic profile crossing the structural trend. Early Miocene Unit E is onlapping onto the faulted surface of the igneous basement of Unit F. It is obvious that the middle-late Miocene Unit D represents growth strata on the tilted block of the basement. Unit D is clearly truncated and exposed on the ocean floor. It is indicative of inversion of previous normal faults that constituted the rift basin wall.

2.3. Miocene stress regimes

Seismic interpretation has described elongated rift basins normal to the present Japan Sea coast. Although it seems discordant with an arc-parallel arrangement of the depocenters that is anticipated by distribution of the early Miocene marine sediments on the back-arc side of southwest Japan (Fig. 2(a)), a similar deformation trend was reported for the Japan Sea coast. Kobayashi et al. (2005) showed that NW–SE grabens had developed on the northeastern part of southwest Japan in the

Table 2
Offshore seismic units and horizons identified in the Cenozoic basin upon the northeastern slope of southwest Japan

Unit	Horizon	Geologic age	Facies (environment)
A		Quaternary	Marine sediments
	dc10		
B		Late Pliocene	Marine sediments
	dc20		
C		Early Pliocene	Marine sediments
	dc30		
D		Middle–late Miocene	Marine sediments
	dc40		
E		Early–middle Miocene	Marine sediments
	dc50		
F		Early Miocene	Andesitic volcanic rocks

See Figs. 2(a), 3 and 4 for the seismic data coverage and line locations. Geologic ages and facies of the units are on the basis of drilling survey of MITI Kanazawa-oki (Fig. 3; Itoh et al., 1994, 1997) and another exploration borehole (Itoh and Arato, 1999).

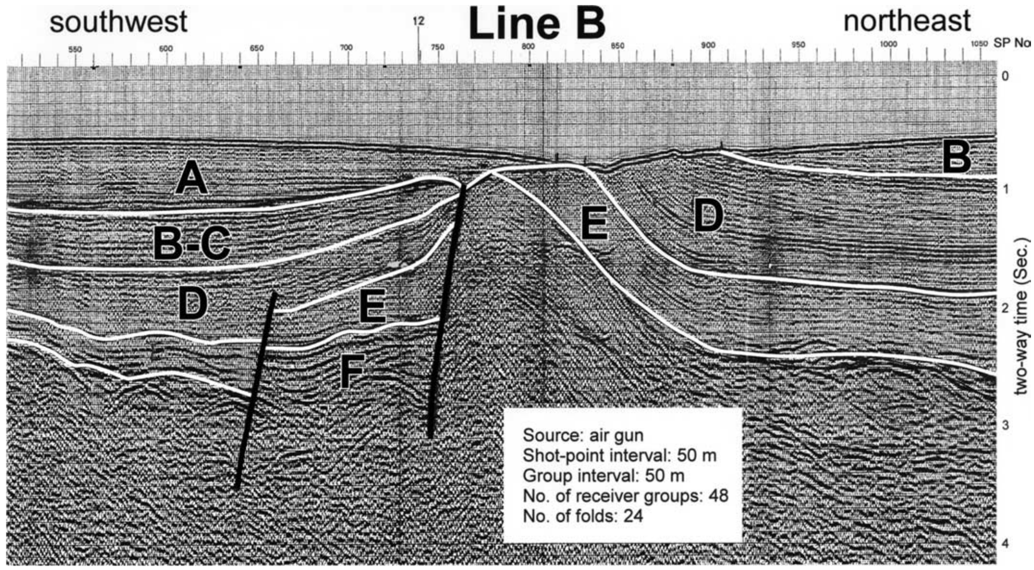

Fig. 5. An NE–SW reflection seismic section on the northern slope of southwest Japan. See Figs. 3 and 4 for line locations. Seismic units are described in Table 2 on the basis of drilling survey of MITI Kanazawa-oki (Fig. 3; Itoh et al., 1994, 1997) and another exploration borehole (Itoh and Arato, 1999).

Early Miocene. This structural trend may be attributed to a divergent stress regime during the initial stage of back-arc rifting, which will be discussed in Section 4. As for the inversion events on the Japan Sea coast, the event identified in the present study has a similar trend (NW–SE) with the pre-existing rift system. It has an older formation age (middle-late Miocene) than a well-known fold belt as the latest Miocene remarkable tectonic feature (e.g. Yamamoto, 1993; Itoh and Nagasaki, 1996; Itoh and Arato, 1999) with a quite different structural trend, E–W to NE–SW (arc-parallel). Thus we identify a tectonic phase characterized by NE–SW compression around the northeastern part of southwest Japan between the formation of the Japan Sea and the intensive arc-parallel inversion throughout the southern coast of the back-arc basin. The newly recognized tectonic phase is supported by onland evidence; a middle Miocene angular unconformity at the top of the syn-rifting Yatsuo Group (Hayakawa and Takemura, 1987).

3. A review: tectonic context of southwest Japan

3.1. Geology

Southwest Japan mainly consists of continental fragments and Mesozoic accretionary complexes with a zonal arrangement (see Fig. 2(a)), which are divided by a large crustal break called the Median Tectonic Line (MTL). It was also characterized by intensive volcano-plutonic activities around the Cretaceous (Murakami, 1979; Kinoshita, 1995). Such geologic features imply that the older rocks comprised a coherent block throughout the Cenozoic tectonic events. Thick marine sedimentary sequences are exposed along the Japan Sea coast, and their basal units are correlated with the early Miocene (Kano et al., 1991; Kurihara et al., 2003).

3.2. Paleomagnetism

According to temporal changes in declination, southwest Japan is regarded as a continental sliver that separated during opening of the Japan Sea and rotated clockwise by as much as 50° during the Miocene (Otofuji et al., 1985, 1991). An older and more regional rotational event occurred sometime in the early Tertiary as postulated from paleomagnetic data in the eastern China and Korean Peninsula (Uno, 2002). Table 1 shows reliable Cretaceous data-sets with demagnetization tests. Even if a data-set is verified through strict rock magnetic experiments, it is excluded if the mean direction was not corrected for tectonic tilting (e.g. Fukuma et al., 2003). As for southwest Japan, we adopted areas immune from differential rotations on both ends of the sliver or local fault motion (Itoh, 1988; Ishikawa, 1997; Uno, 2002). The Eurasian data suggests a significant clockwise rotation of more than 20°, which accounts for one third of the total rotational motion of southwest Japan. The extent of the rotated block will be discussed in Section 4.1.

3.3. Paleogeographic reconstruction

As delineated in Fig. 2(a), the Japan Sea is characterized by abundant topographic highs accompanied with a gravity anomaly indicative of a continental crust origin. On the assumption that the topographic highs are continental fragments submerged during or after the formation of the Japan Sea, Torii et al. (1987); Hayashida et al. (1991) determined geographically best-fitting arrangements of all continental pieces, including southwest Japan, which is similar to the tectonic model of Otsuki (1992). Notably, all the pieces are settled in the present Sino-Korean embayment without serious gap or overlap (Fig. 2(b)) via rotation of southwest Japan by as much as 50°. In the figure, the bent structure of the geologic zones of southwest Japan is restored, as shown by the straight MTL and a gap around the northern Japan Sea coast, according to an estimation of the middle Miocene differential rotation in the eastern part of the rifted sliver (Itoh, 1988). An ambiguity still remains in this reconstruction because the deeper floor of the western part of the Japan Sea is underlain by 'extremely thinned continental crust (Jolivet and Tamaki, 1992)'. If we should take the stretched sialic mass into account, southwest Japan may be restored at a more easterly position. The point is that southwest Japan was a jut along the Eurasian margin in the reconstruction on the basis of the Neogene back-arc spreading, in spite of its geologic continuity with Sikhote Alin (Kojima, 1989).

4. Discussion: Cenozoic tectonic epochs around southwest Japan

The eastern Eurasian margin (Fig. 1) has been the site of dynamic tectonic episodes as a result of plate motions along its ocean-facing boundary over many geologic periods. Its tectonic evolution during the Mesozoic era is generally described as a process of amalgamation of continental fragments and accretion along subduction zones mainly based upon paleomagnetic studies (e.g. Kodama et al., 1983; Oda and Suzuki, 2000). The western half of the Japanese Islands (southwest Japan), characterized by many geologic affinities with the continental margin, was a component of the Mesozoic terrane (shaded parts in Fig. 1). On the other hand, the Cenozoic is defined as a time of decomposition as a result of development of an extensive rift system around the Eurasian margin. In the following sections, we identify and describe four tectonic episodes on the basis of a selected geologic/paleomagnetic database and our original seismic data.

4.1. Basic constraints

Reliable paleomagnetic data-sets for eastern Eurasia suggest a post-Cretaceous clockwise rotation to the east of the Tan-Lu fault (see Fig. 1 and Table 1). Lin et al. (2003) insisted that fan-shaped rifting of intra-continental basins was responsible for the regional rotational motion. Although they regarded Sikhote Alin as a part of the rotated block, Otofuji et al. (2002, 2003a) found that the area experienced counterclockwise rotation by the early Tertiary. Thus a tectonic boundary is assumed between the Korean Peninsula and Sikhote Alin.

On the assumption that the Sino-Korean embayment was filled by continental fragments, including southwest Japan (Fig. 2(b)), the tectonic boundary can be defined within a confined zone. As explained in Section 3.1, southwest Japan is characterized by a continuous zonal arrangement of Mesozoic and older rocks. Therefore the hypothetical early Tertiary tectonic line as the northern margin of the rotated block is located between Sikhote Alin and the northeastern end of intact southwest Japan (see Fig. 6(b)). Since the area lacks paleomagnetic and structural data, further study is necessary in order to understand the detailed nature of the rotational boundary. Hence, we name the clockwise-rotated block the east Tan-Lu block, present-day fragments of which are shown by the shaded areas in Fig. 1. It is a redefinition of the east Liaoning-Korea block after Lin et al. (2003) from the viewpoint of a regional tectonic framework.

If the regional differential rotation was caused by intra-continental rifting, then tectonic movement may have been initiated during the late Cretaceous, because the Song-Liao basin (see Fig. 1) to the west of the Tan-Lu fault was developed by the end of the Mesozoic (Lin et al., 2003).

4.2. Stage 1: Early Tertiary configuration of the regional volcanic arc

As shown in Fig. 6(a), clockwise rotation of the east Tan-Lu block (ca. 23°) is restored assuming that a rotation pivot was around the southern end of the block on the basis of the north-widening shape of rift basins in the continent (Fig. 1). The reconstruction implies that the Mesozoic volcano-plutonic belt and accretionary complexes (simplified from Natal'in, 1993; Geological Survey of Japan, 1996; Chough et al., 2000) constituted a continuous province from Sikhote Alin to southwest Japan and Korean Peninsula, as required by their affinity in pre-Cenozoic constituents (Kojima, 1989). It is also suggested that the major crustal break, central Sikhote Alin fault and MTL, were parts of a larger left-lateral fault trace at the end of the Mesozoic. Coeval metamorphic events in Sikhote Alin are related to strike-slip activity on the fault system (Faure et al., 1995). A synchronous tectono-thermal event is, moreover, inferred from studies of metamorphic rocks along the Median Tectonic Line bisecting southwest Japan (Itaya and Takasugi, 1988; Takasu and Dallmeyer, 1990). Activities on the long fault system may have caused tectonic episodes, including mass transport on a regional scale.

East of the central Sikhote Alin fault, a thick Cretaceous turbidite sequence is exposed, and interpreted as a fore-arc sedimentary basin (Natal'in, 1993). If this is the case, our model casts doubt on the pre-rift location of the northeast Japan arc (Fig. 1). Although it is often regarded as a fore-arc region upon the eastern coast of Sikhote Alin (e.g. Otsuki, 1992), the above-stated Cretaceous basin was to be facing a convergent plate margin. Some of the Cretaceous and early Tertiary paleomagnetic directions within northeast Japan are characterized by anomalously shallow inclinations (e.g. Otofuji et al., 1997) implying a northward translation of the block. At present, the mechanism and path of the considerable lateral translation is unclear. The origin and reconstruction of northeast Japan should be argued on the basis of further tectonic studies.

4.3. Stage 2: Early Tertiary rearrangement of the Eurasian margin

Fig. 6(b) depicts the configuration of the eastern Eurasian margin sometime after early Tertiary differential rotation. At this stage, transcurrent motions on the separated central Sikhote Alin fault and MTL were dormant, possibly controlled by a change in the Pacific plate motion from northerly to westerly directions at ca. 42 Ma. Otofuji et al. (2003b) claimed that northeast Japan reached its present latitude before the

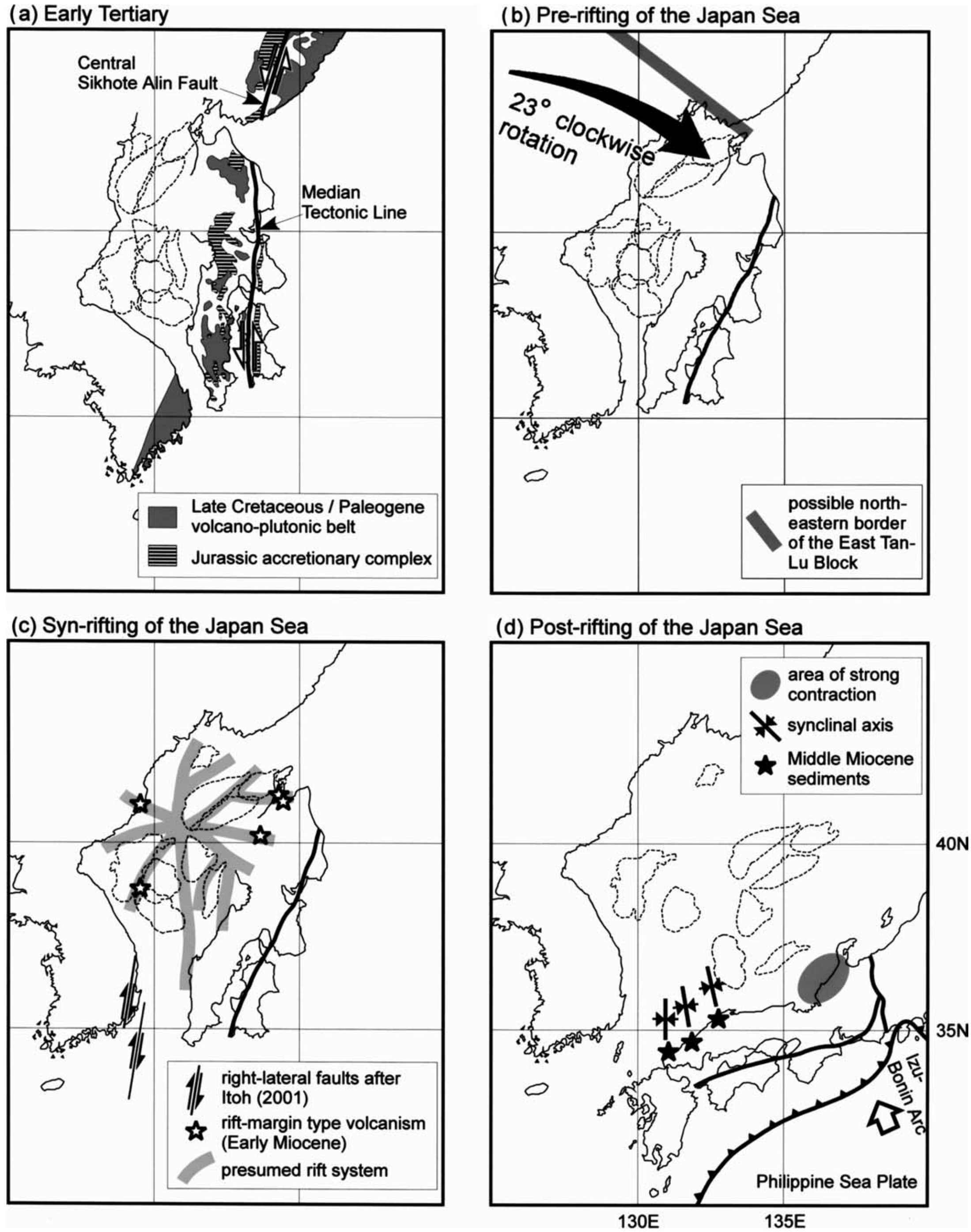

Fig. 6. Reconstruction of the eastern Eurasian margin through the Cenozoic. Early Tertiary left-lateral motions on the Central Sikhote Alin Fault and Median Tectonic Line are after Natal'in (1993); Otsuki (1992), respectively. Emplacements of the rift-margin type volcanism (Early Miocene) are after Ishiwatari and Ishida (1995); Ishida et al. (1998). Middle Miocene synclinal axes on the back-arc shelf, and coeval marine sediments on the Japan Sea coast are compiled from Itoh et al. (1992); JNOC (1990), and Igi et al. (1987), respectively.

Japan Sea opened. Thus, the massive rearrangement on the plate margin had ceased by the early Oligocene.

4.4. Stage 3: Rifting of the Japan Sea, the largest rift basin on the Eurasian margin

The Oligocene marks the incipient rifting stage of the Japan Sea (Jolivet and Tamaki, 1992). Tatsumi et al. (1989) attributed inactive Oligocene volcanism around northeast Japan to asthenospheric injection into the mantle wedge on the Pacific plate. Subaerial volcanic rocks on the Japan Sea coast at the end of the Oligocene (Ganzawa, 1983; Itoh et al., 2001) show a chemical affinity with rift-margin volcanism (Ishida et al., 1998). Since a clear indication of a coeval marine transgression has not been reported for the Japan Sea coast, basin subsidence linked to thinning of lithosphere and block rotations was a later (early Miocene) event resulting from considerable spreading of the back-arc basin.

Fig. 6(c) delineates the Eurasian margin at the early stage of rifting. Since numerous continental fragments within the Japan Sea require a divergent crustal break-up, the hypothetical rift system is drawn to surround the fragments. It is noted that all the rift-type volcanic rocks found around the Japan Sea (open stars: Ishiwatari and Ishida, 1995; Ishida et al., 1998; Ishiwatari, 2000) are located within the divergent zones.

In this figure, elongated offshore early Miocene basins described in Section 2.2 seem to be branches of the rift system network. By this stage, southwest Japan was separated from the east Tan-Lu block and underwent southward translation, which is supported by right-lateral fault motion around the western margin of the back-arc basin (Itoh, 2001), and associated clockwise rotations on the eastern coast of the Korean Peninsula (Lee et al., 1999).

4.5. Stage 4: Post-rifting deformation of the southern Japan Sea and prototype of the present tectonic regime

Although the timing of clockwise rotation of southwest Japan is still controversial, it is generally accepted that the continental sliver reached approximately the present position by the early middle Miocene (e.g. 14 Ma; Otofuji et al., 1991). Southward motion of the island arc inevitably caused a collision against the Izu-Bonin arc on the Philippine Sea plate. For example, Takahashi and Saito (1997) demonstrated that multiple collisional events since the middle Miocene brought about intra-deformation of the eastern part of southwest Japan.

Fig. 6(d) shows the post-rift configuration of the arc–arc junction. Deformation of southwest Japan is expressed by a northward bend of the MTL, which is suggested by paleomagnetic data (Itoh, 1988), and probable contraction on the Japan Sea side. As stated in Section 2.3, NE–SW compression caused inversion of the pre-existing rift basins normal to the older geologic trends of the arc. Middle to late Miocene stagnant subsidence along the coast (Itoh et al., 1997) and a coeval angular unconformity in the marginal basins on southwest Japan (Hayakawa and Takemura, 1987) may be attributed to the tectonic event. A similar stress regime was confirmed in the northeastern part of southwest Japan on the basis of structural analysis of pre-Neogene rocks (Kano, 2002; Yamakita and Otoh, 2002). Although the intra-arc deformation diminished to the west (Itoh and Ito, 1989), middle Miocene synclinal trends (Itoh et al., 1992; JNOC, 1990) on the back-arc shelf, and contemporaneous coastal sediments (solid stars in Fig. 6(d): Igi et al., 1987) indicate that the bending event affected the regional deformation mode.

Amalgamation between southwest and northeast Japan occurred sometime in this tectonic epoch. The timing of their differential rotations and the sizes of coherent blocks during the massive rearrangement of the plate margin should be established through further paleomagnetic and structural data with precise age determinations.

5. Summary

Newly interpreted reflection seismic data delineates part of a divergent rift system on the back-arc shelf of southwest Japan that was activated during spreading in the Japan Sea since the late Oligocene. A subsequent arc–arc collision event is evidenced by the inverted motion on normal faults along the divergent rifts.

We have described four Cenozoic tectonic stages as a decomposition process of eastern Eurasia based on the above seismic survey, and reexamination of paleomagnetic data.

(1) Regional left-lateral fault motion by the early Tertiary, continuous from the central Sikhote Alin fault to the MTL, caused rearrangement of the plate margin.
(2) Intra-cratonic rifting in eastern Eurasia resulted in early Tertiary clockwise rotation of the east Tan-Lu block ($>20°$), including southwest Japan, relative to the North China block.
(3) Divergent rifting within the Japan Sea from Oligocene to early Miocene time separated southwest Japan from the east Tan-Lu block.
(4) An arc–arc collision event brought about deformation of the Japanese Islands fringing easternmost Eurasia from the middle to late Miocene.

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