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Evolution of the Sea of Japan back-arc and some unsolved issues

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ABSTRACT

The Sea of Japan back-arc system provides an exceptional opportunity to study a virtually intact continent-ocean back-arc system in which recent tectonic inversion has exposed entire sequences of back-arc structure on land. Moreover, Japan's dense seismic/geodetic-monitoring networks, deployed country-wide, as well as moveable pools of ocean bottom seismometers, provide a rich data set through which to investigate deep back-arc structure. Earlier investigations have produced an initial understanding of back-arc opening: timing, structural evolution, temporal/spatial patterns of magmatic activity. Many questions remain, among them, the mechanism of back-arc opening (pull-apart or trench-rollback), the dynamics of interacting plates (location of the Philippine Sea plate with time), the origin of the anomalously thick Japan Sea ocean crust, and possible influences of far-field forces (India-Asia collision). Given existing high-resolution geophysical data sets and extensive on-land exposures of back-arc sequences and structures, the Sea of Japan back-arc is a promising context in which to address both local and more universal questions of how back-arc systems evolve. Here we review the tectonic setting and geological evolution of the Sea of Japan, based our own and others' work, and briefly discuss outstanding questions that invite further investigation.

1. Introduction

The 10th Workshop of the International Lithosphere Program (ILP) Task Force on Sedimentary Basins, '*Lithosphere dynamics of sedimentary basins in subduction systems and related analogues*,' highlighted the extent to which sedimentary basins can be a reliable proxy for linking mantle and surface processes in subduction systems when examined in an integrated way. Back-arc basins such as the Alboran, Ebro, and Pannonian Mediterranean basins, the South China Sea, and the Sea of Japan (Japan Sea) emerged as areas of considerable interest (Fig. 1). The Japan Sea back-arc reached ocean-spreading stage in the mid-Miocene and only recently experienced tectonic inversion (15–3.5 Ma: Fabbri et al., 1996; Itoh and Nagasaki, 1996; Lee et al., 2011; Sato, 1994; Tai, 1973; Yamamoto, 1993). It remains virtually intact with most of its original structures readily observed. Hence, it presents an exceptional opportunity to study a mature continent-ocean back-arc system in which fully recognizable sequences of back-arc structure have been uplifted and exposed on land.

In recent years, a concentrated effort of controlled-source, refraction/wide-angle reflection profiling around Japan, both onshore and off, has elucidated the crustal structure of the Sea of Japan back-arc. In addition, the countrywide deployment of a dense seismic and geodetic monitoring network has provided the basis for a substantial geophysical data archive (GSI, 2016; Kasahara et al., 2009; NIED, 2016; Obara et al., 2005). Integration of these multiple geophysical data sets with existing geological and structural data is giving us a new 3-D perspective and a growing understanding of the character and evolution of the Japan Sea back-arc system. Also emerging is a parallel understanding of what questions remain to be answered, eight of which we will pose and discuss below.

Of additional interest is how the Japan Sea back-arc compares with other well-studied systems, e.g. the Mediterranean back-arcs, the South China Sea, or New Zealand's Taupo Rift. For example, hyperextended crust which characterizes the Pannonian Basin and the South China Sea (Savva et al., 2014; Tari et al., 1992) is not found in the Japan back-arc, where there is no exhumed mantle. Also, its rapid speed (>15 cm/yr) and short duration (<10 Ma) of opening places the Sea of Japan among the fastest evolving back-arc systems, perhaps similar to the present Lau-Havre-Taupo Basin (Bevis et al., 1995; Ziegler and Cloetingh, 2004). Having opened in a continent-ocean setting, the Japan Sea back-arc serves as a key link between continent-continent and

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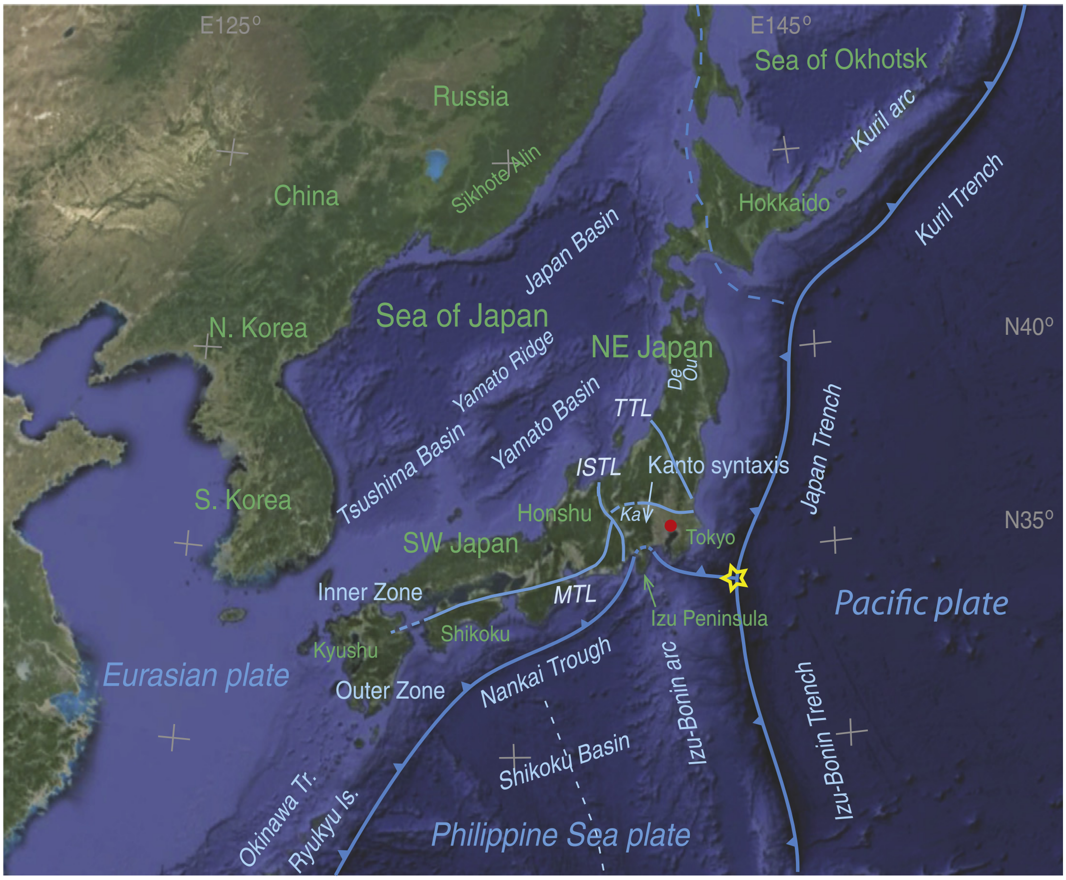


Fig. 1. Tectonic setting. Present tectonic setting for the Japanese island arc which consists of four main islands: Hokkaido, Honshu, Shikoku, and Kyushu. Plate motion for the Pacific and Philippine Sea plates is WNW at 9–11 cm/yr (Northrup et al., 1995) and 3–6 cm/yr (DeMets et al., 2010; Seno and Maruyama, 1984; Seno et al., 1993) respectively. Yellow star: Boso triple junction. Light blue lines, major land faults: MTL – Median Tectonic Line, ISTL – Itoigawa-Shizuoka Tectonic Line, TTL – Tanakura Tectonic Line. Geographical features: De – Dewa Hills, Ou – Ou Backbone Range, Ka – Kanto Mountains. Amur plate omitted for simplicity.

ocean-ocean systems. Understanding the similarities and differences among these regions is likely to advance our understanding of how back-arc basins evolve in general, and what common factors link their larger-scale subduction dynamics.

2. The Japan Sea back-arc: tectonic setting, geology, and structure

2.1. Tectonic setting

The Japan Sea is a continent-ocean back-arc system (Fig. 1). It stands in contrast to other Pacific basins, which lie in ocean-ocean plate settings, and with the Mediterranean region where multiple back-arc basins have opened in a complex overprint on the slow convergence of Africa towards Eurasia (Horvath et al., 2006; Malinverno and Ryan, 1986; Parson and Wright, 1996; Schellart et al., 2006; Wortel and Spakman, 2000). Despite an unusual plate configuration, the Japan Sea has opened in a relatively straightforward manner through rifting of a continental margin.

In the early Tertiary, proto-Japan lay at the eastern edge of Eurasia, along an active continental margin where the Pacific plate was subducting (Maruyama and Seno, 1986). By the mid-Miocene, it was separating from the continent through rifting of the Eurasian continental crust (Otofuji et al., 1985; Sato and Amano, 1991; Tamaki et al., 1992). Since then, the development of the Japanese island arc has been governed by the interaction of three plates, the Eurasian, Pacific, and Philippine Sea plates, which meet at an unstable trench-trench-trench triple junction in the Pacific Ocean offshore of central Japan (Fig. 1) (Matsubara and Seno, 1980).

The Eurasian plate carries the Japanese island arc. Two plates subduct beneath it in a WNW direction: the Pacific plate in the Japan Trench (~9–11 cm/yr; Northrup et al., 1995) and the Philippine Sea plate in the Nankai Trough (3–6 cm/yr; DeMets et al., 2010; Seno and Maruyama, 1984; Seno et al., 1993). A volcanic front runs the length of the arc (Fig. 2) (JMA, 2013). The Pacific and Philippine Sea plates encounter one another under central Japan where they subduct together, with the Philippine Sea plate sandwiched between the Eurasian and Pacific plates (Ishida, 1992; Wu et al., 2007). Southwards from the Boso triple junction, the Pacific plate plunges beneath the Philippine Sea plate along the Izu-Bonin Trench, an interaction which is producing the Izu-Bonin volcanic arc. The still-active Izu-Bonin arc and a defunct Shikoku (back-arc) Basin are being carried by the Philippine Sea plate into the Nankai Trough. The Shikoku Basin subducts with the plate, but the Izu-Bonin arc is colliding with the Japanese island arc at Izu peninsula, to which four exotic crustal blocks have been accreted since the mid-Miocene (Amano, 1991; Ito, 1987; Koyama, 1991; Takahashi and Saito, 1997). In the extreme north of Japan, another arc-arc collision is occurring between Hokkaido and the Kuril island arc; collision began in the mid-Miocene and is ongoing (Den and Hotta, 1973; Ito, 2002; Iwasaki et al., 2004; Kato et al., 2004; Tsumura et al., 1999).

2.2. Pre-Neogene geology and structure

The pre-Neogene bedrock of Japan consists of a series of subduction-related accretionary complexes, associated ophiolites, and granitic intrusives (Fig. 2) (Banno and Nakajima, 1992; GSJ, 2016; Isozaki, 1996; Isozaki et al., 1990; Kimura et al., 1991). In southwest (SW) Japan,

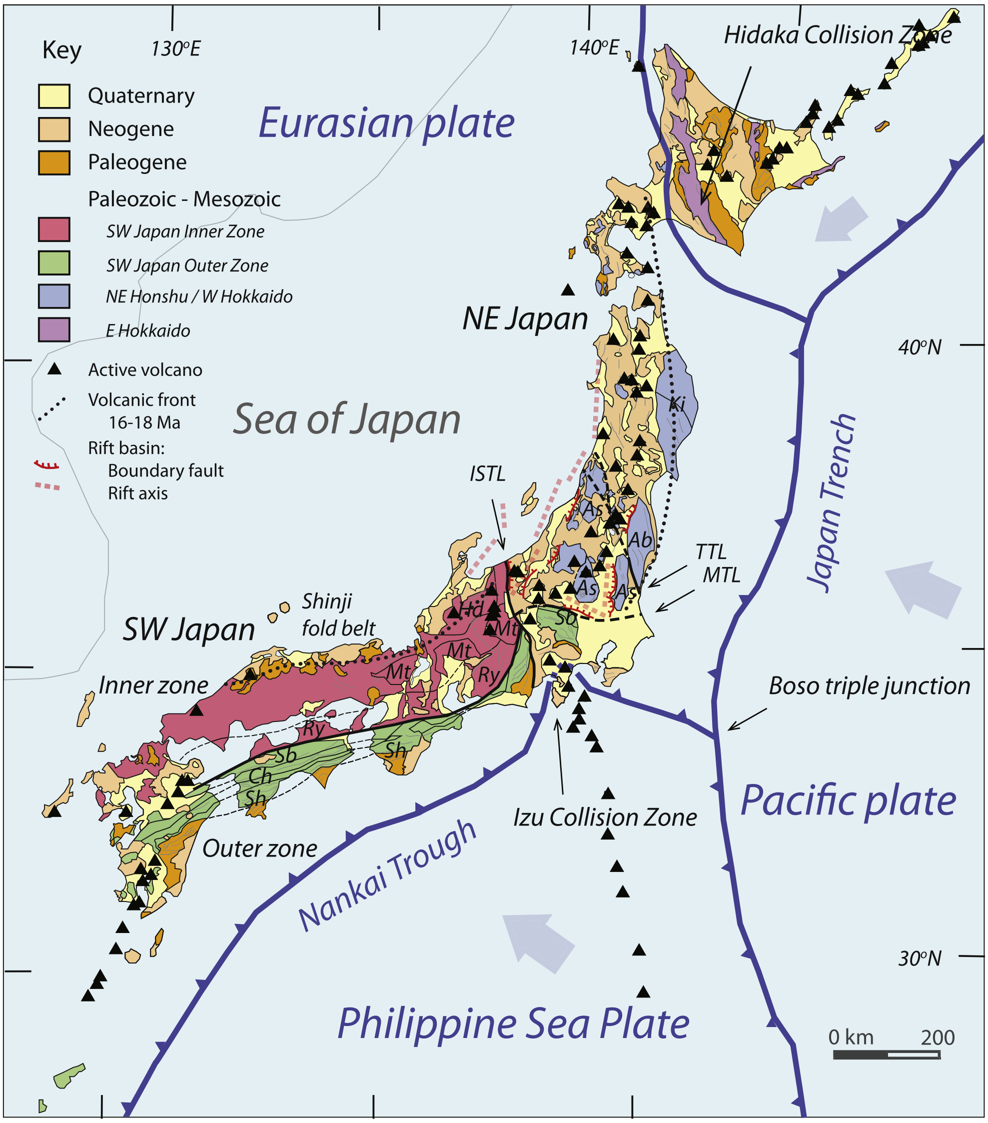


Fig. 2. Age distribution of rocks in Japan. Paleozoic/Mesozoic bedrock is prominently exposed in SW Japan, where it is divided into two geological provinces, Inner and Outer Zones, by the Median Tectonic Line (MTL). Tertiary/Quaternary sediments and volcanics cover extensive areas of NE Japan, and are exposed due to tectonic inversion following back-arc opening. Rift basins are Miocene in age; their rift axes are zones of higher Vp than surrounding bedrock, interpreted as cores of more mafic composition (Sato, 2014; Sato et al., 2015b; unpublished data). The 18–16 Ma volcanic front migrated rapidly trenchwards just before the opening of the Sea of Japan (Takahashi, 2006; Yoshida et al., 2013). The active front has shifted back, leaving the defunct older front stranded in the present fore-arc region in northern Japan. Plate motions for Pacific and Philippine Sea plates are WNW at 9–11 cm/yr (Northrup et al., 1995) and 3–6 cm/yr, respectively (DeMets et al., 2010; Seno and Maruyama, 1984; Seno et al., 1993). Unit abbreviations: Ab – Abukuma, As – Ashio, Ch – Chichibu, Hd – Hida, Ki – Kitakami, Mt – Mino Tamba, Ry – Ryoke, Sb – Sanbagawa, Sh – Shimanto. Based on 1:1,000,000,000 scale Geological Map of Japan (GSJ, 2003). Also, Banno and Sakai, 1989; Charvet, 2013; GSJ, 1982; Geological Society of Japan, 2010; Nakajima, 1994; Taira et al., 1982; Takahashi, 2006. Also, the National Catalog of Active Volcanoes in Japan (JMA, 2013).

these accretionary units are arranged in arc-parallel zones which become progressively younger from north to south. The oldest and northernmost zone, the Hida metamorphic belt, contains gneisses with Proterozoic to mid-Paleozoic protoliths, and late Triassic-early Jurassic granitoid intrusions (Arakawa et al., 2000; Hiroi, 1981). The youngest and southernmost zone, the Shimanto belt, contains weakly-metamorphosed trench sediments of late-Cretaceous to Paleogene age (Taira et al., 1982). The bedrock of SW Japan is divided into two provinces or zones, 'Inner' and 'Outer,' by the Median Tectonic Line (MTL) (Fig. 2) (Kimura et al., 1991; Matsuda et al., 1967).

In northeast (NE) Japan, Inner and Outer Zone rocks and the MTL are absent, and pre-Neogene bedrock is represented by the Kitakami (North and South) and Abukuma massifs, and the Ashio belt. The massifs include a Paleozoic shallow marine sequence, two Mesozoic accretionary complexes, and Mesozoic granitic intrusives (Iwasaki et al., 1994; Minoura and Hasegawa, 1992). The Ashio belt includes unmetamorphosed Jurassic accretionary sediments that are brought into fault contact with the granitic-metamorphic Abukuma rocks across the Tanakura Tectonic Line (TTL) (Fig. 2) (Otsuki, 1992). The TTL is considered to be the dividing line between the granites of NE and SW Japan, which differ in their geochemistry, e.g. ^{86}Sr/^{87}Sr isotope ratios (Shibata and Ishihara, 1979). Despite numerous attempts to correlate bedrock units from NE and SW Japan (Faure and Natal'in, 1992; Kojima and Kametaka, 2000; Isozaki, 1997; Yamakita and Otoh, 2002), no model has been generally accepted (Arakawa et al., 2000; Nakajima, 1997). Further north, the bedrock of western Hokkaido is continuous with that of NE Japan (Den and Hotta, 1973; Geological Society of Japan, 2010); however, eastern Hokkaido, consists of obducted arc crust which is thought to have derived from the Kuril arc in the mid-Miocene (Banno and Nakajima, 1992; Ito, 2002; Kimura, 1994).

The pre-Neogene structural fabrics in NE and SW Japan have nearly perpendicular trends of approximately N–S and E–W, respectively, and are thought to comprise separate crustal blocks (Fig. 2; Takahashi, 2006). In SW Japan, Inner Zone rocks occur as a subhorizontal 'nappe pile,' while Outer Zone rocks occur as a moderately N-dipping, imbricated accretionary stack (Ito et al., 2009). The trend for these structures runs ENE-WSW, parallel or subparallel to the Nankai Trough (Charvet, 2013; Isozaki, 1997; Isozaki et al., 1990). In contrast, the pre-Neogene structural trend in NE Japan runs NNW-SSE, somewhat oblique to the Japan Trench (Iwasaki et al., 1994; Minoura and Hasegawa, 1992). The suture between the NE and SW bedrock domains has traditionally been placed at the Tanakura Tectonic Line (TTL) (Otsuki, 1992) but more recent studies place it in the Kanto region of central Japan (Takahashi, 2006; Yamakita and Otoh, 2002).

2.3. Neogene geology and structure

Neogene deposits throughout Japan consist of thick non-marine to deep-marine sediments, as well as voluminous volcanics, which record the rifting of the Asian margin and the opening of the magma-rich Japan Sea back-arc (Sato, 1994; Yoshida et al., 2013). These deposits now cover the Dewa Hills/Asahi Mountains and the Ou Backbone range in NE Japan (Fig. 1). They also fill a series of deep rift-basins along the eastern margin of the Japan Sea, from Kyushu to Hokkaido, which include the northern Fossa Magna, Niigata, and Akita-Yamagata Basins in NE Japan, and the narrower Shinji fold belt in SW Japan (Figs. 2, 3) (Itoh and Nagasaki, 1996; Sato, 1994; Tai, 1973). The rift-basins are floored with thick submarine basalts (>2000 m), and contain sedimentary fill 4000–6000 m thick (Sato, 1994; Tsuchiya, 1990). They have deep cores of higher P-wave velocity, thought to be more mafic in composition, and are interpreted as failed rifts (Fig. 4b) (Sato, 2014; Sato et al., 2015b; unpublished data). These range from 30 to 50 km wide.

Before ~25 Ma, volcanism in the pre-rift continental margin was dominated by subaerial andesitic activity characteristic of an active subduction margin, along with massive felsic ignimbrite eruptions (Yoshida et al., 2013). By 20 Ma, when production of ocean crust was underway in the Yamato Basin (Kaneoka et al., 1992), submarine mafic magmas erupted inside the rift-basins, and rhyolites on the shoulders ('bimodal volcanism') (Tsuchiya, 1990; Sato, 1994; Yoshida et al., 2013). Japan Sea basement was encountered in three locations by drilling in the Yamato and Japan Basins during ODP Leg 127/128 and was found to be basaltic in composition (Kaneoka et al., 1992; Tamaki et al., 1992).

Of the three basins that comprise the Japan Sea, only the Japan Basin has ocean crust of typical thickness, ~8 km (Fig. 3; Hirata et al., 1992).

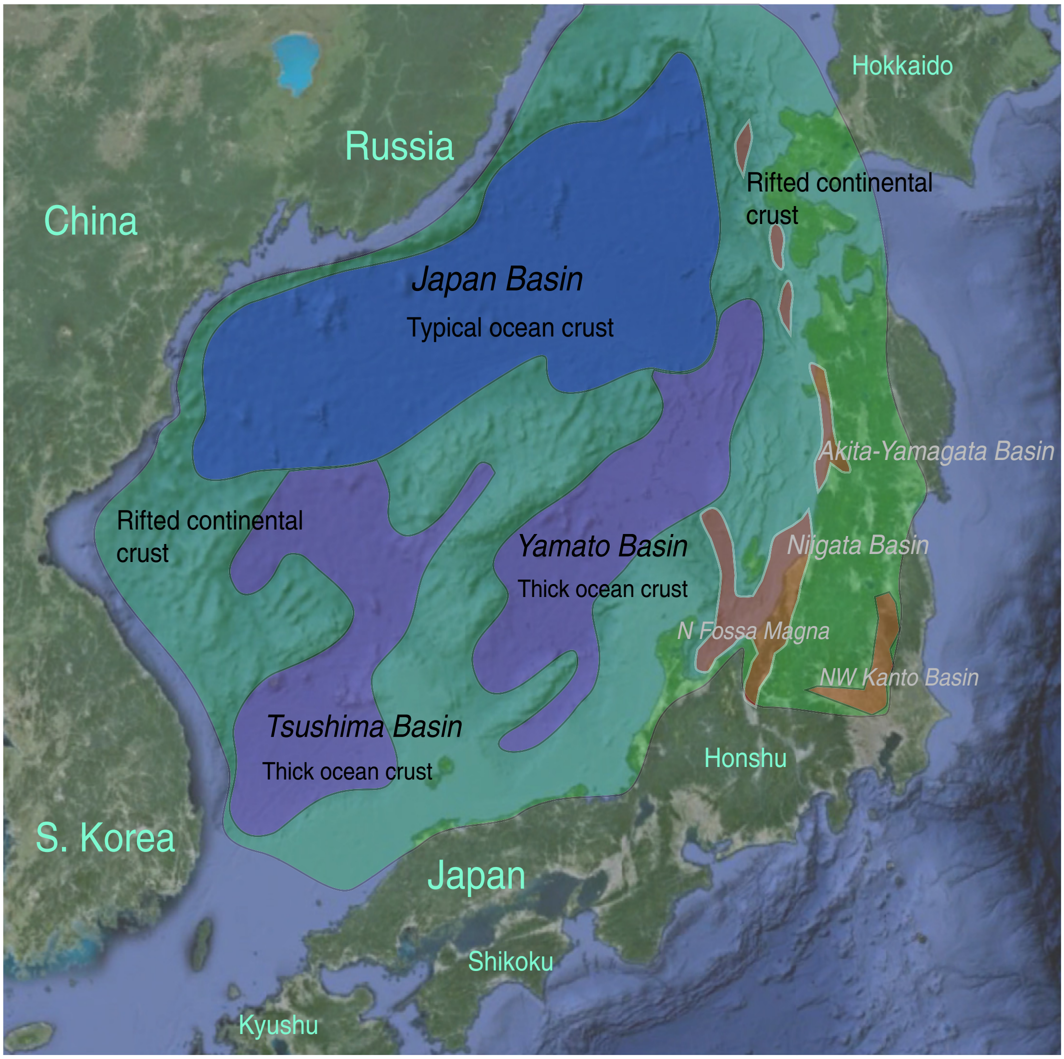


Fig. 3. Distribution of crustal types in the Japan Sea. Blue: *Typical ocean crust* is present in the Japan Basin (~8 km thick: Hirata et al., 1992). Purple: *Thick ocean crust* occupies the Yamato Basin and Tsushima Basin (15–19 km thick: No et al., 2014a; Sato et al., 2014; Shinohara et al., 1992). Green: *Rifted* (*extended*) *continental* crust rims the Japan Sea (22–26 km thick: Sato et al., 2006a, 2006b). It also exists under northern Honshu in NE Japan and the Kanto region of central Japan. Red: *Marginal rift basins* within the extended continental crust failed to mature into ocean spreading centers during back arc rifting.

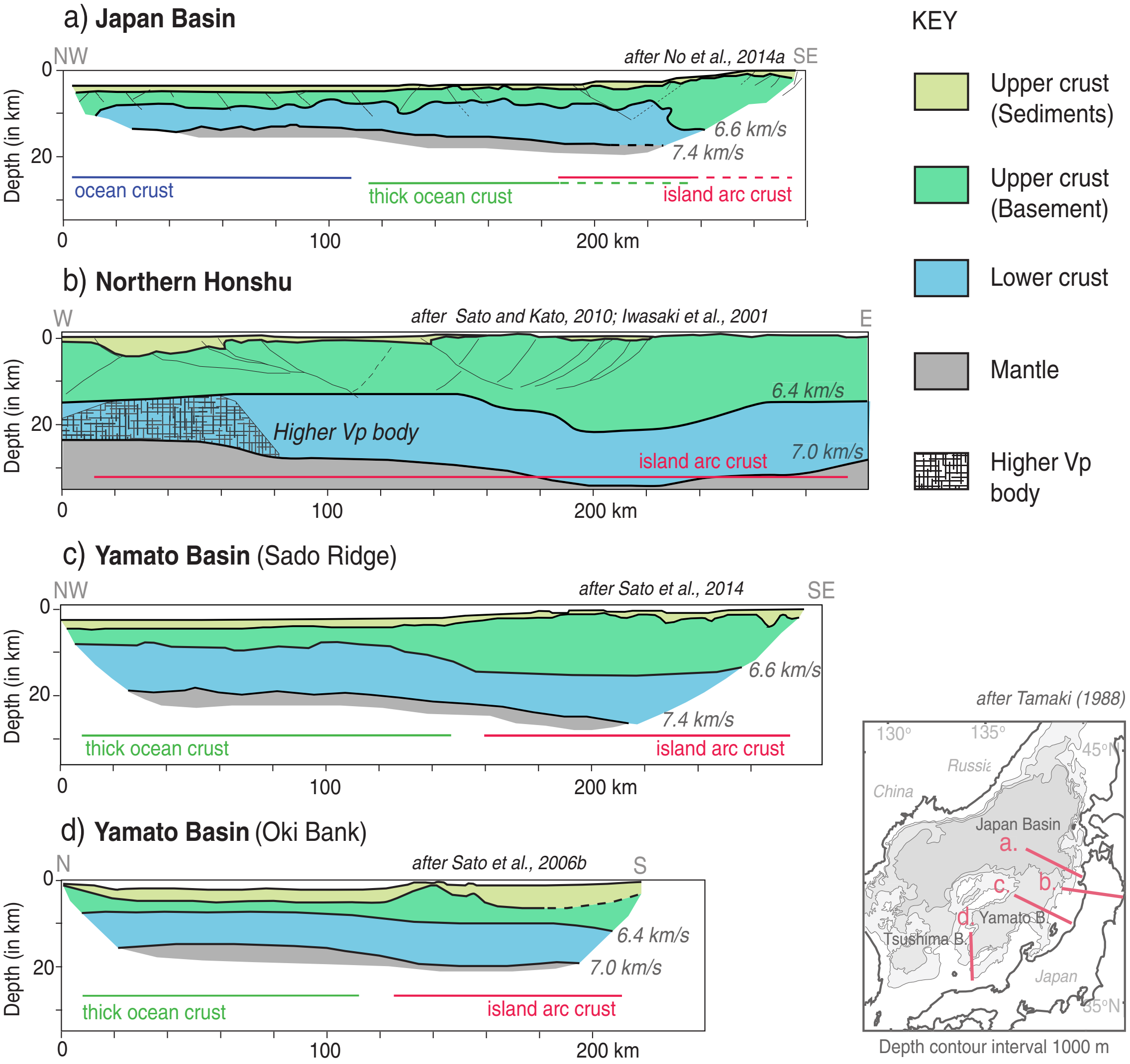


Fig. 4. Crustal structure in and around the eastern Sea of Japan. P-wave velocity structure based on published profiles obtained using seismic reflection/refraction, including OBS, and earthquake tomography methods: (a.) Japan Basin after No et al. (2014a), (b.) Northern Honshu re-interpreted based on Sato and Kato (2010) and Iwasaki et al. (2001); higher Vp body (hatched pattern) in lower crust is interpreted as the mafic core of a failed rift basin, and inferred to be of hornblende-pyroxene gabbro composition, based on Sato (2014) and Nishimoto et al. (2008), (c.) Yamato Basin – Sado Ridge after Sato et al. (2014) and (d.) Yamato Basin – Oki Bank after Sato et al. (2006b). Upper crust basement may consist of pre-rift island-arc (continental) crust, ocean crust, or *syn*-rift volcanics.

The Yamato and Tsushima basins show a velocity structure that resembles that of typical ocean crust, but the crust is anomalously thick, ~15–19 km (Shinohara et al., 1992; No et al., 2014a; Sato et al., 2014). Outside of the areas identified as typical or anomalous ocean crust, the Japan Sea contains areas of extended continental crust, 22–26 km thick (Kurashimo et al., 1996; Nakahigashi et al., 2012). This may occur as either continental fragments, like the Yamato Ridge, or extensively normal-faulted continental crust which forms a broad transition zone between the ~35 km thick crust of the Japan island arc (Iwasaki et al., 2013) and the ~15–19 km thick crust of the Yamato Basin (Fig. 3) (Kurashimo et al., 1996; Lee et al., 1998; Sato et al., 2014; Tamaki, 1988).

3. Development of the back-arc (Sea of Japan)

3.1. Back-arc opening

Intra-arc rifting and back-arc spreading followed in quick succession during the opening of the Japan Sea which lasted for <10 My (see time constraints below). At roughly 23 Ma, the onset of extensional tectonics created numerous half-grabens and grabens in the Asian continental crust, with an axis of extension oriented at right angles to the paleo-trench (Sato, 1994; Yamamoto, 1991). Ultimately, rifting would affect most of the width of NE Japan, yet only a narrow zone in SW Japan on the Japan Sea coast (Fig. 3: rifted continental crust). In the early rift period, the continuing eruption of subaerial andesites and felsic ignimbrites indicated an elevated thermal gradient but resulted in no apparent doming (Yamaji, 1990). The beginning of rifting was accompanied by the rapid trenchward migration of the volcanic front (Tatsumi et al., 1989; Yoshida et al., 2013).

Around 20 Ma, an intensified phase of rifting began that produced a family of rift-basins in the proximal back-arc (Sato, 1994). These are now exposed along the Japan Sea coast in NE Japan (Figs. 2, 3). Large amounts of basalt with back-arc basin affinities erupted on the floors of the rift-basins (Akita Basin, 20 Ma: Sato, 1994; Tsuchiya, 1990; Ujike and Tsuchiya, 1993). Subsidence from crustal stretching quickly followed, and the first marine incursion into the back-arc occurred about 3 My later when the floors of the rift-basins subsided rapidly from sea level to mid-bathyal depths signaling back-arc opening

(Brunner, 1992; Burkle et al., 1992; Sato and Amano, 1991; Yamaji, 1990). Sediments containing microfossils of foraminiferal zone N8 (16.4–15.2 Ma: Berggren et al., 1995; Blow, 1969) accumulated in the basins, ultimately reaching >6000 m where thickest (Takano, 2002; Yamaji, 1990). While the floors of the rift-basins collected deep water sediments, the shoulders remained in a shallow-marine depositional environment (e.g. Kobayashi and Tateishi, 1992). Sato (1994) showed a correlation between paleobathymetry and the distribution of 'failed' rift-basins in NE Japan where Neogene bathyal deposits are associated with rift-basins that have deep cores of higher P-wave velocity than the surrounding bedrock, and are interpreted as failed rifts (Figs. 2, 3, 4b) (Sato, 2014; Sato et al., 2015b; unpublished data).

The earliest reliable ocean floor date suggests that seafloor spreading was underway in the Yamato Basin by 20 Ma, approximately 3 My after extension began (Kaneoka et al., 1992; Nohda, 2009). Ridge-type spreading occurred only in the Japan Basin, which is floored by typical ocean crust (Fig. 3) (~8 km, Hirata et al., 1992). In the Yamato and Tsushima Basins, an anomalously thick ocean crust (15–19 km) developed whose origin is not well-understood (Hirata et al., 1989; No et al., 2014a; Sato et al., 2014; Shinohara et al., 1992). Its thickness may be a primary feature or a result of later intrusive processes (Section 4.5). High P-wave velocity zones are reported from the lower crust in the Yamato Basin suggesting magmatic additions (underplating) although their distribution appears limited (Hirata et al., 1989; No et al., 2014a; Sato et al., 2014).

Conjugate margins of the Japan Sea are asymmetrical. The Russian margin transitions quickly from continental crust (>30 km thick) to ocean crust (~8 km thick) in the Japan Basin (Fig. 3) (Filatova and Rodnikov, 2006; Kulinich and Valitov, 2011), while the Japan margin contains an extended zone of thinned, normal-faulted continental crust (22–26 km thick). This extended crust stretches over a distance of tens of kilometers between the continental crust of the Japan arc and the anomalously thick ocean crust of the Yamato Basin (Fig. 3) (Kurashimo et al., 1996; Nakahigashi et al., 2013; Sato et al., 2006a). Similar extended crust is found at the South Korea Plateau (Kwon et al., 2009).

Time constraints from biostratigraphic, structural, radiometric, and paleomagnetic studies establish a relatively short time window, ~23–15 Ma, for the entire process of back-arc opening, from the initiation of continental rifting to the end of back-arc expansion (Kaneoka et al., 1992; Hoshi et al., 2015; Nohda, 2009; Sato, 1994; Takahashi and Saito, 1997; Yamaji, 1990). Continental rifting within the East Asian margin began around 23–20 Ma, based on fission track and K-Ar dates for felsic ignimbrites that characterize the (subaerial) volcanism from this early period (Sato, 1994; Yamaji, 1990). Seafloor spreading in the Yamato Basin was underway by ~20 Ma, based on ^{40}Ar/^{39}Ar dates for igneous samples, drilled from the ocean floor, which showed reliable plateau ages of 21.2–17.7 My (Kaneoka et al., 1992; Nohda, 2009). An age gap of ≥1 My exists between the seafloor radiometric dates and the biostratigraphic age of the overlying sea-floor sediments in the Japan Sea (Brunner, 1992; Burkle et al., 1992; Kaneoka et al., 1992). Kano et al. (2007) report late Eocene or Oligocene nonmarine to shallow marine deposition from two locations on the back-arc side of central Japan. Radiometric ages for volcanic samples from these two sites, Oga and Noto, range in age from 24 to 18 My, but no actual marine fossils are described, only trace fossils. This contrasts with the mid-Miocene incursion which left abundant and widely distributed marine fossils throughout the back-arc (Yamaji, 1990), including Oga peninsula where the oldest reported marine fossils are from the mid-Miocene (Ingle, 1992). Robust corroboration of this earlier marine event would help to clarify its relevance to the major episode of back-arc opening that followed.

Paleomagnetic evidence shows that NE and SW Japan rotated away from the Asian margin independently in 'saloon-door' fashion during the Miocene, and the initial model showed rotation angles of 50° counterclockwise and 54° clockwise for the respective blocks (Fig. 5) (Otofuji et al., 1985: Fig. 3). The interval over which the rotation occurred is thought to have been short, <2 My, based on progressive changes in paleomagnetic declinations with time (Hoshi et al., 2015; Otofuji et al., 1985; Otofuji, 1996; Takahashi and Saito, 1997; Yamaji et al., 1999). The most recent estimate is that rotation started in SW Japan after 17.5 Ma and ended by 15.8 Ma (Hoshi et al., 2015).

During rotation, NE Japan is thought to have rifted from the Sikhote Alin region of Russia and SW Japan from Korea, however attempts to reconstruct the pre-rift Asian margin are complicated by the fact that the Precambrian bedrock of the Korean peninsula lies opposite Paleozoic and younger bedrock of SW Japan (Fig. 2) (Aoki et al., 2015; de Jong et al., 2009; Jahn, 2010; Kagami et al., 2006; Kojima and Kametaka, 2000). The independently-rotated NE and SW Japan blocks became joined in a structurally complex area of central Japan where at least one failed rift-basin opened at right angles to the predominant N-S trend of the others (Fig. 3: NW Kanto Basin) (Sato, 2014; Sato et al., 2015b, unpublished data). Unfortunately, sea-floor magnetic anomalies lack coherency in most of the Japan Sea and thus shed little light on the age and kinematics of back-arc opening (Chamot-Rooke et al., 1987; Fukuma et al., 1998; Seama and Isezaki, 1990).

3.2. Plate reconfiguration with arrival of PHS

Simultaneous with spreading in the Japan Sea, the Shikoku back-arc basin was opening in the Philippine Sea plate between ~27–15 Ma (Okino et al., 1999; Sdrolias et al., 2004). Most plate models show the Izu-Bonin trench rolling back as the Shikoku Basin expands, and the Eurasian-Pacific-Philippine Sea plate triple junction migrating eastwards along the Nankai Trough with the retreating trench/Pacific plate (Fig. 1). In some plate models, the triple junction had migrated past its current location by 5 Ma, before retreating back westwards (Matsubara and Seno, 1980; Miller et al., 2006). Similar uncertainty surrounds the location of the Shikoku Basin spreading ridge relative to the Japanese island arc. Depending upon the model, the Shikoku Basin spreading ridge is located (1) at its present location at 4 Ma (Matsubara and Seno, 1980), 14 Ma (Wu et al., 2016), or 15 Ma (Hibbard and Karig, 1990), (2) slightly to the west of its present location but still under Shikoku Island at 17 Ma (Seno and Maruyama, 1984), (3) between Shikoku and Kyushu Islands at 10 Ma (Mahony et al., 2011), or (4) further to the southwest but approaching Kyushu Island at 15 Ma (Hall, 2002; Sdrolias et al., 2004; Kimura et al., 2014). Common to all models, the Pacific plate migrates eastward allowing the Philippine Sea plate to move into its present position as the subducting plate at the Nankai Trough, in a plate reorganization.

Plate models that place the triple junction/Shikoku Basin spreading ridge far away from their current positions at ~15 Ma conflict with geological evidence that shows the Izu-Bonin arc impinging on SW Japan around that time. Carried towards the Nankai Trough by the Philippine Sea plate, the Izu-Bonin volcanic arc eventually collided with and indented the pre-Neogene bedrock of central Honshu into an arcuate structure called the Kanto syntaxis (Fig. 1) (Ito, 1987; Ito and Masuda, 1986; Takahashi and Saito, 1997). Amano (1991) identified four separate 'tectonic segments' from the Izu collision zone in area of the syntaxis that had lithological characteristics showing an origin in and around an exotic volcanic arc, and structural associations that suggested four separate arc-arc collision events resulting in their accretion (see also Ito, 1987; Koyama, 1991). The oldest block (Kushigatayama) was accreted by 12 Ma with the implication that the Izu-Bonin arc was in the vicinity of Izu somewhat earlier (15 Ma: Amano, 1991). Evidence for the timing of syntaxis growth comes from paleomagnetic studies that document clockwise rotation of >90° in the pre-Neogene bedrock of the Kanto Mountains, which bends around to form the eastern wing of the syntaxis (Fig. 1) (Takahashi and Saito, 1997). In contrast, deflections in the western wing of the syntaxis, on the far side of the collision axis, show smaller amounts of opposite-sense rotation as might be expected if it were formed in collision. Taken together, the data suggest

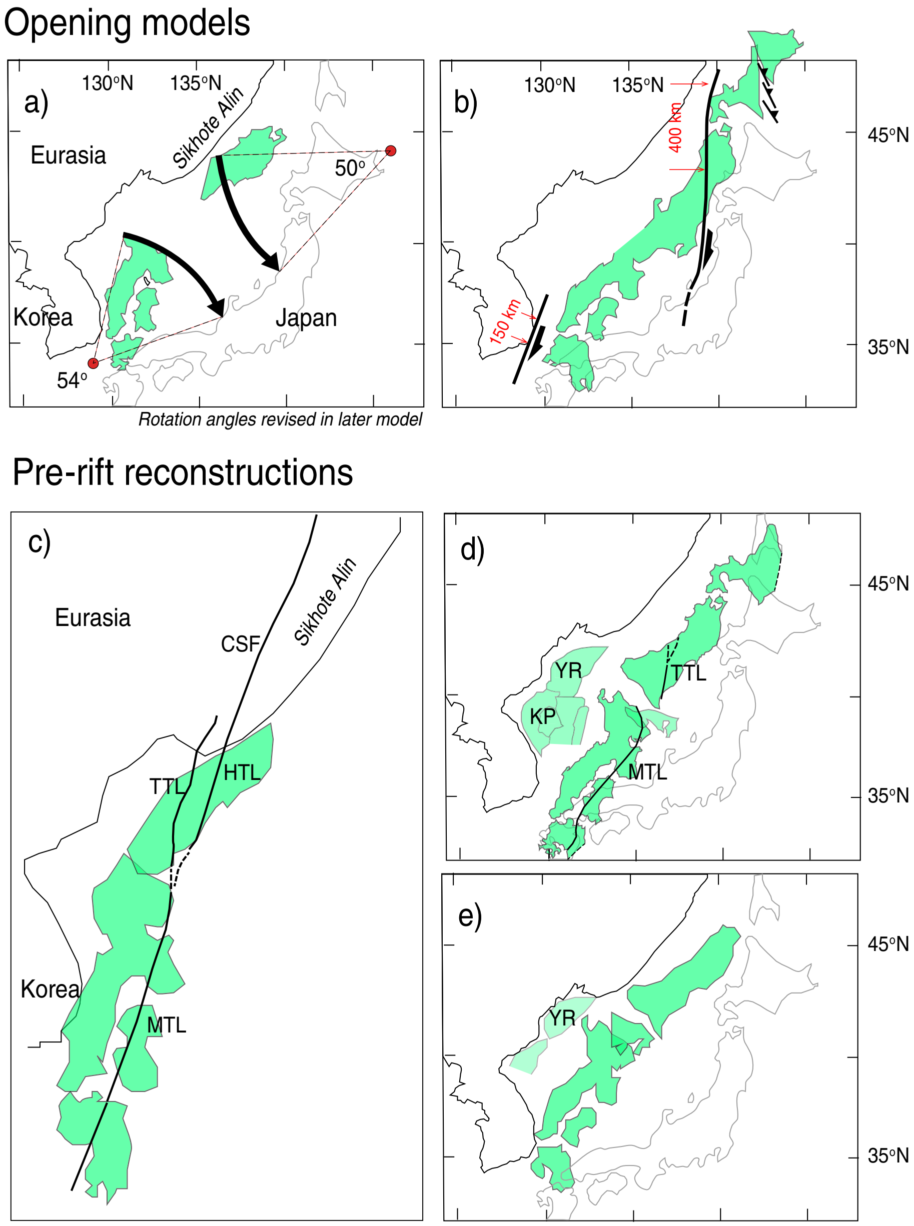


Fig. 5. Two principal opening models for Japan Sea and three reconstructions of the pre-rift Asia margin. Opening models: (a) Otofuji et al. (1985) proposed a 'saloon-door' model where NE and SW Japan rotated away independently from the Eurasian continent, counterclockwise and clockwise, respectively, based on paleomagnetic evidence. Rotation angles were later revised (Otofuji, 1996). (b) Jolivet and Tamaki (1992) proposed a pull-apart model where lateral movement on large strike-slip faults at the margins caused opening of an intervening basin, based on structural data. It did not account for paleomagnetic evidence, but a later model incorporated some rotation (Jolivet et al., 1994). Start of back-arc opening differs between models: Otofuji et al. (1985) - early Miocene, Jolivet and Tamaki (1992) - late Oligocene or earlier. Pre-rift configurations: (c) Yamakita and Otoh (2000), (d) Kim et al. (2007), and (e) Otsuki (1990). Abbreviations: MTL – Median Tectonic Line, TTL – Tanakura Tectonic Line, CSF – Central Sikhote Alin Fault, KP – Korea Plateau, and YR – Yamato Ridge. *All figures after authors cited.*

that half of the rotation can be attributed to the swing of SW Japan away from Asia during Japan Sea opening, and half to continuing collision-related indentation of the Kanto syntaxis by the Kushigatayama and a subsequent colliding block between 12 and 6 Ma (Takahashi and Saito, 1997). Exposure along the northern edge of the Kanto Mountains of a well-dated angular unconformity ('Niwaya'), between sediments deformed during the growth of the Kanto syntaxis and overlying sediments, dates to 14.8 Ma on the basis of biostratigraphy, and further narrows the timing (Kano et al., 1991; Oishi and Takahashi, 1990; Takahashi and Saito, 1997; Yamaji, 1990). Other accreted volcanic island blocks collided at 9–7 Ma, 5 Ma, and 1 Ma (Amano, 1991). Given the geological evidence for early presence of a colliding volcanic arc block at central Honshu, models that includes a later arrival for the Izu-Bonin arc raise the intriguing question of which other volcanic arc is colliding at 15–12 Ma.

3.3. Ending of back-arc opening and inversion

Cessation of back-arc opening at ~15 Ma is synchronous with the impingement of the Izu-Bonin arc and the Shikoku Basin on the Japanese island arc (Kimura et al., 2005). A hot and buoyant Shikoku Basin may have slowed or halted subduction as it approached the Nankai Trough, while collision of the Izu-Bonin arc or other exotic volcanic islands with Honshu would have impeded the swing away from

Asia. In this case, back-arc extension would have halted quickly, as seems to be the case. Throughout Japan, this end stage is recorded in the unconformable deposition of marine sediments containing fossils of foraminiferal zone N10 onto sometimes deformed rift-basin sediments containing fossils of foraminiferal zones N8 and N9 (Kano et al., 1991; Sato, 1994; Takano, 2002; Yamaji, 1990). The unconformity has been dated on the basis of biostratigraphy to 14.8 Ma (Berggren et al., 1995: cited as 14.6 ± 0.4 Ma in Japan). The Niwaya unconformity belongs to this period (Section 3.2).

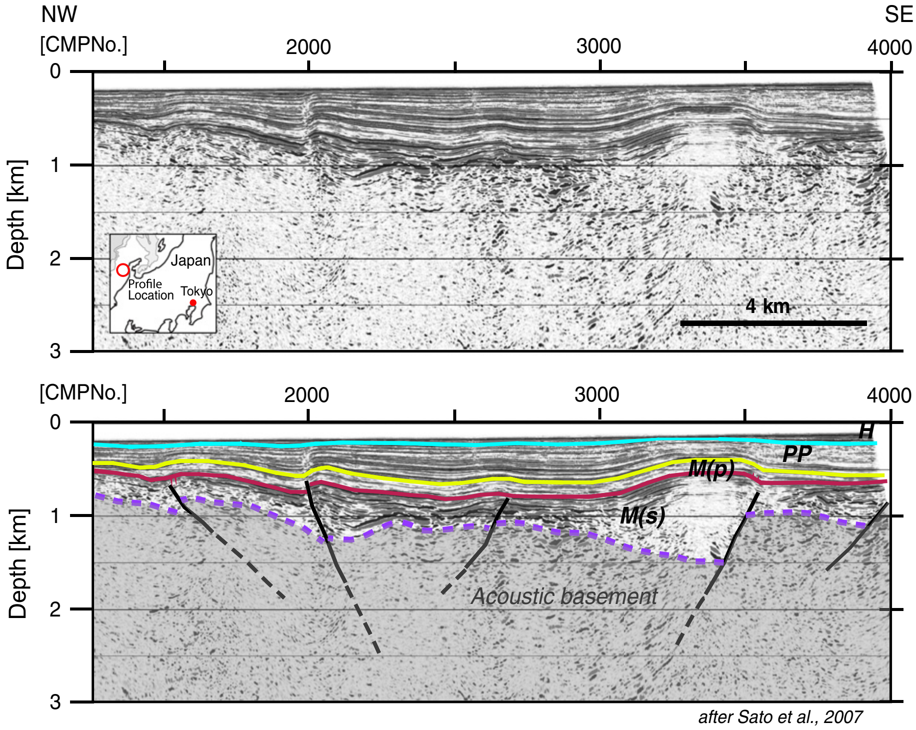
Stress field changes also signaled the end of back-arc opening as extensional stresses weakened and the stress regime became more neutral in NE Japan (Sato, 1994). In SW Japan, a N–S directed compressional stress field appeared (Yamamoto, 1991), perhaps due to buoyancy of the still-hot Shikoku Basin at the Nankai subduction zone. Subduction of the Philippine Sea plate appears to have paused between 11 and 6 Ma according to Kamata and Kodama (1994), who found a synchronicity of events in SW Japan, based upon structural, geological, and paleomagnetic data, that they interpreted as a hiatus in the subduction of the Philippine Sea plate from 11 Ma and a resumption of subduction after 6 Ma.

When back-arc opening ended, deep-to-shallow marine deposits that had accumulated in the basins of the Japan Sea were still submerged. Some basins remain submerged offshore (Okamura, 2003), but other Neogene rift deposits are now exposed along the Japan Sea coast, and in the Dewa Hills/Asahi Mountains/Ou Backbone Range of NE Japan (Figs. 2, 3) (Sato and Amano, 1991). Gentle upwarping began to lift the Ou Backbone Range of NE Japan above sea level beginning about 10 Ma (Sato, 1994). By 3.5 Ma, normal faults that had formed by brittle deformation in the extended continental crust during back-arc opening were reactivated as reverse faults under intense compression, causing basin inversion in the Neogene grabens and half-grabens of central and NE Japan (Fig. 6) (Sato, 1994). Thin-skinned deformation developed in the basin fill of the failed rift-basins (Matsuda et al., 1967; Okamura, 2003; Sato et al., 2015b). The change from extension to compression may have begun earlier in SW Japan where the Shinji fold belt developed in the failed rifts of SW Japan during the latest Miocene, 8–5 Ma (Itoh and Nagasaki, 1996; Tai, 1973; Yamamoto, 1993). Farther south, in the Tsushima straits between Kyushu and South Korea, the change from extension to compression may have begun even earlier, around 15 Ma (Fabbri et al., 1996; Lee et al., 2011).

Tectonic inversion has produced non-uniform contractional deformation across the Japan arc. Shortening increases from fore-arc to back-arc across NE Japan with a maximum shortening ratio of 15% in the failed-rift zones along the Japan Sea coast (Matsuda et al., 1967; Sato, 1989). Similar folding and thrusting has also been identified in offshore failed rift-basins, in which case the zone of maximum deformation could be as wide as 200 km (Okamura, 2003).

3.4. Collision of the Izu block, Quaternary plate shift

The most recent collision between the Izu-Bonin arc and central Honshu occurred around 1 Ma with the accretion of the Izu block at Izu peninsula (Amano, 1991). Izu-Bonin arc upper crust is being transferred from the Philippine Sea plate to the Eurasian plate through accretion, and is accompanied by uplift and subaerial exposure of fore-arc basin sediments as young as 1 My, that were swept up in front of the colliding block (Arai et al., 2013; Yamamoto and Kawakami, 2006). The exposed fore-arc basin sediments have equivalents of the same age still submerged in the accretionary wedge of the Nankai Trough. About the same time, the motion direction of the PHS plate shifted westward, from a NNW to a WNW direction. (Ide, 2010; Nakamura et al., 1984; Yamaji, 2000). Among events which record this change is the onset of strike-slip faulting along the MTL, attributed to slip-



after Sato et al., 2007

Fig. 6. Reactivation structures in the Japan Sea off Noto Peninsula. Depth-converted seismic reflection profile acquired in the Sea of Japan off Noto peninsula, central Japan, by Sato et al. (2007) showing tectonic inversion of extensional structures formed during the mid-Miocene opening of the Sea of Japan. Beginning 23 Ma, back-arc extension produced fault-bounded half-grabens and grabens in the Asian continental crust that filled with syn-rift sediments showing growth structures. Normal faults bounding the basins have been reactivated as reverse faults by a subsequent compressional event that caused tectonic inversion (3.5 Ma, central Japan), producing folding in the overlying post-rift sediments. Unit abbreviations: M(s) – Miocene syn-rift, M(p) – Miocene post-rift, PP – Plio-Pleistocene, and H – Holocene.

partitioning due to increased obliquity of subduction at the Nankai Trough (Sato et al., 2015a).

3.5. Arc magmatism and implications for subduction history

Lying along an active subduction margin, Japan was already a locus of volcanic arc magmatism even before the opening of the Japan Sea. Massive andesite and felsic ignimbrite eruptions blanketed the arc in the early stages of development, ~25 Ma (Sato, 1994; Yoshida et al., 2013). The opening itself was accompanied by a large volume of erupted magma, as large quantities of submarine basalt flooded the rift-basin floors, eventually reaching a thickness of as much as 2000 m, while rhyolites erupted subaerially on the basin flanks (Tsuchiya, 1990). According to Yoshida et al. (2013), the volume of erupted material was greatest in the early rifting period and declined by more than half during the spreading phase. Sato (1994) noted that the erupted volume of basalt in the Akita-Yamagata rift-basins was greatest between 15 and 14 Ma, which would have been late in back-arc opening. In the post-rift period (~13 Ma), the volume of erupted magma declined further, continuing mainly in the form of felsic pyroclastics. The style of volcanism has evolved during the Quaternary from a felsic caldera-forming phase (2–1 Ma) to a dominantly andesitic stratovolcano phase, with a modest rise in the volume of eruptive magma. Andesitic stratovolcanoes, like the iconic Mt. Fuji, characterize the current volcanic front. Volcanoes are distributed throughout the island arc, but activity is diminished in SW Japan due to the presence of a shallow Philippine Sea slab (Fig. 2) (JMA, 2013; Sato et al., 2009).

As a magma-rich system, the Japan back-arc provides proxy data about plate and mantle dynamics through its magmatic history. The retreat of the volcanic front with opening of the back-arc has been attributed to steepening of the subducting plate at the onset of spreading (Tatsumi et al., 1989). Mantle dynamics have been inferred from changes in magmatic composition with time. Over the period of back-arc opening, a change in the magmatic source-signature from enriched to depleted, based on secular variations in Nd and Sr isotopic composition, has been attributed to reduced lithospheric contamination of a mantle source magma, perhaps as a result of asthenospheric injection into the mantle wedge (Nohda, 2009; Nohda and Wasserberg, 1986; Tatsumi et al., 1989; Ujike and Tsuchiya, 1993). Nevertheless, the absence of depleted basalts in the Japan Basin suggests a heterogeneity in the composition of source magmas within the back-arc and/or in source mantle melting conditions (Hirahara et al., 2015).

The magma-rich Japan Sea back-arc possesses few of the markers of a magma-rich continental rifting event. Doming does not appear to have been a factor; the back-arc subsided deeply once rifting began although magmatism continued (Yamaji, 1990). Possible magmatic underplating and seaward-dipping reflectors have been identified at the bottom of the lower crust under the SE Korean margin near the Tsushima Basin (Cho et al., 2004; Kim et al., 2007), under the northern Yamato Basin (Sato et al., 2014), and along the margin of the Japan Basin in northern Japan (No et al., 2014a). If these features are analogous to the large provinces of seaward dipping reflectors (SDRs) and magmatic underplating found along rifted continental margins, they may have a played less important role here.

4. Discussion: peculiar aspects of the Sea of Japan back-arc evolution and outstanding questions

The Japan Sea back-arc system is a little-disturbed example of a mature back-arc system that developed within a continental margin and achieved ocean spreading. Overprinting by later tectonic inversion has been modest and has left the original back-arc structures in situ and fully recognizable. Since at least the early Tertiary, the tectonic setting has been one of long-term but dynamic subduction, punctuated by episodes of arc/arc (Japan/Izu-Bonin) or arc/back-arc basin (Japan/Shikoku Basin) collision, and plate reorganization. Earlier investigations have provided a solid framework in which to understand Japan Sea back-arc development, but there remain outstanding questions. These include, for example, whether the Japan Sea opened in a simultaneous or sequential multi-rift scenario, and what the pre-rift margin looked like. Other questions have broader application, for example, what processes formed the anomalously thick ocean crust, what plate scale controls governed back-arc opening, and why deformation has been concentrated in the back-arc region during tectonic inversion. Here we highlight and briefly consider eight such questions.

4.1. How does the Japan Sea continent-ocean back-arc setting compare to continent-continent or ocean-ocean systems?

The Japan Sea back-arc system involves continental plate – ocean plate subduction, where two oceanic plates (Pacific, Philippine Sea) subduct beneath a continental plate (Eurasia). The opening of the Japan Sea happened through rifting within the active volcanic arc of the Asian margin, and the continental fragment that drifted away became the Japanese island arc. In this respect, the Japan back-arc differs from Pacific back-arc systems that involve mainly ocean – ocean plate subduction or Mediterranean back-arc systems that involve an overall continent (Eurasian) – continent (African) plate convergence (e.g. Schellart et al., 2006; Wortel and Spakman, 2000). The Taupo Rift, for example, has opened in the last 2 My within the continental crust of New Zealand by southward propagation of the Lau-Havre back-arc rift, which is opening in an ocean-ocean setting (Parson and Wright, 1996).

Mediterranean back-arc systems show hyperextended crust, thinned lower crustal layers, and exhumation of lithospheric mantle (e.g. Tari et al., 1992), none of which appear in the Japan Sea back-arc. In contrast, P-wave velocity models of the crustal structure in the Japan Sea back-arc include a ~10 km thick lower crust which can be found under regions of extended continental crust and thick ocean crust across the back-arc, and which have been inferred to mean that stretching in the upper crust was not matched in the lower crust during opening (Fig. 4) (Filatova and Rodnikov, 2006; Kulinich and Valitov, 2011; Nakahigashi et al., 2012, 2013; Sato et al., 2006a, 2006b). This interpretation has been challenged by Nishimoto et al. (2008), who suggest that significant modifications were made to the island arc lower crust during and after back-arc extension. They correlate rock composition/temperature properties, obtained from laboratory studies, with P-wave and S-wave velocity perturbations in the crust interpreted from previously published seismic studies. They infer a granodiorite/diorite composition for the lower crust in the Kitakami Mountains of eastern NE Honshu, which appears to be pre-rift continental/island-arc crust, and contrast it to the hornblende-pyroxene gabbro lower crust under the Akita-Niigata rift-basin (Tobishima Basin), and the hornblende gabbro lower crust under the Dewa Hills and Ou Backbone Range, which experienced crustal extension. These inferred compositional differences between more- and less-extended regions of the crust suggest that back-arc extension has dynamically modified the composition of the lower crust in the more extended regions, and that these compositional differences are not well represented in the P-wave velocity models. We highlight here the active seismicity and dense seismic recording networks in Japan that make possible the high resolution tomography used in the above-mentioned study.

Given different tectonic settings and structures, comparative investigations are likely to be instructive, and the Japan Sea stands as a rare bridge between ocean-ocean and continent-continent end-member back-arc settings. Japan may provide insights not available in more stable tectonic settings due to its active seismicity and dense monitoring networks, with the potential for higher resolution tomography models. A further question arises of why this type of continental-ocean back-arc is so rare and whether there exist fundamental constraints on continental rifting in a subduction setting. Geodynamical modeling studies that incorporate the available geological, petrological-magmatic, structural, and geophysical data sets that exist in Japan might help to address this question.

4.2. Did the Japan Sea open by pull-apart or rotation?

Two mutually-exclusive end-member models have been proposed to explain the opening mechanism for the Japan Sea back-arc (Fig. 5): (1) a pull-apart model in which dextral slip on large-scale transverse faults caused the back-arc region to pull apart (Altis, 1999; Fournier et al., 1994, 2004; Lallemand and Jolivet, 1986; Jolivet and Tamaki, 1992; Jolivet et al., 1991); and (2) a rotational model in which trench-perpendicular extension caused the back-arc region to open in a 'saloon-door' fashion (Otofuji et al., 1985; Lee et al., 1999; Itoh, 2001; Schellart and Lister, 2005). The pull-apart model has been attributed to far-field effects of the India-Asia collision in which the northward motion of the India indenter into Eurasia creates stresses that are being transmitted into NE Asia (Fournier et al., 2004; Xu et al., 2014). The trench-perpendicular extension model is attributed to Pacific and Philippine Sea plate dynamics, specifically Pacific trench rollback (Schellart and Lister, 2005). The models are incompatible.

Current cumulative evidence favors the rotational model because the pull-apart model is difficult to reconcile with (1) paleomagnetic evidence for large-angle, contrary rotation for NE and SW Japan and (2) the absence of significant, well-documented, strike-slip faulting in central or NE Japan during opening. Nevertheless, a pull-apart origin continues to be attributed to the Japan Sea because strike-slip faults at the extreme ends of the back-arc, in the Tsushima Strait and around Hokkaido, were known to be active around the time of opening (Fabbri et al., 1996; Fournier et al., 1994; Kikawa et al., 1994; Yoon and Chough, 1995; Yoon et al., 2014). The most significant difficulty with the pull-apart model involves paleomagnetic evidence for contrary rotations for the NE and SW Japan blocks during back-arc opening, which has since been confirmed in many studies (Baba et al., 2007; Hayashida et al., 1991; Hoshi and Matsubara, 1998; Hoshi et al., 2015; Otofuji, 1996; Otofuji et al., 1994; Takahashi and Saito, 1997; Tosha and Hamano, 1988; Yamaji et al., 1999). Simultaneous clockwise and counterclockwise rotations of up to 54° for the two Honshu blocks are poorly explained by a dextral strike-slip mechanism, and later modifications to the model remain unable to account for the magnitude of rotation (Jolivet et al., 1994). Another difficulty: the pull-apart model requires hundreds of kilometers of strike-slip displacement at its northern end, yet displacement of this magnitude cannot be found in the NE Japan arc proper or in the Japan Sea off northern Honshu. For example, the TTL appears to be an important mid-Miocene dextral-slip feature in the model (Fig. 16: Jolivet and Tamaki, 1992), yet it produced no apparent offset of the early Miocene volcanic front in NE Japan (Fig. 2), implying little movement during or after the period of back-arc opening (Kano et al., 1991; Takahashi, 2006). As for the Japan Sea off northern Honshu, extensive seismic imaging in the area shows no evidence of positive or negative flower structures that might indicate strike-slip faulting. Rather, over multiple seismic profiles, normal faulting and later reactivation of those normal faults characterizes crustal deformation in the Japan Sea back-arc region (No et al., 2014b; Van der Werff, 2000).

A potentially significant factor in the development of the Japan Sea back-arc relates to independent tectonic events occurring at its northern end during the period of opening. Cenozoic compressional deformation in central Hokkaido points to an independent component of active tectonics, perhaps related to the convergent Eurasia - North America plate boundary there (Fig. 1; Chapman and Solomon, 1976; Kato et al., 2004). In a separate event, the Hidaka collision zone became active in the mid-Miocene when the style of faulting changed from strike-slip to thrusting, inferred to be the result of early Kuril arc collision, which is still ongoing (Ito, 2000; Kato et al., 2004). At a minimum, it seems wise to remove any later contractional deformation before attempting to reconstruct the kinematics at the northern end of the back-arc during opening.

A pull-apart mechanism also figures in regional models that explain the broadly synchronous opening of multiple western Pacific back-arcs during the Tertiary (Xu et al., 2014). The shortcomings of the model when applied to the development of the Japan Sea suggest caution in invoking it elsewhere along the western Pacific margin without close attention to whether or not it is supported by local geological and structural field data at various levels of detail (e.g. Savva et al., 2014) (Section 4.7).

4.3. Can we construct a pre-rift margin supported by multiple independent data sets? Where was the MTL?

Ideally, a pre-rift reconstruction of the Asian margin would be a starting point for any opening model of Japan Sea back-arc development. Several reconstructions have been made based on similarities in lithology, structure, biostratigraphy, depositional environment, and zircon geochemistry, but none is definitive (Fig. 5) (Faure and Natal'in, 1992; Kim et al., 2007; Kojima and Kametaka, 2000; Kojima et al., 2008; Otsuki, 1990; Yamakita and Otoh, 2000). Many investigators have also explored isotope ages and signatures in the Hida belt of SW Japan which lies closest to the Korean peninsula, and contains Paleozoic metamorphic rocks with a Precambrian provenance (Aoki et al., 2015; Charvet, 2013; de Jong et al., 2009; Jahn, 2010; Kagami et al., 2006; Kojima and Kametaka, 2000). Unfortunately, it is difficult to fully test the reconstructions because a segment of the conjugate margin lies along the coast of North Korea for which there is a sparse geological literature.

Looking elsewhere, the Sikhote Alin terrane of Russia contains rocks of similar age to those in Japan (Kojima et al., 2008). Some structural correlations link large-scale strike-slip faults that occur in Sikhote Alin with those in Japan and Korea, aligning them along a restored margin (Yamakita and Otoh, 2000; Fig. 5c). One of these faults which runs through SW Japan, the MTL, is an important data point in any reconstruction (Fig. 2). Recently, it has been re-interpreted as an ancient subduction megathrust based on new seismic imaging that shows a 40° dip (Ito et al., 2009; Sato et al., 2015a). If we accept a megathrust origin for the moderately-dipping MTL, then it would have been a major structural feature along the pre-rift continental margin, and not necessarily a natural extension of other regional strike-slip faults, particularly those more nearly vertical. The MTL is closely associated with the thin but ubiquitous Sanbagawa HP metamorphic belt for nearly 1000 km through SW Japan, an association that does not appear to be reproduced along the strike-slip faults to which it has been connected in NE Japan or Sikhote Alin (Figs. 2, 5) (Yamakita and Otoh, 2000). Its moderate dip and close association with an HP metamorphic belt are primary attributes which must strictly constrain any correlations in a reconstruction.

4.4. Did the Japan Sea open in a simultaneous or sequential multi-rift rift scenario?

Tamaki (1988) suggested a multi-rift scenario for back-arc evolution to account for the existence of the Japan, Yamato, and Tsushima Basins in the Japan Sea and the failed rift-basins on the eastern Japan Sea margin. The failed rift-basins have cores with P-wave velocities of 6.8 km/s, which are interpreted to represent mafic intrusions, but the rift system was abandoned before spreading occurred (Sato, 2014; Sato et al., 2015b, unpublished data). Whether these different loci represent simultaneous or sequential rifting events is unclear. The notion of an earlier start to seafloor spreading in the Japan Basin relative to the Yamato Basin was postulated by Tamaki et al. (1992), who apparently relied on ~30 My dates reported from ODP Leg 127/128 (Kaneoka et al., 1992). These dates were rejected as unreliable by the ODP investigators because of poor plateau patterns exhibited by the samples during heating, a conclusion that was reiterated by Nohda (2009). Without the problematic older dates, it is not possible to discriminate a time difference in production of ocean crust between the Japan and Yamato Basins, or between activity in the ocean basins and the eruption of basalts in the failed-rifts. Earliest ocean floor production (21.2–17.7 Ma) and the eruption of basalt in the Akita failed rift-basin (20 Ma) could have occurred simultaneously or in sequence (Kaneoka et al., 1992; Sato, 1994; Tsuchiya, 1990) (Section 3.1). The very fine time resolution needed to distinguish between the two scenarios is unfortunately lacking because of the limited number and distribution of available sea floor dates. Further complicating matters, the Yamato and Tsushima Basins have incoherent magnetic patterns and no definable spreading ridges (Chamot-Rooke et al., 1987; Fukuma et al., 1998; Seama and Isezaki, 1990). Perhaps the only way to resolve time questions and allow testing of the models is with more extensive sampling of the Japan Sea floor as was achieved during ODP Leg 127/128.

Failed rift-basins with apparent mafic cores like those seen in the Japan back-arc (Fig. 4) are reported in continental rift zones (e.g. Thybo and Nielsen, 2009) and in ancient continental rifts, the Mississipian rift and the Oslo graben (Mooney et al., 1983; Stratford and Thybo, 2011), but do not appear to be common in active back-arcs (Stern and Benson, 2011). It is interesting to ask why the Japan Sea opened in this manner and what it might imply about the mechanism of rifting.

4.5. How did the anomalous ocean crust form in the Sea of Japan?

The Yamato and Tsushima Basins of the Japan Sea are floored by an anomalous crust with a thickness up to 19 km and intermediate P-wave velocities (Section 3.1; Fig. 3). This anomalous crust is thinner than continental crust and thicker than ocean crust, yet lacks any spreading centers (Isozaki and Uyeda, 1973) (Section 3.1). Investigators have interpreted it as thick ocean crust (No et al., 2014a; Sato et al., 2014), either original or thickened from below through thermal processes (Hirahara et al., 2015; Hirata et al., 1989; Kim et al., 2003). Hirahara et al. (2015) have modeled the conditions of magma generation in the Yamato Basin during back-arc opening based on incompatible trace element and Sr-Nd-Pb-Hf isotopic compositions, and conclude that hotter-than-normal mantle temperatures were likely responsible for the production of the depleted and undepleted back-arc basin basalts of the Japan Sea compared to the temperatures necessary to produce ordinary mid-ocean ridge basalts. During the Paleocene continental breakup in the North Atlantic, such hotter-than-normal mantle temperatures are thought to have produced thick ocean crust (Parkin and White, 2008). However, the inferred mantle temperature anomaly did not affect production of ocean crust in the Japan Basin, where the crust has a normal thickness (Hirata et al., 1992).

Understanding the origin of the anomalous ocean crust in the Japan back-arc could inform our understanding of its formation in other back-arc systems as well. Anomalous or thick ocean crust has also been found in back-arc basins in the Tyrrhenian Sea, Mediterranean region (Prada et al., 2014) and the South China Sea (Wang et al., 2006). As a result of tectonic inversion, Japan provides an opportunity to investigate the geochemistry of a magma-rich back-arc, and its ocean basement, in particular. Post-rift uplift has exposed an entire marine section of back-arc stratigraphy in NE Japan. In addition to the availability of complete geochemical packages on-land that can be tied to those from Japan Sea ocean crust, ongoing arc-magmatic processes in the Izu-Bonin arc and Okinawa Trough give present-day local analogues for comparison.

4.6. What are the constraints for modeling the (magma-rich) Japan Sea back-arc?

The Japan Sea back-arc has asymmetric margins and whether this is explained by rift migration or some other mechanism is an outstanding question. Numerical models for continental rifting that address the development of asymmetric margins show the rift axis migrating away from the trench and towards the eventual spreading center in the basin (Brune et al., 2014; Huismans and Beaumont, 2002). In the Japan Sea, the relationship appears to be reversed. The failed rift-basins are located closer to the trench than to the spreading center, so the migration would appear to have been towards the trench if they represent a late event. Furthermore, temporal patterns in volcanism show that the volcanic front migrated trenchward with time (Tatsumi et al., 1989; Yoshida et al., 2013). If new rifts are opening within the migrating volcanic front, then again, rift migration is proceeding towards the trench rather than away from it, which is not accounted for in current models of migrating rifts during continental breakup.

While continental rifting models provide some insight into the kinematics of back-arc rifting, critical parameters would change in a back-arc model, most obviously the addition of a subducting plate. Mantle circulation and mixing patterns would be altered, as would their scale. Because the Japan Sea is a magma-rich system, changes in distribution, character, and chemistry of magmatism over time can be used to constrain slab behavior and mantle circulation (Yoshida et al., 2013). Similarly, tomographic studies provide information about structure and fluid distribution beneath the arc (Hasegawa et al., 2013; Hirahara et al., 1989; Matsubara et al., 2004), more enlightening still when combined with rock physics experiments (Section 4.1) (Nishimoto et al., 2008). Given the large available geophysical data-set, mantle anisotropy is also a promising avenue of investigation in the Japan Sea area as a means of further quantifying mantle behavior in the back-arc (Fisher et al., 1998; Huang et al., 2011).

The speed of opening of the Japan Sea appears to have been swift. Determining the total amount of extension across the back-arc would require a full set of balanced cross sections, not yet available, but as a first order approximation, we may estimate ~500 km of extension from map measurements. If this extension was achieved over 3–8 My, beginning at either the onset of rifting at 23 Ma or the time of first generation of ocean crust in the Yamato Basin at 22.2–17.7 Ma (Section 3.1; Kaneoka et al., 1992; Sato, 1994), then we obtain rates of 6–17 cm/yr. A rapid spreading rate similar to the high end of this range is known from the Lau Basin, which is opening at 15.9 cm/yr behind the Tonga Trench (Bevis et al., 1995). However, if we assume a tighter time interval for extension, <2 My, as suggested by the rapid rift-basin subsidence to mid-bathyal depths described by Yamaji (1990) or the rapid rotation of NE and SW Japan indicated by paleomagnetic deflections (Hoshi et al., 2015), the extension rate obtained, 25 cm/yr, far exceeds any known spreading rates. It is clear that a discrepancy exists between evidence from paleomagnetic/basin subsidence studies and plausible extension rates for the Japan Sea back-arc which cannot yet be reconciled.

During back-arc extension, the middle Miocene volcanic front advanced past, and then retreated back, to the location of the present volcanic front (Yoshida et al., 2013). For this reason areas now located in the forearc region, trenchward of the present volcanic front, lay in the back-arc region during the period the period of extension. With both forearc and back-arc stratigraphy and structures now exposed on land, it is possible to investigate forearc/back-arc interactions over time, including the role of volcanism and other magmatic processes in back-arc development through close basin analysis studies.

4.7. What are the plate-scale controls on back-arc opening?

At approximately the same time as the Japan Sea back-arc was opening, the Shikoku and Okhotsk Basins were also opening (Chamot-Rooke et al., 1987; Filatova and Rodnikov, 2006; Seno and Maruyama, 1984). Trench retreat by the Pacific plate can account for the simultaneous opening of these three related back-arc basins, and also for the orientation of their axes, which are not aligned (Schellart and Lister, 2005). Set in a larger context, the Japan Sea belongs to a family of similar Tertiary marginal basins that opened along the western Pacific (Jolivet et al., 1989, 1994; Schellart and Lister, 2005; Xu et al., 2014). Xu et al.

(2014) considered the South China Sea, East China Sea, Java, Sulu and Celebes Seas, Japan Sea, Okhotsk Sea and Bering Sea among this group; Schellart and Lister (2005) also considered the Sumatra and Banda Basins. Timing for basin opening spans the Oligocene to Miocene but may have begun in the Late Cretaceous (see discussions in Schellart and Lister, 2005; Xu et al., 2014). If basin opening around the western Pacific rim was broadly synchronous, then the cause might be regional rather than local. Tapponnier and others (e.g. Tapponnier and Molnar, 1979; Tapponnier et al., 1982) proposed that the collision of India with Eurasia and subsequent extrusion of SE Asia could have been an event of sufficient magnitude for its effects to be felt throughout the SW Pacific and possibly into NE Asia. We have seen this model invoked to explain the opening of the Japan Sea as a pull-apart basin (Section 4.2). It has also been used to explain the formation mechanism for the larger family of Oligocene-Miocene back-arc basins in the western Pacific (Jolivet et al., 1989, 1994; Xu et al., 2014). While it is helpful to view the Sea of Japan back-arc in a larger context, the wide applicability of the regional extrusion model in areas distant from the Himalayan collision zone is not assured. Paleomagnetic and structural evidence that challenge the validity of a pull-apart model for the opening of the Japan Sea (Section 4.2) may also demonstrate that the influence of the South Asia collision event wanes as a tectonic driver in the NW Pacific.

4.8. Why has deformation been concentrated in the failed-rift zones of the back-arc since tectonic inversion?

Sato (1994) evaluated the pattern of shortening across NE Japan and found that maximum compressional deformation occurs in the failed-rift zones along the Japan Sea coast where the shortening ratio reaches 15%. Thus, more shortening occurs in the region behind the volcanic front than in the region closer to the trench, which suggests that the failed rift-basins are particularly weak areas of the crust. Okamura (2003) found similar folding and faulting in offshore rift-basins around central Japan. If we include both onshore and offshore areas, the zone of maximum deformation may be 200 km wide. Why these rift-basins are so deformable and why they deform in preference to the area around the hot volcanic arc is an outstanding question, now being explored with seismic reflection/wide-angle refraction programs that will connect deformation structures onshore and offshore. Once the amount of shortening can be better quantified for the back-arc as a whole, it will be possible to explore with more rigor the mechanisms that created the observed pattern of deformation.

5. Conclusion

Following upon the 10th Workshop of the International Lithosphere Program (ILP) Task Force on Sedimentary Basins, '*Lithosphere dynamics of sedimentary basins in subduction systems and related analogues*,' this special volume highlights the interest generated in back-arc systems, and in the Sea of Japan back-arc region in particular. As noted previously, the Sea of Japan provides an exceptional opportunity to study a mature continent-ocean back-arc system. Entire sequences of back-arc structure have been exposed on land by post-rift compression, but remain fully recognizable and accessible. In addition, continuous geophysical monitoring in seismically-active Japan for over two decades has amassed an archive of high-resolution geophysical data that serves as an extended tool-kit with which to explore back-arc basin structure and evolution. Geophysical insights into deep crustal structure and mantle processes are now being used to test and strengthen the geology-based models that have traditionally shaped our understanding of back-arc development in the Japan Sea. For example, the extent to which the crustal structure of the back-arc has been modified through back-arc opening is emerging by integrating structural studies at the surface with deep/seismic refraction-reflection investigations and high-resolution earthquake tomography studies. This has implications for the mechanism of back-arc opening. Tomographic models with increasingly better resolution constrain slab behavior, which has implications for timing and plate dynamics within the back-arc system. This provides an independent test for geologically-based tectonic models constrained by paleomagnetic data. Ultimately, the strength of such an integrated strategy lies in the ability to link geological data to deep structures and processes, effectively expanding the depth dimension of our existing 3-D understanding. We believe that Japan provides an exceptional opportunity for integrated investigation of a back-arc system.

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