6 TECTONIC SETTING AND EVOLUTION OF JAPAN

In order to discuss the feasibility of predicting future natural phenomena such as earthquakes in the Japanese Islands, it is important to consider how long the present tectonic setting – as characterised, for example, by the movement of oceanic plates and the distribution of tectonic stresses – has been stable. The following sections briefly review current understanding in relevant fields.

Japan lies on the eastern edge of the Asian continental plate, facing the subducting plates of the Pacific Ocean. The regional geography is shown in Figure 6-1. The basement rocks of the Japanese Islands comprise geologically young rocks, mostly younger than 200 Ma, derived from plate margin, subduction zone, trough and island arc tectonic processes. Many sedimentary rocks are "accretionary prisms" consisting of terrigeneous, hemipelagic and pelagic sediments, accompanied by small amount of limestones, cherts and basalts. These sedimentary rocks are intruded by Mesozoic and Tertiary granitic rocks and island arc volcanic rocks. Japan is a tectonically active region and it is widely acknowledged to be the best-studied arc-trench system in the western Pacific area. Intensive monitoring of seismicity and crustal deformation, combined with studies of active faults, has allowed a detailed picture of tectonic processes and deformation over different timescales to be built up over recent decades.

6.1 Tectonic setting

The Japanese Islands lie at the junction of four major tectonic plates – the Pacific and the Philippine Sea oceanic plates and the North American (or Okhotsk) and the Eurasian (or Amurian) continental plates (see Figure 6-2). The Pacific Plate moves towards the WNW at a rate of about 8 cm/year and is subducted beneath the Kuril Arc and the Izu-Bonin (or Izu-Ogasawara) Arc (Wei and Seno, 1998). The Kuril Trench, the Japan Trench and the Izu-Bonin Trench are deeper than 6000 m in the region where the Pacific Plate is subducted. The Quaternary volcanoes lie parallel to these trenches and form a "volcanic front". In the north, subduction of the Pacific Plate is oblique to the Kuril Trench, causing a strike-slip movement along the Kuril Arc, which results in a local collision zone within the Okhotsk Plate in central Hokkaido.

The Philippine Sea Plate moves towards the NW at a rate of approximately 5 cm/year (Wei and Seno, 1998) and is subducting beneath SW Japan and the Ryukyu Arc. In SW Japan, the volcanic front lies parallel to the Ryukyu Trench and the Nankai Trough. The volcanic front becomes less significant in the central part of Honshu and in Shikoku, as the depth of subduction of the Philippine Sea Plate is less than 100 km – above the depth of partial melting . In the south, the Philippine Sea Plate is also subducting obliquely to the Nankai Trough, comprising a tectonic sliver that is moving westward along the strike-slip "Median Tectonic Line".

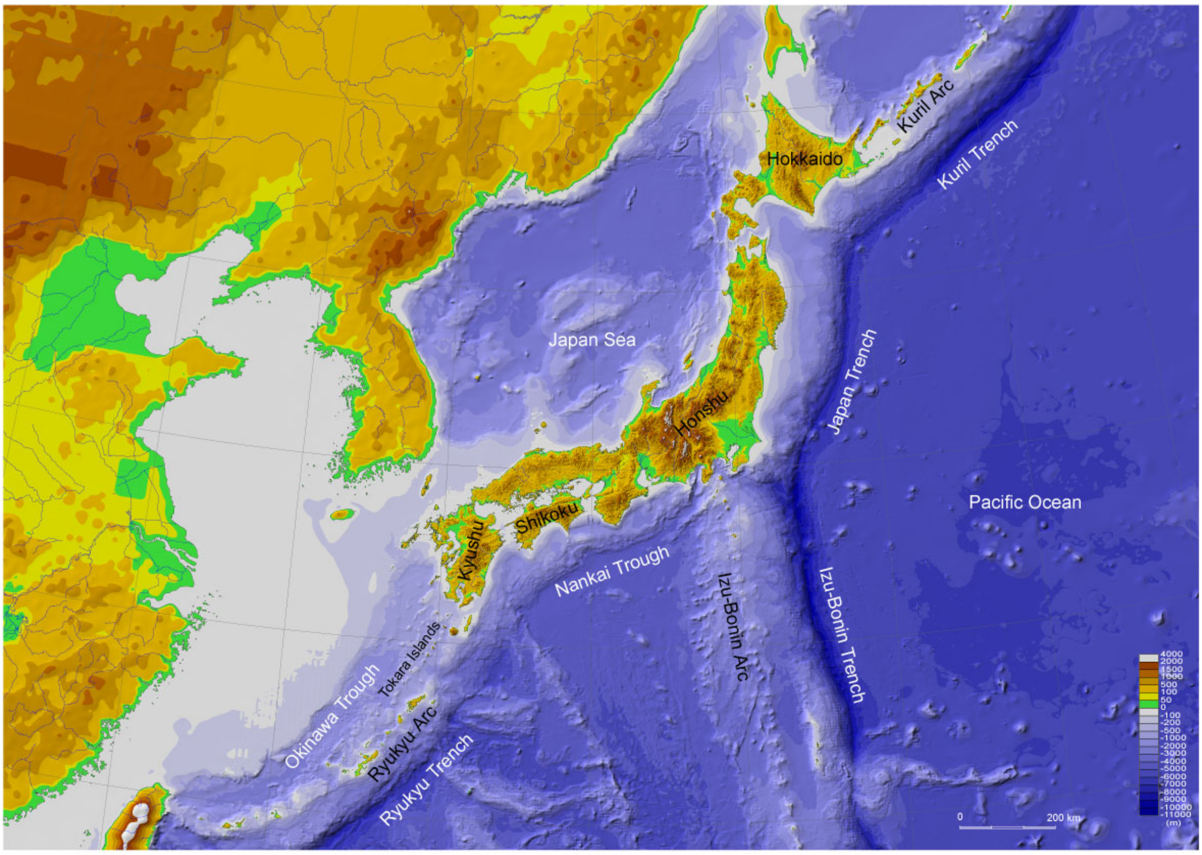

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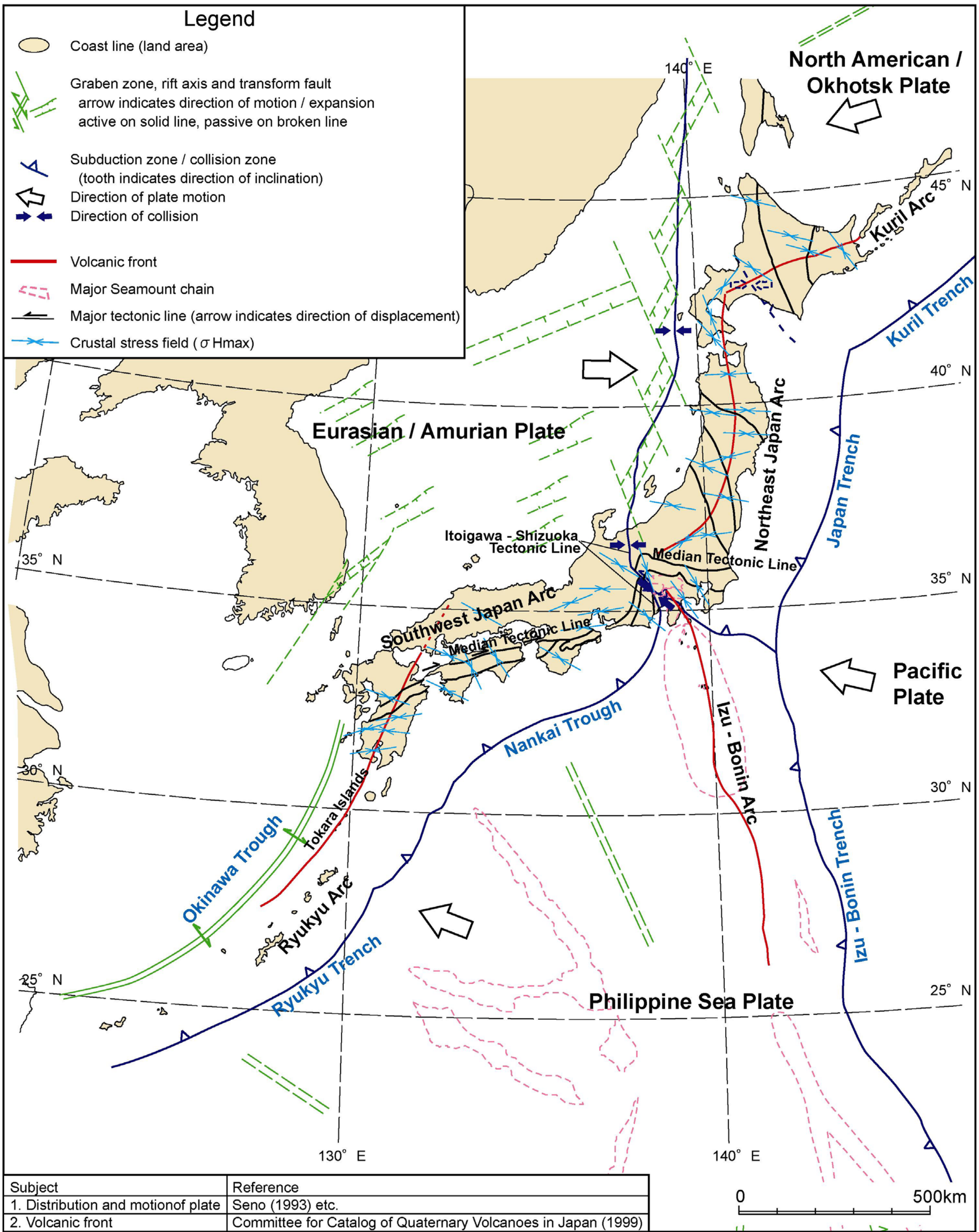
Figure 6-1: Topography and main geographical regions of Japan (modified from Editorial Group for Computer Graphics, Geology of Japanese Islands, MARUZEN Co., Ltd., 1996).

There are various interpretations of the boundaries of the North American/Okhotsk Plate and the Eurasian/Amurian Plate. A recent interpretation, based upon geodetic, seismic and geological observations, suggests that these boundaries run from Sakhalin, via the eastern margin of the Japan Sea, and reach the Itoigawa-Shizuoka Tectonic Line (Nakamura, 1983; Kobayashi, 1983; Seno et al., 1996; Tada, 1997). The Itoigawa-Shizuoka Tectonic Line divides the Japanese Island Arc into the Northeast Japan Arc (NE Japan Arc) and the Southwest Japan Arc (SW Japan Arc). Because the east-west compression at this plate boundary cannot be fully explained only by the subduction of the Pacific Plate and Philippine Sea Plate, a small amount of eastward movement of the Eurasian/Amurian Plate is suggested (Wei and Seno, 1998). The tectonic situation is complicated in the area where the North American/Okhotsk Plate, Eurasian/Amurian Plate and Philippine Sea Plate converge.

In the extreme south, the Ryukyu Arc is backed to the west within the Eurasian/Amurian Plate by a zone of active extensional rifting – the enlarging Okinawa Trough. This horizontal extensional field extends to the west of Kyushu.



Subject	Reference
1. Distribution and motionof plate	Seno (1993) etc.
2. Volcanic front	Committee for Catalog of Quaternary Volcanoes in Japan (1999)
3. Crustal stress field	Nakane (1973)
4. Other	Editional Group for Computer Graphics, Geology of Japanese Islands (1996)

Figure 6-2: Current tectonic situation of Japan and key tectonic features.

The volcanic arc system caused by subduction of the Pacific and Philippine Sea Plates is evident in the chains of volcanoes in northern Honshu and along the Kuril and Izu-Bonin Arcs, and in Kyushu and along the Tokara Islands. In northern Honshu, arc volcanoes form the

main backbone of the island. In this area, on the back-arc (Japan Sea) side, the structure is controlled by inversion tectonics, where extensional basin formation has changed to contraction, folding and uplift. By contrast, the fore-arc region of northern Honshu has less rugged topography. The mountains of central Honshu are in part formed by the collision of the Izu-Bonin Arc with the Eurasian/Amurian Plate, and the interaction between the North American/Okhotsk and the Eurasian/Amurian Plates. In the south, Shikoku Island lies on the fore-arc side and is split by the Median Tectonic Line. On the southeastern side of the Median Tectonic Line, the structure is principally that of an accretionary prism and the area is subject to active uplift as a result of ongoing accretion of material from the subducting zone. In the extreme south of the Japanese Islands, the back-arc extension and rifting in the Okinawa Trough has resulted in crustal thinning that has led to submersion of much of the Ryukyu Arc (Taira, 2001).

Relative plate movements, along with detailed regional crustal deformation, can be clearly detected from the growing database of GPS strain data from the large network of monitoring stations across Japan. Combined with detailed surveys of Quaternary active faults both onshore and offshore, this information provides evidence for interpreting and confirming the tectonics of the region. For example, the reverse faulting characteristic of compressional stresses in northern Honshu, strike-slip and rotational strain in central to SW Honshu and right-lateral strike-slip along the Median Tectonic Line in Shikoku are evident (See Figures 8-4 and 8-5 in Section 8).

6.2 Geological structure and evolution

A distinct picture of the tectonic history of the Japanese Islands can be traced back for about 30 Ma, although the geological history, as reflected by the presence of much older rocks, clearly extends much further back in time. The current outline of the Japanese Islands took shape during the period between 30 Ma and 15-14 Ma, accompanied by the spreading of the Japan Sea. The present rate and pattern of movement of the major plates became established around 2 Ma. This section summarises the geological history before 30 Ma and then presents a more detailed time sequence evolution of the tectonics over the last 30 Ma, in map form.

6.2.1 Summary of geological history before 30 Ma

The Japan region has been in a zone of subduction-related accretionary tectonics since the Permo-Jurassic (>295-135 Ma), when it lay on the eastern edge of Gondwanaland. Accretion has continued since then, on the western margin of the Panthalassa (proto-Pacific) and then Pacific Oceans, with wedges (prisms) of oceanic sediments and underlying ocean crust basalts being detached from the subducting ocean plate and accreted to the fore-arc zone of the continental plate to the west. The crust of the Japanese Islands area has thus grown progressively from the west (Asian continental side), with the rocks becoming younger towards the Pacific side. Crustal thickening by accretion was associated with granite formation, especially during the Cretaceous (135-65 Ma). Consequently, the basement rocks of the islands comprise largely Mesozoic to Palaeogene accretionary prisms, with the older rocks intruded by Cretaceous and Tertiary granites.

6.2.2 Detailed tectonic evolution in the last 30 million years

Figure 6-3(a-d) shows a time sequence reconstruction of the tectonic evolution of the Japanese Islands during the last 30 million years, the period over which such an analysis can be made with confidence. The same information is shown in a longer time context in Table 6-1.

(1) **Figure 6-3(a): Approximately 30 Ma – Start of rifting at the eastern margin of the Eurasian Plate.** Before spreading of the Japan Sea was initiated, the Japanese Islands were attached to the coastal region of the eastern margin of the Eurasian continent (known as Primoski Krai: Yamakita and Oohuji, 1999; 2000). The Pacific Plate was moving towards the WNW (Jolivet et al., 1994). The Philippine Sea Plate was migrating towards the NNW, but subduction ceased about 30 Ma (Seno and Maruyama, 1984; Nishimura and Yuasa, 1991). Around the same time, rifting took place in the east of Primoski Krai and in the east of Sakhalin, and right-lateral transform faulting was initiated in the palaeo-Kuril Arc (central and eastern Hokkaido) (Jolivet et al., 1994). The Tanakura Tectonic Line and the Hatagawa Tectonic Line exhibited right-lateral movement while the Median Tectonic Line showed left-lateral movement (Amano, 1991; Oide et al., 1989; Ichikawa, 1980).

(2) **Figure 6-3 (b): Approximately 20 Ma – Start of spreading of the Japan Sea, the Kuril Basin and the Shikoku Basin, along with rotation of the NE Japan Arc.** As spreading of the Shikoku Basin occurred, the palaeo-Izu-Bonin Arc divided into the Izu-Bonin Arc and the Kyushu-Palau Ridge, around 25 Ma (Taira, 2000). As the Japan Sea continued to spread, the NE Japan Arc began to rotate anti-clockwise, at around 20 Ma. As a result, areas of fresh water were formed, with seawater encroaching into them later (Jolivet et al. 1994; Hamano and Tosha, 1985; Niitsuma, 1985; Sato and Ikeda, 1999). The volcanic front shifted from inland towards the ocean (Kano et al., 1991).

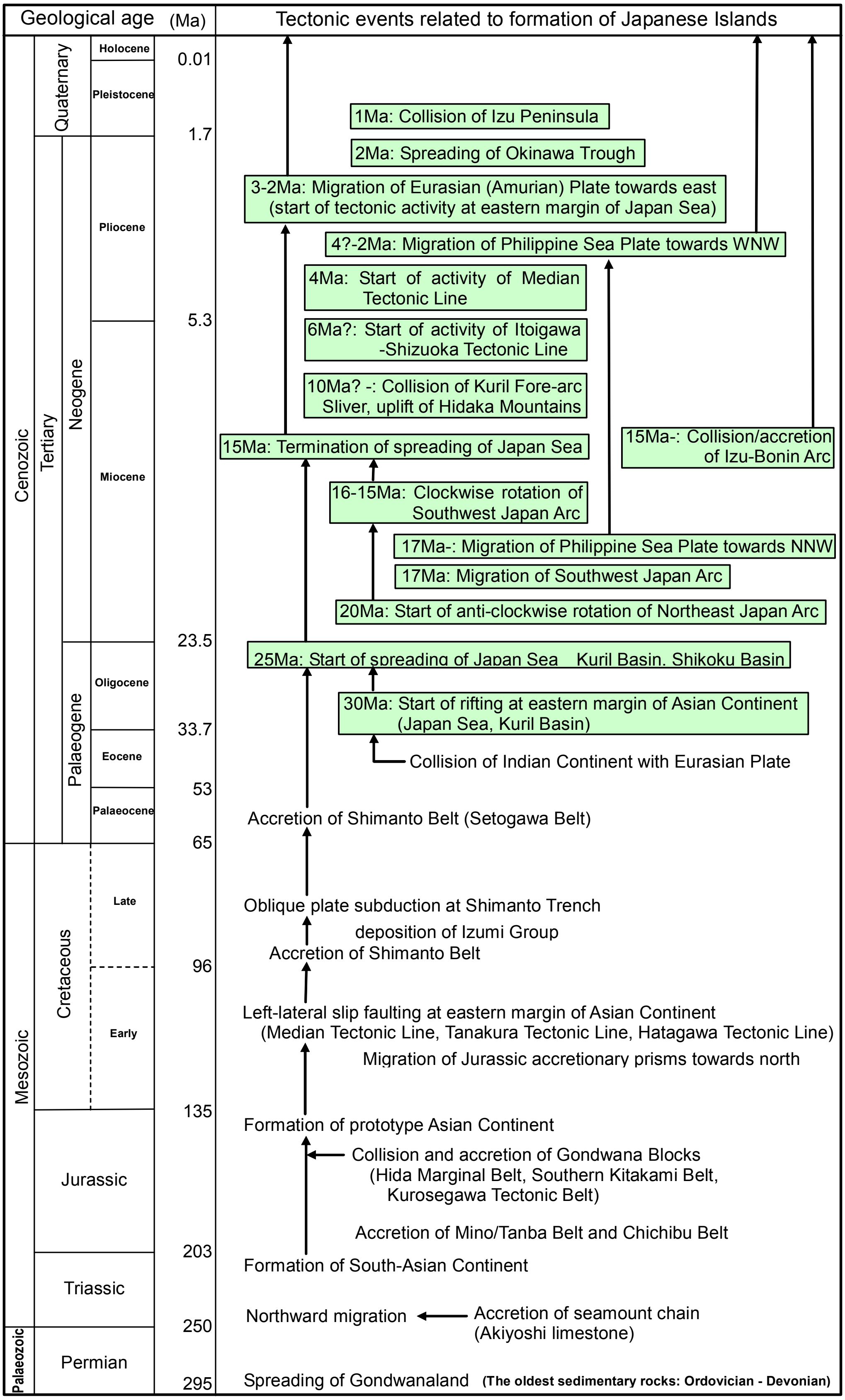
(3) **Figure 6-3 (c): Approximately 15-14 Ma – Completion of rotation of NE and SW Japan Arcs, spreading of the Japan Sea, the Kuril Basin and the Shikoku Basin, and start of collision of the Izu-Bonin Arc.** Subsequent to rotation of the NE Japan Arc, the SW Japan Arc began to rotate clockwise (Jolivet et al., 1994; Tamaki et al., 1992). The subduction zone of the Pacific Plate was located in almost its present location by around 17 Ma (Kano et al., 1991). The Philippine Sea Plate began to migrate towards the NNW (Nishimura and Yuasa, 1991). By around 15-14 Ma, spreading of the Japan Sea, the Kuril Basin and the Shikoku Basin was approaching its end, the Japanese Islands settled in their present location and the framework of the current geological structure of Japan was established. Collision of the Izu-Bonin Arc against Japan was initiated during this period (Takahashi, 1994). In SW Japan, the volcanic front shifted significantly towards the fore-arc side in connection with subduction of the Philippine Sea Plate, which was young and at high temperature (Kano et al., 1991; Uto, 1995).

(4) **Figure 6-3 (d): Approximately 1.8 Ma - Start of collision of the Kuril Fore-arc Sliver, uplifting of the Hidaka Mountains, development of the Itoigawa-Shizuoka Tectonic Line, activation of the Median Tectonic Line, tectonic events at the eastern margin of the Japan Sea, spreading of the Okinawa Trough and Izu-**

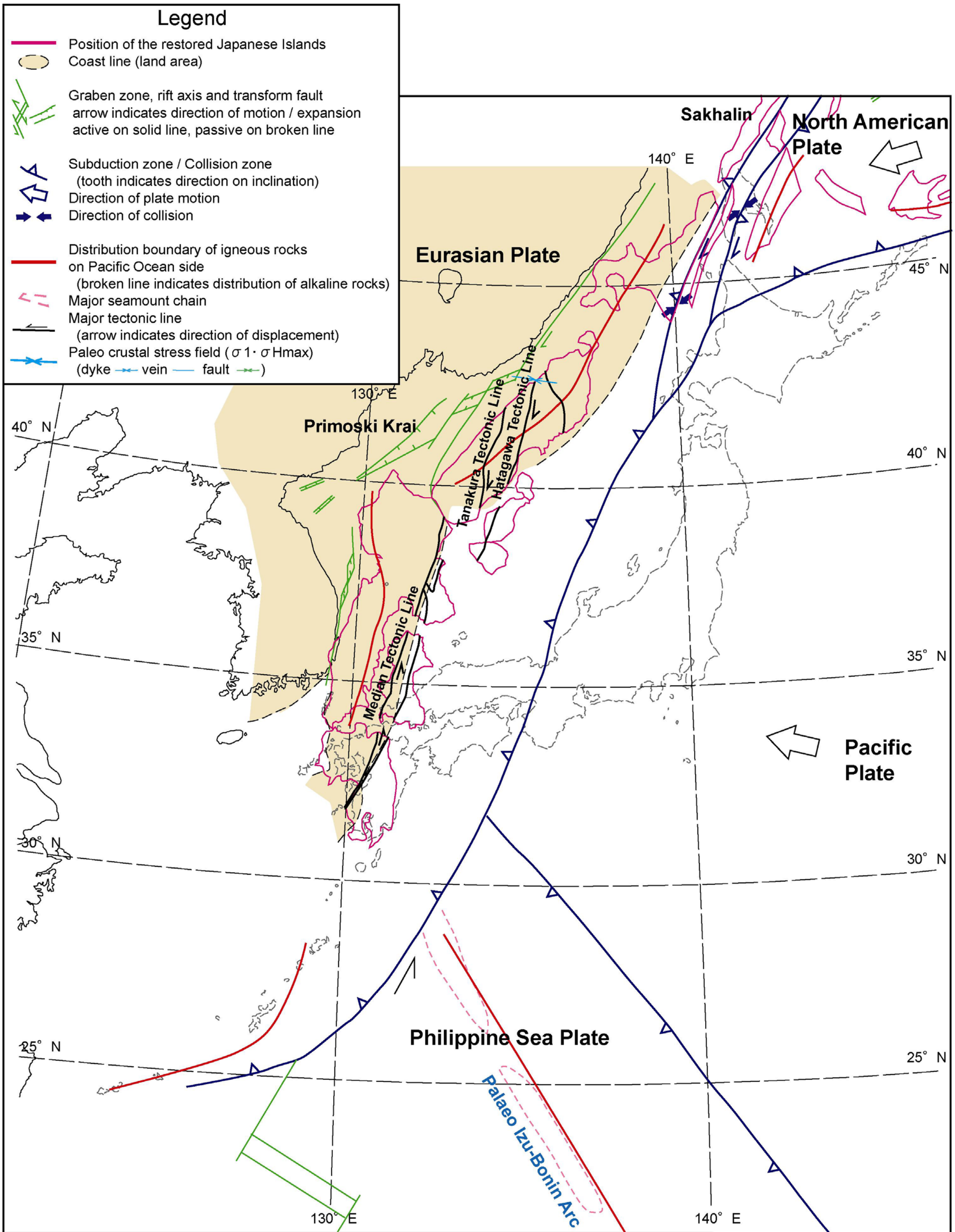
Bonin Back-arc Basins. During the period from 10 to 4 Ma, the Kuril Fore-arc Sliver collided with the Hidaka Main Thrust (Kimura, 1996) and the Hidaka Mountains formed (Miyasaka, 1987). Around 6 Ma, the Itoigawa-Shizuoka Tectonic Line began left-lateral or reverse displacement (Yamashita ed., 1995; Jolivet et al., 1994). Around 5 Ma, right-lateral displacement began from the eastern side of the Median Tectonic Line (Sugiyama, 1991; 1992). At around 3 Ma, tectonic activity occurred on the eastern margin of the Japan Sea, along with eastward advance of the Eurasian (Amurian) Plate (Okamura et al., 1995). Reverse faults also began to appear inland (Sato, 1994; Awata, 1988). About 2 Ma, the Philippine Sea Plate changed its direction of movement from NNW to WNW (Seno, 1984; Nishimura and Yuasa, 1991) and the Okinawa Trough and the back-arc basins of the Izu-Bonin Arc began to spread (Kimura, 1990; Kimura et al. 1999). During the period from 11-5 Ma, the volcanic front regressed towards the back-arc side, both in NE and SW Japan, and some alkaline activity occurred in SW Japan and in the western offshore region of Hokkaido (Kano et al, 1991; Uto, 1995). In SW Japan, after 5 Ma, the subducting Philippine Sea Plate reached to the north of Shikoku. Consequently, the areas of volcanic activity shifted towards the coast of the Japan Sea and eruption of sub-alkaline rocks with alkali basalt took place (Uto, 1995).

The **present-day situation** is shown in **Figure 6-2 - Collision of the Izu Peninsula and conversion of plates along the eastern margin of the Japan Sea.** Around 1 Ma, the Izu Peninsula collided with Honshu (Matsuda, 1989). Along the eastern margin of the Japan Sea, the Eurasian Plate began to form a convergent boundary against NE Japan (the North American/Okhotsk Plate)(Nakamura, 1983; Kobayashi, 1983). Part of the Median Tectonic Line shows right-lateral displacement (Sugiyama, 1991), while the Itoigawa-Shizuoka Tectonic Line shows left-lateral or reverse displacement (Maruyama, 1984).

Table 6-1: Major events related to formation of the Japanese Islands.

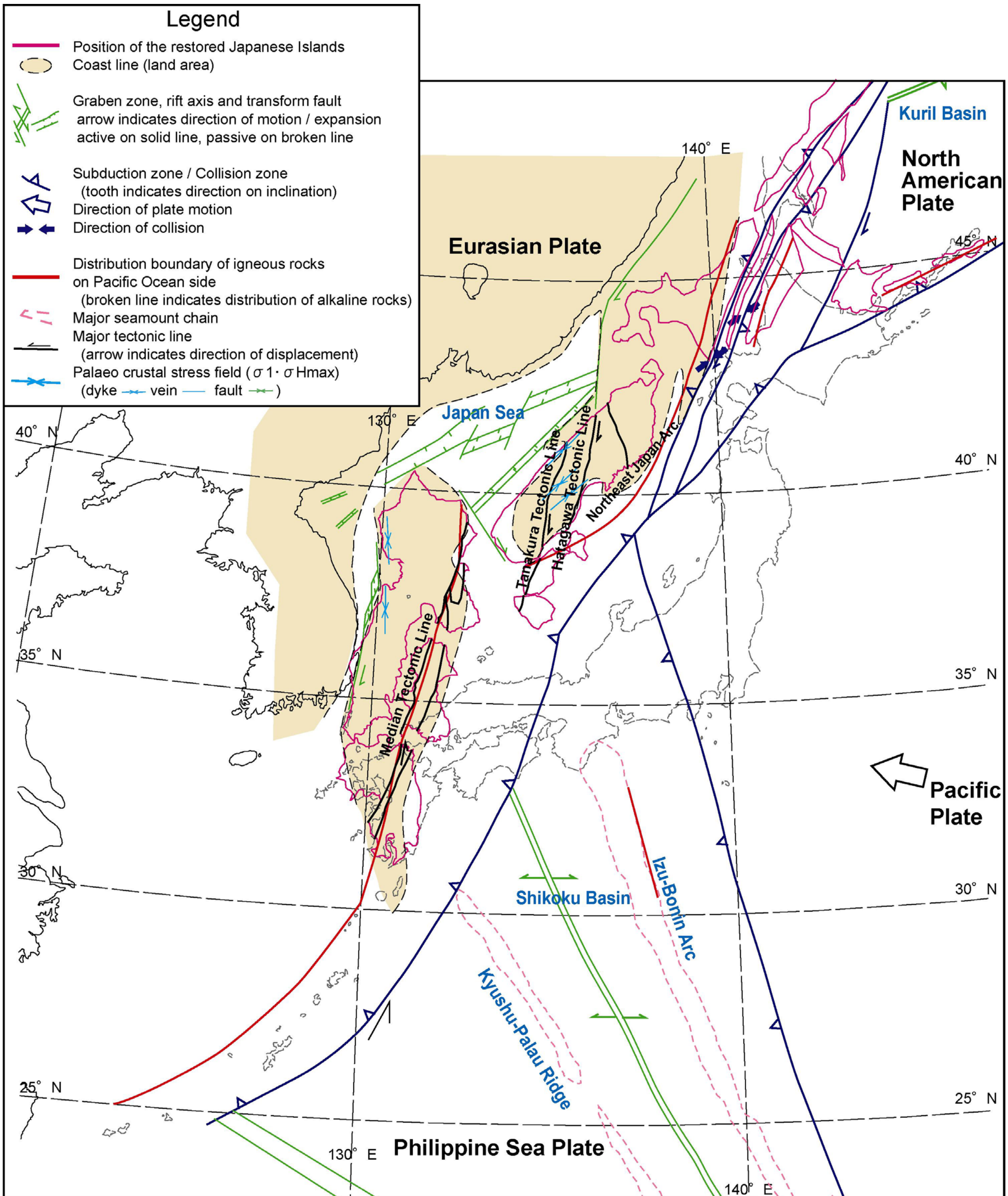


The age of the Pliocene-Pleistocene boundary is based on Japan Association for Quaternary Research and other ages on IUGS (2000).



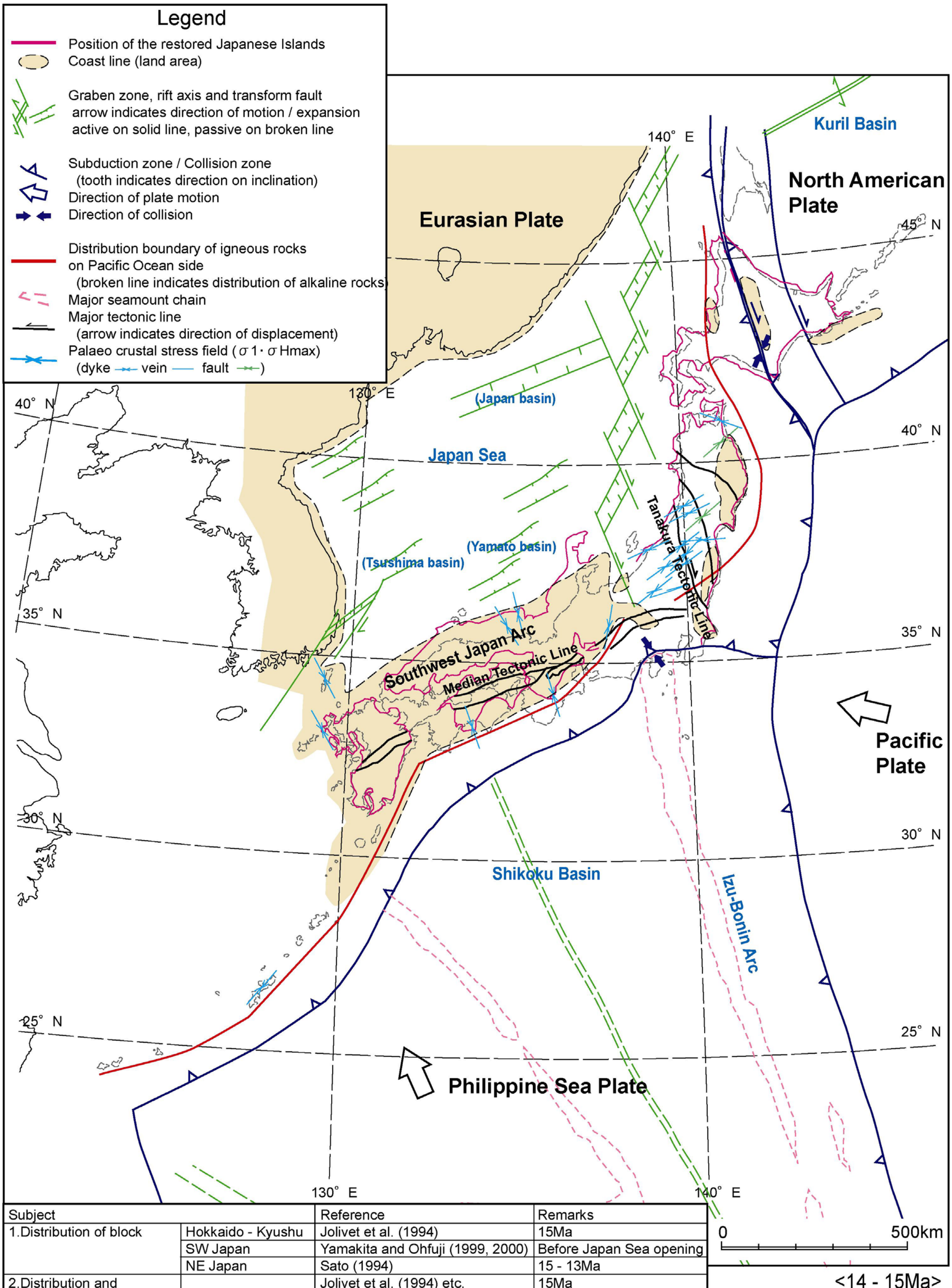
Subject		Reference	Remarks
1.Distribution of block	Hokkaido	Kimura and Kusunomi (1997)	Before right wrenching (Eocene)
	NE Japan - Kyushu	Yamakita and Ohfuji (1999, 2000)	Before Japan Sea opening
2.Distribution and motion of plate	Pacific Plate	Jolivet et al. (1994)	30Ma
	Philippine Sea Plate	Seno and Maruyama (1984)	40Ma
3.Volcanic front		Kano et al. (1991)	40 － 32Ma
4.Coast line		Kano et al. (1991)	40 － 32Ma
5.Other	Tectonic line	Oide et al. (1989), Amano (1991), Ichikawa (1980)	

Figure 6-3 (a): Tectonic situation around 30 Ma.



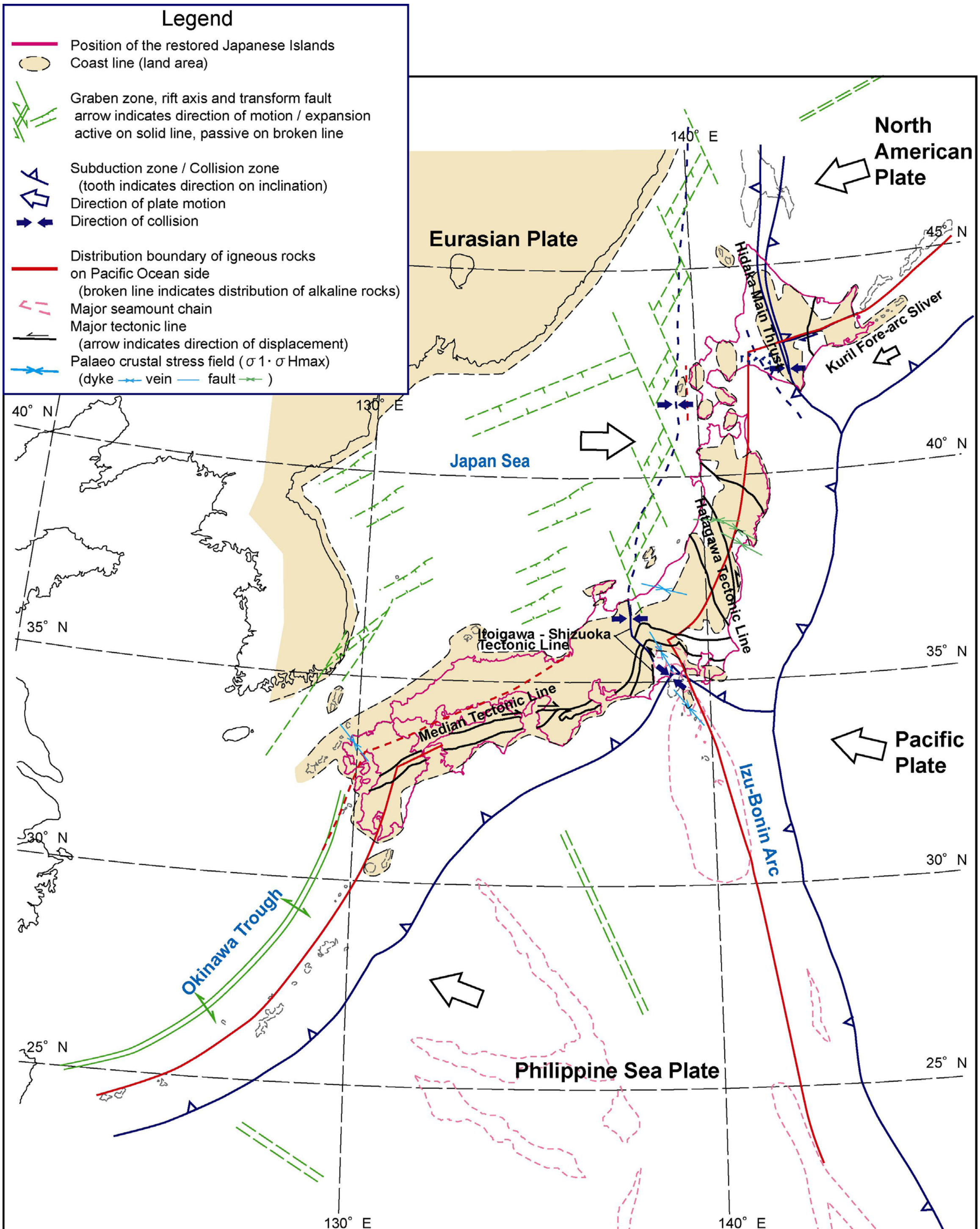
Subject		Reference	Remarks
1.Disttribution of block	Hokkaido	Kimura and Kusunoki (1997)	At paleo-Kuril arc collision (Oligocene)
	SW Japan - Kyushu	Yamakita and Ohfuji (1999, 2000)	Before Japan Sea opening
	NE Japan	Sato (1994)	20～15Ma
2.Distribution and motion of plate	Pacific Plate / Japan Sea	Jolivet et al. (1994) etc.	20Ma
	Philippine Sea Plate	Nishimura and Yuasa (1991)	30～25Ma
		Uto (1995)	Relation between SW Japan and transform
3.Volcanic front		Kano et al. (1991)	22～18Ma
4.Palaeo crustal stress field		Kano et al. (1991)	22～18Ma
5.Coast line		Kano et al. (1991)	22～18Ma
6.Other	Tectonic line	Kimura et al. (1983), Oka (1997), Jolivet et al. (1994), Ichikawa (1980) etc.	

Figure 6-3 (b): Tectonic situation around 20 Ma.



Subject		Reference	Remarks
1.Distribution of block	Hokkaido - Kyushu	Jolivet et al. (1994)	15Ma
	SW Japan	Yamakita and Ohfuji (1999, 2000)	Before Japan Sea opening
	NE Japan	Sato (1994)	15 - 13Ma
2.Distribution and motion of plate		Jolivet et al. (1994) etc.	15Ma
	Philippine Sea Plate	Seno and Maruyama (1984) etc.	
3.Volcanic front		Kano et al. (1991)	15 - 12Ma
4.Palaeo crustal stress field		Kano et al. (1991)	15 - 12Ma
5.Coast line		Kano et al. (1991)	15 - 12Ma
6.Other	Tectonic line	Kimura et al. (1983), Miyasaka (1987), Kimura (1981), Jolivet et al. (1994), Amano (1991) etc.	

Figure 6-3 (c): Tectonic situation around 14-15 Ma.



Subject		Reference	Remarks
1.Distribution of block		Kano et al. (1991)	1.7 - 0.7Ma
2.Distribution and motion of plate		Jolivet et al. (1994) etc.	
	Philippine Sea Plate	Seno and Maruyama (1984) etc.	
	Okinawa Trough	Kimura (1990) etc.	
3.Volcanic front		Kano et al. (1991)	1.7 - 0.7Ma
4.Palaeo crustal stress field		Kano et al. (1991)	1.7 - 0.7Ma
5.Coast line		Kano et al. (1991)	1.7 - 0.7Ma
6.Other	Tectonic line	Miyasaka (1987), Kimura (1981), Oka (1997), Nakamura (1983), Sugiyama (1991), Yamashita (1995)	

Figure 6-3 (d): Tectonic situation around 1.8 Ma.