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# TECTONIC EVOLUTION OF THE JAPANESE ISLAND ARC SYSTEM

Asahiko Taira
*Center for the International Cooperation, Ocean Research Institute, The University of Tokyo, 1-15-1 Minamidai Nakano-ku Tokyo 164-8639, Japan;*
*e-mail: ataira@ori.u-tokyo.ac.jp*

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■ **Abstract** Growth of the Japanese arc system, which has mainly taken place along the continental margin of Asia since the Permian, is the result of subduction of the ancient Pacific ocean floor. Backarc basin formation in the Tertiary shaped the present-day arc configuration. The neotectonic regime, which is characterized by strong east-west compression, has been triggered by the eastward motion of the Amur plate in the Quaternary. The tectonic evolution of the Japanese arc system includes formation of rock assemblages common in most orogenic belts. Because the origin and present-day tectonics of these assemblages are better defined in the case of the Japanese arc system, study of the system provides useful insight into orogenesis and continental crust evolution.

## INTRODUCTION

The Japanese island arcs are the best-studied example of an arc-trench system in the western Pacific (Sugimura & Uyeda 1973). The arcs consist of four segments: the western Kuril, Honshu, Ryukyu, and Izu-Bonin (Ogasawara) arcs (Figure 1*c*). In this review these arcs are collectively referred to as the Japanese island arc system (hereafter called the Japanese arc system). The main part of the Japanese arc system contains four big islands: Hokkaido, Honshu, Shikoku, and Kyushu (Figure 1*b*). The term southwest (SW) Japan indicates that part of the arc that encompasses southwestern Honshu and Shikoku.

In their early syntheses, Matsuda & Uyeda (1971), Uyeda & Miyashiro (1974), and Uyeda & Kanamori (1979) emphasized the importance of the variability of plate subduction processes, including ridge subduction, in the evolution of the Japanese arc system. Since then, three aspects of studies on the geology and geophysics of the arc have emerged as unique contributions to the earth sciences.

Owing to the establishment of an extensive geophysical observatory network, the Japanese arc system is probably the best-monitored arc system in the world,

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in terms of its seismicity and crustal deformation (see Appendix). In addition to this database, field mapping of active faults over the past few decades has revealed a detailed picture of arc deformation (Research Group for Active Faults in Japan 1991). These data sets permit, for the first time, a quantitative assessment of the crustal deformation of an arc system at various time scales.

The second unique aspect of studies on the Japanese arc system arises from the combined results of geological and geophysical studies in both land and marine settings (Geological Survey of Japan 1992; also see Appendix). From the deformation front at the trench to the backarc basin floor, the arc system is largely submerged. It is therefore important to understand the dynamics of the whole arc system, including both the submerged and emergent parts. Although such a synthesis is not yet possible, the geological and geophysical characteristics of the entire Japanese arc system are better known than those of any other arc in the world.

The third aspect comes from the study of the arc's geological history. The protracted history of the Japanese arc system provides a unique example of the evolution of an arc system; this in turn has profound implications for the understanding of orogenesis and the formation of continental crust (i.e. Taira et al 1989, 1998; Maruyama 1997).

This review synthesizes the tectonic evolution of the Japanese arc system, with particular emphasis on the three aspects given above. First, the geological framework and present-day tectonics of the arc system are reviewed. The tectonic evolution of the arc is then summarized. Finally, the tectonic evolution of the Japanese arc system is compared with that of other orogenic belts to identify general implications for the formation of continental crust.

# TECTONIC FRAMEWORK

## Plate Tectonics

The current tectonics of the Japanese arc system can be explained by the interaction of five plates: the Eurasia, Amur, Okhotsk, Pacific, and Philippine Sea plates (Wei & Seno 1998; Figure 1*a*). The plate tectonic model presented here is a result of the synthesis of various data sets, including Global Positioning System (GPS) geodesy, active fault distribution, and seismicity (Hashimoto & Jackson 1993, Taira et al 2001).

Subduction of the Pacific plate at the Kuril arc is oblique, which causes westward migration of the Kuril forearc (Kuril forearc sliver) (Figure 1*c*). The westward motion of the Kuril forearc sliver resulted in formation of a collision zone (Hidaka collision zone) in the central Hokkaido. The subduction of the Pacific plate continues at the Japan trench and Izu-Bonin trench. In addition to subduction of the Pacific plate underneath northeastern (NE) Honshu, the plate tectonic model shows that east-west directed convergence between NE Japan

(Okhotsk plate) and the Amur plate has initiated an incipient subduction zone on the eastern margin of the Japan Sea (i.e. Nakamura 1983, Tamaki & Honza 1985).

Northwestward subduction of the Philippine Sea plate, which is oblique to both the Nankai trough and to the collision zone between the Izu-Bonin oceanic island arc and the Honshu arc (Izu collision zone), results in the westward migration of a forearc sliver (Nankai forearc sliver) (Fitch 1972). The northern boundary of this sliver is a right-lateral strike-slip fault, the Median Tectonic Line (MTL). The westward extension of the MTL at Kyushu is indicated by the presence of a graben (Beppu-Shimabara Rift Zone) that resulted from the counterclockwise rotation of the Nankai forearc sliver. The westward extension of the sliver continues to the forearc of the Ryukyu arc. The Ryukyu arc is paired with an actively rifting backarc basin, the Okinawa trough.

## Topography

The topographic characteristics of the Japanese arc system are closely related to the plate interaction process (Figure 2). Prominent features are the deep trenches that fringe the arc system. In Hokkaido, the collision of the Kuril forearc sliver with the northern extension of the Honshu arc has produced a thrust belt in the Hidaka Mountains (Kimura 1986).

The NE Honshu arc consists of volcanic chains that form its backbone range. Submarine topography on the Japan Sea side of the NE Honshu arc exhibits a basin and range structure that was formed by inversion tectonics of the rifted arc margin (Okamura et al 1995). In contrast, the forearc side of this area shows a smooth topography that can be explained by the bending of the arc lithosphere and gradual subsidence owing to tectonic erosion that is related to the Pacific plate subduction (Von Huene & Lallemand 1990). In the central Honshu area, high mountain ranges are developed in a complex tectonic framework; dominant factors include Izu-collision tectonics (Huchon & Kitazato 1984) and complex tectonic interaction between the SW Honshu arc (Amur plate) and the NE Honshu arc (Okhotsk plate) (Kanaori et al 1992).

A clear trace of MTL fault can be seen on the northern side of Shikoku Island (Figure 2). This island is also subject to active uplift caused by the accretion of trench sediments and thrusting. The forearc side of Shikoku is characterized by fold-thrust topography (a trench–parallel ridge system) on the landward slope of the Nankai trough and by a series of forearc basins. The topography within the Nankai forearc sliver is the result of the active accretion of a trench wedge and the internal deformation of the accretionary prism as a result of the oblique subduction of the Philippine Sea plate (Sugiyama 1994).

Kyushu Island contains caldera volcanoes in the Beppu-Shimabara graben (Kamata & Kodama 1994). The Ryukyu arc is largely submerged, probably because of crustal thinning that took place during rifting of the Okinawa trough (Kimura 1985, Sibuet et al 1998).

## Gravity

The short-wave Bouguer gravity anomaly provides useful information on the relationship between shallow basement relief and tectonics (Hagiwara 1991). The following discussion summarizes these characteristics in the vicinity of the Japanese arc system (Figure 3).

The trenches show positive anomaly belts because of the bending of the lithosphere. On the other hand, the forearc regions are largely negative zones, owing to the accumulation of sediments.

In Hokkaido, the Hidaka Mountains show a positive anomaly zone. This is probably because of the tectonic uplift of the basement rocks that occurred during collision with the Kuril forearc. The Hidaka positive zone is paired with a strongly negative zone to the west, which represents the development of a foreland basin. The NE Honshu arc and its Japan Sea margin are dominated by north-south trending anomaly zones that can be interpreted as the preinversion basement topography that formed during the rifting of the Sea of Japan in the middle Miocene. In contrast, the SW Japan arc does not show such systematic basement features, suggesting that this part of the arc system was not subjected to intense rifting processes.

## Crustal Deformation Deduced by GPS Geodesy

More than 1000 GPS stations, distributed throughout the Japanese arc system at an average spacing of 25–30 km, constitute one of the densest GPS networks in the world (Abe & Tsuji 1994, Miyazaki et al 1997). This network, GEONET, is maintained by the Geographical Survey Institute of Japan and provides a clear and detailed picture of crustal deformation, an example of which is shown in Figure 4. (Note that Figure 4 shows only the velocity vectors; see the Appendix for access to further information.)

The GPS data clearly indicate how plate tectonics relates to crustal deformation in an island arc system (Kato et al 1998, Le Pichon et al 1998, Sagiya et al 2000). The salient observations are summarized below:

1. From the Pacific side of Hokkaido to NE Honshu, the velocity data (relative to the Eurasian plate) are dominated by large westward components that show motion ranging from 3 to 5 cm year$^{-1}$. These components represent the elastic strain on the arc caused by the westward subduction of the Pacific plate.
2. The Pacific side of SW Japan is characterized by movement to the west-northwest that ranges from 2 to 3 cm year$^{-1}$. This movement is a result of the subduction of the Philippine Sea plate.
3. From southern Kyushu to the Ryukyu arc, the velocity data show that movement is predominantly toward the southeast, in contrast to the rest of the Pacific side of the arc system. This movement may represent the effect of backarc basin rifting of the Okinawa trough.

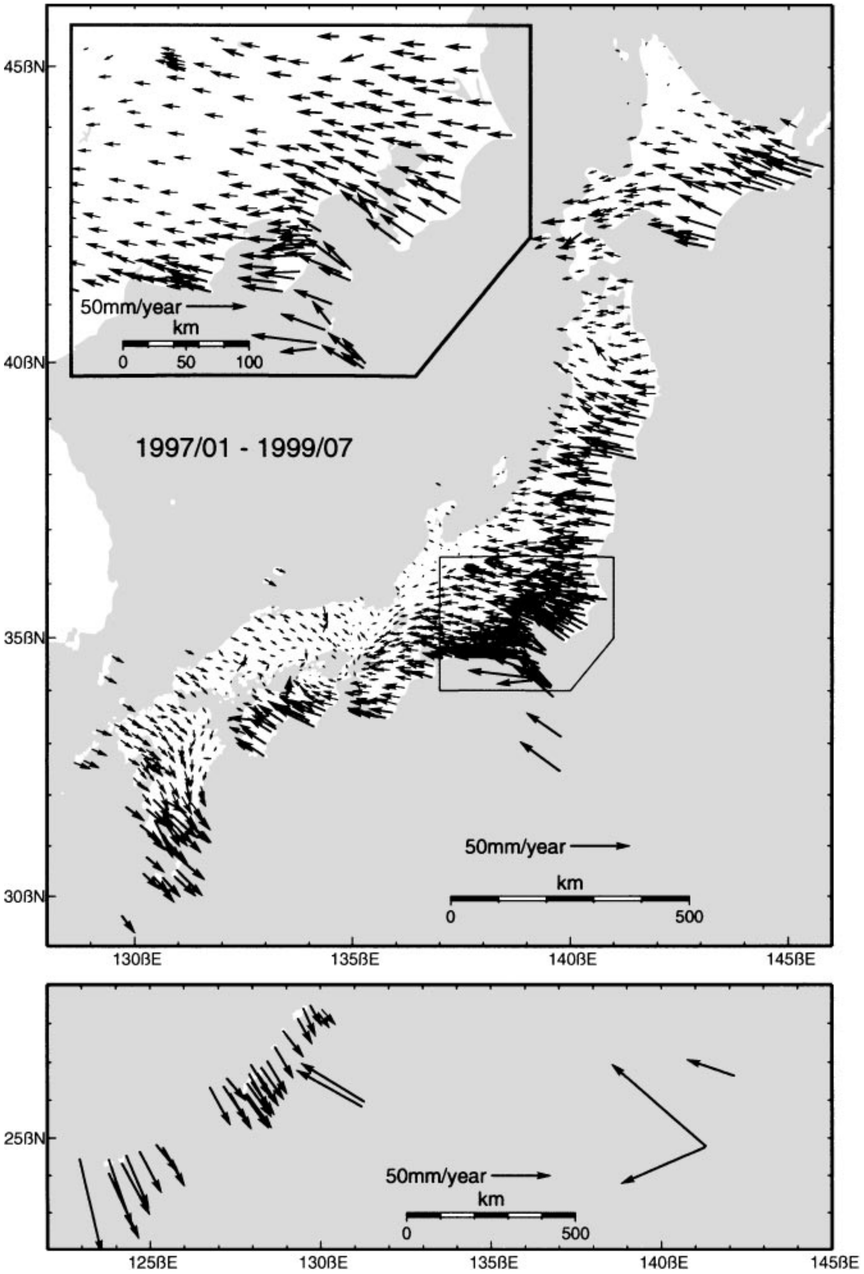


**Figure 4** GPS vector data from GEONET, the GPS network maintained by the Geographical Survey Institute of Japan, showing the recent 2-year crustal deformation of the Japanese arc system (after Sagiya et al 2000).

4. The Japan Sea side of the Honshu arc, including the northern side of the MTL, shows small but consistent eastward velocity components that range from a few micrometers to 1 cm year$^{-1}$. This area of eastward movement belongs to the Amur plate. The existence of the Amur plate was originally proposed by Zonenshain & Savostin (1981) and its plate tectonic significance was later demonstrated by Wei & Seno (1998) and Heki et al (1999). Recent GPS measurements have further confirmed these observations.
5. The change in the GPS velocity field can be translated into the strain field (see Appendix). The principal strain axes and shear strain provide further insight into the plate tectonics of the arc. A zone of high-shear strain along the MTL, the northern part of central Japan, and the Japan Sea side of NE Honshu probably marks the principal zone of deformation. This zone has been interpreted as the currently active boundary between the Amur plate and the Pacific side of the Honshu arc (Taira et al 1999). This suggests that the Amur plate plays an important role in intra-arc crustal deformation, which is dominated by east-west compressional stress.

## Active Fault Distribution

Efforts to map the active faults (faults that show evidence of movement since the Quaternary) of the Japanese arc system by means of topographic analysis, field surveying, and trench excavation have continued for the past ~30 years. The resulting collection of maps was published by Research Group of the Active Faults in Japan (1991) and, more recently, a marine portion was presented by Tokuyama et al (1999). The important findings of these results are reviewed below (see Figure 5).

1. In Hokkaido, a significant fault system is present along the western foothills of the Hidaka Mountains. This active fault system is part of the foreland thrust belt of the Hidaka collision zone.
2. Western Hokkaido and NE Honshu show the development of north-south trending reverse fault systems, which indicates that these areas are under an east-west compressional stress regime. This observation concurs with GPS geodetic results and seismic studies.
3. Central to SW Honshu is dominated by a dense network of NW-SE- and NE-SW-directed conjugate-type strike-slip fault systems. To the south, these fault systems are bounded by the MTL. These systems can be best explained by an east-west-directed compressional stress regime. Kanaori et al (1992) and Kanaori & Kawakami (1996) grouped the fault systems into several major fault zones, which border rotating coherent blocks. Their proposal of bookshelf-type tectonics together with the results of the recent GPS geodetic data was incorporated in the proposed plate tectonic model shown in Figure 1.
4. In the vicinity of the Izu collision zone, the fault system is strongly related to the indented configuration of the plate boundary (Huchon &

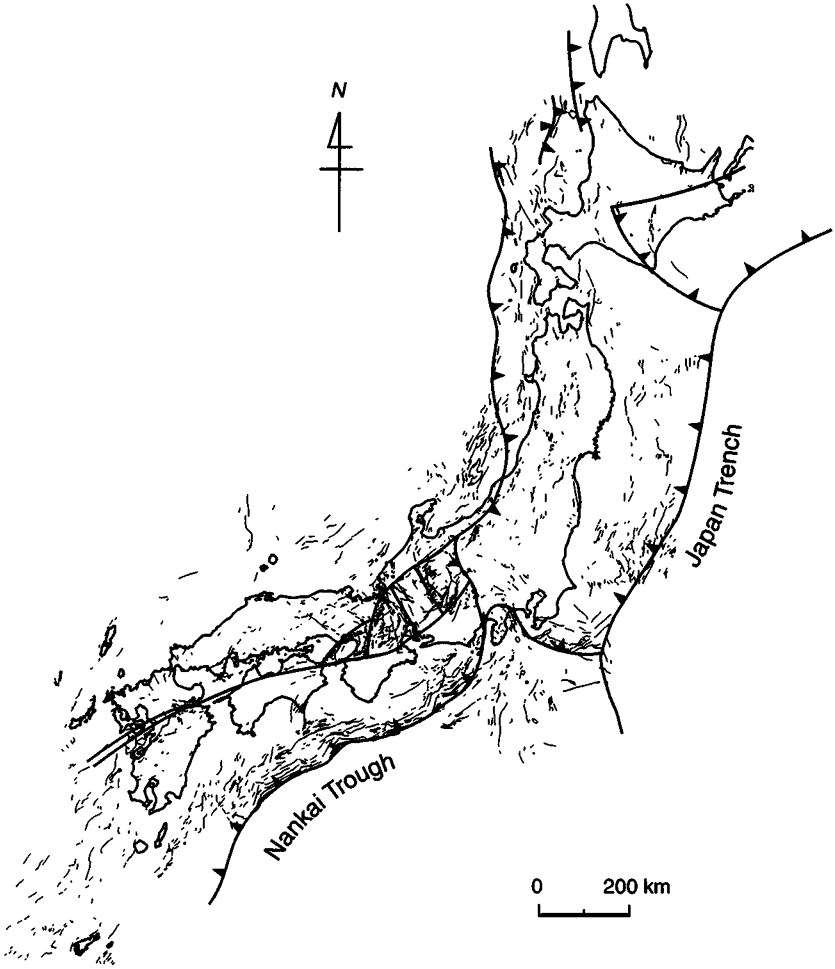


**Figure 5** Distribution of active faults in the Japanese arc system (after Research Group for Active Faults in Japan 1991). The plate boundary configuration is overlaid for reference.

Kitazato 1984). GPS and seismic results also confirm the acute plate boundary shape.

5. The westward extension of the MTL connects with a zone of north-south extension in central Kyushu (Okamura et al 1992), which continues to the eastern end of the Okinawa trough.

## Seismicity

Seismicity in the Japanese arc system is closely related to the plate boundary zones and the active fault systems (Geological Survey of Japan 1992; see Appendix for information on accessing data).

In Hokkaido, the Kuril Trench delineates the loci of plate-boundary earthquakes. Inland, the foreland thrust zone of the western Hidaka Mountains is associated with an active seismic zone. The Japan trench plate boundary is the most active zone of earthquake generation in the Japanese arc system; more than 100 earthquakes larger than *M*6 are known to have occurred there since 1885. The Nankai trough has historically generated earthquakes larger than *M*8 at intervals of approximately 180 years (Ando 1975, Sangawa 1994).

The Japan Sea margin is also known to be a zone of active seismicity (Fukao & Furumoto 1975). A series of large earthquakes (*M*7.5–*M*7.8 class) has occurred where the oceanic lithosphere of the Japan Basin merges with the NE margin of the Japanese arc (including NE Honshu and SW Hokkaido) (Tanioka et al 1995). This is probably caused by incipient subduction of the oceanic lithosphere (Nakamura 1983, Tamaki & Honza 1985).

The presence of intra-arc seismic faults in NE and central Japan is the result of compressional stress induced by the eastward motion of the Amur plate.

## GEOLOGICAL FRAMEWORK

### Surface Geology

The geologic history of the Japanese arc is one of the longest among the western-Pacific arcs. The oldest rocks are Cambrian and Ordovician ophiolites and associated deep-water sedimentary rocks, which may have had their origin in the breakup of the Proterozoic supercontinent (Maruyama et al 1997). The majority of the basement rocks, however, consist of younger Jurassic to Paleogene accretionary prisms that predate the formation of the Sea of Japan in the middle Miocene (Taira et al 1989).

Since the middle Miocene, arc magmatism has been the predominant geological process (Yamaji & Yoshida 1998, Sato 1994). In the Quaternary, the present-day tectonic scheme was fully established, and the modern topography was formed. Two fold-thrust belts developed at the margin of the Japan Sea after the late Miocene: the Sanin fold-thrust belt in SW Japan (Itoh & Nagasaki 1996) and the Japan Sea margin of northern Japan (Nakamura 1983). Tokuyama et al (1992) found that the development of thrusts that involve oceanic basement in the fold-thrust belt of Japan Sea margin off northern Japan provides a mechanism for ophiolite emplacement.

The geology of the arc can be classified into five main categories (Taira et al 1983, Isozaki 1996):

1. Pre-Jurassic units, including Paleozoic ophiolites, sedimentary rocks, metamorphic rocks, and granitic rocks;
2. Permian to Jurassic accretionary prisms, including high-pressure/temperature (P/T) metamorphic rocks and cover sequences;

3. Cretaceous to Tertiary accretionary prisms and cover sequences;
4. Jurassic to Tertiary igneous rocks;
5. Neogene and Quaternary igneous and sedimentary rocks.

The basement geology map (Figure 6) shows that Jurassic to Paleogene accretionary prisms are the main components of the basement rocks. The progressive growth of crust from the Asian side of the continent toward the ocean is well documented in the cross section of SW Japan and geological columns shown in Figure 7 and Figure 8. This growth of crust was accompanied by the emplacement of granitic rocks including granodiorites (Figure 9). In SW Japan, the geological region on the Pacific side of the MTL is called the outer zone and that on the other side of the MTL, the inner zone.

## Crustal Structure

The thickness of the crust in the Japanese arc system is roughly 30–40 km in the central part of the arc, although the thickness varies depending on the tectonic setting. In Hokkaido, the thickness of the crust at the Hidaka Mountains is ∼30–50 km (Miyauchi & Moriya 1984, Ogawa et al 1994), probably the thickest in Hokkaido. Arita et al (1999) documented that crustal delamination occurs in southern Hidaka owing to collision tectonics. In NE Honshu, the crustal thickness is ∼30–35 km and in SW Japan it is ∼35–40 km. In central Honshu, it reaches <40 km under the Akaishi mountain range (Ashiya et al 1987).

Intra-arc seismicity is concentrated in the upper level of the crust. In NE Honshu, seismicity diminishes at depths below 10–20 km (Okubo & Matsunaga 1994), and in SW Honshu, below 12–25 km (Ito 1999). The difference in depth of crustal seismic activity between two arcs may be the result of higher heat flow in NE Honshu, which results in a shallower brittle-ductile transition zone.

## Magnetic Anomaly

The magnetic anomaly map shown in Figure 10 provides useful insight into the geological and tectonic framework. The Pacific and Shikoku basin floors are dominated by a magnetic anomaly pattern related to the seafloor-spreading process. A large positive anomaly zone exists on the forearc side of NE Honshu, with a possible extension into Hokkaido. This conspicuous anomaly is interpreted as a Cretaceous magmatic arc, which is important in reconstructing the tectonic history of the arc system (Finn 1994). Patchy positive anomaly patterns in NE Honshu coincide with the distribution of Neogene and Quaternary volcanic rocks. In SW Honshu, a zone of broader anomaly patterns coincides with the distribution of Paleogene and Cretaceous intrusive rocks.

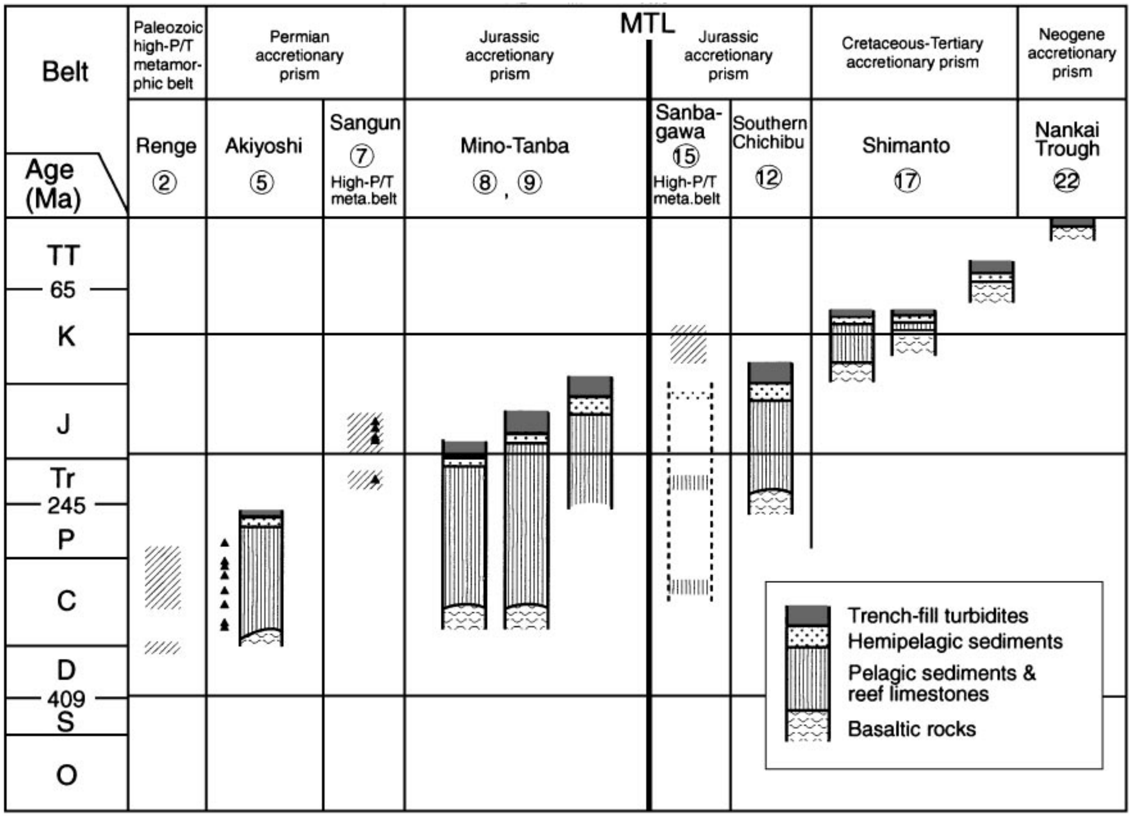


**Figure 8** Reconstructed oceanic plate stratigraphy and the ages of high-pressure/temperature (P/T) metamorphism in SW Japan. (After Taira et al 1989 and Maruyama 1997.)

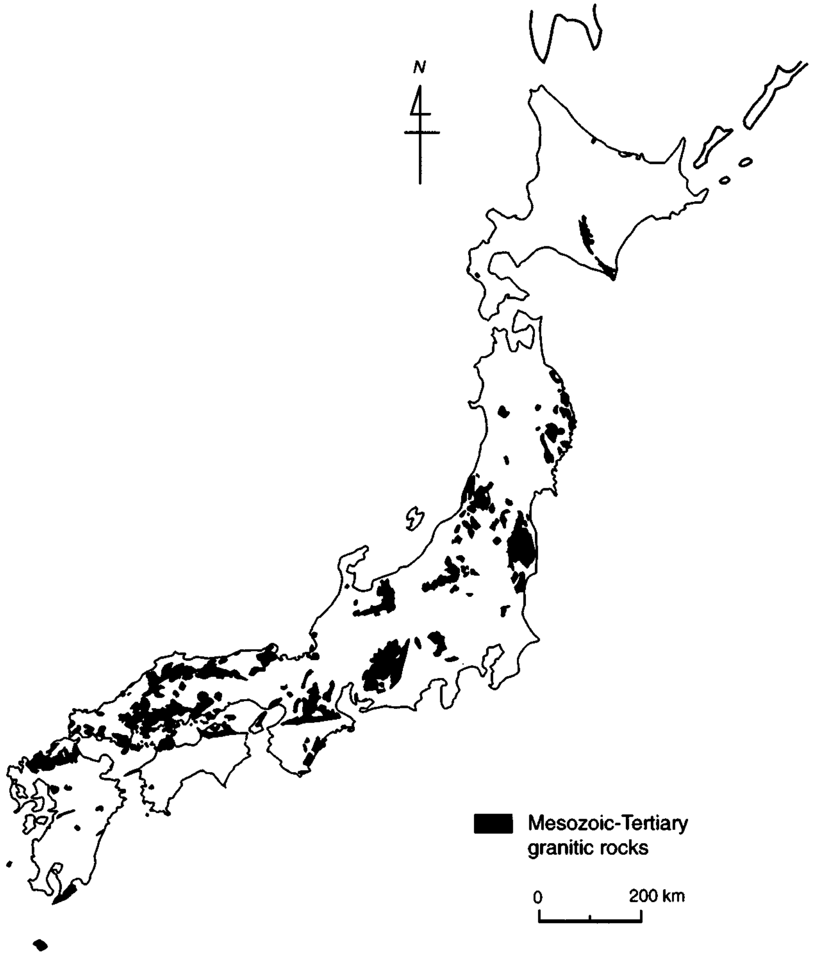


**Figure 9** Distribution of Mesozoic (mostly Cretaceous) and Cenozoic granitic rocks. (After Geological Survey of Japan 1992).

## TECTONIC EVOLUTION

The tectonic evolution of the Japanese arc system is summarized in this section, which describes the history of the arc system in discrete tectonic phases, in reverse chronological order. Time-regressive description is, I believe, an effective way to demonstrate the way in which the tectonic evolution of the arc has led to the development of the present-day arc system, because the older part of the arc's history is less well constrained.

## Neotectonic Evolution

The present-day arc system is dominated by east-west compression. This stress regime is considered to have begun during the late Pliocene to early Quaternary.

In NE Honshu, a strong east-west compressional episode seems to have begun ∼3–2 Ma [mega-annum (Ma) = $10^6$ years]. This episode is best displayed at the eastern margin of the Sea of Japan, where development of a fold belt included the inversion of preexisting horst and graben structures (Okamura et al 1995). The backbone range of NE Honshu has been rising since 2 Ma, based on the timing of deposition of coarse clastic sediments along major north-south-trending reverse faults (Sato & Amano 1991). The Quaternary development of an east-west-directed igneous dike system suggests initiation of an east-west-trending compressional stress field (Sato 1994).

The deformation of central Honshu and the development of the present-day system of faults are clearly marked by the initiation of coarse clastic sediment accumulation in various inland basins in the Quaternary (Huzita 1968). Evidence for the migration of sedimentary basins along the MTL from east to west, beginning ∼4–2 Ma, has been pointed out in several studies (e.g. Mizuno 1992, Sugiyama 1994). The offshore geology of SW Japan also suggests that dominant structures, including a series of forearc basins, have developed since the beginning of the Quaternary (i.e. Okamura et al 1987, Okamura 1990, Tokuyama et al 1999).

Recent investigation shows that the counterclockwise rotation of southern Kyushu (Kodama et al 1995) and the peak rifting of the southern Okinawa trough (Park et al 1998) started after the Quaternary began.

These lines of evidence strongly suggest that the present mode of tectonics in the Japanese arc system started ∼4–3 Ma and was fully developed by 2 Ma. The onset of neotectonics was probably triggered by the initiation of the eastward movement of the Amur plate. The western boundary zone of the Amur plate runs through the Baikal rift zone, where coarse clastic sediments started to accumulate in the late Neogene (Zorin & Cordell 1991). This accumulation may imply that the resumption of active rifting of the Baikal zone correlates with the neotectonic initiation of the Japanese arc system. The reason why the Amur plate started to migrate eastward in the Quaternary is not known.

## Neogene Tectonic Evolution

Six main tectonic events occurred during the Neogene (Kano et al 1991):

1. Rifting of the paleo-Bonin arc and spreading of the Shikoku Basin (25–15 Ma);
2. Rifting of the paleo-Honshu continental arc and spreading of the Japan Sea basin (22–15 Ma);
3. Widespread, even, near-trench igneous activity 17–12 Ma in SW Honshu;

4. Initiation of subduction of the Philippine Sea plate and collision of the Izu-Bonin arc against Honshu at 15 Ma;
5. A main phase of subduction of the Philippine Sea plate beginning at 8 Ma;
6. Collision of the Kuril forearc sliver and formation of the Hidaka mountain belt beginning at 15 Ma.

Rifting of the paleo-Izu-Bonin arc started ∼25 Ma and was followed by the main episode of seafloor spreading, which seems to have occurred in three phases (Okino et al 1994). Seafloor spreading created the Shikoku Basin between the Kyushu-Palau Ridge (remnant arc) and the Izu-Bonin arc (Figure 11).

Rifting of the northeastern margin of the Asian continent started ∼22 Ma and was followed by development of two backarc basins, the Japan Sea basin and the Okhotsk Sea basin (Tamaki et al 1992).

By 15 Ma most of the ocean floor in the Japan Sea had formed (Jolivet et al 1994, Otofuji 1996; Figure 11), and associated rifting of the western margin of NE Honshu produced a series of north-south-trending horst and graben structures (Yamaji 1990). Rifting was accompanied by eruption of a large volume of submarine volcanic rocks, commonly called “Green Tuff.” Rifting of the Kuril basin was followed by westward migration of the Kuril forearc, owing to the oblique subduction of the Pacific plate. This westward migration and collision produced the Hidaka mountain range (Kimura 1986). In the Hidaka Mountains, extensive thrust tectonics brought to the surface one of the youngest granulite-gneiss terranes known, which might have been part of the arc’s lower crust (Komatsu et al 1989).

The geology of central Honshu suggests that the northern tip of the Izu-Bonin arc was in contact with central Honshu by 15 Ma (Itoh 1988, Koyama 1991, Aoike 1999). The initial collision at ∼15 Ma is recorded by emplacement of a succession of turbidites in deep troughs in both the southern and northern parts of central Honshu (Tateishi et al 1997, Aoike 1999).

In SW Japan, widespread igneous activity took place within the forearc, close to the trench, at 17–13 Ma (Kano et al 1991). This episode, including high-magnesium andesite emplacement, is generally interpreted as reflecting the injection of hot asthenosphere and the initial subduction of the young Shikoku Basin seafloor (Takahashi 1999).

From 15 to 10 Ma the collision of the Izu-Ogasawara arc against Honshu was apparently not vigorous, but was persistent enough to maintain a supply of sediment to the collisional trough (Aoike 1999).

From 8 to 6 Ma a fold belt developed on the Japan Sea side of SW Honshu (Itoh & Nagasaki 1996; Figure 11). Fold-axis trends are predominantly NE-SW, indicating NW-SE compression. Widely distributed volcanic activity, starting ∼8 Ma in southern Kyushu and by 6 Ma in SW Japan, suggests the establishment of a volcanic front and a deeply penetrating subducting slab (Kamata & Kodama 1994). In the Izu Collision Zone, the accretion of the Tanzawa massif (part of the volcanic front of the Izu-Bonin arc) seems to have started ∼8 Ma, with the main phase of collision at ∼6–5 Ma (Niitsuma 1989). The collision of the Izu-Bonin arc produced a package of altered volcanic rocks (greenstone) imbricated with granitic intrusive rocks (Taira et al 1989). Accretion of forearc sedimentary rocks of the Izu-Bonin arc at the paleo-Sagami Trough also started ∼6 Ma (Soh et al 1991, Saito 1992). These lines of evidence suggest that the Philippine Sea plate resumed subduction ∼8 Ma, after a comparatively stagnant phase (14–9 Ma).

Subduction of the Philippine Sea plate at the Nankai trough formed a frontal accretionary prism to the SW Japan forearc (Nankai Accretionary Prism; Le Pichon et al 1987, Taira et al 1992a).

After the establishment of the Philippine Sea plate and deep subduction by 6 Ma to a depth of ∼100 km (i.e. deep enough to produce a volcanic arc), the tectonics of the Japanese arc system passed into a neotectonic regime that started ∼4–3 Ma; this regime was fully developed by 2 Ma (see above).

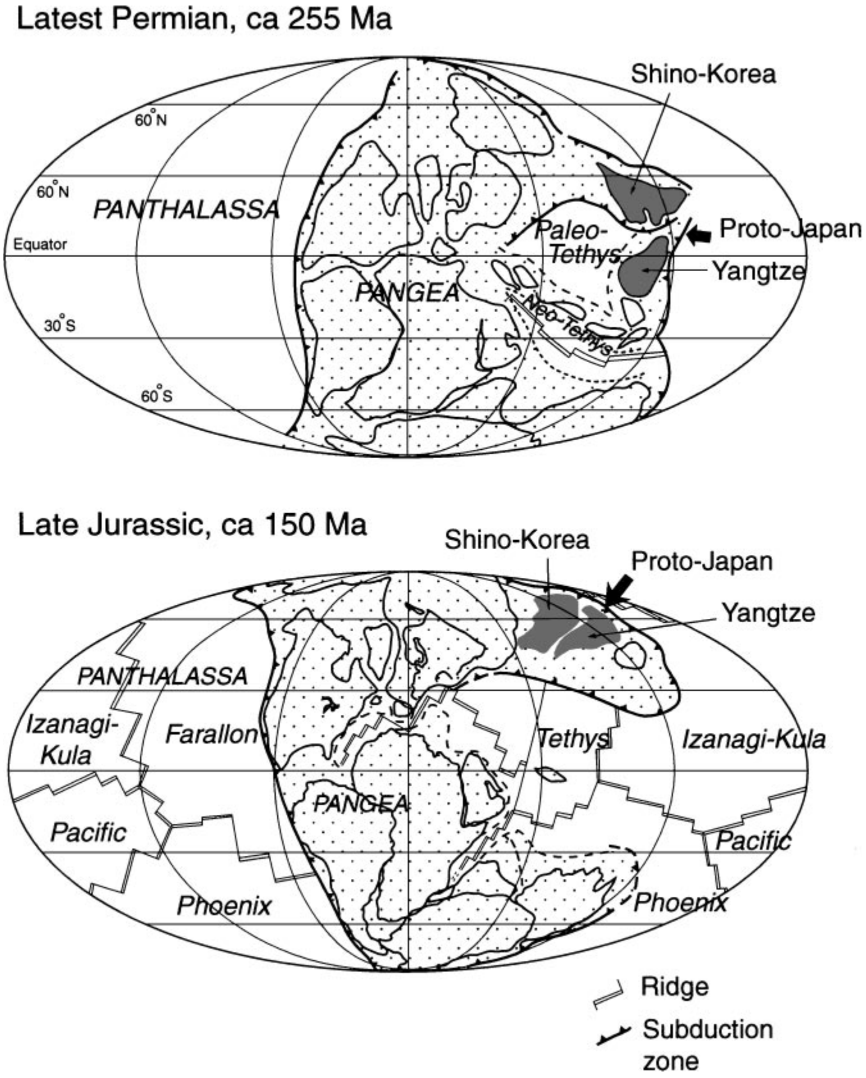
## Jurassic to Paleogene Evolution

The Jurassic to Paleogene interval is an important interval in the tectonic evolution of the Japanese island arc because the majority of the basement rocks were formed during this time. The following episodes of tectonic activity were the most critical:

1. Subduction of oceanic plates at the Asian continental margin and development of the accretionary prism in the Jurassic;
2. Transcurrent tectonics and reorganization of the accretionary prism in the early Cretaceous;
3. Subduction of oceanic plates and development of the Shimanto Accretionary Prism in the late Cretaceous and early Tertiary;
4. Contemporaneous development of continental magmatic arcs from the Jurassic to early Tertiary;
5. Emplacement of a high-P/T metamorphic belt (Sanbagawa Belt) in the late Cretaceous;
6. Collision of the Okhotsk Plate during the Paleogene;
7. Extensional tectonics on the eastern margin of Asia in the Paleogene that affected the paleo-Kyushu and Ryukyu regions.

Jurassic accretionary prisms occupy an extensive area not only in the Japanese arc system (8–12 on Figure 6) but also in eastern Asia (Kojima & Kametaka 2000). Their lithology is dominated by Carboniferous-Permian basaltic rocks, Carboniferous-Permian-Triassic reef limestones, extensive deposits of Permo-Triassic red to green ribbon cherts and shales, and Jurassic turbidites (Matsuoka 1992, Nakae 2000). The original stratigraphy of these oceanic successions that span the evolution of the arc is presented in Figure 8. Paleogeographic reconstruction suggests that Permo-Jurassic accretion tectonics of the basement rocks took place at the eastern margin of Pangea (Isozaki 1997; Figure 12). These accretionary complexes are intruded by predominantly Cretaceous to Tertiary granitic rocks (see Figure 9).

In the outer zone of SW Japan, a part of the Jurassic accretionary prism was metamorphosed under high-P/T conditions. The structural position of this metamorphic complex, called the Sanbagawa Belt, is debatable. Probably, it is



Latest Permian, ca 255 Ma

Late Jurassic, ca 150 Ma

**Figure 12** Paleogeography of Pangea and Panthalassa and the possible location of proto-Japan in the late Permian (∼255 Ma) and late Jurassic (∼150 Ma). Note that proto-Japan evolved from the Tethys-Panthalassa (Pacific) corner. (After Isozaki 1997.)

sandwiched structurally between the overlying Jurassic accretionary complex and the underlying Shimanto Belt (Maruyama 1997; Figure 7). Yamakita & Otoh (2000) indicated that low-angle strike-slip tectonics are responsible for the uplift of the Sanbagawa Belt and the formation of an elongate forearc basin along the MTL (Figure 11). This strike-slip tectonic regime eventually juxtaposed two contrasting metamorphic belts (high-P/T Sanbagawa and low-P/T Ryoke), as recognized originally by Miyashiro (1961). On the other hand, Maruyama (1997) has suggested ridge subduction as a possible mechanism for the Sanbagawa blueschist metamorphism and diapiric emplacement.

The Cretaceous and early Miocene Shimanto accretionary belt extends from central Honshu to the Ryukyu Islands (Taira et al 1988; Figure 6 and Figure 7). The belt extends ~1800 km along the strike and has a maximum width of 100 km. The Shimanto Belt is composed of two main units: a relatively coherent turbidite sequence and a highly deformed melange belt. These rock units are repeatedly intercalated and systematically young toward the ocean. The melange belt includes tectonic slivers of basaltic pillow lavas, nannoplankton-ooze limestones, radiolarian cherts, red pelagic shales, varicolored hemipelagic shales, and layers of dispersed volcanic ash, all of which are in a highly sheared argillaceous matrix.

The best example of oceanic-plate stratigraphy has been reconstructed for the island of Shikoku (Taira et al 1988). Microfossil dating of the various rocks within the Cretaceous melange indicates that the nannofossil-bearing limestones and radiolarian cherts date from the Valanginian (130 Ma) to the Cenomanian (100 Ma), the varicolored shales are from the Coniacian to the Santonian (90 Ma), and the argillaceous melange matrix dates from the Campanian (70 Ma). The adjacent coherent turbidite unit (trench deposits) also dates from the Campanian. Paleomagnetic analysis of these rocks reveals that the Valanginian pillow lavas and nannofossil limestones were formed at equatorial latitudes, but the coherent turbidite units of Campanian age (70 Ma) were deposited at roughly their present latitude (30°N) (Kodama et al 1983). These data have been interpreted to mean that this oceanic crust originated at an equatorial latitude at ~130 Ma, moved north at least 3000 km, and was subducted 70 Ma. Dating of melange lithologies throughout the Shimanto Belt has revealed a systematic change in oceanic plate stratigraphy: a time-progressive decrease in age difference between the basal pelagic unit and the overlying trench-fill succession (see Figure 8). These data suggest that juvenile oceanic lithosphere was subducted during most of the Paleogene, providing a constraint on any plate reconstruction for the western Pacific during the Cretaceous to Tertiary.

The extension of the Jurassic accretionary complex occupies the western part of Hokkaido (Figure 6). To the east are late Jurassic–early Cretaceous ophiolites and cover clastic sequences, a high-P/T metamorphic complex, and Cretaceous to Eocene accretionary prisms (Kiminami et al 1985, Kimura 1997). The present-day structural polarity, however, is reversed (westward convergence), owing to the collision of the Okhotsk block during the Paleogene and subsequent Kuril forearc migration since the Miocene began (Kimura 1986, 1996; Figure 11).

Jurassic and Paleogene accretionary prisms are accompanied by contemporaneous magmatic arcs, represented by belts of granitic intrusives. A conspicuous magnetic anomaly offshore of NE Japan reflects the presence of one such belt (Finn 1994; Figure 10 and Figure 11).

During the Paleogene, accretionary prism development took place in the Shimanto Belt and in western Hokkaido. At the continental borderland, extensive graben formation took place in vast areas of eastern Asia west of the South China Sea basin, east China Sea, and Kyushu (Itoh 2000). Inland, the Baikal rift basin was initiated. Igneous activity that accompanied this widespread rifting has been interpreted as indicating the possibility of asthenospheric upwelling (Zonenshain & Savostin 1981).

## Pre-Jurassic Evolution

The older rocks in the arc can be grouped into several lithological assemblages:

1. Cambro-Ordovician ophiolites and Ordovician to Devonian sedimentary rocks;
2. Carboniferous to Triassic shallow marine sedimentary rocks;
3. Paleozoic high-P/T metamorphic rocks;
4. Paleozoic granitic rocks;
5. Permian accretionary prism rocks.

These rocks have a complex distribution pattern. In the inner belt of SW Japan and NE Honshu, these units seem to occur as thrust sheets (nappes), probably with older sheets in structurally higher positions (Isozaki 1997). In the outer zone of SW Japan, however, the structure seems to be highly complex. For example, in the Kurosegawa tectonic zone, tectonic slivers include Silurian to Devonian limestone and shale, Silurian granites and metamorphic rocks, Carboniferous limestone, Permian molluscan sandstone, Permian blueschist and melange, and Triassic shallow marine sandstone. These tectonic slivers are surrounded by serpentinite matrix and intermixed with tectonic slivers of Jurassic accretionary prism rocks (Maruyama 1981). This combination indicates that tectonic mixing took place after the formation of the Jurassic accretionary prism.

One of the explanations for this structural complexity involves early Cretaceous left-lateral strike-slip tectonics (Taira et al 1983, Taira & Tashiro 1987; Figure 11). Several authors have suggested that $>$1000 km of displacement occurred during this interval ($\sim$40 million years) (Tazawa 2000). This kind of large-scale strike-slip tectonics is part of the East Asian tectonic regime, as exemplified by the Tan-Lu fault system (Taira & Tashiro 1987). Some studies, on the other hand, have suggested that older rocks in the outer zone represent outliers of the thrust sheets present in the inner belts (Isozaki 1997).

The origin of these rather exotic older rocks has been debated for many years. One of the influential suggestions was that these rocks belonged to an accreted microcontinent that originated from Gondwanaland (Saito & Hashimoto 1982). More recently, Isozaki (1996) suggested that Cambro-Ordovician ophiolites and early Paleozoic sedimentary rocks originated at the rifted continental margin of the Late Proterozoic supercontinent. Rifting of the supercontinent was contemporaneous with the birth of the Pacific basin (Bond et al 1984). Rifted continental blocks, including South China, Sino-Korea, and Siberia, accreted later, forming a proto-Asian continental block. The Japanese arc grew at the margin of this block as a result of the subduction of the proto-Pacific ocean floor [Figure 12; also see Figure 13].

### Summary of Tectonic Evolution

Although the earlier part of its history is based largely on speculation, later arc evolution was closely related to the evolution of the Pacific (Panthalassa) ocean basin and the closure of the Tethys Seaway (Figure 12). It is noteworthy that the Japanese arc system evolved at the intersection of the Tethys Seaway and the Pacific Ocean as a part of the accretion of eastern Asia (Taira & Tashiro 1987, Maruyama et al 1989, Sengör & Natalín 1996, Isozaki 1997; see Figure 12). The evolution of the arc did not involve major continent-continent collision. Instead, subduction and accretion of various oceanic materials and episodic emplacement of metamorphic belts were the main mechanisms of basement rock formation.

Since the Neogene, the tectonic evolution of the arc has passed into a new phase: the formation of a backarc basin and subsequent incipient backarc subduction. If backarc subduction continues in the future, the Japanese arc will become a doubly subducting arc. Then, if it eventually collides with the Asian continent, it will probably form a Taiwan-type orogenic wedge, followed by large-scale backarc fold-thrust belt development similar to that in the Cordilleran orogenic belt of the Americas.

## IMPLICATIONS FOR OROGENISIS AND CONTINENTAL CRUST FORMATION

### Classification of Lithologic Assemblages

Based on the geological framework and tectonic evolution described above, the geology of the Japanese arc system can be simplified into five tectono-stratigraphic assemblages (Taira et al 1997):

1. Turbidite-granitoid belt. Most of the basement rocks in the arc are composed of imbricated sequences of accreted turbidites mixed with oceanic materials and granitic intrusives.
2. Volcanic (greenstone)-granitoid belt. The assemblage in the Izu collision zone is characterized by imbricated packages of volcanic rocks that are

metamorphosed to various degrees, together with intrusive rocks, including tonalite-granodiorite plutons.

3. Granulite-gneiss belt. One of the youngest granulite-gneiss belts in the world is in the Hidaka Mountains. This belt is interpreted to be part of the lower crust of the arc, which was brought to the surface by thrust tectonics.
4. Sedimentary fold-thrust belt. On the Japan Sea margin of NE Honshu, a linear fold-thrust belt, probably involving a basement-detachment fault (thin-skinned tectonics), started to develop in the Quaternary as a result of incipient subduction and initiation of closure of a backarc basin.
5. Intrusive rocks and cover sequences. Covering sedimentary successions and various igneous rocks (except those designated in the belts listed above) constitute the rest of the rock assemblages. The Neogene and Quaternary volcanic and sedimentary rocks encompass these groups.

The lithological assemblages listed above are also major constituents of other orogenic belts and include the majority of rock types in the continental upper crust. The following section demonstrates how this classification can be applied to other orogenic belts.

## Comparison of Orogenic Belts

The concept of five tectono-stratigraphic units as the basic constituents of any Phanerozoic orogenic belt has been applied to cross-sections of Japan, the North American Cordillera, the Appalachians, and the Alps (Figure 14). Comparing these orogenic belts in this context indicates that the orogenic belts consist of various proportions of the five tectono-stratigraphic assemblages listed above. Japan, the Cordillera, and Appalachia are mostly composed of an assemblage of these five components, whereas the Alpine belt lacks the turbidite-granitoid and volcanic-granitoid belts. If the closure of the Japan Sea backarc is eventually completed and a fold-thrust belt is fully developed, the Japanese orogenic belt will closely resemble the Cordillera orogenic belt. On the other hand, the Alpine orogenic belt is much smaller in cross section and contains neither a turbidite-granitoid belt nor volcanic-granitoid belt. The Alps were produced by the closure of small oceanic basins without the concomitant development of subduction-related assemblages. In the western Tethys realm, this type of orogenic belt is common. In the Pacific realm, however, Japanese- or Cordilleran-type orogens that contain substantial volcanic(greenstone)-granitoid belts predominate.

## Implications for Continental Evolution

The presence of volcanic(greenstone)-granitoid belts in orogens implies accretion of juvenile materials that originated primarily from mantle melting. In the case of the Japanese arc system, the volcanic-granitoid belt was formed by the accretion of an oceanic island arc (Izu-Bonin arc) that contains felsic middle crust (Suyehiro et al 1996). The felsic middle crust is a potential nucleus for accreted island arc terranes (Taira et al 1998).

It is well known that the geology of Archean cratons are dominated by volcanic(greenstone)-granitoid belts (i.e. Windley 1995). This implies that rapid growth of the continental crust took place through the addition of juvenile material during the early history of the earth (Taira et al 1992b). The mean rate of continental growth is determined by dividing the total volume of continental crust by 4.5 billion years, giving a production rate of 40 $km^3$ $year^{-1}$. The mean growth rate of the western-Pacific oceanic island arc is $\sim$80 $km^3$ $year^{-1}$. Taira et al (1998) suggested that subduction-zone magmatism and the formation of a juvenile volcanic arc may play a major role in continental growth, revisiting the original idea presented by Taylor (1967).

The presence of a turbidite-granitoid belt and a sedimentary fold-thrust belt in an orogenic belt implies the addition of recycled materials in the process of continental crust formation. The relative proportions of these tectono-stratigraphic assemblages in orogenic belts have changed through geologic time. There are virtually no turbidite-granitoid belts older than 3 Ga (giga-annum (Ga) $= 10^9$ years), yet they clearly became important by the time of the 2.5-Ga Superior Province (i.e. Percival & Williams 1989, Card 1990). The appearance of large linear sedimentary fold-thrust belts comparable to the Phanerozoic examples takes place still later in geological time, starting with the 1.9-Ga Trans-Hudson orogen (Lucas et al 1996).

## CONCLUSIONS

The tectonic evolution of the Japanese arc system is apparently related to global geological events:

1. The earlier geologic history of the arc system indicates that the basement rocks may have a history dating back to the breakup of a Proterozoic supercontinent and the evolution of the proto-Pacific basin.
2. Arc growth has taken place since the Permian along the continental margin of the South China and Sino-Korean blocks, as a result of the subduction of the ancient Pacific ocean floor.
3. Major episodes of accretionary prism development occurred in the Jurassic and Cretaceous, and the Paleogene.
4. Neogene backarc basin formation shaped the present-day arc configuration.
5. Neotectonics triggered by the eastward motion of the Amur plate in the Quaternary promoted a strong east-west arc compressional stress regime.
6. Collision of the Izu-Bonin arc against Honshu produced a unique geological assemblage, which resembles Archean greenstone-granitoid belts.

The tectonic evolution of the Japanese arc system includes the formation of rock assemblages common in most orogenic belts. Because their origin is better defined in the case of the Japanese arc, an understanding of the tectonics of this arc system provides useful insight into orogenesis and continental crustal evolution in general.

The GPS geodesy, seismicity, and active fault distribution of the arc are better constrained than anywhere else. The Japanese arc system thus provides a natural laboratory for understanding how the crustal deformation of an arc is related to plate tectonics.

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## APPENDIX

Various web sites can provide readers with background information relevant to the contents of this review. Some examples are listed below:

1. Geographical Survey Institute of Japan (http://www.gsi-mc.go.jp/). This site introduces the topography of Japan and also contains recent GPS information and the status of crustal deformation.
2. Geological Survey of Japan (http://www.aist.go.jp/GSJ/). Basic information of the geology of Japan can be obtained from this site.
3. Hydrographic Department, Japan Coast Guard (http://www.jhd.go.jp/) and Japan Hydrographic Association (http://www.jha.or.jp/). These sites provide information on bathymetry and hydrography around Japan.
4. Earthquake Information Center, Earthquake Research Institute, University of Tokyo (http://wwweic.eri.u-tokyo.ac.jp/). This site releases various kinds of seismic databases and also provides recent earthquake information.

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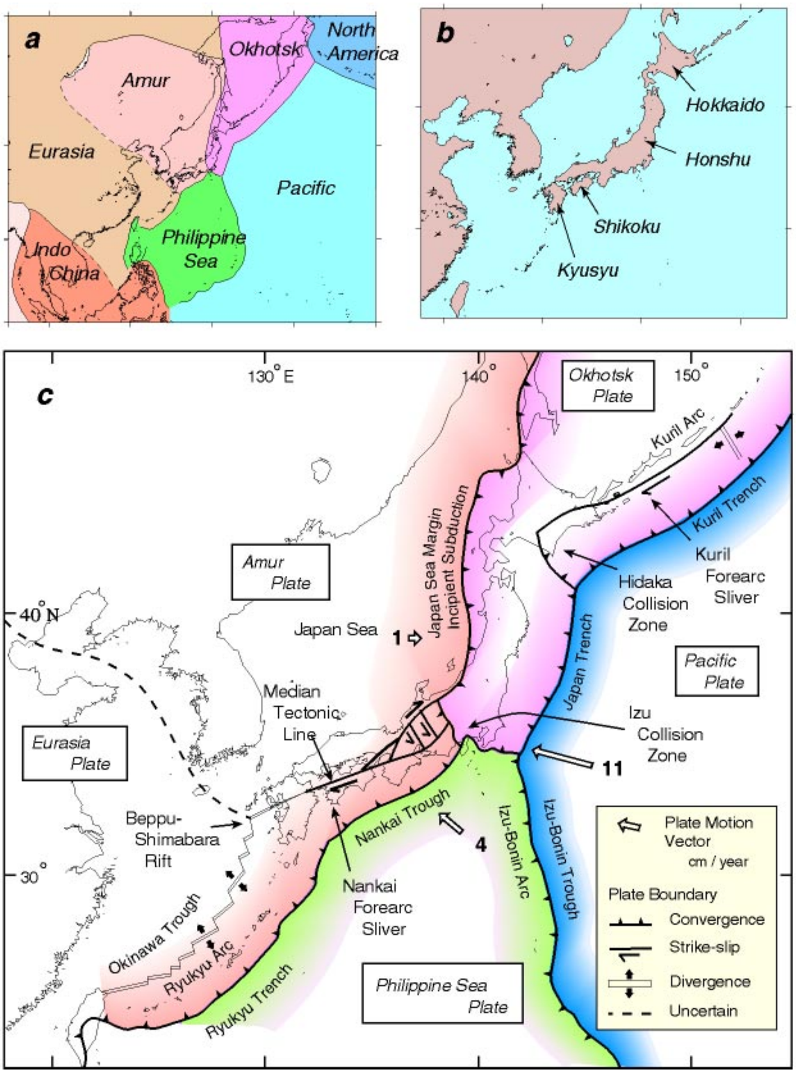


**Figure 1** Plate tectonics of the Japanese arc system. (*a*) Plate tectonic framework of Northeastern Asia (modified after Wei & Seno 1998). (*b*) Main part of the Japanese arc system, showing the distribution of the four big islands. (*c*) Plate boundaries of the Japanese arc system. Note that central Honshu shows complex microplate tectonics dominated by the median tectonic line (MTL), right-lateral motion, and bookshelf-type rotation tectonics. (Modified after Taira et al 2000.)

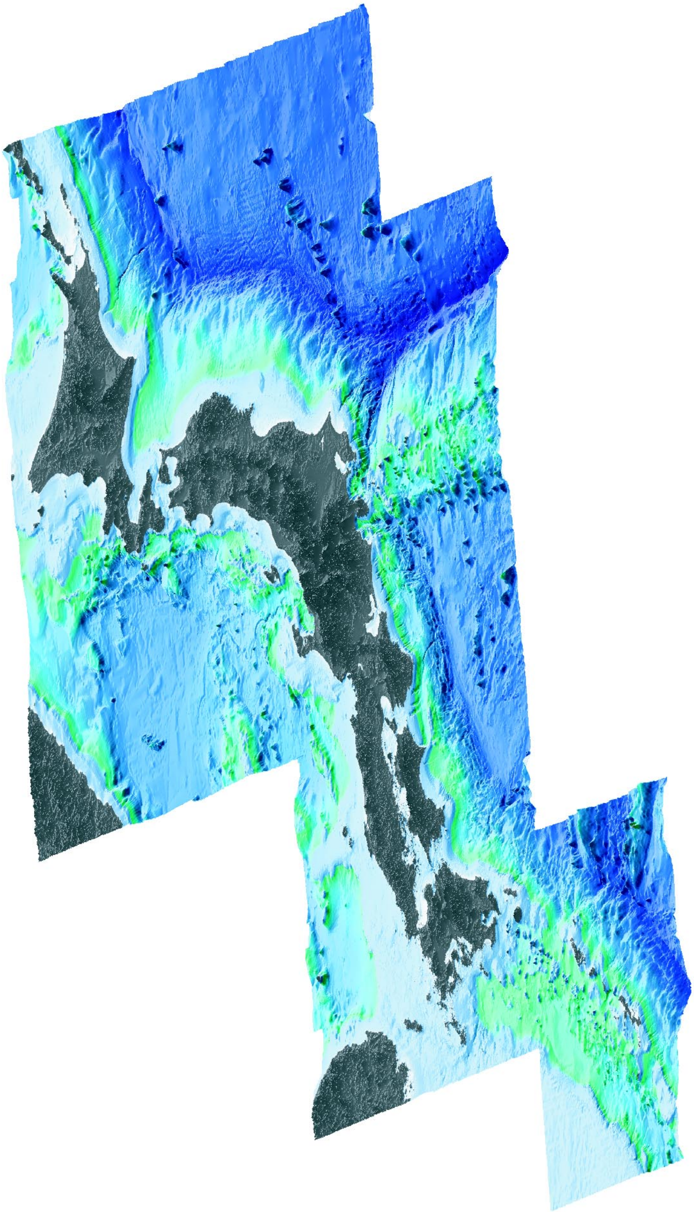


**Figure 2** Topographic relief map of the Japanese arc system, based on 500-m-square mesh data prepared by Hydrographic Department, Maritime Safety Agency of Japan (data from Asada 2000).

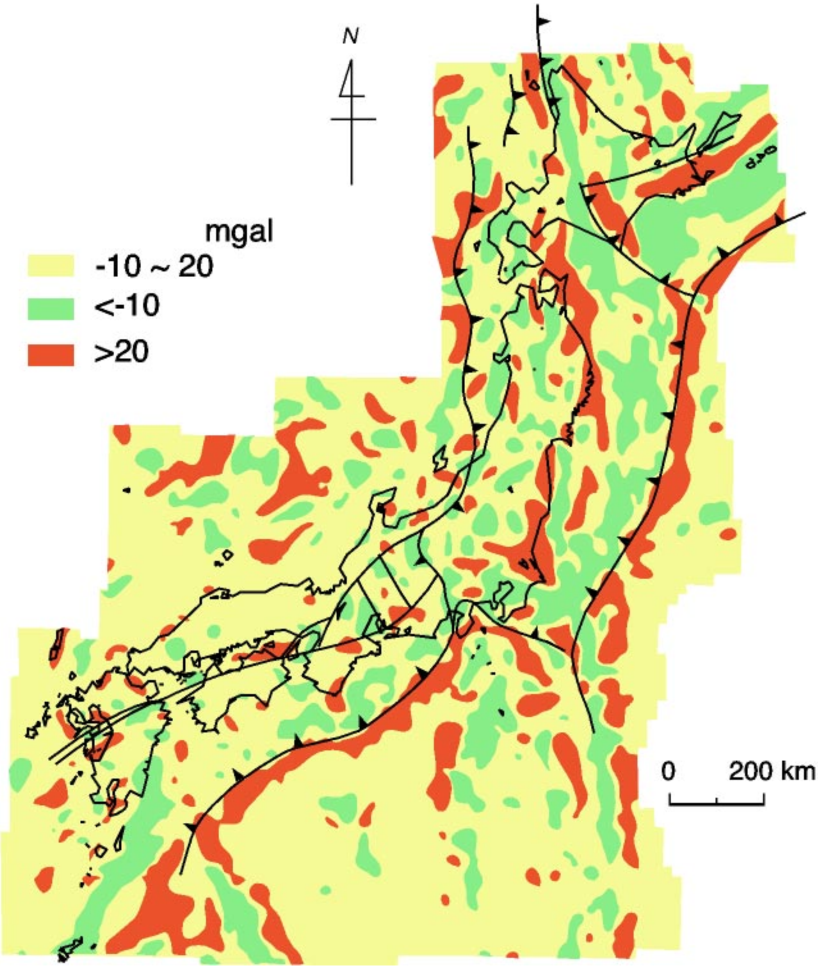


**Figure 3** Short-wave Bouguer anomaly map of the Japanese arc system (after Hagiwara 1991). Plate boundary distribution is overlaid for reference.

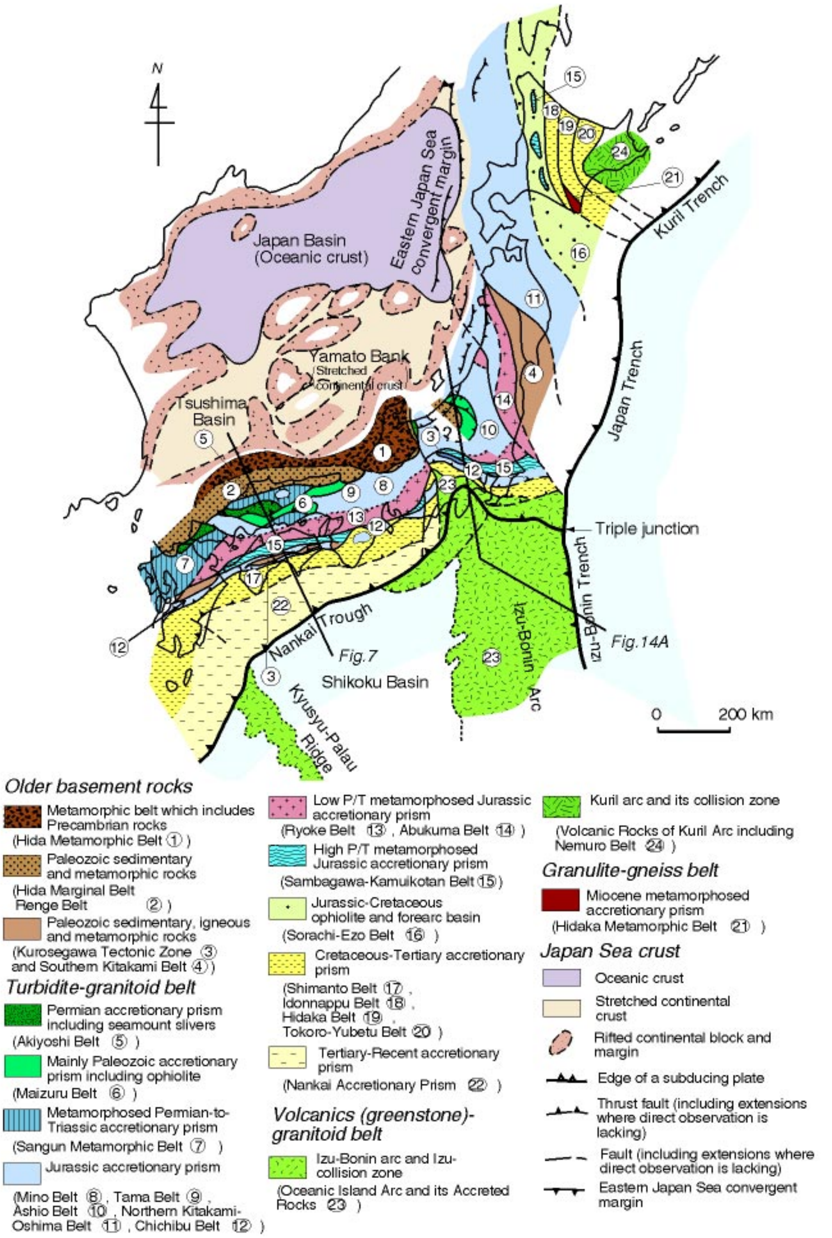


**Figure 6** Basement geology map of the Japanese arc system, excluding the distribution of granitic rocks shown in Figure 9. See text for explanation of geological classification. (After Taira et al 1989, 1998, Maruyama 1997, and Isozaki 1996.)

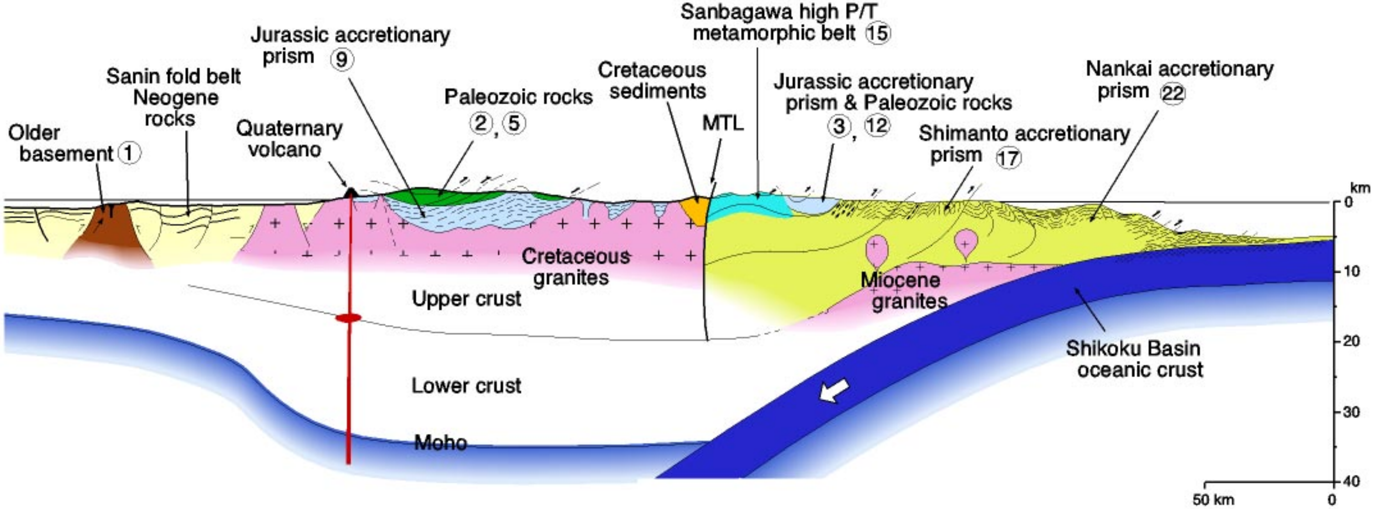


**Figure 7** Geological cross section of SW Japan from the Nankai trough to the Japan Sea. (After Taira et al 1989 and Maruyama 1997.) See Figure 6 for the location of the Profile.

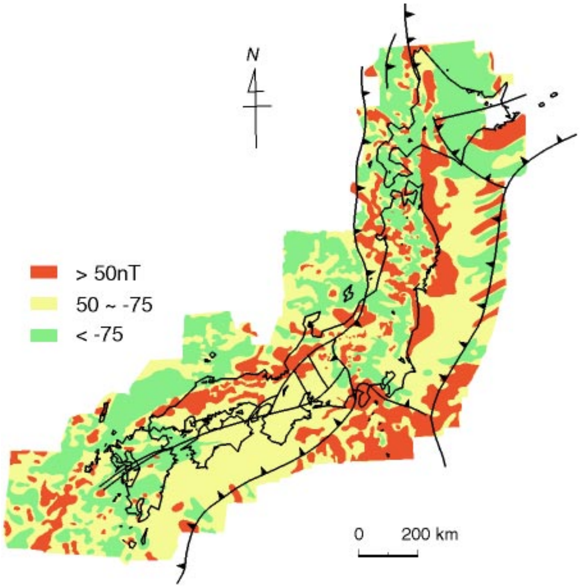


**Figure 10** Magnetic anomaly map of the arc system. The plate boundary distribution is overlaid for reference. (After Hagiwara 1991 and Geological Survey of Japan 1992.)

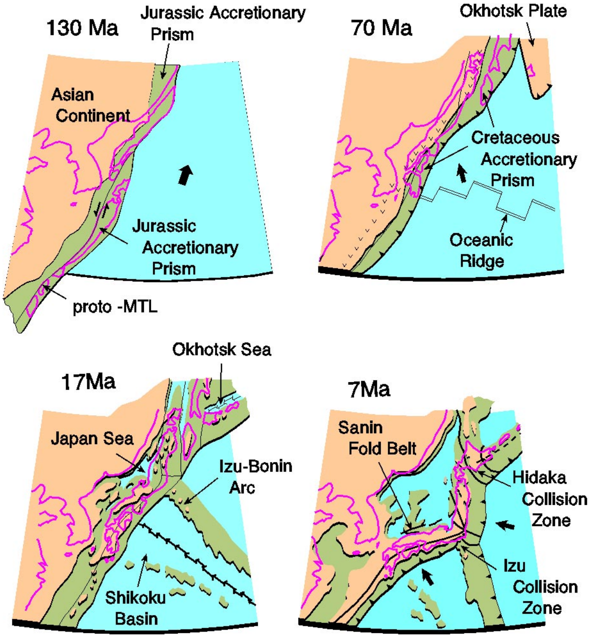
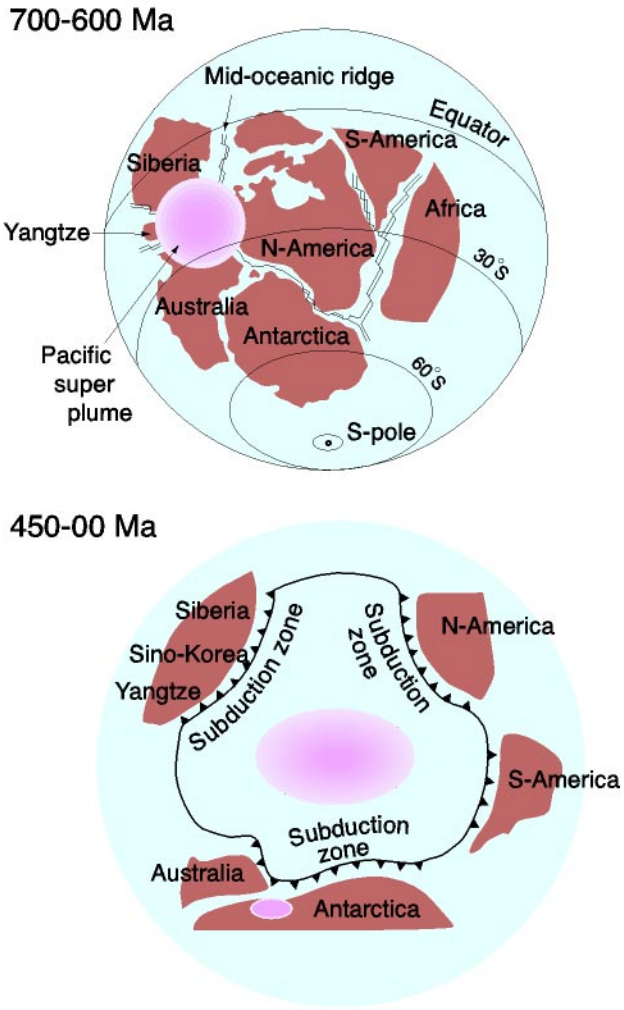


**Figure 11** Paleogeographic reconstruction since 130 Ma. (After Taira et al 1989.)



700-600 Ma

450-00 Ma

**Figure 13** A schematic model showing the breakup of a Late Proterozoic supercontinent by a Pacific super plume and subsequent evolution of the Pacific rim. (After Maruyama 1997.)

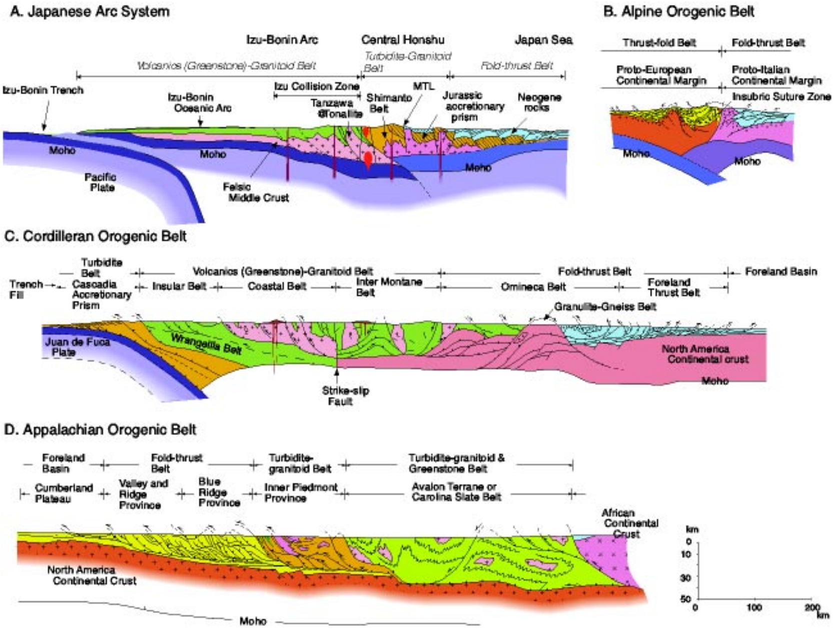


**Figure 14** Comparison of simplified cross sections of four Phanerozoic orogenic belts, all in the same scale. (*a*) The Japanese arc system (after Taira et al 1992b, 1998). See Figure 6 for the location of the cross section. (*b*) The central Alps (after Schmid et al 1996). (*c*) The southern Canadian Cordillera (modified after Cowan & Potter 1986 and Monger 1993). (*d*) The Appalachian orogenic belt in North Carolina (after Hatcher et al 1989).

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