Abstract The Japanese Islands represent a segment of a 450 million year old subduction-related orogen developed along the western Pacific convergent margin. The geotectonic subdivision of the Japanese Islands is newly revised on the basis of recent progress in the 1980s utilizing microfossil and chronometric mapping methods for ancient accretionary complexes and their high-P/T metamorphic equivalents. This new subdivision is based on accretion tectonics, and it contrasts strikingly with previous schemes based on 'geosyncline' tectonics, continent-continent collision-related tectonics, or terrane tectonics. Most of the geotectonic units in Japan are composed of Late Paleozoic to Cenozoic accretionary complexes and their high-P/T metamorphic equivalents, except for two units representing fragments of Precambrian cratons, which were detached from mainland Asia in the Tertiary. These ancient accretionary complexes are identified using the method of oceanic plate stratigraphy. The Japanese Islands are comprised of 12 geotectonic units, all noted in southwest Japan, five of which have along-arc equivalents in the Ryukyus. Northeast Japan has nine of these 12 geotectonic units, and East Hokkaido has three of these units. Recent field observations have shown that most of the primary geotectonic boundaries are demarcated by low-angle faults, and sometimes modified by secondary vertical normal and/or strike-slip faults. On the basis of these new observations, the tectonic evolution of the Japanese Islands is summarized in the following stages: (i) birth at a rifted Yangtze continental margin at ca 750–700 Ma; (ii) tectonic inversion from passive margin to active margin around 500 Ma; (iii) successive oceanic subduction beginning at 450 Ma and continuing to the present time; and (iv) isolation from mainland Asia by back-arc spreading at ca 20 Ma. In addition, a continent-continent collision occurred between the Yangtze and Sino-Korean cratons at 250 Ma during stage three. Five characteristic features of the 450 Ma subduction-related orogen are newly recognized here: (i) step-wise (not steady-state) growth of ancient accretionary complexes; (ii) subhorizontal piled nappe structure; (iii) tectonically downward-younging polarity; (iv) intermittent exhumation of high-P/T metamorphosed accretionary complex; and (v) microplate-induced modification. These features suggest that the subduction-related orogenic growth in Japan resulted from highly episodic processes. The episodic exhumation of high-P/T units and the formation of associated granitic batholith (i.e. formation of paired metamorphic belts) occurred approximately every 100 million years, and the timing of such orogenic culmination apparently coincides with episodic ridge subduction beneath Asia.

Key words: accretionary complex, Japan, microfossil mapping, microplate modification, oceanic plate stratigraphy, orogeny, paired metamorphic belts, ridge subduction, subhorizontal nappe, Yangtze.
INTRODUCTION

The modern Japanese Islands geographically comprise five island arcs: the Kurile, Northeast Japan, Izu–Bonin, Southwest Japan, and Ryukyu arcs, showing complex patterns common in the western Pacific. Four of these form segments of active island arcs between the Eurasian continent and the Pacific Ocean where the seafloor is currently subducting westward beneath Asia; the Izu–Bonin arc is the exception and forms an intra-oceanic arc (Fig. 1). Ongoing subduction processes along these margins add materials to and modify tectonic features of the Asian continental margin. Geological studies in the 1980s revealed that the Japanese Islands evolved under similar tectonic processes to those active today, and that major geologic units exposed on the islands are subduction-related products of the Late Paleozoic to Cenozoic orogenies.

It appears that the orogenic belts in Japan have widened oceanward by about 400 km in 450 million years, by virtue of long-term subduction of the Pacific seafloor along the Yangtze (South China) and Sino–Korean (North China) continental blocks. According to the classic categorization of orogenic belts by Dewey and Bird (1970), this 450 million year old orogen of Japan corresponds to a typical example of a Cordilleran-type orogen between a converging pair of continental and oceanic plates, that features a subduction complex, high-P/T schists and coeval granitic batholiths. The Cordilleran-type orogen is thought to originate from steady-state subduction of an oceanic plate beneath a continental plate, and contrast was emphasized between the Cordilleran-type and the Alpine–Himalayan style (or continent–continent collision-type) orogen. Although great variation in orogenic styles and possible plate tectonic mechanisms within the so-called Cordilleran orogenies has since been described, the distinction between the Cordilleran-type and collision-type orogens still appears justified.

Geologic and tectonic studies in Japan during the last two decades have clarified several new and significant aspects of oceanic subduction-related (or classic Cordilleran-type) orogens. New observations are highlighted in the following five characteristic tectonic features of Japan: (i) intermittent growth of accretionary complexes; (ii) subhorizontal nappe structure; (iii) downward younging polarity; (iv) episodic formation of a tectonic sandwich with a high-P/T unit; and (v) microplate modification. Particularly noteworthy is the episodic (non-steady-state) growth pattern of a subduction-related orogen without a collision of continent or

are because it clearly contrasts with the previous understandings on steady-state growth of the Cordilleran-type orogen.

This article reviews the latest version of the geotectonic subdivision of the Japanese Islands in view of these developments and discusses its tectonic implications. The implications of this review appear to impact also on subduction-related orogens in general. The new geotectonic subdivision is fundamentally adopted from the summary by Isozaki and Itaya (1991) and Isozaki and Maruyama (1991) published in Japanese, and is slightly modified to accommodate recent information. A historical review of studies of orogeny and geotectonic subdivision in Japan is also given in the appendix.

OCEANIC PLATE STRATIGRAPHY (OPS) ANALYSIS FOR ANCIENT ACCRETIONARY COMPLEX (AC)

Nearly 90% of the shallow-level crust of the Japanese Islands is occupied by Late Paleozoic to Mesozoic accretionary complexes and granitic batholiths. This observation suggests that the major orogenic framework of the islands formed at this time, and that the geotectonic subdivision of the Japanese supracrust depends mainly on the 3D configuration of the accretionary complexes and their high-P/T metamorphosed equivalents.

In this article, the term accretionary complex (AC) is strictly used in the following sense: an AC is a geologic entity which grows in situ in trench and trench inner wall in an active subduction zone as a result of subduction-driven layer-parallel shortening and vertical stacking/thickening of trench-fill materials usually composed of oceanic sediments and underlying volcanic rocks. This definition excludes continental blocks or island arcs, even though they once occurred in an oceanic domain prior to arrival at the continental margin. The term OPS is an acronym of ‘oceanic plate stratigraphy’ and this represents a sequence of sediments and volcanic rocks accumulated primarily on an oceanic plate prior to subduction-accretion at trench (Fig. 2). A full spectrum of an ideal OPS is comprised of, in ascending order: (i) MORB basalt; (ii) pelagic/hemipelagic sediments; and (iii) trench-fill turbidites, similar to the rocks recovered from drilling through modern trench floors. In modern examples, almost identical OPS is often preserved also in imbricated thrust packages in the trench inner-wall, that is, the youngest part in an AC. This unique stratigraphy was once called
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Fig. 1 Plate tectonic framework around the present day Japanese Islands. Major plate interactions are oceanic subductions along the Nankai trough off southwest Japan and along the Japan trench off northeast Japan. The former is an accretionary margin, while the latter is an erosional margin with a high convergence rate and rugged-surfaced oceanic plate. The Mariana trench represents another non-accretionary margin. According to the oblique subduction of the Pacific and Philippine Sea plates, southwestward moving fore-arc slivers develop in 3 domains, adding secondary across-arc structural features. The Miocene back-arc basin, Japan Sea, is under destruction along the convergent plate boundary between Eurasian and North American plates, while a new back-arc basin is emerging in the Ryukyus associated with rifting of the continental crust.

'plate stratigraphy' (Berger & Winterer 1974), however, the adjective 'oceanic' is added later in order to exclude sediments derived and accumulated exclusively on continental plate. Details of the concept of OPS and the practical example of the OPS analysis can be found in Isozaki et al. (in press b) and Matsuda and Isozaki (1991).

It is generally easy to recognize the occurrence of modern AC by seismic research simply because they occur immediately next to active trenches. Ancient examples exposed on land, on the contrary, have usually lost contact with their primary tectonic setting nor wedge-like 3D geometry through later overprinting processes, thus their recognition requires more specific information, not by external geometry but by internal structure and composition. The most reliable way to identify ancient AC, and to distinguish them from neighboring ones, is the 'OPS analysis' refined mainly in Japan in the 1980s.

Ancient AC exposed on land also possess OPS which usually consists of a sequence in ascending order of greenstones (less than several tens of metres thick), deep-sea pelagic chert (less than 200 m thick), hemipelagic siliceous claystone (less than 100 m thick), and terrigenous clastics such as mudstone and sandstone (more than 200 m thick). As most AC formed by the same tectonic process from deep-sea rocks and sediments, they are

Fig. 2 Simplified ridge-subduction system and the concept of Oceanic Plate stratigraphy (OPS) (modified from Matsuda & Isozaki 1991). Note the age gap between two distinct horizons (solid triangle: the horizon between pillowed MORB greenstone and pelagic chert marking the birth of oceanic plate, open triangle: the horizon between hemipelagic mudstone and terrigenous clastics marking the arrival at trench) which represents the total travel time of the subducting oceanic plate from mid-oceanic ridge to trench, in other words, the age of the subducting oceanic plate at trench.
best distinguished by accurate age determination. Documenting a well-dated OPS for an ancient AC provides significant information on the timing of accretion and the age of the subducted ancient oceanic plate. Microfossil (conodont and radiolaria) dating of component sedimentary rocks is particularly effective in OPS analysis for ancient AC exposed on land because it reveals (i) the accretion age at trench (i.e. age of the horizon between hemipelagic sediment and trench-fill turbidite); and (ii) an age of subducted oceanic plate responsible for the accretion (i.e. duration of pelagic + hemipelagic deposition) (Fig. 2). Thus if documentation of a unique OPS is available with precise dating, it can provide a prime identity for each ancient AC unit that appears as a look-alike to neighboring units.

The OPS analysis for on-land exposed ancient AC has played the main role in the drastic change in geological studies in Japan in the 1980s (Ichikawa et al. 1990), and the research style of detailed field mapping in 1:5000 scale combined with microfossil dating is here called ‘microfossil mapping’ of ancient AC. An interval of one microfossil zone is less than 5 million years in average for the late Paleozoic to Mesozoic, although their resolution for dating is less precisely controlled with few tie points in time scale. However, it is still generally quite useful to distinguish neighboring units in the field.

In addition, ages of metamorphosed AC of the ‘grey zone’ (see Appendix) that make microfossil dating difficult are determined radiometrically using various methods (K–Ar, Ar–Ar, Rh–Sr, and fission track). In some cases, an AC is accurately dated by two ‘radio ages’ (i.e. radiolarian-based accretion age and radiometrically dated age of subduction-related regional metamorphism). The subduction-related regional low-grade metamorphism usually occurred ~10–20 million years later than the former (Takami et al. 1990, 1993; Kawato et al. 1991; Isozaki in press b), and it can add another reference feature for comparison in OPS. This research style combining geochronology dating and detailed field mapping is here called ‘chronometric mapping’ of ancient AC.

Practical examples of these research styles applied to the Permian and Jurassic AC in SW Japan are reviewed in detail inIsozaki (in press a,b) and Kimura (1996).

GEOTECTONIC SUBDIVISION

The newly proposed geotectonic subdivision of the Japanese Islands based on these methods (Figs 3,4) is described here in four sections, based on domains in southwest Japan, the Ryukyus, northeast Japan, and east Hokkaido that are at present separated physiographically and/or tectonically by secondary transverse faults. The fundamental scheme of this subdivision is after Isozaki and Maruyama (1991), and is slightly modified according to the latest information. The Izu–Bonin Islands are not described in this article, as they form a young island arc of intra-oceanic nature and have lesser significance to the primary orogenic framework along the Asian continental margin.

In southwest Japan, including Kyushu, Shikoku and western Honshu Islands, the Cenozoic volcanosedimentary covers are thinner than those in other domains due to the rapid uplift in the Quaternary, and this allows extensive exposure of Late Paleozoic to Mesozoic AC and their metamorphic equivalents. The Ryukyus and northeast Japan can be essentially treated as lateral extension of southwest Japan, however, these domains were considerably modified and dislocated by secondary tectonism including movement of fore-arc sliver, back-arc spreading, and arc–arc collision. Thus these two domains will be briefly explained after southwest Japan as its lateral equivalents. The island of Hokkaido is characterized by a unique setting with an arc–arc collision between the Northeast Japan arc and Kurile arc. East Hokkaido that belongs to Kurile arc will be mentioned separately.

In the course of explaining geotectonic subdivision, the term ‘belt’ is used in this article to describe the distribution of geotectonic units in two dimensions. When a three-dimensional geologic entity is to be described, non-genetic terms like unit, body, block, complex, and nappe are used. The term ‘terranes’ is avoided here because it may be confused with a prejudicial connotation of allochtonosity (Coney et al. 1980; Howell 1985), which has been suggested by Sengor and Dewey (1991) and Hamilton (1991). Refer to Ichikawa et al. (1990) for more detailed descriptions and relevant references of pre-Cretaceous belts; and to Taira et al. (1988,1989) for those of much younger belts. In this long description section, readers interested in tectonics rather than local geology of the islands may read only the description of southwest Japan and skip those of the Ryukyus, northeast Japan, and East Hokkaido because the latter areas represent lateral equivalents of southwest Japan.

SOUTHWEST JAPAN

In southwest Japan the two-dimensional east–west trending zonal arrangement of various geologic
units is more obvious if surface cover and granitic intrusions are removed. Southwest Japan comprises 12 distinct geotectonic units (Fig. 5); from oldest to youngest; a 2.0 Ga–250 Ma gneiss complex; a 230 Ma intermediate-pressure type metamorphic complex; a 580–450 Ma ophiolite; a 400–300 Ma high-P/T schist; a 250 Ma AC; a 230–200 Ma high-P/T schist; a 180–140 Ma AC; a 120–100 Ma low-P/T metamorphic complex; a 100 Ma high-P/T schist, an 80 Ma AC; and a 40–20 Ma AC. These units are distributed in 15 belts, that is, from the Japan Sea side to the Pacific side: Oki belt; Hida b.; O-eyama b.; Renge b.; Akiyoshi b.; Sangun b.; Maizuru b.; Mino–Tanba b.; Ryoke b.; Sanbagawa b.; Northern Chichibu b.; Sanbagawa b.; Southern Chichibu b.; Northern Shimanto b.; and Southern Shimanto b. Repeated occurrence of the same unit in more than two belts (i.e. outliers in the form of klipps and/or tectonic windows as shown in Fig. 6) in southwest Japan causes a mismatch in the number of belts and geotectonic units. For example, the Jurassic AC apparently occur in three belts, that is, the Mino–Tanba b.; N. Chichibu b.; and Southern Chichibu b., separated from each other for up to 50 km, although these are identical in terms of OPS.

The three belts along the Japan Sea side, that is, the Oki, Hida and O-eyama belts, are intimately linked to Precambrian crusts in nature, and they form the core of the Phanerozoic orogen in southwest Japan (Fig. 3). On the other hand, the other 12 belts surrounding the above three represent zones of subduction-related accretionary growth that account for the 450 million year-long widening and thickening of southwest Japan.

The Oki belt of continental affinity is at present isolated from mainland Asia, as it was rifted and

Fig. 3 New geotectonic subdivision of the Japanese islands (modified from Isozaki & Maruyama 1991). The geotectonic subdivision of the Ryukyus and their correlation are shown separately in Fig. 8. Explanatory symbols for geotectonic units used in the figure and text are as follows: Southwest Japan [Rn. Renge belt; Sn. Sangun b.; Ak. Akiyoshi b.; Mr. Maizuru b.; Ut. Ultra-Tanba b. (included in Mz in text); M-T. Mino-Tanba b.; Ry. Ryoke b.; Sb. Sanbagawa b.; Ch. Chichibu b. (including Northern Chichibu b.; Kurosegawa belt, and Southern Chichibu belt in text); Sh. Shimanto b. (divided into Northern and Southern Shimanto belts in text); Northeast Japan [Ht-Tk: Hitachi-Takanuki b. (= Hida b.); Gs. Gosaisho b. (= Ryoke b.); MM. Matsugatara-Motai b. (= Renge b.); SK. Southern Kitakami b. (= Oki b.); Nk. Northern Kitakami-Oshima b. (= Mino-Tanba b.); Kk. Kamukotan b. (= Sanbagawa b.); Hdk. Hidaka b. (= Shimanto b.); Tokoro b. (= Sanbagawa b. + Shimanto b.); Nm. Nemuro b.]. Solid black area represents ophiolitic zone.
detached by the Miocene opening of a back-arc basin, the Japan Sea (Jolivert et al. 1994; Otofuji 1996, this issue). Judging from the lithologic/chronologic similarity to the Precambrian rocks of the Sobaesan massif in South Korea, the Oki belt is regarded as an eastern extension of the Yangtze (South China) craton (Sohma et al. 1990; Isozaki & Maruyama 1991) which represents one of the continental pieces rifted apart from the supercontinent Rodinia at 750-700 Ma (Powell et al. 1993; Li et al. 1995).

On the other hand, the kyanite-bearing Hida metamorphic rocks are regarded as the northeastern extension of the ultrahigh-pressure to high-pressure metamorphic rocks along the Qinling-Dabie suture (230 Ma continent-continent collision zone) in central China between the Yangtze and Sino-Korean (North China) blocks (Wang et al. 1989; Maruyama et al. 1994; Cong & Wang 1995). The unique occurrence of Middle to Late Paleozoic shelf strata with Boreal fauna in the periphery of the Hida belt (Igo 1990; Kato 1990) suggests a strong link between the Hida belt and Sino-Korean block. The present position of the Hida belt in the central part of Japan is due to later across-arc contraction and juxtaposition (Komatsu 1990), and the primary contact with the Oki belt (the Yangtze block) has been lost. Concerning the geotectonic correlation of the Oki and Hida belts with continental blocks and later tectonic juxtaposition, refer to Isozaki (in press a).

The 450–580 Ma ophiolite of the O-eyama belt along the southern margin of the Oki belt is the oldest oceanic material in Japan. As its easterly extension in northeast Japan has mid-Paleozoic sedimentary cover of continental shelf facies...
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Fig. 5  Geotectonic subdivision of southwest Japan (modified from Isozaki & Itaya 1991). Hatched areas represent occurrence of Paleozoic AC, and solid black areas indicate their tectonic outliers on the Pacific side (=Kurosegawa b). The Nagato-Hida Marginal tectonic line (b) separates the continental Oki belt from the younger Paleozoic-Mesozoic AC belts. The Ishigaki-Kuga tectonic line (f) divides Paleozoic AC belts and Mesozoic ones in southwest Japan. Note its winding surface trajectory indicating a low-angle nature as shown in Fig. 6.

(Ozawa 1988), the O-eyeama ophiolite probably represents a remnant of the initial oceanic crust that formed through the break-up of Rodinia at ca 750–700 Ma. Prior to the subduction regime started from 450 Ma at the latest, a piece of the initial Pacific ocean floor was likely attached to the rifted continental margin of the Yangtze block; that is, the Oki belt (Isozaki & Maruyama 1991). The occurrence of the medium-pressure-type amphibolite in the O-eyeama belt probably suggests its involvement in the 250 Ma collision event (Isozaki in press a). The lithologic assemblage, age, and other characteristics of these three units, with continental affinity, are briefly described.

1. Hida belt (Hd); 1.1 Ga to 250 Ma medium-pressure-type metamorphic rocks and 180 Ma granites (Sohma & Kunugiza 1993). The highest metamorphic grade reaches the upper amphibolite facies, only locally to the granulate facies. Protoliths of paragneiss are composed of sedimentary rocks that most likely accumulated along the passive continental margin. These include peraluminous siliciclastic rocks and impure carbonates with a minor amount of mafic igneous rocks. Non- to weakly metamorphosed Middle to Late Paleozoic shelf sequences occur fragmentally in the periphery of the belt; 2. Oki belt (Ok): 2.0 Ga to 250 Ma medium-pressure-type gneiss and granite complex (Suzuki & Adachi 1994). The highest metamorphic grade reaches the upper amphibolite to granulate facies. Protolith is continental sedimentary rocks with minor amount of mafic igneous rocks; 3. O-eyeama belt (Oe): 450 to 580 Ma dismembered ophiolite composed mostly of serpentinitized ultramafic rocks (Iherzolitic harzburgite), metagabbros, and a fragment of medium-pressure-type amphibolite (Arai 1980; Kurokawa 1985).

The belts 4–15 listed below are zones of subduction-related accretionary growth that practically account for the 450 million year-long orogenic widening and thickening of southwest Japan (Figs 5, 6) together with underlying granitic batholiths emplaced later. These AC belts including metamorphosed equivalents were successively added to the southeastern margin of the continent, in particular around the Yangtze block. A summary on OPS for these AC units in southwest Japan is shown in Fig. 7. It is noteworthy that the timing of accretion is generally getting younger oceanward from the 400 Ma meta-AC to the Miocene AC, and that the age of the subducted oceanic plate responsible for accretion has been considerably variable; from ~160 million years old for the Jurassic AC to almost zero for the Southern Shimanto AC. For a more detailed description of belts 5–7 and 12, refer to Isozaki (1996a); for a description of belts 8, 11 and 13 refer to Isozaki (in press b). 4. Renge belt (Rn): 400–300 Ma high-P/T schists and associated serpentinite (Nishimura 1990). The highest metamorphic grade reaches the high-pressure amphibolite facies through glaucophane schist facies. The protolith is an AC of unknown age composed of
greenstones, siliciclastics and chert; 5, Akiyoshi belt (Ak): Late Permian (250 Ma) AC composed of oceanic greenstones mostly of oceanic island basalt (OIB) origin, chert, reef limestone, and terrigenous clastics (Kanmera et al. 1990). This unit suffered from low grade regional metamorphism up to the lower greenschist facies at 220 Ma; 6, Sangun belt (Sn): 230–210 Ma high-P/T schists (Nishimura 1990). The highest metamorphic grade reaches the high-pressure amphibolite through the glaucophane schist facies. The protolith is an AC, probably containing a part of the 250 Ma Akiyoshi AC. Neighboring schist unit with problematic 200–180 Ma ages (probably secondarily annealed) are also included here; 7, Maizuru belt (Mz): Middle–Late Permian AC with 280 Ma ophiolite (Hayasaka 1990; Ishiwatari et al. 1990). The unit sometimes discriminated as the ‘Ultra-Tanba belt’ (Caridroit et al. 1981; Ishiga 1990) is included here. The ophiolite suite is dismembered but its primary thickness is estimated to be ~25 km; 8, Mino-Tanba belt (MT): Jurassic AC with a minor amount of latest Triassic and earliest Cretaceous parts (200–140 Ma) (Wakita 1988; Nakae 1993). This unit is composed of oceanic greenstones of OIB origin, deep-sea pelagic chert, reef limestone, and terrigenous clastics. Secondarily mixed AC (olistostromes and melanges) occur commonly. This AC unit is tentatively subdivided into three parts; (i) Early Jurassic part (accreted at 200 Ma; metamorphosed at 170 Ma); (ii) Middle Jurassic part (accreted at 170 Ma; metamorphosed at 140 Ma); and (iii) Late Jurassic part (accreted at 140–150 Ma; metamorphosed at 120 Ma); 9, Ryoke belt (Ry): 120–100 Ma low-P/T metamorphic rocks and associated granites (Nakajima in press). The highest grade part includes sillimanite-bearing gneiss. Pro-
70 Ma with eastward younging polarity along the Southwest Japan arc; 10, Sanbagawa belt (Sb): high-P/T metamorphosed Early Cretaceous AC (Banno & Sakai 1989; Takasu & Dallmeyer 1990), well known as the Sanbagawa schists. The highest grade reaches the high-pressure amphibolite facies and radiometric ages concentrate in 100–80 Ma. The high-P/T Sanbagawa belt and the low-P/T Ryoke belt (9) form paired metamorphic belts (Miyashiro 1961); 11, Northern Chichibu belt (Cn): Latest Triassic to Middle Jurassic AC equivalent to the older part of the Jurassic AC in the Mino–Tanba belt (8) (Hada & Kurimoto 1990). This unit is regarded as forming a tectonic outlier of the Jurassic complex of the Mino–Tanba belt; 12, Kurosegawa belt (Kr): Fault-bounded mixture of the pre-Jurassic elements (Yoshikura et al. 1990; Isozaki et al. 1992). Components of above-mentioned belts 3 to 7 occur chaotically as slivers, lenses and/or blocks of various sizes and shapes, enveloped within serpentinite matrix. As a whole, this unit represents a tectonic outlier of the pre-Jurassic rocks, which occurred on the Asian continent side; 13, Southern Chichibu belt (Cs): Early Jurassic to earliest Cretaceous AC equivalent to the younger part of the Jurassic AC in the Mino–Tanba belt (8) and partly to that in the Northern Chichibu belt (11) (Matsuoka 1992); 14, Northern Shimanto belt (Shn): Late Cretaceous scarcely metamorphosed AC composed mostly of terrigenous clastics with lesser amount of oceanic rocks (Taira et al. 1988). Sporadically intervened are thin tectonic slices of melanges that include oceanic greenstones and bedded chert within scaly argillaceous matrices; 15, Southern Shimanto belt (Shs): Paleogene and Miocene little metamorphosed AC composed mostly of terrigenous clastic rocks (Taira et al. 1988). A minor amount of tectonic melanges occur in this belt.

Major geotectonic boundaries in southwest Japan (Figs 5,6) are listed with their nature. Also noted in parentheses are well-documented examples of these boundary faults: (a) boundary between belts 1 and 2 (Hida b./Oki b.): low-angle thrust? (Unazuki suture) activated probably in late Mesozoic; (b) boundary between belts 2 and 3 (Oki b./O-eyama b.), and between belts 2 and 4 (Oki b./Renge b.); low-angle thrust (Nagato-Hida marginal tectonic line); (c) boundary between belts 4 and 5 (Renge b./Akiyoshi b.): low-angle thrust (Toyogadake thrust;
Kabashima et al. 1994); (d) boundary between belts 5 and 6 (Akiyoshi b./Sangun b.): low-angle thrust (Kitayama thrust), (e) boundary between belts 6 and 7 (Sangun b./Maizuru b.): unexamined; (f) boundary between belts 7 and 8 (Maizuru b./Mino–Tanba b.): low-angle thrust (Ishigaki–Kuga tectonic line); (g) boundary between belts 8 and 9 (Mino–Tanba b./Ryoke b.): high-angle normal fault (Arima–Takatsuki line, Iwakuni fault); essential contact: gradual metamorphic aureole; (h) boundary between belts 9 and 10 (Ryoke b./Sanbagawa b.): primary low-angle thrust (Paleo-Median Tectonic Line activated in the Tertiary) and secondary high-angle strike–slip fault (Neo-MTL active in Quaternary). (i) boundary between belts 10 and 11 (Sanbagawa b./N. Chichibu b.): low-angle thrust (Sasagatani fault; Kawato et al. 1991); (j) boundary between belts 11 and 12 (Northern Chichibu b./Kurosegawa b.): low-angle thrust (Agekura thrust, Nakatsu thrust) = oceanward extension of the boundary fault f (Ishigaki–Kuga tectonic line); (k) boundary between belts 12 and 13 (Kurosegawa b./Southern Chichibu b.): low-angle thrust (Kanbaradani thrust) = oceanward extension of the boundary fault f (Ishigaki–Kuga tectonic line). (l) boundary between belts 13 and 14 (S. Chichibu b./N. Shimanto b.): low-angle thrust (Butsuzo Tectonic Line, Tsaburo thrust; Sasaki & Isozaki 1992). (m) boundary between belts 14 and 15 (N. Shimanto b./S. Shimanto b.): low-angle thrust (Nobeoka thrust, Aki tectonic line).

THE RYUKYUS

On the basis of strong similarity of components, the Ryuku Islands are basically regarded as the southwestern extension of southwest Japan (Fig. 8), however, a north–south trending transverse fault clearly separates the Ryukyu Islands from Southwest Japan. This fault in west Kyushu Island sharply cuts off the zonal arrangement of southwest Japan. Right-lateral off-set of the Late Cretaceous high-P/T unit in mid-west Kyushu suggests the boundary fault between southwest Japan and the Ryukyus belongs to the right-lateral strike–slip fault system as well as the Tsushima fault and Yangshan fault in southeast Korea (Yoon & Chough 1995), probably formed in relation to the Miocene opening of the Japan Sea. This faulting leads to uncertainty in the primary geometry and nature of contact among the component units. However, a comparison with southwest Japan can help in the reconstruction of primary features of this domain.

Geological information on the Ryuku Islands is limited by the lack of exposures but some geotectonic units are well correlated with those in southwest Japan. Most of the units in this domain are composed of Late Paleozoic and Mesozoic AC and their metamorphic equivalents. There is no geotectonic unit with continental affinity in this domain except Early Paleozoic ophiolite in west Kyushu. According to dredging data, the East China Sea is underlain by Precambrian rocks that probably belong to the Yangtze (South China) craton.

The geotectonic units hitherto known from Ryukyus are listed below. For convenience, the numbering and symbols that were used for units in southwest Japan are also used to describe units in the Ryukyus: 3, metagabbro from Nomo point: 450–580 Ma ophiolite (=Oe) (Igi & Shibata 1979; Nishimura 1990); 6, Tomuru metamorphic rocks: 220 Ma high-P/T schists (=Sn) (Nishimura 1990); 8, Fusaki Formation: Jurassic AC (=MT) (Isozaki & Nishimura 1989); 10, Yuan Formation and Takashima schists: Early Cretaceous AC and 60–90 Ma high-P/T metamorphic equivalents (=Sh) (Ujiie & Hashimoto 1983); 14, 15, Kunchan Group: Cretaceous and Paleogene AC (=Sh) (Osozawa 1984).

The following two belt boundaries have been examined on land in Ryukyu: (f) boundary between belts 6 and 8 (Sn/MT): low-angle thrust (Ishigaki–Kuga tectonic line); and (l) boundary between belts 10 and 14 (Sb/Shn): high-angle fault (Butsuzo tectonic line).

NORTHEAST JAPAN

Northeast Japan comprises northeastern Honshu and the western Hokkaido Islands, and is separated from southwest Japan by a left-lateral strike–slip fault called Tanakura tectonic line (T.T.L.), and from eastern Hokkaido by a north–south trending fault in central Hokkaido, respectively (Fig. 3). Northeast Japan is also characterized by an apparent zonal arrangement of several geotectonic units on the surface (Fig. 9). This domain has been intensely modified by secondary tectonism, however, in particular by left-lateral strike–slip faults relevant to the Miocene opening of the Japan Sea. This faulting leads to uncertainty in the primary geometry and nature of contact among the component units. However, a comparison with southwest Japan can help in the reconstruction of primary features of this domain. Component units of northeast Japan are listed through comparison with those in southwest Japan, and short comments will be added for recent advances. As well as the Hida, Oki and O-eyama belts in southwest Japan, the three belts in northeast Japan, that is, the Hitachi–Takanuki b., Southern
Kitakami b., and Miyamori-hayachine b., have strong continental affinities, in particular to the Yangtze craton and the collisional suture between the Yangtze and Sino–Korean cratons. The rest are AC units which later accreted to northeast Japan.

1. Hitachi-Takanuki belt (Ht-Tk): 250 Ma medium-pressure metamorphics (Tagiri 1973; Hiroi & Kishi 1989). The protoliths include Late Paleozoic sedimentary rocks accumulated on the continental shelf and volcanic rocks of bimodal characteristics (=Hd). Granite-related thermal overprint occurred regionally at 110 Ma which is correlated to the Ryoke metamorphism in southwest Japan (=Ry); 2, Southern Kitakami belt (SK): 440 Ma granite and gneiss, 350 Ma and 250 Ma granites (=Ok) with Middle to Late Paleozoic sedimentary covers characterized by marine fauna of Australian (Gondwanan) affinity (Suzuki & Adachi 1993; Kawamura et al. 1990; Kato 1990); 3, Miyamori-hayachine belt (MH): 450 Ma ophiolite (=Oe) with Paleozoic sedimentary covers (Ozawa 1988; Okami & Ehiro 1988); 4, Matsugataira-Motai belt (MM): 300–400 Ma high-P/T schists (=Rn) (Maekawa 1981); 8, Northern Kitakami-Oshima belt (NK-Os): Jurassic AC (=MT) + Early Cretaceous AC (=Sb) (Minoura 1990; Okami & Ehiro 1988); 9, Gosaisho belt (Gs): 110 Ma low-P/T metamorphic rocks and granites (=Ry). Protoliths include components of the Jurassic AC (=MT) (Tagiri et al. 1993); 10, Sorachi–Yezo belt (SY): Early Cretaceous AC + 100 Ma high-P/T (Kamuikotan) schists associated with (Horokanai) ophiolite (=Sb); 14,
Idonnappu belt (Id): Early Cretaceous to early Late Cretaceous AC (= Sh); 14, 15, Hidaka belt (Hdk): Late Cretaceous to Paleogene AC (= Sh) partly metamorphosed into low- to medium-pressure type metamorphics associated with 50 Ma migmatite-granite.

Although several units are well correlated to their counterparts in southwest Japan, some of the units in southwest Japan are apparently missing in northeast Japan, such as Permian AC (5), 200 Ma high-P/T schists (6), and 280 Ma ophiolite (7). Their counterparts, however, may possibly be found also in northwest Japan in future as subsurface underlying units bounded by blind thrusts, owing to the subhorizontal structure mentioned below. The geotectonic boundaries between these units in northeast Japan are cut by a series of left-lateral strike-slip faults that were activated by the back-arc basin (Japan Sea) opening in the Miocene.
Japan are listed here: (i) boundary between belts 1 and 2 (Hitachi-Takanuki b./Southern Kitakami b.): unknown; (ii) boundary between belts 2 and 3 (Southern Kitakami b./Miyamori-Hayachine b.): vertical fault but primarily low-angle thrust (western margin of the Hayachine tectonic zone); (iii) boundary between belts 3 and 8 (Miyamori-Hayachine b./Northern Kitakami b.): vertical fault but primarily low-angle thrust (eastern margin of the Hayachine tectonic zone; Tazawa 1988).

The boundaries (ii) and (iii) appear almost vertical in outcrop but the large-scale sinuous trajectory on the surface suggests a potentially low-angle nature in deeper levels (Fig. 10). The zone between these two faults has been traditionally called the Hayachine tectonic zone because serpentinitized ophiolite occurs in an apparently narrow belt. The eastern margin of this zone ( = b) corresponds to the Ishigaki–Kuga tectonic line (f) in southwest Japan.

(iv) boundary between belts 1 and 9 (Hitachi-Takanuki b./Gosaisho b.): east-dipping low-angle fault probably activated before the intrusion of the Cretaceous granite; (v) boundary between belts 9 and 4 (Gosaisho b./Matsugataira-Motai b.): left-lateral strike-slip fault (Hatagawa tectonic line); (vi) boundary between belts 4 and 8 (Matsugataira-Motai b./Northern Kitakami-Oshima b.): left-lateral strike-slip fault (Futaba fault); (vii) boundary between belts 14 and 15 (Idonappu b./Hidaka b.): east-dipping high-angle thrust (Hidaka Main Thrust) on the surface that translates into a low-angle one in deeper level (Ikawa et al. 1995).

The faults (v) and (vi) are typical examples of sinistral strike-slip faults as well as the Hizume-Kesen'numa tectonic line that activated during the Miocene opening event of the Japan Sea along its eastern margin. These faults clearly cut the primary sinuous boundary faults such as the faults (ii) and (iii). The fault (vii) (Hidaka Main thrusts) represents another example of the secondary modification upon the primary structure, and this transpressional fault has been activated probably by ongoing westward collision of the Kurile fore-arc sliver (Kumiai 1985, 1996).

Due to severe secondary modifications, primary orogenic structures in northeast Japan have not been fully clarified, however, an analogy in rock type, age and OPS of AC to southwest Japan suggests that a similar subhorizontal piled nappe structure also predominates in northeast Japan which may be represented by a series of subsurface blind thrusts (Fig. 10).

**EAST HOKKAIDO**

East Hokkaido has a rather complicated tectonic history compared to the rest of the Japanese Islands, probably reflecting its peculiar geotectonic condition, sandwiched between two Cenozoic back-arc basins, that is, the Japan Sea and Kurile basin (Fig. 1). The domain boundary between northeast Japan including West Hokkaido and East Hokkaido is inferred in central Hokkaido in the name of the Tokoro fault or Shibetu fault, however, its precise position, geometry and nature are unknown owing to thick Quaternary covers in between. Three geotectonic units are recognized in East Hokkaido, as described below (Fig. 11). There is no Paleozoic and Early Mesozoic unit in East Hokkaido, and this implies a unique geohistory for East Hokkaido: 13, Yubetsu belt (Yb): Cretaceous AC; 10, 14, Tokoro belt (Tk): Cretaceous AC and high-P/T metamorphic equivalents; 14, 15, Nemuro belt (Nm): Cretaceous-Tertiary shelf sequences with unknown basement probably composed of Mesozoic–Cenozoic crystalline rocks of arc affinity.

These three belts are separated from each other by north–south trending faults. The fault between the Tokoro and Nemuro belts has a strike-slip
nature, and this fault, called the Abashiri tectonic line, has activated in a right-lateral manner during the opening event of the Kurile back-arc basin. Refer to Kimura (1996) for further details.

The main problem in Hokkaido lies in how to interpret the origin of the parallel-running two coeval blueschists belts, that is, the Kamuikotan b. of northeast Japan and the Tokoro belt of East Hokkaido. The opposite younging polarity in AC units across the arc since the mid-Paleozoic. On the basis of the new geological data and the revised subdivision of the Japanese Islands, the geotectonic history of the Japanese Islands is summarized below. The history began with rifting of a supercontinent in the late Neoproterozoic, and was followed by a tectonic inversion shifting from an extensional (Atlantic-type) regime to a convergent (Pacific-type) regime around 500 Ma. Since then an oceanic subduction-related accretion regime has

GEOTECTONIC HISTORY OF THE JAPANESE ISLANDS

The time-space relationships among the orogenic units described here suggest that the Japanese Islands have grown oceanward by almost 400 km across the arc since the mid-Paleozoic. On the basis of the new geological data and the revised subdivision of the Japanese Islands, the geotectonic history of the Japanese Islands is summarized below. The history began with rifting of a supercontinent in the late Neoproterozoic, and was followed by a tectonic inversion shifting from an extensional (Atlantic-type) regime to a convergent (Pacific-type) regime around 500 Ma. Since then an oceanic subduction-related accretion regime has
Anatomy and evolution of Japanese Islands

The core of Japan, which began as a segment of the Yangtze continental margin. In addition, a fragment of the Sino-Korean continental block also participated in the orogenic growth of Japan after the 250 Ma collisional event (Isozaki in press a). These two continental blocks, particularly the Yangtze block, have played the most important roles in constraining the configuration of the Japanese Phanerozoic orogen.

Figure 12 summarizes this history from the birth of the islands at ca 700 Ma to their separation from Asia in the Miocene.

**BIRTHPLACE OF PROTO-JAPAN**

The Oki belt in southwest Japan and the Southern Kitakami belt in northeast Japan represents part of the oceanward growth of the islands. Figure 12 shows the 700 million years of geotectonic evolution of the Japanese Islands.

**At a glance**
- **Fig. 12** Series of simplified cartoons (a-g) showing 700 million years of geotectonic evolution of the Japanese Islands. (a) The birth of Japan along a Proterozoic rifted continental margin of Yangtze by the break-up of the supercontinent Rodinia and the birth of the Pacific Ocean at 750–700 Ma. (b) After widening of the proto-Pacific Ocean basin, tectonic inversion occurred to initiate an intraoceanic subduction zone off the rifted Yangtze margin around 500 Ma, leaving a small fragment of primitive oceanic crust (O-eyama ophiolite). (c) The arc-trench system was established by ca450 Ma and gave a calc-alkaline overprint on the fore-arc ophiolite. (d) The subduction zone matured to accommodate the oldest AC which corresponds to the protoliths of the 400 Ma high-P/T Renge schists. The high-P/T Renge belt together with coeval granite belt (fragmented) form the oldest set of paired metamorphic belts. (e) Successive oceanic subduction widened the accretionary edifice during the Late Paleozoic (the Renge and Akiyoshi belts). On the opposite side of the Yangtze block, another continental block (Sino-Korea) collided and thrust over the Yangtze at around 250 Ma. (f) Oceanward growth on the Pacific side continued during the Mesozoic and Cenozoic to widen and thicken the accretionary edifice in the form of subhorizontal piled nappes. The accretionary growth was punctuated by the episodic arrival of mid-oceanic ridge roughly every 100 million years, which generated 3 to 4 sets of sandwich structure of high-P/T nappes between low-pressure AC units above and below (e.g. Sangun and Sanbagawa belts; see text for details). (g) By the back-arc opening of the Japan Sea at 20 Ma, Japan detached from mainland Asia; a continental arc became an island arc. The Hida belt represents a remnant of the 250 Ma collision suture between the Yangtze and Sino-Korean blocks that partly features an ultrahigh-pressure metamorphic belt.
The relation of the Yangtze and Sino-Korean continental margins to proto-Japan goes back to nearly 750-700 Ma when it is believed that the supercontinent Rodinia started rifting apart (Hoffman 1991; Dalziel 1992; Powell et al. 1993). Judging from the patterns of radial dyke swarms and rifted basins (Park et al. 1995; Bond et al. 1984), the breakup of Rodinia was probably triggered by a superplume rising to the surface from the mantle boundary. Consequently, the proto-Pacific ocean was born in 750-700 Ma by the rifting of Rodinia, and several continental fragments, including the Sino-Korean and Yangtze blocks were dispersed in various directions (Fig. 12a). Due to similarities in Neoproterozoic to Cambrian stratigraphy, Laurentia (North America) and Australia are probably the conjugate continental block(s) to the rifted Yangtze margins (Li et al. 1995). However, the paleoposition of the Sino-Korean block with respect to Rodinia remains highly enigmatic. The birthplace of Japan was probably located somewhere in the northern periphery of Rodinia in mid-latitudes at about 700 Ma. Most of the dispersed continental fragments once again assembled to form another (semi-)supercontinent, Gondwana, about 500 Ma (Hoffman 1991; Dalziel 1992), however, some large blocks such as Laurentia, Siberia and Baltica were isolated from the supercontinental mass. Likewise, the absence of evidence for late Neoproterozoic to Cambrian collision in China suggests that both the Sino-Korean and Yangtze blocks, including proto-Japan, were also isolated from Gondwana, although Early to mid-Paleozoic faunal provincialism suggests that the Yangtze block (including proto-Japan) and Australia were close neighbors (Burrett et al. 1990; Kato 1990).

Due to limited exposure and later tectonic modification in Japan, there is little evidence to conclude that continental rifting, such as extensional fault system, rift-related bimodal volcanism, and rift-related sedimentary sequences were active at this time. Stratigraphical and paleontological studies suggest that the small distribution of Early to Middle Paleozoic (Ordovician to Devonian) terrigenous clastic/carbonate sequences in the periphery of the Hida belt, Hitachi-Takanuki belt, Southern Kitakami/Matsugataira-Motai belt, and the Kurosegawa belt all represent remnants of continental shelf facies accumulated along the rifted Proterozoic continental margins. The Korean peninsula and/or mainland China may have preserved such features of Rodinian rifting, however, further structural and stratigraphical analyses are needed.

INVERSION FROM PASSIVE TO ACTIVE MARGIN

With the exception of Precambrian gneissic clasts in younger sediments, the oldest unit of oceanic affinity in Japan is the 580 Ma ophiolite in the O-eyama belt, southwest Japan. Its occurrence in the periphery of the Oki belt (ancient Yangtze margin) suggests that this unit is a remnant of proto-Pacific oceanic crust. The O-eyama ophiolite and its equivalent in the Miymori-Hayachine belt in northeast Japan have a bimodal distribution of radiometric ages; one at 580 Ma and another at 480-450 Ma (Ozawa 1988; Nishimura & Shibata 1989). Isozaki and Maruyama (1991) explained the age distribution of the oldest ophiolite in Japan in the following way.

The tectonic history of the O-eyama ophiolite is two-fold: (i) following rifting with the emplacement of nascent oceanic crust, a MORB-like oceanic crust formed at the proto-Pacific mid-oceanic ridge around 580 Ma (Fig. 12a); and (ii) these rocks were then intruded around 450 Ma by calc-alkaline volcanism of arc affinity when a new intra-oceanic subduction was initiated (Fig. 12b,c).

O-eyama is regarded as the only example of a fore-arc ophiolite in Japan, while other ophiolitic rocks are regarded as accreted fragments of ancient seamounts, rises and plateaus (Isozaki et al. 1990b; Kimura & Maruyama in press). Between 580 Ma and 480 Ma, tectonics in proto-Japan changed dramatically from rift/ridge-related extension to subduction-related compression, and passive margins changed rapidly to active margins. This tectonic inversion probably corresponds to global plate reorganization, in particular to the opening of the proto-Atlantic (Iapetus) ocean on the opposite side of the globe. Acreton of the O-eyama ophiolite can be explained by either of the following two mechanisms: (i) initiation of a landward dipping subduction zone within the primary oceanic crust (see Fig. 12b,c); or (ii) collision of an island arc system from the ocean side and a reversal of subduction polarity.

ACCRETIONARY GROWTH OF THE JAPANESE ISLANDS

After the tectonic inversion around 500 Ma, proto-Japan began a state of accretionary growth that persists today. Within 50 million years after initiation of intra-oceanic subduction, the arc-trench system featured AC, high-P/T schists (metamorphosed AC), and granite batholiths (Fig. 12d,e) that is, in the Renge belt plus Kurosegawa belt (=tectonic outlier of the former) in southwest
Japan, and in Southern Kitakami and Matsugataira-Motai belts in northeast Japan. In particular, the oldest AC in Japan is the protolith of the 450–400 Ma high-P/T schists. The high-P/T schists and coeval granitic rocks are elements of a paired metamorphic belt (with a high-P/T belt on the ocean side and a low-P/T belt on the continent side; Miyashiro 1961).

Following the oldest 450 Ma unit, Late Paleozoic, Mesozoic and Cenozoic AC were formed through subsequent subduction. At least several major oceanic plates have subducted beneath the Yangtze margin, leaving more than 10 distinct AC belts. Numerous oceanic fragments derived from subducted oceanic plates, including deep-sea sediments and seamount-derived basalts/reef limestone, were accreted to Japan. Details of the accretion processes during the Permian and Jurassic periods are reported in Isozaki (in press a,b).

Accretionary growth apparently has been not continuous. Including the youngest AC now under construction along the Nankai trough off southwest Japan, total accretionary growth is nearly 400 km in across-arc width (Fig. 12f), not taking into account the material loss by subduction-erosion. Thus the overall AC-dominated orogen in Japan has grown oceanward for almost 400 km during the 450 million years (~100 km per 100 million years).

As all of the AC units in Japan were formed in situ by subduction along the Yangtze (South China) continental margin, they are autochthonous to Asia, with the exception of small oceanic fragments peeled off from subducting oceanic crust and accreted landward into AC (Isozaki et al. 1990b). It thus appeared that the Japanese islands do not represent a collage of ‘suspect or exotic terranes’ that had existed prior to subduction and accretion processes (Coney et al. 1980).

It was a mere 20 million years ago when the Japanese Islands obtained their present configuration through back-arc spreading (Fig. 12g). However, the accretionary growth of the Japanese Islands will likely continue until other continental blocks, such as Australia or North America, collide against Asia to form a future supercontinent (Maruyama 1994).

DISCUSSION

The newly revised geotectonic subdivision and reconstructed tectonic history of the Japanese Islands clarifies the properties of the Cordilleran-type orogenic growth. Five tectonic features are described following these observations in Japan. They are: (i) step-wise growth of AC; (ii) subhorizontal nappe structure; (iii) downward younging polarity; (iv) a tectonic sandwich of high-P/T metamorphic units; and (v) secondary tectonic modifications. These may represent the principal characteristics of subduction-related orogenic belts in general.

STEP-WISE GROWTH OF AC UNITS

The 450 million-year-old subduction-related history of the Japanese Islands is characterized by the intermittent formation of AC, clearly detected by OPS analysis (Fig. 7). Several intervals lack AC (Carboniferous–Early Permian, Early–Middle Triassic, and late Early Cretaceous), and this empha-
sizes the overall zonal (piled nappe) arrangement of AC in Japan (Figs 5, 6, 8–11). Secular changes in relative plate motion between the Asian continent (or its precursory fragment) and subducted oceanic plates may be responsible for such episodicity because AC cannot form from a highly oblique subduction or in an along-arc strike-slip regime (Maruyama & Seno 1986).

On the other hand, extensive modern AC can be constructed where a large amount of sediments are supplied and the subduction rate is moderately low. No accretion or tectonic erosion (subduction-erosion) occurs when a trench is starved of sediments or the subduction rate is too high (von Huene & Lallemand 1990; von Huene & Scholle 1991). Thus the apparent episodicity in the formation of AC in Japan may also indicate the episodic preservation of AC rather than formation. Nonetheless such episodic growth of AC is a primary characteristic of oceanic subduction-related orogens that persist for 100 million years or longer.

The formation of high-P/T metamorphic and coeval granitic belts also appears episodic as these occur in highly restricted time intervals. As they occur roughly every 100 million years, their formation may also be episodic and/or periodic.

In contrast, the classic concept of the Cordilleran-type orogeny proposed by Dewey and Bird (1970) assumed a steady-state orogenic process, including the simultaneous formation of subduction...
complexes (= AC), granitic batholiths, regional metamorphic belts, and relevant geologic structures. Later publications, however, emphasized the non-steady-state nature of the arc-subduction zone setting (Dewey 1980). Although various interpretations are given, causes for the episodicity in subduction-related orogeny has not been well clarified. A possible cause for the episodic exhumation of high-P/T metamorphosed AC and coeval granitic activity associated with low-P/T regional metamorphism will be discussed later.

**SUBHORIZONTAL PILED NAPPE STRUCTURE OF AC**

Most of the geotectonic boundaries between adjacent AC units in southwest Japan are low-angle faults, and therefore the AC units are considered to be piled nappes (Fig. 6). Recent microfossil/chronometric mapping documented the occurrences of regional klipps and windows of these nappes even in thickly vegetated areas. These observations indicate that the subhorizontal piled nappe structure governs the fundamental tectonic framework of the 450 million-year-old orogen in southwest Japan (this study; see also Hara et al. 1977; Charvet et al. 1985; Faure 1985). Primary orogenic structures in the Ryukyus and northeast Japan have not yet been fully mapped but a subhorizontal piled nappe structure controlled by subsurface blind thrusts has been predicted (Tazawa 1988; Isozaki & Nishimura 1989; Fig. 10).

To a first approximation, such a subhorizontal piled nappe structure is consistent with subduction-related deformations, particularly to the subhorizontal shortening caused by underplating through which new materials are added to the sole of the previously formed accretionary wedge through step-wise activation of a subhorizontal decollement. The size of an individual ancient AC nappe is nearly 200 km in width across the arc, similar to the size of the widest modern AC wedge (von Huene & Scholle 1991).

The documentation of a predominant subhorizontal structure in Japan is contrary to the traditional view that vertical tectonics dominated horizontal tectonics. There are, in fact, some along-arc vertical faults of strike-slip nature (Neo-M.T.L., T.T.L.), but most of them became active in the Cenozoic and were driven by microplate activities. The total amount of displacement along the vertical fault, however, is too small to account for the present zonal arrangement of belts in Japan that extend along the arc for more than 1000 km.

Subhorizontal piled nappe structures generally characterize continent–continent collision-type orogens, like the European Alps or the foreland fold-and-thrust belt in the Appalachian and Canadian Rocky mountains. Development of similar structures in an arc–trench setting dominated by subduction tectonics is noteworthy and should be tested in other AC-dominated orogens older than 100 million years.

**DOWNWARD YOUNGING POLARITY IN AC NAPPES**

The along-arc zonal arrangement of these ancient AC is most clearly demonstrated in southwest Japan (Fig. 14a). Remarkably, these AC show an oceanward younging polarity in map view without windows and klipps. In addition, ages of regional metamorphic belts and granitic batholiths also suggest an oceanward younging polarity. This apparent polarity is a function of the piled nappe structure of the AC (Figs 6,12f). Downward younging polarity is also recognized within an individual AC nappe; this was clearly demonstrated in the Jurassic AC, which comprises six or more subnappes (Isozaki in press b). Such oceanward and downward younging polarity is consistent with the growth patterns of modern AC.

Although detailed information is scarce, the Ryukyus and northeast Japan plus East Hokkaido also appear to display younging polarity. The present zonal arrangement in northeast Japan, however, does not fit with the oceanward younging polarity in southwest Japan (Fig. 14b). This is due to secondary strike-slip faulting related to the opening of the Japan Sea in the Miocene which modified the primary orogenic configuration.

**TECTONIC SANDWICH OF HIGH-P/T AC UNIT**

There are three geotectonic units composed of high-P/T schist in the Japanese Islands formed at around 450–300 Ma, 200 Ma, and 100 Ma. The 450–300 schists can be further subdivided into two distinct units. All of these high-P/T units also occur as subhorizontal nappes (Fig. 6). The most striking feature of the high-P/T nappes is their sandwich-like structure, where a high-P/T nappe is tectonically interleaved between two unmetamorphosed AC nappes (Maruyama 1990; Isozaki & Maruyama 1991). The nappes composed of high-P/T metamorphosed units can be traced laterally for more than 500 km along the arc, even though they are usually thinner than 2 km. For example, the 100–70 Ma Sanbagawa schists (Sb) occur as a
nappe sandwiched between the overlying Jurassic AC (MT) and the underlying Cretaceous AC (Sh) (Kawato et al. 1992; Sasaki & Isozaki 1992).

There are high pressure gaps between the high-P/T nappe in the middle of the sandwich and the adjacent AC nappes. These gaps, which are greater than several kilobars in pressure, correspond to 10–20 km of crustal thickness. In order to preserve these pressure gaps without metamorphic annealing, the tectonic insertion of the high-P/T nappe must have been rapid and caused by tectonic exhumation of a high-P/T nappe into a low-pressure domain. In fact, all of the high-P/T nappes are bounded by a set of subhorizontal faults along their top and bottom surfaces, however, the sense of dislocation between these faults is opposite. To compensate for the pressure gap between the hanging wall and foot wall, the upper fault is normal while the bottom fault is reverse. Synchronous activation of such paired faults is believed to result in the insertion of the thin high-P/T nappe into the low-pressure domain.

These observations strongly suggest that the exhumation of the high-P/T nappes was tectonic and episodic rather than caused by steady-state processes wherein buoyant uplift of a metamorphic domain together with over- and underlying unmetamorphosed units was proposed. This episodic tectonic exhumation mechanism called ‘wedge extrusion’ was first suggested by Maruyama (1990; see also Maruyama in press). A very similar model was also proposed for Himalayan medium-pressure gneisses by Burchfiel et al. (1992). The downward younging polarity among AC is not disturbed by the intermittent intercalation of high-P/T nappes. This suggests that subduction-driven burial of the protolith AC, high-P/T metamorphism, and tectonic exhumation of metamorphosed AC all occurred in the same structural horizon, likely along the Wadati-Benioff plane. The large-scale sandwich (containing a thin well-done steak) with downward younging polarity cannot be formed through any other known exhumation process (Suppe 1974; Cloos 1982; Platt 1986).

Based on radiometric ages determined by various methods, the timing of metamorphic peak temperature and the subsequent cooling history of high-P/T units in Japan (Itaya & Takasugi 1989; Nishi-
gests an eastward along-arc younging polarity for these intrusions (Nakajima et al. 1990; Kinoshita 1995). This observation is consistent with the oblique subduction of the Kula/Pacific ridge beneath Asia as mentioned above (i.e. northeastward passage of the TTR triple junction of the Eurasia/Kula/Pacific plates, because the subducted ridge-related slab window may have been a heat source).

The coincident timing of high-P/T nappe exhumation and granite belt formation suggests a causal relationship to ridge subduction. Further research is needed to elucidate the mechanism of the subhorizontal ejection of high-P/T nappes under a buoyant subduction regime induced by the movement of young oceanic crust. The preservation of high-P/T units in the fore-arc is possible even under high heat flow from the subducted ridge if the exhumation of the high-P/T nappe preceded the arrival of the ridge-crest at the trench. The metamorphic/cooling ages of the high-P/T unit (100-70 Ma) are slightly older than the subduction timing of the brand new oceanic plate (ca. 75 Ma), and this may support the interpretation provided above.

Prior to the 100-70 Ma event, exhumation of the high-P/T nappe occurred probably three times in the 600 million year history of the Japanese Islands (Fig. 15). Such episodic occurrences of the high-P/T sandwich structure suggests that these were also consequences of episodic ridge-subduction in the Paleozoic and early Mesozoic (Fig. 16). The distribution of pre-Cretaceous granites in Japan is highly limited; most of them are fragmented. Nonetheless the ages of the granites that are preserved suggest episodic formation of a granitic belt in the intervals of 450-400 Ma, 350 Ma, and 250 Ma.

If those three pre-Cretaceous geologic episodes are regarded as the result of episodic ridge subduction, the tectonic history of the Japanese Islands

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**Fig. 15** Simplified diagram of geotectonic profile of the Japanese Islands (modified from Isozaki & Maruyama 1991). Note the oceanward and tectonically downward younging growth of AC nappes including high-P/T blueschist (BS) nappe. Formation of the sandwich structure of BS nappe occurs intermittently, roughly every 100 million years, by the collision of granitic batholith belt with low-P/T metamorphic belt which is usually positioned ~100-200 km continentward from coeval BS belt. The intermittent oceanward propagation of the BS belt and granite belt appears to have occurred when mid-oceanic ridges episodically collided and subducted beneath proto-Japan.
can be simplified to 450 million years of oceanward accretionary growth punctuated four times by ridge subduction. For each event, granites and associated low-P/T metamorphic belts formed on the continent side of Japan, probably separated by 200 km or more from the coeval high-P/T schist belt (Fig. 15). The nearly 100 million year periodicity in sandwich formation may correspond to the consumption of a major oceanic plate dissected by mid-oceanic ridges on both sides. The Japanese Islands experienced subduction of at least five major oceanic plates (from young to old, Pacific, Kula–Izanagi, Farallon, an unnamed older oceanic plate, and the plate which originated during initial rifting; Fig. 16).

The anatomy of the subduction-related orogen in Japan and the tectonic interpretation of these structures strongly contradict earlier views of ‘Cordilleran-type’ orogeny. The most significant difference lies in the recognition of episodicity in orogenic activity related to ridge subduction. Previous models for exhumation of high-P/T units assumed a steady-state and long-term process related to subduction of the normal ocean floor. For such an oceanic subduction-related orogenic process involving episodic culmination by ridge subduction, Isozaki and Maruyama (1991) introduced a new term, ‘Miyashiro-type orogeny’. The name is given after Akiko Miyashiro’s outstanding contributions to subduction zone tectonics, particularly the first perception of paired metamorphic belts (Miyashiro 1961) prior to the birth of plate tectonics in the mid-1960s, and a keen perspective on ridge subduction and relevant geologic phenomena in the 1970s (Uyeda & Miyashiro 1974).

SECONDARY MODIFICATION: MICROPLATE TECTONICS

The primary orogenic structures of the Japanese Islands are controlled by the spatial arrangement of main components (i.e. ancient AC, regional metamorphic rocks and granitic batholiths). Subduction-related orogens in Japan are characterized by subhorizontal piled nappes of AC with downward younging polarity, and by the episodic occurrence of a sandwich structure of high-P/T nappes and unmetamorphosed AC. The primary orogenic features, however, were modified or destroyed in some cases by secondary tectonic processes. In particular, microplate-related tectonics has the profound ability to secondarily reorganize primary structures (Miyashiro 1982). In Japan, there are three important secondary tectonic processes (Fig. 17; fore-arc sliver movement, back-arc basin opening, and arc–arc collision) that are all orogenic manifestations of microplate activities (Isozaki 1989; Isozaki & Maruyama 1991).

A fore-arc sliver is a decoupled microplate of a frontal arc driven by a strike–slip component of the oblique subduction of an oceanic plate. In the Japanese Islands, there are three active fore-arc slivers (the South Ryukyu sliver, Nankai sliver in southwest Japan, and Kurile sliver in East Hokkaido; Fig. 1). Along-arc movement of fore-arc slivers can create three distinct features that destroy the primary orogenic edifice (i.e. along-arc strike–slip fault on arc-side margin, and across-arc compressional structure in front, plus an extensional one in rear of the sliver). The best example of an along-arc strike–slip fault is the Quaternary Neo-M.T.L. in the Kii peninsula and on Shikoku Island that demonstrates a remarkably linear surface trajectory for more than 500 km (Figs 3,5). This right-lateral strike–slip fault was driven by the westward movement of the Nankai fore-arc sliver (Fig. 17b), cutting the older low-angle feature of the Tertiary paleo-M.T.L. (Isozaki 1989; Yamakita et al. 1995; Fig. 6). This westward sliver translation is also associated with across-arc compression along the Bungo Strait between Shikoku
Anatomy and evolution of Japanese Islands

Fig. 17 Three representative modes of secondary modification of primary orogenic structure related to microplate tectonics (modified from Isozaki & Maruyama 1991). (a) Formation of syntaxis in the older accretionary orogenic system and accretion of exotic arc crust occur at an arc-arc collision front around the Izu peninsula where the Izu arc penetrates almost perpendicularly to the Southwest Japan arc. (b) Formation of along-arc strike-slip fault (Neo-M.T.L.) and across-arc extensional and compressional structure by along-arc movement of the Nanakai fore-arc sliver. (c) Formation of along-arc extensional structure (Miocene rifted basins with bimodal volcanism), compressional structures (thrusting along paleo-M.T.L.) and the strike-slip fault (T.T.L.) occurred when the Japan segment detached from mainland Asia through the rifting-opening of the Japan Sea. Note these Neogene to Quaternary structures have modified considerably the pre-existing major structures of the ca 450 Ma accretionary orogen.

and Kyushu Islands, and across-arc extension in Ise Bay. Across-arc compression related to a fore-arc sliver is best observed in the elevated Hidaka mountains in central Hokkaido. Kimura (1985) explained the exposure of lower crustal rocks of the Hidaka belt (Komatsu et al. 1989) as a tectonic manifestation of westward frontal collision of the Kurile fore-arc sliver to northeast Japan. Seismic reflection research (Ikawa et al. 1995) recently documented the crust-cutting detachment surface that dips eastward from the Hidaka main thrust (Fig. 11).

Back-arc spreading is another tectonic process that has occurred frequently in the western Pacific since the latest Mesozoic, and is also a powerful modifier of primary orogenic structures in Japan. For example, when the Japan Sea opened in the Miocene, it split pre-existing orogenic structures into several blocks (Figs 9,10,14). Although a certain amount of rotation was involved, the opening of the Japan Sea basin has been attributed to dislocation of a pair of north-south running strike-slip faults along the basin margin (Fig. 17c). The chaotic alignment of belts in northeast Japan is primarily due to the series of left-lateral strike-slips along the eastern margin of the Japan Sea. The T.T.L. presently dividing southwest Japan and northeast Japan, and the parallel Futaba and Hata-gawa faults are typical examples of an eastern margin strike-slip fault that obliquely dissects an older along-arc zonal arrangement. In contrast, a segment of the right-lateral strike-slip fault marking the western margin in east Korea was recently noted (Yoon & Chough 1995). In addition, a domain of compression in the fore-arc may have been associated with back-arc spreading (Fig. 17c). It is difficult to explain the side-by-side juxtaposition of the low-P/T Ryoke metamorphic belt and high-P/T
Sanbagawa metamorphic belt in modern southwest Japan (Fig. 5). These belts should have been separated from each other by at least 100–200 km when they formed in the Late Cretaceous arc-trench system (Fig. 18a). The origin of the low-angle Paleo-M.T.L. between these two belts (Fig. 6) may be related to development of a horizontal detachment surface in the arc crust and to trenchward dislocation of the upper crust along this surface, probably by back-arc spreading (Isozaki & Maruyama 1991; Fig. 18b). For further details on the opening of the Japan Sea, refer to Jolivet et al. (1994), Ototfuji (1996) and Yamashita et al. (1996). The present-day opening of the Okinawa trough (Kimura et al. 1988) is still in a nascent stage of back-arc spreading (Fig. 1). This extensional regime appears to propagate northward into mid-Kyushu (note the Beppu-Shimabara

![Diagram](image-url)
graben with active Aso and Unzen volcanoes), accordingly, Kyushu Island, now composed of several geotectonic units, may eventually split into two.

Arc–arc collisions are the third process that can modify the primary geotectonic structures in Japan. The ongoing collision of the Izu–Bonin arc against the southwest Japan arc is a typical example of this process (Fig. 17a). The northward buoyant subduction of an intra-oceanic arc can indent into a pre-existing orogenic structure, leaving a clear V-shaped mark called ‘orogenic syntaxis’, in the west of Tokyo (Fig. 4). In addition, the accretion of arc crust basement has been achieved in a step-wise manner, adding a significant volume in central Japan (Taira et al. 1989). Several tectonic blocks of intra-oceanic arc origin around Mt. Fuji (Amano 1986) thus represent bona fide ‘allochthonous or exotic terranes’ in Japan.

CONCLUSION

The Japanese Islands represent a segment of a Phanerozoic subduction-related orogen developed along the western margin of the Pacific Ocean. Significantly, this orogen has grown oceanward nearly 400 km during the last 450 million years. The anatomy of the Japanese orogen, best preserved in southwest Japan, is characterized by a subhorizontal piled nappe structure, which involves multiple AC nappes including those of high-P/T metamorphosed AC. Orogenic growth is unusual in that it includes: (i) step-wise growth of AC units; (ii) tectonically downward younging polarity; and (iii) intermittent sandwich structure of high-P/T nappes. Episodic subduction of mid-oceanic ridges (= migration of TTR triple junctions) appears to explain the episodic exhumation of high-P/T nappes and the formation of granite/low-P/T metamorphic belts every 100 million years. Microplate tectonic processes such as the movement of fore-arc slivers, back-arc spreading and arc–arc collisions, secondarily modified the primary structure of Japan.

In order to establish a general model for subduction-related orogenic processes, the new geotectonic model for the origin of Japan needs to be tested on other orogens formed in similar tectonic environments. For example, the occurrence of a subduction-related orogen characterized by a similar anatomy would be expected in Circumpacific Phanerozoic orogens in western North America, western South America, Western Antarctic, and eastern Australia, as the Paleo-Pacific ocean floor was subducted along these continental margins after the 750–700 Ma breakup of Rodinia. Reconnaissance studies (Sedlock & Isozaki 1990; Isozaki et al. 1992; Isozaki & Blake 1994) including a compilation of previous works for the Klamath–Franciscan belt in California (Isozaki & Maruyama 1992; Maruyama et al. 1992) suggests fundamental similarities between the geotectonic evolution of California and that of Japan. It appears promising to extrapolate the above-described new aspects and analyzing schemes for ancient AC to other orogenic belts of different time-space co-ordinates in the Earth’s history, including the Precambrian.

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APPENDIX: HISTORICAL REVIEW ON STUDIES OF OROGENY AND GEOTECTONIC SUBDIVISION OF THE JAPANESE ISLANDS

In order to establish a geotectonic subdivision for a particular region, conventional field mapping on a regional scale is essential, and this usually requires painstaking work by numerous geologists over an extended period of time, particularly in thickly vegetated regions like the Japanese Islands that are at a humid mid-latitude. In the 100-year history of geological research in Japan, many efforts have been made to synthesize all available geological information into an overall tectonic framework. Although later criticized and discarded, several outstanding geotectonic syntheses were compiled, and these all came together with the revised summary of the geotectonic subdivision of the Japanese Islands. The history of geological studies of the Japanese Islands can be roughly divided into four stages, based on the orogenic concept that governed the understanding of contemporary geologists; these are: (i) the pre-geosyncline concept stage (1865–1940); (ii) the stage of importing the geosyncline concept (1941–1955); (iii) the stage of popularization of geosyncline-based orogeny (1956–1975); and (iv) the stage of plate tectonics-based orogeny (1976–present).

The first stage is represented by activities of E. Naumann, B. Lyman and other foreign geologists who imported modern geology as well as other sciences to Japan immediately after the Meiji revolution in 1868, after two century-long diplomatic isolation. During this stage, foreign and domestic geologists recognized fundamental structures of the Islands, particularly major tectonic boundaries such as the Median Tectonic Line (M.T.L.) and Itoigawa-Shizuoka Tectonic Line (I.-S. T.L); how-
ever, the overall geotectonic subdivision of the Islands was still a rough sketch. In hindsight, this era up to the 1930s in Japan may be called a time of fundamental ‘find-and-describe’ in preparation for the following stage of importing the concept of the geosyncline.

During the second stage, T. Kobayashi was the first Japanese geologist to synthesize a grand view of the geotectonic evolution of the Islands on the basis of the stratigraphic and megafossil age data (Kobayashi 1941). He recognized most of the important geotectonic units currently known, but his subdivision (Fig. 19a) was strongly biased by the geosynclinal concept. In particular, he emphasized the importance of distinguishing orogenic phase in H. Stille’s sense. His summary was the first application of the then world-popular geosyncline concept to a terra incognita named Japan. His achievement, however, marks a prime milestone in geological studies in Japan and his subdivision provided a foundation for later works. One point to note is his emphasis on nappe structures throughout southwest Japan, as this idea was revived in the 1990s in the plate tectonic framework.

The third stage was governed by geologists of the post-World War II generation who strongly criticized Kobayashi’s summary. They emphasized the higher resolution and accuracy of their data set through detailed mapping and the advantage of their new tectonic models (Yamashita 1957; Minato et al. 1965; Ichikawa et al. 1970), however, their perspective was more or less the same as that of Kobayashi, that is, popularization of the classic geosynclinal concept with minor modification in the context of regional geology. Although the world according to fixism was still there, the quality of the regional geological description of the Japanese Islands improved much during this stage, with the use of megafossil dating, particularly fusulinid biostratigraphy. Regional distribution of geotectonic units and locations of mutual boundaries were clarified, and the geotectonic subdivision made in this stage appears very similar to the present one in map view except for ‘vertical’ major boundary faults (Fig. 19b). Accordingly, sporadically exposed older mid-Paleozoic rocks, including high-grade metamorphic rocks and serpentinites, were all explained as geosynclinal basement rocks squeezed out from deeper levels along putative ‘crust-penetrating vertical faults’. In the early 1970s, several avant-garde geologists from Japan were the first to propose plate tectonic interpretations for the evolution of the Japanese Islands, with special emphasis on subduction-related tectonics (Matsuda & Uyeda 1971; Uyeda & Miyashiro 1974). The majority of scientists, however, still held conservative understandings linked to the geosyncline concept, and the geotectonic subdivision was not revised from the plate tectonic viewpoint.

The most significant reform in the geotectonic subdivision occurred in the fourth stage. Nearly a decade after the fundamental construction of plate tectonics in the late 1960s, younger Japanese geologists started to prefer mobilism rather than fixism. Down a long and winding road with many arguments, including the conversion from a geosynclinal world to a plate tectonics world, both in individuals and in society (Kanmera 1976), re-

Fig. 19 Classic examples of geotectonic map and profile of the Japanese Islands (modified from (a): Kobayashi 1941, (b): Ichikawa et al. 1970). Compare these classic geotectonic subdivisions and profiles backgrounded by geosynclinal viewpoint with the current version shown in Figs 3, 4. Before 1975, major geotectonic units in Japan were all explained as Precambrian sialic basement and overlying Paleozoic to Mesozoic geosynclinal sediments. Hd. Hida b., Ok. Oki b., Cq: Chugoku b., Mz: Maizuru b., MT: Mino-Tanba b.; Ry: Ryoke b.; Sb: Sanbagawa b.; Ch: Chichibu b.; Hd: Hidagawa b. (= Sh: Shimanto b.); Mr. Muro b. (= NK: Nakamura b.); Km: Kitakami marginal b.; Kt: Kitakami b.; Sm: Soma b.; Ab: Abukuma b., As: Ashio b.; Jo: Joetsu b.
gional geologic information was constantly accumulated on a nationwide basis. The great reform came in two waves, the first one in the early 1980s and the second in the early 1990s.

The first wave was brought by two factors combined: (i) the remarkable enhancement in microfossil (conodont and radiolarians) biostratigraphy, in particular the high resolution dating of the pre-Cretaceous or ‘so-called Paleoozoic eugeosynclinal sedimentary rocks’ in Japan (Koike 1979; Isozaki & Matsuda 1980; Tanaka 1980; Yao et al. 1980, Yamato-Omine Research Group 1981; Nakaseko et al. 1982); and (ii) the acceptance of a subduction-accretion concept (Kanmera 1980; Taira et al. 1983) which was constructed mainly through deep-sea drilling and regional seismic profiling on modern AC. As a result, most of the ‘so-called Paleoozoic eugeosynclinal rocks’ in Japan were revealed to be Jurassic AC by the mid-1980s. Age of accretion for each AC unit was precisely dated, and this enabled mutual discrimination of neighboring and similar-looking Paleozoic to Cenozoic AC in Japan. This reform initiated a considerable redrafting of the geotectonic history of the Islands in terms of accretion tectonics, as well as their geotectonic subdivision. Utility of microfossil dating for ancient AC and the relevant results in geotectonic subdivision of Japan up to the late 1980s are summarized in Ichikawa et al. (1990).

On the other hand, concerning tectonic interpretation, the ‘allochthonous or suspect terrane’ concept (Jones et al. 1977; Coney et al. 1980; Howell 1985) invaded Japan in the early 1980s and allowed many geologists in Japan to believe the occurrence of exotic continental and/or oceanic blocks and to use the term ‘terrane’ to describe various orogenic units (Saito & Hashimoto 1982; Mizutani 1987; Ichikawa et al. 1990). On the geotectonic subdivision, the ‘terrane’-based understanding of the attitude of boundary faults between the orogenic units is of note because most of the ‘terrane boundaries’ were regarded as vertical faults of a strike-slip nature related to ‘terrane dispersion’ (Taira et al. 1983). The nappe tectonics, on the contrary, was revived also in the early 1980s, and its significance with subhorizontal boundary faults was emphasized by French and domestic geologists (Hara et al. 1977; Yamato-Omine Research Group 1981; Faure 1985; Charvet et al. 1985; Hayasaka 1987). French geologists, in particular, interpreted the nappe-related subhorizontal structure as a result of an ancient continent–microcontinent collision, however, evidence for the putative collided micro-continent per se was not persuasive. Independent from these works, relative plate motions were partly reconstructed for the late Mesozoic and Cenozoic Pacific region by Engebretson et al. (1985), and the correlation between the plate interactions in East Asia and orogenic events recorded in Japan was first discussed by Maruyama and Seno (1986). Owing to the mixed effects of these various interpretations and existence of problematic ‘gray zones’ mentioned below, understanding of the 3D structure and tectonic evolution of the Japanese orogen was in a state of confusion in the 1980s.

The second wave in the early 1990s that provided the final tool for redrawing the subdivision of the Islands came in the form of success in chronometric dating of weakly metamorphosed AC. AC well-recrystallized by regional metamorphism, such as the Sanbagawa blueschists, had already been dated by radiometric methods in the 1970s, however, less recrystallized metamorphic AC had not been dated at all owing to difficulty in mineral separation techniques. Similarly, while microfossil analysis is powerful in dating non- to weakly metamorphosed AC, those metamorphosed to the greenschists facies were mostly left untouched owing to difficulty in microfossil extraction. Such a dilemma had left a considerable number of undated weakly metamorphosed AC units, the ‘gray zones’, in Japan even after the 1980s, and this delayed the completion of the geotectonic subdivision of the Japanese Islands. In the late 1980s, an advanced technique of fine-grained mineral separation was developed (Nishimura et al. 1989) that solved the ‘gray zone’ problem (Isozaki et al. 1990a, 1992; Isozaki & Itaya 1991; Suzuki et al. 1990; Takami et al. 1990; Kawato et al. 1991). Not only did this permit the dating of the greenschist facies AC rocks, but it allowed subdivision of high-P/T regional metamorphosed units in the same basis as non- to weakly metamorphosed ones (Isozaki & Maruyama 1991). By 1993, most of the important geotectonic boundaries were clearly defined by age difference and were re-examined in the field. This clarified that these boundary faults, that is, the nappes, are essentially subhorizontal, except for several vertical ones of secondary origin. In other words, there is no deep crust-cutting vertical fault zones nor a collage of exotic terranes in Japan. The predominance in subhorizontal structures of the Japanese Islands are currently accepted by many, and are utilized, for example, in the latest version of a geologic map of the islands issued by the Geological Survey of Japan (1992).