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METAMORPHIC BELTS OF JAPANESE ISLANDS

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INTRODUCTION

In 1961 Miyashiro presented the concept of paired metamorphic belts based on the mode of occurrences of high-pressure metamorphic belts along the Circum-Pacific orogenic belts, particularly in Japan. According to him the Japanese islands are composed essentially of three paired metamorphic belts: the late Paleozoic Hida–Sangun and late Mesozoic Ryoke–Sanbagawa pairs in Honshu, and the late Mesozoic Kamuikotan–Hidaka in Hokkaido. At that time he could use only 11 K-Ar mica ages.

Detailed petrographic work has continued since that time, and many radiometric ages are now available in the literature. From the late 1970s to the early 1980s, two major breakthroughs were made in Japanese basement geology; the first was in conodont-biostratigraphy followed by radiolaria-biostratigraphy, and the second was due to the increased productivity of K-Ar dating. Finally, the geosyncline concept was abandoned, and has been replaced by plate-tectonics approaches for explaining why particular metamorphic belts are located where they are today. Uyeda & Miyashiro (1974), Saito & Hashimoto (1982), and Maruyama & Seno (1986) pioneered this research. These and later works revealed that many metamorphic areas actually consist of several units.

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We will use the terms "belt" for an elongated metamorphic area, and "unit" for a metamorphic area of any shape and size. Both a belt and a unit may be terrane rooted in the lithosphere or a thrust sheet. A unit may also be a tectonic block having a distinct *P-T-t* path. "Zone" is used to denote a geologically distinct area, including regions of unmetamorphosed rocks. As Japan is an island arc, many geological units occur as a belt or zone rather than as a circular area.

After a general review, we will introduce recent petrological works of three belts from well studied areas: the Sanbagawa, Ryoke, and Hidaka metamorphic belts. The first two may form a pair of late Mesozoic age, and the third represents a cross section through island arc crust. Brief reviews of the metamorphism of the Abukuma, Sangun, and Shimanto belts are available elsewhere (Banno & Nakajima 1991).

METAMORPHIC BELTS AND UNITS

In the Japanese Islands, metamorphic rocks occur in two modes; one forms a belt consisting of a single metamorphic unit, and the other is a zone where various metamorphic and unmetamorphosed units are mixed by tectonic processes in one way or another. Herein, the latter type of zone is denoted as a zone containing multiple metamorphic units. Figure 1 schematically shows the metamorphic belts of the Japanese Islands. The ages of protolith and metamorphism, and the baric type of each metamorphic belt are listed in Table 1. Those of zones with multiple metamorphic units are listed in Table 2. These belts and zones are briefly discussed below. The metamorphic geology and petrology of the Sanbagawa, Ryoke, and Hidaka belts will be reviewed in more detail in later sections. The details of the ages of metamorphic rocks in Japan will be published by T. Nakajima by mid–1992.

Zones Containing Multiple Metamorphic Units

As shown in Table 2, we designate the Hida Marginal, Kurosegawa, Nagasaki, and Motai-Yakuki zones as belonging to this category. Some other zones may be added to this category or eliminated. In these zones, various types of rock occur as fault-bounded blocks or inclusions in serpentinite. A typical example is the Hida Marginal zone, where high-pressure schists of ca. 320 Ma, eclogite, granitoid of 400 Ma, low- to medium-pressure garnet amphibolite and metagabbro of 400–440 Ma, and serpentinite occur along with the fragments of the late Paleozoic Akiyoshi complex (Komatsu 1990).

The Kurosegawa zone includes unmetamorphosed Silurian and Devonian sediments and volcanics and various igneous and metamorphic rocks:

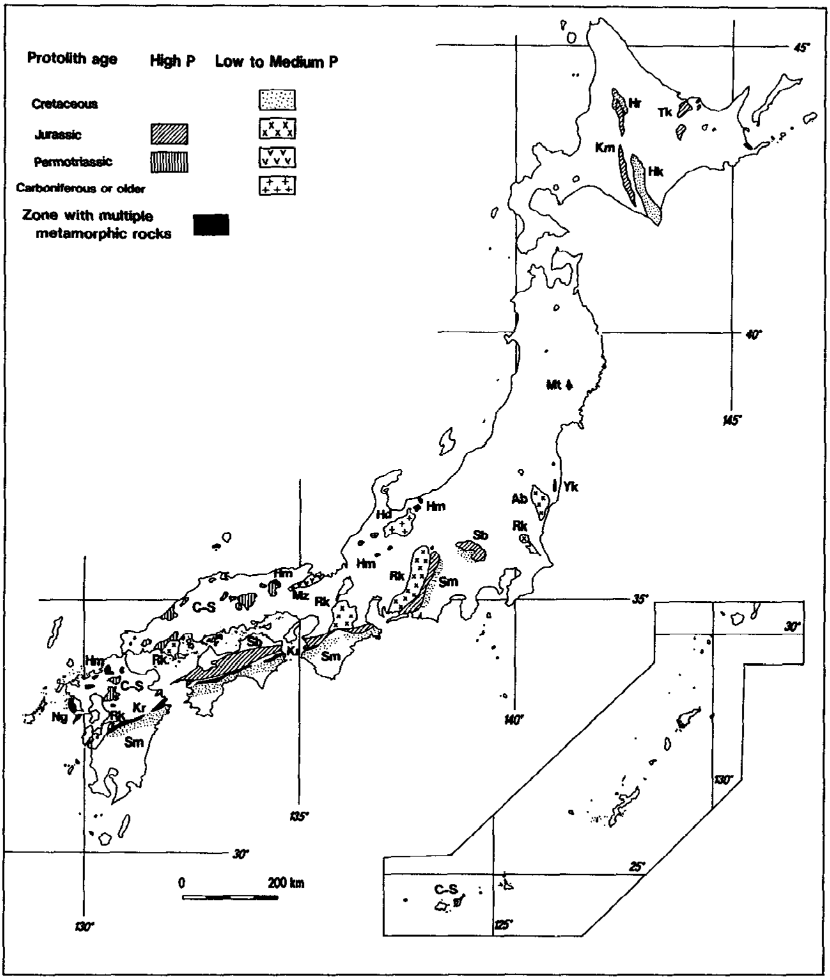

Figure 1 Metamorphic belts in the Japanese Islands. Abbreviations are: Tk, Tokoro; Km, Kamuikotan; Hk, Hidaka; Mt, Motai; Yk, Yakuki; Ab, Abukuma; Hd, Hida; Hm, Hida Marginal; Rk, Ryoke; Sb, Sanbagawa; Sm, Shimanto; Kr, Kurosegawa; Mz, Maizuru; C-S, Chizu-Suo; Ng, Nagasaki.

granitoid and gneiss of ca. 400 Ma, high-pressure schists with ca. 370, 310, and 210 K-Ar mica ages, staurolite-bearing and other medium *P*-*T* schists, garnet + cpx-bearing granulite, serpentinite, and low-grade schists of 185–230 Ma K-Ar muscovite ages. The 185–230 Ma schists are not associated with serpentinite and are developed in the northern part of the Kurosegawa

Table 1 Metamorphic belts of Japanese Islands—belts with single metamorphic units

Name	Baric type	Facies series†	Protolith	Metamorphic age (Ma)	References[d]
Tokoro	high P *a	PA/EG	Cretaceous	90-95 (K-Ar)	1
Kamuikotan tectonic block	high P *a ,c	LG/EG EA	Late Jurassic/Early Cretaceous	70-110 (K-Ar) 130-140 (K-Ar)	2, 3 3
Hidaka Main	low P	GS/AM/GR	Late Cretaceous/Paleogene	17-50 (K-Ar, Rb-Sr)	4
Hidaka West	low P	GS/AM/GR		17-24 (K-Ar)	4
Horokanai	low P	ZL/PP/GS/AM/GR	Jurassic	100 (^{39}Ar-^{40}Ar)	2
Abukuma	low P	GS/AM/GR	Jurassic and ?	90-116 (K-Ar, Rb-Sr, Sm-Nd) both metamorphics and granitoids	5
Hida-Oki	low P	AM/GR	?	170-240 (K-Ar, Rb-Sr) 410 (Sm-Nd)	6 7
Unazuki	medium P	GS/AM	Carboniferous	210-240 (Rb-Sr)	6
Yakuno (Maizuru)	low-medium P	PA/GS/AM	Permian	220-270 (K-Ar)	8
Suo	high P *b	PA/EG	Permian	200-240 (K-Ar)	9, 10 11
Chizu	high P *b	PA/EG	Jurassic ?	160-190 (K-Ar)	9
Ryoke	low P	GS/AM(/GR)	Jurassic	60-110 see text both metamorphics and granotoids	12, 13
Sanbagawa eroded unit	high P *b	PA/EG/EA/EC EA	Jurassic - ? ?	60-90 (K-Ar, ^{39}Ar-^{40}Ar) 84-157 (K-Ar, ^{39}Ar-^{40}Ar) see text	14 - 18 19, 20
Chichibu	medium or high P	PP?/PA	Jurassic	140 (K-Ar)	21
Shimanto	medium P ?	PP/PA/GS	Cretaceous/Paleogene	63-75 (K-Ar)	22

*a Aragonite stable but no jadeite+quartz.
*b Aragonite unstable but lawsonite and crossite.
*c Include jadeite+quartz in tectonic block.
† Abbreviation of facies name: ZL, zeolite; PP, prehnite-pumpellyite; PA, pumpellyite-actinolite; GS, greenschist; EG, epidote-glaucophane; EA, epidote-amphibolite; AM, amphibolite; GR, granulite; EC, eclogite.
For references, see Table 2.

Table 2 Zones containing multiple metamorphic units

Name	Age (Ma)	Rock types	References[d]
Kurosegawa	400-440 (K-Ar, Rb-Sr)	Granitoid, Garnet amphibolite, Gneiss	23, 24
	400 (K-Ar, Rb-Sr)	Garnet two mica schist, Staurolite schist	23, 24
	340-380 (K-Ar)	High pressure schist	25
	315-330 (K-Ar)	High pressure schist	25
	210-240 (K-Ar)	Jadeite-glaucophane schist	23
	above units occur associated with serpentinite		
	185-225 (K-Ar)	PP and PA schist, formerly regarded as Chichibu Group	15
Hida Marginal	240-426 (K-Ar, Rb-Sr)	Metagabbro, Amphibolite	7, 8, 26
	300-350 (K-Ar, Rb-Sr)	High pressure schist	9
	?	Eclogite, Garnet Amphibolite	
	370-420 (K-Ar, Rb-Sr)	Granitoid	
		Serpentinite	
Motai-Yakuki	280 (K-Ar)	High pressure schist	
	100 (K-Ar)	High pressure schist	
		Serpentinite-Peridotite	
Nagasaki	60-80 (K-Ar)	High pressure schist	
	440-480 (K-Ar)	Metagabbro, Serpentinite	8
		Serpentinite	

[d] List of major data source for Tables 1 and 2.

1. Sakakibara (1991); 2. Ishizuka (1987); 3. Imaizumi & Ueda (1981); 4. Osanai et al (1991); 5. Hiroi & Kishi (1989); 6. Shibata et al (1970); 7. Asano et al (1990); 8. Shibata et al (1977); 9. Shibata & Nishimura (1989); 10. Nishimura et al (1990); 11. Faure et al (1986); 12. Shiba et al (1979); 13. Nakajima et al (1990); 14. Itaya & Takasugi (1988); 15. Suzuki et al (1990); 16. Takasu & Dallmeyer (1990); 17. Isozaki & Itaya (1990); 18. Isozaki & Itaya (1991); 19. Takasu & Dallmeyer (1991); 20. Yokoyama & Itaya (1990); 21. Isozaki et al (1990); 22. Shibata et al (1988); 23. Maruyama et al (1984); 24. Hayase & Nohda (1969); 25. Ueda et al (1980); 26. Nishina et al (1990).

zone for several tens to one hundred kilometers in Shikoku as revealed recently (Isozaki & Itaya 1991). The Kurosegawa zone runs subparallel to Southwest Japan, but obliquely cuts the Sanbagawa and Chichibu belts in western Shikoku and Kyushu. Its tectonic interpretation has changed from time to time (Maruyama et al 1984, Taira et al 1983, Banno 1991). Recently, Maruyama et al (1990) and Isozaki & Itaya (1991) proposed that it is a tectonic outlier of the Hida Marginal zone, and the Suo and Chizu zones located on the top of the nappe sequence of Southwest Japan.

Other zones listed here are not as variegated as above, but still accompany several metamorphic units. The Nagasaki zone has a 60–80 Ma K-Ar age and an epidote-glaucophane type facies series along with metagabbro of 400–480 Ma hornblende K-Ar age as fault-bounded blocks.

Belts With a Single Metamorphic Unit

Among the metamorphic belts listed in Table 1, the Tokoro, Kamuikotan, Suo+Chizu, Ryoke, Sanbagawa, Chichibu, and Shimanto belts were derived from accretionary complexes. The Tokoro belt is predominantly a basic complex of possibly seamount origin. The high-pressure part lies in the albite-aragonite field with epidote-glaucophane at higher grade, but most of the area is occupied by zeolite to prehnite-pumpellyite facies (Sakakibara 1991). The Kamuikotan belt was derived from an accretionary complex, and is accompanied by 140 Ma tectonic blocks of garnet amphibolite. The coherent sequence is in the albite-aragonite field, but quartz+jadeite occurs in a few tectonic blocks.

Nishimura (1990) has demonstrated that the metamorphic rocks formerly called the Sangun belt actually consists of at least two distinct units, the ca. 300 Ma schist in northern Kyushu and in the Hida Marginal belt, and 160–230 Ma units with two apparent maxima, the Chizu unit of 180 Ma and the Suo unit of 220 Ma. They are considered to be a metamorphosed Permian Akiyoshi complex, but could include a Jurassic protolith in the Chizu unit. The 160–230 Ma unit also occurs in Ishigaki Island, Southwest Ryukyu (Nishimura et al 1989).

The Chichibu belt, which has been regarded as an unmetamorphosed equivalent of the Sanbagawa belt, is composed of three distinct units of ca. 120 Ma, 140 Ma, and 185–222 Ma (Isozaki & Itaya 1991). The ca. 120 Ma unit which occupies the northernmost part next to the Sanbagawa belt may be a part of the latter, but the 185–220 Ma unit is added to the Kurosegawa zone in Table 2. The significance of the 140 Ma unit is not clear. The redefinition of the Chichibu zone will be proposed in the near future, but in Figures 1 and 2, we include it in the Sanbagawa belt.

The Shimanto accretionary complex consists of Cretaceous and

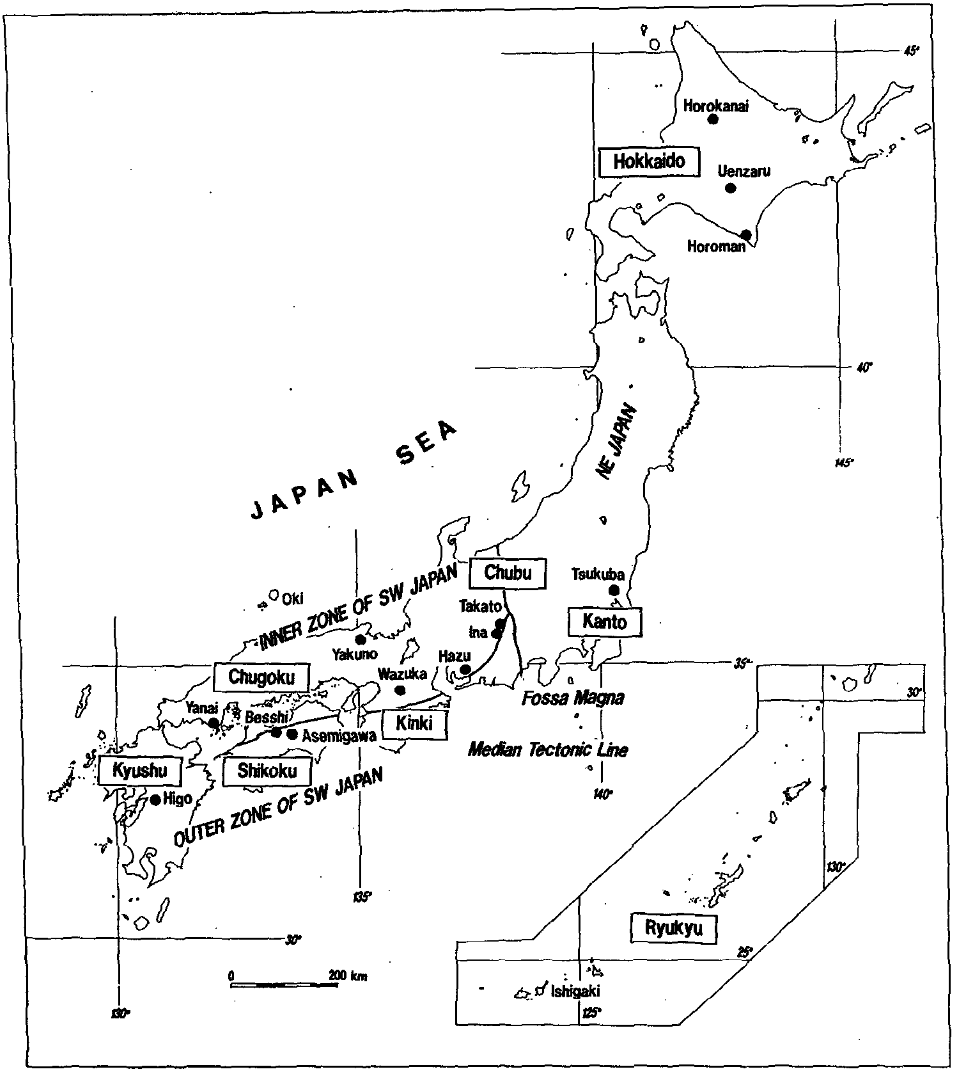

Figure 2 Locality names referred to in the text.

Miocene complex. Pumpellyite-actinolite facies phyllite develop locally in the former.

The Hida-Oki complex is made of gneiss of the amphibolite facies and locally of the granulite facies, and is intruded by granitoid of ca. 180 Ma.

Andalusite occurs but it is not certain whether its origin is due to regional or contact metamorphism. The Hida-Oki complex is expected and believed to be a part of the Precambrian Eurasian craton. This may well be correct, but a great many isotopic ages that have been collected in the past 30 years have revealed 180 and 220 Ma maxima in K-Ar ages, and 410 Ma Sm-Nd (Asano et al 1990) without providing any dated Precambrian metamorphism.

The Unazuki schists at the eastern margin of the Hida belt is the only kyanite-sillimanite metamorphic belt, and includes chloritoid and staurolite-bearing pelitic schists. It contains Carboniferous bryozoa and has a 220–240 isotopic age. The Unazuki belt is petrologically similar to the Ogcheon zone of Korea, and provides a clue for reconstructing the pre–Japan Sea geology (Hiroi 1983).

The central Abukuma metamorphic belt consists of the higher-grade Takanuki series—consisting predominantly of pelitic and psammitic gneiss, and the Gosaisyo series—predominantly with basalt which accompanies Jurassic radiolaria. The predominant facies series is the famous low-pressure type, ranging from greenschist to amphibolite and low granulite. Kyanite occurs locally in the Takanuki series, but has been ascribed to temporal high pressure caused by the obduction of the oceanic Gosaisyo series on the Takanuki series of an accretionary complex (Hiroi & Kishi 1989).

The Yakuno, Horokanai, and Hidaka West ophiolite have the common feature that the metamorphic grade increases with ophiolite stratigraphy until the granulite facies is reached at the peridotite layer. The Yakuno ophiolite is a higher pressure facies series than the others—as judged from the absence of prehnite-pumpellyite facies in it. The Yakuno ophiolite and overlying Permo-Triassic sedimentary rocks constitute the Maizuru zone, which thrust over the late Paleozoic ultra-Tamba and Mesozoic Mino-Tamba accretionary complex (Ishiwatari 1990).

The Birthplace of the Protolith and Metamorphic Belts

The geological and lithological features of the metamorphic belts mentioned above and certain paleomagnetic and paleontological features constrain the birthplaces of protolith and metamorphism.

1. The Japanese Islands were located at the Eurasian continental margin before 20–15 Ma, the date of the opening of the Japan Sea.
2. In Southwest Japan, the pile of nappe with younger accretionary complex lower in the sequence is a general feature (Hayasaka & Hara 1982, Charvet et al 1987).
3. High-pressure metamorphism took place in subduction zones.

4. The paleolatitude of oceanic components of the accretionary complex, such as the Mino-Tamba and Shimanto, is equatorial (Hirooka 1990).

Some metamorphic units, such as the Hida-Oki belt and the Takanuki series of the central Abukuma belt, may be fragments of the Asian continent, but the majority of Japanese regional metamorphic belts developed from accretionary complexes, composed of trench fill sediments and oceanic components transported from the south by the plates converging on the eastern border of Asia. During the middle Miocene, they split apart from the Asian continent and the Japan Sea opened.

This is the most simplified story and is tolerant to various modifications. For example, the present position could also be due to syn- or post-tectonic strike slip movement as exemplified by the Median Tectonic Line (MTL), which was left-lateral in the Cretaceous. Such movement may explain the chaotic mixing of assorted metamorphic units occurring in the zone with multiple metamorphic units. We don't know yet how much displacement of the MTL and other transcurrent faults occurred. This makes it difficult to answer the crucial question of whether or not the Ryoke and Sanbagawa belt were paired.

METAMORPHIC GEOLOGY AND PETROLOGY OF THREE PARTICULAR AREAS

Past petrological studies of Japanese metamorphic belts have already produced data characterizing their baric type and have briefly discussed the tectonics of the Japanese Islands. More elaborate *P-T-D* (deformation)-*t* paths of individual belts are necessary, however, to decipher what took place in the depths of orogenic belts. In this paper we focus on three particular Japanese metamorphic belts: the Sanbagawa and Ryoke belts which run on the south and north sides of the MTL for 700 and 1000 km, respectively, and the Hidaka belt in Hokkaido.

Sanbagawa (Sambagawa) Metamorphic Belt

The Sanbagawa belt underwent high-pressure intermediate type metamorphism, in which jadeite + quartz and probably aragonite were unstable, but epidote + crossite was stable. The petrology of this belt has been studied in most detail in central Shikoku, especially in the Bessi (Besshi) and Asemigawa areas. The metamorphic geology of the other parts of the Sanbagawa belt is more or less similar to that of central Shikoku, and the same mineral zones are used for their mapping.

PROTOLITH The main rock types of the Sanbagawa belt are metamorphosed basaltic rocks, shale, greywacke sandstone, chert, rare conglomerate, and limestone. These form a coherent sequence throughout the Sanbagawa belt. Bedded cupriferous-pyrite ore of the Bessi (Besshi)-type is also a member of this coherent sequence. In the higher grade area in central Shikoku, tectonic blocks of higher grade than the coherent schists occur. These are eclogitized gabbro, granulitized gabbro, dunite with garnet clinopyroxenite, and kyanite-bearing eclogitic mica schists (Takasu 1989). Only metabasite and meta-ultramafics were regarded as tectonic blocks.

Two types of datable fossils are known. One is Triassic conodonts in low-grade limestone, and the other is late Jurassic radiolaria in meta-volcanic sediments of the Mikabu Greenstone complex of Shikoku. As both are oceanic components, the depositional age in the trench should be younger than these ages (Isozaki & Itaya 1990).

METAMORPHIC ZONATION The areal distribution of metamorphic grades can be mapped in terms of the chlorite (Chl-z.), garnet (Grt z.), albite-biotite (Ab-Bt z.), and oligoclase-biotite zones (Ol-Bt z.) using pelitic assemblages. The chemistry of amphibole in basic schist is sensitive to metamorphic temperature and is used to define the grade of metamorphism. From low to high grade, the mineral zones and associated amphiboles species are: pumpellyite + actinolite (Chl z.), epidote + winchite + hematite (Chl z.), epidote + crossite + hematite (Chl z. Grt z.), albite + epidote + barroisite (Ab-Bt z.), and oligoclase + epidote + hornblende (Ol-Bt z.). X_{an} is ca. 0.15–0.28 in pelitic schists of the Ol-Bt zone. The tectonic blocks are now mostly equilibrated in the epidote amphibolite facies under the same physical conditions as the coherent sequence they were emplaced into. However, they also retain relics of the facies they once belonged to, namely the eclogite and granulite facies. A contact aureole is developed around the tectonic block of eclogitized metagabbro, Sebadani body (Takasu 1989). The *P-T-t* trajectories of two groups of Sanbagawa schists are shown in Figure 3. The retrograde trajectory in this figure is less steep than those previously given, because the retrograde trajectory locally passes the crossite field in central Shikoku (Hara et al 1990).

An inverted thermal structure has been recognized in Shikoku, where the biotite zone schists occur structurally within the garnet zone. Hara et al (1977, 1990) proposed that this is a part of a pile of nappes that formed in central Shikoku. However, so far, no distinct gap of metamorphic grade has been recognized in the whole of central Shikoku, even where a discontinuity is suggested from the structural and geochronological points of view (Banno & Sakai 1989).

GEOCHRONOLOGY The impact of isotope chronology has also been large with regard to the higher grade area. Itaya & Takasugi (1988) have shown

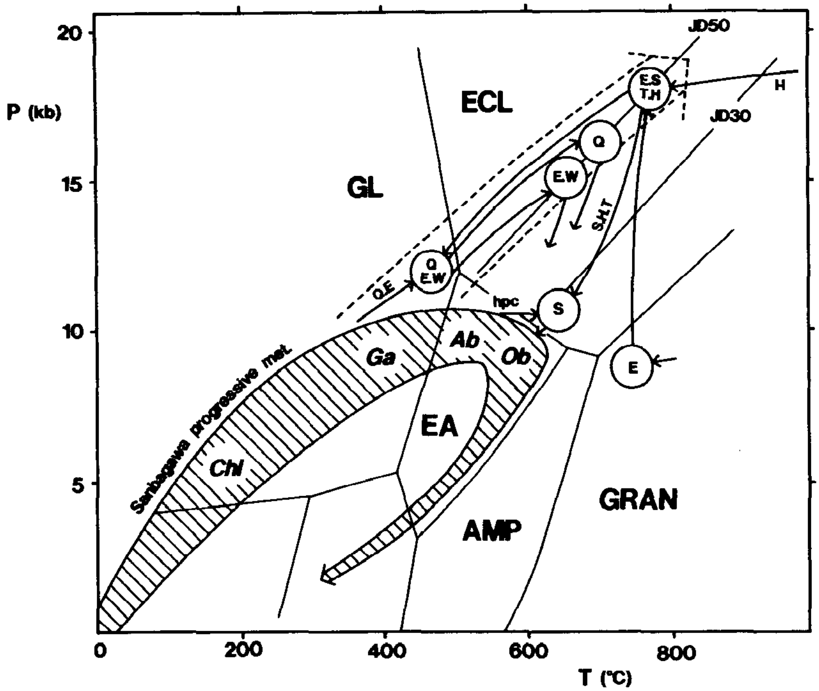

Figure 3 The *P-T* trajectory of the Sanbagawa progressive metamorphism and the tectonic blocks in central Shikoku (from Takasu 1989, Figure 2). ECL, GL, EA, AMP, and GRAN = eclogite facies, glaucophane schist facies, epidote amphibolite, amphibolite, and granulite facies, respectively. Sanbagawa progressive met. = metamorphic field gradient of the Sanbagawa progressive metamorphism. Chl, Ga, Ab, Ob = chlorite, garnet, albite-biotite, and oligoclase-biotite zones, respectively. S, T, W, E, H, N, and Q represent individual tectonic blocks. hpc = high-pressure contact metamorphism by the Sebadani (S) mass.

that the K-Ar muscovite age of the central Shikoku ranges from 67–90 Ma with a greater age for higher grade material. Takasu & Dallmeyer (1990) distinguish three groups of ^{40}Ar-^{39}Ar ages within the schists. The hornblende ^{40}Ar-^{39}Ar age fall in the 80 to 95 Ma range in most of central Shikoku, which they called the Besshi nappe. In contrast, the psammitic formation of the lower-chlorite zone (their Oboke nappe) has a muscovite ^{40}Ar-^{39}Ar age of around 70 Ma. They have further found ^{40}Ar-^{39}Ar isotope correlation ages of 133 and 160 Ma for hornblende in epidote amphibolite clasts in Eocene conglomerate overlying the Sanbagawa schists, and proposed the former existence of the Kuma nappe now eroded away. The Oboke nappe has similar radiometric ages to the Cretaceous through early Paleogene Shimanto accretionary complex, which developed to the south and in some places directly underlies the Sanbagawa belt. This led Hara et al (1990) to regard the Oboke nappe as a part of the Shimanto belt.

KINEMATIC STUDY Takagi & Hara (1979) described albite porphyroblasts that showed rotation about a N-S axis. Faure (1983) described a curvilinear fold including sheath folds in eastern Shikoku, and considered that the major movement of the schists was top to the east, which carried the Besshi nappe [nomenclature of Takasu & Dallmeyer (1990)] over the Oboke nappe. He considered that after the east-west flow, north-south compression gave rise to the exhumation of the Sanbagawa belt. On the contrary, Wallis (1990) considers that the major movement of the Sanbagawa belt in central Shikoku was top to the west, and that ductile deformation that post-dated the EW flow was only locally associated with high strain.

SCENARIO OF EVOLUTION Possibly in the late Jurassic to early Cretaceous, the protolith of the Sanbagawa belt was deposited in a trench along the eastern border of Asia. The subduction went as deep as 50 km to produce kyanite-bearing eclogitic mica schist, and associated eclogitized metagabbro. In the major part of the Sanbagawa schists, the coherent sequence reached around 10 kbars recorded in the zoisite + kyanite + quartz assemblage of metagabbro. At the time of peak metamorphism, the higher grade Ol-Bt and Ab-Bt zone schists were at lower pressure than the lower grade Grt zone (Banno et al 1986). This may sound unusual, but is possible if the isotherm in the subduction zone is inclined with respect to the isobar. Then followed a large scale top-to-west shear of the metamorphic belt, which gave rise to the formation of large sheath folds. The Sanbagawa schists have EW mineral lineation in both prograde and retrograde stages, suggesting their exhumation was accompanied by EW shear.

This scenario does not tell us where metamorphism took place. We know that the MTL was left-lateral in Cretaceous, but have no reliable estimate of the associated displacement. Thus, we are not certain whether the Ryoke and Sanbagawa belts were paired. Many models accounting for the exhumation of the Sanbagawa belt, which was largely completed by the Eocene, have been proposed: oblique subduction, collision of the alleged Kurosegawa continent and Eurasia, change of direction of plate motion, underplating by the Shimanto complex that is now developed south of the Sanbagawa belt, decoupling of the subducted ridge, etc (Maruyama 1990). Such events potentially may all have affected the tectonics of the Sanbagawa belt. However, none can account for the exhumation by itself. Much thought as to how and why it occurred is needed.

The Ryoke Belt

The Ryoke belt is a low-pressure, i.e. andalusite-sillimanite type, regional metamorphic belt accompanied by abundant granitoid. The metamorphic rocks of the central Abukuma Plateau were once considered to be a part of the Ryoke belt, but we will reserve this view since the former belt is much older (90–115 Ma) than the neighboring strict sense Ryoke belt (60 Ma). In the Ryoke belt the granitoids occupy a far larger area than the regional metamorphic rocks. The metamorphic rocks are confined to several areas, such as Kyushu (Higo), Yanai, Kinki (Wazuka etc), Chubu (Hazu, Ina, Takato), and Tsukuba.

PROTOLITH The Ryoke metamorphic rocks gradually change to the Jurassic Mino-Tamba complex, which is composed of Jurassic trench fill matrix and exotic chert, limestone, and greenstone of Carboniferous to Triassic. The greenstones and limestones are rare in the Ryoke belt except in western Kyushu. Epidote-glaucophane schists, probably of the Chizu and Suo zones were also affected by the Ryoke metamorphism in Kyushu.

GRANITOIDS The granitic rocks associated with gneiss and migmatite are commonly gneissose and intruded concordantly to the general trend of gneisses, while massive granitoids crosscut the trend of metamorphosed and unmetamorphosed rocks. Most granitoid in the Ryoke metamorphic belt is of ilmenite series and I-type, although some gneissose granitoid contain garnet and muscovite. The high-grade part of the Ryoke belt is a migmatite zone.

METAMORPHIC ZONATION AND THERMAL STRUCTURE Most of the Ryoke metamorphic belt can be mapped in terms of the chlorite, chlorite-biotite, and biotite zone for the lower- to medium-grade areas. In the Wazuka area, Wang et al (1986) has shown that biotite was first formed in psammitic rock by the reaction, K-feldspar + chlorite + quartz = biotite + muscovite + H_2O. Cordierite zone and sillimanite zone were used for medium to higher grade. In the Yanai area, the sillimanite stability field is further divided into two, lower-grade zones where sillimanite + biotite + Ksp is stable and a higher-grade cordierite–garnet zone where sillimanite + biotite is no longer stable. In the Ryoke belt, the first appearance of andalusite and sillimanite is not clearly differentiated. Muscovite breakdown and andalusite and sillimanite transition are often considered to have taken place at the same grade, but muscovite is rather common in much of the sillimanite zone. Probably prograde and retrograde muscovite have not been distinguished properly. In the Hazu area, where staurolite occurs in pelitic schist, the muscovite breakdown took place well within

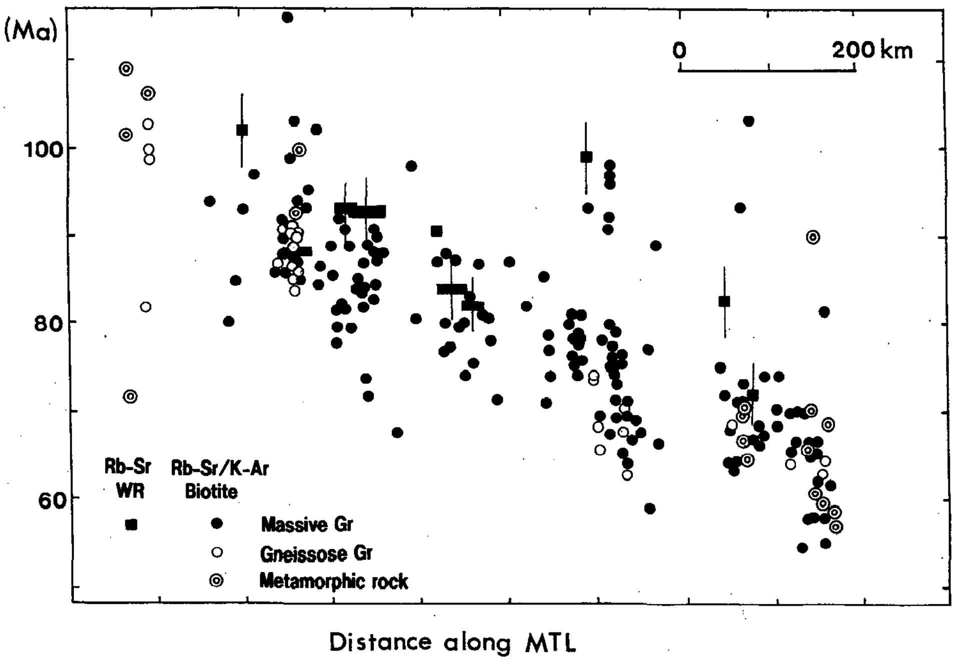

Figure 4 Along-arc lateral variation of radiometric ages of the Ryoke granitic and metamorphic rocks.

the sillimanite zone (Asami et al 1982). The amphibolite facies is the dominant highest grade but orthopyroxene-bearing rocks occur in western Kyushu (Yamamoto 1962).

Contact metamorphism around granitoid intrusion is common even in high-grade areas, but the regional isograd is independent of the shape of granitoid body.

The thermal axis of the metamorphic belt lies north of the MTL in the Yanai and Kinki regions, and coincides with the MTL in the Chubu region. In the Yanai region, the high-grade zone lies 50 km north of the MTL. The geobarometry in the Yanai area by Nakajima suggests 7–10 km burial of the sillimanite zone, implying a 50–70°C km^{-1} geotherm.

GEOCHRONOLOGY It is noteworthy that the isotopic age of Ryoke granitic and metamorphic rocks show a systematic along-arc decrease from 100 Ma in westernmost Chugoku to 60 Ma in Chubu (Nakajima et al 1990). Rb-Sr whole rock isochron ages were obtained for massive granitoid but not for gneissose granitoid and metamorphics. However, since the cooling history of these rocks—as indicated by K-Ar hornblende, biotite, and K-feldspar—are similar, we may assume that the age of massive granitoid is similar to the age of gneissose granitoid.

The Rb-Sr and K-Ar biotite ages of the granitic and metamorphic rocks follow the same eastward younging trend, with a 5 to 10 Ma time lag from the Rb-Sr isochron age for the entire Ryoke belt. Therefore, the tectonic setting responsible for the Ryoke magmatism and metamorphism cannot be explained by the steady subduction model and needs an episodic event such as the encounter of the Kula-Pacific ridge with the Eurasia plate and subsequent ridge-trench-trench migration along the eastern margin of the Asian continent.

Hidaka Belt in Hokkaido

The southwestern region of Hokkaido is geologically the extension of Northeast Japan, and its basement is composed of a Jurassic accretionary complex intruded by Cretaceous granitoid. However, the central and eastern parts of Hokkaido comprise metamorphic belts that are absent in Northeast Japan: the Kamuikotan high-pressure schists, the Horokanai metamorphosed ophiolite, the Hidaka belt, and the Tokoro belt. As is seen in Figures 1 and 2, the so-called Hidaka belt is divided into the Western belt ("zone" in Komatsu et al 1989) and Main belt (zone), respectively. The Western belt is a metamorphosed ophiolite, and the Main belt consists of island arc crust which thrust from east to west over the Western belt (Komatsu et al 1989). The metamorphosed ophiolite consists of gabbro, layered gabbro and ultramafic rocks, and tectonized peridotite, and is partly overturned. Its facies series includes greenschist, epidote amphibolite, amphibolite and lower granulite facies.

HIDAKA BELT, ISLAND ARC CRUST In Hokkaido, the tectonic debate has focused on whether the Hidaka belt is an island arc that collided with an island arc or was formed in situ in an accretionary prism that developed on the east of Northeast Japan, but further to the north. The Main belt is composed of two sequences, an upper metasediment sequence of two mica schist and two mica gneiss, and a lower sequence of basic and pelitic granulite, amphibolite intercalated with pelitic gneiss, and the hornblende gneiss which is the alternation of pelitic biotite gneiss and biotite amphibolite. These two sequences are thought to have been tectonically stacked within the accretionary complex. The lower sequence has abundant oceanic components, i.e. metabasite. The upper sequence is transitional to the unmetamorphosed Nakanogawa Formation of the Cretaceous (although Paleogene has been recently reported; see Kiminami et al 1990). Komatsu et al (1989) designated the major regional metamorphism as M0 stage.

According to Komatsu et al (1989), shear zones, which are developed at various levels and are layer-parallel and dextral, were formed by a D1 event—i.e. post-dating the major metamorphism. This was accompanied by retrograde metamorphism (M1) at slightly lower temperature than the M0 metamorphism. Thus D1 is a horizontal flow which could have detached the present Hidaka belt from the lowest crustal layer. The D2 phase deformation is represented by mylonite that develops at the base, i.e. at the contact with the Western belt. The mylonitization (M2) proceeded in the greenschist facies. Post-dating the mylonite, pseudotachylite was formed, filling veins that crosscut the mylonite (Toyoshima 1990).

Igneous intrusions are common. In the lower to middle structural level, S-type tonalite which locally contains abundant metamorphic enclaves, is common. I-type granitoid were intruded discordantly to both the upper sequence and concordant S-type granitoid. The granulite facies area includes high-temperature peridotite bodies, which are solid intrusions of mantle material. The Uenzaru and Horoman bodies, especially the latter, have been studied in detail petrologically.

METAMORPHIC ZONATION The mineral zones are not standardized. The zones shown in Figure 5 follow Komatsu et al (1989), who distinguished zones I, II, III, and IV in terms of the paragenesis of pelitic rocks. The characteristic assemblages are from the lower to higher grade as follows: chlorite+phengite, biotite+muscovite (+ And, Grt, Crd), biotite+garnet+sillimanite (+ Crd or Kfs), and garnet+cordierite+Kfs (+ Sil or Bt). However, Shiba (1988) who has worked in the southern part of the belt, distinguished five mineral zones for the area comprising zones II, III, and IV. The *P-T-D-t* trajectory by Osanai et al (1991) shown in Figure

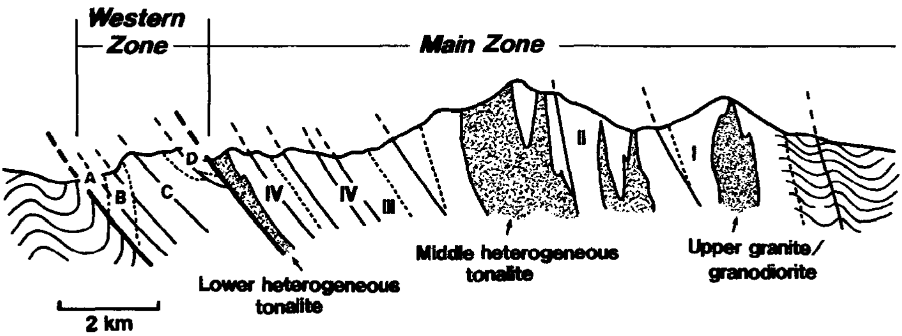

Figure 5 Cross section of the Hidaka belt (Komatsu et al 1989, Figure 1). I to IV and A to D represent metamorphic mineral zones in the order of increasing metamorphic grade, for the Main Zone and West Zone, respectively.

6 is similar to that of Shiba (1988). Both authors consider that the peak *P-T* path leaves the muscovite+quartz field in the andalusite field and goes to biotite+almandine ($X_{Mn} = 0.1$)+sillimanite field. The geothermobarometry suggests that granulite formed at 700°C and 7 kbar. Both of these authors postulate isobaric heating. Osanai et al's path for an indi-

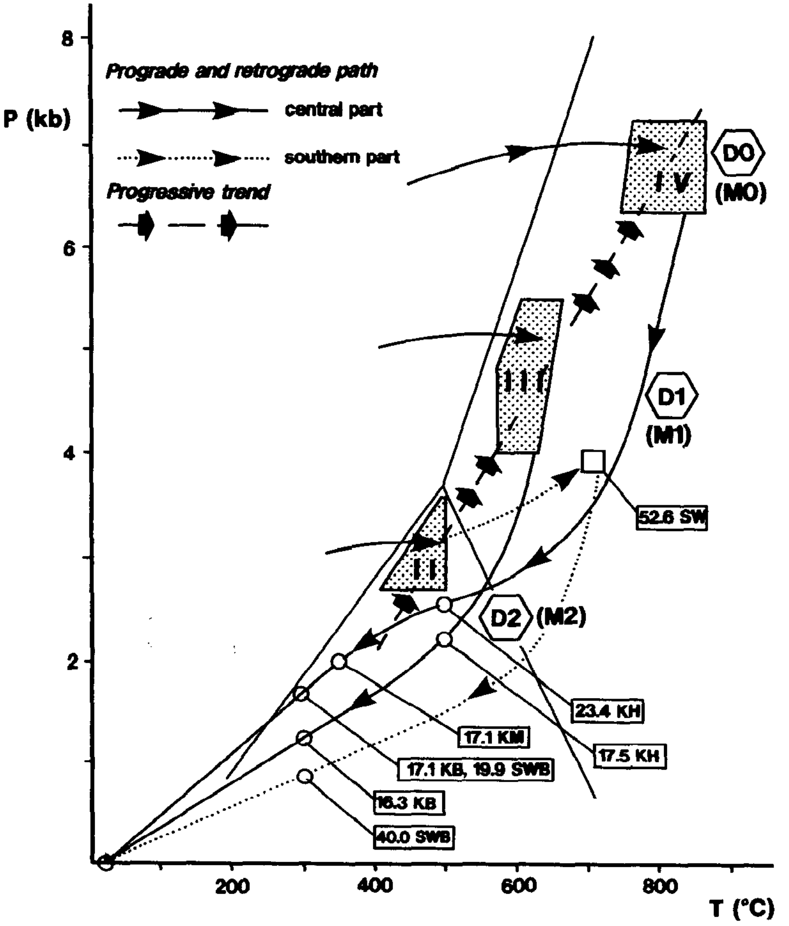

Figure 6 The *P-T-t* trajectory of the Hidaka Main belt (modified from Figure 7 of Osanai et al 1991). Metamorphic events of M0, M1, M2 and deformation events of D0, D1, D2 are shown. Arrowed dotted line shows the reheating process by granitic intrusion in the southern area. Numbers in the boxes are radiometric ages. K = K-Ar, S = Rb-Sr, W = whole rock isochron, H = hornblende, B = biotite, M = muscovite, and WB = whole rock-biotite isochron ages.

vidual zone goes from the kyanite to sillimanite field, whereas Shiba's proceeds from the andalusite to sillimanite field. This may be favored by a tectonic model with the accretionary prism being heated by a source such as the subducting ridge, but this has not been substantiated petrologically. The analysis of Osanai et al's staurolite breakdown fits a wide range of dP/dT. The sphalerite geobarometry on which Shiba (1988) bases his model is popular but faces serious doubt in its thermodynamic ground (Banno 1988).

MIGMATITE Migmatite is common in the granulite and amphibolite facies areas. The 700°C and 7 kbar estimated for the granulite and the presence of garnet + orthopyroxene + quartz with little K-feldspar suggests that partial melting occurred at such depth. However, Osanai et al (1991) did not consider that this anatexis formed magma that intruded into a shallower depth of the Hidaka belt. In addition to rock composed of leucosome and melanosome, there also occurs a quartz-rich pod of millimeter size objects, which are accompanied by idiomorphic and normally zoned plagioclase (X_{an} = 0.80–0.50), biotite, and rare K-feldspar. Tagiri et al (1989) considered this patch to be the melt produced in gneiss in situ. This could be due to the heat of tonalitic granitoid intrusion in the middle of the structural level (cf Osanai et al 1991). A general decrease of large lithophile elements in the granulite is reported (Ba, K, Sr depletion by Osanai et al; and Cs, Rb, K depletion by Tagiri et al). For us, however, it seems that only Cs, Rb, K, and Ba were depleted.

Much detailed work has been accumulated in the past 15 years. The Hidaka belt has granulite facies rocks at the structural bottom (west), and greenschist facies and unmetamorphosed rocks at the top (east), and presents an essentially continuous section of island arc crust. Much more research remains to be done on this unique example of island arc crust, which may help the modeling of the regional metamorphism and magma genesis in accretionary prisms, such as the Ryoke belt and possibly the Shimanto belt.

CONCLUDING REMARKS

The Japanese islands are composed of many metamorphic belts. Most of them were derived from late Paleozoic to Cenozoic accretionary complexes which developed along the eastern border of the Asian continent. They are either andalusite-sillimanite type, low-pressure metamorphic belts, or intermediate high-pressure belts where epidote + glaucophane and locally aragonite are stable. No regional jadeite-quartz area exists, though such an assemblage occurs in tectonic blocks in high-pressure areas.

Besides metamorphic belts consisting of a single metamorphic unit, there are regions where small areas and blocks of various metamorphic rocks are abundant within serpentinite and sedimentary sequences.

In these past 30 years, the study of the metamorphic belts of Japan has succeeded in allowing us to identify the geological and petrological characteristics of these belts. It is helping to establish a more quantitative understanding of regional metamorphism, which is the process going on in the depth of the orogenic zone underneath the continental margin.

Of course many problems await more extensive studies. The genesis of zones with multiple metamorphic units and the validity of the concept of paired metamorphism in Japan are two of the most urgent problems which in particular lie ahead of us.

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Literature Cited

Asami, M., Hoshino, M., Miyakawa, K., Suwa, K. 1982. Metamorphic conditions of staurolite schists of the Ryoke metamorphic belt in the Hazu-Hongusan area, central Japan. *J. Geol. Soc. Jpn.* 88: 437–50

Asano, M., Tanaka, T., Suwa, K. 1990. Sm-Nd and Rb-Sr ages of the Hida metamorphic rocks in the Wada-gawa area, Toyoma Prefecture. *J. Geol. Soc. Jpn.* 96: 957–66[1]

Banno, S. 1991. Metamorphism in island arcs—the Japanese islands. In *Dynamic Process of Material Transport in the Earth's Interior*, ed. F. Marumo, pp. 433–52. Tokyo: Terapub

Banno, S., Nakajima, T. 1991. Metamorphic belts of Japan. *Episodes*. In press

Banno, S., Sakai, C. 1989. Geology and metamorphic evolution of the Sambagawa belt, Japan. See Daly et al 1989, pp. 519–32

Banno, S., Sakai, C., Higashino, T. 1986. Pressure-temperature trajectory of the Sanbagawa metamorphism deduced from garnet zoning. *Lithos* 19: 51–63

Charvet, J., Faure, M., Caridroit, M., Guidi, A. 1987. Some tectonic and tectonogenetic aspects of southwest Japan: an alpine-type orogen in an island arc position. In *Formation of Active Ocean Margin*, ed. N. Nasu, pp. 791–817. Tokyo: Terrapub

Daly, J. S., Cliff, R. A., Yardley, B. W. D., eds. 1989. *Evolution of Metamorphic Belts*. Geol. Soc. London Sp. Pub. 43. 566 pp.

Faure, M. 1983. The Mesozoic orogeny in the outer zone of SW Japan in eastern Shikoku. *J. Gakugei, Tokushima Univ.* 34: 1–35

Faure, M., Monie, J., Fabbri, O. 1986. Microtectonics and ^{40}Ar-^{39}Ar dating of high pressure metamorphic rocks of the south Ryoko Arc and their bearing on the pre-Eocene geodynamic evolution of Eastern Asia. *Tectonophysics* 156: 143–66

Hayasaka, Y., Hara, I. 1982. *89th Ann. Meeting, Geol. Soc. Jpn.* Niigata. 556 pp.[2]

Hara, I., Hide, K., Takeda, K., Tsukuda, E., Shiota, T. 1977. Tectonic movement in the Sambagawa Belt. In *The Sambagawa Belt*,

[1] In Japanese with English abstract.
[2] In Japanese.

ed. K. Hide, pp. 307–90. Hiroshima: Hiroshima Univ. Press. 440 pp.[1]
Hara, I., Shiota, T., Hide, K., Okamoto, K., Takeda, K., et al 1990. Nappe structure of the Sanbagawa belt. *J. Metamorph. Geol.* 8: 441–56
Hara, I., Shiota, T., Takeda, K., Okamoto, K., Hide, K. 1990. Sambagawa belt. See Ichikawa et al 1990, pp. 137–64
Hayase, I., Nohda, S. 1969. Geochronology on the "Oldest Rocks" of Japan. *Geochem. J.* 3: 45–53
Hiroi, Y. 1983. Subdivision of the Hida metamorphic complex, central Japan, and its bearing on the geology of far east in Pre-Sea of Japan time. *Tectonophysics* 78: 317–33
Hiroi, Y., Kishi, S. 1989. P-T evolution of the Abukuma metamorphic rocks in northeast Japan: metamorphic evidence for oceanic crust obduction. See Daly et al 1989, pp. 481–86
Hirooka, K. 1990. Paleomagnetic studies of Pre-Cretaceous rocks in Japan. See Ichikawa et al 1990, pp. 401–6
Ichikawa, K., Mizutani, S., Hara, I., Hada, S., Yao, A., eds. 1990. *Pre-Cretaceous terranes of Japan.* Osaka: Osaka City Univ. 413 pp.
Imaizumi, M., Ueda, Y. 1981. On the K-Ar ages of the rocks of two kinds existing in the Kamuikotan metamorphic rocks located in the Horokanai district, Hokkaido. *J. Jpn. Assoc. Miner. Petrol. Econ. Geol.* 76: 88–92[1]
Ishiwatari, A. 1990. Yakuno ophiolite and related rocks in the Maizuru terrane. See Ichikawa et al 1990, pp. 109–20
Ishizuka, H. 1987. Igneous and metamorphic geology of the Horokanai ophiolite in the Kamuikotan zone, Hokkaido, Japan: a synthetic study. *Mem. Fac. Sci. Kochi Univ.* 8: 1–70
Isozaki, Y., Itaya, T. 1990. Chronology of Sanbagawa metamorphism. *J. Metamorph. Geol.* 8: 401–11
Isozaki, Y., Itaya, T., Kawato, K. 1990. Metamorphic age of Jurassic accretionary complex in the Northern Chichibu belt, Southwest Japan. *J. Geol. Soc. Jpn.* 96: 557–60[1]
Isozaki, Y., Itaya, T. 1991. Pre-Jurassic klippe in northern Chichibu belt in west-central Shikoku, Southwest Japan—Kurosegawa terrane as a tectonic outlier of the pre-Jurassic rocks of the Inner zone. *J. Geol. Soc. Jpn.* 97: 431–50[1]
Itaya, T., Takasugi, H. 1988. Muscovite K-Ar ages of the Sanbagawa schists, Japan and argon depletion during cooling and deformation. *Contrib. Mineral. Petrol.* 100: 281–90
Kiminami, K., Kawabata, S. Miyashita, S. 1990. Discovery of Paleogene radiolarians from the Hidaka Supergroup and its significance with special reference to the ridge subduction. *J. Geol. Soc. Jpn.* 96: 323–26[1]
Komatsu, M. 1990. Hida "Gaien" belt and Joetsu belt. See Ichikawa et al 1990, pp. 25–40
Komatsu, M., Osanai, Y., Toyoshima, T. M., Miyashita, S. 1989. Evolution of the Hidaka metamorphic belt, northern Japan. See Daly et al 1989, pp. 487–93
Komatsu, M., Sakakibara, M., Fukuzawa, H., Toyoshima, T. 1990. Opening of Chishima Basin and the tectonics of the Hidaka metamorphic belt. *Chikyu.* 12: 501–6[2]
Maruyama, S. 1990. *97th Annu. Meeting, Geol. Soc. Jpn.* Toyama. p. 484[2]
Maruyama, S., Banno, S., Matsuda, T., Nakajima, T. 1984. Kurosegawa zone and its bearing on the development of the Japanese Islands. *Tectonophysics* 110: 47–60
Maruyama, S., Isozaki, Y., Soma, T. 1990. *97th Annu. Meeting, Geol. Soc. Jpn.* Toyama. pp. 32–33[2]
Maruyama, S., Seno, T. 1986. Orogeny and relative plate motions: example of the Japanese Islands. *Tectonophysics* 127: 305–29
Miyashiro, A. 1961. Evolution of metamorphic belt. *J. Petrol.* 2: 277–311
Nakajima, T., Shirahase, T., Shibata, K. 1990. Along-arc variation of Rb-Sr and K-Ar ages of Cretaceous granitic rocks in Southwest Japan. *Contrib. Mineral. Petrol.* 104: 381–89
Nishimura, Y. 1990. Sangun metamorphic rocks: terrane problem. See Ichikawa et al 1990, pp. 63–80
Nishimura, Y., Itaya, T., Isozaki, Y., Kameya, A. 1989. Depositional age and metamorphic history of 220 Ma high P/T metamorphic rocks: an example of the Nishikicho area, Yamaguch Prefecture, Southwest Japan. *Mem. Geol. Soc. Jpn.* 33: 143–66[1]
Nishina, K., Itaya, T., Ishiwatari, A. 1990. *97th Annu. Meeting, Geol. Soc. Jpn.* Toyama
Osanai, Y., Komatsu, M., Owada, M. 1991. Metamorphism and granite genesis in the Hidaka metamorphic belt, Hokkaido, Japan. *J. Metamorph. Geol.* 9: 111–24
Saito, Y., Hashimoto, M. 1982. South Kitakami Region: An allochthonous terrane in Japan. *J. Geophys. Res.* 87: 3691–96
Sakakibara, M. 1991. Metamorphic petrology of the northern Tokoro metabasites, eastern Hokkaido, Japan. *J. Petrol.* 32: 333–64
Shiba, M. 1988. Metamorphic evolution of

southern part of the Hidaka belt, Hokkaido, Japan. *J. Metamorph. Geol.* 6: 273–96
Shiba, M., Ueda, Y., Onuki, H. 1979. K-Ar ages of metamorphic rocks from the Tsukuba district, Ibaraki Prefecture. *J. Jpn. Assoc. Mineral. Petrol. Econ. Geol.* 74: 122–25[1]
Shibata, K., Igi, S., Uchiumi, S. 1977. K-Ar ages of hornblendes from gabbroic rocks in Southwest Japan. *Geochem. J.* 11: 57–64
Shibata, K., Nishimura, Y. 1989. Isotopic ages of the Sangun crystalline schists, Southwest Japan. *Mem. Geol. Soc. Jpn.* 33: 317–41[1]
Shibata, K., Nozawa, T., Wanless, R. K. 1970. Rb-Sr geochronology of the Hida metamorphic belt, Japan. *Can. J. Earth Sci.* 7: 1381–1401
Shibata, K., Sugiyama, Y., Takagi, H., Uchiumi, S. 1988. Isotopic ages of rocks along the Median Tectonic Line in the Yoshino area, Nara Prefecture. *Bull. Geol. Surv. Jpn.* 39: 759–81[1]
Suzuki, H., Isozaki, Y., Itaya, T. 1990. Tectonic superposition of the Kurosegawa terrane upon the Sanbagawa metamorphic belt in eastern Shikoku, Southwest Japan—K-Ar ages of weakly metamorphosed rocks in the northeastern Kamikatsu Town, Tokushima Prefecture. *J. Geol. Soc. Jpn.* 96: 145–53[1]
Tagiri, M., Shiba, M., Onuki, H. 1989. Anatexis and chemical evolution of pelitic rocks during metamorphism and migmatization in the Hidaka belt, Hokkaido. *Geochem. J.* 23: 321–38
Taira, A., Saito, Y., Hashimoto, M. 1983. The role of oblique subduction and strike-slip tectonics in the evolution of Japan. *Geodynamic Ser. AGU* 11: 303–16
Takagi, K., Hara, I. 1979. Relationship between growth of albite porphyroblasts and deformation in a Sambagawa schist, central Shikoku, Japan. *Tectonophysics* 58: 113–25
Takasu, A. 1989. P-T histories of peridotite and amphibolite tectonic blocks in the Sambagawa metamorphic belt, Japan. See Daly et al 1989, pp. 533–38
Takasu, A., Dallmeyer, R. D. 1990. ^{40}Ar-^{39}Ar age constraints for the tectonothermal evolution of the Sambagawa metamorphic belt, central Shikoku, Japan: a Cretaceous accretionary prism. *Tectonophysics* 185: 303–24
Takasu, A., Dallmeyer, R. D. 1991. ^{40}Ar-^{39}Ar mineral ages of metamorphic clasts from the Kuma Group (Eocene), central Shikoku, Japan: implications for tectonic development of the Sambagawa accretionary complex. *Lithos.* In press
Toyoshima, T. 1990. Pseudotachylite from the Main zone of the Hidaka metamorphic belt, Hokkaido, Northern Japan. *J. Metamorph. Geol.* 8: 507–23
Ueda, Y., Nakajima, T., Maruyama, S., Matsuoka, K. 1980. K-Ar ages of muscovite from greenstone in the Ino Formation and schists blocks associated with the Kurosegawa tectonic zone near Kochi city, central Shikoku. *J. Jpn. Assoc. Mineral. Petrol. Econ. Geol.* 75: 230–33
Uyeda, S., Miyashiro, A. 1974. Plate tectonics and Japanese islands; a synthesis. *Bull. Geol. Soc. Am.* 85: 1159–70
Wallis, S. R. 1990. Folding and stretching in the Sambagawa metamorphic belt: the Asemigawa region, central Shikoku. *J. Geol. Soc. Jpn.* 96: 345–52
Wang, G.-F., Banno, S., Takeuchi, K. 1986. Reactions to define the biotite isograd in the Ryoke metamorphic belt, Kii Peninsula, Japan. *Contrib. Mineral. Petrol.* 93: 9–17
Yamamoto, H. 1962. Plutonic and metamorphic rocks along the Usuki-Yatsushiro tectonic line in the western part of central Kyushu. *Bull. Fukuoka Gakugei Univ.* 12: 93–172
Yokoyama, K., Itaya, T. 1990. Clasts of high-grade Sanbagawa schist in Middle Eocene conglomerates from the Kuma Group, central Shikoku, Southwest Japan. *J. Metamorph. Geol.* 8: 467–74

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