by Shohei Banno and Takashi Nakajima

Metamorphic belts of Japan

Dramatic progress in the study of the metamorphic basement geology of Japan has resulted from developments in our knowledge of conodonts and radiolarian biostratigraphy and from the dramatically increased activity in radiometric dating. Together, these results have compelled us to reconsider the age and extent of many metamorphic belts, as well as their tectonic significance. Petrological research on the Sangun, Ryoke, Abukuma, Chichibu, and Shimanto belts has revealed many new findings about the geology of these metamorphic belts and has caused us to make corrections to some of our previously held theories.

Introduction

The Japanese islands were located on the eastern border of the Asian continent before 20–15 Ma, the date of the opening of the Sea of Japan. However, restoration of the geology before that time is only partly possible. We will discuss the geology of the metamorphic belts of Japan, shown in figure 1, by using the geographical coordinates of today. Among the many metamorphic terranes in Japan, the majority of them formed in continental margin or subduction zone settings. The question of how these metamorphic terranes reached their current positions is one of the major subjects of Japanese geology. This article, however, concentrates instead on introducing some of the recent progress concerning their tectonic evolution.

A general synthesis of the metamorphic geology of the Japanese islands was established in 1960s (see Miyashiro, 1961). Advancements in our knowledge over the past 30 years have been remarkable, if not revolutionary, as a result of a few breakthroughs. The most important of these is the progress of conodont and radiolarian biostratigraphy, which together have compelled a conceptual change in our understanding of the basement geology. Thus, the concept of a Paleozoic Chichibu (or Honshu) geosyncline has been replaced by the concept of the accretionary prisms of the late Paleozoic Akiyoshi complex and the Jurassic Mino-Tanba complex. Radiometric dating, which had been a weak point in Japanese metamorphic geology, has improved very much owing to the activity of Okayama University of Science and the Geological Survey of Japan. Therefore, many areas have been studied now by using both biostratigraphy and radiometric dating. We have found that some areas treated previously as single tectonic-metamorphic terranes actually consist of several independent units. Thus, the concept of the Inner zone of southwestern Japan and the Sangun high-pressure metamorphic belt has changed drastically, as well as the concept of the Chichibu Group in the Outer zone. Many of the ages discussed herein are taken from recent conferences, which thereby demonstrates the rapidly changing geochronology of Japanese metamorphic terranes. Furthermore, the Shimanto belt, which once hardly attracted ambitious youngsters, is now the most actively studied area of island arc geology.

An overview of the metamorphic geology of the Japanese islands can be found in a number of textbooks and review papers (Hashimoto and others, 1970; Miyashiro, 1973; Banno, 1990). Details of individual belts may be studied in the proceedings of recent conferences or special issues, such as those edited by Evans and Brown (1986), Taira and Ogawa (1988), Daly and others (1989), Nishimura and others (1989), Ichikawa and others (1990), and Banno and Wallis (1990). In this review, we will discuss the geology of metamorphic belts such as the so-called Sangun, Ryoke, Abukuma, Chichibu, and Shimanto belts. For other metamorphic belts, we will cite some representative papers. Radiometric ages compiled by Nozawa (1977) will be quoted without references.

New findings and corrections to some commonly accepted theories

New blueschist terrane

Surprisingly, this country has overlooked one high-pressure metamorphic terrane, the Tokoro belt in Hokkaido (Sakakibara, 1991) (fig. 1). This is a Cretaceous high-pressure complex containing aragonite but not jadeite and quartz.

Eclogite and regional jadeite and quartz assemblage

Eclogite was known previously only in the Bessi area of the Sanbagawa metamorphic terrane. However, Komatsu (1990) has described a new find of eclogite as exotic blocks in the serpentinite mélange of the Hida marginal belt. It is a low-temperature type of eclogite that has retrograded to epidote amphibolite. In the Bessi area of the Sanbagawa belt, many, but not all, of the metagabbro bodies contain relic eclogite of a medium-temperature type. That eclogite has retrograded to epidote amphibolite facies as well.

No regional jadeite and quartz area is found in Japan, but such an assemblage occurs in tectonic blocks in the serpentinite of the Kurosegawa zone in Shikoku, Kanto Mountains near Tokyo, and the Kamuikotan belt in Hokkaido.

Oldest metamorphic rock

From the viewpoint of the comparative geology of Japan, speculation exists that the Hida-Oki belt (usually called Hida belt) includes Precambrian rocks. However, Hiroi (1983) separated from this belt Carboniferous sediments that were metamorphosed in the Triassic, the Unazuki schists. This is the only regional kyanite-sillimanite type of metamorphic belt in Japan, and it has been thoroughly studied petrologically. It extends to the Ogcheon zone of Korea. No Precambrian metamorphic age has been found in the Hida-Oki complex. The oldest metamorphic age of this belt is 415 ± 60 Ma in the samarium-neodymium (Sm-Nd) mineral isochron (Asano and others, 1990). So far, the only dated Precambrian rocks in Japan are gneiss clasts from conglomerate in a Jurassic accretionary complex, which gave a potassium-argon (K-Ar) muscovite age of 1,600 Ma. Ordovician mudstone in the Hida marginal belt and metagabbro blocks in serpen-

tinite zones have K-Ar hornblende ages of about 480 Ma (Ozawa and others, 1988) and are the oldest known in-place rocks in Japan.

Metamorphic belts

Sangun belt and the structure of the Inner zone of southwestern Japan

The Sangun belt was once considered to be paired with the Hida-Oki complex (fig. 1). Nishimura (1990) has shown that it contains at least

two distinct groups. One group is a high-pressure schist of the Sangun-Renge belt that belongs to the Hida marginal belt, which has K-Ar muscovite ages of 300 Ma, and the other includes the Suo and Chizu complexes that are the metamorphosed Permian Akiyoshi complex, which have K-Ar muscovite ages of 220 and 180 Ma, respectively. Regarding the so-called Sangun belt, the type locality and recent understanding are in disharmony, and new nomenclature should be introduced in the near future. The Paleozoic to Mesozoic accretionary complex and its metamorphosed facies form a pile of nappes, which generally has the older rocks on a higher structural level. Figure 2 sketches the geology of the Inner zone of southwestern Japan, that is, the area north of the Median Tectonic Line

Figure 1.—Distribution of metamorphic belts in Japan. Abbreviations: Hk, Hidaka; Tk, Tokoro; Hd, Hida-Oki; Sg, Sangun; Rk, Ryoke; Sb, Sanbagawa; Sm, Shimanto; Tz, Tanzawa.

(Nishimura, 1990). The association of the 200-Ma high-pressure schist derived from the Permian Akiyoshi complex and the Jurassic accretionary complex of the Tanba complex extends to Ishigaki island, the southernmost part of the Ryukyu Islands (Isozaki and Nishimura, 1989).

Abundant Cretaceous granitic rocks intruded this area and caused contact metamorphism on high-pressure metamorphic rocks. This makes it difficult to establish the thermal structure of the regional metamorphism. However, in general, the facies series is a high-pressure intermediate type and includes pumpellyite-actinolite, epidote-glaucophane, and albite-epidote amphibolite facies.

Ryoke belt

The Ryoke belt is a part of the Jurassic accretionary complex, the Mino-Tanba complex, and it underwent low-pressure metamorphism in the Cretaceous. The Ryoke belt in the strict sense runs along the northern side of the whole Median Tectonic Line (figs. 1 and 2) and even further to the east to the Tsukuba area. It has been considered to form a pair with the Sanbagawa belt.

Petrologically, the Ryoke belt is in the andalusite-sillimanite-type facies series. Typically, the mineral zones are chlorite, chlorite-biotite, cordierite, and sillimanite zones (Wang and others, 1986; Ikeda, oral communication). Staurolite occurs locally but is rare. Migmatite is common in the areas of the amphibolite facies. Abundant granitic rocks occur in the Ryoke belt, but the regional isograds are independent of the outline of the intrusive rocks. Sometimes, however, the contact aureoles of the granitic rocks are hardly separated from the regional metamorphism.

The isotopic ages of the granitic rocks and of the metamorphic rocks are similar, and both show a systematic shift along the Japanese island arc. The age becomes younger going from Kyushu in southwestern Japan, 100 Ma, to central Japan, 60 Ma. Nakajima and others (1990) believe that the granitic magmatism of southwestern Japan was driven by episodic events such as the encounter of a midoceanic ridge and a trench and the subsequent ridge-trench-trench triple point migration along the eastern margin of the Eurasian plate.

Central Abukuma metamorphic rocks

The geology of this well-known area of low-pressure metamorphism has been controversial since the finding by Uruno (1977) of kyanite in the river sand and its later confirmation at outcrops. The central Abukuma metamorphic terrane consists of the Takanuki Series of pelitic and psammitic gneisses and the Gosaisyo Series of predominantly metabasites. The latter accompanies chert that contains Jurassic radiolarians. Structurally, the oceanic Gosaisyo Series is thrust over the Takanuki Series, which represents a former accretionary complex, but metamorphism is continuous across the tectonic boundary between them. Hiroi and Kishi (1989) have shown that garnet underneath the collision zone has a normal bell-shaped profile for X_{Mn} (X_{Mn} denoting mole fraction of Mn), but X_{Ca} has its maximum in an intermediate part. Moreover, the associated plagioclase has a zonal structure that has minimum X_{an} in a middle. This model may explain why kyanite always occurs as a rounded grain enclosed in plagioclase. They interpreted this thermal history to represent the increase of pressure of metamorphism caused by the obduction of the oceanic Gosaisyo Series on the Takanuki Series of an accretionary complex. The temperature-pressure-time (T-P-t) history in figure 3

Figure 2.—The so-called Sangun metamorphic terranes of the Inner zone of southwestern Japan (fig. 2 of Nishimura, 1990).

Figure 3.—Pressure-temperature (P-Temp) trajectory of the central Abukuma metamorphic terrane (fig. 2 of Hiroi and Kishi, 1989) of east Honshu. Abbreviations: Ky, kyanite; And, andalusite; Sil, sillimanite; Alm, almandine; Crn, carnegieite; Hc, hercynite; Qtz, quartz; Grs, grossular; An, anorthite; Wo, wollastonite; G, prograde path of the Gosaisyo Series. 1 and 2 in rhombuses show the stages of the obduction of the Gosaisyo Series and of granite intrusions, respectively. a and b in circles are K-Ar ages of hornblende and biotite, respectively.

suggests that the maximum burial of such rock was in the kyanite stability field. If strictly interpreted, this diagram requires an obduction at constant temperature, and it appears a little strange compared to the normal thermal regime of an orogenic zone. However, it conforms with geological and petrographical evidence, and some improvement of the P-T trajectory may satisfy the constraints of the geological and heat regime requirements. According to Hiroi and Kishi (1989), the last crystallization of garnet took place at 0.2 to 0.3 GPa, and the phase equilibrium at this pressure prevailed in the whole central Abukuma metamorphic terrane and gave rise to the facies series of low-pressure type. Thus, the facies series given by Miyashiro (1961) for the central Abukuma was essentially correct, although notable progress has been made since then on the distribution of the hornblende granulite facies and on the chemical mineralogy of hornblende and garnet. This facies series comprises the greenschist, amphibolite, and granulite facies and is characterized by the scarcity of garnet and by the abundance of cordierite.

Chichibu belt and Sanbagawa metamorphism

The age of deposition and metamorphism of the Chichibu Group, which is located on the south side of the Sanbagawa belt, has become fairly clear owing to extensive work done on the biostratigraphy and the K-Ar age determinations made on this group by Isozaki and Itaya and their collaborators (see Isozaki and Itaya, 1991, as the most recent contribution). Even the summary of the Sanbagawa belt by Banno and Sakai (1989) now needs revision regarding the lowest grade of the Sanbagawa schists. A nappe of the higher pumpellyite-actinolite facies overlying the lower pumpellyite-actinolite facies, an

area that Banno and Sakai showed on the southernmost part of the Sanbagawa belt, actually contains metamorphic rocks dating from 200 Ma. Thus, this area cannot belong to the Sanbagawa belt, whose metamorphic age lies in the range of 100–70 Ma. The Chichibu Group may be divided into three parts, the lowest grade of the Sanbagawa belt having a K-Ar age of about 120 Ma, the Jurassic complex having a K-Ar muscovite age of 140 Ma, and prehnite-pumpellyite facies rocks having a probable age of 200 Ma.

Petrologically, glaucophane schist is characteristic of the Sanbagawa belt, whose lowest grade part belongs to the pumpellyite-actinolite facies. Because low-grade metabasites dating from 200 and 140 Ma accompany pumpellyite, only very detailed petrographical work can distinguish the Sanbagawa metamorphism from the low-grade metamorphism of other parts of the so-called Chichibu belt.

A simple stratigraphic analysis of the Chichibu Group is unwarranted, as it did not behave as a tectonically independent unit. A new framework has to be proposed for the nomenclature of the Paleozoic and Mesozoic rocks of the Outer zone of southwestern Japan, namely the area south of the Median Tectonic Line.

Shimanto belt

The Shimanto belt is a Cretaceous to Miocene accretionary complex that is being studied extensively in various disciplines. Usually, reviews of Japanese metamorphic rocks do not refer to this belt because the metamorphism is of low grade and is confined to a few small areas. However, two points of this belt attract attention. One is that the low-grade metamorphism is located in an area that is well

characterized stratigraphically. The other is the presence of the granite and gneiss complex that probably occupies a large part of the depth of the complex.

The low-grade metamorphism of the Shimanto complex is known in both the Cretaceous unit and the Paleogene unit. The highest grade of the Cretaceous unit is the pumpellyite-actinolite and possible greenschist facies, which has a K-Ar muscovite age of 66 Ma (Tanino, Hara, and others quoted in Hara and others, 1990). The Paleogene unit reached the prehnite-pumpellyite facies but not higher. The cleavage of the mica in the Paleogene unit dates from 48 Ma according to the K-Ar ages (MacKenzie and others, 1990). Therefore, these two metamorphic facies represent different events in an evolving accretionary complex.

The prehnite-pumpellyite facies of this belt may be lower in grade than the P-T regime where solid-solution equilibrium was established. The constituent minerals, such as epidote and pumpellyite, are quite heterogeneous for applying rigorous thermodynamic arguments (Toriumi and Teruya, 1988; Hiramatsu, 1991). The older, higher grade rocks on the continental side occur above the younger, lower grade rocks on the oceanic side. This is in harmony with the kinematic model of the accretionary complex. The K-Ar age of the Cretaceous unit, 66 Ma, overlaps with those of the Sanbagawa belt, which thereby raises the possibility that the Sanbagawa and Shimanto belts cannot be separated (Hara and others, 1990).

The Shimanto belt accompanies acidic plutonic rocks dating from 14 Ma and their extrusive rocks. Some of these plutons contain abundant xenoliths of amphibolite and low-pressure granulite facies rocks. This may suggest that the low-pressure and high-temperature metamorphic belt develops at depth in the Shimanto belt. Its tectonic history may offer a model of low-pressure metamorphism of an accretionary complex, such as the Ryoke belt (Komatsu and others, 1989).

Other metamorphic regions

Sanbagawa belt

Banno and Sakai (1989) reviewed the metamorphic petrology of the Sanbagawa belt, a Cretaceous high-pressure metamorphic belt that was derived from a Jurassic accretionary complex. A special issue of the *Journal of Metamorphic Geology* (Banno and Wallis, 1990) covers developments in the study of this belt. The lower grade area of this belt is under debate and may still change, but we consider the 120-Ma metamorphic rocks to be a part of the Sanbagawa belt. Other important contributions are available in the field of ^{40}Ar - ^{39}Ar dating and in deformational studies, namely work by Takasu and Dallmeyer (1990), Shimizu (1988), and Wallis (1990).

Metamorphic rocks in Hokkaido

Most Japanese metamorphic rocks are either high-pressure metamorphic rocks of the subduction complex or low-pressure metamorphic rocks of a continental margin or accretionary complex. An exceptional case is the Hidaka belt of central Hokkaido. A comprehensive account of the metamorphic belts in Hokkaido is available in Komatsu and others (1989) and in Osanai and others (1991).

Metamorphic rocks in "Green Tuff" region

In the Miocene, voluminous basalt, andesite, and dacite erupted along the Sea of Japan coast and were associated with marine deposits. These units have undergone zeolite to prehnite-pumpellyite facies

metamorphism on a regional scale in the "Green Tuff" region on the Sea of Japan side of northern Honshu.

Tanzawa metamorphism of about 6 Ma

In central Japan, at the root of the Izu peninsula where the Izu-Mariana arc on the Philippine plate has collided with the island of Honshu, we find the Tanzawa quartz diorite of about 10–6 Ma. This is accompanied by a metamorphic aureole comprising the zeolite, prehnite-pumpellyite, greenschist, and amphibolite facies. The southern side of the intrusive body is composed of schists that were formed by the forceful intrusion of the quartz diorite intrusive body. Arai (1987) performed a detailed phase petrological study on this area, and it serves as a typical facies series of low-pressure and low-temperature metamorphism.

Hornfels

Hornfels is widespread in Japan. Thorough phase petrological studies have been made on the aureole of the Kasuga granodiorite (77–71 Ma; Suzuki, 1977) and on the Tono aureole (120–110 Ma; Okuyama-Kusunose, 1985).

Conclusions

This article is intended to introduce some important findings in the metamorphic geology of the Japanese islands. Except for a few areas that possibly represent fragments of continents, namely the Hida-Ohi belt and the Takanuki Series of the Abukuma, all other metamorphic rocks were derived from the accretionary complex that formed on the eastern margin of Asia. Although the metamorphic geology of the typical schist area remains valid in P-T conditions and age of metamorphism, the metamorphic ages of the lower grade areas, corresponding to the prehnite-pumpellyite or pumpellyite-actinolite facies, may still change owing to intensive biostratigraphic and geochronological work.

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