OROGENY, REGIONAL METAMORPHISM, AND MAGMATISM IN THE JAPANESE ISLANDS

by

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Abstract

The Japanese Islands are composed of several island arcs (Fig. 1), and would represent a front of the accretive growth of the Asiatic Continent. In the main part of the Japanese Islands, a thick geosynclinal pile was accumulated in Paleozoic time. The pile shows clear sedimentary differentiation on a grand scale.

In Late Paleozoic and Mesozoic time, regional metamorphism occurred repeatedly in different parts of the pile, leading to the formation of two pairs of metamorphic belts. Each of the pairs is composed of a metamorphic belt of the low P/T type on the continental (i. e., inner) side and that of the high P/T type on the oceanic (i. e., outer) side (Fig. 6–7). The low P/T type of metamorphism produces andalusite in pelitic rocks of appropriate composition, and the high P/T type is glaucophanitic.

Recent progress in the petrological study of these metamorphic belts is reviewed in some detail (Fig. 8–12). The progressive variation of individual metamorphic minerals with rising temperature is summarized and discussed. An outline of the geologic structures of metamorphic terrains is also given.

The regional metamorphism of the low P/T type is genetically associated with the formation of a vast amount of granitic and rhyolitic rocks (Fig. 15–16). The close association of abundant rhyolitic rocks with orogenic granitic ones and regional metamorphism might be characteristic of the low P/T type metamorphic belt.

On the other hand, the regional metamorphic belt of the high P/T type is associated with a vast amount of geosynclinal basalt and serpentinite (Fig. 17–18).

Geological and geophysical features of the present-day orogeny in the Japanese Islands are summarized, and their significance in the understanding of the older orogeny is discussed. New pairs of metamorphic belts may be formed in the depths of the Japanese Islands and some other double arcs in the western Pacific owing to the orogeny now in progress.

A new hypothesis for the origin of the paired metamorphic belts and associated magmatism is proposed. The deep-reaching shear-zones in, and the degassing of, the mantle are regarded as playing the most important part in the formation of the paired metamorphic belts.

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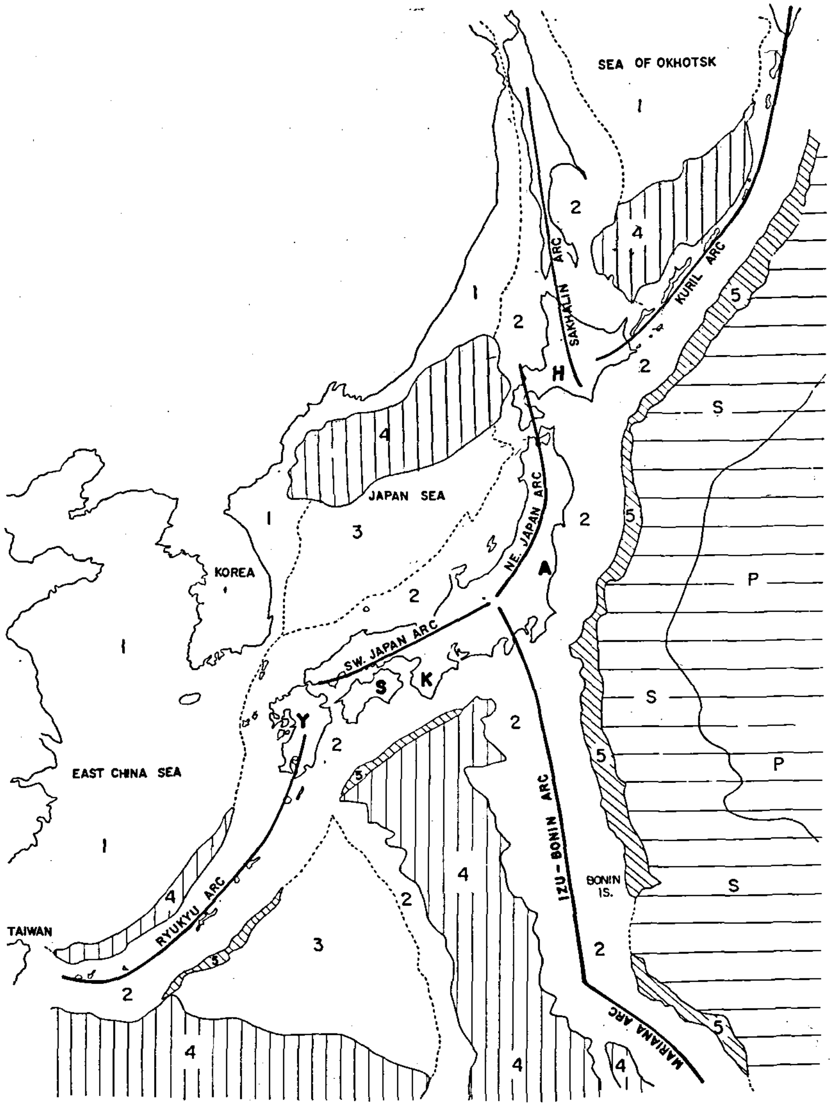

Fig. 1. Present-day island arcs of Japan and its vicinity.
Here, the main arc of Japan is divided into the Southwest and Northeast Japan Arcs. Letters H, A, K, S, and Y indicate Hokkaido, Abukuma Plateau, Kii Peninsula, Sikoku (Shikoku), and Kyusyu (Kyushu), respectively. The classification of the sea floors is based on the "Tectonic Map of Eurasia" (YANSHIN, 1966), as follows:

1, Regions of Epi-Mesozoic and older platform;
2, Cenozoic folded and geosynclinal systems;
3, Regions of pre-Neogenic folding;
4, Deep basins without granitic layer;
5, Deep oceanic trenches;
S, Marginal swells of oceanic platforms;
P, Old oceanic plates between zones of elevations.

INTRODUCTION

The Japanese Islands are composed of several island arcs, as shown in Fig. 1. Here the main arc of Japan is divided into the Southwest and Northeast Japan Arcs. The Izu-Bonin Arc reaches the junction of the above two arcs. The southwestern part of Hokkaido is a continuation of the Northeast Japan Arc, whereas the rest of Hokkaido is made up of the Sakhalin and Kuril Arcs. The Ryukyu Arc connects Kyusyu (Kyushu) to Taiwan (Formosa). There is one more arc that, though indistinct, protrudes from southern Kyusyu toward the southeast to ultimately reach the Palau Islands. This arc is composed mostly of submarine ridges.

The channel between Sakhalin and the Asiatic Continent and that between Taiwan and the Continent are only 10 and 35 meters deep respectively. The channel between the main island of Japan and Korea is only 140 meters deep. Hence, geologically the island arcs may be regarded as being connected with the Asiatic Continent at these places. However, the

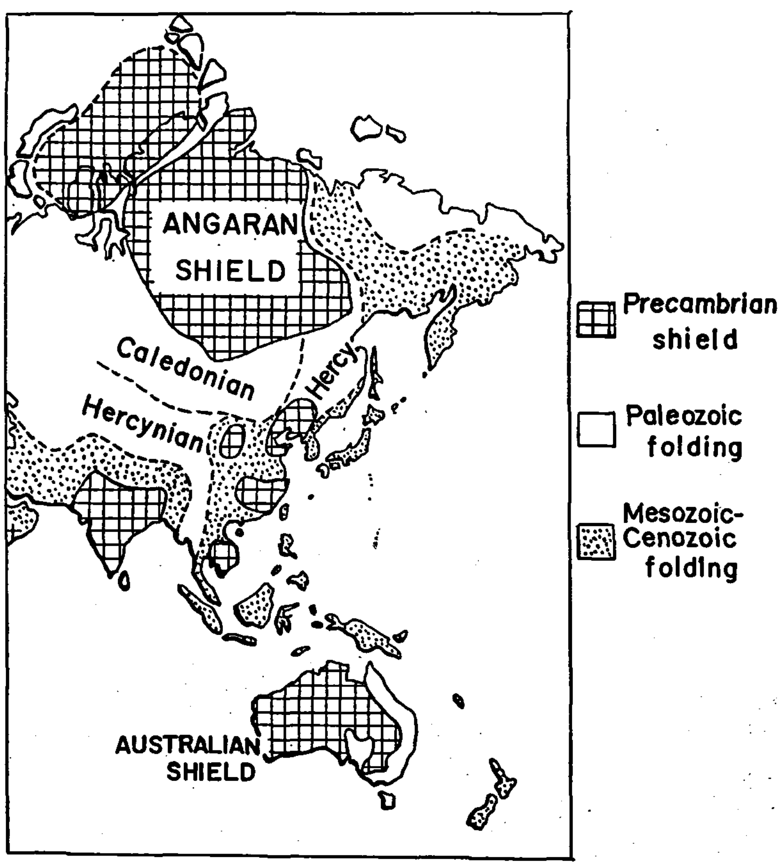

Fig. 2. Generalized structure of Asia, Australia and the western Pacific.

deepest parts of the East China, Japan, and Okhotsk Seas are 2717, 4049 and 3374 meters deep, respectively. The Japanese Islands have a sialic crust with intermediate thickness (20–35 km). The deeper parts of the East China, Japan, and Okhotsk Seas, however, appear to be devoid of a sialic crust.

There is a very wide Precambrian shield in the northern part of Siberia, as shown in Fig. 2. It is usually called the Angaran shield, and appears to be the core of accretive growth of the Asiatic Continent. There are a few other smaller Precambrian massifs to the south of this shield. One of them is in southern Manchuria and northern Korea.

Broadly speaking, orogenic belts of Paleozoic time were formed to surround these Precambrian regions, especially the Angaran shield. Orogenic belts of Mesozoic and Cenozoic time were formed outwards, especially southwards. Japanese Islands might be regarded broadly as belonging to the last-mentioned belts. Thus, the Islands would be a front of accretive growth of the Asiatic Continent.

In this paper I would like to synthesize the development of the Japanese Islands mainly from a viewpoint of a hard-rock geologist, or petrologist. Special attention will be paid to the formation of metamorphic belts and related processes. I am not well acquainted with the stratigraphy and paleontology of the Islands.

PALEOZOIC GEOSYNCLINE

Geosynclinal Pile and its Regular Compositional Variation

We will begin with a big geosyncline that existed in Paleozoic time at the present position of the Japanese Islands and its vicinity (especially to the immediate north). The total stratigraphic thickness is probably of the order of 20 kilometers. The oldest part of the geosynclinal pile, so far known,

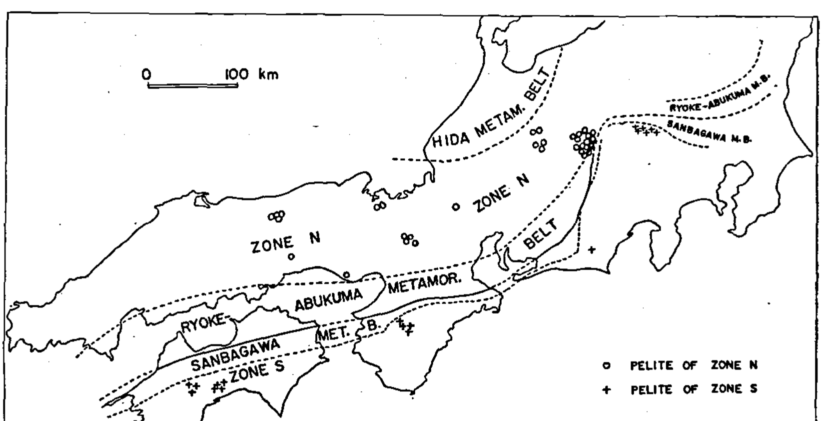

Fig. 3. Division of the Paleozoic geosynclinal terrain of Japan and the localities of analyzed virtually non-metamorphic pelites (MIYASHIRO and HARAMURA, 1966).

was deposited in Silurian time. The bulk of the pile, however, is made up of Carboniferous and Permian sediments. Graywacke, clay slate, and chert are dominant. Limestone and basaltic volcanics are abundant in some parts.

I have been interested for the past several years in the problem of sedimentary differentiation on a grand scale across the Paleozoic geosyncline. Part of the new chemical data, mostly of Permian pelitic rocks and discussions on them, were already published (MIYASHIRO and HARAMURA, 1966 etc.).

As is shown in Fig. 3, the Ryoke-Abukuma and Sanbagawa metamorphic belts are jointly exposed roughly along the central axis of the Southwest Japan Arc. The virtually non-metamorphic Paleozoic terrains to the immediate north and to the immediate south of the two metamorphic belts are here called *zones N and S*, respectively, for convenience. It was found that the pelitic rocks of zone N tend to be higher in K/Na ratio and in excess Al_2O_3 content than those of zone S. These relations are illus-

Table I.

Paleozoic pelitic rocks of Japan (MIYASHIRO and HARAMURA, 1966).

	N	Kiso	Bessi	S
SiO_2	65.31	61.96	67.12	66.16
TiO_2	0.63	0.65	0.50	0.59
Al_2O_3	15.81	18.35	15.41	15.37
Fe_2O_3	1.83	1.38	0.92	1.48
FeO	3.25	4.57	3.75	3.30
MnO	0.08	0.11	0.12	0.11
MgO	2.08	2.49	1.96	1.84
CaO	0.34	1.12	0.59	0.49
Na_2O	2.09	2.41	2.20	2.95
K_2O	3.84	3.98	3.43	3.28
H_2O+	3.36	2.91	3.63	2.88
$H_2O\div$	0.61	0.27	0.13	0.73
P_2O_5	0.10	0.14	0.07	0.12
C	0.76	n. d.	tr.	0.67
Total	100.09	100.34	99.83	99.97
$\frac{K_2O^*}{Na_2O + K_2O}$	0.55	0.52	0.51	0.42
$\frac{Al_2O_3^*}{Na_2O}$	4.60	4.63	4.26	3.17
$\frac{Fe_2O_3^{**}}{FeO}$	0.56	0.30	0.25	0.45

* Molecular ratio; ** Weight ratio.

N: Average composition of 31 virtually unmetamorphosed Paleozoic clayslates from zone N.

Kiso: Average composition of 13 pelitic metamorphic rocks of the Kiso-Komagane area in the Ryoke metamorphic belt.

Bessi: Average composition of 8 pelitic metamorphic rocks of the Bessi area in the Sanbagawa metamorphic belt.

S: Average composition of 12 virtually unmetamorphosed Paleozoic clayslates from zone S.

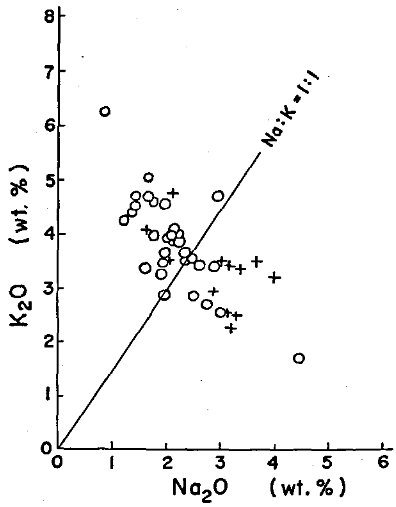

Fig. 4. K_2O and Na_2O contents of virtually non-metamorphic pelites of zones N and S (MIYASHIRO and HARAMURA, 1966).

trated in Fig. 4 and 5. The average chemical compositions are shown in Table I.

In the Southwest Japan Arc, the pelitic rocks of the Ryoke-Abukuma metamorphic belt are chemically similar to those of zone N, whereas the

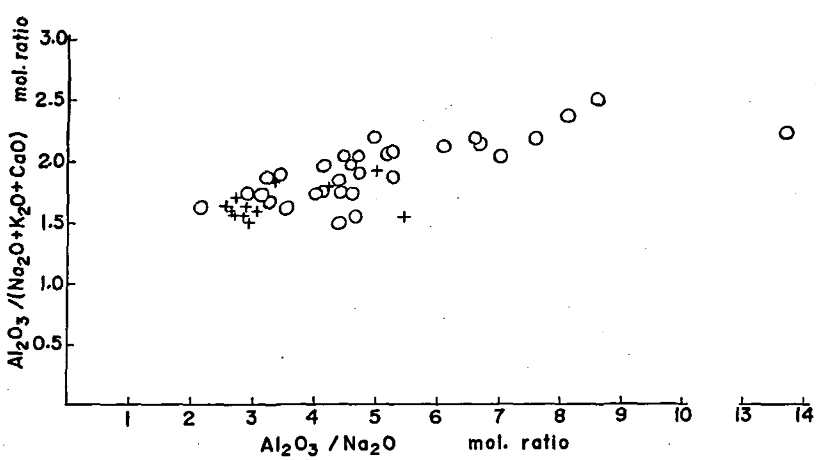

Fig. 5. Al_2O_3/Na_2O ratios and the excess alumina ratios of virtually non-metamorphic pelites of zones N and S (MIYASHIRO and HARAMURA, 1966).

pelitic rocks of the Sanbagawa metamorphic belt are chemically intermediate between those of zones N and S. Thus, we may conclude that the K/Na ratio and the excess Al_2O_3 content of pelitic rocks tend to decrease regularly southward across the geosyncline, regardless of regional metamorphism.

Somewhat similar sedimentary differentiation in the Caledonian geosyncline of Europe was formerly pointed out by VOGT and KENNEDY (KENNEDY, 1951).

It may be imagined that there was a chain of volcanic islands in Paleozoic time, roughly in the present position of the Sanbagawa metamorphic belt and zone S. The bulk of the sedimentary materials would have been derived from the volcanic islands. Thus, the maturity of the sediments would have been lower in the vicinity of the volcanic islands, resulting in a lower K/Na ratio and a lower excess of Al_2O_3. Paleozoic volcanics are indeed abundant in the Sanbagawa belt and zone S.

Basement and Japan Sea

The basement on which the geosynclinal pile was deposited is not clearly known. However, small masses of metamorphic complexes which may represent remnants of the basement are known in some areas in Japan. It is conceivable that there may have been an earlier cycle of orogeny to produce such a crystalline basement in early Paleozoic, or even in late Precambrian time.

The origin and nature of the Japan Sea are an important but difficult problem. As is shown in Fig. 1, the southern part of the Sea, adjacent to Japan, is entirely shallow and has a relatively thick sialic crust. From a geological viewpoint, it is certainly a continuation of the Japanese Islands. On the other hand, the northern part of the Sea is deep and has a thin basaltic crust of a nearly oceanic type (9–12 km thick) according to Soviet geophysicists.

It may be considered that the Japanese Islands were produced as a front of the continental growth, leaving the region with a thin crust of the oceanic type behind. This process would be similar to the formation of the Izu-Bonin Arc at the present time, leaving a deep sea with a thin crust of the oceanic type to the west. The Japan Sea is, however, nearly completely surrounded by dry lands, and the rate of transportation of sediments into it should be fairly high. It is not easy to imagine that the Sea could have remained unburied throughout the geologic ages.

It can be imagined, however, that a thick sedimentary layer was formed in the northern Japan Sea, but was later swept away toward the Japanese Islands during Paleozoic-Mesozoic orogeny. It may have been ultimately used in the construction of the sialic crust of the Japanese Islands and its vicinity.

Someone may imagine that the present-day oceanic crust of the Japan Sea was formed secondarily by the wear and tear of a once-formed continental crust. This problem will be discussed later (p. 431).

FORMATION OF PAIRED METAMORPHIC BELTS

Diversity of Regional Metamorphism

There is a great diversity in the temperature and pressure operating during regional metamorphism. MIYASHIRO (1961a) attempted to classify regional metamorphisms with special reference to this aspect.

For example, glaucophane schists and associated metamorphic rocks are considered to have been recrystallized under a relatively high pressure and low temperature. Jadeite and lawsonite are characteristic minerals of such a metamorphism. In this paper, such a metamorphism will be called high P/T type metamorphism or glaucophanitic metamorphism (Fig. 6).

On the other hand, some regional metamorphic terrains contain andalusite in rocks of appropriate chemical composition. The metamorphism of such a terrain represents a relatively low pressure and high temperature. In this paper, such a metamorphism will be called low P/T type metamorphism.

For a more detailed classification and description of regional metamor-

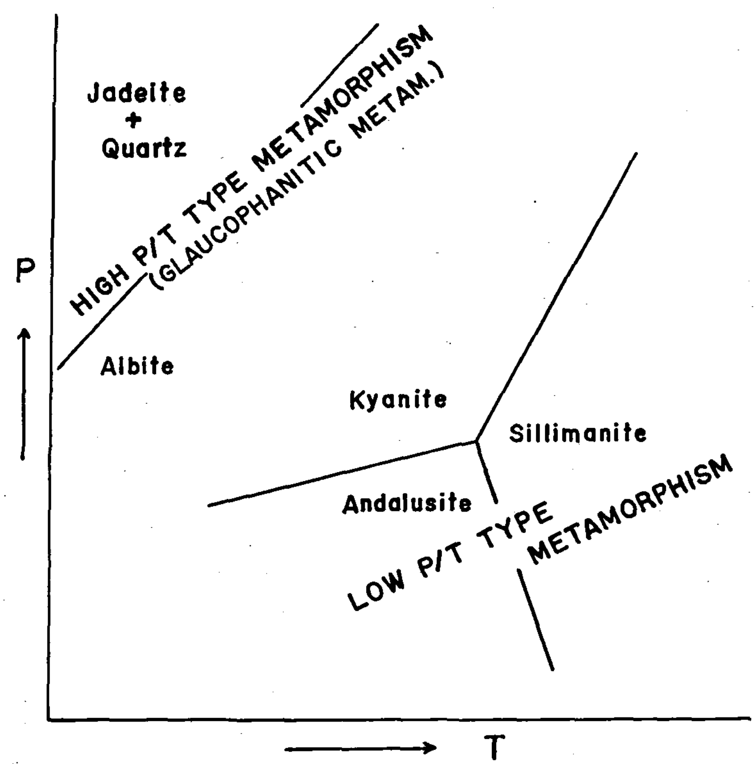

Fig. 6. Pressure and temperature in regional metamorphism and the stability relation of some metamorphic minerals. The numerical values of pressure and temperature are still uncertain to some extent.

Table II.
Classification and nomenclature of regional metamorphisms.

MIYASHIRO, 1961a, 1965	MIYASHIRO, 1967c	This paper	W.G. 1967
(1) Andalusite-sillimanite type (2) Low-pressure intermediate group	Low-pressure metamorphism	Low P/T type metamorphism	Low-pressure metamorphism
(3) Kyanite-sillimanite type	Kyanite-sillimanite-type	——	Intermediate-pressure metamorphism
(4) High-pressure intermediate group (5) Jadeite-glaucophane type	Glaucophanitic metamorphism	High P/T type metamorphism or glaucophanitic metamorphism	High-pressure metamorphism

Note: W.G. means the Working Group for the Cartography of the Metamorphic Belts of the World. The term "glaucophanitic metamorphism" has been used to denote the metamorphism to produce not only glaucophanebearing rocks, but also all the associated metamorphic rocks free from glaucophane. Usually only a part of the rocks belongs to the glaucophane schist facies.

phisms, the reader is suggested to read MIYASHIRO (1961a, 1965, 1967c). Table II gives a synoptical representation of the classification and nomenclature of regional metamorphisms used in some papers.

Paired Metamorphic Belts

The Paleozoic geosynclinal pile in the main part of the Japanese Islands has suffered a number of phases of regional metamorphism. As a result, two pairs of metamorphic belts, older and younger, were produced generally along the main arc of Japan. They are shown in Fig. 7. Each pair of metamorphic belts is composed of one belt of low P/T type on the concave side (continental side) of the arc, and the other belt of high P/T type on the convex side (oceanic side) of the arc (MIYASHIRO, 1961a). In this paper, the concave side is called the *inner side* and the convex side, the *outer side*.

The older pair of metamorphic belts is, as is noticed in Fig. 7, composed of the Hida belt on the inner side and the Sangun belt on the outer side. A large part of the Hida belt lies beneath the Japan Sea. The Sangun metamorphic belt is not a continuous, recrystallized terrain, but a dappled belt consisting of recrystallized and unrecrystallized areas. Therefore, the areal extent of the belt is not clearly defined. There is reason to suppose that the

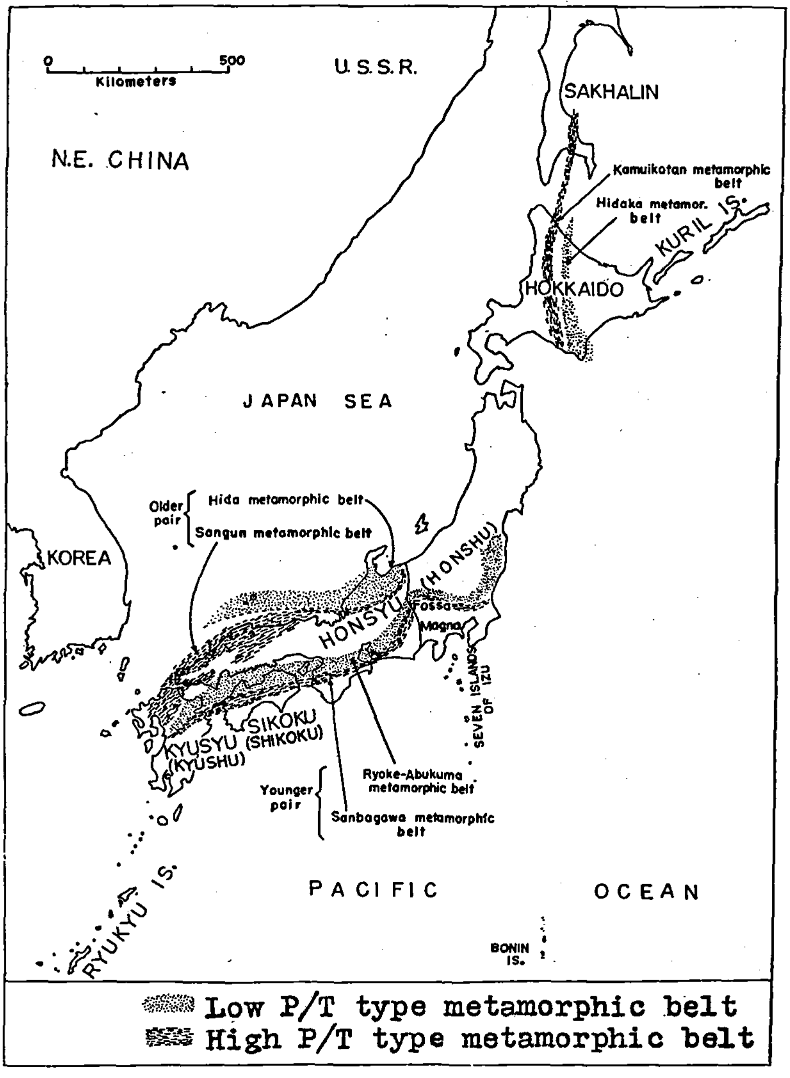

Fig. 7. Metamorphic belts of Japan. Slightly modified from MIYASHIRO (1961a).

true extent of the Sangun metamorphic belt was much wider toward the south than is shown in Fig. 7. Some parts of the younger pair of metamorphic belts may have been produced by superposing a younger phase of metamorphism on the southern part of the much wider Sangun belt.

The younger pair of metamorphic belts is composed of the Ryoke-Abukuma belt on the inner side and the Sanbagawa belt on the outer side.

Igneous Cycle in Paired Metamorphic Belts

It is usually stated in geologic literature that a simplified picture of the igneous cycle of an orogenic belt contains three distinct phases as follows: first phase—basaltic activity in the geosynclinal stage; second phase—syntectonic and late-tectonic emplacement of granitic rocks; third phase—post-tectonic volcanism.

In the orogenic belts with paired metamorphic belts, the first and second phases tend to take place at different zones within an orogenic belt. Basaltic volcanism of the geosynclinal stage takes place mainly in the zone that is composed of the belt of glaucophanitic metamorphism and the terrain on its outer side. Granitic activity of the syntectonic and late-tectonic stages usually takes place exclusively in the zone that is composed of the low P/T type metamorphic belt and the terrain on its inner side.

This relation holds in the above two pairs of metamorphic belts in the main part of Japan. The Hida metamorphic belt has abundant granitic rocks. The granitic rocks related to the Ryoke-Abukuma metamorphism of the younger pair are very widely distributed within the metamorphic belt and to the north. Some of them intruded into the Sangun metamorphic terrains and gave contact metamorphism on them. The Sangun and Sanbagawa glaucophanitic belts have abundant basaltic volcanics.

Serpentinite occurs commonly in association with basaltic volcanics. Thus, the Sangun and Sanbagawa belt have a big serpentinite belt.

Ages and Duration of Regional Metamorphism

The ages of regional metamorphism and orogeny have been a subject of hot dispute in Japan. In most of the dispute it was explicitly or implicitly assumed that regional metamorphism and orogeny occur in a relatively short period such as, say early Triassic or earliest Cretaceous. Events in such a short period, however, would represent only a phase in a much longer sequence of happenings.

I would like to emphasize the view that regional metamorphism and orogeny are probably a very long process even on a geological scale. They include a number of phases. In Japan, for example, in late Paleozoic time when geosynclinal sedimentation was going on, some parts of the depths of the geosynclinal pile were probably already subjected to some early phases of regional metamorphism. Thus, in the period ranging from late Paleozoic to Triassic time, the older pair of metamorphic belts appear to have formed. At the level of the present-day surface, the Sangun glaucophanitic metamorphism took place in many separate areas over a wide region, not only at the present position as shown in Fig. 7, but probably to its south.

In the region of the so-called Hida and Sangun metamorphic belts, metamorphism ceased in Triassic time, whereas in a region to the south of it, metamorphism continued probably to Cretaceous time, thus resulting in the younger pair of metamorphic belts there. If this view is acceptable, the Sanbagawa metamorphic belt represents simply the part of the Sangun belt where metamorphic recrystallization continued into Cretaceous times.

It is conceivable that the main theater of regional metamorphism is in the axial zone of the glaucophanitic belt, and that the metamorphic belt of the low P/T type tends to be formed just on the inner side of it to result in paired metamorphic belts (p. 441). Thus, in this paper, the development of the main part of the Japanese Islands in the long period ranging from Silurian to Cretaceous is regarded as forming a single cycle of orogeny. The period is about 350 million years long, and contains some phases of metamorphism and igneous activity, leading to the two remarkable pairs of metamorphic belts.

Regional metamorphism in some parts of the geosynclinal pile would actually be synchronous with sedimentation in others. Metamorphic rocks produced in earlier phases may be exposed on the surface, eroded, transported and deposited in later sediments, which in turn may suffer some later phases of regional metamorphism. In this meaning, the geosyncline is decidedly auto-cannibalistic, as called by LANDIS and COOMBS (1967).

Owing to the orogeny, geosynclinal sedimentation ceased in most of the main part of Japan at the end of Paleozoic time. A new Mesozoic geosyncline was formed on the outer (i. e., Pacific Ocean) side of the Paleozoic one.

Disposition of the Paired Metamorphic Belts in Hokkaido

There is a third pair of metamorphic belts in Hokkaido, as shown in Fig. 7. It is composed of the Hidaka metamorphic belt of the low P/T type on the eastern side, and the Kamuikotan metamorphic belt of the high P/T type on the western side. The original sedimentary rocks appear to be Mesozoic in this case.

There is one important point as regards the disposition of the metamorphic belts. It we regard these metamorphic belts as being formed along the northern extension of the Northeast Japan Arc, the Japan Sea side is the inner side, and hence the Kamuikotan metamorphic belt of the high P/T type lies on the inner side. This is contrary to the disposition that was noticed in the main part of Japan. Probably, it is not the case, however.

From comparison of Fig. 7 with Fig. 1, it will be noticed that only the southwestern part of Hokkaido represents the northern extension of the Northeast Japan Arc. The main part of Hokkaido, where the paired metamorphic belts are exposed, may be regarded as belonging to the Sakhalin Arc, which was formed along the western border of the Sea of Okhotsk. The paired metamorphic belts probably formed along an ancient Sakhalin Arc, surrounding the Sea of Okhotsk. Thus, the Hidaka belt of the low P/T type is on the inner side and the Kamuikotan belt of the high P/T type is on the outer side. This is the same disposition as is found in the main part of Japan.

RECENT PROGRESS IN THE PETROLOGICAL STUDY OF METAMORPHIC BELTS

Introductory Statement

A rather detailed review of petrological features of the Ryoke-Abukuma and Sanbagawa metamorphic belts was given by MIYASHIRO (1961a). In this chapter, great emphasis will be laid on the progress of study in the

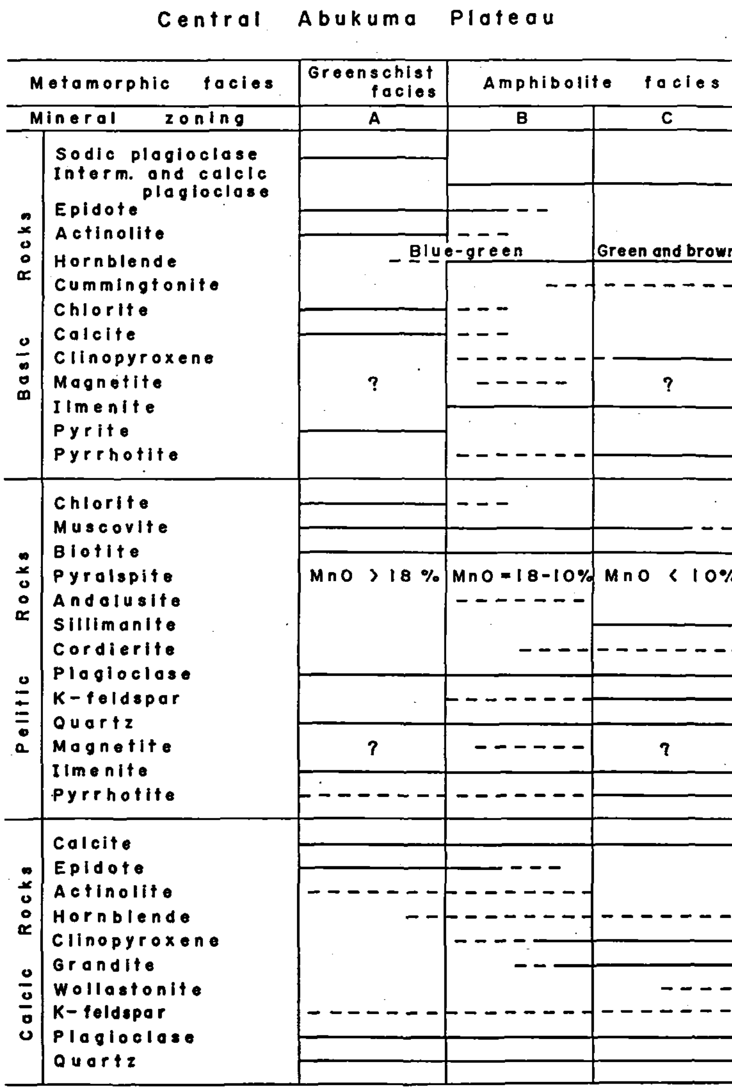

Fig. 8. Progressive regional metamorphism in the central Abukuma Plateau (MIYASHIRO, 1958, 1967c; BANNO and KANEHIRA, 1961).

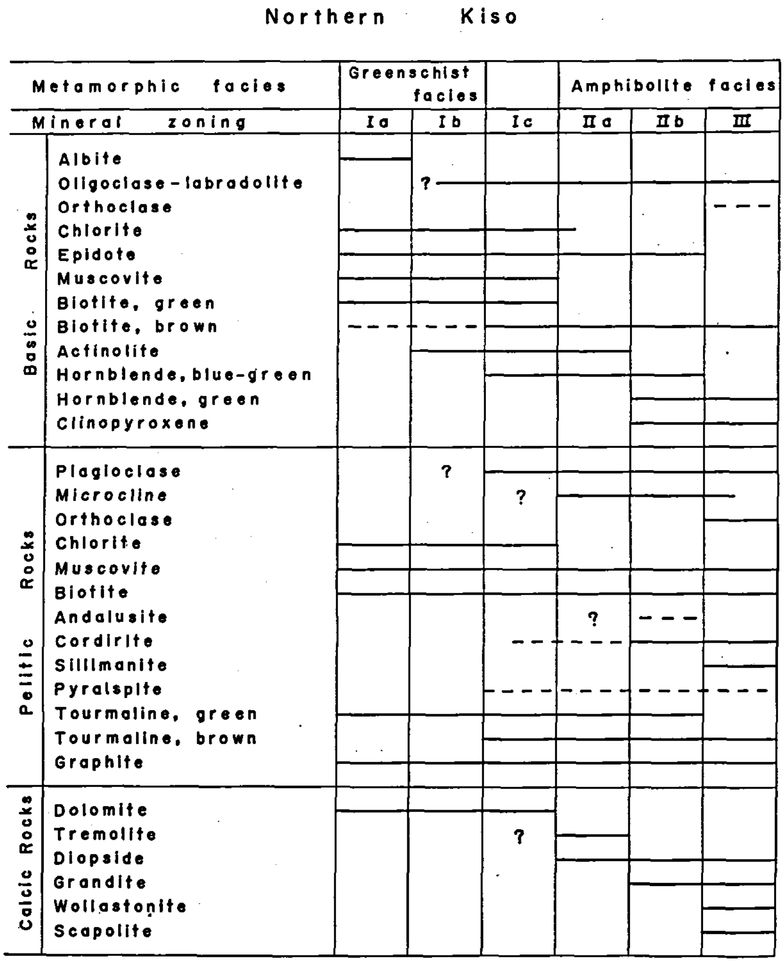

Fig. 9. Progressive regional metamorphism of the Ryoke terrain in the northern Kiso area (KATADA, 1965).

last several years. For the petrology of metabasites, the reader is referred to MIYASHIRO (1967c).

Ryoke-Abukuma Metamorphic Belt

The part of the Ryoke-Abukuma metamorphic belt which is in the Southwest Japan Arc is called the *Ryoke belt*, whereas the eastern end of the belt is in the Abukuma Plateau (indicated by letter A in Fig. 1). Detailed petrological works were published on the Abukuma Plateau in the 1950's, that is, earlier than the works on the Ryoke belt, because of the abundance of metabasites in, and of the proximity to Tokyo of, the former (SHIDO, 1958a; MIYASHIRO, 1958; KURODA, 1959). The progressive mineralogical changes observed there are summarized in Fig. 8.

In the 1960's, however, a number of rather detailed petrological studies were published on the Ryoke belt as follows: studies of OKI (1961a), HAYAMA (1964) and KATADA (KATADA, 1965; KATADA, ISOMI, et al. 1961) in the Tenryu Valley in central Japan, and the studies of UETA (1961), YAMAMOTO (1962) and TSUJI (1967) in central Kyusyu. In the Ryoke belt, pelitic and psammitic metamorphic rocks are predominant, except in central Kyusyu.

The progressive metamorphism of pelitic rocks in the Ryoke belt may be outlined as follows: in central Kyusyu, TSUJI discovered the existence of a relatively wide, low-temperature zone characterized by chlorite without biotite, whereas in Nagano Prefecture, KATADA noticed that biotite begins to occur roughly at the same temperature as the beginning of recrystallization, and hence a zone characterized by chlorite is lacking there. With some increase of temperature, andalusite and cordierite begin to occur. With a further rise in temperature, sillimanite becomes stable instead of andalusite. In this grade garnet becomes rather common in more or less manganiferous pelitic and psammitic rocks, if present, but not in amphibolite. In the highest-temperature part, muscovite breaks down in reaction with quartz to produce sillimanite and K-feldspar (microcline or orthoclase). The progressive mineralogical changes are summarized in Fig. 9–10.

The Tukuba area, about 60 km northeast of Tokyo, is a petrologically classic area belonging to the Ryoke-Abukuma metamorphic belt. There, SUGI (1930) claimed the occurrence of large-scale injection of granitic magma into gneisses. UNO (1961) re-investigated the area, concluding that SUGI's view was based on insufficient chemical data, and that actually there exists no evidence of large-scale injection. Pelitic rocks which devel-

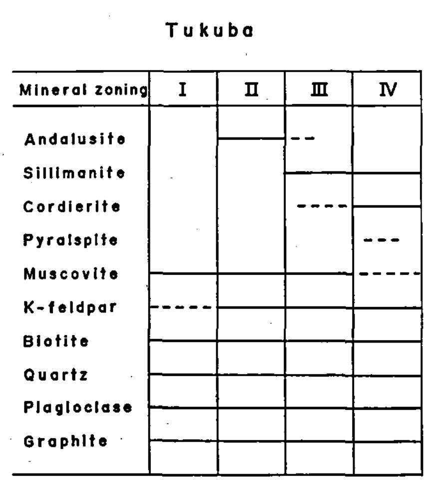

Fig. 10. Progressive regional metamorphism of pelitic rocks in the Tukuba area (UNO, 1961).

Table III.

Chemical composition of pelitic metamorphic rocks of the Tukuba area (UNO, 1961).

Mineral zoning	I			II	III		IV	
Number of mixed specimens	7	10	11	12	12	12	8	12
SiO_2	64.10	68.25	67.83	66.93	66.30	66.54	66.69	67.06
TiO_2	0.71	0.55	0.63	0.70	0.68	0.74	0.63	0.72
Al_2O_3	17.72	15.37	15.80	16.04	16.39	16.05	16.34	15.34
Fe_2O_3	0.28	0.66	0.44	0.91	1.06	0.56	0.47	0.76
FeO	3.67	3.23	3.80	3.38	3.47	4.30	4.31	4.99
MnO	0.07	0.05	0.08	0.06	0.06	0.07	0.07	0.17
MgO	1.74	1.58	1.89	1.87	1.97	2.01	2.08	2.64
CaO	1.22	0.98	0.99	0.96	0.69	0.89	1.17	0.26
Na_2O	2.97	2.82	2.31	2.11	2.01	2.13	2.18	1.37
K_2O	3.85	3.48	3.44	4.10	4.38	3.94	3.78	3.75
H_2O+	2.32	2.20	2.19	1.67	1.90	1.70	1.27	1.88
$H_2O\div$	0.07	0.07	0.05	0.15	0.18	0.12	0.15	0.15
P_2O_5	0.18	0.16	0.05	0.13	0.13	0.13	0.88	0.68
C	0.89	0.71	0.78	0.86	0.64	0.78	0.07	0.06
Total	99.79	100.11	100.28	99.87	99.86	99.96	100.09	99.83

Note: The analyses shown in the individual columns were made on the average samples prepared by mixing of a number (as shown above) of rock specimens which were collected in certain small areas within the individual metamorphic zones. Analyzed by H. HARAMURA. For the mineral zoning, refer to Fig. 10.

oped there suffered no significant variation in chemical composition in progressive metamorphism from biotite slates to *sillimanite gneiss*, except for a decrease of the H_2O content. The uniformity in chemical composition of metamorphic rocks is impressive. The progressive mineralogical changes of the Tukuba area are shown in Fig. 10, and the chemical analyses of pelitic rocks are quoted in Table III. These metamorphic rocks are very similar to the pelites of zone N (Table I) in chemical composition.

I have found in the central Abukuma Plateau that the K content of metabasites and pelites increases regularly westward, apparently with an increase of metamorphism. It was suspected that this might be due to an introduction of K from outside (MIYASHIRO, 1958). It may be due, however, to compositional difference of their original rocks between the low- and high- temperature zones. Judging from our chemical study of the geosynclinal pile, mentioned in pp. 394–396, the difference in K content of pelites at least might well be regarded as being due to original compositional difference. The difference in K content of metabasites will be discussed later (p. 440).

Chloritoid and staurolite occur in rocks of anomalous chemical compositions, only at a few localities in the Abukuma Plateau, but not in the rest of the Ryoke-Abukuma belt. Staurolite is a very rare mineral in Japan, and this fact is probably partly due to the limited chemical composition of metamorphic rocks developed. Some Japanese geologists supposed the existence of one more older cycle of regional metamorphism to produce staurolite in Abukuma. However, staurolite is a common mineral even in some low P/T metamorphism such as in the Pyrenees, and hence its occurrence by itself gives no sound basis for such supposition. The problem of the supposed older metamorphism is an open question.

Though the whole belt belongs to the low P/T type, there may have existed some difference in pressure in different parts. As mentioned above, staurolite and chloritoid were found to occur only in the Abukuma Plateau. Pyralspite garnet is much more common in the Abukuma Plateau than in the rest of the belt. These facts suggest that the prevailing pressure would have been somewhat higher in the Abukuma Plateau than in the rest. The occurence of staurolite, chloritoid and pyralspite garnet depends largely on the chemical composition of the rocks developed. Hence, we have to make more elaborate paragenetic analyses of metamorphic rocks in different parts of the metamorphic belt to reach a definite conclusion on the problem of pressure difference.

There is a long fault between the Ryoke metamorphic belt in the north and the Sanbagawa metamorphic belt in the south. It is usually called the *median line* or the *median tectonic line*. In most of the Ryoke belt, the metamorphic temperature increases southwards, i.e., toward the median tectonic line. In other words, the southern half of the belt was lost by the fault. In central Kyusyu, however, the axis of the maximum metamorphic temperature lies decidedly to the north of the fault. Hence, the symmetrical thermal structure of the belt with an axis of the maximum temperature can be noticed (UETA, 1961). In the central Abukuma Plateau also, the axis of the maximum temperature appears to exist at a considerable distance on the concave side from the extension of the median tectonic line, if present.

Sanbagawa Metamorphic Belt

The progressive metamorphism in a few areas of the eastern half of the Sanbagawa belt was investigated in detail by SEKI (1958, 1960, 1961b). Since then, a number of important works have been published on the petrology of the western half of the belt as follows: studies of IWASAKI (1963) and ERNST(1964) in eastern Sikoku; study of BANNO (1964) in the Bessi-Ino area in central Sikoku; and study of KANEHIRA (1967) in western Kii Peninsula. It has become clear that the eastern and western halves of the belt appear to have been recrystallized under mutually different physical conditions. The central part of Kii Peninsula (designated by letter K in Fig. 1) is just in between the eastern and western halves. SEKI et al. (1964) studied this area, discovering that it differs from either of the eastern and western halves, in physical conditions.

The areal extent of the Sanbagawa metamorphic belt that is shown in Fig. 3 is based on a traditional geologic map issued by the Geological Survey of Japan. SEKI, BANNO, and others have shown however, that metamorphic recrystallization has taken place in a much wider area toward

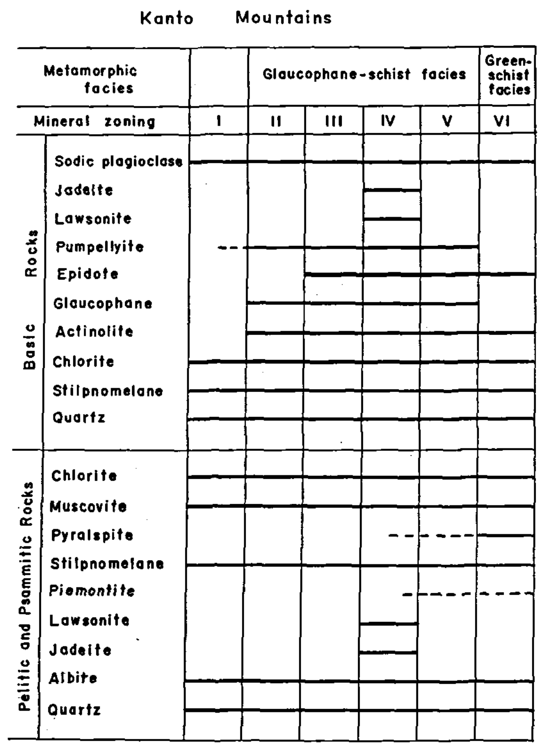

Fig. 11. Progressive glaucophanitic metamorpism of the Sanbagawa terrain in the Kanto Mountains (SEKI, 1958, 1960, 1961a). Most of the "actinolite" in zone VI would actually be barroisite, judging from their optical constants.

the south. Metamorphic temperature usually increases toward the north, i. e., toward the median tectonic line.

In the eastern half of the belt, SEKI (1958, 1960, 1961a) has shown that the unrecrystallized Paleozoic terrain grades into the zone of the glaucophane-schist facies, which in turn grades into the zone of the greenschist facies with rising temperature. In part of the zone of the glaucophane-schist facies, lawsonite and the jadeite-quartz assemblage are common. Jadeite, however, is usually so fine-grained that microscopic identification is difficult. Concentration and X-ray powder method have been successfully used. The progressive mineralogical changes in a part of the eastern half are summarized in Fig. 11.

On the other hand, in the western half of the Sanbagawa belt, the unrecrystallized Paleozoic terrain grades into the zone of the glaucophane-schist facies, which in turn usually grades into the zone of the epidote-amphibolite facies. (A zone of the greenschist facies may be present in some cases between the zones of the glaucophane-schist and epidote-amphibolite facies.) Lawsonite is extremely rare, and the jadeite-quartz as-

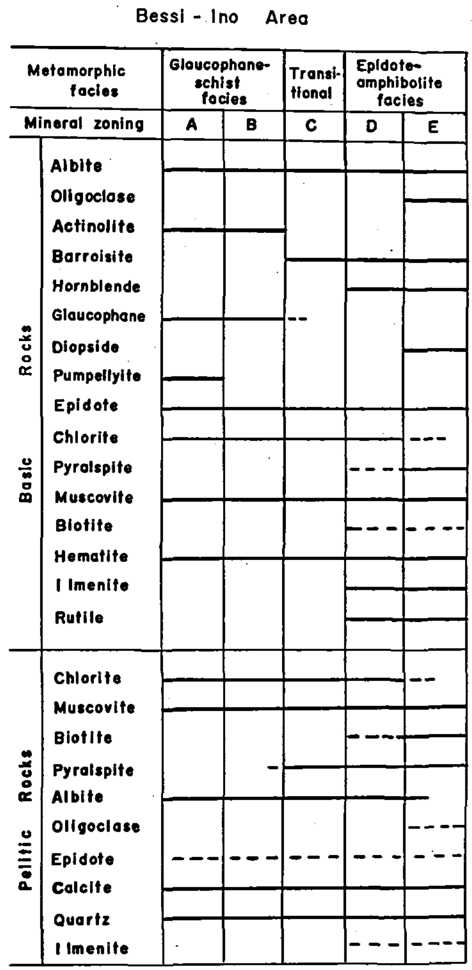

Fig. 12. Progressive glaucophanitic metamorphism of the Sanbagawa terrain in the Bessi-Ino area, central Sikoku (BANNO, 1964).

semblage is lacking. Prehnite, which was absent in the eastern half, occurs in some areas in the lowest temperature part. The progressive mineralogical changes in a part of the western half are summarized in Fig. 12.

In the central part of the belt, i.e., in central Kii Peninsula, neither lawsonite nor glaucophane occur! The jadeite-quartz assemblage is also lacking. The Sanbagawa metamorphism occurred here not only in the Paleozoic terrain, but also in Jurassic sedimentary rocks. Unrecrystallized Jurassic terrain grades northwards into the zone of the prehnite-pumpellyite facies, which in turn grades into the zone without prehnite, but still with pumpellyite. This zone grades further into the zone of the typical actinolite-greenschist facies.

It may appear that the prevailing pressure was very high in the eastern half of the belt, where the jadeite-quartz assemblage, lawsonite and glaucophane are widespread, while it was lower in the western half, where the jadeite-quartz assemblage is lacking, and lawsonite is rare, though glaucophane is still widespread. The pressure may have been still lower in the central part, where not only the jadeite-quartz assemblage, but also lawsonite and glaucophane are lacking, and instead prehnite is common. Epidote, pumpellyite, and stilpnomelane are widespread in all the three parts of the belt.

BANNO (1964) found some laumontite in the lowest-temperature part of the Bessi-Ino area. It is not clear, however, whether it is truly a mineral produced by the Sanbagawa metamorphism.

Sangun Metamorphic Belt

The Omi area in the easternmost part of the Sangun belt was the one where successful zonal mapping of the glaucophanitic metamorphic terrain was made for the first time in the world (BANNO, 1958; MIYASHIRO and BANNO, 1958). There were relatively insufficient studies of the rest of the belt until recently. Very recently, however, HASHIMOTO (in press) made a detailed petrological work in the Katuyama area in the central part of the belt. He divided three progressive metamorphic zones. Zone I belongs to the prehnite-pumpellyite facies, zone II to the glaucophane-schist facies, and zone III to the actinolite-greenschist facies. Epidote and albite occur in all zones. Neither jadeite nor lawsonite was found. The occurrence of the zone of the prehnite-pumpellyite facies on the lower-temperature side of the glaucophane-schist facies is characteristic.

Kamuikotan Metamorphic Belt

Cursory petrological investigations of the progressive metamorphism of the Kamuikotan belt were recently published by BANNO and HATANO (1963) and by TAZAKI (1964). Lawsonite and the jadeite-quartz assemblage occur commonly in a lower-temperature part. Glaucophane, epidote, pumpellyite and albite occur in all grades.

MINERALS OF METAMORPHIC ROCKS

Introductory Statement

The main purpose of the study of metamorphic minerals is to enable us to know the physical conditions of metamorphism. In this chapter I wish to summarize some of the important regular relations in metamorphic minerals that were found in Japan. Special attention will be directed to the variation of chemical composition of solid solution minerals in progressive metamorphism under different pressures. We have accumulated a lot of data on this problem since 1953 in Tokyo.

Pyralspite garnet

MIYASHIRO (1953, 1958) showed that the MnO content of garnet in pelitic metamorphic rocks of the central Abukuma Plateau is as high as about 20% in lower grades, and regularly decreases with rising metamorphic temperature. The frequency of occurrence of garnet increases also with rising temperature. If we compare different metamorphic regions, the MnO content tends to be lower in metamorphism under higher pressures. For example, garnets in Barrovian metamorphic regions are decidedly lower in MnO content than those of Abukuma.

BANNO (1964) studied garnets in glaucophanitic metamorphic rocks of the Bessi-Ino area of the Sanbagawa belt. He showed that the MnO content of garnet in pelitic metamorphic rocks is about 12% in lower grades, and tends to decrease with rising temperature down to 3 % or less in the highest-temperature part.

Pyralspite garnet is usually absent in metabasites of the low P/T type, while it occurs in some epidote amphibolites and glaucophane schists of the Sanbagawa belt.

ERNST (1964) noticed in Sanbagawa metamorphic rocks that there is regular partitioning of elements between coexisting minerals except in the pairs of garnet and associated minerals. BANNO (1965) showed the very common occurrence of zonal structure in Sanbagawa garnets. Part of the irregular paragenetic relations as noticed by ERNST may be due to such zoning.

Chlorite

IWASAKI (1963), ERNST (1964), BANNO (1964) and HORIKOSHI (1965) gave many new chemical analyses of chlorites of the Sanbagawa metamorphic belt. Most of them are orthochlorites, and only a few of them are leptochlorites. In ordinary nomenclature, most of them may be called ripidolite.

BANNO (1964) emphasized that the compositional variation of metamorphic chlorites as regards the (Mg,Fe) Si $\rightleftarrows$ AlAl substitution is very limited. The atomic number of Si on the anhydrous basis of O=14 is usually in the range of 2.60–2.80.

On the other hand, there is a relatively wide range in the Mg-Fe substitution. As the pelitic rocks usually have a higher Fe/Mg ratio than basic ones, the chlorites of pelitic rocks tend to have a higher Fe/Mg ratio than those of basic ones (BANNO, 1964; KANEHIRA, 1967). BANNO (1964) and HORIKOSHI (1965) suggested that the FeO content of chlorite in Sanbagawa basic schists tends to increase with rising temperature. However, KATADA (1959) showed a progressive change of chlorite in basic metamorphic rocks of the Ryoke belt in the reverse direction. On the other hand, the FeO content of chlorite in Sanbagawa pelitic schists is claimed to tend to decrease with rising temperature (BANNO, 1964). This may be due to reactions producing pyralspite from chlorite.

Biotite

In the Ryoke-Abukuma metamorphic belt, biotite of a brown color (Z) occurs in pelitic and basic metamorphic rocks at any metamorphic temperature. On the other hand, biotite of a greenish color is confined to a relatively low temperature range, whereas that of a reddish shade is confined to a relatively high temperature range (MIYASHIRO, 1958; SHIDO, 1958a; KATADA, 1965). Many chemical analyses were given by MIYASHIRO (1958), OKI (1961a) and HAYAMA (1964).

The MnO content of biotites in pelitic metamorphic rocks of the Ryoke-Abukuma belt is in the range of 0.05–0.51%, and mostly more than 0.15 %, whereas that of biotites in Barrovian pelitic metamorphic rocks of Scotland is mostly below 0.15%. It appears that the higher MnO content of biotite is a result of lower pressure. This is due to the variation in partition of Mg, Fe, and Mn between garnet and associated mafic minerals (MIYASHIRO, 1958, p. 251–253, 266).

In most of the Sanbagawa glaucophanitic belt, the prevailing metamorphic temperature was too low to produce biotite. Only in the Bessi area and vicinity, light brown or greenish brown biotite occurs. BANNO (1964) gave several chemical analyses and showed that the biotites of Sanbagawa pelitic rocks are usually a little lower in the $Fe^{+2}/(Mg + Fe^{+2})$ ratio than those of pelitic metamorphic rocks of Ryoke-Abukuma (about 0.40 in the former and 0.40–0.63 in the latter).

OKI (1961b) showed that an increasing amount of Al tends to replace Si, and an increasing amount of Ti tends to replace $Mg + Fe^{+2}$, with rising metamorphic temperature. More or less similar views were expressed by SHIDO (1958a), MIYASHIRO (1958), BANNO (1964) and HAYAMA (1964).

Muscovite

Phengitic muscovite rich in Fe^{+3} and Mg occurs commonly in Sanbagawa metamorphic rocks (KANEHIRA and BANNO, 1960; MIYASHIRO, 1962). This problem was analyzed by ERNST (1963).

At a higher grade of metamorphism, the phengite molecule of muscovite appears to decrease (e.g., HASHIMOTO, in press).

Paragonite

BANNO (1960) found paragonite in some basic metamorphic rocks of the Bessi area of the Sanbagawa belt. On the other hand, although he examined 80 pelitic schists, he did not find paragonite in them. The rarity of paragonite was ascribed to the limited chemical composition of metamorphic rocks developed.

Epidote

Epidote is common in the Ryoke-Abukuma as well as in the Sanbagawa metamorphic belts, as far as chemical conditions permit. It can occur even in most of the lawsonite- and/or pumpellyite-bearing areas. In most cases, epidote shows zonal structure with an Fe^{+3}-richer core and Fe^{+3}-poorer rim. In other parts of the Sanbagawa belt, however, zonal structure in the reverse direction was commonly observed (MIYASHIRO and SEKI, 1958).

It was shown that the composition range of epidote becomes larger with rising temperature of metamorphism in the Kanto Mountains and Bessi area, both in the Sanbagawa belt. A possible crystallo-chemical explanation is given for it (MIYASHIRO and SEKI, 1958; BANNO, 1964).

BANNO (1964) discussed the equilibria between epidote and zoisite.

Piemontite

The occurrence of piemontite in schist was found for the first time in the world by KOTO (1887) in the Sanbagawa metamorphic belt. It was one of the earliest petrographical studies made in Japan. Since then, piemontite has been known as a most characteristic and beautifully colored metamorphic mineral of Japan. At present, piemontite schist is known to occur in some other circum-Pacific countries. However, piemontite may be still regarded as a characteristic metamorphic mineral of Japan, because it is widespread, and key beds of piemontite-quartz schist are useful for structural analysis of Sanbagawa metamorphic terrains. Piemontite occurs also in the Sangun and Kamuikotan belts.

MIYASHIRO and SEKI (1958) discussed that the limit of MnO content of piemontite may become higher with rising temperature.

Pumpellyite, Lawsonite, and Prehnite

Pumpellyite is very widespread in the Sanbagawa and Sangun metamorphic belt. SEKI (1961a) pointed out that pumpellyites in glaucophanitic metamorphic terrains tend to have generally lower refractive index and hence lower $Fe^{+3}/(Fe^{+3} + Al)$ ratio than those in non-glaucophanitic environments. HASHIMOTO (in press) discussed that the composition range of pumpellyite in the glaucophane-schist facies appears to be wider than that in the prehnite-pumpellyite facies in the Katuyama area of the Sangun belt.

Lawsonite occurs in some limited areas of the Sanbagawa belt (SEKI, 1958, 1960). Prehnite occurs in very limited low-temperature parts of the same belt and also in the Sangun belt. SEKI (1965) and HASHIMOTO (1964) reviewed the existing petrological and optical data of prehnite, respectively.

Calciferous Amphiboles

In the regional metamorphism of the central Abukuma Plateau, the calciferous amphibole in basic metamorphic rocks is actinolite in the low-temperature zone, blue-green hornblende in the medium-temperature zone, and green or brown hornblende in the high-temperature zone (MIYASHIRO, 1958; SHIDO and MIYASHIRO, 1959). A more or less similar variation was noticed in the Ryoke terrain of northern Kiso (KATADA, 1965) and in central Kyusyu (YAMAMOTO, 1962, p. 135).

Within the high-temperature regional-metamorphic zone of the central Abukuma Plateau, however, green, greenish brown and brown hornblendes occur in irregular distribution. This would be at least partly due to the

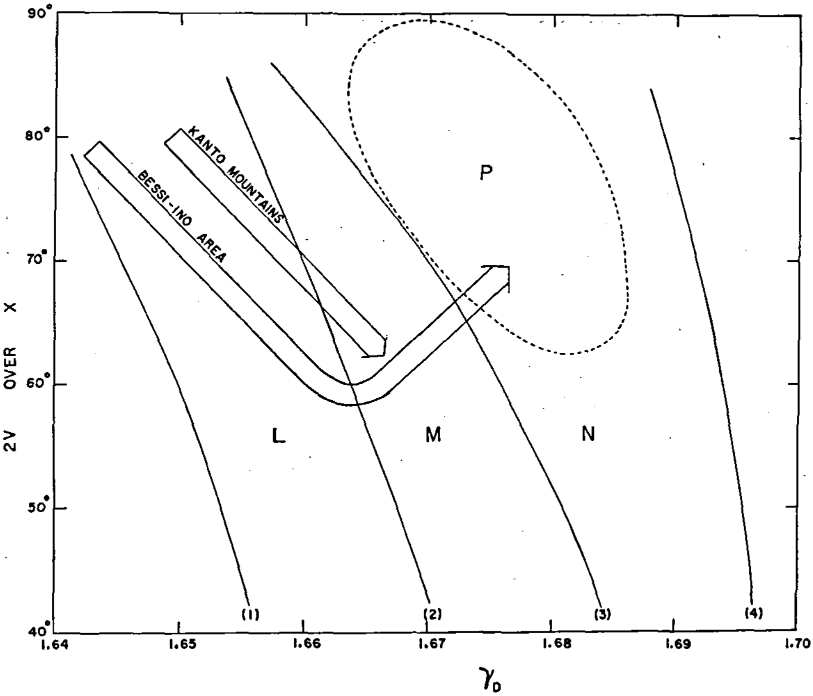

Fig. 13. Simplified 2V – γ relations for actinolite, barroisite, and hornblende in metabasites (MIYASHIRO, 1967c). The three fields L, M, and N are delineated by full lines (1), (2), (3), and (4). In the central Abukuma Plateau, fields L and M jointly represent actinolites, and field N blue-green, green and brown hornblendes. Among them green and brown hornblendes tend to concentrate in the area P that is delineated by a dotted line. Thus, the amphiboles of metamorphosed basic rocks move generally toward the right with increasing metamorphism in this case.
In the Bessi-Ino area of the Sanbagawa belt, field L represents actinolites, field M barroisites, and field N blue-green hornblendes. The general trend of variation with increasing temperature in glaucophanitic metamorphism was noticed as shown by arrows.

effect of the chemical composition of the host rock, but might be partly due to some retrogressive change that has taken place in irregular areal distribution.

The contact metamorphic aureole in the Nakoso area is much smaller in scale, and it may be considered that retrogressive change is much weaker here, owing to more rapid cooling. The calciferous amphibole in basic metamorphic rocks of Nakoso shows a very regular change with progressive metamorphism as follows: actinolite → blue-green hornblende → green and greenish brown hornblende → brown hornblende (SHIDO, 1958a). Similar relation will be cited later as regards K-feldspars of the Nakoso area.

The different kinds of calciferous amphiboles were found to plot in different fields in the 2V-γ diagram (SHIDO and MIYASHIRO, 1959). The

2V-γ relation of calciferous amphiboles was studied also in some other metamorphic areas in Japan. The results are summarized in Fig. 13.

Many chemical analyses of calciferous amphiboles from the Abukuma Plateau and genetical discussions on them are presented by SHIDO (1958a) and SHIDO and MIYASHIRO (1959).

In recent years, IWASAKI (1963), BANNO (1964) and KANEHIRA (1967) studied the calciferous amphiboles of the Sanbagawa belt in great detail. In the zone of the glaucophane-schist facies, the stable calciferous amphibole is actinolite, whereas in the zone of the epidote-amphibolite facies the common calciferous amphibole is blue-green hornblende with Ca$>$1.5 for 23 O on the anhydrous basis. BANNO found in the Bessi-Ino area that in the transitional zone between the glaucophane-schist and epidote-amphibolite facies, calciferous amphibole with Ca content between 1.0 and 1.5 for 23 O occurs. IWASAKI noticed in eastern Sikoku that such an amphibole is rather common in the higher-temperature part of the glaucophane-schist facies. Such an amphibole which does not occur in the low P/T type of metamorphism, may well be regarded as a characteristic mineral of glaucophanitic metamorphism. IWASAKI called it *barroisite,* whereas BANNO called it *subcalcic hornblende* and regarded it as a variety of calciferous amphibole.

HALLIMOND (1943) considered that amphiboles with Ca between 1.0 and 1.5 are rare in nature. In his definition calciferous amphiboles contain Ca over 1.5. BANNO re-defined calciferous amphiboles as having Ca over 1.0. BANNO's definition comes mainly from the practical reason that amphibole with Ca between 1.0–1.5 is indistinguishable under the microscope from that with Ca over 1.5. In this paper, the name of barroisite will be used.

In the Bessi-Ino area, barroisite was found to occur in equilibrium with glaucophane in the zone of the epidote-amphibolite facies. There appears to exist a miscibility gap between the two amphiboles.

SHIDO and MIYASHIRO (1959) emphasized the possible existence of a miscibility gap between actinolite and hornblende in the lower-grade part of the amphibolite facies in non-glaucophanitic metamorphism. BANNO (1964) examined the relevant data as regards glaucophanitic metamorphism, and concluded that a similar gap may exist in glaucophanitic metamorphism as well, though the available data are not enough to prove or disprove it. The widespread occurence of actinolite in basic metamorphic rocks of glaucophanitic terrains, such as in Japan, is probably a characteristic feature of regions intermediate between typical glaucophanitic and non-glaucophanitic ones, as will be discussed later (p. 426).

Alkali Amphiboles

Glaucophane, subglaucophane as defined by MIYASHIRO (1957), and crossite occur in the areas of the glaucophane-schist facies. Occurrence of one or another appears to depend largely on the chemical composition of the host rock.

Riebeckite and magnesioriebeckite occur not infrequently in some highly silicic rocks in glaucophanitic terrains (e.g., MIYASHIRO and IWASAKI, 1957; SUZUKI and SUZUKI, 1959). The range of physical conditions for the formation of these minerals appears to be wider than that of glaucophane. Most commonly, riebeckite and magnesioriebeckite appear to be formed by metasomatic introduction of Na into ferruginous silicic rock (MIYASHIRO, 1967b).

Zonal structure between alkali amphiboles or between alkali and calciferous amphiboles is common. For example, see MIYASHIRO and IWASAKI (1957) or IWASAKI (1963).

A completely colorless variety of glaucophane that is very poor in FeO but rich in Fe_2O_3 was described from piemontite-quartz schists of Bizan in the Sanbagawa belt (IWASAKI, 1960). A magnesioriebeckite with apparent departure of the optical absorption axes from the indicatrix axes was found from a nearby locality (MIYASHIRO and IWASAKI, 1957).

Alkali Pyroxenes

Aegirine occurs in some quartzose metamorphic rocks of the Sanbagawa and Kamuikotan belts (e.g., SUZUKI and SUZUKI, 1959; BANNO, 1959).

SEKI and SHIDO found that jadeite occurs in association with quartz in limited zones of the Sanbagawa and Kamuikotan belts (SEKI and SHIDO, 1959; SEKI, 1960; BANNO and HATANO, 1963). It is commonly very fine-grained and can be identified with the aid of the X-ray powder method. It is to be noted that albite always occurs in association with the jadeite.

Jadeite was found also to occur abundantly in some rocks associated with serpentinite in the Sanbagawa metamorphic belt (e.g., SEKI, et al., 1960).

Before 1959, the only known locality of jadeite in Japan was the Kotaki-Omi area in the Sangun belt. Here, jadeite occurs in albitite associated with serpentinite. Some of the jadeite is of green gem quality. However, the jadeite-quartz assemblage has not been found in any rocks of the Sangun belt.

As to the abundant occurrence of jadeite in serpentinite, desilication reaction appears to play an important role (SHIDO, 1958b).

Clinopyroxenes intermediate between aegirine and jadeite were described by IWASAKI (1963) and KANEHIRA and BANNO (1960) both from metamorphic rocks of the Sanbagawa belt. They called the mineral *aegirinjadeite*.

Stilpnomelane

Stilpnomelane occurs in basic, pelitic, psammitic, quartzose, and calcareous metamorphic rocks in all grades, with the possible exception of the highest one, of the Sanbagawa, Sangun, and Kamuikotan glaucophanitic belts (KOJIMA, 1944; SEKI, 1958; IWASAKI, 1963; BANNO and HATANO, 1963).

IWASAKI (1963) found that the refractive indices of stilpnomelane tend to decrease with increasing metamorphic temperature, probably owing to gradual reduction of iron.

YUI (1962) found that magnetite-Fe_2O_3-poor stilpnomelane layers, several millimeters to 1 centimeter thick, are in fine alternation with pyrite-F_2O_3-rich stilpnomelane layers in the Motoyasu mine within the Sanbagawa metamorphic belt. This alternation is considered to have formed by original compositional difference and very limited diffusion of S and O during metamorphism. KOJIMA (1944) and YUI (1962) gave several new chemical analyses of stilpnomelanes.

Very recently, stilpnomelane in association with biotite was reported to occur in a rock of anomalous chemical composition in a very low-grade part of the Ryoke metamorphic belt (KATADA and SUMI, 1966).

Andalusite, Sillimanite and Cordierite

All these minerals occur in some pelitic rocks of the low P/T type of metamorphic belts in Japan. The occurrence of andalusite is usually confined to more highly aluminous rocks ($Al_2O_3 > 20\%$) than that of the other two. The transformation of andalusite to sillimanite with rising temperature takes place at a somewhat lower temperature than the breakdown of muscovite in reaction with quartz to produce sillimanite and K-feldspar.

It has been noted that the stable association of K-feldspar with andalusite and cordierite can occur at much lower temperatures than the breakdown of muscovite in the Ryoke belt (HAYAMA, 1964).

K-Feldspars

SHIDO (1958a, p. 165–170) showed in the Nakaso area of the central Abukuma Plateau that microcline is stable at lower temperatures of metamorphism, whereas orthoclase is stable at higher temperatures. The stability boundary between microcline and orthoclase appears to lie in the middle of the amphibolite facies. A similar relation was found in the Ryoke metamorphic terrain of the northern Kiso area (KATADA, 1965).

In many other areas of the Ryoke-Abukuma metamorphic belt, however, microcline continues to occur up to the high-temperature part of the amphibolite facies together with orthoclase. It is conceivable in this case that orthoclase was formed at the maximum temperature during metamorphism and part of it was later transformed retrogressively to microcline with declining temperature. The metamorphic terrain of Nakaso is relatively small in scale, and hence the temperature fall may have been so rapid as to prohibit backward transformation of orthoclase. Similar relation was suspected on an earlier page, as regards calciferous amphiboles (p. 413).

Plagioclase

Albite is very widespread in the glaucophanitic metamorphic belts of Japan. (This problem will be discussed in p. 426). Usually it forms fresh, unzoned grains. Porphyroblastic growth is common in the higher-temperature parts of the Sanbagawa belt. The schists or the terrains with conspicuous porphyroblasts of albite have usually been called spotted schists or spotted zones, respectively.

Most of the albite grains are not twinned. The percentage of twinned grains tends to increase with rising temperature (IWASAKI, 1963). In the highest-temperature part of the Sanbagawa belt, a zone of the epidote-amphibolite facies occurs, where plagioclase with compositions of 5–15% An is present (BANNO, 1964).

In the low P/T type of regional metamorphism, plagioclase becomes more calcic very rapidly with rising temperature (MIYASHIRO, 1958, p. 264; 1967c).

Tourmaline

In pelitic metamorphic rocks of the Ryoke-Abukuma and Sanbagawa belts, it was commonly observed that tourmaline is bluish green or green in thin section in lower-temperature zones, whereas it is brown in higher-temperature zones. Zoned crystals with a green core and brown margin are common (UNO, 1961; BANNO, 1964; HAYAMA, 1964; KATADA, 1965). The corresponding compositional variation has not been clarified. The color variation from blue or blue-green to brown with progressive metamorphism is a tendency observed in biotite, calciferous amphibole and tourmaline.

Oxides and Sulfides

BANNO and KANEHIRA (1961) and KANEHIRA, BANNO and NISHIDA (1964) studied the modes of occurrence of the oxides and sulfides of iron in metamorphic rocks.

In glaucophanitic metamorphic terrains, hematite and pyrite are common in basic schists, whereas iron oxide minerals do not occur and pyrite and pyrrhotite are common in pelitic schists. In pelitic schists, the widespread presence of graphite could cause reduction of iron into the ferrous state, and the ferrous iron could be readily incorporated into the silicate minerals. This is probably the reason why iron oxide minerals do not occur in pelitic schists. For the reducing effect of graphite, see MIYASHIRO (1964).

On the other hand, in the medium- and high-temperature part of low P/T type metamorphic terrains, hematite does not occur either in basic or in pelitic schists, whereas magnetite and pyrrhotite are common.

The hematite-ilmenite equilibria were described and discussed by BANNO (1964, p. 272–274).

GEOLOGIC STRUCTURE OF METAMORPHIC BELTS

Introductory Statement

I am not familiar with details of the structural aspects of the study of metamorphic belts. For the last 20 years, the structures of metamorphic rocks and terrains have been laboriously worked out by many geologists, mainly under the leadership of GEORGE KOJIMA of Hiroshima University. The works have been made partly for academic interest, and partly in relation to the prospecting of bedded cupriferous pyrite ore deposits in the Sanbagawa terrain.

Here I would like to summarize only some important structural features mainly on the basis of their works.

Structure of the Ryoke Terrain

Usually the original sedimentary rocks of the Ryoke terrain are rather monotonous and are devoid of reliable key beds. Abundant granitic rocks are intruded into the metamorphic terrain. Hence, it is difficult to establish the stratigraphy and structure of large areas in the belt.

Rather detailed structural studies have been made by KATADA et al. (1961) in the Tenryu Valley, by NAKAJIMA and HARA in the Kasagi area (e.g., HARA, 1962) and by KOJIMA (1953), OKAMURA (1960) and NUREKI (1960) in the Yanai area. YOSHIZAWA et al. (1966) published a geologic map of a Ryoke terrain, about 50 by 70 km, in northern Kii Peninsula (including the Kasagi area).

The rocks are strongly folded, often with high inclination (40–90°). The fold axes are roughly parallel to the elongation of the metamorphic belt.

In the Yanai area, about 40 km southwest of Hiroshima, the quartz fabric of biotite schists in the lower-temperature zone show marked orthorhombic symmetry. On the other hand, the quartz fabric of banded gneisses in the high-temperature zone show no preferred orientation. Thus, it was inferred that the Ryoke metamorphism may be divided into two phases: the earlier phase characterized by penetrative movement to produce the quartz fabric of biotite schists, and the later phase leading to the formation of banded gneisses without penetrative movement (NUREKI, 1960).

In virtually all parts of the Ryoke-Abukuma metamorphic belt, granitic rocks have been divided into the so-called older and younger groups. The granitic bodies of the older group have been claimed to be intrusive broadly concordantly into the surrounding schistose metamorphic rocks, and to have no or little noticeable contact metamorphic effect on them. They appear to form domes or sheets. The older granitic rocks show strong or weak gneissosity, and the quartz grains were found to show preferred orientation. Some of them appear to have been formed by granitization nearly *in situ,* but others show evidence of forcible intrusion.

The granitic bodies of the younger group, on the other hand, are intrusive clearly discordantly into the surrounding schistose metamorphic rocks, and have strong contact metamorphic effect on them. The younger granitic rocks are usually massive, but not infrequently show weak foliation due to flow movement. In some bodies, the foliation plane shows a broadly concentric disposition along the outline of the body.

The too sharp division into the older and younger groups, however, appears to be artificial in many areas. Some of the so-called older granites were proved to have had considerable contact metamorphic effects.

The temperature of regional metamorphism usually increases toward the median tectonic line, i.e., the big boundary fault between the Ryoke and Sanbagawa metamorphic belts. The isograds are usually broadly parallel to the boundaries of geological formations. However, KATADA (1965) emphasized that in the northern Kiso area the isograds cross the strike of the formations. The distribution of metamorphic temperature is virtually independent of that of granitic bodies.

Structure of the Sanbagawa Terrain

The Sanbagawa metamorphic belt is relatively wide in Sikoku. Moreover, the original structure is relatively well preserved in this region. Hence, the stratigraphy and structure have been most successfully worked out in central Sikoku by G. KOJIMA, K. HIDE, G. YOSHINO, T. SUZUKI and N. OYAGI.

KOJIMA (1951) and KOJIMA et al. (1956) divided the stratigraphic sequence of the Sanbagawa terrain in central Sikoku into groups and formations as shown in Table IV. The total stratigraphic thickness is said to vary in the range of 5 to 11 km. They considered all these rocks to be Permian and older Paleozoic. The Sanbagawa metamorphic rocks in other parts of the belt have been correlated with members of the abovementioned sequence on the basis of lithological similarity.

In ordinary exposures, the schists usually show more or less complicated minor folding, and hence give the impression that the whole geologic structure is so complicated as to make an analysis almost impossible. If we neglect, however, such minor structures and trace key beds as indicative of the structure of the order of one kilometer or more, it is noticeable that the large-scale structure thus revealed is relatively simple in many cases.

In this way, KOJIMA (1963) divided the Sanbagawa metamorphic terrain of central Sikoku into the following three kinds of structural units: (1) zones of anticlinorium; (2) zones of flexure; (3) zones of synclinorium.

Fig. 14 shows the Sanbagawa metamorphic terrain in Sikoku, in which three zones of anticlinorium are shown. Each of these zones is about 100 km long and 10 km wide. They stretch broadly in the E-W direction, i.e., a little obliquely to the elongation of the Sanbagawa belt in this region.

The zones of synclinorium are in between the zones of anticlinorium. They are about 10–15 km wide. The zones of flexure represent the transitional areas between the above two kinds of zones. Each of the three kinds of units has structural and petrological features distinct from those of the others, and hence appears to represent different conditions of formation.

The zones of anticlinorium show gentle wavy folding, and the dips of the beds are usually less than 40 degrees. Not infrequently beds are nearly horizontal over a wide area. The anticlinal axis shows axial culmination at some places, resulting in a dome-like structure.

The zones of synclinorium have much more complicated structures,

Table IV.

Stratigraphic sequence of the Sanbagawa terrain in central Sikoku (KOJIMA, 1951; KOJIMA et al., 1956).

Yoshinogawa group	Upper subgroup	Ojoin formation (mainly pelitic)
	Middle subgroup	Minawa formation (mainly metabasites and highly silicic rocks)
		Koboke formation (mainly psammitic and pelitic)
	Lower subgroup	Kawaguchi formation (mainly pelitic)
		Oboke formation (mainly psammitic)
Nishiiya group (mainly pelitic)		

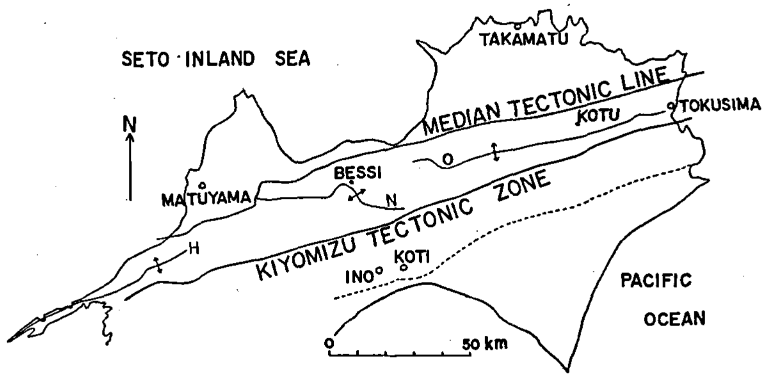

Fig. 14. Sanbagawa metamorphic terrain in Sikoku.
Three zones of anticlinorium O, N, and H are usually called the Oboke, Notaniyama-Nakasitiban, and Hijikawa anticlines, respectively. The median tectonic line is the northern limit of the Sanbagawa terrain. The area between this line and the Kiyomizu tectonic zone is a well-recrystallized Sanbagawa terrain. The Sanbagawa metamorphism, however, has some recrystallization effect to the further south, almost to Ino and Koti. The dotted line represents the approximate boundary between the Paleozoic terrain in the north and the Mesozoic terrain in the south. Bessi (Besshi) and Kotu (Kotsu) are mines of bedded cupriferous pyrite deposits. After G. KOJIMA et al. (1956).

probably partly with a recumbent type of folding (HIDE, 1961). The zones of anticlinorium do not have porphyroblastic development of albite, whereas the zones of synclinorium do. The latter appears to have recrystallized at higher temperatures than the former.

KOJIMA (1963) considers that the differentiation of the metamorphic terrain into these structural units began in the geosynclinal stage. Hence, the thickness and rock facies of sediments differ to some extent in different units. The zones of synclinorium moved downwards, and this produced the zones of flexure along their borders. This movement appears to be responsible for the formation of bedding schistosity of metamorphic rocks. In the zones of flexure and synclinorium, submarine volcanism took place, as is represented by metabasites of the Minawa formation. The original material for the formation of bedded cupriferous pyrite deposits appears to have been deposited in genetic relation to the submarine volcanism. Minor folds were largely formed by deformation at some later stages, which resulted in the generation of fracture cleavages with relatively wide spacing in the schists.

In other parts of the Sanbagawa belt, NAKAYAMA (1959) published structural studies in Kii Peninsula and the Tenryu Valley.

In almost all parts of the Sanbagawa belt, the metamorphic temperature increases towards the median tectonic line, i.e., northwards. The temperature increases at some places towards the lower stratigraphic horizon, and at others towards the higher. In other words, the distribution of metamorphic temperature is independent of the stratigraphy. Moreover, it is independent of the distribution of igneous rocks.

In most cases, the isograds are broadly parallel to the boundaries of geological formations. In central Kii Peninsula, SEKI et al. (1964) showed that an isograd cuts across a thrust fault which is the boundary between the Paleozoic and Mesozoic formations in this area.

Structure of the Sangun Terrain

The stratigraphy and structure of the Sangun metamorphic terrain in western Honsyu region were studied by KOJIMA (1953) and MITSUNO (1963).

MITSUNO divided the Upper Paleozoic formations in Okayama Prefecture in descending order as follows: (1) upper group mainly consisting of slate with intercalated acidic volcanics; (2) middle group mainly consisting of alternations of sandstone and pelitic and quartzose schist together with a greenschist bed; (3) lower group mainly consisting of thick beds of greenschist with intercalated schistose acidic lava and pyroclastics; (4) lowest

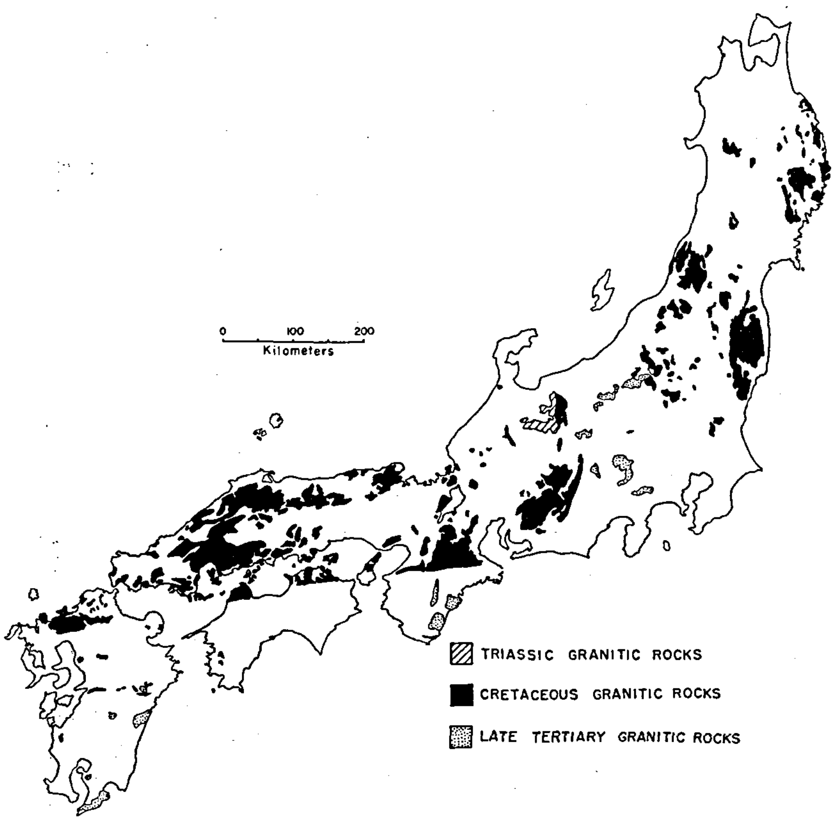

Fig. 15. Distribution and provisional classification of granitic rocks in Japan. The Triassic and Cretaceous granitic rocks are related to the Hida and Ryoke metamorphism, respectively. Early Tertiary granites are included in the latter.

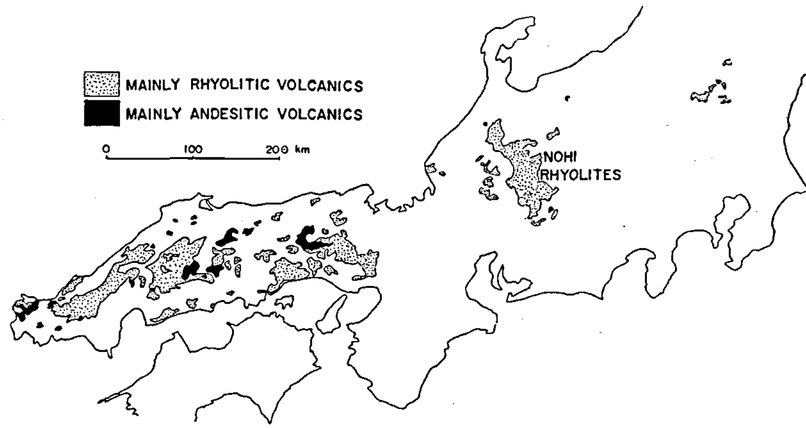

Fig. 16. Distribution of Cretaceous volcanic rocks in Japan.

group consisting mainly of pelitic schist. The total stratigraphic thickness appears to be to the order of 8 kilometers. Bedded cupriferous pyrite deposits occur in association with the lower group.

Only some parts of the formations are recrystallized to become Sangun metamorphic rocks. Metamorphic and non-metamorphic parts are stratigraphically conformable, but the boundary surfaces between them cut the bedding surface.

The terrain has gentle dome- and basin-like folds. The wave length of the folds is about 3–5 km.

GRANITE-RHYOLITE ASSOCIATION IN RELATION TO RYOKE-ABUKUMA METAMORPHISM

The areal extent of outcrops of granitic rocks in Japan is estimated at 49,300 km^2, i.e., 13% of the whole country (Fig. 15). HATTORI and NOZAWA (1959) published a table of about 500 chemical analyses of granitic rocks of Japan that were made public in and before 1956. A similar number of new analyses have been published since then. K-Ar dating has been made on a few hundred granitic rocks. The bulk of these rocks were formed in Cretaceous and early Tertiary time (110 to 50 million years ago). Some of them occur within the Ryoke-Abukuma metamorphic belt, and others in regions to the north or northwest. It may be considered that most granitic rocks of Cretaceous and early Tertiary ages were formed in some genetical relation to the Ryoke-Abukuma metamorphism. It is a worldwide tendency that regional metamorphism of the low P/T type is always accompanied by abundant granitic rocks.

It deserves special attention that a vast quantity of rhyolitic volcanics occurs in close association with the Cretaceous granitic rocks in the central and western parts of Japan, as shown in Fig. 16. They are mostly welded tuff and other pyroclastic rocks of rhyolitic compositions. In some cases, a smaller amount of dacitic and andesitic rocks is associated with them. A large mass in the central part of Japan is called the Nohi rhyolites, covering an area of about 5,000 km^2 with an average thickness of about 600 m (KAWADA et al., 1961). Some rhyolitic volcanics cover Cretaceous granitic rocks unconformably, whereas others are cut and contact-metamorphosed by other Cretaceous granitic rocks (YOSHIDA, 1961). All the rhyolitic volcanics appear to have been erupted in Cretaceous (and possibly early Tertiary) time. The close spatial association, broad contemporaneity, and similar chemical composition of the granitic and rhyolitic rocks suggest the existence of genetic connection between them (YAMADA, 1966).

It has been conventional for the last 25 years to emphasize the general independence of granitic rocks of orogenic belts from volcanic ones (KENNEDY and ANDERSON, 1938). The former was called to belong to the plutonic associations, whereas the latter, to the volcanic associations. There is no doubt that this view reflects some aspects of the truth. That does not seem to be the case here, however.

It is conceivable that the granite-rhyolite association of the orogenic nature may be characteristic of the low P/T type of regional metamorphism. It may be related to the relatively shallow depths of the formation of the metamorphic and granitic rocks there. If so, we might be able to find similar examples in other metamorphic belts of the low P/T type in the world.

In the southeastern part of Australia, Paleozoic metamorphic rocks of the low P/T type are widely exposed, e.g., in Cooma and Wantabadgery (JOPLIN, 1942, 1943; VALLANCE, 1953). The metamorphism is Ordovician to Silurian. The associated granitic rocks are also Silurian (PIDGEON and COMPSTON, 1965). It is of interest that rhyolitic volcanic rocks are also present roughly near the boundary between Silurian and Devonian (A. J. R. WHITE and S. BANNO, personal communication). Here may exist a series ranging from orogenic granite to rhyolitic volcanics.

USTIYEV (1965) emphasized the existence of a close association of some volcanic and plutonic rocks. Some of the examples cited are clearly of non-orogenic nature. Others, however, appear to be of orogenic nature. For example, the granite-rhyolite association occurring to the northwest of Kamchatka Peninsula may be of the latter category. The "Map of Metamorphic Facies of the USSR" (DOBRETSOV et al., 1966) indicates that this area is a high-temperature metamorphic one. It is also to be noted that a glaucophanitic metamorphic belt occurs just on the east side of the area (DOBRETSOV and PONOMAREVA, 1965). There may be paired metamorphic belts present.

BASALT-SERPENTINITE ASSOCIATION

The incipient stage of the Paleozoic geosynclinal development in Japan is said to have been accompanied by some andesitic and rhyolitic volcanism in Silurian and Devonian time. The main part of the geosynclinal pile, however, is made up of Carboniferous and especially Permian formations

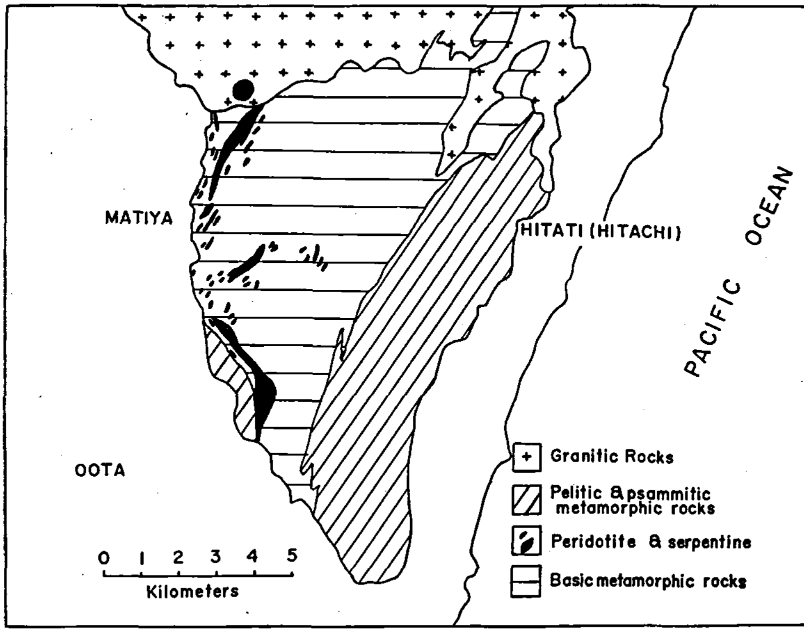

Fig. 17. Ultrabasic rocks of the Hitati area in the southern Abukuma Plateau. Ultrabasic rocks are abundant in the western part where basaltic volcanism was intense in the geosynclinal stage. The basaltic rocks were metamorphosed into amphibolites (MIYASHIRO, 1966).

accompanied by abundant basaltic volcanics. The basaltic rocks are commonly closely associated with serpentinite. All these rocks collectively form the so-called *ophiolites*. Their close spatial association was emphasized by MIYASHIRO (1966), as is exemplified by Fig. 17. The close spatial association, however, would not necessarily mean that they were derived from the same magma. This problem will be discussed toward the end of this paper (p. 439).

The distribution of basalt and serpentinite within the geosynclinal pile is not uniform. They are very abundant in the Sangun and Sanbagawa glaucophanitic metamorphic belts as well as in the zone on the oceanic side of Sanbagawa (i.e., zone S of Fig. 3). On the other hand, they are relatively scarce in the metamorphic belts of the low P/T type as well as in the zone on the immediate continental side of the Ryoke belt.

Fig. 18 shows the distribution of serpentinite in Japan. The Ryoke-Abukuma metamorphic belt is accompanied by a small serpentinite belt in the Abukuma Plateau (shown by A). On the other hand, the Sanbagawa and Sangun glaucophanitic metamorphic belts have a big serpentinite belt. The Kamuikotan glaucophanitic belt also has a big serpentinite belt. These serpentinite belts may be regarded as representing the distribution of the basalt-serpentinite association. The great abundance of the basalt-serpentinite association in glaucophanitic belts and its scarcity in low P/T type metamorphic belts are clearly noticed in this figure.

Within the metamorphic belts, basaltic rocks are recrystallized to greenschist, glaucophane schist, epidote amphibolite and amphibolite. The present mineralogy of serpentinites is also probably of metamorphic origin in most cases. Serpentinites in metamorphic terrains tend to have a lower Fe^{+3}/Fe^{+2} ratio than those in non-metamorphic ones, though this relation is not very regular (MIYASHIRO, 1966). Most masses of serpentinite appear to be intrusive into the country rocks, whereas others may be metamorphic derivatives of picrite basalt.

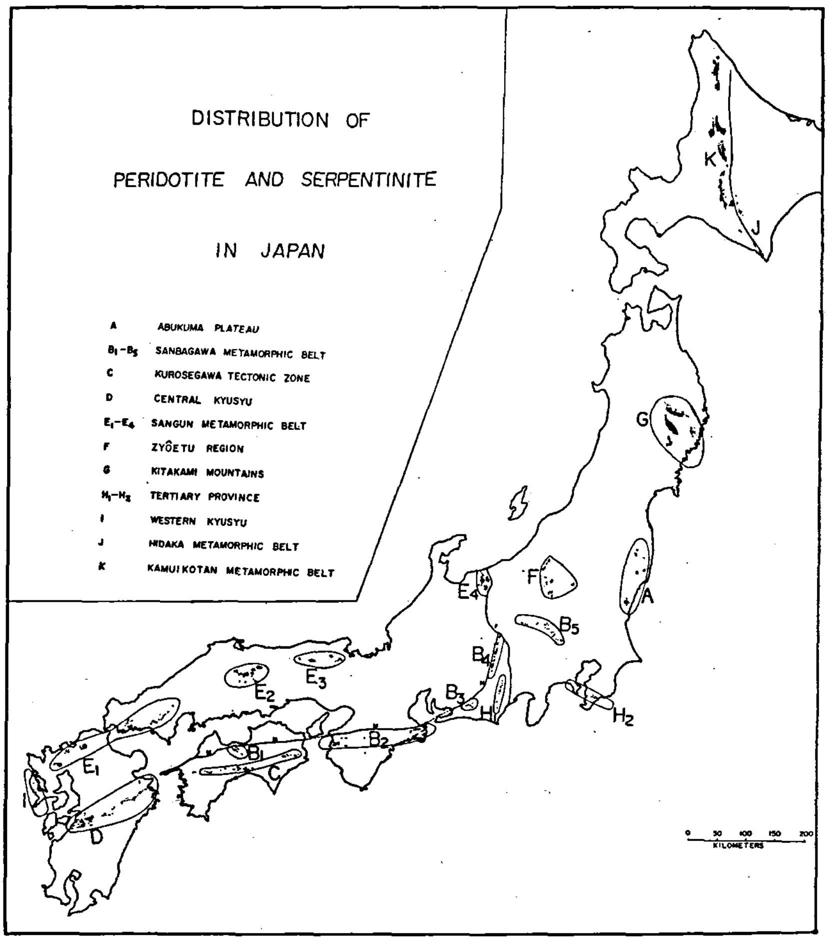

Fig. 18. Distribution of peridotite and serpentinite in the Japanese Islands. They are grouped into ultrabasic belts (A) – (K). The median tectonic line is shown by full line M-M-M-M.

A most remarkable feature of geosynclinal basaltic volcanics in the Sanbagawa belt and further south of it is that the bulk of them is tuff breccia and other pyroclastic rocks. Basaltic lavas exist, but are not abundant. In this respect, the geosynclinal basaltic volcanism of the Sanbagawa belt differs essentially in the mode of eruption from all the present-day basaltic volcanos, which mainly produce lavas and not pyroclastics.

NAGASAKI (1966) described a large, exceptionally fresh, layered mass of peridotite at Horoman in the Hidaka metamorphic belt, Hokkaido. The layering may have been produced by crystallization differentiation.

COMPARISON WITH METAMORPHIC BELTS IN OTHER PARTS OF THE WORLD

Similarity in the Circum-Pacific Region

Paired metamorphic belts occur not only in Japan, but also in other parts of the circum-Pacific region. Examples are known in Celebes, New Zealand and California (MIYASHIRO, 1961a).

Recently LEBEDEV, et al. (1967) have clarified the existence of paired metamorphic belts in Kamchatka. LANDIS and COOMBS (1967) found a median fault between the paired metamorphic belts of New Zealand. This fault would correspond to the median tectonic line of Japan and Celebes. LANDIS and COOMBS have emphasized that the New Zealand geosyncline is auto-cannibalistic. This is true in Japan, also.

Differences in the Circum-Pacific Region

It is important, on the other hand, that different parts of the circum-Pacific region show some different characteristics in spite of some fundamental features they have in common. For example, the glaucophanitic metamorphism of the Franciscan in California probably represents higher P/T conditions than the glaucophanitic belts of Japan. This problem is being studied in detail especially by W. G. ERNST and Y. SEKI (e.g., ERNST and SEKI, 1967).

In this respect, we may say that the glaucophane-schist facies represented by the Franciscan is more typical than that represented by the Sanbagawa and Sangun belts. In other words, the latter glauophane-schist facies may be regarded as being intermediate between the typical one and the greenschist facies. In Japan, even in the area of the glaucophane schist facies, glaucophane occurs only in some basic and highly silicic rocks, and moreover among metabasites, glaucophane schists are usually less common than actinolite greenschists. In such cases glaucophane schists tend to have a higher Fe^{+3}/Fe^{+2} ratio than the associated actinolite greenschists (IWASAKI, 1963, p. 32–34; ERNST, 1964). The mineralogical differences are probably due to the chemical ones.

ESKOLA (1939) established the concept of the glaucophane schist facies, and DE ROEVER and other Dutch geologists contributed much to the development of the concept, coining the term glaucophanitic metamorphism.

They never regarded glaucophanitic metamorphism, however, as a type of progressive metamorphism whose characteristics are most clearly shown by zonal mapping of metamorphic terrains. Zonal mapping of glaucophanitic terrain was first attempted successfully by BANNO (1958) in the Omi area of the Sangun belt, and by SEKI (1958) in the Kanto Mountains of the Sanbagawa belt. Since then, we have had many fine additional examples, as reviewed before.

It is rather strange that such zonal mapping of glaucophanitic terrains has not been successfully made in any other parts of the circum-Pacific region. The reason for this is not clear. It appears, however, that the difficulty in other parts lies partly in the different characteristics of glaucophanitic metamorphism itself. Recently zonal mapping of glaucophanitic terrains was made in the Swiss Alps. Both Japanese and Swiss glaucophanitic metamorphism are not so typical as that of the Franciscan (MIYASHIRO, 1967a).

According to personal communication of YOTARO SEKI, most rocks of the Franciscan metamorphic terrain have no schistosity, whereas most rocks of the glaucophane schist belts in Japan are schistose.

Possible Paired Metamorphic Belts in Europe

The paired metamorphic belts are well-developed in the circum-Pacific region. Hence, paired belts may be regarded as a characteristic feature of the region. However, this statement does not preclude the possibility that some form of paired metamorphic belt may occur in other parts of the world.

Within the Caledonides of Great Britain, the Scottish Highlands have a high-temperature metamophic belt with abundant granitic rocks, whereas the Southern Uplands of Scotland have some glaucophane schists associated with abundant geosynclinal basaltic volcanics. In this case, recrystallization in most of the Southern Uplands appears to be very poor. The Scottish Highlands and Southern Uplands might, however, be regarded as an incipient form of paired metamorphic belts in Paleozoic time (MIYASHIRO 1967c).

On the global scale, the time difference of the order of 200 million years may not be very great. If so, the Hercynian and Alpine metamorphic belts in Europe might be regarded as forming a pair. The former represent the low P/T type belt and the latter the high P/T type belt (MIYASHIRO, 1967c).

PRESENT-DAY OROGENY IN JAPAN

Volcanoes, Earthquakes, and Trenches

It has generally been stated that Japan is a recent or present-day orogenic region. This idea seems to have come from the impression that a large number of active volcanoes and earthquakes occur there. There are more than 200 Quaternary volcanoes present in Japan. About 40 of them

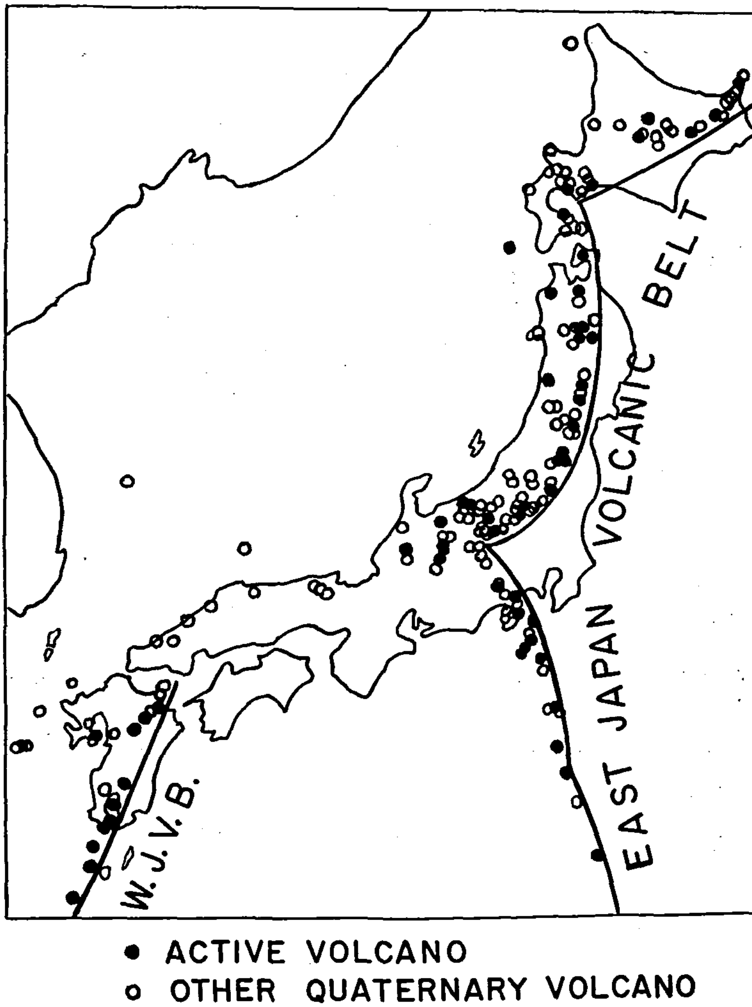

Fig. 19. Distribution of Quaternary volcanoes of Japan. The heavy arcuate lines represent the sharp eastern limit of the distribution areas of volcanoes, having been called "volcanic fronts" by SUGIMURA (1960, 1965, 1967). Volcanoes are especially crowded in the zone to the immediate west of the volcanic front.

erupted in historic time. The energies released by volcanic activity and by earthquakes in Japan and its vicinity have been estimated at 7×10^{23} ergs/year and 5×10^{23} ergs/year respectively. These are about $^1/_5$ and $^1/_{10}$, respectively, of the energies released by volcanic activity and by earthquakes of the entire earth.

SUGIMURA (1960) pointed out that Quaternary volcanoes of Japan are distributed along two broad belts, as shown in Fig. 19. He named them the *East Japan and West Japan volcanic belts.* The former stretches along the Kuril, Northeast Japan, and Isu-Bonin Arcs. The latter stretches along Kyusyu and the Ryukyu Arc. The intermediate region, i.e., most of the Southwest Japan Arc, is nearly devoid of recent volcanoes. It is remarkable that there are deep trenches just on the eastern sides of East Japan and West Japan volcanic belts.

This relation suggests that the region of a volcanic belt associated with a trench represents a present-day active orogenic zone. As compared with it, the Southwest Japan Arc represents a relatively stabilized region, at present.

The distribution pattern of Quaternary volcanoes in Japan is similar to that of Late Tertiary ones. This appears to mean that the present-day orogeny is a continuation of a Late Tertiary one, beginning in Miocene time.

The old cycle of orogeny ranging at least from Silurian to Cretaceous occurred along the main arc of Japan, composed of the Southwest Japan and Northeast Japan Arcs. The two pairs of metamorphic belts formed along the main arc. The new cycle of orogeny, different in areal pattern, began in Miocene and continues to the present.

SUGIMURA, MATSUDA and co-workers made important contributions to our understanding of the relationship between the present-day and Late Tertiary orogenies in Japan (SUGIMURA, 1960, 1965; SUGIMURA et al. 1963; MATSUDA, 1964).

Crust and Mantle

KANAMORI (1963) and others determined the thickness of the crust above the Moho discontinuity in Japan. A simplified result is shown in Fig. 20. It is noticed that the crust is relatively thin (22–30 km) in most of the Northeast Japan Arc, whereas it is generally thicker (28–35 km) in most of the Southwest Japan Arc. In other words, the crust is thinner in the present-day active orogenic region than in the relatively stabilized region.

In the western United States, PAKISER (1963) emphasized the geophysical contrast between the present-day active region and the stable continental region. The Basin and Range province of Nevada is an active region. The crust there is relatively thin (about 30 km), and the uppermost mantle has compressional wave velocities of 7.7–8.0 km/sec and a relatively low density. On the other hand, the Great Plains to the east of the Rockies are a stable continental region. The crust there is thick (about 50 km), and the uppermost mantle has compressional wave velocities of 8.0–8.2 km/sec and a relatively high density. It is interesting that active regions have a thinner crust in both Japan and the western United States.

The compressional wave velocity in the uppermost mantle is known to be 7.7–7.8 km/sec in Northeast Japan, similarly as in the active region of the western United States. It appears to be a little higher in the stabilized region of southwest Japan.

It might be imagined that the crust is young and thin in the active region, and it would gradually become thicker in the course of geologic time. There is reason to believe, however, that the growth of a thick crust is not so monotonously forward a process, but usually contains some phases of

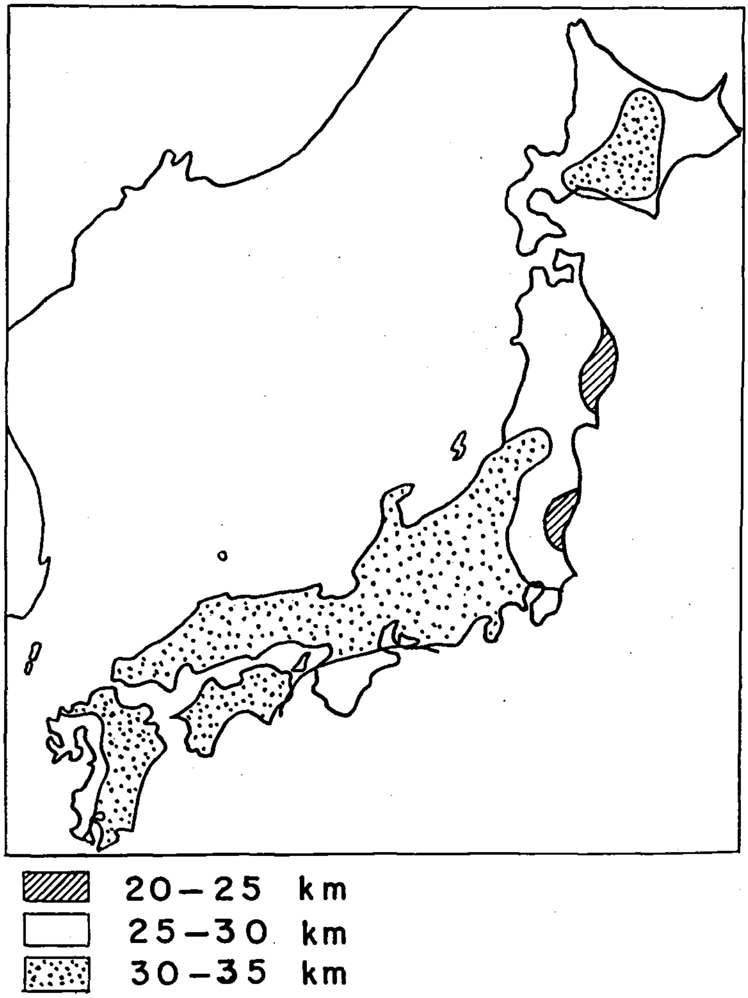

Fig. 20. Depth of the Moho discontinuity in Japan. Simplified from KANAMORI (1963).

backward changes. For example, in Japan the crust is thinnest in the Abukuma and Kitakami region (about 22–26 km). The thinness of the crust of this region is probably a result of Cretaceous or later upward tectonic movements, followed by surface erosion. The original Paleozoic geosynclinal pile, undeformed or deformed, of Abukuma would have had a similar thickness as that of southwestern Japan (i.e., 28–35 km). Hence, we can imagine that erosion in the Abukuma Plateau has exposed a 6–9 km deeper level within the original metamorphosed geosynclinal pile than that in southwestern Japan.

On an earlier page (p. 396), I mentioned the problem of the origin of the Japan Sea. There is a thin crust of the oceanic type in the northern part of the Japan Sea (Fig. 1). In this case also, there is a possibility that a once-formed crust of sialic composition may have been thinned away and eventually lost by surface erosion at a later time. A serious problem is how and why the crust can continue to upheave so enormously as to lose all its sialic layer. Hsu (1965) gave a possible mechanism for it.

We could imagine that the interior of the earth beneath the deeper part of the Japan Sea has been higher in temperature at some time in the past than it is at present. The higher temperature might cause some phase transformation of mantle material leading to a decrease of its density. For the requirement of isostasy, the region with lower density of the mantle should tend to upheave, leading to the appearance above the sea level. Hence, surface erosion would become possible. A decrease of temperature of the mantle at a later time would cause sinking of the region below sea level, leading to the formation of a deep sea.

Terrestrial Heat Flow in Relation to Paired Metamorphic Belts

Some years ago I pointed out the possible significance of terrestrial heat flow to the problem of regional metamorphism (Miyashiro, 1961a, p. 303). Since then, a lot of heat flow data has been published and their

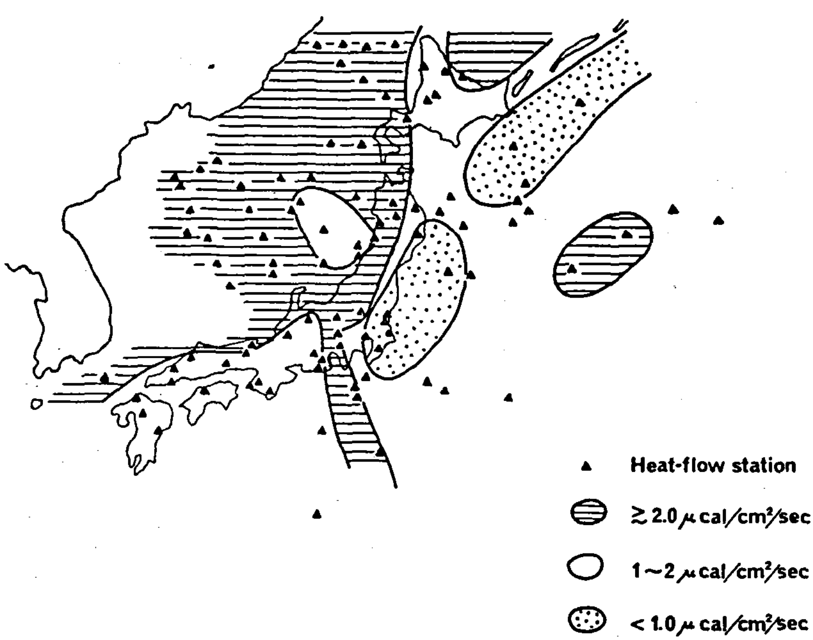

Fig. 21. Distribution of heat flow in and around Japan (Uyeda and Horai, 1964; Takeuchi and Uyeda, 1965).

remarkable relationship to the geologic provinces has been clarified in Japan by K. HORAI, S. UYEDA, and others, (e.g., UYEDA and HORAI, 1964). The results are summarized in Fig. 21.

In the volcanic regions of Miocene to the present on the Japan Sea side of northeast Japan, the heat flow is usually over 2.0×10^{-6} cal/cm^2 sec. On the other hand, in the zone of the Japan Trench and immediately to the west, the heat flow is usually lower than 1.0×10^{-6} cal/cm^2 sec. Thus, in the Northeast Japan Arc and adjacent part of the Japan Trench, there exist contrasted zones of high and low heat flow.

Higher heat flow suggests a generally higher temperature in the depths. Hence, the contrasted zones of heat flow suggest the existence of contrasted zones of high and low temperatures in the depths of the earth. This may mean the possible formation of paired metamorphic belts—in the past, at present, or in the future (MATSUDA, 1964; MIYASHIRO, 1965; TAKEUCHI and UYEDA, 1965). For glaucophanitic metamorphism to take place, prevailing pressure must be very high. The geologic condition for it will be discussed in the next chapter.

The high heat flow region on the Japan Sea side of northeast Japan has a fairly thick pile of Late Tertiary sediments interbedded with abundant volcanics. The volcanics range from basaltic through andesitic and dacitic to rhyolitic rocks. A considerable number of small quartz-dioritic and granodioritic plutons were intruded into them. This situation reminds us of the Sierra Nevada region where geosynclinal andesitic volcanics are associated with granitic plutons (DICKINSON, 1962).

In this paper, the older cycle of orogeny in Japan was regarded as ranging at least from Silurian to Cretaceous, and hence, as being about 350 million years long (p. 401). The new orogeny began in Miocene, i.e., only 20 million years ago. Hence, we could consider that the present is still in the initial phase of the new orogeny. It will last for a long period.

Some authors pointed out that the Late Tertiary orogeny differs in characteristics from many older orogenies in the world. It must be taken into consideration, however, that the new orogeny is really only in the initial phase, and the whole picture of the orogeny may become very different from the situation of the last 20 million years.

Double Arcs of the Western Pacific

If the sea level is raised by 500 m from its present position, the Northeast Japan Arc will become two chains of islands. As shown in Fig. 22, the western chain (i.e., inner chain) will be composed of a large number of Quaternary volcanoes, whereas the eastern chain (i.e., outer chain) will be composed of large non-volcanic islands: Abukuma and Kitakami. The Japan Trench lies further to the east.

Since the present sea level is fortuitous, the Northeast Japan Arc may be regarded as a double arc. At some time in the Miocene, the inner volcanic arc was represented by a chain of submarine volcanoes, and the double arc structure was much clearer at that time than at present. Such a double arc structure with an inner volcanic arc, an outer non-volcanic arc and a

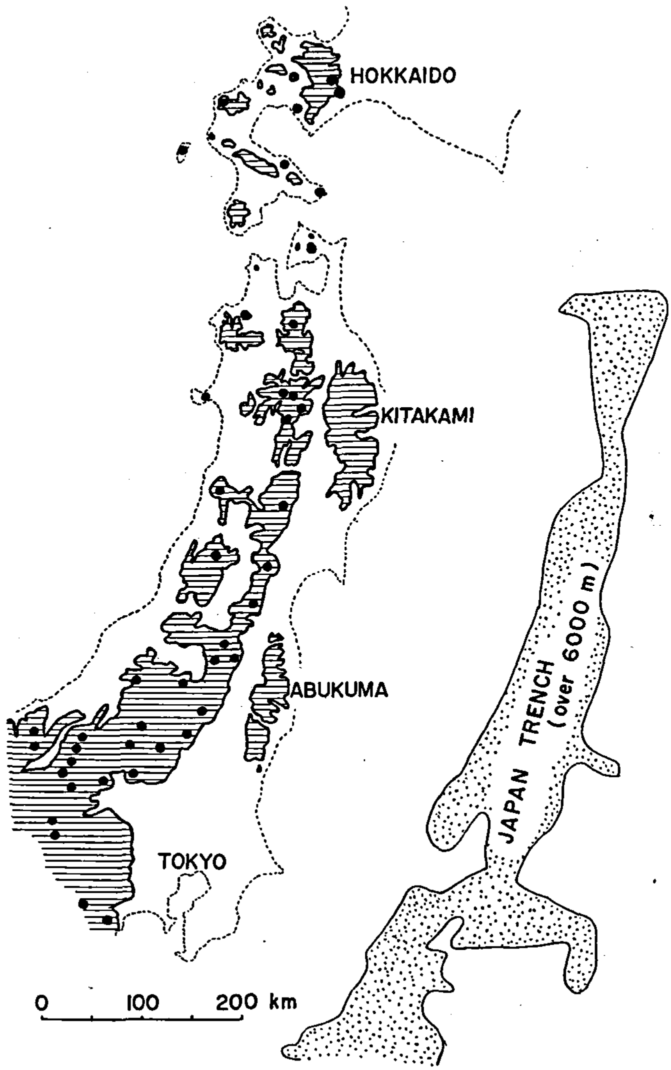

Fig. 22. Double arc structure of the Northeast Japan Arc. The present-day coastline is shown by dotted lines. The areas more than 500 meters above sea level are horizontally ruled. Quaternary volcanoes are shown by solid circles.

trench is common in the western Pacific. This relation was pointed out and emphasized by MATSUDA (1964).

In the Kuril Arc, the present-day main chain of islands represents the inner volcanic arc. The outer non-volcanic arc is well-developed only near the southwestern end of the arc, i.e., near Hokkaido. A deep trench is present further outside.

In the Ryukyu Arc, the present-day main chain of islands represents the outer non-volcanic arc. The inner volcanic arc is represented by a chain of small volcanic islands and submarine volcanoes lying to the west, whereas a deep trench is present to the east.

In the Izu-Bonin Arc, the main chain of islands and submarine ridges represent the inner volcanic arc. Only in the vicinity of the Bonin Islands does it show a double arc structure, with the Bonin Islands on the outer arc. The Japan trench is present further outside.

In the Kuril, Northeast Japan and Izu-Bonin Arcs, fairly detailed geophysical data are available. The outer arc is always characterized by a large positive value of isostatic anomaly in gravity. There is a zone of large negative values of isostatic anomaly between the outer arc and the axis of the trench (Fig. 23).

The existence of contrasted zones of the high and low heat flow values was found not only in Northeast Japan but also in the Kuril Arc (M. YASUI, personal communication). If we may consider that the contrasted zones of Northeast Japan are related to paired metamorphic belts, paired metamorphic belts may also be formed in other double arcs of the western Pacific.

UMBGROVE (1947) discussed the double arc structure in the East Indies. In this case, the outer non-volcanic arc represents the axis of great negative isostatic anomaly (Fig. 23). There appear to exist some essential

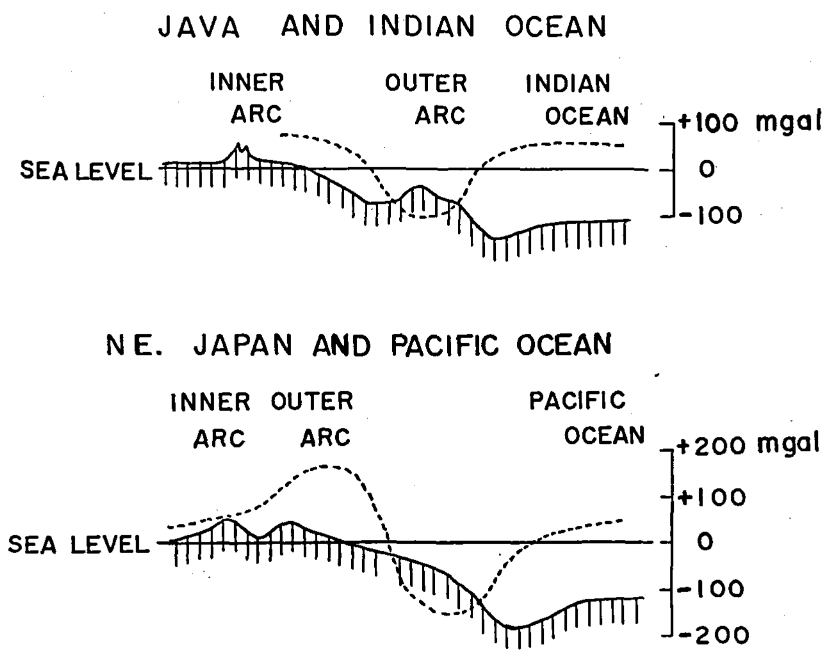

Fig. 23. Topography and gravity profile of the East Indian and Northeast Japan Arcs. Full lines represent the topography, and dotted lines the corresponding gravity profile.

difference between the East Indian Arc and the Northeast Japan and Kuril Arcs, where the outer non-volcanic arc represents the axis of great positive anomaly.

HYPOTHESIS ON THE ULTIMATE ORIGIN OF THE PAIRED METAMORPHIC BELTS AND ASSOCIATED MAGMATISM

Introductory Statement

The origin of the paired metamorphic belts in the circum-Pacific region is a challenging problem. As early as 1959, I expressed the idea that the geosynclinal pile which was subjected to metamorphism might be compared to sedimentary accumulations in and around the present-day trench, and that the metamorphism would be caused by the down-buckling and underthrusting due to movement along such deep-reaching shear-zones as is suggested by deep-focus earthquakes (MIYASHIRO, 1959). Later, my attention was drawn to the then published new data of the low terrestrial heat flow in a deep trench in the east Pacific, and hence, I began to think that glaucophanitic metamorphism would take place in such a trench region, owing to underthrust movement related to the deep-reaching shear-zones (MIYASHIRO, 1961a, b). As a possible cause of contrasted low and high P/T conditions in paired metamorphic belts, I emphasized the difference between the presence and absence of sialic basement in the relevant zones of the geosynclinal pile (MIYASHIRO, 1959, 1961a, b).

A few years later, heat flow measurements by S. UYEDA and K. HORAI (1964) clarified the existence of contrasted zones in heat flow values (as was already shown in Fig. 21). Under this new situation, MATSUDA (1964) published an important synthesis of the present-day geophysical data and abundant data on the geologic development of Japan. He clearly pointed out the possible analogy between the Mesozoic and present-day orogenic belts in Japan. His knowledge of the Late Tertiary geology of Japan played an important role. Unfortunately, this paper was written in Japanese and attracted no attention of geologists in other countries. MIYASHIRO (1965) and TAKEUCHI and UYEDA (1965) proposed possible mechanisms for the formation of metamorphic belts.

Based on all these earlier works, I here wish to try to construct a new unified picture on the ultimate origin of the paired metamorphic belts and associated magmatism in the circum-Pacific region. Since magmatism is an essential part of the orogeny, the origin of magmatism must be involved in the unified picture. The discussion is inevitably highly speculative.

Deep-reaching Shear-zones and the Ultimate Origin of the Glaucophanitic Metamorphic Belt

I wish to begin with an examination of the Northeast Japan Arc. On the western slope of the Japan Trench, the earthquake foci are mostly relatively shallow, i.e., 0–60 kilometers deep. Further westward away from the

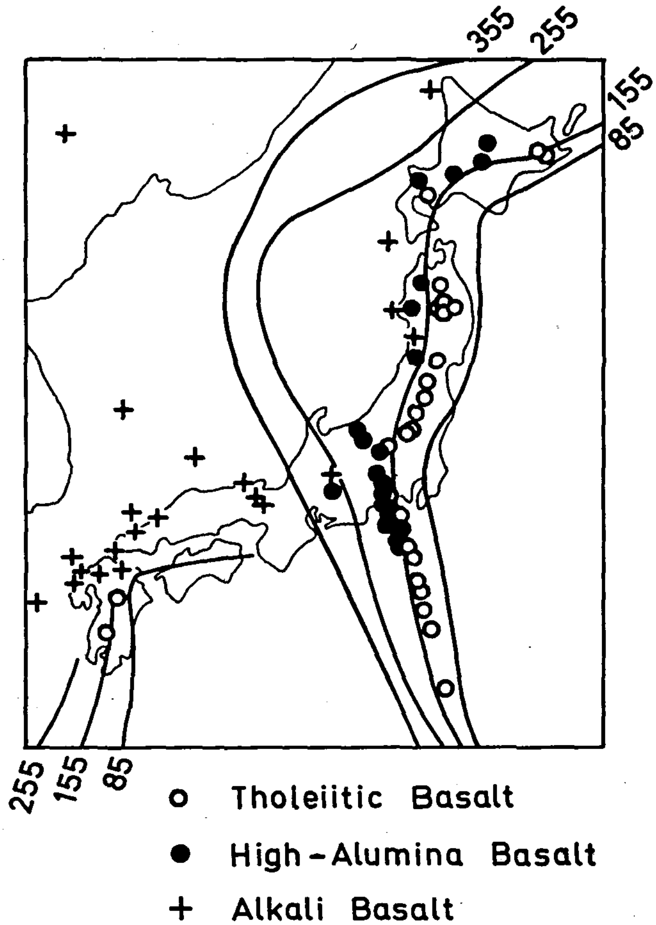

Fig. 24. Average depths of the earthquake foci in the mantle and distribution of Quaternary basaltic rocks in Japan and its vicinity. The figures represent the average depths in kilometers (KUNO, 1966; SUGIMURA, 1965, 1967).

Trench, i.e., in the dry land region of the Northeast Japan Arc, the foci of earthquakes within the mantle tend to be much deeper, being mostly in the range of depths of 100–300 kilometers. The foci tend to become still deeper further westward, as is shown in Fig. 24.

It is widely known that these deep-focus earthquakes may well be regarded as originating on a group of roughly parallel shear-zones, which have a dip of about 30°–60° to the west. The Pacific Ocean floor appears to be thrust under the crust of the Japanese Islands by the movement along these shear-zones. The Japan Trench is formed just along the trace of the shear-zones on the earth's surface. The Trench itself might be regarded as originating from the underthrust movement of the Pacific Ocean floor. This movement appears to be caused by the convection current within the mantle (Fig. 25).

Owing to the underthrust movement, the sedimentary pile in and around the Trench may be deformed and pushed down into great depths along the shear-zones. The sedimentary pile, which may or may not be originally thick, will be thickened by the deformation. Ultramafic rocks would be intruded into it from the mantle.

The geosynclinal pile in geologic past would be regarded as representing very thick sedimentary deposits in and around such a trench. When it is deformed and pushed down into great depths along the shear-zones, the operating pressure in its deeper parts should become very high.

As discussed before (p. 432), the zone of the Japan Trench and its western slope is characterized by an unusually low heat flow. Hence, the sedimentary pile in the deeper parts of this zone would be subjected to metamorphic recrystallization at high pressure and low temperature. If the pressure is very high, glaucophanitic metamorphism will take place. I believe that metamorphic belts of the high P/T type in the paired belts are probably formed in this mechanism (MIYASHIRO, 1959; 1961a, p. 303, 1961b). Thus, soft geosynclinal sediments are transformed into hard crystalline sialic crust (Fig. 25).

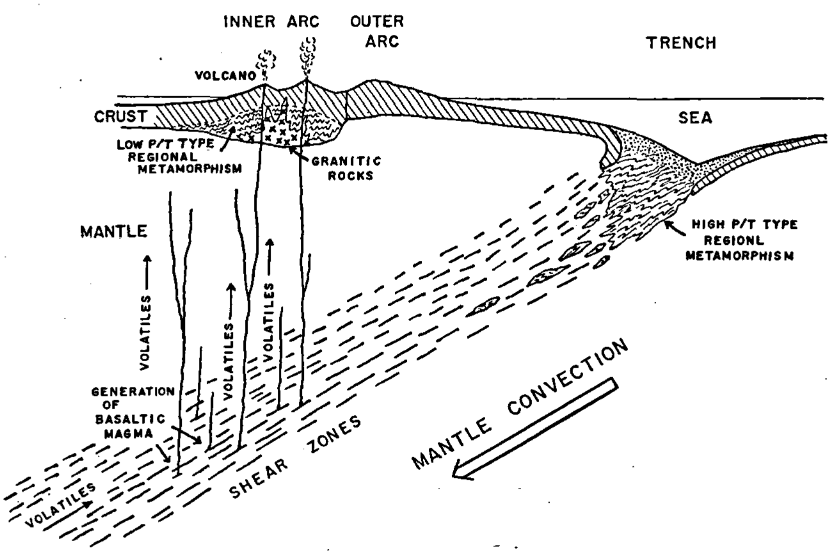

Fig. 25. Schematic figure representing the origin of paired metamorphic belts. This represents a cross section of an active double arc and associated deep trench, down to a depth of about 400 kilometers in the mantle. The mountains, trench, and crust are exaggerated. The fractures to promote the ascent of volatiles are not shown in this figure. At some later time, the two metamorphic belts would come closer to each other by movements along the median fault between them.

Origin of Basaltic and Andesitic Magmas in the Double Arc and the Relevant Heat Problems

The inner metamorphic belt of the low P/T type is recrystallized at relatively high temperature at a shallow depth in the crust. I suppose that the high temperature at a shallow depth *is not* a result of simple conduction of heat, but a result of combined effect of conduction of heat and migration of materials from the greater depths of the earth. In relation to the possible migration of material, I wish to begin with the problem of the genesis of basaltic magmas.

In the inner volcanic arc of the double arc of northeast Japan, the petrological characteristics of Quaternary basaltic rocks are known to change regularly with the distance from the eastern limit of the East Japan Volcanic Belt. It is noticed in Fig. 24 that near the eastern limit, basaltic rocks are highly tholeiitic in composition. Toward the west, they gradually become more alkalic, as was shown by KUNO (1959, 1960, 1966) and SUGIMURA (1960, 1965, 1967). A more or less similar relationship was found to exist in the volcanic rocks of the Northeast Japan Arc in Late Tertiary time (KUNO, 1959; MIYAGI, 1964).

As a conceivable explanation for this regularity, KUNO and SUGIMURA figured that basaltic magmas are generated by partial melting of the ultramafic mantle material in the above-mentioned deep-reaching shear-zones dipping westward. In the very shallow part of the shear-zones, the prevailing temperature would be too low to cause partial melting. Just below the eastern limit of the volcanic belt, the shear-zones are about 130–160 kilometers in depth. At this level, partial melting would produce highly tholeiitic magmas. The depth of generation of basaltic magmas increases westward, and correspondingly the generated magmas become increasingly more alkalic westward, owing to variations in phase relations under higher pressures.

Why are basaltic magmas generated in the shear-zones within the mantle? Where does the heat necessary for it come from? I assume that the degassing of the earth is still in progress, and that H_2O and other volatile materials are moving upward within the mantle. The existence of shear-zones, reaching to a depth of 700 km in the mantle, would greatly promote the ascent of the volatiles. A large amount of volatiles would be collected by, and would ascend along, the shear-zones. The hot volatiles would transport much heat to cause partial melting of the mantle material in the shear-zones, leading to the generation of basaltic magmas, as was supposed by GREEN and POLDERVAART (1955). The melting point of the mantle material is to be lowered to some extent by the presence of H_2O and other volatiles, and this would promote the generation of magmas. The basaltic magmas thus formed would move upwards to reach the surface of the earth. The upward movement may be facilitated by the nearly vertical fractures produced by orogenic deformation, if really produced, as is schematically shown in Fig. 25. In this case, basaltic volcanism should occur in the inner arc of the active region. Sinking of the crust along some fractures would lead to the formation of smallscale geosynclinal pile in the inner arc.

In some phases of geosynclinal evolution, however, such nearly vertical fractures may not be produced, and hence, basaltic magmas may flow upwards mainly along the shear-zones to reach the surface of the earth in the vicinity of the trench. In this case, basaltic volcanism should occur in the geosynclinal pile in the vicinity of the trench, which later becomes the metamorphic complex of the high P/T type. The ultramafic material of the mantle would also move upward along the same shear-zones, to be intruded into the same geosynclinal pile. Thus, the basalt-serpentinite association in the high P/T type metamorphic belt is to be produced.

The mechanism of the genesis of basaltic magmas appears to differ between the active orogenic region and the stable continental and oceanic ones. The above-proposed mechanism that is essentially related to the deep-reaching shear-zones can be applicable only for the active orogenic region. In this mechanism, H_2O and other volatiles are to be concentrated in the deep-reaching shear-zones, and some of the generated magmas would tend to be more hydrous than in any other mechanisms.

The calc-alkali rock series is widely believed to be lower in temperature of crystallization, as is suggested by the presence of orthopyroxene in the groundmass. The lower temperature of crystallization is due to the higher H_2O content in this series than in the others. Since some of the magmas generated in the above-proposed mechanism would be relatively more hydrous, it would be expected to lead to the formation of the calc-alkali rock series (hypersthenic series) though others might be relatively less hydrous, leading to the formation of tholeiitic (pigeonitic) or alkali rock series. This is in harmony with the well-known fact that not only the basalts of the tholeiitic and alkali series but also the andesitic volcanic rocks of the calc-alkali series occur abundantly in the active orogenic region (e.g., KUNO, 1959). In some cases, the greater abundance of H_2O may shift the cotectic liquid magma toward the more feldspathic composition, thus leading to the generation of high-alumina basalt common in the active orogenic region.

The mechanism of magma generation in the stable continental and oceanic regions would be fundamentally different from that outlined above. The rocks of the calc-alkali series are lacking there, though some high-alumina basalt occurs.

The Late Tertiary and Quaternary volcanism in the Northeast Japan Arc produced abundant basaltic and andesitic rocks of the tholeiitic, alkali and calc-alkali series, together with some rhyolitic rocks. On the other hand, the Cretaceous volcanism related to the Ryoke metamorphism produced mainly rhyolitic rocks together with only a small amount of basaltic and andesitic rocks (Fig. 16). It is of interest that the volcanism of the Sierra Nevada Zone was dominantly andesitic (DICKINSON, 1962). This zone may be regarded as representing the inner arc of the double arc that involves the Sierra Nevada and the Franciscan zones in the western United States. Thus, the ratio of basaltic and andesitic volcanism in the inner arc appears to differ in different cases. Some of the rhyolitic rocks may be genetically related to basaltic and andesitic ones, whereas others may be genetically related to granitic ones, as will be discussed in the next section.

As was briefly mentioned before (p. 405), basic metamorphic rocks in the easternmost part of the central Abukuma Plateau are usually typically tholeiitic with 45–48% SiO_2, 1.6–1.9% Na_2O, and 0.14–0.19% K_2O by weight. The Na_2O and K_2O contents tend to increase fairly regularly westward (without an increase of SiO_2 content). Thus, in the western part of the central Abukuma Plateau, basic metamorphic rocks are usually alkali basaltic in chemical composition. We may consider that this regular variation would represent the original compositional variation of geosynclinal basaltic rocks in the inner arc in Late Paleozoic time. The tendency that Paleozoic basaltic rocks become more alkalic westward here, appears to be analogous to the before-mentioned regular compositional variation of Quaternary volcanic rocks in the Northeast Japan Arc.

Ultimate Origin of the Metamorphic Belt of the Low P/T Type and Related Granitic and Rhyolitic Rocks

If my speculation of the heat transport by ascending volatile material is acceptable, we could account for the ultimate origin of the metamorphic belt of the low P/T type and associated granitic and rhyolitic rocks by a similar mechanism.

In the inner arc of the active orogenic region, a number of deep-reaching, nearly vertical fractures would be formed, as was mentioned in the preceding section. At some phases, basaltic and andesitic magmas would ascend along the fractures, whereas at others, H_2O and other volatile materials would ascend along them, as schematically shown in Fig. 25. These ascending volatiles would reach the base of the crust. Some basal parts of the crust, thus heated, would be melted, leading to the generation of broadly granitic magmas. The ascending volatiles may bring some other components in solution with them. For example, SiO_2 may be brought up. Though at least some granitic magmas would be formed by the melting of a part of the crust, I do not intend to preclude the possibility that other granitic magmas or some components of granitic rocks may be derived from the depths of the mantle.

The volatile materials and granitic magmas will tend to ascend further within the crust. They will heat successively higher levels of the crust. In this way, some parts of the geosynclinal pile at relatively shallow depths of the inner arc will be strongly heated, leading to the formation of low P/T type of metamorphic belts (Fig. 25). Abundant granitic rocks will accompany it. Some parts of the granitic magma may erupt to the surface to produce rhyolitic volcanics. Thus, the inner arc is roughly the theater of high-temperature regional metamorphism and granitic and rhyolitic magmatism (MIYASHIRO, 1965, p. 422–423).

The volatile materials will spread in a wide region on a regional scale. The distribution of metamorphic temperature in this case will be controlled largely by the spreading of the volatiles in the terrain, though it will be partly controlled by the distribution of individual granitic bodies. Such metamorphism may be regarded as a variety of regional, not contact, metamorphism, so far as the temperature distribution in the metamorphic terrain is not controlled by individual granitic bodies. However, too sharp a distinction between regional and contact metamorphism does not correspond to the real situation in this case.

The granitic and rhyolitic magmas would move to a much wider region than the belts of regional metamorphism.

Someone may consider that the ascending basaltic and andesitic magmas in the inner arc would bring enough heat to cause low P/T type regional metamorphism. This is not the case, however, as is clear from the fact that many of the low P/T type metamorphic belts have almost no basaltic or andesitic rocks.

Thus I think that both of the two metamorphic belts in a pair in the circum-Pacific region are presumably controlled by the deep-reaching shear zones. So far as the metamorphic belt of the high P/T type is directly related to the shear movement itself, it may be regarded as the main theater of metamorphism. The belt of the low P/T type is subsidiary, though it is accompanied by abundant granitic rocks. So far as the deep-reaching shear-zones dip toward the continent, the metamorphic belt of the low P/T type would be always formed on the continental (inner) side of that of the high P/T type.

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