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GEOLOGICAL SURVEY OF JAPAN

LATE MESOZOIC TO RECENT TECTOGENESIS AND ITS BEARING ON THE METAMORPHISM IN NEW ZEALAND AND IN JAPAN

By

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GEOLOGICAL SURVEY OF JAPAN

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Konosuke SATO, Director

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Late Mesozoic to Recent Tectogenesis and Its Bearing on the Metamorphism in New Zealand and in Japan

By

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Abstract

The geologic developments since Late Mesozoic in New Zealand and Japan are reviewed on the basis of recent advances in metamorphic zoning, radiometric dating, structural analysis, and geophysical interpretation. The origin of paired metamorphic belts is discussed as well.

In the South Island, New Zealand, two metamorphic belts have been recognized: the Tasman Metamorphic Belt in the Western Province and the Wakatipu Metamorphic Belt in the Eastern Province. The progressive regional metamorphism in the Wakatipu Metamorphic Belt influenced the larger part of the New Zealand Geosyncline and may be recognized in three different trends of metamorphic zoning: (1) in east Otago and Southland, zeolite facies → prehnite-pumpellyite metagreywacke facies → pumpellyite-actinolite schist facies → greenschist facies; (2) in west Otago and east Nelson, prehnite-pumpellyite metagreywacke facies → glaucophane schist facies, (3) in the narrow zone lying to the east of the Alpine Fault, prehnite-pumpellyite metagreywacke facies → greenschist facies → epidote amphibolite facies → amphibolite facies. All these three trends of progressive regional metamorphism probably belong to the high-pressure intermediate group of metamorphic facies series.

The Tasman Metamorphic Belt which lies to the west of the Median Tectonic Line is of the low-pressure intermediate group and with the Wakatipu Metamorphic Belt forms a pair in Cretaceous time, although the metamorphism identified by the trend (3) was probably formed in quite recent metamorphic events, as demonstrated by a distribution of hot springs with areas of very young radiometric dates.

The culmination axis of the Wakatipu Metamorphic Belt may have migrated eastwards from the axial part of the New Zealand Geosyncline toward the Hikurangi Trench. This inference is consistent with that of the eastward retreating Hikurangi Trench. Present-day paired metamorphic belts are expected in the area near the East Coast of the North Island along the Hikurangi Trench: one is represented by the volcanic zone of rhyolite, the other by active faults and the remarkable high Bouguer anomalies close to the Trench. This model for the origin of paired metamorphic belts is called "New Zealand type present-day paired metamorphism".

In western Japan, the marked contrast of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt offers strong evidence for a pair in Cretaceous orogeny. The Ryoke metamorphism is of intrinsically thermal phenomenon as well understood with emplacement of granitic rocks and plentiful high-temperature mineral assemblages of andalusite-sillimanite type, in association with volcanic activities of rhyolite. Once parts of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt may have been involved in the Late Paleozoic to Early Mesozoic orogenic movement. Therefore the Ryoke Metamorphic Belt has probably been subjected to two different types of regional metamorphism.

The Paleozoic Geosyncline migrated southwards in the Shimanto Terrane, that is, the

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migration is nearly normal to the axial trend of the Paleozoic Geosyncline. This manner is extrapolated farther south of Shikoku.

Different manners in migration of the culmination axis of regional metamorphism and the axis of geosyncline as seen in trenches, caused a slight difference between the geologic developments in both New Zealand and Japan.

I. Introduction

Problems of tectogenesis in the Pacific mobile belt have received a great deal of attention, concerning continental growth, nature of island arcs, and origin of the Pacific Ocean. Latest geophysical information offers grounds to postulate hypothesis of diverse opinions. One of remarkable features in this mobile belt can be displayed by the two distinct metamorphic belts : one is of very high-pressure type on the oceanic side and the other is of low-pressure type accompanied by voluminous granitic and rhyolitic rocks on the continental side. The two metamorphic belts lie side by side and separated by the intervening salient fault (the Median Tectonic Line).

Apart from a discussion whether the two metamorphic belts form a pair or not, it is naturally understood that the contrast is significant. Among many countries characterized by the contrast, New Zealand and Japan may be most suited to consider the origin of the contrast, as there is a similar distribution pattern in the shape of islands and trenches. Moreover, geological and geophysical investigations in both New Zealand and Japan appear to be valued to make consideration on the bearing of the contrast.

Therefore in an attempt to throw light on genesis of the marked contrast, the geologic developments of New Zealand and Japan since Late Mesozoic are compared on the basis of data on metamorphic petrology, stratigraphy, radiometric dating, major faults, bathymetry, gravity anomalies, seismicity, heat flow and others.

Among many features, the nature of the New Zealand Sub-Crustal Rift is emphasized to account for the contrast. Finally the author puts forward a hypothesis—that northeast New Zealand provides a model for "New Zealand type present-day paired metamorphism", and that a slight difference in the geologic developments in New Zealand and Japan is caused by the different manner of geosyncline and trench migration since Late Mesozoic.

II. New Zealand

II. 1 Metamorphic Belts and their Metamorphic Zoning

The South Island, New Zealand is largely made up of metamorphic rocks. All the metamorphic rocks, and associated plutonic rocks in the South Island were divided into three major groups — the high-stress, low-temperature metamorphic rocks of the New Zealand Geosyncline, the low-stress, high-temperature metamorphic rocks of Nelson, Westland, Fiordland and Stewart Island, and the large granite batholiths and granite-gneiss complexes (GRINDLEY et al., 1959). These groups are distributed separately, and geological evidences to demonstrate the direct relations among them seem to be very little, largely influenced by intervening tectonic displacements as the Alpine Fault, the Wairau Fault, and the Skelmorlie — Skippers Fault, or by overlying younger sediments.

Working from HATTORI's (1967) petrologic study on the sillimanite-garnet-biotite gneisses occurring close to the Alpine Fault and available data on radiometric dating, HATTORI (1966) reached the conclusion that the metamorphic belts of the South Island may be classified into three groups : i) Eastern metamorphic belt of the high-pressure intermediate group (one of metamorphic facies series proposed by MIYASHIRO, 1961), ii) Western metamorphic belt of the low-pressure intermediate group, and iii) Older metamorphic belt. He also considered that the Eastern metamorphic belt and the Western metamorphic belt form paired metamorphic belts.

The concept of paired metamorphic belts in the South Island, was also examined in detail on the basis of advances in the mapping of metamorphic mineral assemblages, in structural interpretation, and in radiometric dating of thermal events (LANDIS and COOMBS, 1967). They recognized three metamorphic belts which coincide roughly with HATTORI's classification in their geographical distribution and geological settings.

In this paper, descriptions of metamorphic belts are made through the division proposed by LANDIS and COOMBS (1967) : the Tasman Metamorphic Belt in the Western Province, the Wakatipu Metamorphic Belt in the Eastern Province, and the older metamorphic rocks involved in the Tuhua Orogeny (Devonian—Carboniferous). The former two Belts were formed during the Rangitata Orogeny (Cretaceous), and constitute paired metamorphic belts (Fig. 1).

II. 1. 1 The Wakatipu Metamorphic Belt

a) Metamorphic Zoning

The Wakatipu Metamorphic Belt is essentially made of rocks of the New Zealand Geosyncline which have undergone burial metamorphism. The rocks show extensive mineralogical reconstitution from undeformed sediments to higher-grade crystalline schists. Schistose rocks in the Wakatipu Metamorphic Belt were called the Alpine Schist, the Marlborough Schist, and the Otago Schist, respectively in each of their representative areas. But SUGGATE (1961) proposed a new omnibus term, Haast Schist Group, which is now applied to all the schist areas.

Metamorphic zoning of the Haast Schist Group was initiated by TURNER (1933) in south Westland, describing zones using the index minerals chlorite, biotite, and oligoclase. Following this division, the Chlorite Zone of Otago was subdivided into four textural subzones, Chl. 1—4 (HUTTON and TURNER, 1936). The subzones proposed are based primarily upon the degree of internal reconstitution and may be described simply as :

Chlorite 1 subzone	Partly reconstituted greywacke
Chlorite 2 subzone	Fine-grained non-foliated schist
Chlorite 3 subzone	Fine-grained poorly foliated schist
Chlorite 4 subzone	Coarse-grained well foliated schist

Further subdivision of the lower end of the Chlorite Zone has been made by COOMBS (1960) based on mineral facies : prehnite-pumpellyite metagreywacke facies (quartz-prehnite zone, and zone of the appearance of actinolite and stilpnomelane), along with still further lower-grade burial metamorphic zone of zeolite facies (heulandite stage and laumontite stage). A Garnet Zone was first recognized in south-east Nelson (REED, 1953), where the Chlorite 4 subzone is not developed (REED, 1958a). MASON (1962) distinguished the Almandine Zone in place of the Garnet Zone along the Southern Alps, and mapped Chlorite 1, 2 and 3 subzones, Biotite Zone, Almandine Zone, and Oligoclase Zone. The Chlorite 4 subzone is found to develop only to the south of the Paringa River.

b) Pumpellyite-bearing rocks

SEKI (1966) and HASHIMOTO (1966) made individually a detailed petrogenetic study on the prehnite-pumpellyite metagreywacke facies. According to SEKI (1966), four different trends of progressive metamorphism are recognized in four representative metamorphic

Franciscan type	Z	P	PG	
Sambagawa type	Z	P	PA	A
New Zealand type	Z	PP	PA	A
Tanzawa type	Z	PP		A

Progressive metamorphism →

Fig. 2a Schematic representation of metamorphic zones in progressive metamorphism on the basis of zonal distribution of the pumpellyite-bearing mineral assemblages. After SEKI (1966).
Z, zeolite zone ; P, pumpellyite zone (without prehnite) ; PP. pumpellyite-prehnite zone (without actinolite) ; PA, pumpellyite-actinolite zone (without prehnite) ; PG, pumpellyite-glaucophane zone (with neither actinolite nor prehnite) ; A, actinolite (greenschist) zone (with neither pumpellyite nor prehnite).

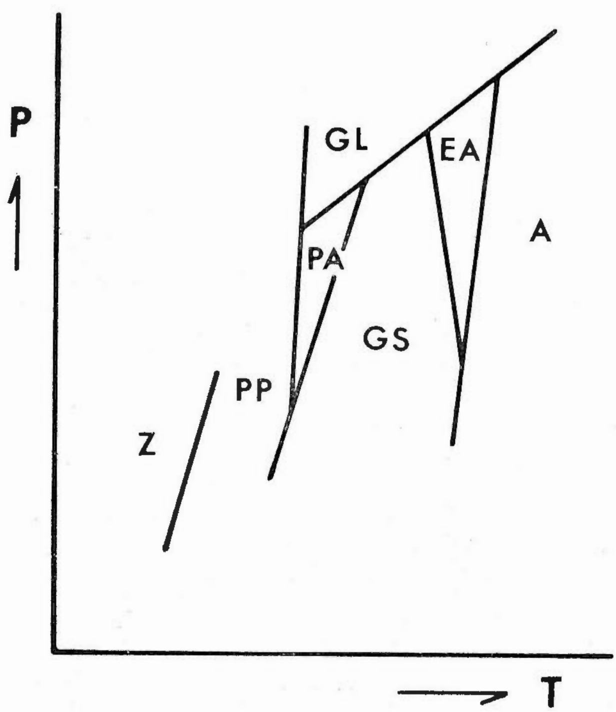


Fig. 2b P-T diagram showing the relation of the pumpellyite-actinolite schist facies with other mineral facies. After HASHIMOTO (1966).
Symbols are the same with those of Fig. 4.

terranes : Franciscan type, Sambagawa type, New Zealand type, and Tanzawa type in order of decreasing solid pressure and water pressure (Fig. 2a). In the Franciscan Metamorphic Terrane, the United States, the trend starts from zeolite zone through pumpellyite zone (without prehnite), and ends with pumpellyite-glaucophane zone (with neither actinolite nor prehnite). In the Sambagawa Terrane, Japan, the change is from zeolite zone, through pumpellyite zone (without prehnite) and pumpellyite-actinolite zone (without prehnite), and finally to actinolite zone of the greenschist facies (with neither pumpellyite nor prehnite), and in New Zealand (Otago) from zeolite zone through pumpellyite-prehnite zone (without actinolite) and pumpellyite-actinolite zone (without prehnite), to actinolite zone. Whereas in the Tanzawa Mountains, Japan, progressive metamorphism is displayed in the change from zeolite zone through pumpellyite-prehnite zone to actinolite zone.

In the type locality of Otago, the Chlorite 1-2 subzones are identical to the prehnite-pumpellyite metagreywacke facies and the Chlorite 3-4 subzones to the greenschist facies (Coombs, 1960). Prehnite is absent in the Chlorite 1-2 subzones, but pumpellyite survives up to the Chlorite 2 subzone. Actinolite probably starts crystallizing at the Chlorite 1 subzone. Therefore, the pumpellyite-actinolite zone of Seki (1966), or the pumpellyite-actinolite schist facies named by Hashimoto (1966 ; see Fig. 2b), is quite distinct in the high-grade part of the prehnite-pumpellyite metagreywacke facies : in the Chlorite 1-2 subzones.

The prehnite-pumpellyite metagreywacke facies defined by Coombs (1960) is therefore subdivided into the prehnite-pumpellyite metagreywacke facies (in the strict usage), and the pumpellyite-actinolite schist facies or the pumpellyite-actinolite zone.

On the other hand, as already discussed by Seki (1966), in south-east Nelson (Reed, 1958a), the direct progressive change from the prehnite-pumpellyite zone to actinolite zone and the absence of the pumpellyite-actinolite zone must be noticed. This phenomenon is interpreted as the result of relatively low solid and H_2O pressures (Seki, 1966). In other words, it can be said that probable temperature distribution is slightly higher and pressure conditions are relatively lower than the normal changes from the prehnite-pumpellyite zone through the pumpellyite-actinolite zone to the greenschist facies in the Otago district. In addition, Seki stated that the progressive increase with a lack of the pumpellyite-actinolite zone in south-east Nelson occurred at a shallower depth comparable to that of the Tanzawa Mountains, Japan, which represents the lowest-pressure type in all including other metamorphic terranes in Otago, Sambagawa, and Franciscan.

c) A lack of the Chlorite 4 subzone

The direct progressive change from the Chlorite 3 subzone to the Biotite Zone without well developed Chlorite 4 subzone in south-east Nelson is also quite important. The slightly higher temperature distribution stated above may well explain this phenomenon of the direct change which has been disclosed not only in south-east Nelson but also farther southwards along the narrow zone lying to the east of the Alpine Fault.

General subdivisions of metamorphic zoning and an illustration of mineral assemblages in rocks (when quartz is present) of the Haast Schist Group are shown in Fig. 3. As mentioned previously, however, there are cases of a lack of the Chlorite 4 subzone, and of a direct change from the greenschist facies to the amphibolite facies, and from the prehnite-pumpellyite metagreywacke facies to the actinolite zone with a lack of the pumpellyite-actinolite zone.

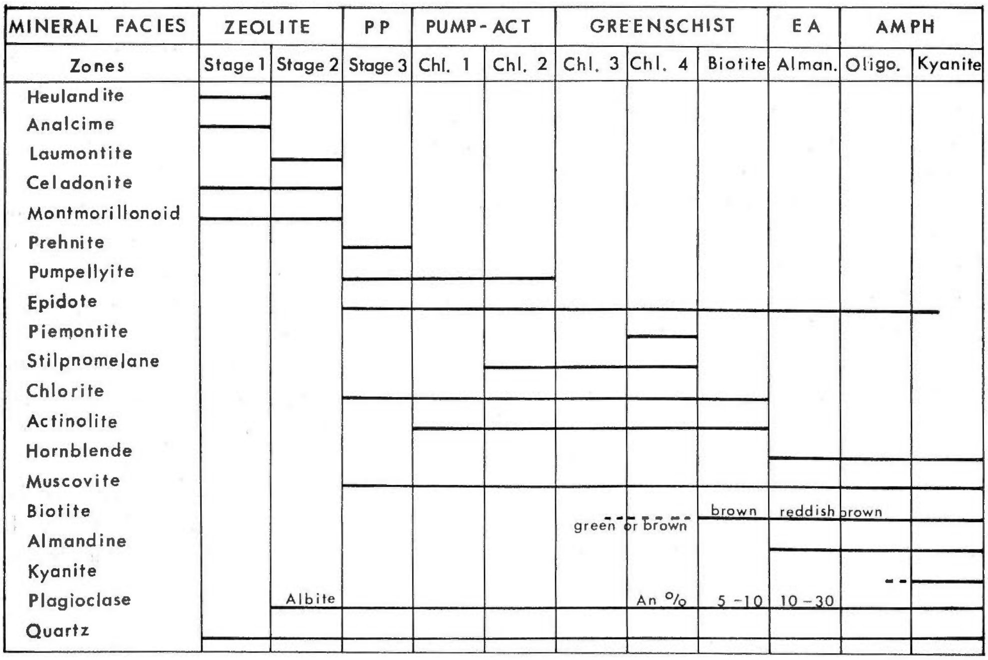


Fig. 3 Schematic illustration of progressive mineralogical variations in rocks of the Haast Schist Group with Kyanite Zone postulated in this paper. Data largely depend upon MIYASHIRO (1965), together with REED (1958a), COOMBS et al. (1959), COOMBS (1960), and MASON (1962).
PP, prehnite-pumpellyite metagreywacke facies; PUMP-ACT, pumpellyite-actinolite schist facies; EA, epidote amphibolite facies; AMPH, amphibolite facies.

d) Lawsonite-bearing rock

The unique status of the narrow strip of glaucophane schist facies in the Wakatipu Metamorphic Belt has been emphasized by LANDIS and COOMBS (1967). Critical indicator of this glaucophane schist facies is lawsonite and occurs ubiquitously in the Bryneira Group, about 0.3–2.5 km thick. A similar sequence of metamorphic rocks for the glaucophane schist facies appears in the Maitai Group of Nelson Province. Lawsonite is confined inside the narrow strip, although blue amphibole sometimes occurs outside.

e) Some other features

Significant absence of paragonite, jadeite, sillimanite, potassium-feldspar and wollastonite has already been pointed out by MASON (1962) in prospect of still higher-grade metamorphic minerals. He suggested that part at least of the Oligoclase Zone is equivalent to the kyanite zone, judging from kyanite schist boulders in coastal moraines and detrital kyanite.

REED (1964) suggested that the Garnet Zone would be followed by a sillimanite zone and granite. Although the position of kyanite zone is difficult to link with regional metamorphism, it seems desirable to relate a zone higher than the Garnet Zone and the Oligoclase Zone to the Kyanite zone. In Fig. 3 possible position of here proposed Kyanite Zone is shown. Significant occurrence of sillimanite along the Alpine Fault will be discussed later.

Before LANDIS and COOMBS (1967) established the Biotite Zone along the Core region of New Zealand Geanticline from the Haast River to Dunedin, biotite in the Chlorite Zone was often recognized as relict minerals during later retrogressive metamorphism which is widespread in schists not only near the Alpine Fault but also in schists of other areas.

f) P-T conditions in the Wakatipu Metamorphic Belt

Although LANDIS and COOMBS (1967) attempted to display geothermal gradient for

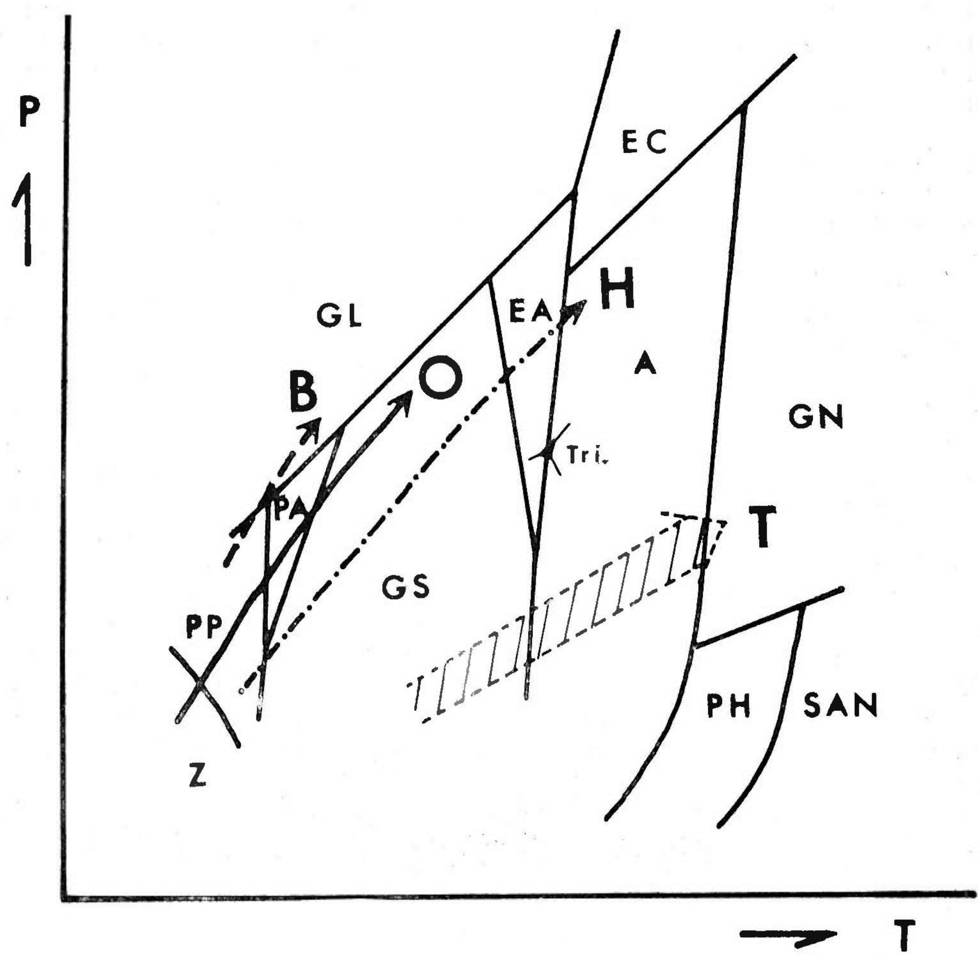


Fig. 4 Generalized figure showing three different trends of progressive regional metamorphism in the Wakatipu Metamorphic Belt (O-curve, Haast Schist Group in east Otago and Southland; H-curve, Haast Schist Group from south-east Nelson to the Haast River; B-curve, Bryneira Group in west Otago) and that of the Tasman Metamorphic Belt (T).
GL, glaucophane schist facies; EA, epidote amphibolite facies; EC, eclogite facies; PA, pumpellyite-actinolite schist facies; PP, prehnite-pumpellyite metagreywacke facies; Z, zeolite facies; A, amphibolite facies; GN, granulite facies; PH, pyroxene hornfels facies; SAN, sanidinite facies; Tri., triple point of andalusite, kyanite and sillimanite.
The trend of the Tasman Metamorphic Belt, i. e., T-curve has been suggested in Fig. 9 of HATTORI (1967).

the Wakatipu Metamorphic Belt, assessment of the exact positioning in a P–T field is not definitely known. Here the author gives an idea to identify three different trends of progressive regional metamorphism in the Wakatipu Metamorphic Belt (Fig. 4). All mentioned above can explain the trends of O-curve for the Haast Schist Group (east Otago and Southland), of H-curve for the Haast Schist Group (south-east Nelson to the Haast River), and of B-curve for the Bryneira Group (west Otago). Relatively higher-temperature distribution and lower-pressure conditions of the H-curve are quite noticeable.

However, there is still a remarkable gap in metamorphic zoning between the rocks of the Haast Schist Group and the sillimanite-garnet-biotite gneisses to the west of the Alpine Fault, as clearly shown in Fig. 4 and also in the chemical composition of garnet contained (HATTORI, 1967). As a result, the metamorphic zoning in south-east Nelson can belong to the high-pressure intermediate group.

II. 1. 2 The Tasman Metamorphic Belt and related rocks

In contrast to the detailed metamorphic zoning of the Wakatipu Metamorphic Belt, the distribution of metamorphic facies in rocks of the Western Province remains largely unmapped. HATTORI (1967) suggested a zone of sillimanite–potassium-feldspar isograd rocks is present to the west of the Alpine Fault on the basis of distinctive mineralogical features of garnet and biotite between the rocks of the Haast Schist Group and the sillimanite-garnet-biotite gneisses. He reviewed occurrences of sillimanite, kyanite, and andalusite in various types of sources; detrital heavy minerals in Paleozoic, Mesozoic, Tertiary, and Recent sediments, together with constituent minerals in metamorphic rocks as boulders or in place. Occurrences of chloritoid-sillimanite schist from Nelson, chloritoid-bearing schist of Nelson, andalusite bearing schist from Haast and Nelson, and sillimanite schist from Fiordland form the basis of a proposed possible extension of regional metamorphism of the low-pressure intermediate group represented by the highest-grade metamorphism of the sillimanite–potassium-feldspar isograd (See Fig. 10 of HATTORI, 1967).

Although the regional metamorphic terrane of the low-pressure intermediate group intimately associated with the emplacement of granitic rocks, as proposed by HATTORI (1967), is identical to the Tasman Metamorphic Belt, a difficulty arises to distinguish probable older metamorphic rocks, from the rocks of essentially the Tasman Metamorphic Belt. Less negligible areas in the Tasman Metamorphic Belt are mapped of Precambrian age, and these older rocks have been called the Constant Gneiss, the South Westland Schist, the Waiuta and Greenland Groups.

Whereas little attention has been paid on ages of granite emplacement, REED (1958b) summarized the distribution and petrographic features, together with possible association with mineralization. Unfortunately any exposed granite has not been recorded in Cretaceous time, in spite of strong information provided by the data of radiometric dating.

II. 2 Stratigraphy and Radiometric Dating

a) A single period of regional metamorphism

The age of the metamorphism that formed the rocks of the Tasman Metamorphic Belt, the Wakatipu Metamorphic Belt, and other metamorphic and plutonic rocks has been the subject of diverse opinions. It is not certain whether more than one period of regional metamorphism were involved in each of the Belts. Most geologists favour a single period of regional metamorphism in a metamorphic belt and they attempt to interpret unexpected young ages as the result of natural diffusion of radiogenic daughter elements out of measured minerals which are supposed to have crystallized long before. This phenomenon has been expected to happen during certain geologic episodes occurred later than the single period of regional metamorphism (MASON, 1961, HURLEY et al., 1962). The basis that any loss of radiogenic daughter element by diffusion or other mechanism is preferred really depends upon the postulation of a single period of regional metamorphism in a metamorphic belt for the Haast Schist Group.

b) Upper age limit

On this point, HATTORI (1966) critically reviewed the data of radiometric dating, and cast doubt on their interpretation of loss of radiogenic element. According to him, there is little ground to postulate that the schists of the Oligoclase Zone along the Alpine Fault, showing K-Ar ages of biotite 4 to 8 m. y., have undergone regional metamorphism which ended in Early Cretaceous time or older on geological evidences. Stratigraphically, the first appearance of the high-grade schist is indeed in the Pleistocene moraines accumulated in zones along the Alpine Fault. In addition, high-grade schist pebbles are still not known in Tertiary conglomerates. On the contrary, the low-grade schist pebbles are common in the Cretaceous conglomerates in east Otago (HARRINGTON, 1955 ; MUTCH, 1963; MCKELLAR, 1966). These are hitherto known direct stratigraphic observations to date the upper age limit to the schists of the Haast Schist Group (Fig. 5), and these are unlikely to be any sign of a short-range life span of the Wakatipu Metamorphic Belt.

ARONSON (1965) has already directed attention to a necessity to distinguish the Alpine Schist from the Otago Schist. That both Schists have undergone different metamorphic conditions is his suggestion to consider that many of even the youngest ages may result from distinct very recent metamorphic events.

c) Temperature for biotite crystallization

HATTORI's (1966) question was also laid on that the temperature assessment of the biotite formation in the Oligoclase Zone is too high, judged from the result of recent experimental verifications on the triple point of sillimanite, kyanite and andalusite (KHITAROV et al., 1962 ; BELL, 1963 ; WALDBAUM, 1965 ; NEWTON, 1966 ; WEILL, 1966 ; HOLM and KLEPPA, 1966). The triple point may well be laid below 300～350°C in certain cases. In a progressive regional metamorphic terrane biotite can crystallize or recrystallize before kyanite or sillimanite may appear, from the geological evidences as already stated in the preceding section. This in turn implies that the biotite in the Oligoclase Zone can crystallize even at any moderate temperatures much below 300～350°C, in spite of the assessment of the temperature 500～550°C at which the biotite in the Oligoclase Zone would crystallize (HURLEY et al., 1962). If so, the biotite can crystallize even in such a geologic environment as that the diffusive loss of radiogenic argon and strontium was postulated to happen by HURLEY et al. (1962).

When crystallization of metamorphic biotite is permitted at moderately low temperatures of this sort of geologic environment, there will be no longer necessity to assume any diffusive loss of radiogenic argon and strontium out of the biotite which is supposed to have crystallized long before. This reasonably leads to such a conclusion that the age of biotite crystallization as shown in radiometric dating is nearly coeval with a time of a certain metamorphic event in the sense of SUTTON (1965).

d) Rapid uplift as the result of final geologic event in orogeny

Generally duration of metamorphic events or life span of a metamorphic belt is difficult to precisely assume on geological evidences. However, it seems desirable to assume that the youngest ages of 4~8 m. y. in the Wakatipu Metamorphic Belt indicate the final episode of the metamorphic events in the area close to the Alpine Fault. In other word, that the cessation of an orogenic movement is accompanied by unusually rapid uplift of metamorphic terrane is most probable, and therefore the small age is very close to the time of major unconformity which is confirmed only by direct observation between rapidly uplifted basement metamorphic rocks and their overlying sediments. For this reason, the conclusion led by HURLEY et al. (1962) must be taken into account. That is, the ages commonly measured by K-Ar and Rb-Sr methods on biotite may actually reflect the time of major uplift and erosion, which coincides with that of sedimentation, and not with the initial period of metamorphism and igneous intrusion in the orogenic belt. One of their conclusions that in New Zealand the biotite age values post-dated the time of metamorphism by more than 100 m. y. is, however, hardly acceptable. The position of some important conglomerates underlain by basal metamorphic rocks with major unconformity between is illustrated in Fig. 5.

There is a slight disagree between the radiometric ages, for instance, of the Westland crystalline basement (about 100 m. y.) and the stratigraphic ages of the overlying Hawks Crag Breccia (Upper Jurassic Kawhia Series) on the basis of paleobotanical data. However, if certain systematic errors are allowed in assessing geologic ages by both radiometric dating and paleobotanical methods, this discrepancy may be minimized.

e) More than one metamorphic event in a single regional metamorphism

Even though an interpretation that the Wakatipu Metamorphic Belt has undergone regional metamorphism during long-range life span being from 120 to 4 m. y. is here put forward, another problem still arises as to whether the events occurred in the Wakatipu Metamorphic Belt must be divided into several metamorphic events in a single regional metamorphism or into events of more than one regional metamorphism. When the former is favoured, then the customary terms of the Rangitata Orogeny and the Kaikoura Orogeny are advocated. It may be inadequate to consider more than one regional metamorphism in the order of 120 m. y. life span.

The author will summarize the available data on bathymetry, seismicity, gravity anomaly and heat flow in and around New Zealand in the later section. Here, however, he would like to point out a possibility that the culmination of metamorphic events has shifted from the Core region of the New Zealand Geanticline through the Haast River area to farther north along the Alpine Fault. This is nothing but a best fit idea for the radiometric dating hitherto known.

II. 3 Faults of the South Island

The major faults of the South Island (Fig. 6) have been discussed by HENDERSON (1929), HENDERSON (1937), MACPHERSON (1946), WELLMAN (1955a), KINGMA (1959) and SUGGATE (1963).

The most remarkable major fault continuing from Lake Rotoroa to Milford Sound was first recognized by WELLMAN and WILLETT (1942), and was named the Alpine Fault. And the extension of the Alpine Fault from Cook Strait to Milford Sound was clearly shown on the 1 : 1,000,000 Geological Map of New Zealand published by the New Zealand Geological Survey in 1948. But the northern part of the Alpine Fault is equivalent to the Wairau Fault. The nature of the Alpine Fault has played a decisive role in determining the relation of the Wakatipu Metamorphic Belt to the Tasman Metamorphic Belt since then.

a) Alpine Fault controversies

According to SUGGATE's (1963) historical review, the hypothesis of a 300-mile lateral shift along the Alpine Fault was introduced by WELLMAN at the Pacific Science Congress in 1949, and again at the Seventh New Zealand Science Congress in 1951. Since WELLMAN's postulation appeared as the first document in print in 1955 and 1956, the Alpine Fault has received a great deal of attention among many earth scientists.

The basis of WELLMAN's (1956) hypothesis largely depends on the relation of rocks exposed in Nelson and Marlborough to similar sequences 300 miles to the south in south Westland, Southland and Otago. The sequences are the Upper Paleozoic and Mesozoic formations which were grouped as a "marginal syncline" by WELLMAN (1956), and schists of the Chlorite Zone.

This hypothesis has received strong support from SUGGATE (1963). The problem of dating the movements, however, still remains. In recent years, several critical alternatives against WELLMAN's 300-mile lateral shift have been postulated. Therefore, on this occasion it seems very convenient to summarize the diverse opinions into two opposing schools of thought; one is for a 300-mile lateral shift along the Alpine Fault and the other is against it.

b) A 300-mile lateral shift

There are two main variations of this idea in the first school for a 300-mile lateral shift. One favours a beginning of the movement in Jurassic in connection with the Rangitata Orogeny, and a culmination of the movement in the Kaikoura Orogeny of Late Tertiary to Quaternary (WELLMAN, 1956; quoted by SUGGATE, 1963 ; WELLMAN and WILSON, 1964). The other is by SUGGATE (1963) who distinguished two main periods of movements, the lateral shift being largely completed during the Rangitata Orogeny, both vertical and horizontal movement taking place in the Kaikoura Orogeny.

On the contrary, the alternatives favour rather vertical movement as main features of tectonic displacement along the Alpine Fault, with minor horizontal components.

c) Nappe hypothesis

The nappe hypothesis was put forward by KINGMA (1959) who described in detail a tectonic history of New Zealand with many schematic diagrams demonstrating various stages of deformation. One of KINGMA's main reasons opposing large-scale transcurrent fault was focussed on quite different movements between the Alpine Fault and the Wairau Fault which has been supposed to be a continuous line of the Alpine Fault.

d) Differential uplift and erosion

The hypothesis of differential uplift and erosion (REED, 1964) is another opinion opposing large-scale lateral shift. Working from the relation of mylonite along the Alpine Fault passing into the Haast Schist Group through schist-derived mylonite, and also from petrologic evidence that the mylonites were formed at depths and temperatures comparable to those of the Haast Schist Group, he reached the conclusion that mylonitization was penecontemporaneous with the Rangitata regional metamorphism mainly associated with vertical movement. Another REED's (1964) question was made on the relationship of the marginal syncline in Nelson and Southland. He emphasized that the position of the Pounamu ultramafites near the biotite-garnet isograds is highly significant, referring to that in New Zealand Geosyncline ultramafites are associated only with the marginal syncline and not with the Torlesse Group (Permian to Jurassic). He stressed a probable extension of the "marginal syncline" to the area east of Hokitika, Westland, that is, to the east of the Alpine Fault. This implies that the field evidence is not favourable to a large-scale lateral shift.

KUPFER (1964) stated a similar critical review, as saying that if the critical measure of displacement would change, stressing the unique geologic position of ultramafites, then the horizontal displacement might be reduced from 300 miles to a disturbingly small amount.

Judged from BRODIE (1964, p. 41), it is possible to assume that the morphological feature of the Fiord Trough, probable extension of the Alpine Fault can simply be interpreted as the result of vertical movement rather than postulated strike movement.

e) High-pressure mineral

In this section, the extent to which a 300-mile lateral shift was accompanied by vertical displacements is considered from a petrological point of view.

Large horizontal displacements have been analysed in several places along the Alpine Fault and the Wairau Fault (WELLMAN, 1952; WELLMAN et al., 1952; WELLMAN, 1955a; CLARK and WELLMAN, 1959), and all of these are commonly accompanied by considerable vertical components. Therefore, it seems quite reasonable to assume that at least 10% vertical components was accompanying with a 300-mile lateral shift. This vertical component is equivalent to 30 miles (50 km) in depths.

In connection with the significant absence of high pressure mineral assemblages of jadeite+quartz and others, HATTORI (1967) considered that any rocks along the Alpine Fault have not been formed at great depths as 50 km. If tectonic thickening or tectonic overpressures could provide supplementary pressure effect on formation of high-pressure type minerals, it might reduce great depths to moderate depths.

In the Wakatipu Metamorphic Belt, one of critical minerals indicative of high pressures, i. e., great depths is lawsonite, whereas in the Tasman Metamorphic Belt it is sillimanite. Both sillimanite and lawsonite could have crystallized in depths like 20～25 km. This amount of depths 25 km seems too shallow to be compared to even such a small component as 10% of a 300-mile lateral shift. For this reason the author is of the opinion that a 300-mile lateral shift is not likely.

Finally, it is safely concluded that the hypothesis of a 300-mile lateral shift offers very little grounds compelling alternatives which seem to be a growing belief.

f) Median Tectonic Line

One of the outstanding features in the concept of paired metamorphic belts is the nature of the fault separating two distinct types of metamorphic terranes. Considering possible paired metamorphic belts composed of the Wakatipu Metamorphic Belt and the Tasman Metamorphic Belt, HATTORI (1966) expected the existence of an older Alpine Fault which largely coincides with the Median Tectonic Line of LANDIS and COOMBS (1967). In east Nelson COPE and REED (1967) recognized the Waimea Fault which is probably correlated with the Median Tectonic Line of LANDIS and COOMBS (1967). This is shown in Fig. 6. Nature of the Median Tectonic Line has not yet been studied, but the Median Tectonic Line may have started moving during early or middle stages of the Rangitata Orogeny. And it may have completed before accumulation of the Eocene Arnold Series, judged from geologic setting in Southland.

However, it is highly speculative to decide whether the Median Tectonic Line has activated largely during only the period of the Rangitata Orogeny throughout its postulated line as seen in the present positions, and also when two distinct types of metamorphic terranes have attained the culmination of metamorphism as seen in metamorphic zoning demonstrated in Figs. 3 and 4. Furthermore, a question on whether the Wakatipu Metamorphic Belt has been involved in more than one metamorphic event since 120 m. y. ago arises in this connection. In Fig. 4 three different trends of progressive regional metamorphism are suggested. O-curve for the Haast Schist Group in east Otago and Southland probably shows the common trend of metamorphic zoning in the Wakatipu Metamorphic Belt, and B-curve for the Bryneira Group in west Otago is slightly lower than the common trend, on the contrary, H-curve is a little higher in terms of temperature distribution. Here, it must be questioned if the regional metamorphism of the Haast Schist Group shown in the trend of H-curve has completed in a time similar to that of the regional metamorphism represented by the trend of O-curve and B-curve. Because the age of the regional metamorphism in the trend of H-curve is a problem still to be elucidated.

As the Haast Schist Group from south-east Nelson to the Haast River suggests slightly higher temperature distribution, this could be dealt with a different metamorphic event in nature and age. This phenomenon is quite important to apply the data of radiometric dating. Again it seems likely that the youngest ages of 4～8 m. y. provide true ages for final episode of metamorphic event.

Finally, the author would like to consider that the nature of the Median Tectonic Line was dominantly vertical in favour of REED's (1964) hypothesis of differential uplift and erosion, as well as in the case of the Alpine Fault. This consideration is based on petrogenetic significance of the absence of high-pressure minerals, as discussed earlier.

II. 4 Some Geophysical Considerations on the Earth's Crust in and around New Zealand

II. 4. 1 Bathymetry

Geologic structures in the South Island has frequently been considered in relation of new geosyncline other than the New Zealand Geosyncline to some features of bathymetry around New Zealand (WELLMAN, 1956; KINGMA, 1959).

According to BRODIE (1958), the oceanic highs and deeps around New Zealand exhibit a marked linearity and fall into three groups whose features trend NW-SE, E-W, and NNE-SSW, and that these groups are recognized as structural provinces—the Northwestern, Chatham, and Kermadec Provinces respectively. The New Zealand land mass occupies a position at the meeting of the three structural trends. However, later he introduced the term of a morphological unity, "New Zealand Plateau" on which the New Zealand land mass is centering (Fig. 7).

Concerning the age of oceanic structures, BRODIE (1958) pointed out that in Southland the Mesozoic Southland Syncline and the Tertiary Waiau Syncline are probably related to submarine structures in the Bounty Trough and the Solander Trough respectively. Therefore, he concluded that no signs of late structural activity along trends referable to the Northwestern and Chatham Provinces have been observed in New Zealand, and the submarine relief in these Provinces could be of pre-Tertiary age. Active movement on the Kermadec Province trend has taken place up to Recent time, and the submarine features of this Province are considerably younger. The only obviously active crustal deforming process along the Kermadec trend is well demonstrated with active NNE-oriented

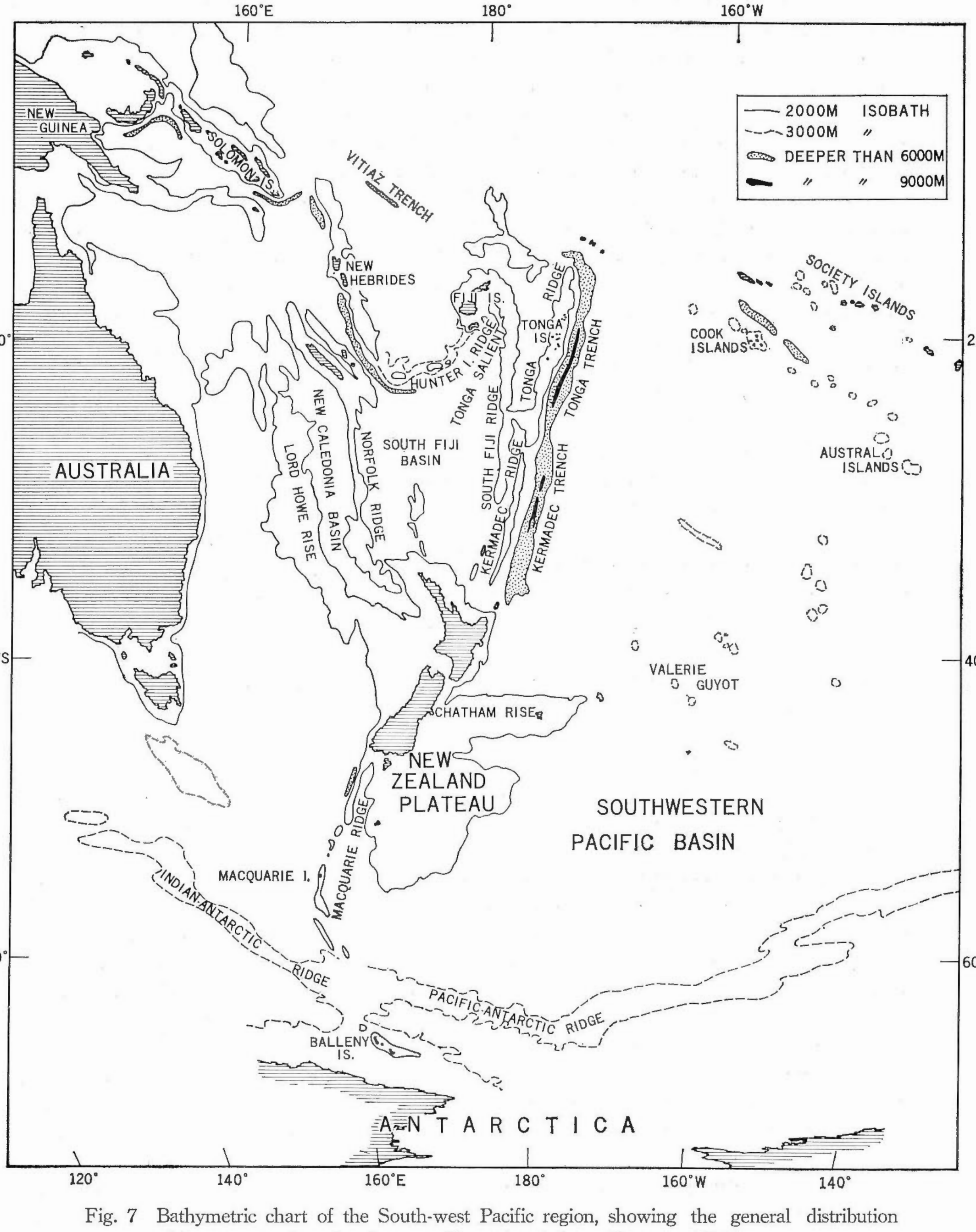


Fig. 7 Bathymetric chart of the South-west Pacific region, showing the general distribution of important submarine features. Reproduced from CULLEN (1967).

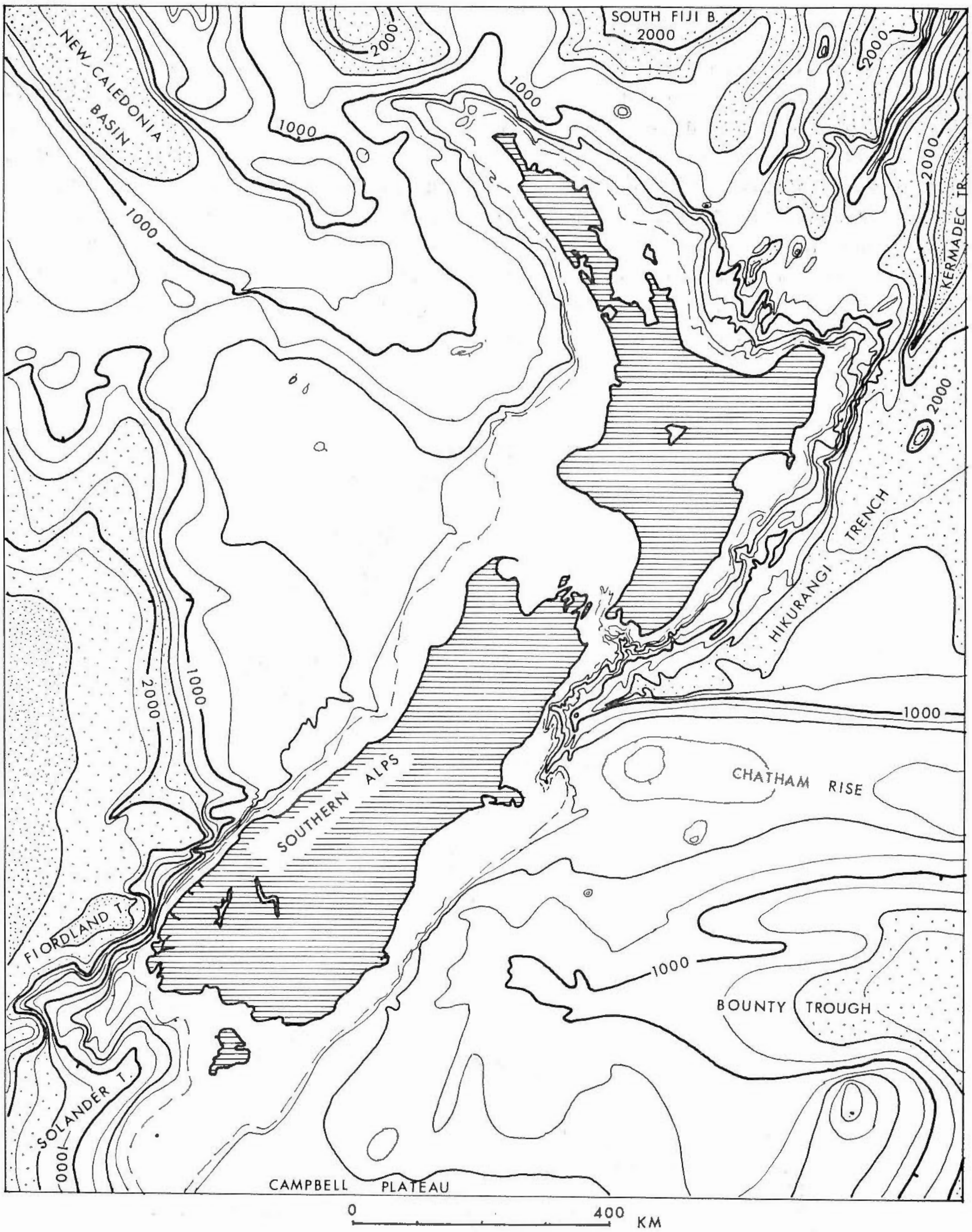


Fig. 8 Bathymetric chart of the New Zealand region. Reproduced from BRODIE (1958; 1964). Isobaths at 250 fathom intervals with depth in fathoms.

faults down southwards from the oceanic floor, through minor trench, New Zealand land mass accompanied by the Taupo Graben and Alpine Fault, to the minor marginal trough, i. e., Fiordland Trough probably associated with the Macquarie Ridge named by BRODIE and DAWSON (1965).

Morphological features of the Hikurangi Trench named by BRODIE and HATHERTON (1958) must be noticed (Fig. 8). The Hikurangi Trench lies immediately off the eastern coast of New Zealand, from East Cape to Cook Strait and offshore of Kaikoura. According to BRODIE and HATHERTON (1958), the Trench extends 300 mile southwards from offshore of East Cape, with an average width of 60 miles. At its northern end the trench axis is offset 50 miles eastwards from that of the Kermadec Trench. In the south the Trench abuts against the Chatham Rise. The western flank rises abruptly to the New Zealand land mass, forming the continental slope of the East Coast, the North Island. With only a narrow, benched and shallow trench-form along the axis, the Hikurangi Trench has a remarkably broad near-level floor, which is quite extensive and has probably been subjected to thick accumulation of sediments.

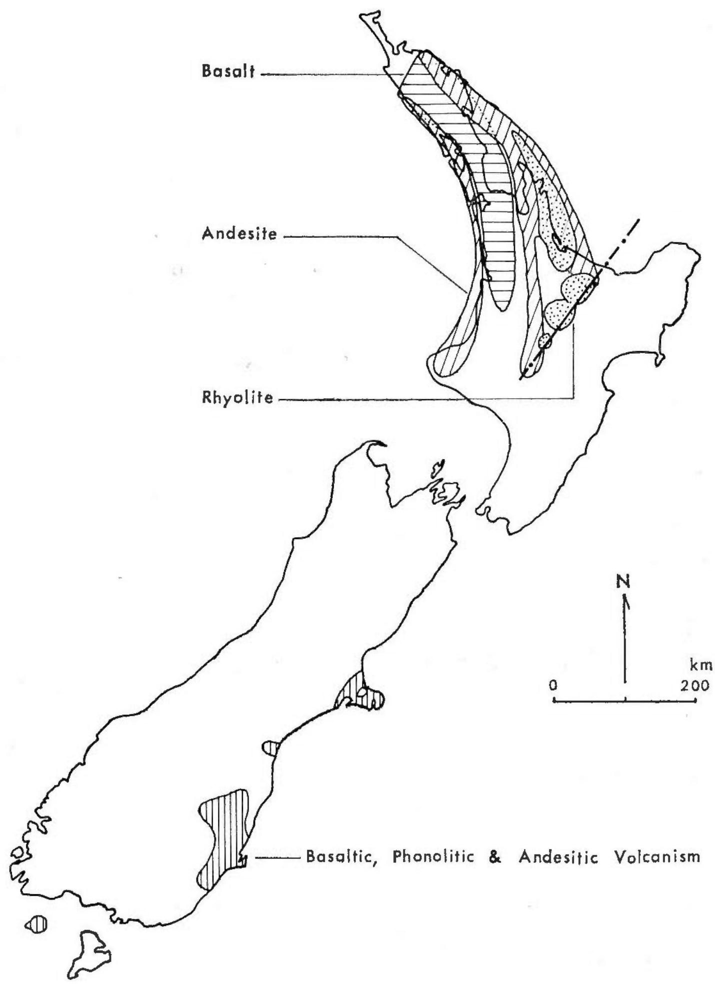


Fig. 9 Distribution of Late Tertiary to Quaternary volcanic rocks and the belt of active andesitic volcanoes. Data from GREGG and COOMBS (1965), and THOMPSON (1965).

Comparing those features suggested by BRODIE and HATHERTON (1958) with those of the Kermadec Trench, it may be said that the Hikurangi Trench has been shallowing and retreating northwards, and has possibly been dying out leaving level-floor behind with thick sediments. And its most subsided part has migrated along the axial trend toward the Kermadec Trench with a 50-mile offset at offshore of East Cape.

Bathymetric chart of the southwest Pacific is shown in Fig. 7, which was made by CULLEN (1967) based on the Soviet Union's Bathymetric chart (1963).

II. 4. 2 Volcanoes

The distribution of Late Tertiary and Quaternary volcanic rocks in New Zealand is shown in Fig. 9. The distinct belt of active, Late Quaternary andesitic volcanoes trends northeast from Ruapehu, through Ngauruhoe to White Island, and farther northeast through the Kermadec Ridge (including Raoul Island) to the Tonga Islands. Volcanic activity along this belt (shown as a line in Fig. 9) is without doubt influenced by activity of seismic belt to the west of the Kermadec and Hikurangi Trenches.

In regard to the well-known occurrence of ignimbrites, HEALY (1962) stated that nearly 4,000 cubic miles (about 17,000 km^3) of lava, chiefly of rhyolitic composition, have erupted in Pliocene to Recent time from the Taupo Volcanic Zone.

II. 4. 3 Heat flow

Although any heat flow data in and around New Zealand are not available, the distribution of hot spring gives a useful clue to probe areas of possible high heat flow. In

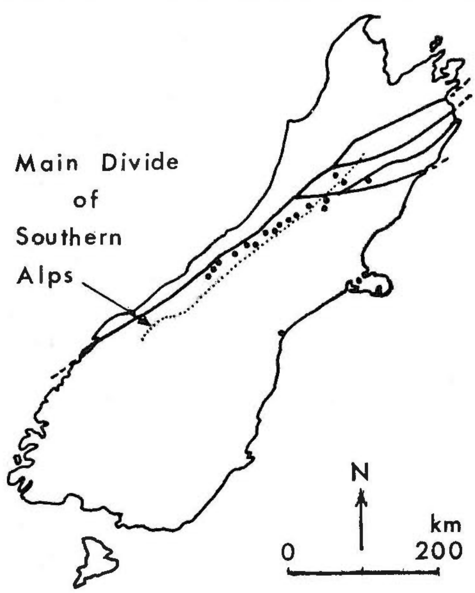


Fig. 10a Map of the South Island showing the distribution of hot springs. Data from ELLIS and MAHON (1964).

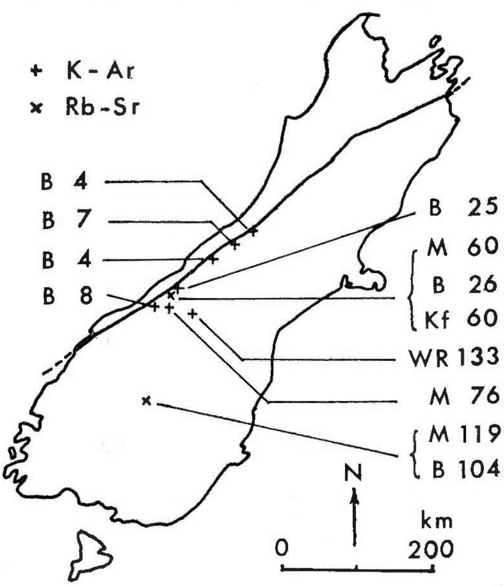


Fig. 10b Radiometric dates for the rocks of the Wakatipu Metamorphic Belt. Number is read in million years. Data from HURLEY et al. (1962), and ARONSON (1965).
B, biotite; Kf, potassium-feldspar; M, muscovite; WR, whole rock.

Fig. 10a the distribution of thermal spring (21~58°C) of the South Island (ELLIS and MAHON, 1964) is shown. Hydrothermal systems rise in Mesozoic and Paleozoic greywacke of the New Zealand Geosyncline, partly in the least metamorphosed rock of the Chlorite 2 subzone (LENSEN, 1962; BOWEN, 1964; GREGG, 1964), and pass through Recent sands and gravels.

As quoted by ELLIS and MAHON (1964), HEALY (1948) considered that major faulting and uparching of the old rocks has occurred in the zone about the flanks of the Southern Alps, and the hot waters seem to be associated with these rock movement and a high geothermal gradient.

As there is no sign of volcanic activity that could be considered as a heat source, it should also be noted that this phenomenon is closely related with the activity along the major faults.

II. 4. 4 Gravity anomaly

Bouguer Anomaly Map of New Zealand made by REILLY (1965) is shown in Fig. 11. Strongly negative Bouguer anomalies in the North Island (Rangitikei-Waiapu Anomaly) have been considered to be due to geosynclinal downwarping and in the South Island to formation of mountain roots (BRODIE, 1964). On the contrary, large positive Bouguer anomalies implies probable crustal thinning, in the extreme south of the South Island. It must be noticed that the position of these Bouguer anomalies is not consistent with the distribution of the Late Tertiary to Quaternary volcanic rocks.

II. 4. 5 Seismicity

From the distribution and nature of seismic activity in New Zealand, EIBY (1958) made structural deductions and demonstrated a structural picture of New Zealand. He divided the New Zealand structure into three layers,—the crust, a transition zone, and a sub-crust. The sub-crust extending to at least 370 km, is separated by a transition layer extending from the base of the crust to a depth of about 100 km.

The sub-crust is traversed by a major wedge-shaped structure within which the deep focus seismicity is confined. This has been named the "Sub-Crustal Rift".

The regional gravity anomaly pattern on the two sides of the Rift is markedly different. The gradient is low on the north-west side, and abnormally high on the south-east. In addition, the structural trends of the surface geology to the south-east lie parallel to the Rift, on the other hand, those to the north-west are cut off by it. Later EIBY (1964) slightly modified the earlier account (EIBY, 1958) and attempted to make the form of the Rift much clearer. As seen in Fig. 12, it shapes like a tetrahedral wedge, and reaches a maximum depth of slightly less than 400 km beneath the Bay of Plenty. The depth decreases in almost uniform manner southwards along the Rift. The general attitude of the western face is nearly vertical, though the shallower parts have an average dip of about 80° towards the west. The eastern face dips more gently at an angle between 40° and 50°. He suggested that the northern end of the Rift is closed, and therefore that New Zealand deep-focus seismicity should not be considered as a simple prolongation of the activity associated with the Kermadec Trench. Strikingly however, 50-mile southeastward offset of the axial part of the Hikurangi Trench from that of the Kermadec Trench is positioned nearly at the northern end of the Rift. This can explain EIBY's (1964) account for the relation between deep-focus seismicity within the Rift and seismic activity associated with the Kermadec Trench. That is, possible northerly prolongation of the Rift is situated 50 miles north-west of the northern end of the Rift along the trench offset.

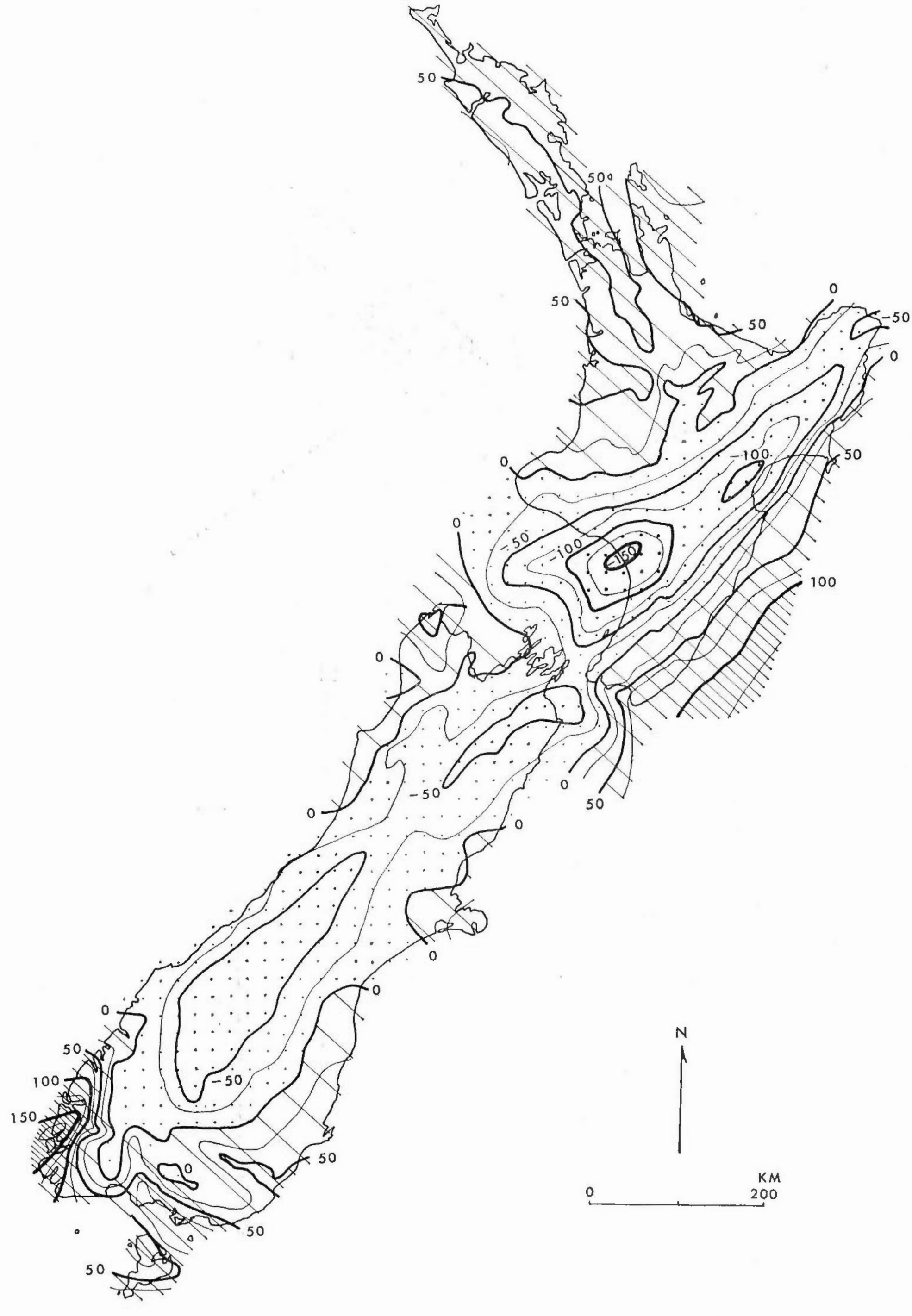


Fig. 11 Map showing Bouguer Anomalies of New Zealand. Contour interval 25 mgal. Anomalies in mgal. Reproduced from REILLY (1965).

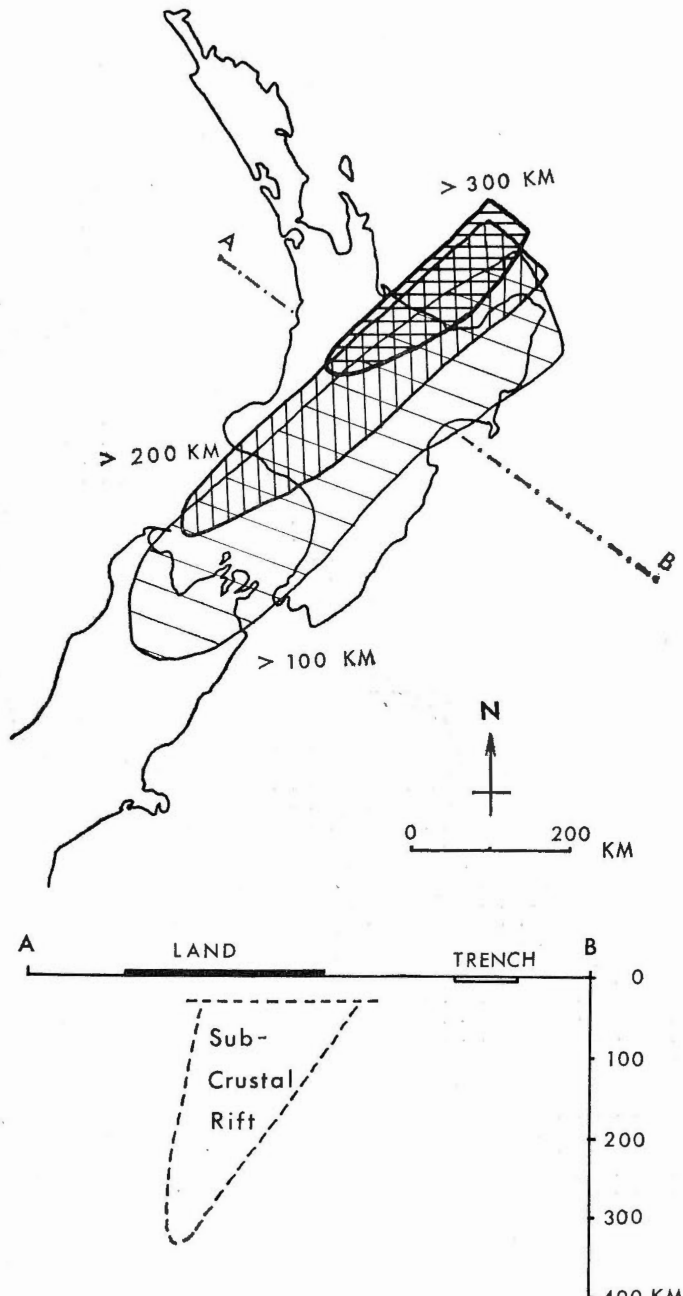


Fig. 12 Map showing the form of the New Zealand Sub-Crustal Rift. Based on EIBY (1964). Lower; cross section along A—B line.

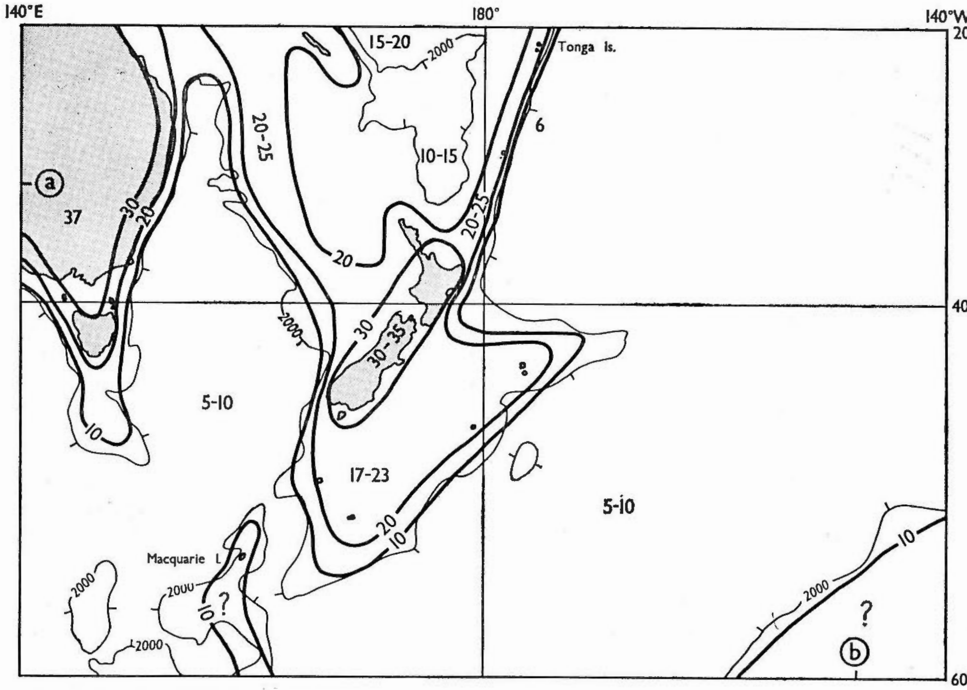


Fig. 13a Thickness of the earth's crust in the Southwest Pacific region. Reproduced from BRODIE (1964).

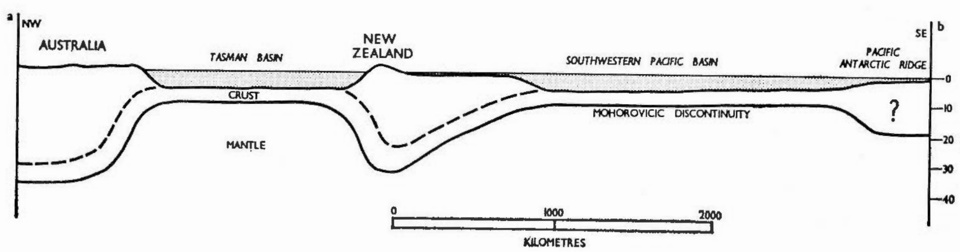


Fig. 13b Crustal section cut on the line from a to b on Fig. 13a. Reproduced from BRODIE (1964).

Although the negative Bouguer anomaly pattern, i. e., Rangitikei-Waiapu anomaly in the North Island is not consistent with the distribution of the Late Tertiary to Quaternary volcanic rocks, it seems likely to be largely identical with that of the Rift. From this, EIBY (1964) suggested that the mean density of the material within the Rift is about 1 per cent less than that of adjacent parts of the mantle.

II. 4. 6 Crustal thickness

BRODIE (1964) summarized the available data from various geophysical investigations and drew a generalized picture of the crust of the New Zealand region (Figs. 13a and 13b). He concluded that the New Zealand Plateau is an area of crust of intermediate and relatively uniform thickness and of continental rock types. He further stated that in the New Zealand Plateau the major crustal anomaly is within the extent of New Zealand itself, where the crust is 10 km thicker.

II. 5 Possible Present-day Paired Metamorphism in North-east New Zealand

The geology and tectonic history of New Zealand are to be accounted for on the basis of both geological and geophysical data, as seen in the previous works made by WELLMAN (1956) and KINGMA (1959). In this section the author would like to put forward a hypothesis of present-day paired metamorphism in north-east New Zealand.

a) Significant Sub-Crustal Rift

The crust of the New Zealand land mass is about 30 km thick, and is quite distinct from adjacent oceanic crust in various geophysical features. Beneath the crust the sub-crust extends to at least 370 km, and is traversed by the Sub-Crustal Rift, of which material is suggested to have the mean density about 1 per cent less than that of the adjacent parts of the mantle. This account is very important to consider any resultant geological happenings.

As already mentioned by EIBY (1958), the main crustal faults could have developed as the result of successive positioning above the Sub-Crustal Rift. This implies that the movements along active faults like the Alpine Fault are reflected indirectly by activities within the Rift (Fig. 14).

Although the distribution of the Late Tertiary and Quaternary volcanic rocks is not consistent with the positioning of the Sub-Crustal Rift, a remarkable belt of active, andesitic volcanoes and the Taupo Volcanic Zone is comparable to the pattern of the Rift. According to HEALY (1962), from the Taupo Volcanic Zone nearly 4,000 cubic miles (about 17,000 km^3) of lava have been erupted in Pliocene to Recent time, chiefly of rhyolitic composition, including ignimbrites.

Concerning the origin of magma responsible for the formation of these volcanic rocks, the nature of material in the Sub-Crustal Rift is most important. As frequently stated earlier, the material is lighter than that of the adjacent parts of the mantle. This probably implies that the Sub-Crustal Rift could provide huge volume of granitic magma in itself. In other words, granitic magma might have risen from a certain depth within the Rift. The nature of the granitic xenoliths from the Taupo Volcanic Zone revealed by EWART and COLE (1967) is of special interest. Probably there is a genetically close relation between the volcanic rocks and the granitic xenoliths. Therefore it can be said that it is not necessary to link the origin of the volcanic rocks with any basaltic magma in the mantle.

b) Retreating Hikurangi Trench

The northern end of the Rift is closed. But a close relation of the Rift with the Kermadec Trench might be expected and, of course, with the Hikurangi Trench. There is a remarkably uniform manner in which the depths of both the Rift and the Hikurangi Trench decrease southwards to a first approximation. Moreover, the Rift and the Trench run parallel side by side.

In the preceding section, the author points out that the Hikurangi Trench has been shallowing and retreating, and has been dying out from the southern end, leaving thickly accumulated sediments behind. If this interpretation is allowed, the following hypothesis is realized.

The zone of salient volcanic activity lies farther west of the Hikurangi Trench, and the zone is underlain by the Sub-Crustal Rift. Probably granitic rocks may have been formed in a certain depth, whereas rhyolitic lava and ignimbrite erupted on surface. On

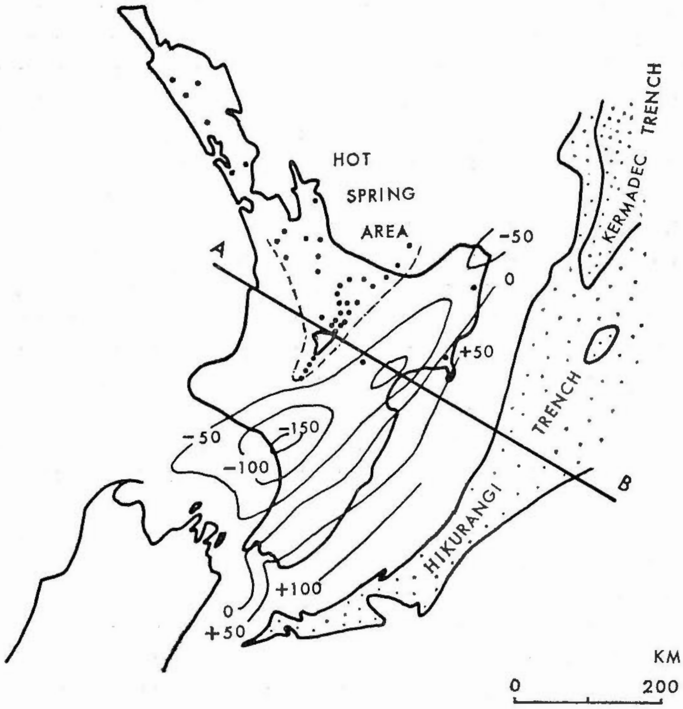


Fig. 15a Synthesis of information showing a general idea of a model of "New Zealand type present-day paired metamorphism". Bouguer anomalies at 50 mgal intervals. Data from GRINDLEY et al. (1959), BRODIE (1964), EIBY (1964), ELLIS and MAHON (1964), and REILLY (1965).

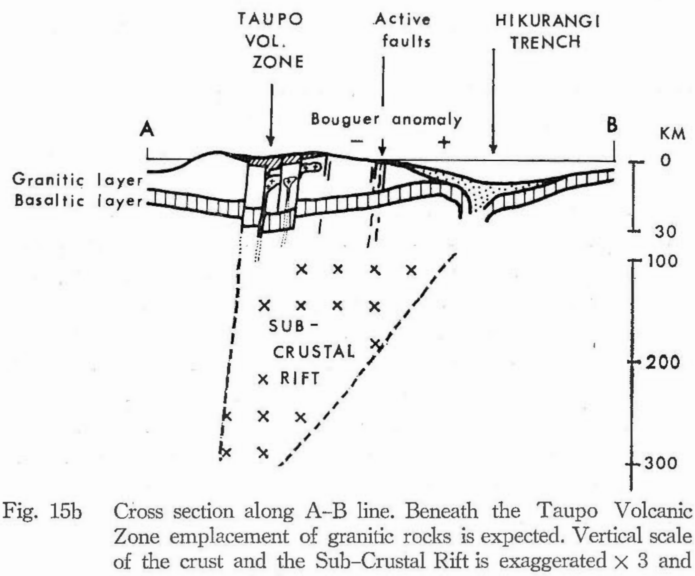


Fig. 15b Cross section along A–B line. Beneath the Taupo Volcanic Zone emplacement of granitic rocks is expected. Vertical scale of the crust and the Sub-Crustal Rift is exaggerated × 3 and × 1. 3, respectively.

the other hand, greater positive Bouguer anomalies are observed near the Hikurangi Trench, and provide non-isostatic relation. Therefore the following phenomenon is expected: thickly accumulated sediments immediately west of the Hikurangi Trench and in the Trench itself may have undergone burial regional metamorphism of high-pressure type. Between two regions postulated to undergo present-day regional metamorphism, many active faults run parallel with the Hikurangi Trench and also the Sub-Crustal Rift. These active faults probably result from the successive positioning above a possible present-day Median Tectonic Line in depths. This account is strongly constructive for a hypothesis of a **present-day paired metamorphism in north-east New Zealand** (Fig. 15). The author would like to call this model "New Zealand type present-day paired metamorphism".

In this regard, the retreat of the Hikurangi Trench has to be taken into consideration. This implies that successive migration of culmination of postulated regional metamorphism along the axial trend of the Hikurangi Trench might be traced back farther southwestwards. There might have happened quite recent regional metamorphism along the still active faults like the Alpine Fault. The unexpected young radiometric mineral ages of the schist close to the Alpine Fault could be interpreted in the manner mentioned above.

c) Distribution of hot springs in favour of very young regional metamorphism

In addition, there is strong evidence to support this interpretation, as the distribution of hot springs close to the active faults provide positive signs of high heat flow in the region. And the regional metamorphism of the trend represented by the H-curve in Fig. 4 might have occurred, in response to relatively high temperature distribution which practically existed in certain geological past, as strongly suggested by the distribution of present-day hot springs (Figs. 10a and 10b).

II. 6 Brief Summary of the Geologic Development of New Zealand

In conclusion, a simplified model of the geologic development of the South Island since Late Mesozoic is presented, on the basis of the Geological Map of New Zealand at 1:250,000 and synthesis of information mentioned above.

The beginnings of the New Zealand Geosyncline is not clear, but the oldest sediments are considered to be as old as Carboniferous age. The New Zealand Geosyncline has developed in quite wide areas showing a world-scale feature in its dimensions and depths comparable with a typical "eugeosyncline" (Suggate, 1965).

Towards the end of sedimentation in the Geosyncline, about in Late Jurassic time, the southwestern side of the Geosyncline changed its nature of subsidence to uplift, and developed fresh water sediments with coal measures, on the other side the northeastern side was still subjected to submergence to form marine sediments. Subsequent to major folding in Cretaceous, deep burial and regional metamorphism (Wakatipu Metamorphic Belt) took place in Otago, followed by differential uplift and erosion which led to form regional unconformities. At the same time emplacement of granitic rocks and volcanic rocks in the Tasman Metamorphic Belt took place. The Tasman Metamorphic Belt therefore contains the rocks affected by the Tuhua Orogeny which has been considered to be of Devonian—Carboniferous time by Landis and Coombs (1967).

The Median Tectonic Line may have evolved in the Cretaceous tectonic event, thus forming the paired metamorphic belts.

In Early Tertiary, marine transgression reached farther west close to the Haast Schist

Group in Canterbury, however the axial belt of dominant subsidence migrated northeastwards. To the south and west of the elevated area, the Eocene nonmarine sediments were developed. It is not certain whether the northeastward migration of the axial belt has lasted in connection with the development of the Hikurangi Trench or changed abruptly.

In Miocene time, block faulting and differential elevation began in north Canterbury and Marlborough, followed by dominantly transcurrent faulting represented by the Alpine Fault, the Wairau Fault, the Awatere Fault, the Clarence Fault, and the Hope Fault. Moderately high heat flow associated with the faulting resulted in the youngest regional metamorphism along the Alpine Fault.

Tectonic movements in Late Tertiary and Quaternary times took place mainly in and around the North Island. The dominant features are the formation of volcanic rocks on one side, and the accumulation of thick sediments on the other side along the Hikurangi Trench. The present-day paired metamorphism is possible in this region.

III. JAPAN

III. 1 General Description of Metamorphic Belts

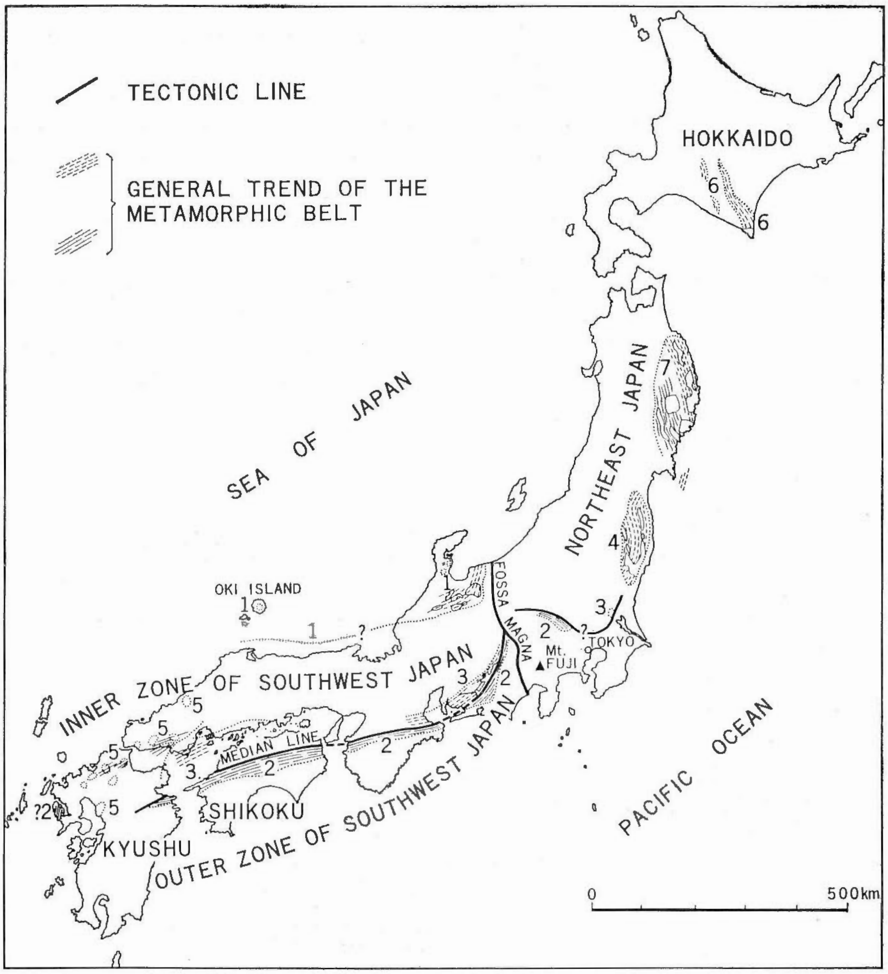
The geology of Japan is customarily divided into two tectonic units by a great ruptured zone called the "Fossa Magna" which traverses the central part of Honshu (Main Island of Japan) from the Sea of Japan to the Pacific Ocean: Southwest Japan and Northeast Japan (Fig. 16).

Regionally metamorphosed rocks are most widespread in Southwest Japan and they are recognized to constitute four metamorphic belts. The most remarkable feature in Southwest Japan is zonal arrangements of the metamorphic belts, running roughly parallel with the trend of Honshu. Each of metamorphic belts is called the Hida Metamorphic Belt, the Sangun Metamorphic Belt, the Ryoke Metamorphic Belt, and the Sambagawa Metamorphic Belt from north to south. Recently an extension of a regional metamorphism has been revealed in the Chichibu Terrane and the Shimanto Terrane which lie to the south of the Sambagawa Metamorphic Belt (SEKI et al., 1964).

The Ryoke Metamorphic Belt is separated by a salient tectonic line called the Median Tectonic Line from the Sambagawa Metamorphic Belt. The southern part of the Sambagawa Metamorphic Belt gradually merges into the Chichibu Terrane or is cut by the Mikabu Fault Line. The Chichibu Terrane is separated from the Shimanto Terrane by the Butsuzo Line.

Ages of metamorphic events in each metamorphic belt and regional metamorphism have been the subject of diverse opinions, and seem to be still in the melting pot. Among many debates, the most intriguing problem is the relation of the Ryoke Metamorphic Belt with the Sambagawa Metamorphic Belt, concerning whether or not both Metamorphic Belts form paired metamorphic belts, and whether radiometric dating intrinsically indicate the age of final metamorphic events and probably of uplift as a last phase of orogenesis, or the age of uplift which is considered to post-date the time of metamorphism, that is, regardless of any metamorphic event in an orogeny.

In this paper the author attempts to make a general review on this problem, and build up a hypothesis of a possible mechanism that could be responsible for the formation of paired metamorphic belts in the case of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt in Southwest Japan.



1. Hida Metamorphic Belt
2. Sambagawa—Mikabu Metamorphic Belt
3. Ryoke Metamorphic Belt
4. Abukuma Metamorphic Belt
5. Sangun Metamorphic Belt
6. Hidaka—Kamuikotan Metamorphic Belt
7. Kitakami Metamorphic Belt

Fig. 16 Map showing the distribution of the main metamorphic terranes in Japan. Reproduced from Geological Survey of Japan (1960).

III. 2 Some Features of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt

The natures of both Metamorphic Belts are briefly summarized as follows, based on Geological Survey of Japan (1960).

III. 2. 1 The Ryoke Metamorphic Belt

The Ryoke metamorphic rocks are distributed in a belt along the northern side of the Median Tectonic Line, from the eastern part of Kyushu to the middle of the Fossa Magna (see Figs. 16 and 17). The belt is about 40 to 70 kilometers in width and 650 kilometers in length. At many places the Ryoke metamorphic rocks have been intruded by granitic rocks. Generally they have parallel structure which coincides with the direction of the Median Tectonic Line. The metamorphic rocks are considered to have been derived chiefly from clayslate, sandstone, chert and others of probably Permian age. Mica schist, mica gneiss, and biotite hornfels (or schistose hornfels) are most abundant, accompanied by small amounts of amphibole schist, amphibolite, and amphibole gneiss. Sillimanite, andalusite and cordierite are found in argillaceous rocks of the higher-grade zone and around the intrusives. The lowest-grade zone is the Biotite Zone, therefore, a lack of the chlorite zone is most characteristic.

III. 2. 2 The Sambagawa Metamorphic Belt

This Belt continues from the central part of Honshu to Kyushu along the southern side of the Median Tectonic Line (Figs. 16 and 17). The rocks in this Belt are crystalline schists formed by regional metamorphism and are called the Sambagawa-Mikabu metamorphic rocks. The relation between these crystalline schists and the non-metamorphic or weakly metamorphosed Paleozoic strata is usually fault, but transitional at certain places. The Sambagawa metamorphic rocks consist chiefly of crystalline schists, and the Mikabu metamorphic rocks consist of semi-schists, phyllites, and green metamorphic rocks. The original rocks are Upper Paleozoic and possibly Middle Paleozoic rocks comprising argillaceous and arenaceous sediments, and mafic to felsic lava and tuff. The higher-grade metamorphic rocks have the mineral assemblages of greenschist facies, rarely of epidote amphibolite facies. Porphyroblastic albite spots are frequently found in this higher-grade rocks. Jadeite and glaucophane are found in the schists of some members.

III. 3 Focal Point of "Paired Metamorphic Belts" Controversies

a) Historical review

The relation between the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt was first considered by KOBAYASHI (1941) in the light of orogenic movement and its bearing on metamorphism. According to KOBAYASHI (1941) the Sambagawa Metamorphic Belt (practically called Sambagawa (-Mikabu) metamorphosed zone) is the miomagmatic metamorphosed zone of the Sakawa folded mountains, whereas the Ryoke Metamorphic Belt (practically called Ryoke zone) is the pliomagmatic metamorphosed zone of the Sakawa folded mountains. That both Metamorphic Belts are the products of the Middle Cretaceous Sakawa Orogeny was his conclusion.

To the contrary KOJIMA (1953) expressed a different opinion that both Metamorphic Belts were constructed in the Late Paleozoic or the Early Mesozoic orogeny, and also that the Sambagawa Metamorphic Belt was formed by the southerly up-thrusting movement of the Ryoke Metamorphic Belt.

On the basis of metamorphic facies series, MIYASHIRO (1961) directed attention to the presence of a pair of metamorphic belts in the Circum-Pacific Region. He considered that the Ryoke Metamorphic Belt is of the andalusite-sillimanite type and/or low-pressure intermediate group accompanied by abundant granitic rocks, whereas that the Sambagawa Metamorphic Belt is of the jadeite-glaucophane type and/or high-pressure intermediate group accompanied by abundant ultramafic rocks. He reached the conclusion that both Metamorphic Belts were formed in Cretaceous time, thus forming a pair.

SUWA (1961) reached a similar conclusion and stated that both Metamorphic Belts constitute a pair in the Middle Cretaceous period of orogeny.

ICHIKAWA (1964, p. 95) suggested a considerable time-gap between the Ryoke metamorphism and the overlying Late Cretaceous Izumi Group, assuming that the Ryoke Metamorphic Belt had been constructed long before Late Cretaceous. He also stated that the last phase of the Sambagawa metamorphism was prior to Late Triassic and after Middle Permian.

BANNO (1964) suggested that some parts of the Sambagawa Metamorphic Belt would have been pushed down beneath the Ryoke Metamorphic Belt, where intrusion of granitic rocks took place roughly contemporaneous with the Sambagawa metamorphism. He further stated that after regional metamorphism, probably in Early or Middle Cretaceous time the Sambagawa Metamorphic Belt was uplifted.

Recently MINATO et al. (1965) compiled quite a deal of latest information on the geology of Japan, and published an enormous work in "The geologic development of the Japanese Islands". They considered that both the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt were formed by the Permian and Triassic movements. In spite of realizing the importance of the Median Tectonic Line and remarkable contrast between the two Metamorphic Belts, MINATO et al. (1965, p. 115) kept away from elucidating the process by which the two Metamorphic Belts came into contact, saying that their present knowledge is not sufficient enough.

b) Time-gap between regional metamorphism and uplift

As far as radiometric dating is concerned, there is no opposing evidence against the concept of paired metamorphic belts: both Belts were involved in the Cretaceous Orogeny, corresponding to the Sakawa cycle of orogeny proposed by KOBAYASHI (1941). On the other hand, the alternative opposing the presence of the paired Metamorphic Belts or the Cretaceous Orogeny is not consistent with the results of radiometric dating. However, from their geologic interpretation, MINATO et al. (1965, p. 101) considered that radiometric ages by K-Ar method do not indicate any phase in metamorphic events in great depths, but indicate the phase in which metamorphic terranes were rapidly and intensely uplifted through subsequent epeirogeny to certain depths. MINATO et al. (1965, p. 89) in turn recognized a large time-gap between the time of the regional metamorphism and that of exposure on surface which provided regional unconformities in the case of the Ryoke Metamorphic Belt.

c) Upper age limit

Upper age limit of both Metamorphic Belts has stratigraphically been determined as follows. In eastern Kyushu pebbles derived from the Sambagawa Metamorphic Belt are known in the Upper Cretaceous Onogawa Formation, but the relation between the Sambagawa Metamorphic Belt and the Onogawa Formation is fault. In western Shikoku the Paleogene (probably Eocene) Ishizuchi Formation rests unconformably on the Sambagawa metamorphic rocks, and this field evidence provides the only direct relation to limit the upper age of the Sambagawa Metamorphic Belt.

In the case of the Ryoke Metamorphic Belt, the nature of the Late Cretaceous Izumi Group is to be noted. The Izumi Group is exposed to the north of the Median Tectonic Line from western Shikoku to the western Kii Peninsula, and rests upon granite which is related to the Ryoke metamorphic rocks. The Group is characterized by the presence of abundant arkosic sandstone, together with shale, conglomerate, and a small amount of tuff. Therefore it seems likely that the sediments were largely supplied from the emerged Ryoke Metamorphic Belt.

As mentioned here, very little is known to date the upper age limit of regional metamorphism on the basis of direct stratigraphic relation between regional metamorphic rocks and overlying strata. However, some attempts have been made on this matter, employing stratigraphic relations in adjacent areas to a metamorphic terrane concerned. The following account is by far the most well known.

In the middle sub-belt of the Chichibu Terrane which lies immediately south of the Sambagawa Metamorphic Belt, a marked clino-unconformity between the Middle Permian and the Upper Triassic has been known in Shikoku and western Kyushu. This is called the Sakashu unconformity in eastern Shikoku (ICHIKAWA et al., 1953) and the Uminoura unconformity in western Kyushu (KANMERA, 1961 ; ORITA, 1962).

Based on that the Middle Permian are strongly sheared and deformed, the clino-unconformity has been considered to indicate the tectogenesis essentially prior to the Upper Triassic, i. e., the Permian–Triassic tectogenesis (ICHIKAWA, 1964). This interpretation does really form a strong ground for assuming that the Sambagawa metamorphism ended before Late Triassic.

d) Median Tectonic Line

This Line is a salient tectonic line running between the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt. Four phases of movements along the Median Tectonic Line were first recognized by KOBAYASHI (1941) : the Middle Cretaceous Kashio phase (southward thrusting and mylonitization), the Ichinokawa phase (normal faulting with downthrow on the north side), the Tobe phase (northward thrusting), and the Shobudani phase (southward thrusting in Quaternary).

In this paper the Median Tectonic Line is strictly used to mean the first phase of movement which essentially governed the nature of the Line, i. e., the Kashio phase. There have also been many arguments concerning ages and natures of each phase of movements along the Median Tectonic Line. And these arguments are largely controlled by how and when both Metamorphic Belts are considered to have come into contact. If the age of the Kashio phase is not taken into account, the nature of the movement has commonly considered to be of southward thrusting. The only different opinion was presented by BANNO (1964). He considered that it was a normal fault, based on the following assumption. The Ryoke Metamorphic Belt was formed in a shallower part of the earth's crust, lying at the hanging wall of the fault, whereas the Sambagawa Metamorphic Belt was formed in a deeper part of the crust, lying at the foot wall.

Among many opinions, KOBAYASHI's (1941, p. 288) interpretation is by far the most important, that is, the Median Tectonic Line divided one orogenic zone into two parts, instead of uniting two orogenic zones of different tectonic systems.

e) Rhyolite and its pyroclastics

As seen in Fig. 17, the Cretaceous volcanic rocks are quite widespread to the north of the Ryoke Metamorphic Belt. The Nohi Ryolites named by KAWADA et al. (1961) are situated near the eastern part of the Ryoke Metamorphic Belt. The Nohi Rhyolites consist mainly of tuff of ignimbrite nature.

At many places the Cretaceous volcanic rocks have been intruded by granitic rocks of similar age. Large granite mass in the Chugoku Province is described as the " Chugoku Batholith ". Although a genetically close relation has been suggested between the Cretaceous volcanic rocks and the granitic rocks, any attempt to determine a definite relation still remains not successful.

As mentioned earlier, ICHIKAWA (1964) considered that the Ryoke Metamorphic Belt had been constructed long before Late Cretaceous, connecting with the Paleotectonic era (Silurian-Early Mesozoic) of his own definition. But, with regard to the extensive volcanic and plutonic activity concerned, ICHIKAWA (1966) stated that the formation of large amounts of the Late Mesozoic magma should be recognized as a particular type of the subsequent diastrophism of the Paleotectonic evolution.

Quite recently SAKAI et al. (1965) and YAMADA (1966) found the following phenomenon: one of the granites of the Ryoke Metamorphic Belt intruded into the Nohi Rhyolites. This discovery is of special interest to discuss genetical relations between the Ryoke granites and the Cretaceous rhyolites as a whole.

f) A possible clue to the origin of the paired Metamorphic Belts

As already discussed in the preceding sections on the New Zealand metamorphic belts, grounds for assuming or doubting a geologic development seem to have become much clearer. The grounds do really depend upon how to interpret geological and geophysical data such as nature of metamorphism, upper age limit, radiometric dates, and length of life of a single regional metamorphism. Although so many interpretations have been made to ascribe very young radiometric date to diffusive loss of radiometric daughter elements or to the time of uplift, no geological evidence has been recorded to conflict any results of radiometric dating for both Metamorphic Belts in Cretaceous time.

The author is of the opinion that there are rather many constructive geological evidences to support the nature of both Ryoke and Sambagawa Metamorphic Belts forming a pair.

It may be worthwhile to consider the relation of both Metamorphic Belts in the light of a model of "New Zealand type present-day paired metamorphism in north-east New Zealand". This attempt may provide a strong clue to the origin of the pair, and will be described later.

III. 4 Distinct Petrochemical Features of the Paleozoic Sediments

The Paleozoic Geosyncline has been considered to occupy quite wide areas in Southwest Japan, covering the larger part of western Japan. Stratigraphic evidence in Southwest Japan indicates that sedimentation in the Geosyncline was most dominant in Carboniferous and Permian times. The main constituents of the Paleozoic sediments are greywacke and clayslate. Abundant mafic volcanics, limestone lenses, and chert and siliceous rocks are lithologically noted. There is a tendency to show the strong volcanic activity of mafic nature in the southern strip.

In an attempt to get information on a probable systematic change of lithologic characters, discrimination of petrochemical features from place to place may help to further study in discussing the relation between the two Metamorphic Belts. Working mainly from MIYASHIRO and HARAMURA (1962), KATADA et al. (1963 a), and BANNO (1964), MIYASHIRO and HARAMURA (1966) divided the Paleozoic geosynclinal sedimentary terrane of Japan into four zones from north to south: 1) practically unmetamorphosed zone N, 2) Ryoke-Abukuma Metamorphic Belt, 3) Sambagawa Metamorphic Belt, and 4) practically unmetamorphosed zone S (Fig. 18). The pelites of zone N tend to have higher ratios of $K_2O/(Na_2O+K_2O)$ and of Al/Na ratios than those of zone S. And the ratio of $K_2O/(Na_2O+K_2O)$ of pelitic rocks tend to decrease continuously southwards, irrespective of regional metamorphism. Zone S is identical with the Chichibu Terrane, and is characteristic with pelites of lower maturity and the presence of volcanic nature, that is of typical "eugeosynclinal" sedimentation. On the contrary, MIYASHIRO and HARAMURA (1966)

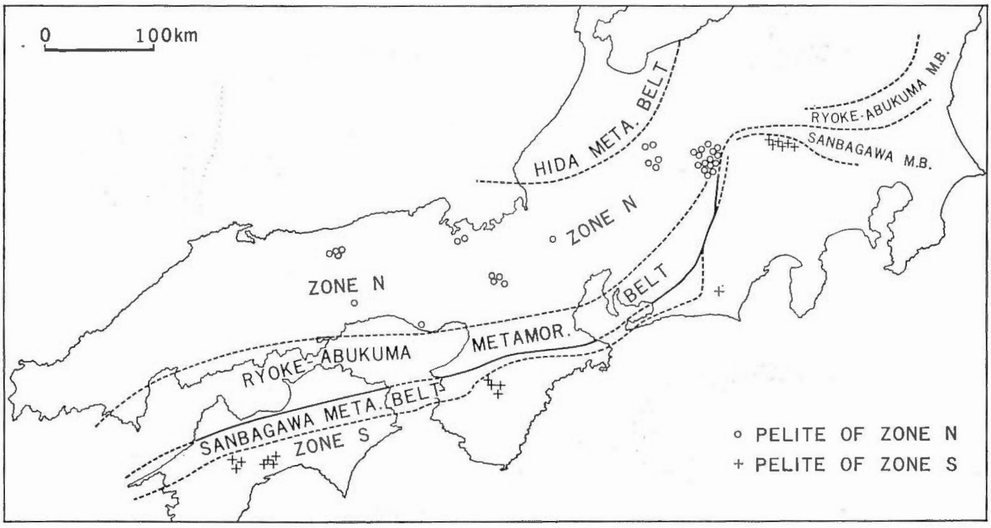


Fig. 18 Map showing four zones in the Paleozoic geosynclinal terrane of Japan. Reproduced from MIYASHIRO and HARAMURA (1966).

considered that zone N represents the miogeosynclinal zone of the Paleozoic Geosyncline.

In addition they suggested that most of the original pelitic sediments of the Ryoke Metamorphic Belt were probably similar in chemical composition to those of zone N, whereas most of the pelitic metamorphic rocks of the Sambagawa Metamorphic Belt were intermediate between those of zones N and S, provided that the regional metamorphisms were essentially isochemical except the removal of H_2O and the reduction of Fe. Their account in turn implies that the nature of sediments varies systematically from north to south and that sedimentation in each of four zones was genetically related each other.

III. 5 Thermal Phenomenon in the Ryoke Metamorphic Belt

In contrast to the Sambagawa Metamorphic Belt, the Ryoke Metamorphic Belt is not uncommonly accompanied by emplacement of granitic rocks. There is little evidence, however, to indicate contact metamorphic effects on the surrounding rocks, as the metamorphic conditions have been considered to be different from hornfels facies. For this reason the regional metamorphism in the Ryoke Metamorphic Belt is described as regional high-level or high-temperature metamorphism, that is, the nature is of MIYASHIRO's (1961) andalusite-sillimanite type and/or low-pressure intermediate group.

With respect to the process of regional upheaval of iso-geothermal surface, the origin of heat energy must be taken into account. Boundary of granite body does not always coincide with that of metamorphic zoning, however, the highest zone is largely confined to near around the granite body. Thus it is quite natural to assume that heat transportation was made upwards along with the intrusion of granitic magma.

HAYAMA (1962) concluded that the Ryoke metamorphism took place in a relatively shallower depth, and the age is coeval with that of granitic rocks: of Middle Cretaceous time. His conclusion is based on the assumption that the emplacement of granitic rocks in the Ryoke Metamorphic Belt is intrinsically upheaval phenomenon. Furthermore, he stated that it is difficult to postulate a considerable time-gap between the time of the granite emplacement and the time of upheaval, referring to the result of radiometric

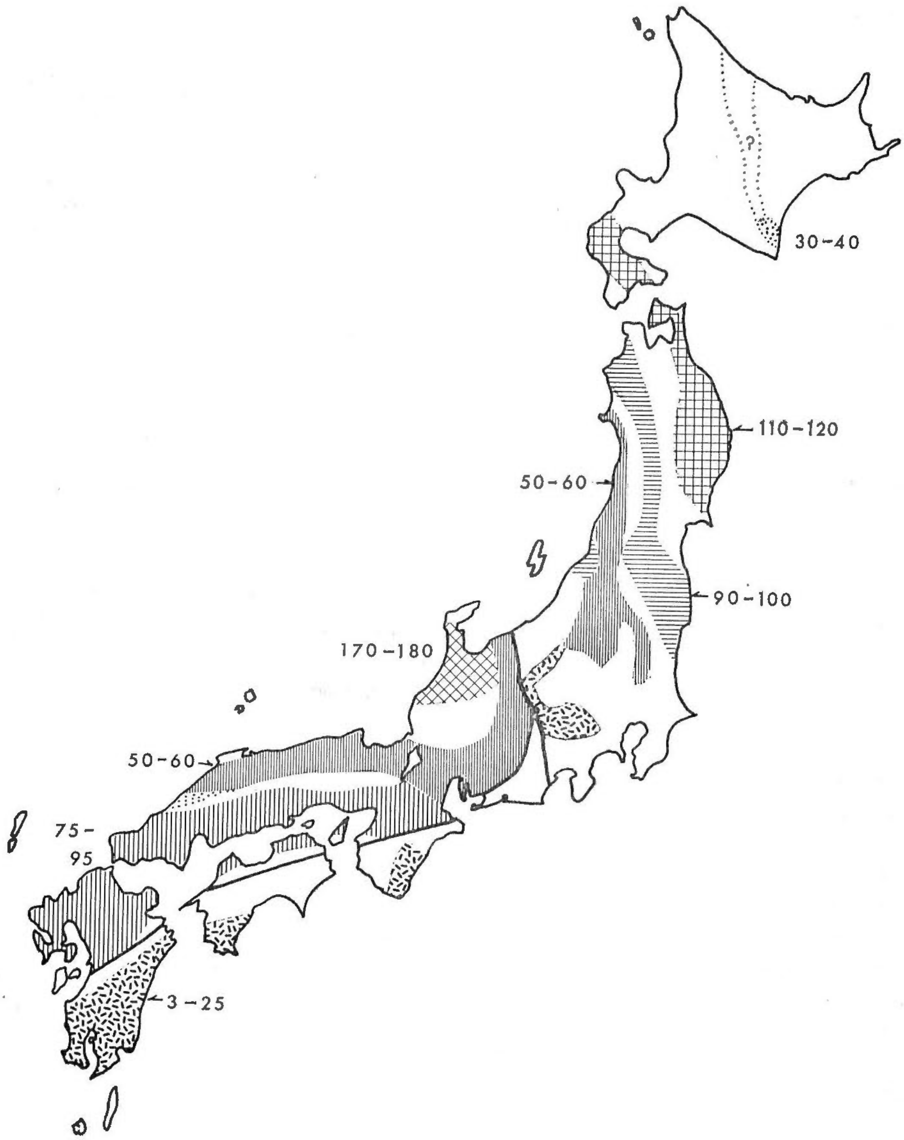


Fig. 19 Map showing the zonal distribution of granitic rocks, based on their K–Ar ages. Reproduced from KAWANO and UEDA (1967).

dating. KAWANO and UEDA (1966 ; 1967) made a general account for the ages of many granitic masses in Southwest Japan (Fig. 19). They considered that a marked zonal distribution of granitic rocks is the result of progressive migration of igneous activity. They did not regard radiometric dates as the time of uplift itself.

The relation that one of the Ryoke granites intruded into the Nohi Rhyolites of Cretaceous age (SAKAI et al., 1965 ; YAMADA, 1966) is of much interest to consider the nature of the Ryoke metamorphism. Probably this strongly implies that the volcanism is accompanied by the granite emplacement. Although the author will discuss a possible mechanism to produce granitic magma in the later section, it is quite probable that at least part of granitic magma associated with the Ryoke metamorphism erupted onto surface, thus forming volcanic rocks like the Nohi Rhyolites.

MATSUMOTO's (1965a) assumption that the plutonic activity associated with the Ryoke metamorphism is intrinsic of magma formation within the upper mantle should be taken into consideration in this regard. In addition, MATSUMOTO (1965b) threw doubt upon if the Ryoke Metamorphic Belt has gained the character of the culmination axis of regional metamorphism in an orogenic belt, and furthermore if the plutonic activity played significant roles in the processes of geologic development from geosynclinal to orogenic stages.

III. 6 Nature of Rocks in the Ryoke Metamorphic Belt Prior to the Ryoke Metamorphism

There still arises another problem : before the Ryoke Metamorphic Belt was subjected to the granitic intrusion, what strata or rocks may have been there. Comments made by HAYAMA (1962) and HAYAMA et al. (1963) on this point is very important to postulate the nature of the rocks prior to the Ryoke metamorphism. According to them, the rocks were nearly unmetamorphosed Paleozoic geosynclinal sediments, and some of the rocks may have been crystalline schists. Thus it is likely that parts of the sediments have undergone regional metamorphism during the period of the Early Mesozoic orogenic movement in the Sangun Metamorphic Belt, as will be discussed later.

MIYASHIRO (1965, pp. 401—402) suggested that the salient metamorphism in the Sangun Metamorphic Belt and the Sambagawa Metamorphic Belt may have lasted for a long-range span of life of a single regional metamorphism in the Japanese Islands, and on the contrary that the Ryoke Metamorphic Belt continued only in a very short span of life, subordiante to the main events of the Sangun-Sambagawa metamorphism.

It is therefore most likely that not less amounts of the rocks existed before the Ryoke metamorphism might have been involved in the Late Paleozoic to Early Mesozoic phase of the Sangun metamorphism. In this connection ICHIKAWA's (1964 ; 1966) account that the Late Mesozoic tectonic movement is subordinate diastrophism of the major eugeosynclinal tectogenetic process in Early Mesozoic is significant to explain the postulation made by HAYAMA (1962) and MIYASHIRO (1965).

Some constructive evidences may be pointed out to support the existence of the rocks which have been slightly metamorphosed during the Late Paleozoic to Early Mesozoic phase of the Sangun metamorphism, as follows.

a) Geologic structures

In a discussion on superficial folding of the Paleozoic eugeosynclinal sediments in Southwest Japan, MIZUTANI (1964) reached the conclusion that the tectonic movement of dominant folds of the Paleozoic strata occurred in relation to the Early Mesozoic orogenic movement. In the central Alps, the metamorphic zone has developed obliquely with fold axis, and the metamorphism accomodated static condition without disturbing pre-existed structures (KATADA et al., 1961). Further they stated that the age of the Ryoke metamorphism is not penecontemporaneous with the main phase of folding, suggesting a large time-gap between the age of main structural deformation and of metamorphism.

b) Petrographical and petrological significance

Well-known descriptive term " schistose hornfels " for the Ryoke metamorphic rocks sounds unusual, for the process of constructing schistose structure is quite different from the process of essentially thermal phenomenon for the formation of hornfels. And this question has been made not infrequently among Japanese petrologists. This suggests that schistose structure might have been formed before hornfels. For instance, HAYAMA et al. (1963) revealed that in the hornfels zone of the eastern Ryoke Metamorphic Belt there occur some crystalline schists hardly discernible with those of the Sambagawa Metamorphic Belt, and that the schists gradually merge into hornfels.

Another evidence for this may be provided in IWAO's (1938) study: progressive recrystallization of porphyroblastic quartz including different pattern of helicitic structure in biotite schist of the Yanai district, west Japan. It seems probable to assume that this type of helicitic structure is the product of two distinct metamorphic events.

Petrologically the occurrence of stilpnomelane coexisting with biotite in the Ryoke metamorphic rock (KATADA and SUMI, 1966) draws much attention. Apart from genetical relation of stilpnomelane to the low-pressure intermediate group metamorphism, a possibility arises as the occurrence indicates a remnant mineral from the rocks which have already experienced the tectonic deformation comparable to the prominent folding in the Early Mesozoic orogenic movement. For instance, the rocks of the Sangun Metamorphic Belt underwent the similar orogenic movement and contain stilpnomelane-bearing schistose rocks. Thus relevant condition is expected in the area of the Ryoke Metamorphic Belt.

III. 7 Areal Extent of the Sambagawa Metamorphism

a) Sambagawa metamorphism in the Sambagawa Metamorphic Belt and the Chichibu Terrane

Referring to the structural pattern of the Sambagawa Metamorphic Belt, HAYAMA (1962) divided this Belt into two regions placing the divide at the central part of the Kii Peninsula. In the eastern region, it is simple with gently dipping monoclinal structure, and the metamorphism gradually increases to the lower stratigraphic member. This implies that the subsidence was continuous in a uniform rate. On the contrary in the western region the subsidence was probably violent, and thus reversed order of stratigraphic succession are dominant and also the metamorphic grade increases to the upper stratigraphic member. This interpretation made by HAYAMA (1962) has been supported by detailed petrologic studies of the Sambagawa metamorphic rocks in the Kotsu-Bizan district (IWASAKI, 1963), the Besshi-Ino district (BANNO, 1964), and the Iimori district (KANEHIRA, 1967).

The Chichibu Terrane largely separated from the Sambagawa Metamorphic Belt by the Mikabu Fault had been considered to be non-metamorphosed, but IWASAKI (1963) and BANNO (1964) revealed that the greater part of the Chichibu Terrane was affected by the regional metamorphism which drove part of rocks to form the Sambagawa crystalline schists. As far as the metamorphic zoning is concerned, the presence of the Mikabu Fault Line is no longer significant.

b) Possible extension of the Sambagawa metamorphism farther south to the Shimanto Terrane

SEKI et al. (1964) found that most of the Mesozoic rocks of the Shimanto Terrane in the central part of the Kii Peninsula have mineral assemblages of the lower-grade metamorphism: combination of prehnite and pumpellyite, and of pumpellyite and actinolite. They concluded that the lower-grade metamorphic rocks progressively become the higher-grade rocks from south to north, and finally grade up to the "spotted" zone of the Sambagawa Metamorphic Belt. Isograds of the metamorphism cut the conspicuous thrust which separated the Paleozoic strata of the Chichibu Terrane to the north and the Mesozoic of the Shimanto Terrane to the south. The Mesozoic strata contain the Jurassic. Therefore the metamorphism took place even in later than Jurassic time. In addition, their suggestion that the Sambagawa metamorphism may have lasted for a long time since Late Paleozoic to later than Jurassic should be noted.

III. 8 Migration of the Paleozoic Geosyncline to the Shimanto Geosyncline

ICHIKAWA (1964, p. 96) summarized the Permian—Triassic tectogenesis in Southwest Japan, as follows. The Permian eugeosynclinal condition was brought to an end in the late Middle Permian, followed by the Late Permian "terminal" sediment of conglomerate-bearing facies. In a few provinces, for instance in the Ryoke Metamorphic Belt, a possibility was not excluded that a thick marine accumulation might have lasted partially until the earlier half of Triassic, although there is no positive evidence for it.

In the probable southern extremity of the Paleozoic Geosyncline which is referable to the southern sub-belt of the Chichibu Terrane, the sedimentation of the Permian and Triassic strata (Sambosan Group) was still of eugeosynclinal nature, characterized by a considerable amount of chert, limestone and mafic tuff. Therefore it can be said that this evidence is a positive sign for the southward migration of the eugeosynclinal environments.

Geological Survey of Japan (1960) classified the vast area to the south of the Chichibu Terrane into the so-called "Undifferentiated Mesozoic" of the Shimanto Terrane on the north and the Cretaceous—Paleogene of the Nakamura Terrane on the south. But later these two Terranes were mapped by an omnibus term, the "Shimanto Complex" in the Geological Map of Japan at 1:2, 000, 000 (1964). ICHIKAWA (1964;1966) called this vast area the "Shimanto Major Belt". In this paper the "Shimanto Terrane" is used in a wide sense, and is identical to the "Shimanto Complex" and the "Shimanto Major Belt".

The nature of the sediments in the Shimanto Terrane is briefly described as follows, based on Geological Survey of Japan (1960). In the northern part of the Shimanto Terrane the rocks are composed of geosynclinal sediments with great thickness. Some parts of the facies are rich in radiolarian chert and others occasionally carry limestone of Later Jurassic age. Other parts contain diabase or altered mafic pyroclastics. These sediments are believed to be from Jurassic to Earlier Cretaceous in age. Whereas in the southern part of the Shimanto Terrane the rocks are thick, geosynclinal sediments chiefly composed of alternating sandstone and shale. In the upper part tuffaceous shale appears. These strata are assumed to be Cretaceous—Paleogene in age, that is, younger than those of the northern part of the Shimanto Terrane.

From geological evidence mentioned above, it is quite obvious that there is a tendency of progressive migration of geosyncline from the Chichibu Terrane to the southern part of the Shimanto Terrane.

III. 9 Possible Origin of a Pair of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt

Working from many geologic evidence and postulations mentioned in the preceding sections, and also referring to a proposed model of "New Zealand type present-day paired metamorphism", the author would like to consider a possible mechanism to form the paired Metamorphic Belts in Southwest Japan.

The Paleozoic sediments deposited in a wider belt of eugeosyncline. Volcanism was dominant in the southern narrow strip of the present Sambagawa Metamorphic Belt. As sedimentation proceeds, the sediments start undergoing burial metamorphism in a moderate depth, in a manner suggested by MATSUDA and KURIYAGAWA (1965) as follows: as sedimentation proceeds continually, the sediments of the lower member are pushed down and buried into a certain depth where burial metamorphism takes place ; provided that geosyncline migrates laterally, then corresponding migration of burial regional metamorphism is also expected.

In Late Paleozoic to Early Mesozoic the Paleozoic Geosyncline changed its nature of subsidence to uplift. And the burial regional metamorphism in the northern part of the Paleozoic Geosyncline ends with uplift in Middle Triassic and resultant regional unconformity, as known in the relation of the Sangun Metamorphic Belt and overlying Upper Triassic strata. This evidence implies the Late Paleozoic—Early Mesozoic Sangun metamorphism. However, burial regional metamorphism continued in other terranes including the Sambagawa Metamorphic Belt retained in a considerable depth.

In connection with this tectonic movement, the Paleozoic Geosyncline was dying out, and migrated to the south where another geosyncline (Shimanto Geosyncline) was formed as seen in the present Shimanto Terrane.

In Early Cretaceous, a great rift of wedge-shaped comparable to the New Zealand Sub-Crustal Rift probably occurred in the sub-crust beneath the Median Tectonic Line or its neighbouring depths. The appearance of a trench is postulated near the axial part of the Shimanto Geosyncline where volcanic activity of mafic nature was accompanying with the sedimentation. To the north of this trench, that is, near the Median Tectonic Line and farther north, activity within sub-crustal rift produced continually certain volume of granitic magma in various times and places on one side, and led to rapid uplift. On the other side, to the south of the Median Tectonic Line occurred a remarkable downward buckling to form high-pressure minerals. Between them the salient tectonic line appeared to make two distinct types of metamorphic terranes into direct contact. Some of granitic magmas erupted upwards to the earth's surface through faults, and formed volcanic rocks like the Nohi Rhyolites.

This hypothesis is postulated to explain possible origin of the paired Metamorphic Belts in Southwest Japan: the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt including parts of the Chichibu Terrane and the Shimanto Terrane.

Working hypotheses to account for paired metamorphic belts have been put forward by MIYASHIRO (1961 ; 1965), MATSUDA (1964) and TAKEUCHI and UYEDA (1965). MIYASHIRO (1965) and TAKEUCHI and UYEDA (1965) directed their attention on the relation between the zone of deep focus earthquake and magma production as well as on the possible tectogenesis near the Japan Trench.

The present author's attempt, however, is slightly different from their hypotheses. One of advantages by the author's hypothesis may be emphasized: wedge-shaped sub-crustal rift of New Zealand type can produce huge volume of granitic magma; whereas the well-known inclined zone of deep focus earthquake in Northeast Japan can well explain the origin of lateral variation of basalt magmas (KUNO, 1959), but not explain granitic magma. The author would like to stress that this hypothesis would help to reconcile the conflicting views on the concept of paired metamorphic belts.

IV. Comparison between the Two Geologic Developments of New Zealand and Japan

In the case of the geologic development of New Zealand, three characteristic points may be stressed as follows.

(1) Long duration of life of the New Zealand Geosyncline from Carboniferous to Jurassic is recognized along the axis of the Geosyncline. Since Late Mesozoic time, the axial part probably represented by an area close to a certain trench has started migrating northeastwards nearly along the trend of the axis of the New Zealand Geosyncline, and emerged into the present Hikurangi Trench and also farther north into the Kermadec Trench (Fig. 20a)

(2) Late Mesozoic volcanic activities are not so conspicuous when compared with those of Southwest Japan. Two interpretations are possible. a) This probably results from emplacement of the corresponding granitic rocks in depths which is expected only on a small scale. Therefore a pair of the Tasman Metamorphic Belt and the Wakatipu Metamorphic Belt may not have been established well. b) Volcanic rocks possibly existed in response to the intrusion of the granitic magma and together with the rocks of the Tasman Metamorphic Belt may have already been eroded out.

(3) Large lateral shifts are recognized in the Kaikoura area, where the movement has taken place since Miocene time. However, it seems [redacted]likely that total displacement along the Alpine Fault never reaches the generally accepted amount of 300 miles. Recent tectogenesis is displayed by the postulated present-day paired metamorphic belts in north-east New Zealand where rhyolite, active faults and the Trench run parallel side by side.

Whereas in Japan similarly three points may be stressed.

(1) The Paleozoic Geosyncline migrated to the south, that is, toward the oceanic side, and a new geosyncline—the Shimanto Geosyncline was formed in parallel with the Paleozoic Geosyncline. In Recent time, the distribution of geosyncline suggested by the present Japan Trench—the Izu-Ogasawara Trench and the Ryukyu Trench—the Nanseishoto Trench has developed in a quite different manner (Fig. 20b).

(2) Southwest Japan is characterized by the salient paired metamorphic belts in Cretaceous time: the Ryoke Metamorphic Belt, and the Sambagawa Metamorphic Belt and parts of the Chichibu Terrane and the Shimanto Terrane. Once parts of the rocks of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt were probably involved in the Late Paleozoic to Early Triassic tectonic movement of the Sangun metamorphism. And the present status of the paired Metamorphic Belts is considered to be due to the later tectonic events in Cretaceous time. It is therefore concluded that the rocks of the Ryoke Metamorphic Belt may have experienced two different types of metamorphic events. This in turn implies that the rocks of the Ryoke Metamorphic Belt can be assigned to be of polymetamorphic origin.

The rocks of the Sambagawa Metamorphic Belt have been influenced by the continual tectonic movements of burial metamorphism since Late Paleozoic time until considerably high-pressure regional metamorphism took place in the area close to the Median Tectonic Line as a result of intense downward buckling in Cretaceous time. The Median Tectonic Line was formed by the two markedly contrast movements between the upheaving Ryoke Metamorphic Belt and the rapidly subsiding Sambagawa Metamorphic Belt.

(3) Large lateral shifts are recognized only in the area around the Akaishi Mountains, where the movements along the Akaishi Tectonic Line were largely of lateral nature in pre-Miocene time. According to KIMURA (1959) the trend of the Line is strikingly in

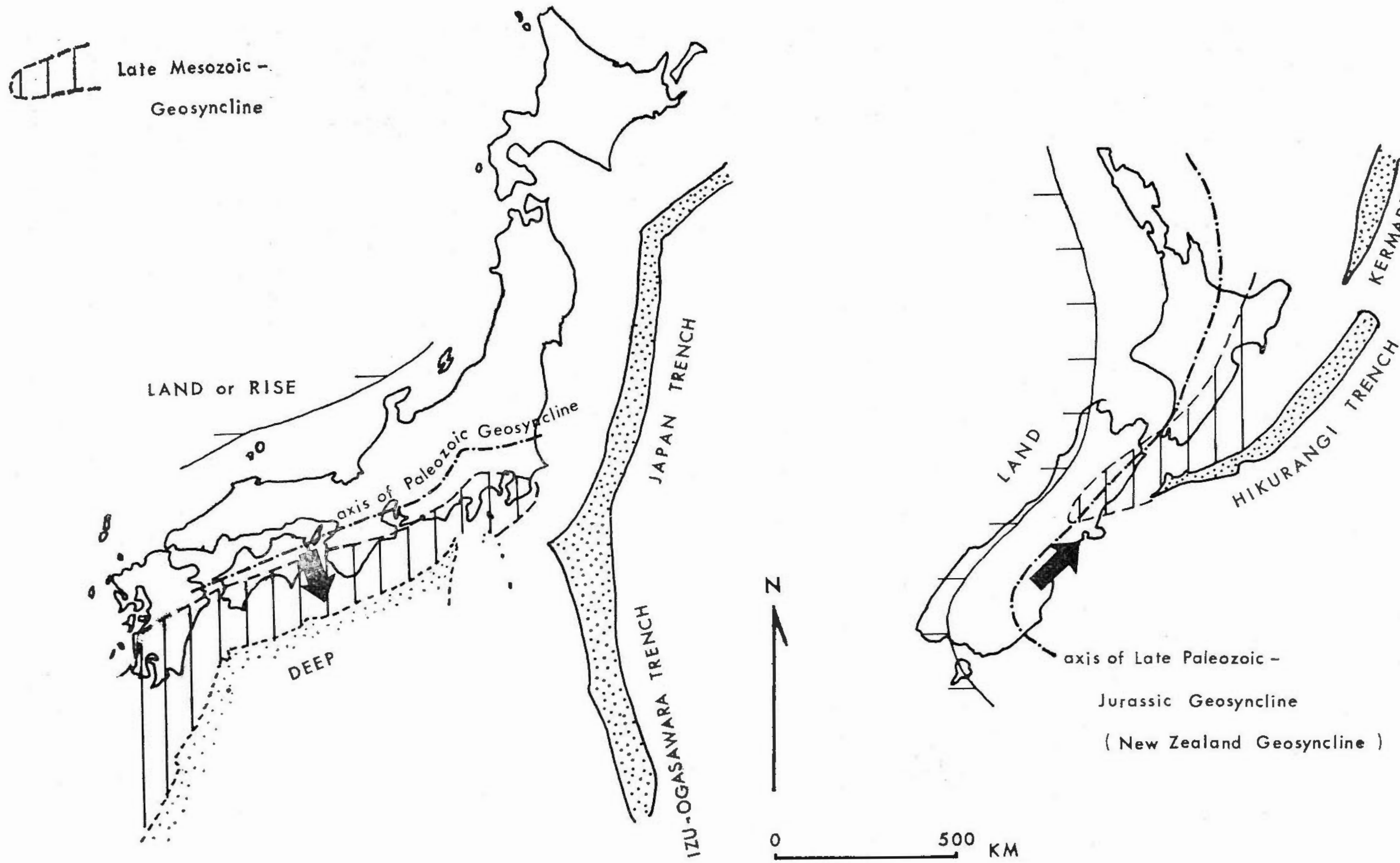


Fig. 20 Schematic illustration of two different trends in the manner of postulated migration of geosyncline and trench since Late Mesozoic in New Zealand (a) and in Japan (b).
"Land" west of New Zealand and "Land or Rise" northwest of Japan appear to have existed during the sedimentation in the New Zealand Geosyncline and the Paleozoic Geosyncline of Japan, respectively.

harmony with that of the Japan Trench, and moreover it is compared with the case of the New Zealand lateral faults in the Kaikoura area which lie in parallel with the Hikurangi Trench.

It may be concluded with some degree of confidence that the slight difference in the manner of the geologic developments in both New Zealand and Japan is well explained in the different progressive migration of axial part of geosyncline, as seen in the present status of trenches, and that the origin of paired metamorphic belts can be accounted for by a model of "New Zealand type present-day paired metamorphism". Furthermore the facts that the formation of paired metamorphic belts happened in both New Zealand and Japan in Cretaceous time is prime importance to consider as to whether the formation simply means a tectogenesis in each place or a global phenomenon as suggested by the Cretaceous tectonic movement in the Circum-Pacific Region.

In the South Island, New Zealand, the pair of the Tasman Metamorphic Belt and the Wakatipu Metamorphic Belt was formed shortly after the last sedimentation in the New Zealand Geosyncline. Whereas in Southwest Japan the pair of the Ryoke Metamorphic Belt and the Sambagawa Metamorphic Belt was formed long after the cessation of sedimentation in the Paleozoic Geosyncline.

For this reason the formation of a pair in both cases is quite independent of the process in a geologic development from geosynclinal stage to subsequent upheaval-denudation. In other words, it seems likely that the Cretaceous tectogenesis to form the paired metamorphic belts concerned are probably generated by a global tectogenesis in the Circum-Pacific Region.

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ニュージーランドにおける後期中生代ー現世の造構運動とその変成作用に及ぼす意義，および日本における場合

服　部　仁

要　旨

ニュージーランドおよび日本における後期中生代以降の地質構造発達史を，変成分帯，放射性アイソトープによる年代測定，地質構造解析および地球物理学的研究の最近の成果に基づいて概観した。また2つの異なるタイプの広域変成帯が1つの対をなす，いわゆるペア変成帯の成因についても考察した。

ニュージーランドにおいては，変成岩はほとんど南島に分布する。南島の西部をほぼ島の延長方向に並んで走る中央構造線により，南島の変成岩を東部と西部に2大別することができる。東部の変成岩はWakatipu 変成帯とよび比較的高い固相圧下で生じた変成岩により特徴づけられる。他方，西部の変成岩はおもに Tasman 変成帯とよぶ比較的低固相圧下で生じ，花崗岩の形成を伴う変成岩からなり，一部にこれよりも古い時代の変成岩も含んでいる。

Wakatipu 変成帯では変成岩の原岩は石炭紀以降ジュラ紀にいたる長い地質時代の間に堆積したニュージーランド地向斜の岩石である。この変成岩類は変成分帯の上で地域別に，3つの累進広域変成作用の傾向が認められる。すなわち，(1) 東 Otago と Southland において，沸石相→ブドウ石ーパンペリ石変グレイワッケ相→パンペリ石ーアクチノ閃石片岩相→緑色片岩相(Fig. 4 のなかのOー曲線)，(2) 西 Otago と東 Nelson において，ブドウ石ーパンペリ石変グレイワッケ相→藍閃石片岩相 (Fig. 4 のなかのBー曲線)，および(3) Alpine 断層に沿って南北に延びる細長い地域において，ブドウ石ーパンペリ石変グレイワッケ相→緑色片岩相→緑レン石角閃岩相→角閃岩相 (Fig. 4 のなかのHー曲線)。以上3つの広域変成作用は変成相系列の高圧中間群に近い性質をもっている。

他方，Tasman 変成帯は最高部が珪線石ーカリウム長石アイソグラッドで代表される低圧中間群の変成岩からなる。

これら2つの変成帯は両者ともにほぼ同時代すなわち白亜紀に形成され，1つのペアをなす。しかしWakatipu 変成帯のなかの(3)の累進広域変成作用を示す変成岩は，放射性アイソトープ年代測定の資料によれば，きわめて若い地質時代に生じたことになる。この若い年代は層序学的資料と矛盾しない。放射性娘元素の逸散とか拡散の現象をあえて推定しなくても，現在もなお活動中の活断層や，活断層近くにとくに分布する温泉の存在で示唆されるような高地熱流と関係づけて判断すれば若い年代はより合理的に解釈できる。いいかえると，きわめて若い地質時代に広域変成岩を形成する条件があって，まもなく急激な上昇により変成作用が終了し，つづいて地表に露出したと考えることが可能である。したがって Wakatipu 変成帯のなかには，白亜紀以降にも変成作用がひきつづいて進行し，急激な上昇にともなってその変成作用を終了した地域が認められる。

Wakatipu 変成帯を構成するニュージーランド地向斜の岩石は白亜紀の褶曲運動に先き立ち，その中心部が北東方へ移動をはじめ，新第三紀に小規模の海進があるものの，現在の Hikurangi 海溝に向かって移動する傾向にあった。Hikurangi 海溝はいまではごく狭い溝がその中央に存在するものの，その底面はほぼ水平に近く厚い堆積物によりおおわれている。北島の東方沖においてこの現象はいちじるしく，大きな正のブーゲー異常を示す。これに対して，北島の中央から東部にかけて多くの活断層があ

り，Hikurangi 海溝にほぼ平行する。また北島中央部の負のブーゲー異常および現世の火山活動の分布と Sub-Crustal Rift(深発地震帯)の形態との間には強い相関関係がある。この Rift 内のマントル物質が海洋地域のそれに較べ1％軽く，また Rift の上の地表において多量の流紋岩を生じていることから，Rift 内に花崗岩マグマが発生し，一部は流紋岩として地表に噴出し，また一部は地下深所に貫入し花崗岩になることが期待される。したがって，北島の中央部から東方沖合にかけて現在進行中のペア変成帯の存在が予想される。

日本においては，西南日本の変成岩の並列配置が目立っている。これらのなかで，領家変成帯と三波川変成帯との関係がペア変成帯を考察するうえにおいてもっとも重要である。もともと，三郡・領家・三波川の各変成帯の原岩を堆積した古生代の地向斜はひとつづきであった。これは，粘土質岩石の化学組成における南北方向の連続変化によって裏付けることもできる。

古生代地向斜の堆積物は，三畳紀始め頃には埋没変成作用を受けており，地向斜の南方移動にともない三郡変成帯が上昇した。白堊紀に入り，現在の中央構造線付近に，ニュージーランド北島にみられるような Sub-Crustal Rift が生じ，花崗岩マグマができた。このマグマの上昇と貫入により領家変成帯が生じ，一部は地表に噴出し濃飛流紋岩のように多量の火山岩を形成した。これに対して，三波川変成帯の北部は downward buckling により高固相圧下で現在みられるような高圧中間群またはヒスイ輝石—藍閃石タイプの変成岩になった。異なる運動形態をなす両者の間には中央構造線が生じた。

三波川変成作用は三波川変成帯のみならずさらに南側の秩父帯や四万十帯にも及んでおり，その変成作用の性質は埋没変成作用に近くなる。

領家変成作用は花崗岩マグマが地殻浅所に侵入したために生じた現象であり，花崗岩マグマの侵入以前には，領家変成帯の一部において，かって三郡変成作用に似た埋没変成作用および褶曲運動の影響を受けたところがあった。したがって，領家変成岩のなかの少なくとも一部は2つの異なるタイプすなわち比較的高圧の変成作用および低圧・高温型の変成作用を受けたと思われる。

ニュージーランド南島の変成帯と日本の領家および三波川両変成帯の生長・発展過程を，地向斜の発達・移動の観点からまとめると Fig. 20 に示した模式図にあらわすことができる。

ニュージーランドにおいては，ニュージーランド地向斜の堆積作用終了にひきつづいて，白堊紀にペア変成帯を生じた。しかし，花崗岩マグマの地表への噴出すなわち火山砕屑岩などの形成は激しくなかったか，すでに削剝されてしまったか，あるいは南島西方の海中に没したため現在みることができないのかもしれない。高圧型の変成作用は白堊紀以降も Alpine 断層に近い地域にひきつづいて進行し，その活動はニュージーランド地向斜から Hikurangi 海溝へ向かう方向に移行していった。現在活動の中心は北島の東部にあり，広域変成作用が行なわれている。ニュージーランドにおける地殻変動の中心はこのようにニュージーランド地向斜の軸部にほぼ平行の北東方向への移動により特徴づけられる。

これに対して，領家および三波川両変成帯，秩父帯および四万十帯以南における変動は古生代地向斜の延長方向にほぼ直角方向の太平洋側への移動により特徴づけられる。

ニュージーランドの Tasman および Wakatipu 両変成帯と日本の領家および三波川両変成帯の比較は簡単ではないが，あえて要約すると，両者の間には地向斜期から造山期への発達史にかなりの相違がみられる。その原因は地向斜の移動様式のちがいに求められよう。そして地向斜期終了から造山期にいたる時間の長さは，1つの変成帯のなかでも場所により異なり，全体としてかなり長い地質時代，たとえば 120 m.y. くらいのオーダー，にわたり継続するものと思われる。

しかし両者ともに，白堊紀においてそれぞれペア変成帯を形成したことは，地向斜から造山への発展様式を超えた別の原因を考えなくてはならない。

本文ではペア変成帯形成過程を解明するためのモデルとして，Sub-Crustal Rift および海溝の出現とその特質を強調した。

地質調査所報告は１報文について報告１冊を原則とし，その分類の便宜のために，次のようにアルファベットによる略号をつける。

A．地質およびその基礎科学に関するもの
- a．地　質
- b．岩石・鉱物
- c．古生物
- d．火山・温泉
- e．地球物理
- f．地球化学

B．応用地質に関するもの
- a．鉱　床
- b．石　炭
- c．石油・天然ガス
- d．地下水
- e．農林地質・土木地質
- f．物理探鉱・化学探鉱および試錐

C．そ の 他

D．事業報告

As a general rule, each issue of the Report, Geological Survey of Japan will have one number, and for convenience's sake, the following classification according to the field of interest will be indicated on each Report.

A. Geological & allied sciences
- a. Geology
- b. Petrology and Mineralogy
- c. Paleontology
- d. Volcanology and Hot spring
- e. Geophysics
- f. Geochemistry

B. Applied geology
- a. Ore deposits
- b. Coal
- c. Petroleum and Natural gas
- d. Underground water
- e. Agricultural geology and Engineering geology
- f. Physical prospecting, Chemical prospecting & Boring

C. Miscellaneous

D. Annual Report of Progress

地質調査所報告

第 224 号

MIYAMURA, M.: Stratigraphy and geological structure of the Permian formations of Mt. Ibuki and its vicinity, central Japan, 1967

第 225 号

SUMI, K.: Hydrothermal rock alteration of the Matsukawa geothermal area, Northeast Japan, 1968

第 226 号

HIRAYAMA, K.: Geological study on the Anguran mine, northwestern part of Iran, 1968

第 227 号

SHIBATA, K.: K–Ar age determinations on granitic and metamorphic rocks in Japan, 1968

第 228 号

鈴木尉元：日本列島とその周辺地域の震源分布についての試論, 1968

REPORT, GEOLOGICAL SURVEY OF JAPAN

No. 224

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SHIBATA, K.: K–Ar age determinations on granitic and metamorphic rocks in Japan, 1968 (in English)

No. 228

SUZUKI, Y.: Seismicity and tectogenesis in the Japanese Islands and their neighbourhood, 1968 (in Japanese with English abstract)

H. HATTORI

Late Mesozoic to Recent Tectogenesis and Its Bearing on the Metamorphism in New Zealand and in Japan

Hitoshi HATTORI

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The geologic developments since Late Mesozoic in New Zealand and Japan are reviewed on the basis of recent advances in metamorphic zoning, radiometric dating, and geophysical interpretation. In New Zealand, the Wakatipu and Tasman Metamorphic Belts constitute a pair in Cretaceous, separated by the Median Tectonic Line. Very young mineral ages obtained from rocks of the Wakatipu Metamorphic Belt may well be explained by a close relation with the distribution of hot springs. A hypothesis of a present-day paired metamorphism in northeast New Zealand is proposed to account for the origin of paired metamorphism. Referring to this hypothesis the marked contrast of the Ryoke and Sambagawa Metamorphic Belts is explained. A slight difference between the geologic developments in both New Zealand and Japan is also discussed.

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