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METAMORPHISM AND RELATED MAGMATISM IN PLATE TECTONICS

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ABSTRACT. The rapid descent of an oceanic plate in a trench zone would create an unusually low geothermal gradient with resultant formation of a high-pressure regional metamorphic complex (containing glaucophane). The descent of the plate would induce upwelling (diapirism) of mantle peridotite and rise of magmas and aqueous fluids within the upper mantle and crust above the descending slab. These processes would result in a high geothermal gradient and low-pressure regional metamorphism in the crust and the formation of a volcanic chain on the surface. The low-pressure metamorphic complex is paired with the above-mentioned high-pressure complex, which is usually on its oceanic side.

Island arcs characterized by rapid plate convergence have very deep earthquakes, a very deep trench, and typical tholeiitic volcanics. Calc-alkali volcanics occur in mature arcs but not in immature arcs of this group. Island arcs characterized by slow convergence usually have only shallow earthquakes, a shallower trench, and well-developed calc-alkali and/or alkali volcanics. The tholeiitic, calc-alkali, and alkali rocks, when they occur, are distributed in this order from the oceanic to the continental side of an arc.

Probably, the motion and descent of plates have become increasingly more rapid in younger geologic time, in particular in the Pacific region, resulting in the abundant formation of Mesozoic and Cenozoic glaucophane schists and paired metamorphic belts. When the rate of descent is slow, medium-pressure instead of hig-pressure metamorphism would take place.

Except for a thin surface layer, the oceanic crust has probably been subjected to ocean-floor metamorphism beneath mid-oceanic ridges with resultant demagnetization and increase of H_2O content. Flow of aqueous fluids during metamorphism would cause intense chemical migration and a variation of heat flow over the ridges.

INTRODUCTION

Metamorphism in plate junctures.—Metamorphism takes place along all the boundaries of lithospheric plates. The convergent junctures of lithospheric plates are zones of orogeny. Large-scale metamorphism which takes place in orogenic belts has been called *regional metamorphism.* Regional metamorphic rocks usually occur in belts, called *metamorphic belts,* within orogenic belts. Most of our knowledge of the response of minerals to variable temperature and pressure has come from detailed petrologic investigations of regional metamorphic rocks and belts. The study of regional metamorphism gives important information on the tectonic processes of orogeny. Most of this paper is concerned with regional metamorphism.

In the last several years, it has been clarified that large-scale metamorphism is taking place beneath mid-oceanic ridges along the divergent junctures of lithospheric plates. This class of metamorphism, called *ocean-floor metamorphism* by Miyashiro, Shido, and Ewing (1971, p. 602) and Miyashiro (1972), gives information on the conditions and processes in the depths of mid-oceanic ridges. This problem is discussed briefly in the last chapter of this paper.

Transform faults between lithospheric plates are accompanied by cataclastic metamorphic rocks (crushed rocks). The San Andreas fault zone of California and the Alpine fault of New Zealand, for example, have a zone, up to several kilometers wide, of cataclastic rocks (Waters and Campbell, 1935; Reed, 1964). Dredges along transform faults across the Mid-Atlantic Ridge also give cataclastic rocks. Our understanding of this class of metamorphism, however, is still in its infancy. Hence, it is not discussed in this paper.

Metamorphism and tectonics.—Though the foundation of metamorphic petrology was established by Eskola, Harker, and other great masters in the 1930's, the extents of areas petrographically mapped at that time were too narrow to allow any successful correlation between petrologic studies and large-scale tectonic features of the orogenic belts. After World War II, an important pioneering work in such correlation was made by W. Q. Kennedy (1948), who claimed that the thermal axis of the regional metamorphic terrane of the Scottish Highlands is approximately parallel to the axis of the Caledonian orogenic belt, suggesting the metamorphism to be of Caledonian age.

Meanwhile, it was found that paired metamorphic belts are well developed in Japan and many other parts of the circum-Pacific regions (Miyashiro, 1961a). A pair is composed of two metamorphic belts of contrasted character which run parallel: one is of the high-pressure type, and the other is of the low-pressure type, though the two belts may contain some areas of the medium-pressure type (fig. 1). The high-pressure belt is usually on the oceanic side of the low-pressure belt. The paired metamorphic belts were ascribed to the underthrusting of an ocean floor along a Benioff zone beneath island arcs and continental margins (Miyashiro, 1961a, b, 1965, 1967; Matsuda, 1964; Takeuchi and Uyeda, 1965). The high-pressure belt was regarded as corresponding to the zone of a trench, which shows very low heat flow values, and the low-pressure belt to a zone of island-arc volcanism with high heat flow (fig. 2).

These ideas have been widely accepted in plate-tectonic interpretations of orogeny. Plate tectonics (Morgan, 1968; Le Pichon, 1968; Isacks, Oliver, and Sykes, 1968) has been applied in particular to the geologic interpretation of metamorphic belts in California by many authors (Yeats, 1968; Hamilton, 1969; Ernst, 1970, 1971; Bailey, Blake, and Jones, 1970; Coleman, 1971). There, the Franciscan terrane has been regarded as thick deposits in a late Mesozoic trench and on the adjacent deep ocean floor along the then west coast of North America. Its high-pressure metamorphism was regarded as a result of underthrusting of the Pacific plate beneath the North American plate.

TECTONIC SIGNIFICANCE OF *P–T* RELATIONS

The progress of synthetic experiment in the past decade has given us a *P–T* scale of metamorphism (or metamorphic facies) with considerable reliability as reviewed, for example, by Winkler (1967) and Miyashiro (1972).

Regional metamorphism may be classified into three categories, here called *baric types*, representing different geothermal gradients: low-pressure type characterized by andalusite, medium-pressure type characterized

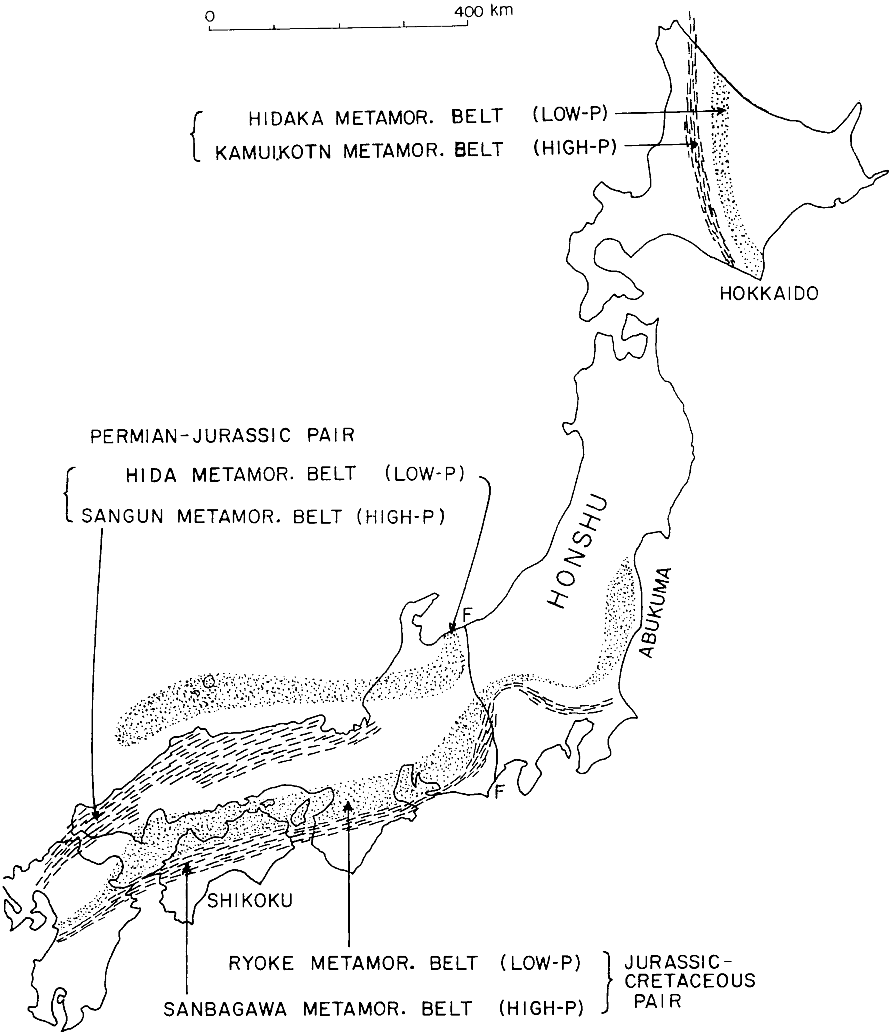

Fig. 1. Three pairs of metamorphic belts in Japan. F–F: Itoigawa-Shizuoka Line (boundary between northeast and southwest Japan).

by kyanite (without glaucophane), and high-pressure type characterized by glaucophane and jadeite (Miyashiro, 1961a, in preparation). As shown in figure 3, geothermal curves for low-pressure metamorphism lie on the lower pressure side of the triple point of the Al_2SiO_5 system, whereas those for medium-pressure metamorphism are steeper and lie on the higher pressure side of the point. Curves for high-pressure metamorphism are still steeper and in the vicinity of the equilibrium curve for the reaction jadeite + quartz = albite. Rough estimates of the average geothermal gradients are as follows: greater than 25°C/km for low-pres-

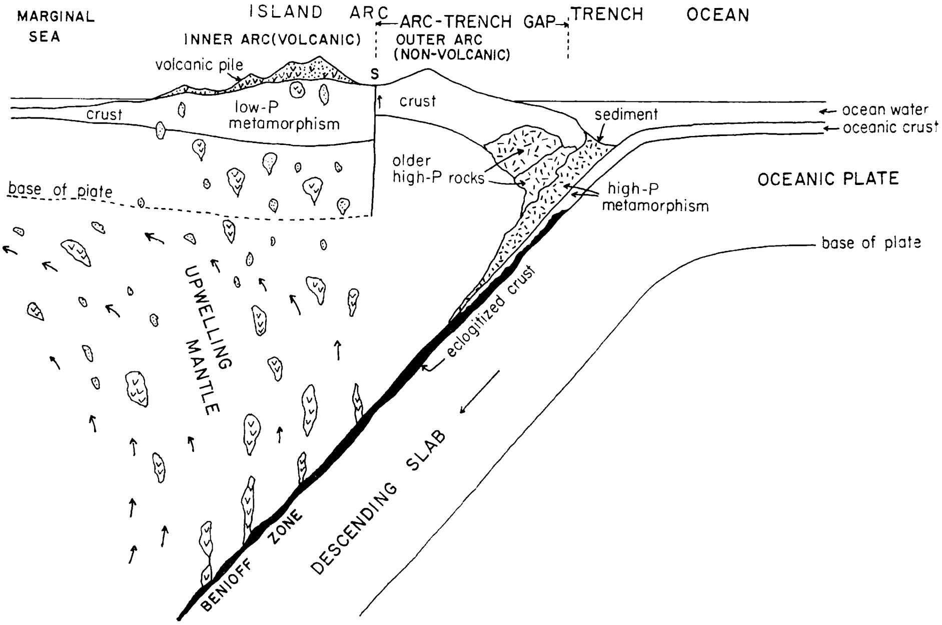

Fig. 2. Schematic cross section of an island arc with special reference to the Northeast Japan Arc. Magmas generated along the Benioff zone are distinguished from magmas produced in the upwelling mantle by different symbols. S: fault boundary of the uplifted block.

sure metamorphism, about 20°C/km for medium-pressure metamorphism, about 10°C/km for high-pressure metamorphism. This three-fold classification may well be applied to other classes of metamorphism also.

The average geothermal gradients in some low-pressure metamorphic terranes are greater than 50°C/km. Such high values could be produced not through simple thermal conduction but through the cooperation of conduction with the migration of magmas and aqueous fluids. Indeed, abundant granitic masses occur in the low-pressure regional metamorphic terranes.

Average geothermal gradients as low as 10°C/km in high-pressure metamorphism cannot represent a stationary state. They are produced probably by rapid tectonic descent. If descent halts, the gradient should increase in a geologically short period. This is consistent with the above-mentioned view that high-pressure regional metamorphism takes place as a result of underthrusting of an oceanic plate along a Benioff zone.

The geothermal curve for high-pressure metamorphism shown in figure 3 is convex upward. In the Kanto Mountains of Japan, the occurrence of jadeite is confined to a medium-temperature part of the Sanbagawa high-pressure metamorphic terrane and only albite occurs in the lower and higher temperature parts (Seki, 1960). This probably reflects the upward convexity of the geothermal curve. This abnormal shape is consistent with the hypothesis of rapid tectonic descent. That glau-

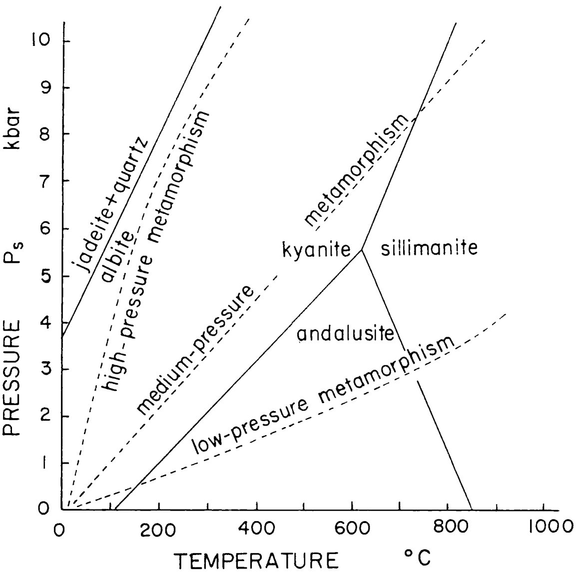

Fig. 3. Geothermal curves for low-, medium-, and high-pressure metamorphism in relation to the stability relations of the Al_2SiO_5 minerals (Richardson, Gilbert, and Bell, 1969) and jadeite + quartz (Birch and LeComte, 1960; Newton and Kennedy, 1968).

cophane is confined to a medium-temperature part of the metamorphic facies series in other areas (for example, Hashimoto, 1968) may have the same meaning. The occurrence of jadeite only in better recrystallized zones of many Franciscan areas (Ernst, 1965; Ernst and others, 1970) could correspond to the lower temperature half of the above-mentioned series.

Physical models to account for contrasted heat-flow belts and paired metamorphic belts in convergent junctures have been proposed by Hasebe, Fujii, and Uyeda (1970), Toksöz, Minear, and Julian (1971), and Oxburgh and Turcotte (1971).

CONTRASTING MAGMATISM BETWEEN LOW- AND HIGH-PRESSURE METAMORPHIC BELTS

In a classic view, one cycle of orogeny includes a long series of events beginning with geosynclinal sedimentation, followed by phases of deformation, regional metamorphism, and plutonic intrusion accompanied or followed by topographical upheaval. It was believed that three distinct phases of magmatism exist in a cycle of orogeny: namely, basaltic magmatism in the geosynclinal stage, granitic intrusion in the orogenic stage, and post-orogenic magmatism (Knopf, 1948; de Sitter, 1956).

However, this view has ignored the close connection of magmatism with the associated metamorphism and the spatial relation of different phases of magmatism. The characteristics of magmatism vary with the baric type of associated regional metamorphism (Miyashiro, 1961a; Zwart, 1967, 1969). The products of the associated magmatism are mainly of acidic and intermediate composition (that is, granitic, rhyolitic, dacitic, and andesitic) in low-pressure metamorphic terranes but of mafic and ultramafic compositions in high-pressure metamorphic terranes. Abundant mafic and ultramafic rocks in such a geologic setting have been collectively called *ophiolites.* Medium-pressure terranes tend to be intermediate in character in this respect also. The contrast in magmatism is very clear between the two metamorphic belts of a pair in the circum-Pacific region.

In paired metamorphic belts, therefore, the so-called eugeosynclinal zone may be divided into two contrasted subzones: one is the belt of low-pressure regional metamorphism, granitic plutonism, and andesitic volcanism, which is usually on the continental side, and the other is the belt of high-pressure regional metamorphism and mafic and ultramafic rocks, which is usually on the oceanic side. The former would correspond to the belt of volcanoes in island arcs and continental margins, whereas the latter would correspond to the trench zone.

The occurrence of ophiolites is not always confined to metamorphosed areas. The well-documented ophiolites of the Troodos massif, Cyprus (Gass, 1967; Moores and Vine, 1971), and of the Vourinos complex, Greece (Moores, 1969), have not been metamorphosed. However, the extensive development of ophiolites, even though some of them may not have been metamorphosed, is characteristic of such orogenic belts as contain a high-pressure metamorphic belt. Thus, the problem of ophiolites is connected with that of high-pressure metamorphism.

A large number of papers have been published on the origin of ophiolites in the last several years. Most papers appear to support one of the following three hypotheses:

1. Ophiolites represent intrusions and extrusions in the geosynclinal stage, possibly accompanied by crystallization differentiation in situ (for example, Aubouin, 1965).
2. Ophiolites form by diapiric emplacement of partially fused upper mantle materials in the geosynclinal stage (for example, Maxwell, 1969, 1970).
3. Ophiolites represent fragments of oceanic crust and upper mantle pushed into a preexisting geosynclinal sediment pile in the main disturbance stage (for example, Dietz, 1963; Coleman, 1971; Moores and Vine, 1971). This hypothesis is fashionable.

This problem is too complicated and obscure to be discussed in the limited space of this paper.

LOW-PRESSURE METAMORPHIC BELTS AND VOLCANIC ARCS

There exist regions representing a series of gradational variation in character from typical low-pressure metamorphic terranes to chains of volcanoes in island arcs and active continental margins, as exemplified in table 1. A brief comment will be given below of the regions shown in a presumed order from a deeper to a shallower original depth.

TABLE 1

Hypothetical series of increasing depth

Presumed depths	Examples	Andesitic-rhyolitic volcanics	Granites	Regional metamorphism
Surface	Quaternary volcanic arcs	Usually abundant	Absent	Absent
↓	Late Tertiary terrane of northeast Japan	Abundant	Scarce	Zeolite and prehnite-pumpellyite facies
↓	Sierra Nevada-Klamath zone of North America	Abundant	Abundant	Mainly greenschist facies
Relatively deep	Ryoke belt of Japan	Present	Abundant	Mainly amphibolite facies

The Ryoke low-pressure metamorphic belt of Japan is accompanied not only by abundant granitic masses but also by a great amount of rhyolitic volcanic rocks, which occur mainly as welded tuffs broadly contemporaneous with the granitic intrusions (for example, Yamada, Kawada, and Morohashi, 1971). Dickinson (1962) showed that the volcanic rocks of the Sierra Nevada-Klamath granitic belt are mainly of andesitic composition.

The Japan Sea side of the Northeast Japan Arc (that is, northeastern Honshu) is a Miocene and Pliocene orogenic region, which has abundant volcanic rocks of basaltic, andesitic, dacitic, and rhyolitic compositions together with occasional small granitic masses (see fig. 4). The thick sediment accumulations are partly unmetamorphosed and partly metamorphosed in the zeolite and prehnite-pumpellyite facies. This region may be regarded as representing an original section shallower than the Ryoke and Sierra Nevada-Klamath zones. The volcanic rocks become more alkalic toward the west, like the present-day volcanic chain of this region. Indeed, the Miocene and Pliocene volcanism of this region is a direct predecessor of the present-day volcanism.

As in many present-day island arcs, the proportion of andesitic, dacitic, and rhyolitic rocks is high in the volcanic rocks of these regions. Thus, a low-pressure metamorphic complex probably lies beneath the belt of andesitic volcanism (Dickinson, 1970; Miyashiro, 1972). However, granitic plutonism could be comagmatic only with a part (that is, the calc-alkali series) of the volcanic rocks in island arcs, as discussed in the next section.

IGNEOUS PETROLOGY OF ISLAND ARCS

Igneous rock series.—In the first half of the 20th century it was realized that the chains of volcanoes in island arcs and active continental margins contain large amounts of basalt, andesite, dacite, and rhyolite, in which the SiO_2 and alkali contents tend to increase and the MgO and $Fe_2O_3 + FeO$ contents tend to decrease in the above-named order. Bowen

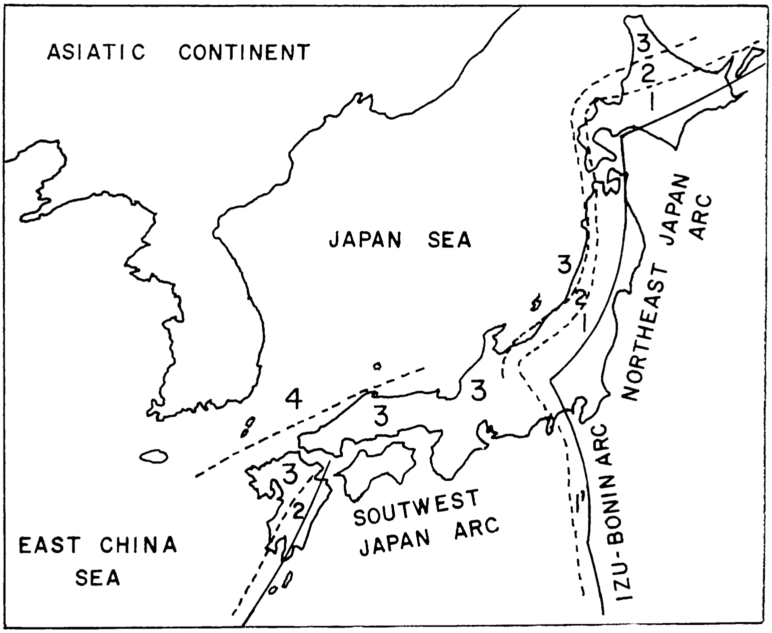

Fig. 4. Petrographic provinces for the Quaternary volcanic rocks of Japan. The full lines represent the oceanic-side limits of volcanic belts (called volcanic fronts): 1 = tholeiitic and calc-alkali rocks, 2 = calc-alkali rocks, 3 = calc-alkali and sodic alkali rocks, 4 = sodic alkali rocks. The part of zone 1 that runs along the Izu-Bonin Arc (denoted as 1′) has abundant tholeiites but few calc-alkali rocks.

(1928) regarded this order as representing progressive fractional crystallization controlled by two main reaction series, one for colorless and the other for colored minerals. The colored minerals were considered to crystallize in the order: olivine → orthopyroxene → clinopyroxene → amphibole → biotite. Such volcanics were usually classed as subalkali or *calc-alkali rocks.*

Fenner (1929) and more spectacularly Wager and Deer (1939) demonstrated the existence of the tholeiitic series of igneous rocks which is not alkalic but is distinct from the above subalkali or calc-alkali rocks. The tholeiitic series shows little or no increase in SiO_2 content and instead a considerable increase in Fe_2O_3 + FeO content in the early (or main) part of its course of crystallization. This series has olivine and pyroxenes as the main colored minerals but little or no amphibole and biotite. The tholeiitic series is usually composed of abundant mafic, less abundant intermediate and few acidic rocks, whereas the calc-alkali series usually includes abundant intermediate and acidic rocks.

Thus, Nockolds and Allen (1953, 1954, 1956) have discussed the compositional variation of igneous rocks with a three-fold classification into the tholeiitic, calc-alkali, and alkali series. Kuno (1959), Taylor and White (1965), Jakeš and White (1969, 1972), and Jakeš and Gill (1970) have accepted this classification with certain modifications in their studies of island-arc volcanism in Japan and southwest Pacific regions. Alkali basalts in some areas have K_2O/Na_2O ratios much lower than unity, whereas those in others have K_2O/Na_2O ratios near unity. Joplin (1964) and Jakeš and White (1969, 1972) have accepted the name *shoshonite* for the latter group of alkali basalts.

Text-books of petrography may define the name *andesite* mainly in terms of SiO_2 content, color index, or the ratios of plagioclase–alkali feldspar–silica minerals. In such definitions, the three series of volcanic rocks include andesites as members. However, the "andesites" so defined show different chemical and mineralogical characteristics in the three different series. This situation is undesirable as the rock series classification is of great genetic implication. Thus, Macdonald (1960) has proposed to use the name *hawaiite* and *mugearite* for the so-called "andesites" of the alkali series. Carmichael (1964, p. 442) coined the name *icelandite* for "andesites" of Iceland, and Taylor and White (1965) have accepted this name for the "andesites" of the tholeiitic series. In this way, the use of the name of andesite can be limited to the "andesites" of the calc-alkali series.

Thus, we have the following three series of volcanic rocks in island arcs and active continental margins:

1. Tholeiitic series, including tholeiitic basalt, icelandite, and some dacite. The SiO_2 contents are mostly in the range 48 to 63 percent by weight.

2. Calc-alkali series, including abundant andesite and dacite, and some rhyolite. The SiO_2 contents are mostly in the range 52 to 70 percent.

Series (1) and (2) are "calc-alkalic" in the broader meaning that they both have Peacock's (1931) alkali-lime indices as high as 56 to 67. Rocks of series (1) contain augite and pigeonite (sometimes accompanied by orthopyroxene) in the groundmass and show a considerable extent of iron-enrichment in the middle stage of fractional crystallization, whereas those of series (2) contain orthopyroxene (and no pigeonite) in the groundmass and show little iron-enrichment in fractional crystallization. Table 2 shows a comparison of chemical composition between icelandites of series (1) and andesites of series (2) with a similar SiO_2 content from the Northeast Japan Arc.

3. Alkali series, which may well be subdivided into: (A) the sodic alkali group, including alkali olivine basalt, hawaiite, mugearite, trachyte, and alkali rhyolite; and (B) the shoshonite group, including shoshonite, latite, and leucite-bearing rocks.

Compositional variation across volcanic arcs.—In island arcs that have a Benioff zone inclined toward the continent as in northeast Japan, the Kurile Islands, and Indonesia, the volcanic rocks tend to be increasingly more alkalic toward the continent. In other words, the K_2O and $Na_2O + K_2O$ contents, the K/Na ratio, and the degree of undersaturation with SiO_2 of volcanic rocks tend to increase toward the continent, if we compare rocks with the same SiO_2 content. Such regular relations

TABLE 2

Average compositions of volcanic rocks in the range 55.0 to 57.5 percent SiO_2 from the Northeast Japan Arc (Yagi, Kawano, and Aoki, 1963)

Zone	Oceanic-side zone (Nasu zone)		Continental-side zone (Tyokai zone)
Series	Tholeiitic	Calc-alkali	Calc-alkali
Rock name	Icelandite	Andesite	Andesite
SiO_2	55.53	56.53	56.05
TiO_2	0.92	0.96	0.93
Al_2O_3	16.61	16.88	18.09
Fe_2O_3	3.62	2.76	3.70
FeO	6.60	5.61	4.49
MnO	0.13	0.12	0.16
MgO	3.89	4.37	3.81
CaO	8.40	7.98	7.18
Na_2O	2.55	2.46	3.14
K_2O	0.40	0.96	1.30
H_2O^-	0.58	0.50	0.31
H_2O^+	0.64	0.74	0.61
P_2O_5	0.13	0.13	0.23
FeO*	9.86	8.09	7.82
No. of analyses	8	16	9
Peacock's alkali-lime index of the series	65	66	64

Note: The average compositions are recalculated to a total of 100.00%.
FeO* means total iron as FeO.

hold in many island arcs, not only when all the volcanic rocks are considered, as in Sugimura (1960, 1968) and Dickinson (1968), but also when the calc-alkali series is excluded from consideration on the assumption that it has been formed by some secondary processes including contamination, as in Kuno (1959, 1960).

In mature, active island arcs such as northeast Japan and Kamchatka, petrographic provinces of the tholeiitic series, calc-alkali series, and alkali series are present successively in this order from the oceanic to the continental side of the volcanic belt, though there may be marked overlapping of provinces, as shown in figure 4. Well-organized summaries of detailed investigations of the volcanic rocks of the Northeast Japan Arc were given by Kawano, Yagi, and Aoki (1961) and Yagi, Kawano, and Aoki (1963). In the oceanic-side zone (called the Nasu zone) within the volcanic belt, tholeiitic rocks are accompanied by calc-alkali rocks, whose chemical compositions are similar to those of the tholeiitic series with the same SiO_2 content except that iron-enrichment in the middle stage of evolution takes place only in the tholeiitic series (table 2). The calc-alkali rocks are slightly higher in K_2O than the associated tholeiitic rocks. The continental-side zone (called the Tyokai or Chokai zone) within the volcanic belt is characterized by the absence of typical tholeiite and the abundance of rocks of the calc-alkali series (especially andesites), which have a higher K_2O content and a higher Fe_2O_3/FeO ratio than the tholeiites and associated calc-alkali rocks of the oceanic-side zone. The rocks of the tholeiitic series have no hornblende and biotite, whereas the associated calc-alkali rocks of the oceanic-side zone rarely contain hornblende and biotite, and the calc-alkali rocks of the continental-side zone contain hornblende and biotite more commonly. Basalts of the sodic alkali group occur in Itinomegata near the continental-side limit of the volcanic belt.

The Miocene and Pliocene petrographic provinces in northeast Japan (Miyagi, 1964; Chihara, 1967; Shibata, 1968) are similar to the Quaternary provinces shown in figure 4. This suggests that the position of plate descent has not been greatly shifted since the Miocene.

Nature of the calc-alkali series.—The status and character of basalt in the calc-alkali series are not clear. Many volcanoes made up of rocks of the calc-alkali series have no basalt. This series may begin with andesite. Nockolds and Allen (1953) found in variation diagrams that acidic and intermediate rocks of the calc-alkali series fall on a smooth curve for each area, whereas more mafic rocks show more or less random scattering. They interpreted this as suggesting that the parental magmas were intermediate (that is, andesitic or dioritic) in composition (with SiO_2 = 52-56 percent), and that more mafic rocks of the series were formed by the accumulation of early crystals. Green and Ringwood (1966, 1968) demonstrated experimentally the possibility of the formation of primary andesitic magma.

Kuno (1960) proposed the name of high-alumina basalt for rocks generally intermediate in chemical composition and geographic distribution between tholeiite and alkali-olivine basalt. This means that high-alumina basalt occurs roughly in the same zone as rocks of the calc-alkali series. Conceivably, high-alumina basalt may be the parental basalt of the calc-alkali series (for example Jakeš and White, 1972; Aoki and Oji, 1966; Kuno, 1968). Osborn (1962) has emphasized the possible importance of oxygen fugacity in the derivation of the tholeiitic and the calc-alkali series from more or less similar basaltic magmas. (He used the name of "gabbroic layered intrusions" for rocks of the tholeiitic series.)

Volcanic rocks of the calc-alkali series are confined to orogenic regions (table 3). The occurrence of calc-alkali rocks or of a great amount of andesitic and rhyolitic rocks may be regarded as suggesting island arcs and active continental margins. It is to be noted, however, that such rocks do not occur in immature arcs as shown in table 3 and discussed on a later page.

The volcanic rocks of the calc-alkali series resemble granitic rocks in chemical composition, and they both occur in orogenic belts. They could have been derived from the same andesitic (dioritic) magma (for example, Nockolds and Allen, 1953; Dickinson, 1970). It is of interest whether granitic rocks show a regular compositional variation across an island arc and a continental margin like the volcanic rocks. The

TABLE 3

Younger volcanic rocks and tectonic environments

	Stable continents	Orogenic belts			Oceanic islands	Mid-oceanic ridges
		immature, very active island arcs	mature, very active island arcs	less active island arcs (group II of Table 4)		
Tholeiitic series	++	++	+	(+)	+	++
Calc-alkali series			++	++		
Alkali series	++		+	+	++	+

++, abundant; +, subordinate.

existence of such a variation in granitic rocks has been demonstrated by Moore (1959) and Moore, Grantz, and Blake (1961) on the west coast of North America and by Taneda (1965) in Japan.

Factors controlling the diversity of magmas.—Magmas that cause volcanism in island arcs and active continental margins should be created in some genetic relationship to the descending lithospheric slab. Since in particular volcanic rocks of the calc-alkali series are confined to volcanic arcs (table 3), they could be most directly related to the descending slab. For example, the primary andesitic magma to result in this series could be created by partial melting of the oceanic crust which forms the uppermost layer of the descending slab, as shown in figure 2 (see Ringwood, 1969).

Basaltic magmas for the tholeiitic and alkali series could be produced by partial melting either in the descending slab or in the upper mantle overlying it. The oceanic crust with abyssal tholeiitic composition and the underlying presumably peridotitic layer of the descending lithospheric slab should undergo a series of phase changes with increasing depth, that is, with increasing pressure. The equilibrium relations between melt and solid residue should differ at different pressures. Recent experimental results suggest that the melt formed in peridotite under a greater pressure tends to be more undersaturated with silica (for example, Green and Ringwood, 1967; Kushiro, 1968). Even under the same P–T conditions, the composition of the magmas tends to be less alkalic as the proportion of the melt increases. The pressure and the proportion of melt could vary regularly with depth in the descending slab, resulting in a regular compositional variation in volcanic rocks across the volcanic arc.

Even if we may assume with Ringwood (1969) that basaltic magmas are generated by partial melting not in the descending slab but in the overlying upper mantle where convective upwelling or diapiric rise occurs (fig. 2), the upwelling and the generation and separation of basaltic magmas should be controlled largely by the descending slab, and hence the resulting magmas could vary regularly across the arc.

RATE OF PLATE MOTION AND THE EVOLUTION OF ISLAND ARCS

Though the available petrographic data for island arcs are not always adequate enough for the unequivocal determination of the rock series present, the existence of a clear correlation between the activity and the volcanic petrography of arcs can be easily observed. Table 4 summarizes the correlation between the rate of relative motion of the converging plates, the depth of mantle earthquakes, and the volcanic rock series in several island arcs. Since the depth of a trench is strongly influenced by the rate of burial by sediments, it may not be so essential as the above-mentioned factors. However, it shows some correlation with the other factors (compare Sugimura, 1968).

In table 4, group I of island arcs is characterized by a rate of relative motion (convergence) of plates as high as 8 to 9 cm/year. Here, the maximum depth of earthquakes is 600 to 700 km, that of the trench is 10 to 11 km, and volcanic rocks of the typical tholeiitic series are well developed. The calc-alkali and alkali series are developed only in arcs in the mature stage of development in this group. It is understood that figure 4 illustrates petrographic provinces in a mature stage.

In group II of island arcs, the rate of convergence of plates is slower, and the maximum depths of earthquakes and the trench are smaller than in group I. Here, typical tholeiite is absent, though some rocks present show an affinity to the tholeiitic series. Calc-alkali volcanic rocks are abundant. Alkali rocks, though usually present, are not abundant.

Group III is characterized by a very slow rate of plate convergence. Alkali rocks are well developed. A few atypical tholeiites and calc-alkali rocks occur in the southern part of South Island, New Zealand,

Table 4

Correlation between the activity and volcanic rock series in island arcs

Group	Arc and trench	Rate of plate convergence (cm/yr)	Maximum depth of earthquakes (km)	Maximum depth of the trench (km)	Volcanic rock series
I	Tonga	9	700	11	Th
	Izu-Bonin	9	600	11	Th + (C) + (A)
	Northeast Japan	9	600	11	Th + C + (A)
	Kurile-kamchatka	8	600	10	Th + C + A
II	Aleutian	6	300	8	(Th) + C + A
	Indonesia	5-6	600	7	(Th) + C + A
	Ryukyu	?	300	7	(Th) + C
	North Island (New Zealand)	Slow (3 ?)	300	4	C + A
	Hellenic (Aegean)	Slow (3 ?)	200	4	(Th) +C + A
III	Calabrian (Sicily)	Very slow (2 ?)	300	Buried	A
	Macquarie	Very slow	100	Shallow	(Th) + (C) + A

Note: The activity of arcs decreases in the order: group I ⟶ II ⟶ III. Th = tholeiitic series, C = calk-alkali series, A = alkali series. The rocks of the series shown in parentheses ( ) are not typical of the series and are very small in quantity. The rates of plate convergence are mainly after Le Pichon (1968).

where late Tertiary and Quaternary volcanism is probably due to the activity of the Macquarie Arc. The distribution of tholeiitic, calc-alkali, and alkali rocks there is irregular.

Since the K_2O and usually also the Na_2O content decrease across the arc toward the ocean (trench), the volcanic rocks in the oceanic-side zone within the volcanic belt usually have smaller K_2O and Na_2O contents than the volcanic rocks in the continental-side zone. Figure 5 shows a comparison of the Na_2O and K_2O contents of volcanic rocks in the oceanic-side zone within the volcanic belts of several island arcs. The very active arcs (group I in table 4) always show lower K_2O contents than less active arcs (groups II and III) and usually lower Na_2O contents.

In group I, the alkali basaltic rocks are sodic, whereas arcs of groups II and III appear to have both sodic and potassic (shoshonitic) types of alkali basaltic rocks. The Calabrian Arc has especially well-developed potassic basaltic rocks.

The activity of the Northeast Japan Arc began in the early Miocene, and magmatism of the tholeiitic, calc-alkali, and sodic-alkali series took place from the beginning (Ozawa, 1968; Miyagi, 1964). Jakeš and White (1969, 1972) claimed that the occurrence of shoshonite begins at a later stage in the development of island arcs.

VARIATION IN THE RATE OF PLATE MOTION AND THE RELATION BETWEEN PAIRED AND UNPAIRED METAMORPHIC BELTS

Secular variation in the baric types of regional metamorphism and the rate of plate motion.—Low-pressure metamorphic rocks occur in any geologic age, at least from the middle Precambrian (for example, the Svecofennides) to the Tertiary. On the other hand, most of the glaucophane-schist facies rocks of the world were formed in Mesozoic and Cenozoic time (de Roever, 1956, 1965; Miyashiro, 1961a; Zwart, 1967; Ernst, 1972). Some glaucophane-schist areas are Paleozoic, and the Anglesey glaucophane schists in Wales are latest Precambrian (Shackleton, 1969). However, the preferential occurrence of glaucophane-schist facies rocks in younger terranes is remarkable (table 5).

Generally speaking, if in younger geologic time the oceanic plate has become thicker, the inclination of the descending plate has become steeper, and the velocity of plate underthrusting has increased, then the subduction zone must have come to have a lower geothermal gradient, with resultant formation of glaucophane-schists and a high-pressure metamorphic belt (Ernst, 1972). The velocity of plate underthrusting in particular would have been the most important factor.

The present cycle of continental drift began in early Mesozoic time in coincidence with the beginning of the abundant formation of glaucophane schists and paired metamorphic belts. Therefore, we may consider that plate motion has become more intense since the early Mesozoic, and, as a result, the movement and underthrusting of oceanic plates have become more rapid, leading to the common formation of glaucophane schists and paired belts.

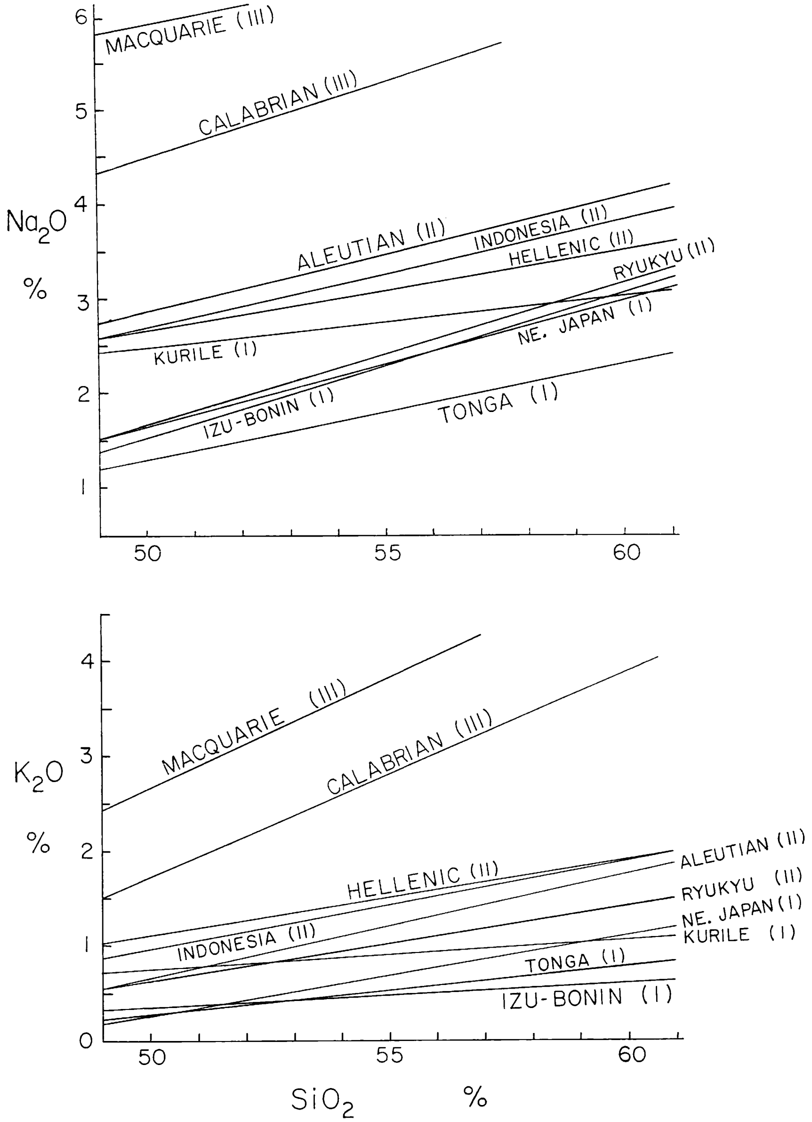

Fig. 5. Na_2O and K_2O versus SiO_2 for volcanic rocks of the oceanic-side (trench-side) zone within the volcanic belts of several island arcs. The Roman numerals in parentheses represent the group numbers in table 4. For the Hellenic Arc, the Quaternary lavas of Santorini have been ignored after Nicholls (1971).

TABLE 5
Baric types of regional metamorphism and geologic ages

Baric types	Precambrian	Paleozoic	Mesozoic-Cenozoic
Low-pressure	Svecofennides Karelides Canada (partly) Australia Northeast China	Hercynides Appalachians (partly) Eastern and South Australia Hida belt (Japan) Pichilemu series (Chile)	Ryoke-Abukuma belt (Japan) Hidaka belt (Japan)
Medium-pressure	Canada (partly)	Caledonides Appalachians (partly)	North American Cordillera (partly)
High-pressure	Anglesey (Wales)	Kiyama (Japan) Omi (Japan) Sangun belt (Japan) Curepto series (Chile) Northwest Kamchatka (USSR)	Alps Franciscan Group (California) Sanbagawa belt (Japan) Kamuikotan belt (Japan) New Caledonia Central Kamchatka (USSR)

In Paleozoic and Precambrian time, plate motion would not have been so rapid, and the mild descent of oceanic plates at that time could have produced usually only medium-pressure metamorphic rocks and, at most, atypical glaucophane schists. Conceivably, the pattern of currents in mantle convection has drastically changed in early Mesozoic time as suggested by Runcorn (1965), and this resulted in rapid plate motion, the onset of secular continental drift, and the formation of glaucophane schists and paired metamorphic belts.

Contrast in the rate of plate motion between the Pacific and Atlantic.—Though the pattern of spreading in the Pacific should have undergone a number of changes since early Mesozoic time, the rapidity of the plate motion has apparently continued to the present. The recent rate of spreading in the East Pacific Rise is as high as 2 to 6 cm/yr in contrast to the rate of 1 to 2 cm/yr in the Mid-Atlantic Ridge, and it has been demonstrated that the contrast has existed at least since late Mesozoic time (Heirtzler and others, 1968).

Presumably, the plate motion in the Pacific was fairly rapid in the Paleozoic so that atypical high-pressure metamorphic belts were formed in many parts of the circum-Pacific region, and it became more rapid in the Mesozoic so as to produce typical high-pressure belts. It may be conceived that arc-trench systems of group I in table 4 can produce typical high-pressure belts and paired belts.

It appears that the Atlantic Ocean was closed and opened repeatedly, and this caused the orogenies of the Appalachian, Caledonian, and even older belts (Wilson, 1966; Dietz and Holden, 1966; Dewey, 1969). We may consider that usually the velocity of plate descent in the Atlantic regions was not high enough to produce well-developed belts of glaucophane schists. Metamorphic belts of the medium-pressure type would have been formed instead.

However, the medium- and low-pressure Caledonian metamorphic belt of the Scottish Highlands may be regarded as being paired with the poorly developed glaucophane schist area of the Southern Uplands of Scotland. This pair was formed probably in early Ordovician time. Presumably the Benioff zone at that time was inclined to the north, but a new Benioff zone inclined to the south may have been formed in late Ordovician time so as to produce a volcanic arc to the south (Fitton and Hughes, 1970).

Nature of apparently unpaired younger metamorphic belts.—Most of the Phanerozoic orogenic belts in the Atlantic region and Europe are apparently unpaired. We may expect, however, that if a high-pressure metamorphic belt occurs, it could be accompanied by a belt of low-pressure metamorphism, since the descending slab of the former belt should tend to create the latter. A most remarkable example of a young, apparently unpaired high-pressure belt is in the Pennine zone of the Alps. It is of interest whether this belt fulfills the above expectation.

The Alpine Ranges continue eastward to the Carpathians. Andesitic and rhyolitic rocks of late Tertiary and Quaternary ages are abundant in Hungary, southern Slovakia, and Transylvania, which are on the south side of the Alpine-Carpathian Ranges (Pantó, 1968; Karolus, Forgáč, and Konečný, 1968). Tertiary granitic rocks also occur in the andesitic-rhyolitic belt, though at the western end of the belt the Bergell granite has been intruded into the Pennine zone. This belt of granite, andesite, and rhyolite shows unusually high heat flow values (Boldizsár, 1964) and may be a surface manifestation of a hidden low-pressure metamorphic complex which is paired with the high-pressure belt exposed in the Pennine zone of the Alps.

The Hercynian metamorphic belts in western Europe are mostly of the low-pressure type (Zwart, 1967, 1969). They might be regarded as a typical example of unpaired metamorphic belts. However, a part of the Hercynides may have paired belts. Hercynian glaucophane schists occur in the Ile de Groix to the south of Bretagne. It is possible that an extension of the Ile de Groix metamorphic complex forms a Hercynian high-pressure belt which is now covered mostly by the sea and is paired with a Hercynian low-pressure belt.

In this connection, it is noteworthy that in some pairs the high-pressure metamorphic belt is much narrower than the total area of the associated low-pressure metamorphic and granitic rocks, and hence it may readily be lost sight of by younger sediment covers, submergence beneath the sea, or later recrystallization at medium- or low-pressure conditions. A good example is the Jurassic-Cretaceous pair of southwest Japan. The Sanbagawa high-pressure metamorphic belt of the pair is only 50 km wide. The contemporaneous granitic activity took place not only in the Ryoke low-pressure belt but also in a wide region to the north. In Jurassic-Cretaceous time, this region of granitic activity was probably a part of the East Asiatic volcano-plutonic belt (Ustiev, 1965, fig. 6) on the east coast of the Asiatic continent. Even if we assume that

Japan was in the coast region of the Asiatic continent at that time, the total width of the granitic region was about 2000 km. In figure 2, such a great width is explained as a result of the continentward transportation of magmas by mantle convection, though other possibilities cannot be precluded (see Lipman, Prostka, and Christiansen, 1971).

TECTONIC CLASSIFICATION OF METAMORPHIC BELTS

Three main categories of metamorphic belts.—From the viewpoint of plate tectonics, most of the regional metamorphic belts of Phanerozoic time and possibly of the Precambrian appear to have formed in the following three tectonic settings (Miyashiro, in preparation):

1. Metamorphic belts formed in continental margins. This type of belt could be forming now at the Pacific margin of South America, where the oceanic plate of the Pacific is being underthrust. The Mesozoic paired belts of the Franciscan and Sierra Nevada (Miyashiro, 1961a; Hamilton, 1969) and the late Paleozoic paired belts in Chile (González-Bonorino, 1971) could have been formed in a similar way on the western margin of North and South Americas, respectively.

2. Metamorphic belts formed beneath ordinary island arcs. This type of belt could be forming now beneath the Northeast Japan and Kurile Arcs, where the oceanic plate of the Pacific is being underthrust. The Mesozoic paired belts in New Zealand (Landis and Coombs, 1967) appear to have been formed beneath an ordinary island arc. The late Paleozoic and Mesozoic paired belts in southwest Japan may have been formed by a similar mechanism beneath island arcs, though it is more likely that they were formed on the margin of the Asiatic continent of that time and were drifted afterward to form an island arc.

3. Metamorphic belts formed beneath reversed island arcs. This type of belt would be forming now beneath the New Hebrides Islands, where the plate of the adjacent marginal sea is being underthrust (compare, Isacks and Molnar, 1971). The paired metamorphic belts in Hokkaido (fig. 1) could have been formed by the eastward underthrusting of the Japan Sea plate beneath the Sakhalin Arc.

Paired metamorphic belts can form in any of the three categories. All the metamorphic belts in these categories might well be expected to show a tendency to be paired only if the velocity of plate descent is rapid, as discussed in the preceding section.

Orogenic belts due to continental collision.—Some orogenic belts such as the Alps, Urals, and Himalayas are believed to have been formed by the collision of two continental plates. In the initial stage of continental collision, the two plates are separated by an oceanic plate. The two continental blocks approach each other by the consumption of the intervening oceanic plate due to underthrusting along one or more trench zones. In this stage, the tectonic settings and resultant metamorphic belts, some of which may be paired, should belong to the above-discussed three categories. The Alps and Urals have glaucophane schist belts, which would have formed in this stage.

In the final stage, the intervening ocean is completely lost resulting in a direct collision of the two continental blocks. The buoyancy of the continental blocks would counteract and halt the descent of one plate beneath another. Hence, the characteristics of orogeny in this stage should differ from those of any of the above-discussed three categories. At present we cannot tell whether metamorphism on a large scale takes place at this stage or not. This stage may be now realized in the Himalayas, where there has been no sign of igneous activity (Gilluly, 1971.) Metamorphic rocks are exposed in the Himalayas, but most or all of them appear to be of Precambrian age and formerly belonged probably to the Precambrian metamorphic basement of the Indian subcontinent (Petrushevsky, 1971).

MAJOR FAULTS, BENIOFF ZONES, AND UPLIFT

Three classes of major faults.—Metamorphic belts are usually cut by a large number of faults. Our interpretation of the origin and history of metamorphic belts depends largely on our interpretation of the nature of the major faults. The following three classes of major faults are probably of particular interest in this connection.

1. Transform faults (Wilson, 1965). The San Andreas fault of California and the Alpine fault of New Zealand appear to belong to this class. If the angle between the strike of a strike-slip fault and the axis of a metamorphic belt is small, the strike-slip movement will be difficult to find. It is possible that some large strike-slip faults have been overlooked in metamorphic terranes.
2. Benioff zone, or the upper surface of a descending lithospheric slab, which would represent a large fault or the like cutting through the crust and upper mantle. Some such faults in the geologic past may now be exposed on the surface of the Earth. As high-pressure metamorphism has been regarded as due to underthrusting of a lithospheric slab along a Benioff zone, such faults, if exposed, could be discovered in or near high-pressure metamorphic terranes. Ernst (1970, 1971) suggested that the Coast Range thrust of California and the Median Tectonic Line of Japan may be Benioff-zone faults.
3. Faults, along which crustal blocks that contain high-pressure metamorphic complexes are uplifted. A high-pressure complex formed at a considerable depth must be subsequently uplifted to be exposed on the surface.

The western segment of the Median Tectonic Line of southwest Japan (fig. 6) is the fault boundary between the Sanbagawa metamorphic terrane to the south and the upper Cretaceous Izumi Sandstone Group to the north. The Izumi Group was deposited on an eroded surface of the Ryoke metamorphic terrane which is paired with Sanbagawa. Hence, this segment of the Median Tectonic Line was formed distinctly later than the Ryoke and Sanbagawa metamorphism, and the Sanbagawa high-pressure terrane should have been uplifted along the Line, though this does not

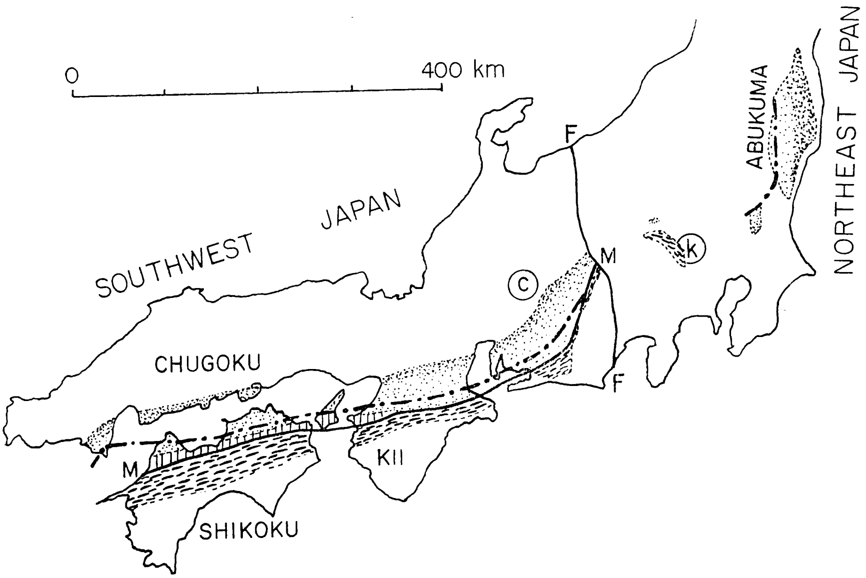

Fig. 6. Median Tectonic Line (M-M) in relation to the Ryoke-Abukuma (dotted) and Sanbagawa (dashed) metamorphic belts as well as to the Izumi Sandstone Group (vertically ruled). The lower grade parts of Ryoke-Abukuma are more densely dotted. The chain lines represent the thermal axis of the Ryoke-Abukuma belt. F-F: Itoigawa-Shizuoka Line. k: Kanto Mountains. c: Chubu region.

preclude the possibility that the movement of the Line involved a great strike-slip component.

The Northeast Japan Arc (that is, northeast Honshu) has been active since the Miocene. As schematically shown in figure 2, it is composed of the outer non-volcanic arc and the inner volcanic arc with a large tectonic line, called the *Morioka-Shirakawa Line* (S in the figure) between them. The Line was detected by a gravity survey by Tsuboi and others (1953-1956), though the fault is entirely covered by younger sediments. The outer arc is characterized by high values of positive Bouguer anomalies. It is conceivable that the outer arc has been uplifted since the Miocene along this fault, with resultant approach to the surface of a Miocene high-pressure metamorphic complex in the crust on the oceanic side of this fault. Since the isostatic anomalies in the outer arc are on the order of +100 mgal, the uplift cannot be ascribed to the buoyancy of a thickened crust. The uplift could be due to the continentward push exerted by the Pacific plate on the prismatic block above the descending slab.

Models for the mechanism of uplift of a high-pressure metamorphic complex.—Three alternative possible mechanisms for uplift of a high-pressure metamorphic complex are discussed below.

1. High-pressure metamorphic recrystallization may take place mainly in the descending oceanic crust and the overlying sediment mass, as illustrated in figure 2. The resultant metamorphic rocks may be added

to the crust on the continental side and uplifted by movement along a high-angle fault (S in fig. 2). In this model, the Benioff-zone would occur at or near the oceanic-side limit of the high-pressure terrane.

2. A high-pressure metamorphic complex may be formed in the foot wall of a Benioff-zone fault, and subsequently it may be uplifted (A) along the same Benioff-zone fault after the halt of the descent of the lithospheric slab, or (B) along a newly formed high-angle fault presumably like the Morioka-Shirakawa Line. In model (A), the major fault, which represents both the Benioff zone and the boundary fault of the uplifted block, should occur at the continental-side limit of the high-pressure metamorphic terrane. This model has been proposed by Ernst (1970, 1971). Model (B) means that a high-pressure complex, which formed in the foot wall of a Benioff-zone fault is subsequently scraped off, added to the hanging wall, and then uplifted along a newly formed high-angle fault.

3. If the position of the Benioff zone shifts successively oceanward, a high-pressure metamorphic complex formed at an older time should become a part of the hanging wall of a subsequently formed Benioff zone and could be uplifted along a newly formed high-angle fault. In the Franciscan terrane, metamorphism involves a number of distinct phases of recrystallization (Suppe, 1969), and the rocks in the western part are generally younger than those in the eastern. This may be the result of successive oceanward shifts of the Benioff zone (Hsü, 1971). A younger high-pressure metamorphic belt tends to form on the oceanic side of an older high-pressure belt, as exemplified in Japan (fig. 1) and the Kamchatka Peninsula (Dobretsov and Kuroda, 1969). This means that a new Benioff zone tends to form on the oceanic side of an older one.

In models (1) and (3), a Benioff-zone fault should appear at or near the oceanic-side limit of the high-pressure metamorphic terrane. In the Sanbagawa high-pressure belt of Japan, the Kurosegawa Tectonic Zone (Ichikawa and others, 1956) is a group of large subparallel faults exposed near the oceanic-side limit of the metamorphic terrane (Banno, 1964) and might be a fossil Benioff zone. The Kiyomizu Tectonic Zone, which is exposed about 20 km north of Kurosegawa, might also be a fossil Benioff zone. This zone is not a simple fault but a zone, up to 1 km wide, of "papery" schists probably representing an unusually strong shear movement contemporaneous with the Sanbagawa metamorphism (Kojima and Suzuki, 1958).

Distance between paired metamorphic belts.—In the present-day island arc regions, there exists a non-volcanic zone, usually 100 to 250 km wide, between a volcanic belt and the associated trench. Dickinson (1971) has proposed the name *arc-trench gap* for such a zone. The arc-trench gaps of some present-day arcs are occupied by uplifted mountains, whereas those of others are occupied by troughs where active sedimentation is taking place. Since high-pressure metamorphism takes place in and near the trench zone, the resultant metamorphic complex should originally have been situated about 50 to 200 km from the low-pressure metamorphic complex beneath the associated volcanic belt.

Among the above-discussed models for the mechanism of uplift of high-pressure metamorphic complexes, model (3) may apparently reduce the distance between paired belts. In this case, the Benioff zone shifts oceanward, and as a consequence, the volcanic zone also should shift oceanward with the resultant approach of the underlying low-pressure complex to an earlier-formed high-pressure complex.

The two metamorphic belts of the pairs in Hokkaido and California are separated from each other by a zone of virtually unmetamorphosed rocks, which may correspond to the arc-trench gaps. On the other hand, in the Jurassic-Cretaceous pair of southwest Japan, the Ryoke low-pressure belt is in direct contact with the Sanbagawa high-pressure belt along the Median Tectonic Line. During the metamorphism, the trench was situated probably to the south of the Sanbagawa belt, that is, in the Shimanto terrane, and hence the distance between Ryoke and Shimanto may represent the arc-trench gap (Dickinson, 1971). The Sanbagawa metamorphism is the recrystallization not of the contemporaneous geosynclinal sediments but of their basement. However, it is still an important question how the high-pressure complex has come into direct contact with the low-pressure complex.

The direct contact may have been caused by an oceanward shift of the Benioff zone as in the above model (3). However, it is more likely that the direct contact is due to a large strike-slip movement along the Median Tectonic Line. Figure 7 illustrates how a left-lateral movement on the order of at least 400 km can account for the three main features of the observed thermal structure of the paired belts: (1) In the westernmost part (Chugoku and Shikoku), the thermal axis of Ryoke lies far to the north of the Line; (2) in the central part (Chubu), the two belts are in direct contact with each other and the metamorphic temperature of the Ryoke terrane increases southward; and (3) in the easternmost part (Abukuma), the oceanic-side half of the low-pressure belt is well exposed. Geologic evidence indicates that the age of the large strike-slip movement must be older than the Miocene and may presumably be Paleocene or early Eocene and contemporaneous with the uplift of the

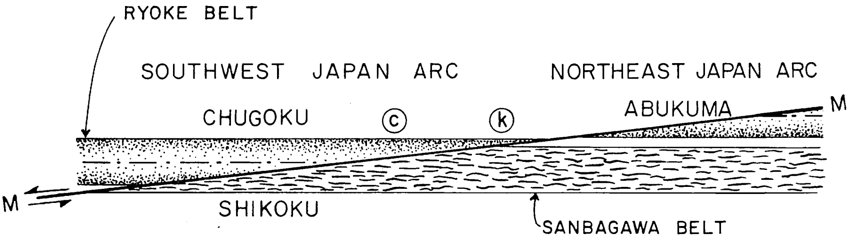

Fig.7. Schematic diagram showing a possible relationship of the Median Tectonic Line (M-M) to the Ryoke-Abukuma and Sanbagawa belts. It is assumed that prior to the strike-slip movement there was a virtually unmetamorphosed zone (white) between the two belts. The symbols and letters k and c are the same as in figure 6.

Sanbagawa belt discussed before. The movement could be related to the formation of the Philippine Sea plate or to the oceanward drift and bending of the Japanese Islands.

ROLE OF OCEAN-FLOOR METAMORPHISM

Discovery of metamorphic rocks in ocean floors.—The existence of metamorphic rocks formed beneath ocean floors has been known since 1966. Such rocks were dredged from the Mid-Atlantic and Mid-Indian Ocean Ridges, that is, the ridges with a well-developed median valley, fracture zones and a low rate of spreading (Melson, Thompson, and Andel, 1968; Cann and Funnell, 1967; Aumento and Loncarevic, 1969; Miyashiro, Shido, and Ewing, 1970, 1971). Intense fault movement and serpentinite intrusion in such ridges would increase the chance of exposure of metamorphic rocks that had originally formed at some depths below the ocean floor. The metamorphic rocks were derived from basalts, dolerites, and gabbros and are usually nearly or entirely devoid of schistosity. They usually belong to the zeolite, greenschist, or amphibolite facies.

Mid-oceanic ridges that have a smooth surface and no median valley, such as the East Pacific Rise, do not have metamorphic rocks exposed on the surface. Conceivably metamorphic rocks are present beneath such ridges also but have little chance of exposure because of the weaker fault movement and the absence of serpentinite intrusion.

Since the oceanic crust is much thinner than the continental one, a temperature rise that causes greenschist facies or higher metamorphism can occur only beneath mid-oceanic ridges where the existence of high thermal gradients is suggested by high heat-flow values. Even zeolite facies metamorphism may take place mainly beneath mid-oceanic ridges. Some of the amphibolite facies metamorphic rocks were probably recrystallized in the upper mantle and subsequently brought up to the surface by serpentinite intrusion.

Metamorphosed crust should move laterally from a mid-oceanic ridge to a normal ocean basin by ocean-floor spreading. Hence, it is likely that the major part of the oceanic crust is composed of metamorphic rocks.

Significance of ocean-floor metamorphism.—The stripes of magnetic anomalies observed on the ocean surface appear to be due to a thin surface layer, about 0.5 to 2.0 km thick, of magnetized basaltic and gabbroic rocks (for example, Heirtzler, 1968). The major part of the oceanic crust underlying the above layer is virtually demagnetized. It is natural to presume that the demagnetization is due to metamorphic recrystallization.

Metasomatic introduction of Na and removal of Ca are intense in the rocks subjected to zeolite- and greenschist-facies recrystallization, respectively. The chemical migration is caused probably by moving aqueous fluids. The rise of such fluids should have resulted in a great variation in the apparent heat flow value on mid-oceanic ridges. High heat-flows observed on mid-oceanic ridges were usually interpreted as suggesting the presence of convective upwelling of mantle materials beneath the ridges. Alternatively, however, they may simply be a result of igneous intrusion and rise of aqueous fluids in ridges. It is yet to be decided whether we have to presume an active role of mantle convection in the framework of plate tectonics or not.

If the bulk of the oceanic crust and the underlying layer has been metamorphosed in the zeolite and greenschist facies, it should have a considerable H_2O content. When the oceanic plate descends into depths in a trench zone, the metamorphosed layers should be gradually dehydrated. The H_2O content should have a strong effect on the mineralogy of the descending slab and the composition of the magmas generated in and near the slab.

If some ophiolites in convergent junctures are fragments of oceanic crust, they may still preserve the influence of ocean-floor metamorphism.

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