Tectonophysics, 17 (1973) 241–254
Elsevier Scientific Publishing Company, Amsterdam – Printed in The Netherlands

PAIRED AND UNPAIRED METAMORPHIC BELTS

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(Accepted for publication December 27, 1972)

ABSTRACT

Miyashiro, A., 1973. Paired and unpaired metamorphic belts. In: P.J. Wyllie (Editor), *Experimental Petrology and Global Tectonics. Tectonophysics,* 17 (3): 241–254.

Paired metamorphic belts occur in many parts of the circum-Pacific regions. A pair is composed of two contrasting belts running parallel: a high-pressure metamorphic belt which probably formed beneath a trench zone, and a low-pressure metamorphic belt which probably formed beneath a volcanic chain in the adjacent island arc or continental margin. The former and the latter belt are accompanied by basic-ultrabasic rocks and by granitic-andesitic-rhyolitic rocks, respectively.

The rapid descent of a thick, cold oceanic plate along a convergent plate juncture should create an unusually low geothermal gradient to cause high-pressure metamorphism. If the rate of plate descent is relatively slow, or if the descending oceanic lithosphere is too thin or too hot, the resultant geothermal gradient will not be low enough to cause high-pressure, but may cause medium-pressure metamorphism. In this case, the contrast between the two associated metamorphic belts will be obscure. The heat transfer by the rise of magmas and mantle materials appears to be a necessary condition for the formation of low-pressure metamorphic belts.

Presumably, paired and unpaired (single) metamorphic belts form by the same mechanism, and an unpaired belt represents paired belts in which the contrast between the two belts is obscure, or in which one of the two belts is undeveloped or lost.

Progress in experimental petrology enables us to estimate the pressure and temperature during metamorphism, and to know the relations between the conditions of partial melting and the composition of the resultant magmas. This sets limits to our ideas about the relevant tectonic processes in plate junctures.

OCCURRENCE OF PAIRED AND UNPAIRED METAMORPHIC BELTS

Regional metamorphism takes place in orogenic belts along convergent junctures of lithospheric plates. In many ancient orogenic belts, the rocks subjected to regional metamorphism form a pair of metamorphic belts showing contrasting characteristics. A pair is composed of a high-pressure metamorphic belt (with glaucophane) accompanied by basic and ultrabasic (ophiolitic) rocks, and a low-pressure metamorphic belt (with andalusite) accompanied by granitic, andesitic and/or rhyolitic rocks. The two belts run parallel and their metamorphism is approximately of the same geologic age. Usually, but not always, the high-pressure belt is on the oceanic side of the low-pressure belt (Miyashiro, 1961, 1965, 1967, 1972b).

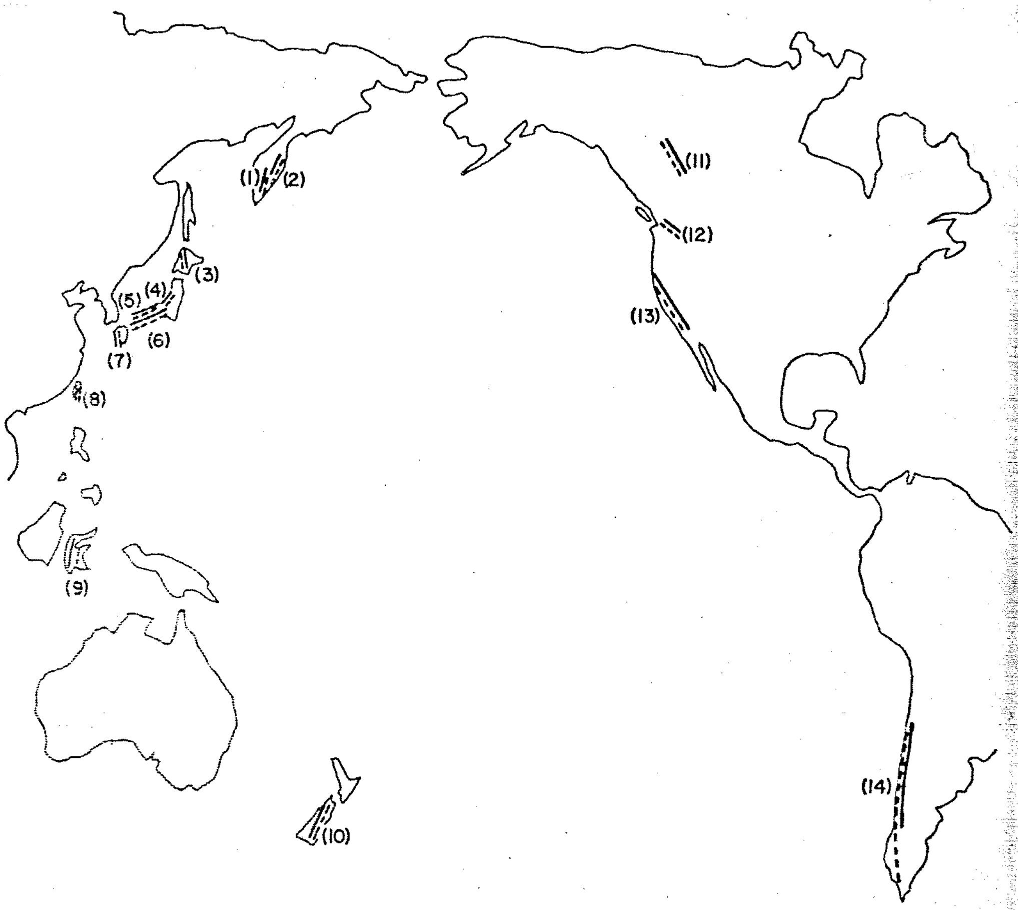

Fig. 1. Paired metamorphic belts in the circum-Pacific regions. Thick broken lines represent high-pressure metamorphic belts, and thick full lines low-pressure metamorphic belts. The deformation by faulting after their formation is ignored for simplicity. The names and geologic ages of these belts are shown in Table I.

Paired metamorphic belts are well developed in the circum-Pacific regions, as shown in Fig. 1 and Table I. The concept and the tectonic and geophysical interpretation of paired metamorphic belts were initiated and developed in Japan prior to the beginning of plate tectonics (Miyashiro, 1961, 1965, 1967; Matsuda, 1964; Takeuchi and Uyeda, 1965). Afterwards, the concept was incorporated into plate tectonics (e.g., Hamilton, 1969; Dewey and Bird, 1970; Miyashiro, 1972b) and was applied particularly to California (e.g., Hamilton, 1969; Suppe, 1970).

In the Atlantic region, high-pressure metamorphism is rare and most metamorphic belts are apparently single (unpaired). However, there are a few atypical paired belts (Miyashiro, 1972b, p. 645).

The term high- and low-pressure metamorphism refers to high and low rock-pressures

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TABLE I

Paired metamorphic

Number	Region
1	Kamch
2	Kamch
3	Hokkai
4	Central
5	South Japan
6	Southw Japan
7	Western Kyushu
8	Taiwan
9	Celebes
10	New Ze
11	Canada
12	Washing State
13	Californ
14	Chile

Note: The numbers of

TABLE I

Paired metamorphic belts in the circum-Pacific regions

Number	Region	High-pressure belt	Low-pressure belt	Age of metamorphism	References
1	Kamchatka	Ganalsky	Sredinny	Early Mesozoic (?)	Lebedev et al. (1967), Dobretsov and Kuroda (1969)
2	Kamchatka	Karaginsko-Kronotskaya	(Central Kamchatka)	Late Mesozoic (?)	Lebedev et al. (1967), Dobretsov and Kuroda (1969)
3	Hokkaido	Kamuikotan	Hidaka	Cretaceous–Tertiary	Miyashiro (1961, 1967)
4	Central Japan	Circum-Hida (Omi)	Hida (partly)	Carboniferous	–
5	Southwest Japan	Sangun	Hida (partly)	Permian–Jurassic	Miyashiro (1961, 1967)
6	Southwest Japan	Sanbagawa	Ryoke	Jurassic–Cretaceous	Miyashiro (1961, 1967)
7	Westernmost Kyushu	Nishisonogi (Nagasaki)	Ai-no-shima	Cretaceous	Miyashiro (1965), Karakida et al. (1969)
8	Taiwan	Yüli	Tailuko	Late Mesozoic (?)	Yen (1963)
9	Celebes	–	–	–	Miyashiro (1961)
10	New Zealand	Wakatipu	Tasman	Jurassic–Cretaceous	Landis and Coombs (1967)
11	Canada	–	Cassia-Omineca-Columbia	Mesozoic	Monger and Hutchison (1970)
12	Washington State	Shuksan	Skagit	Permian (?)	Misch (1966)
13	California	Franciscan	Sierra Nevada	Jurassic–Cretaceous	Hamilton (1969), Suppe (1970)
14	Chile	Pichilemu (Western)	Curepto (Eastern)	Late Paleozoic	Gonzalez-Bonorino (1971), Aguirre (1972)

Note: The numbers of regions in this table are shown in Fig. 1.

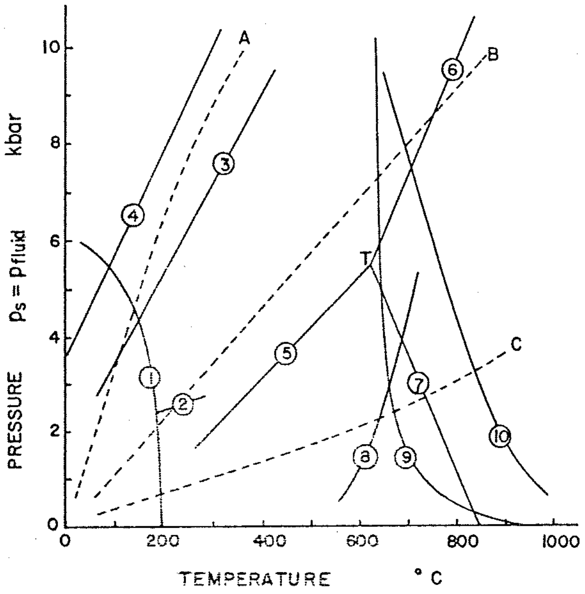


Fig. 2. Pressure and temperature conditions of regional metamorphism. Broken lines represent geothermal curves for high-pressure metamorphism (*A*), medium-pressure metamorphism (*B*), and low-pressure metamorphism (*C*). Curves *B* and *C* lie on the upper and lower sides, respectively, of the triple point (*T*) of the Al_2SiO_5 system.

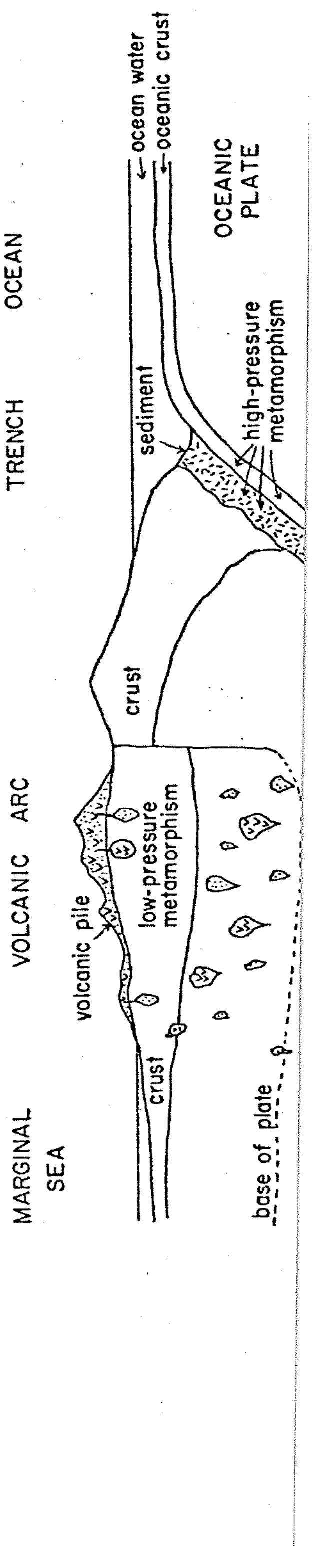
Equilibrium curves for the following reactions are shown: (*1*) analcime + quartz = albite + H_2O (Thompson, 1971); (*2*) lawsonite + 2 quartz + 2 H_2O = laumontite (Thompson, 1970); (*3*) aragonite = calcite (Crawford and Fyfe, 1964; Johannes and Puhan, 1971); (*4*) jadeite + quartz = albite (Birch and LeComte, 1960; Newton and Kennedy, 1968); (*5*) kyanite = andalusite (Richardson et al., 1969); (*6*) kyanite = sillimanite (Richardson et al., 1969); (*7*) andalusite = sillimanite (Richardson et al., 1969); (*8*) muscovite + quartz = K feldspar + Al_2SiO_5 + H_2O (Evans, 1965); (*9*) beginning of melting of granite (Yoder and Tilley, 1962); (*10*) beginning of melting of olivine tholeiite (Yoder and Tilley, 1962);

respectively at the same temperature (Fig. 2). Hence, they actually represent low and high geothermal gradients respectively rather than high and low numerical values of rock-pressure. Metamorphism with an intermediate geothermal gradient is called medium-pressure metamorphism. Parts of the so-called high- and low-pressure metamorphic belts commonly belong to the medium-pressure type.

ORIGIN AND RELATIONSHIP OF PAIRED AND UNPAIRED METAMORPHIC BELTS

Cause of high-pressure metamorphism

High-pressure metamorphism takes place probably in rock masses (usually geosynclinal piles) that are brought into depth by the rapid descent (underthrusting) of an oceanic plate beneath an island arc or a continental margin, as shown schematically in Fig. 3. The descent of a thick, cold slab and associated rock masses should produce an unusually low geo-



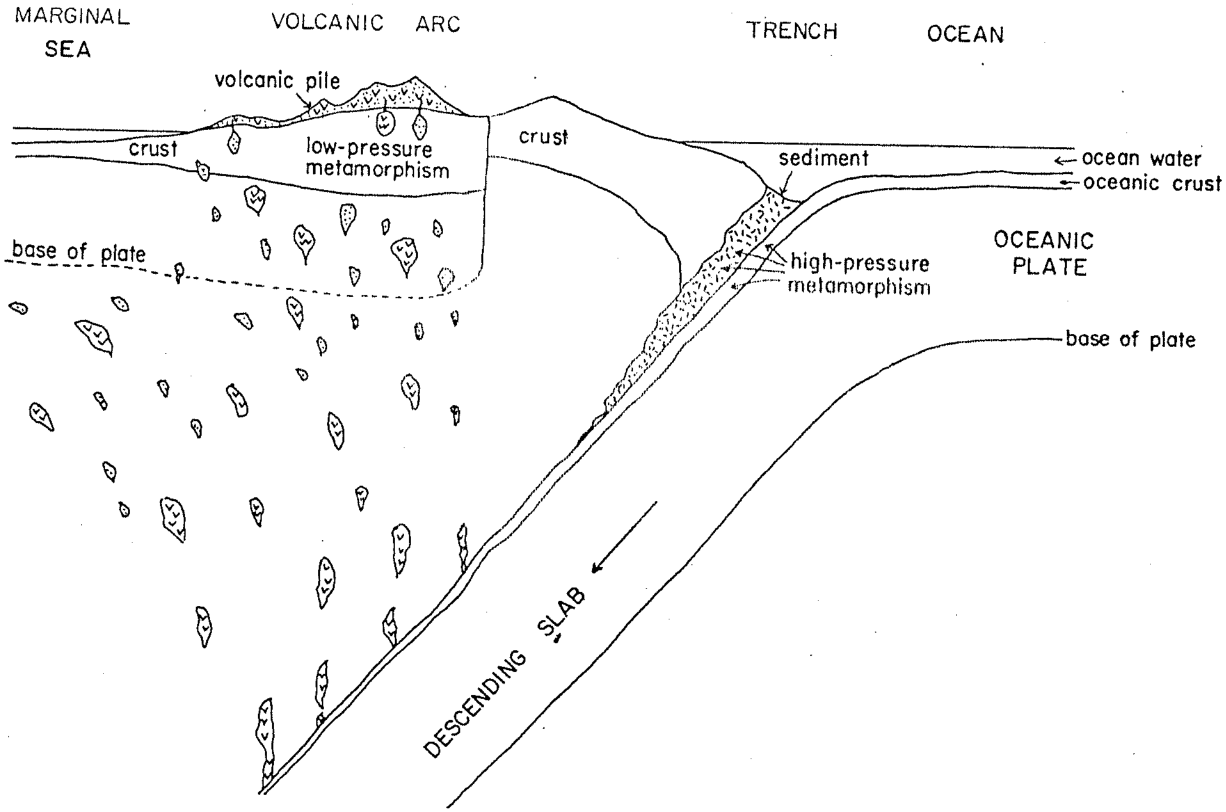


Fig. 3. Origin of paired metamorphic belts in an island arc, as exemplified by the northeast Japan arc (Miyashiro, 1972b).

thermal gradient. Hence, we may consider that an exposed high-pressure metamorphic belt represents an ancient subduction zone along a trench.

When the rate of plate descent in a trench zone is very rapid, the resultant geothermal gradient will be low enough to cause typical high-pressure metamorphism. When the rate of plate descent is slow, the resultant geothermal gradient may not be low enough for high-pressure, but may cause medium-pressure metamorphism. In this case, the contrast between the two associated belts is obsucre (Miyashiro, 1972b). Katz (1972) described a possible example of such paired belts from the Precambrian of Ceylon.

There may have been geologic times when plate motion was unusually active all over the world, as suggested by Larson and Pitman (1972). High-pressure metamorphism may have taken place commonly in such periods.

Conceivably, the initial temperature of a descending slab is another important factor for high-pressure metamorphism. Probably a plate remains considerably hot for a period of tens of million years after its creation in a mid-oceanic ridge (e.g., Forsyth and Press, 1971). If the rate of plate creation is 10 cm/year, a new ocean floor, thousands of kilometers wide, will be formed in this period, and hence the descent of an initially hot plate may not be rare. It cannot produce an unusually low geothermal gradient, even if the rate of descent is high (S. Uyeda and A. Miyashiro, in preparation).

The thickness (Ernst, 1972) and the slope of descending slabs also may be important factors that control the P–T conditions of metamorphism in the subduction zones.

Cause of low-pressure metamorphism

A low-pressure metamorphic belt, accompanied by granitic, andesitic and/or rhyolitic rocks, probably represents the zone of an ancient volcanic chain and underlying metamorphic complex in an island arc or a continental margin. Heat transfer by the rise of magmas and other materials appears to play an essential role for the creation of high-geothermal gradients in low-pressure metamorphic belts.

The composition and amount of magmas generated in orogenic belts would vary with the rate of plate convergence and the amount of plate consumption. The descent of hot lithosphere near a mid-oceanic ridge could increase the amount of generated magmas and the width of the zone of magmatism (S. Uyeda and A. Miyashiro, in preparation). These factors would influence the heat transfer and hence the properties of low-pressure metamorphic belts.

Hence, the degree of development and the properties of high-pressure and low-pressure metamorphic belts in convergent junctures should differ in different cases. When the contrast between the two associated belts is obscure, or when one of the two belts is undeveloped or lost, the resultant metamorphic terrane forms an unpaired (single) belt. Thus, unpaired metamorphic belts form conceivably by the same mechanism as paired belts in convergent junctures.

Tectonic characteristics of the Pacific regions

The common occurrence of high-pressure metamorphic belts and paired belts in the circum-Pacific regions appears to be due to the following two factors.

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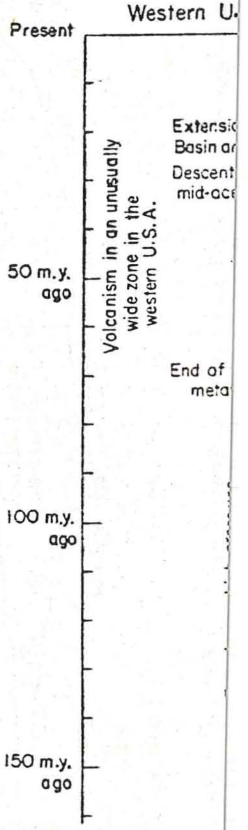

Fig. 4. Comparison of
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First, the rapid plate motion as observed now in the Pacific regions in contrast to the slow motion in the Atlantic (e.g., Le Pichon, 1968) may have existed since late Paleozoic time, and this may have been the basic cause for the common occurrence of high-pressure belts in the circum-Pacific regions and for their rarity in the Atlantic (Miyashiro, 1972b, p. 644).

Secondly, the rate of underthrusting of oceanic plates may be unusually rapid over a period preceding the descent of some mid-oceanic ridges beneath island arcs or continental margins, because the rate should be increased by the rate of creation of new lithosphere on the ridges. Atwater (1970) has shown that the mid-oceanic ridge between the Farallon and Pacific plates descended beneath the North American plate in middle Tertiary time. The Franciscan high-pressure metamorphism took place tens of million years prior to the ridge descent, possibly owing to the rapid underthrusting in this period (Fig. 4). Larson and Chase (1972) have shown that the mid-oceanic ridge between the Kula and Pacific plates descended beneath Japan and the Asiatic continent in late Cretaceous time. The Sanbagawa

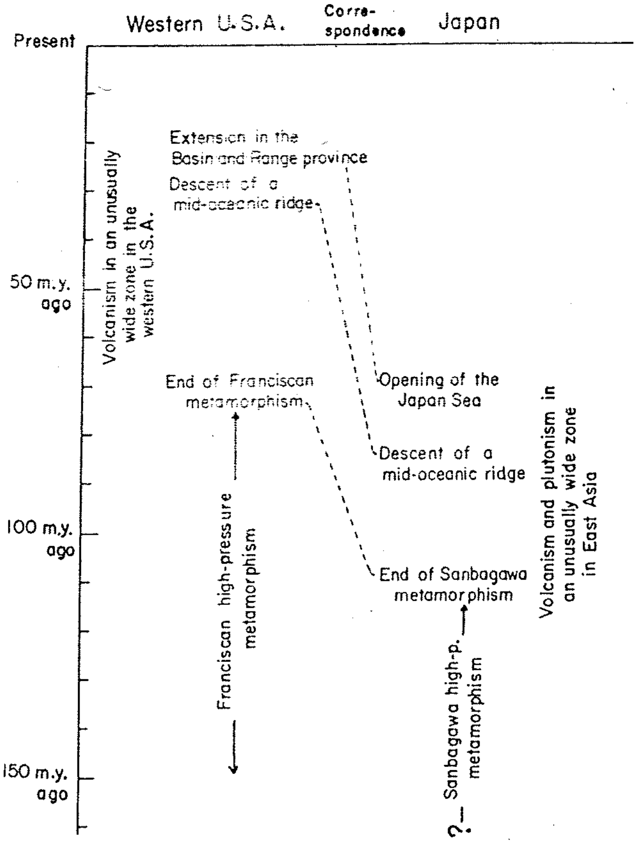

Fig. 4. Comparison of geologic events in the western United States and in East Asia including Japan with special reference to the descent of mid-oceanic ridges beneath continental plates. In both regions, high-pressure metamorphism took place tens of million years prior to the ridge descent, volcanism spread over an unusually wide zone in a period around the ridge descent, and possibly a large strike-slip fault formed by the descent.

high-pressure metamorphism took place tens of million years prior to the ridge descent. The time relation between the ridge descent and high-pressure metamorphism is very similar in these two cases, suggesting that the ridge descent played an essential role for the metamorphism (Fig. 4).

In both cases, high-pressure metamorphism was halted about 30 or 40 m.y. prior to the ridge descent. Conceivably the descending oceanic lithospheres near the ridges were still hot enough to increase the geothermal gradients in the subduction zones, and thereby to put an end to high-pressure metamorphism (S. Uyeda and A. Miyashiro, in preparation).

Geophysical models

Hasebe et al. (1970), Oxburgh and Turcotte (1971), and Toksöz et al. (1971) have made numerical calculations on thermal models of orogenic belts in island arcs and continental margins with special attention to the descent of a cold oceanic plate from a trench zone. It has been shown that the descent causes an unusually low geothermal gradient in the trench zone and results in the formation of a high-pressure metamorphic belt. On the other hand, the formation of low-pressure metamorphic belts and associated granitic and andesitic rocks is not so easy to explain. Simple thermal conduction is not effective enough to cause upward transfer of frictional heat from the upper surface of a descending slab to the crust to result in low-pressure, high-temperature metamorphism and high heat flow as observed on the continental side of many island arcs. All these authors assume that the magmas and/or mantle materials rising from the upper surface of the descending slab and/or its vicinity contribute greatly to the heat transfer.

The rise of water and possibly also the convective (or diapiric) rise of mantle materials on the upper side of the descending slab may be an essential factor in the heat transfer. Conceivably, the water is derived partly by the dehydration of the descending slab, and partly by degassing of the deeper mantle. Recent studies in oxygen isotope geochemistry have suggested the importance of juvenile water in regional metamorphism and associated plutonism (Garlick and Epstein, 1967).

We are ignorant of the rate of rise of such materials, and of the mechanism of the rise of magmas in such circumstances. If the heat transfer requires a considerable length of time, low-pressure metamorphism should be delayed as compared with the associated high-pressure metamorphism. Though the two metamorphic belts of a pair form approximately in the same geologic age, more precise time relations between them are not well known.

High-pressure metamorphism in a belt is usually a long process made up of a number of separate epochs (e.g., Suppe, 1969). Granite emplacement in the associated low-pressure belt also include a number of epochs (e.g., Evernden and Kistler, 1970). It is not possible to prove or disprove the existence of genetic connections between epochs of different belts.

Nature of magmatism in island arcs and continental margins

The island arc volcanism appears to be diverse in response to the different rate of plate convergence and other tectonic conditions (Miyashiro, 1972b, p. 641–643). However, the available petrographic data are not adequate. Only a few arcs, particularly of Japan, are petrographically well documented.

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We do not know where and how magmas form beneath island arcs and continental margins. They may form by partial melting of the oceanic crust (basaltic in composition) along the upper surface of a descending slab, or in the main body (presumably peridotitic) of the slab, or within the upward moving mantle material above the slab, or in the deeper crust. In the last 15 years, a considerable number of experimental studies have been made to clarify the relationship between the conditions of partial melting and crystallization on the one hand, and the compositions of the resultant magmas on the other (refer to the papers by A.L. Boettcher, D.H. Green and W.S. Fyfe in this issue).

Future progress in these fields will help us to formulate more reliable models for the structures and processes in island arcs and continental margins.

GEOTHERMAL GRADIENTS IN HIGH-PRESSURE METAMORPHIC BELTS

The pressure and temperature of typical high-pressure metamorphism are considered to be near the equilibrium curves for the following two reactions:

$$\overset{\text{jadeite}}{NaAlSi_2O_6} \quad + \quad \overset{\text{quartz}}{SiO_2} \quad = \quad \overset{\text{albite}}{NaAlSi_3O_8}$$

$$\overset{\text{aragonite}}{CaCO_3} \quad = \quad \overset{\text{calcite}}{CaCO_3}$$

The left-hand sides represent high-pressure assemblages. Jadeite and aragonite occur in some high-pressure metamorphic terranes. The equilibrium curves for these reactions are shown in Fig. 2 (curves 4 and 3). There, curve 4 gives the conditions near the high-pressure, low-temperature limit of regional metamorphism. Most of the natural jadeites associated with quartz contain other pyroxene components in solid solution, and hence is stable down to a lower pressure than curve 4. The geothermal gradients of high-pressure metamorphism estimated from these curves, combined with oxygen isotope geothermometry (Taylor and Coleman, 1968), are around 10°C/km (refer to W.G. Ernst's paper, this issue).

In the Kanto mountains in the Sanbagawa belt, the jadeite+quartz assemblage occurs only in the middle grade zone, and albite is stable in both lower and higher grades. This suggests that the geothermal curve was convex upwards as shown by curve *A* in Fig. 2 (Miyashiro, 1972b; also 1961, fig. 4). Probably this shape is also due to the rapid descent of the metamorphic complex into depth.

GEOTHERMAL GRADIENTS IN LOW-PRESSURE METAMORPHIC BELTS

The three polymorphs of Al_2SiO_5 composition (i.e., andalusite, kyanite and sillimanite) are widespread in medium- and low-pressure regional metamorphic terranes. Though great efforts have been concentrated on the experimental clarification of the stability relations of the polymorphs in the last 15 years, we have not come to any reasonable agreement.

The Al_2SiO_5 system has a triple point where the three polymorphs can stably coexist

TABLE II

Recently determined values * of the pressure and temperature for the triple point of the Al_2SiO_5 system

Authors	Pressure (kbar)	Temperature (°C)
Pugin and Khitarov (1968)	7.6	540
Althaus (1967)	6.5	595
Richardson et al. (1969)	5.5	620
Newton (1966)	4.0	520
Holdaway (1971)	3.76	501
Fyfe (1967)	about 2.5	about 450
Brown and Fyfe (1971)	2.0	460

* In the order of decreasing pressure.

(point *T* in Fig. 2). The geothermal curve passing through the triple point is the boundary between low- and medium-pressure metamorphism by definition. Table II and Fig. 5 show the great diversity in the experimentally determined values of the pressure and temperature for the triple point. It is only tentative that the triple point shown in Fig. 2 is based on the values by Richardson et al. (1969), which are now widely but not universally accepted.

Zen (1969) has discussed the following possible factors to account for the discrepancy: (1) large derivations from equilibrium; (2) the incorrect calibration of the pressure apparatus and the existence of pressure inhomogeneities; and (3) the compositional and struc-

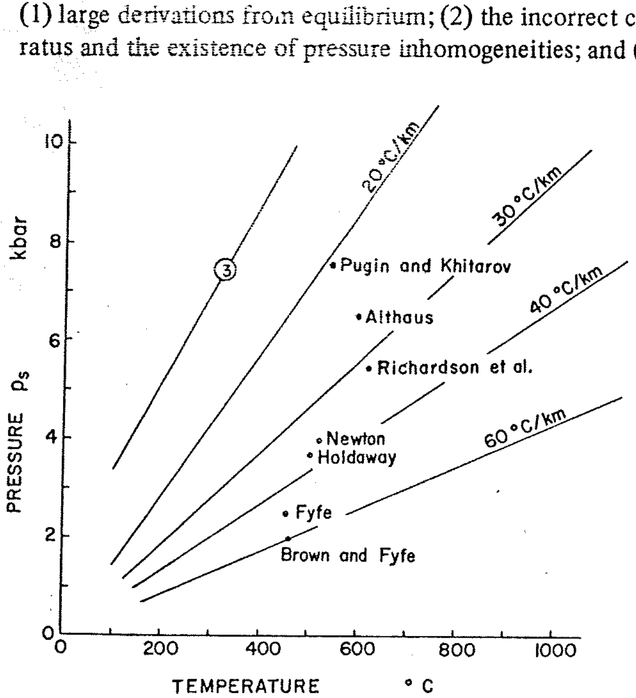

Fig. 5. Pressure and temperature of the triple point of the Al_2SiO_5 system, as determined by the authors shown in Table II. The geothermal curves for 60°, 40°, 30°, and 20°C/km as well as the equilibrium curve for the aragonite–calcite transformation (curve *3*) are shown for comparison.

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tural variability of polymorphs. Holdaway (1971) has attempted to ascribe the discrepancy between different workers mainly to the effects of: (1) intense grinding and the extremely fine grain size of samples; and (2) the disorder between the tetrahedral Al and Si sites in artificial sillimanite.

Available petrographic data indicate that the temperature of recrystallization in large parts of low- and medium-pressure regional metamorphic terranes is higher than that of the triple point. If we accept a temperature around 600°C for the triple point, it follows that large parts of the metamorphic terranes must have been heated at temperatures higher than the minimum melting curve of granitic rocks (curve 9 in Fig. 2). This suggests the possibility that partial melting may have been widespread and may have played an important role in the migration of the materials and heat. On the other hand, if we accept a temperature around 450°C for the triple point, we may come to a very different picture on this matter.

For a more comprehensive review of the geologic significance of the recent progress in experimental petrology, refer to Miyashiro (1972a).

EXPERIMENTAL INVESTIGATIONS OF SOME MINERALS RELEVANT TO LOW- AND MEDIUM-PRESSURE METAMORPHISM

There is an extensive literature on the experimental determination of the stability relations of minerals which occur commonly in low- and medium-pressure metamorphic terranes. Progress in this field will someday enable us to know, for example, the detailed distribution of temperature in low-pressure metamorphic terranes, which may serve as a clue to the role of plutonic masses and material migration in such metamorphism.

Some of the recent results in this field will be reviewed below.

Chloritoid and staurolite

Both chloritoid and staurolite are hydrous aluminous minerals with high Fe/Mg ratios. Petrographic experience suggests that staurolite-bearing mineral assemblages are generally stable at higher temperatures than chloritoid-bearing assemblages. The experimental determination of the stability relations of these minerals has been made by Halferdahl (1961), Hoschek (1967, 1969), Ganguly (1968), Ganguly and Newton (1968) and Richardson (1968).

The oxygen pressure during regional metamorphism may be most commonly within the stability field of magnetite. Under an oxygen pressure corresponding to the middle of the magnetite field, chloritoid breaks down into a staurolite-bearing assemblage at about 600°C (Ganguly and Newton, 1968). A theoretical analysis of the paragenetic relations of chloritoid and staurolite has been made by Hoschek (1969).

Cordierite and garnet

The stability relations of cordierite have been worked out mainly by Schreyer and coworkers (Schreyer and Schairer, 1961; Schreyer and Yoder, 1964; Schreyer, 1965). For pure Mg-cordierite composition in the presence of excess H_2O, the high-pressure stability limit of this mineral has been found to be close to the boundary between the sillimanite and kyanite fields (curve *6* in Fig. 2). This corresponds to the common occurrence of the cordierite–sillimanite and cordierite–andalusite assemblages and the rarity of the cordierite–kyanite assemblage.

The stability field of almandine varies greatly with oxygen pressure. Under an oxygen pressure in the middle of the magnetite field, almandine is stable in a wide range of rock-pressure down to zero, but in a narrow range of temperature around 600°C. With decrease in oxygen pressure, the stability temperature range becomes wider (Hsu, 1968). On the other hand, pyrope is stable only at high pressures (Boyd and England, 1959).

Hensen (1971) and Hensen and Green (1971) have shown that cordierite-bearing assemblages are replaced by garnet-bearing assemblages with increase in pressure. The paragenetic relations of cordierite have been discussed by Hess (1969) with special reference to the compositional variation in metapelites.

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Tectonophysics, 17 (1973) 2
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BLUESCHIST META
DUCTION ZONES*

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(Accepted for publication No

ABSTRACT

Ernst, W.G., 1973. Blueschist
P.J. Wyllie (Editor), *Exper*

Blueschist-type metamorp
minerals: at low grades, zeolit
then at higher grades, zoisite-e
parisons of natural assemblage
analyses yield apparent physic
on the order of 3–8 + kbar. T
order of 10–15°C/km.

Blueschist belts seem to be
sized to represent subducted n
tion. Calculated downward de
similar or even lower geotherm
of relatively high-pressure isog
strates that the observed seque
descent.

The approximate magnitud
contemporaneous high-temper
lithospheric plate. Greater am
high-temperature, low-pressure

Blueschist belts tend to be
many convergent plate junctio
lithospheric slabs. The fact tha
farther inland suggests that in
for the episodic return toward
plates.

INTRODUCTION

Glaucophane-schist terr
belts which are located chi
generally lie on the oceanw
metamorphic + plutonic co

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* Institute of Geophysics and