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A petrological model of the mantle wedge and lower crust in the Japanese island arcs

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Abstract—A petrological model of the mantle wedge and the lower crust in the Japanese Island arcs has been developed from deep-seated inclusions, melting relations of arc basalts, and the phase relations of peridotite combined with seismic wave velocities in the mantle wedge and laboratory measurements of velocities of peridotite at high pressures and temperatures. It is suggested that the amount of melt in the mantle wedge source region is approximately 2 volume percent below the volcanic zone and increases in ascending diapirs. The maximum amount of water in most parts of the mantle wedge is 0.2 weight percent. The highest temperature region in the mantle wedge would exist at a depth of 70–80 km beneath the volcanic front and slightly deeper near the coast of the Japan Sea and has the lowest density. A density reversal below the volcanic zone would cause the ascent of diapirs in the mantle wedge. Magmas would segregate at a level where the diapirs stop ascending. This depth would be determined by the peridotite solidus in the absence of excess vapor phase, and increase from about 35 km to about 60 km from the volcanic front to the Japan Sea coast.

Lower crustal materials in the Japanese Islands inferred from the deep-seated inclusions in basalts and tuffs are hornblende-gabbro, granulite, and amphibolite. In NE Honshu, at least near the coast of Japan Sea, the original rocks for these metamorphic rocks are mostly hornblende gabbros formed by accumulation from hydrous basaltic magmas, and subsequently metamorphosed with decreasing temperature toward the ambient geotherm. In SW Honshu, the original rocks are both gabbros and sedimentary rocks enriched in silica and alumina, as inferred from the chemical analyses of the inclusions and the presence of aluminous phases such as kyanite and corundum in some of the inclusions. The geotherm estimated by the pyroxene geothermometry passes 850°C at about 25 km in NE Honshu and at about 35 km in SW Honshu. The crust of the volcanic zone in NE Honshu would have been thickened essentially by the intrusion of basalt magmas from the mantle wedge, whereas that of the SW Honshu may have been formed by both magmatic and sedimentary or accretionary processes. By the latter process, sedimentary rocks could be brought to the base of the crust. The crust of the island arcs can thus be classified as igneous crust and sedimentary or accretionary crust. There is also a mixed crust consisting of both the rocks as major constituents, such as at SW Honshu. I-type and S-type granites may be formed in the igneous crust and sedimentary or accretionary crust, respectively. "Paired granite belts" may be formed in mature island arcs.

INTRODUCTION

ISLAND ARCS and active continental margins associated with the subduction of oceanic lithospheres are the place of active magmatic processes and formation of the earth's crust. Although the amount of magmas produced in these regions is much less than that in the mid-oceanic ridges, the process taking place in the subduction zone are important for the formation and development of the continental-type crust (*e.g.,* KAY, 1985).

The Japanese island arcs consist of five different segments of arcs with different geophysical and geological characteristic; they are southern Kurile, NE Japan, Izu-Bonin, SW Japan and Ryukyu arcs (Figure 1). For example, the angle of subduction is steeper in the Izu-Bonin and Ryukyu arcs than in the NE Japan and southern Kurile arcs, and Quaternary calc-alkalic andesite is common in the NE Japan and southern Kurile arcs, whereas it is less common in the Izu-Bonin arc. Heat flow data are different between the NE and SW Japan arcs. In addition, most of these arcs have a double arc structure consisting of an outer arc (presently non-volcanic) and an inner arc (presently volcanic) (MIYASHIRO, 1974). Such variations in the Japanese island arcs may reflect the complexity of the processes in the development of the island arcs. Detailed studies of the Japanese island arcs will, therefore, be important for understanding the nature and origin of arcs in general.

A number of geological, geophysical and petrological studies have been made in the Japanese Island arcs, and these arcs are among the most extensively studied arcs in the world. However, the materials, structure and evolution of the lower crust and the upper mantle in the Japanese island arcs are still not well understood. In the present study this problem is revisited on the basis of a synthesis of recent experimental and petrological studies together with previous studies, especially those by KUNO (1959, 1960), SUGIMURA (1960), AOKI

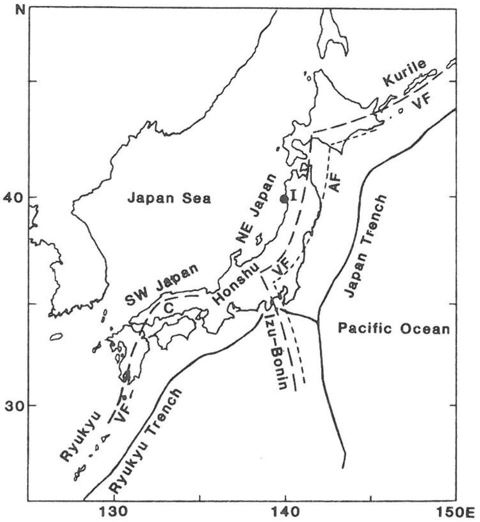

FIG. 1. Japanese Island arcs. Abbreviations: VF, volcanic front; AF, aseismic front; I, Ichinomegata; C, Chugoku district.

(1971), Miyashiro (1974), Ishihara (1977) and Sakuyama (1979). The conditions of magma generation and a petrological model of the mantle wedge beneath the NE Japan arc are discussed first. This is an extension of the work by Tatsumi *et al.* (1983); here, the physical properties of the mantle wedge are discussed in more detail. Secondly, the lower crustal materials and the geotherms in the NE and SW Japan arcs are compared based on deep-seated inclusions in volcanic rocks. Finally, the process of formation of the lower crustal materials and the evolution of the crust of the Japanese arcs are briefly discussed.

CONDITIONS OF BASALT MAGMA GENERATION

Kuno (1959) first proposed a model for generation of basalt magmas in the Japanese Islands and their adjacent areas based on his petrological observations on basalts and the deep seismicity studied by Wadati and his colleagues (*e.g.*, Wadati and Iwai, 1954). According to this model, basalt magmas are generated along the deep seismic zone (Wadati-Benioff zone); tholeiitic basalt magma, which is erupted near the volcanic front, is generated at depths shallower than 200 km, whereas alkali basalt magma, which is erupted near the Japan Sea coast, at depths greater than 200 km. Later, Kuno (1960) proposed that high-alumina basalt, which is erupted in a zone between the tholeiite and alkali basalt zones, is generated at depths around 200 km.

The depths of generation of basalt magmas proposed by Kuno were found to be too deep when experimental data on natural and synthetic basalt systems became available (*e.g.*, Green and Ringwood, 1967; Kushiro, 1968). Based on experimental results, Green *et al.* (1967) proposed a model for the generation of basalt magmas in island arcs; tholeiitic magma is segregated from the source upper mantle materials at depths shallower than 30 km, high-alumina basalt magma, at 30–40 km, and alkali olivine basalt magma, at 50–60 km. The chemical compositions of the basalts which Green *et al.* (1967) used for this estimation are, however, not appropriate for the primary basalt magmas in the Japanese Islands. Recently, Tatsumi *et al.* (1983) estimated the chemical compositions of the primary magmas for tholeiite, high-alumina basalt, and alkali olivine basalt in the NE Japan arc using the compositions of the least fractionated basalts of these three basalt types and maximum fractionation model. The most magnesian olivine tholeiite found in the Ryozen district, NE Honshu (Kotoku, 1986) has a composition very close to that of the primary olivine tholeiite magma estimated by Tatsumi *et al.* (1983) as shown in Table 1. This olivine tholeiite contains about 10 volume percent olivine phenocrysts and microphenocrysts in a fine-grained groundmass; however, their compositions (Fo_{90}) in

Table 1. Chemical compositions of olivine tholeiite from Ryozen district and estimated primary olivine tholeiite magma

	Olivine tholeiite, Ryozen district, NE Honshu*	Primary olivine tholeiite magma†
SiO_2	49.03	49.71
TiO_2	0.64	0.74
Al_2O_3	13.95	14.97
Fe_2O_3	2.36	—
FeO	6.83	10.57††
MnO	0.15	0.14
MgO	12.38	13.03
CaO	10.75	9.00
Na_2O	1.93	1.56
K_2O	0.27	0.28
$H_2O(-)$	0.60	—
$H_2O(+)$	1.30	—
P_2O_5	0.07	—
Cr_2O_3	0.12	—
Total	100.38	100.00
Fe/(Fe + Mg)	0.289	0.313

* Described by Kotoku (1986); this sample (IK85060803) was collected by the author and analyzed by H. Haramura.

† Tatsumi *et al.* (1983).

†† Total iron as FeO.

the core and the bulk composition of the rock indicate that the olivine phenocrysts are not cumulates.

TATSUMI *et al.* (1983) made a series of experiments on the estimated compositions of the three primary basalt magmas under both anhydrous and hydrous conditions to determine the pressure-temperature conditions where these magmas can be in equilibrium with olivine and orthopyroxene with or without clinopyroxene. The results indicate that the primary tholeiite (olivine tholeiite) magma can be in equilibrium with olivine and orthopyroxene at about 11 kbar and 1320°C under anydrous conditions, the primary high-alumina basalt magma can be in equilibrium with olivine, orthopyroxene and clinopyroxene at about 15 kbar and 1340°C under anhydrous conditions and 17 kbar and 1325°C in the presence of 1.5 weight percent H_2O, and the primary alkali olivine basalt magma can be in equilibrium with the above three minerals at about 17 kbar and 1360°C under anhydrous conditions and 23 kbar and 1320°C in the presence of 3 weight percent H_2O. These H_2O contents applied are maximum values estimated by SAKUYAMA (1979). The primary tholeiite magma would contain less than 1 weight percent H_2O.

In the present study, melting experiments have been made on the olivine tholeiite from Ryozen district. The results, shown in Appendix, indicate that both olivine ($Fo_{89}Fa_{11}$) and orthopyroxene ($En_{89}Fs_{11}$) crystallize on the liquidus at about 1315°C at 11 kbar. The results are very close to those obtained by TATSUMI *et al.* (1983) on the primary olivine tholeiite composition; the temperature of olivine-orthopyroxene cotectic is only about 5° lower in the present experiments.

Because of high temperature of equilibration with peridotites (1300°C) at relatively shallow depths, it was suggested that the primary basalt magmas are initially formed within hot diapirs that have ascended from the deeper regions in the mantle wedge (SAKUYAMA, 1983a; TATSUMI *et al.*, 1983; KUSHIRO, 1983). A similar model was suggested by GREEN *et al.* (1967). If the diapirs (or magmas) ascend adiabatically, the temperature of the source region must be higher than that during the final equilibration; the temperature at a depth of 80 km is estimated to be about 1400°C or a little higher (TATSUMI *et al.*, 1983).

GEOTHERMS AND PHASE RELATIONS IN THE MANTLE WEDGE

As discussed above, the temperature of the source region for primary olivine tholeiite magma is estimated to be about 1400°C or a little higher at a depth of about 80 km. Because the depth of the top of the subducting slab below the volcanic front in NE Japan is about 100 km (*e.g.*, YOSHII, 1972, 1979; HASEGAWA *et al.*, 1978; HASEMI *et al.*, 1984), the zone of highest temperature near the volcanic front must be shallower than 100 km, and is most likely 70–80 km deep. The temperature at the Moho is estimated at about 850°C near the coast of the Japan Sea in NE Honshu where the depth of the Moho is about 25 km, as discussed later, and is probably 950–1000°C near the volcanic front where the depth of the Moho is about 35 km. A possible geotherm near the volcanic front (VF) in NE Honshu is drawn based on these estimated temperatures (Figure 2). The geotherm near the coast of the Japan Sea is also constrained by the temperatures of the source regions for the primary high-alumina basalt and alkali olivine basalt magmas. The geotherm near the coast of the Japan Sea is slightly lower than that near the volcanic front. The temperature along the subducting slab is from TOKSOZ *et al.* (1971).

The phase relations for the mantle wedge in NE Honshu constructed from the experimental data are consistent with the mineral assemblages of peridotite inclusions in the tuff of Ichinomegata crater at the coast of Japan Sea, NE Honshu. The most abundant deep-seated inclusions at Ichinomegata are spinel-lherzolite. Many of them contain amphibole and some show evidence of partial melting such as the presence of interstitial glass and fine-grained crystal aggregates. These inclusions indicate

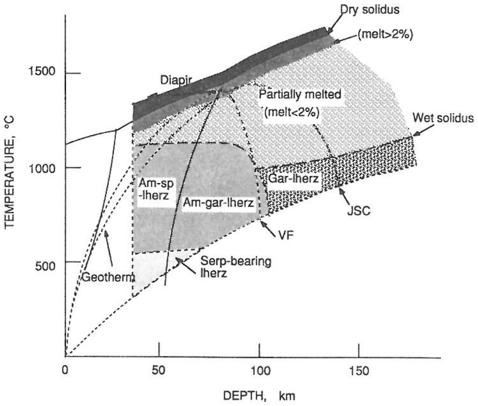

FIG. 2. Phase relations for hydrous lherzolite. Abbreviations: am, amphibole; gar, garnet; lherz, lherzolite; serp, serpentine; sp, spinel; VF, volcanic front; JSC, Japan Sea coast. Wet solidus with about 0.2 weight percent H_2O is from GREEN (1973), dry solidus from TAKAHASHI and KUSHIRO (1983), boundary between spinel- and garnet-lherzolite from O'HARA *et al.* (1971). See text for geotherms and partially melted region.

that H_2O exists in the mantle wedge in NE Honshu. The amount of $H_2O(+)$ in the Ichinomegata peridotite inclusions ranges from 0.09 to 0.44 weight percent with an average of 0.25 weight percent (KUNO and AOKI, 1970). These values, however, do not necessarily represent the H_2O content in the upper mantle. As shown below, this water content can be estimated indirectly from seismic wave velocities combined with the results of laboratory measurements of elastic wave velocities at high pressures and temperatures. The amount of H_2O thus estimated is less than 0.2 weight percent in most part of the mantle wedge. The phase relations for lherzolite under water-undersaturated conditions such as those with about 0.2 weight percent H_2O determined by GREEN (1973) would, therefore, be applicable. In Figure 2, the mineral assemblages for lherzolite are shown on the basis of the experimental results of GREEN (1973) for the stability field of amphibole-bearing lherzolite and the hydrous solidus, in addition to those of KUSHIRO and YODER (1966), YODER (1967), MACGREGOR (1974), O'HARA *et al.*, (1971) and OBATA (1976) for those of spinel- and garnet-lherzolites. The water-saturated solidii of some lherzolites are 100–150° lower depending on bulk composition according to the results by MYSEN and BOETTCHER (1975). The anhydrous solidus of lherzolite is based on the experimental results by TAKAHASHI and KUSHIRO (1983). Above the hydrous solidus, lherzolite containing H_2O should be partially melted. The amount of melt increases only slightly with increasing temperature above the hydrous solidus; however, near the anhydrous solidus, the amount of melt would increase rapidly. According to the experimental results of MYSEN and KUSHIRO (1977) on partial melting of a lherzolite in the presence of about 1.9 weight percent H_2O,* the amount of melt increases rapidly near the anhydrous solidus; from 5 to about 20% in a 50° temperature interval just below the anhydrous solidus. Because the amount of H_2O in the mantle wedge is about $^1/_{10}$ of that in the experiments by MYSEN and KUSHIRO (1977), the amount of melt formed would be also much smaller. However, the amount of melt must increase rapidly (>2 weight percent) within a 50° temperature interval immediately below the anhydrous solidus of lherzolite.

From the geotherms estimated for the volcanic front and the coast of the Japan Sea and the phase relations for lherzolite, a petrologic model in the mantle wedge of the NE Japan arc has been constructed (Figure 3). Beneath the volcanic front, amphibole-bearing lherzolite may be present in the uppermost part of the mantle, which is underlain by a region of partially melted lherzolite. The amount of melt in this region increases with increasing depth to 70–80 km or the highest temperature region and then decreases rapidly.

The partially melted spinel-lherzolite is underlain by a partially melted garnet-lherzolite at depths greater than about 80 km. Just above the subducted slab, there may be a thin zone of unmelted garnet-lherzolite. The thickness of this unmelted zone, however, depends on the temperatures of the hydrous solidus of lherzolite and the bottom of the mantle wedge and, because of the uncertainties of these temperatures, the thickness of this zone is not certain at present.

As mentioned above, the geotherm near the coast of the Japan Sea would be less steep than that near the volcanic front. In consequence, the amphibole-bearing lherzolite should have a wider stability range and the initiation of partial melting should be deeper. It is also expected that the zone of high degree of partial melting (melt >2%) becomes thinner toward the Japan Sea, although the partially melted region becomes thicker.

In the partially melted region where the amount of melt is less than 2%, the melt may not segregate but may stay along the grain boundaries. The source region of magmas probably contains more melt; that is, it is the region of higher degree of melting (>2%) as shown in Figure 3. As discussed below, this zone would also be the source of the diapirs. The presence of a sharp volcanic front requires termination of the zone of high degree of melting at the volcanic front (Figure 3).

The region of partial melting may extend to the aseismic front which is the ocean-side limit of the non-seismic region of the mantle wedge. The upper limit of partial melting may correspond to the depths at which diapirs stop ascending or the rate of their ascent become much less and magmas segregate from the diapirs. The depth of magma segregation increases from 35 to 60 km from the volcanic front to the coast of the Japan Sea in NE Japan (TATSUMI *et al.*, 1983). The region of partial melting should have low Q values. The low-Q region in the mantle wedge beneath the NE Japan arc (*e.g.*, YOSHII, 1979), though not well defined, is consis-

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* The amount of H_2O is probably lower. This amount is the total ignition loss including H_2O and CO_2. MYSEN and KUSHIRO (1977) assumed that this ignition loss was all due to H_2O. The composition of the melt formed, however, is slightly more silica-deficient than that formed under volatile-free conditions, suggesting the presence of CO_2 in the starting material.

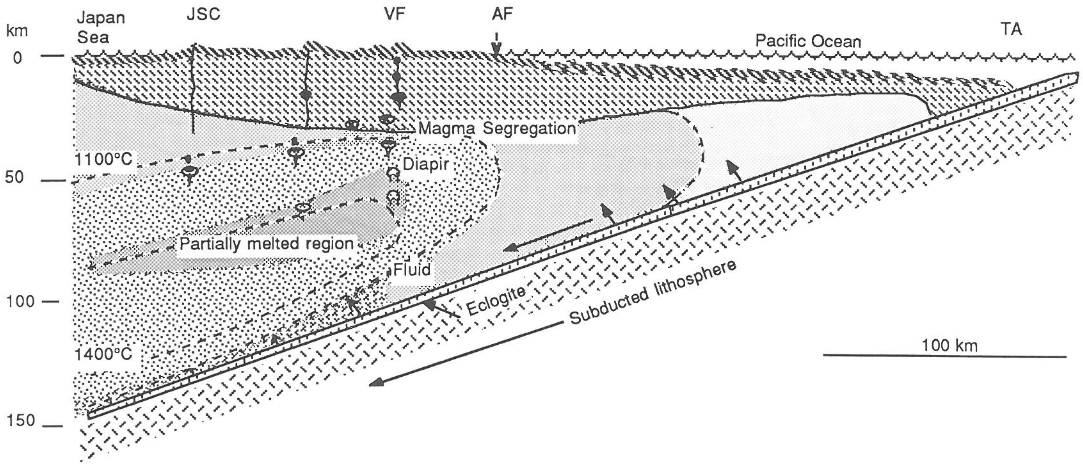

FIG. 3. A schematic cross section of the mantle wedge beneath the NE Japan arc. Abbreviations: TA, trench axis; others as in Figs. 1 and 2. Isotherms and depths of segregation of magmas from diapirs are from TATSUMI *et al.* (1983).

tent with the region of partial melting shown in Figure 3.

THE VELOCITY STRUCTURE OF SEISMIC WAVES AND THE AMOUNT OF MELT IN THE MANTLE WEDGE

The velocity structure in the mantle wedge beneath the NE Japan arc can be determined from the basis of the above petrological model and from the velocity measurements of peridotites at high pressures and temperatures by MURASE and KUSHIRO (1979) and MURASE and FUKUYAMA (1980). MURASE and KUSHIRO (1979) demonstrated that the compressional wave velocity of a spinel-lherzolite at 10 kbar decreases from 7.8 km/sec at 1000°C to 7.4 km/sec at 1225°C and sharply decreases to 7.0 km/sec at 1270°C when the amount of melt is about 3 volume percent. MURASE and FUKUYAMA (1980) measured the shear wave velocity of the same peridotite at 5 and 10 kbar in the temperature range between 1000 and 1400°C. They showed that the velocity decreases from 4.5 km/sec at 1100°C to 4.4 km/sec at 1200°C and to 4.0 km/sec at 1270°C at 10 kbar. The relation between the change of the compressional wave velocity and the degree of melting at 10 kbar is close to that at 5 kbar, although the absolute velocity is about 3% higher at 10 kbar than at 5 kbar. Assuming that the relation between the change of velocity and the degree of melting at 10 kbar can be applied to higher pressures (~30 kbar), the velocity structure for compressional wave in the shallow portion of the mantle wedge beneath the NE Japan arc can be constructed (Figure 4). The effect of pressure on the velocity obtained at 5 and 10 kbar was extrapolated to estimate the velocities at depths to 100 km. The velocity immediately below the Moho is estimated to be 7.6–7.8 km/sec in most part of the NE Japan arc (NE Honshu), which agrees fairly well with the actual velocities obtained (*e.g.*, YOSHII, 1979). The so-called "anomalous mantle" with relatively low velocity (as low as 7.5 km/sec), which lies just below the Moho in NE Japan, does not require phases with low velocities such as melt and plagioclase, but may be just due to relatively high temperatures in this zone. The velocity in the partially melted region with melt greater than 2% is smaller than 7.3 km/sec.

The three dimensional velocity structures in the mantle wedge beneath NE Honshu have been determined by HASEMI *et al.* (1984) and HASEGAWA *et al.* (1985) using the method of Aki and Lee (1976). The velocity structure in Figure 4 is compared with that obtained recently by HASEGAWA *et al.* (1985) who derived the velocity structures for both P and S waves. The results on the compressional wave velocity obtained by them at latitude of about 39°N (Figure 5) is quite consistent at least qualitatively with the velocity structure obtained by the experimental-petrological method. The velocity structures at different latitudes are more or less similar to that at 39°N. The rate of velocity decrease is, however, slightly smaller in the seismic model compared to the petrologic model; the region with velocity decrease greater than 4% in the seismic model corresponds to that with more than 5% decrease in the petrological model. This suggests that the melt in the mantle wedge assumed in the pet-

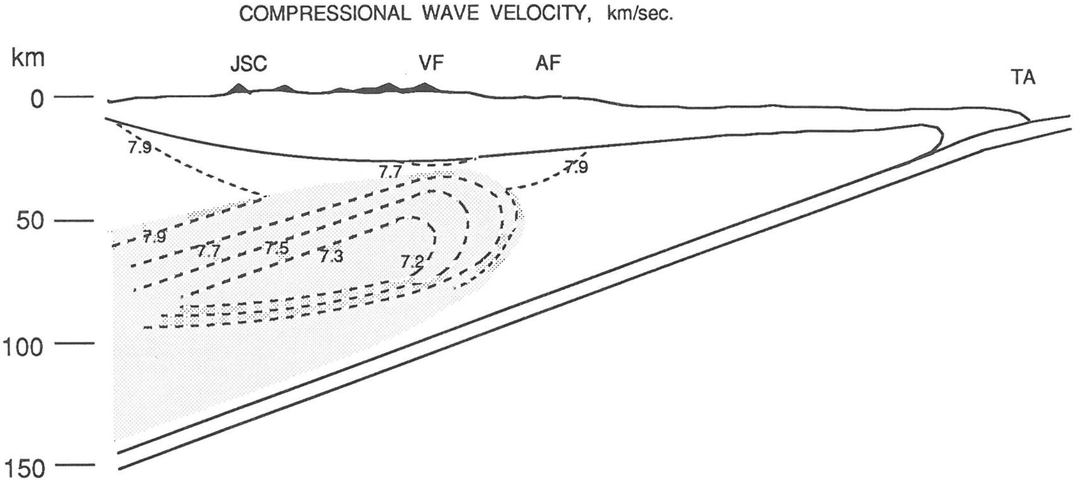

FIG. 4. Velocity structure for compressional wave in the mantle wedge beneath the NE Japan arc obtained by experimental petrological methods.

rologic model is slightly overestimated; about 1.5% instead of 2% melt would be most consistent with the velocity structure obtained by the seismic observations. Also, the depth of the low-velocity region is about 10 km deeper in the petrologic model than that in the three-dimensional velocity model. A similar velocity structure has been shown in the northern Kurile area by BOLDYREV (1985). In this case, the velocity decrease is about 6% beneath the volcanic zone at depths between 50 and 100 km, and 2% melt may explain such a velocity decrease. However, the velocity measurements and the estimation of such a small amount of melt include considerable uncertainties, and therefore, the above estimation of the amount of melt also includes significant uncertainties (but probably less than ±1% melt).

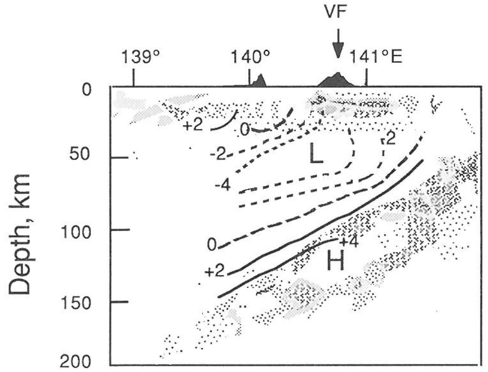

FIG. 5. Velocity structure for compressional wave in the mantle wedge beneath the NE Japan arc at 39°N obtained by the method of AKI and LEE (1976) using local earthquakes (HASEGAWA *et al.*, 1985). Dashed lines are isopleths for compressional wave velocity, and numbers indicate change of the compressional wave velocity (in percent) from the reference isopleths denoted as 0%. L and H denote the regions of low and high velocities, respectively. Dots indicate foci of local earthquakes.

The three-dimensional velocity structure for shear waves is similar to that for compressional waves, although the slowest region is located slightly to the ocean-side of the volcanic front. The maximum drop of the velocity is 6%, and the amount of melt for such a decrease estimated from the velocity measurements in the laboratory (MURASE and FUKUYAMA, 1980) is about 2% when the pressure effect is taken into account.

The maximum H_2O content in the mantle wedge can be estimated from the amount of melt and the solubility of H_2O in the melt. The solubility of H_2O in basaltic melts ranges from 10 to 20 weight percent in the pressure range between 10 and 20 kbar at 1000–1200°C. If the melt is saturated with H_2O and the amount of melt is 1.5 volume percent (~1.3 weight percent), the amount of H_2O in most parts of the mantle wedge is 0.07–0.13 weight percent. However, there is a possibility that local enrichment of H_2O may occur in some part of the mantle wedge.

DENSITIES OF MELT AND PARTIALLY MELTED MANTLE WEDGE

The densities of melts of basaltic compositions at pressures to 15 kbar can be obtained by a simple equation derived from the results of the density measurements of basaltic melts at high pressures with the falling/floating sphere method (FUJII and KUSHIRO, 1977; KUSHIRO, 1982, 1983). Within the limited pressure range, the equation is linear with a coefficient of 0.014 g/cm^3 kbar (KUSHIRO, 1986a). This is consistent with the compressibility of silicate melts obtained by shock wave measurements on a synthetic silicate melt (RIGDEN *et al.*, 1985). By using this equation and the method of BOTTINGA and WEILL (1970) for estimating the density of silicate melts at 1 atm, the densities of melts at shallow levels in the upper mantle can be calculated. The densities of anhydrous partial melts formed in the upper mantle thus calculated increases from 2.78 g/cm^3 at 8 kbar to 2.92 g/cm^3 at 15 kbar along the anhydrous solidus of peridotite (KUSHIRO, 1986a). Extrapolating the above equation to higher pressures, the density of partial melts is calculated to be 2.96 g/cm^3 at 20 kbar. The effect of H_2O on the density of silicate melts can be evaluated by the partial molar volume of H_2O given by BURNHAM and DAVIS (1969) and experimental data (KUSHIRO, 1986b); for example, 1 weight percent H_2O reduces the density of a basaltic melt by 0.05 g/cm^3 at 10 kbar.

The density variations of the mantle wedge beneath the NE Japan arc have been calculated based on the geotherms at the volcanic front and near the coast of Japan Sea. The compressibility and thermal expansivity of olivine and pyroxene (CLARK, 1966) have been used to calculate the densities of unmelted lherzolite and the crystalline portion of the partially melted lherzolite in the mantle wedge. The thermal expansivity of olivine above 1200°C used for the calculation is the extrapolated value. Figure 6 shows the results of these calculations.

At the volcanic front, the density of unmelted lherzolite is 3.23 g/cm^3 just below the Moho, decreases slightly to 3.215–3.22 g/cm^3 at 80–100 km where the temperature is highest (*i.e.*, $\sim$1400°C), and increases considerably with increasing depth below the minimum. In the presence of melt, the density decrease is more pronounced; if the maximum amount of melt is 3% at the highest temperature ($>$2% in the region of high-degree of partial melting), the density at the minimum is about 3.20 g/cm^3. Such a density reversal, though it is not large, may cause a density instability and trigger the ascent of diapirs. Once diapirs start ascending adiabatically, their bulk density decreases, although the temperature of the diapirs decreases. TATSUMI *et al.* (1983) calculated the rate of temperature decrease of a diapir, taking into account the heat of fusion of basalt at high pressures measured by FUKUYAMA (1985b). The density decrease of a diapir based on their calculation is shown in Figure 6. A diapir with a temperature of 1320°C at a depth of about 40 km, which contains about 20 weight percent melt as estimated on the basis of the experimental results by MYSEN and KUSHIRO (1977) has a density of about 3.14 g/cm^3.

Near the coast of the Japan Sea, the density of unmelted lherzolite is essentially constant to the depth of about 100 km and increases with increasing depth below 100 km. The amount of melt in this region is less than that at the volcanic front, so that the effect of melt on the density variation is smaller. The density reversal is, therefore, very small and ascent of diapirs may be less frequent and less intense than near the volcanic front. In addition, the rate of increase in the amount of melt in the diapirs is also smaller because the adiabatic ascending path of the diapirs from the region of highest temperature is close to the anhydrous solidus of peridotite, so that the amount of melt remains relatively small. This may explain the fact that the volcanic activity and the volume of the erupted materials decrease from the volcanic front toward the coast of Japan Sea across the NE Japan arc.

PETROLOGY OF THE LOWER CRUST IN NE AND SW JAPAN ARCS

Deep-seated inclusions are found in alkali basalts and tuffs in many localities in the Japanese Islands. Among these localities, Ichinomegata at the coast of the Japan Sea, NE Honshu (Figure 1), is best known, because the inclusions are abundant, fresh and variable in rock types and have been studied in detail by several investigators (KUNO, 1967; KUNO and AOKI, 1970; AOKI, 1971; TAKAHASHI, 1980, 1986; TANAKA and AOKI, 1981; FUKUYAMA, 1985a). Ichinomegata is one of the three tuff cones formed by an explosive eruption about 10,000 years ago and is one of the rare localities for deep-seated inclusions in island arcs. Most other localities in Japan are not in the typical island arc geological setting, but rather are in the back arc basin settings.

The inclusions in the Ichinomegata tuff cone consist of ultramafic rocks such as spinel-lherzolite with or without amphibole and plagioclase, harzburgite, wehrlite, and pyroxenite, and mafic rocks such as gabbro, granulite, amphibolite, and low grade metamorphic rocks. Most of the latter rocks are of crustal origin, and have not been studied in detail. AOKI (1971) analyzed minerals and bulk rocks of some gabbros and amphibolite, and TANAKA and AOKI (1981) analyzed trace elements (REE and Ba) in some gabbroic inclusions. Recently, FUKUYAMA (1985a) analyzed 57 gabbroic inclusions by the XRF method. In the present study the author re-examined under the microscope more than 200 mafic inclusions collected by H. Kuno,

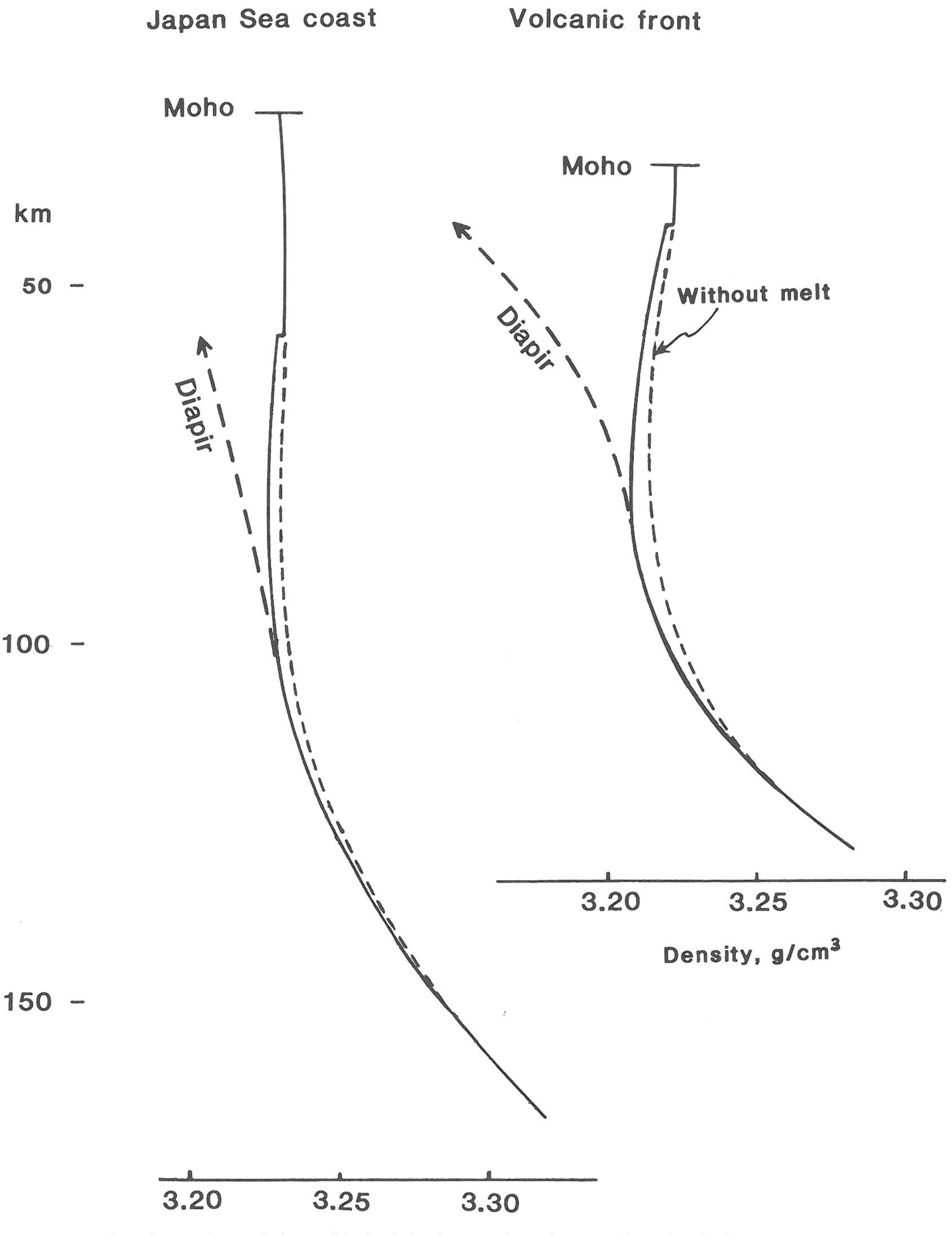

FIG. 6. Density variations with depth in the mantle wedge near the volcanic front and the coast of the Japan Sea and those of the ascending diapirs. The density has been calculated on the basis of the model shown in Figure 3. Dashed lines are the density variations without melt.

K. Ozawa and T. Fujii. Minerals in some of them have been analyzed with the electron microprobe.

According to AOKI (1971), FUKUYAMA (1985a) and this work, the mineral assemblages of the mafic inclusions are classified into the following different types; (1) ol + cpx + opx + hb + pl + mt, (2) ol

+ cpx + hb + pl + mt, (3) cpx + opx + hb + pl + mt, (4) cpx + hb + pl + mt, (5) opx + hb + pl + mt, and (6) hb + pl + mt (Abbreviations: cpx, clinopyroxene; hb, hornblende; mt, magnetite; ol, olivine; opx, orthopyroxene; pl, plagioclase). Apatite is present in most of these inclusions as an accessory mineral. Green spinel exists in some them, and is especially abundant in the assemblages (1) and (2) as a reaction product between olivine and plagioclase. Some of these inclusions show igneous textures and are gabbros but others show recrystallized textures and are metamorphic rocks. The gabbroic inclusions are in general very similar to the inclusions found in the Lesser Antilles lavas (*e.g.*, WAGER, 1962; LEWIS, 1973; ARCULUS and WILLIS, 1980); in particular the assemblages (1), (2) and (3) are identical to those described in St. Kitts, Dominica, and St. Vincent. Amphibole-bearing inclusions have been also reported in calc-alkaline volcanoes on Adak Island in the Aleutian arc (CONRAD and KAY, 1985; KAY *et al.*, 1986; DEBARI *et al.*, 1986), and are considered to be cumulates from calc-alkaline magmas. Phenocryst assemblages in calc-alkaline andesites in Shirouma-Oike, Myoko and other volcanoes in central Honshu (SAKUYAMA, 1978; 1981; and 1983b) are the same as the above six assemblages. Most of the metamorphic mafic inclusions have been described as amphibolite (AOKI, 1971; TAKAHASHI, 1978; FUKUYAMA, 1985a), and granulites have not been clearly mentioned among the Ichinomegata mafic inclusions, except IRVING (1974) who pointed the presence of granulite in these inclusions. In the present work, it was found that about 20% of the metamorphic inclusions are granulite consisting of aluminous clinopyroxene and orthopyroxene, plagioclase, amphibole with or without green spinel and magnetite. They show granular textures. Pyroxene crystals are in contact with one another with about 120° angle, indicating recrystallization to textural equilibrium. The granulites have mineral assemblages (1), (3) and (5); however, some are almost free of amphibole. Most of amphibole crystals contain numerous fine-grained inclusions of pyroxene and spinel and appear to be partially broken down. Some mafic inclusions contain olivine, which is often surrounded or replaced by pyroxene-spinel symplectite, especially near plagioclase crystals. The analyses of pyroxene (K. OZAWA and K. AOKI, personal communication, 1985) indicate that clinopyroxene ($\sim Ca_{49}Mg_{40}Fe_{11}$) and orthopyroxene ($\sim Ca_{1.1}Mg_{76.0}Fe_{22.9}$) contain up to 7.2 and 5.2 weight percent Al_2O_3, respectively. They are homogeneous in single rock specimens. Temperatures estimated by pyroxene geothermometry (WOOD and BANNO, 1973; WELLS, 1977) range from 830° to 870° depending on the inclusions. These temperatures are within the temperature range of the granulite facies. More detailed descriptions will be presented by Ozawa (in preparation).

The granulite inclusions with the orthopyroxene-clinopyroxene-spinel assemblage must have been formed or equilibrated on the higher-pressure or lower-temperature side of the reaction olivine + calcic plagioclase $\rightleftharpoons$ orthopyroxene + clinopyroxene + spinel. The pressure-temperature conditions for this reaction has been determined experimentally by KUSHIRO and YODER (1966), YODER (1967), GREEN and HIBBERSON (1970), EMSLIE (1970) and HERZBERG (1978). According to these studies the reaction takes place at 8–9 kbar at 1100°C and 7–8 kbar at 800°C for basaltic compositions (Figure 7). The inclusions containing relic olivine surrounded by spinel-pyroxene symplectite must have been cooled from a higher temperature to lower temperatures crossing the curve for this reaction. The absence of garnet gives a further constraint on the pressure; two-pyroxene granulite transforms to garnet granulite at about 10 kbar at 1100°C and about 9 kbar at 900°C (IRVING, 1974).

The lower crust of the Ichinomegata or NE Honshu has been considered to consist of amphibolite and hornblende gabbros (AOKI, 1971; TAKAHASHI, 1978, 1986). However, it is most likely that the lowest part of the crust in this region consists of granulite, although it may belong to the hornblende subfacies.

Some mafic inclusions have a greenschist facies assemblage consisting of chlorite, epidote, actinolitic amphibole and albite. They often show gabbroic textures; large elongated feldspar crystals and aggregates of mafic minerals, the form of which appears to be subhedral pyroxene or hornblende in gabbros. Such inclusions may have been originally gabbros which recrystallized under greenschist facies conditions.

FUKUYAMA (1985a) analyzed 57 mafic inclusions (mostly gabbroic inclusions) and found that their chemical compositions lie essentially between those of amphibole and plagioclase; they were interpreted to be cumulates from hydrous basaltic magmas. The chemical compositions of the metamorphic mafic inclusions (AOKI, 1971; FUKUYAMA, 1985a) are included in the compositional range of the gabbroic inclusions and they cannot be distinguished from each other.

It is strongly suggested that the metamorphic mafic inclusions were originally hornblende gabbro and they were later metamorphosed to granulite, amphibolite and greenschist depending on the depth

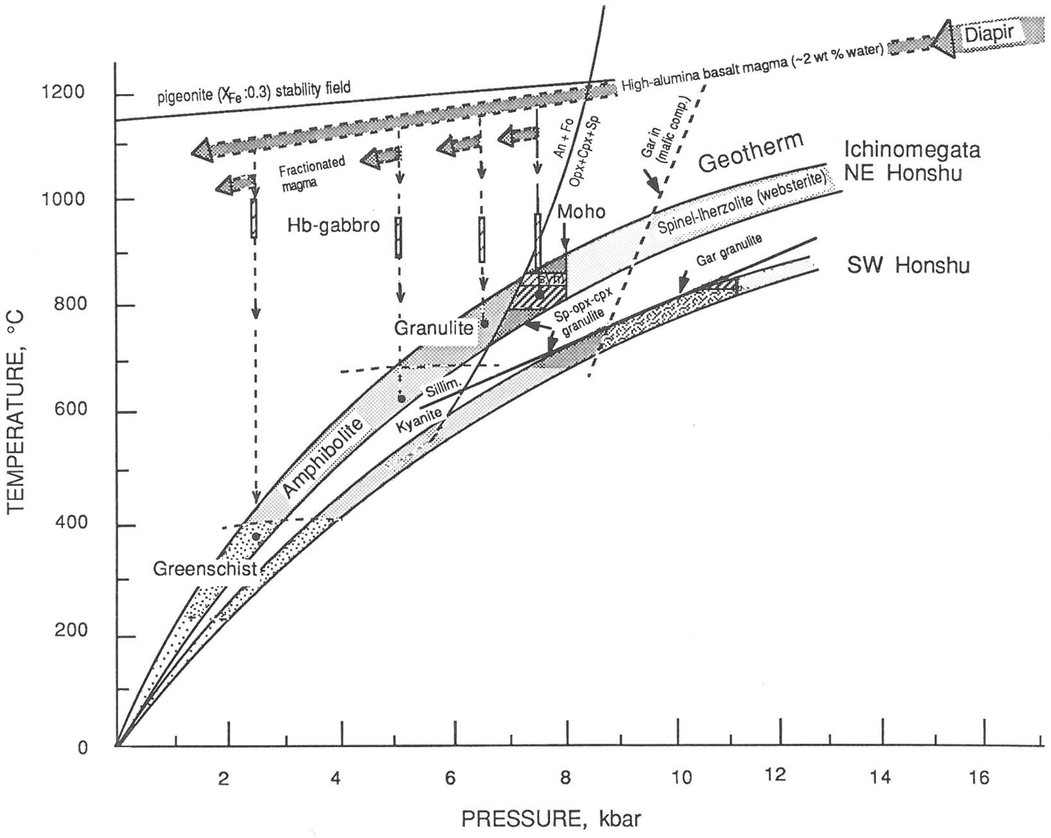

FIG. 7. Geotherms and rock types in the crusts at Ichinomegata in NE Japan and in central Chugoku district in SW Japan. The boundary curve for An + Fo ⇌ Opx + Cpx + SP is from KUSHIRO and YODER (1966), OBATA (1976), and HERZBERG (1978), the sillimanite-kyanite transition curve is from HOLDAWAY (1971), and the garnet-in curve for basaltic composition from IRVING (1974).

of metamorphism. The final equilibration temperature is assumed to lie on the geotherm. KAY and KAY (1985) and KAY *et al.* (1986) suggested that amphibole-free pyroxene granulites in the Aleutian arc could be remnants from the original oceanic crust on which the Aleutian volcanic islands were formed. Although this possibility cannot be entirely discarded in the NE Japan arc, the presence of amphibole with various degrees of breakdown and the bulk chemical compositions strongly suggest that the granulites were originally hornblende gabbros formed from arc magmas.

The geotherm has been estimated on the basis of the equilibrium temperature of granulite and the fact that there are many plagioclase-bearing lherzolite inclusions. The equilibration temperature of spinel- and plagioclase-lherzolites ranges from 800° to 1000°C (TAKAHASHI, 1980). Because these lherzolite inclusions are most probably upper mantle materials, the upper most mantle beneath Ichinomegata would have been once in the stability field of olivine and plagioclase. On the other hand, as mentioned above, spinel-two pyroxene granulites were probably materials of the lower part of the crust. This assemblage is stable on the higher pressure side of the above reaction where olivine + plagioclase assemblage is unstable. Such an apparent inconsistency may be explained by the compositional effect on the reaction; the reaction would take place at slightly higher pressures for ultramafic (more magnesian) compositions than for mafic compositions. Another possibility is that the upper mantle is more frequently heated locally by uprising hot diapirs or magmas than the lower crust, so that it becomes located to the higher temperature side of the reaction curve. In any case the Moho must be close to the boundary between the stability fields of olivine + calcic plagioclase and spinel + orthopyroxene + clinopyroxene assemblages. The equilibrium temperature of the spinel-two pyroxene granulites is 830°–870°C. The pressure range of the boundary within this temperature range is 7–8 kbar or a depth range of 20–25 km, which is not inconsistent with the depth of the Moho in this region estimated from seismic observations (YOSHII, 1979).

A possible geotherm at Ichinomegata is drawn in Figure 7 assuming that the spinel-two pyroxene granulite lies near the base of the crust, the condition of which is very close to that of the reaction of olivine and plagioclase. The geotherm should also extend to the source region of the basalt magmas (*i.e.*, ~1400°C at depth of about 100 km). This geotherm would be applicable to that near the coast of the Japan Sea in the NE Japan arc where the heat flow data, the distribution of volcanoes and the chemical compositions of volcanic rocks are similar to those near Ichinomegata. Near the volcanic front, however, the geotherm may be steeper. As mentioned before, the temperature of the source region for basalt magmas is higher near the volcanic front than near the coast of the Japan Sea when the temperature at the same depth is compared. This indicates that the temperatures of basalt magmas (at least those which formed gabbroic inclusions) were higher than those of basaltic magmas formed near the coast of Japan Sea. Other evidence which might support the higher geotherm near the volcanic front is that large volumes Quaternary felsic magmas have been erupted mostly near the volcanic front. At least some of such felsic magmas would have been formed by melting of the lower crust. Heat supply from the mantle must be significantly larger for the generation of the large volume of felsic magmas and in consequence, the geotherm would have become steeper.

In SW Honshu the geotherm is lower than that at Ichinomegata. Deep-seated inclusions in basaltic rocks in the Chugoku district, SW Honshu (Figure 1), have been studied by several investigators (MURAKAMI, 1954, 1975; KURASAWA *et al.*, 1961; KOYAGUCHI and FUJII, 1981). In the present study, inclusions of crustal rocks in alkali basalts in the central Chugoku district collected by M. Iwamori and the author have been examined. Among these inclusions, pyroxene gabbros and granulites are most abundant. Granulites are mostly quartz-bearing and often contain aluminous phases such as spinel, corundum, kyanite and garnet (MURAKAMI, 1954; KOYAGUCHI and FUJII, 1981; IWAMORI, 1986). No sillimanite has been found among the inclusions examined. Primary amphibole is absent in most of the inclusions. The presence of kyanite in granulites provides a constraint on the temperature of equilibration of these rocks. In Figure 7, the sillimanite-kyanite transition curve by HOLDAWAY (1971) is given. The temperature of a garnet-bearing granulite has been estimated by KOYAGUCHI and FUJII (1981) at about 820°C from plagioclase geothermometry. If kyanite-bearing granulite was equilibrated at a similar temperature, the geotherm must be very close to but at the lower temperature side of the kyanite-sillimanite transition curve, as shown in Figure 7. This geotherm, which is late Pliocene, is significantly lower than the Quaternary geotherms at Ichinomegata and that near the volcanic front in the NE Japan arc. In the central Chugoku district, necks and minor lava flows of alkali basalts of late Pliocene age are distributed widely, but no Quaternary volcanoes are present and the heat flow is low compared to the northern part of the Chugoku district where several Quaternary volcanoes are present (UYEDA and HORAI, 1964). Eruption of a small amount of alkali basalt magmas is a feature often observed in backarc basin and continental regions. As shown in Figure 7, the depth of the Moho must be deeper than 30 km in the central Chugoku district; it is significantly deeper than that at Ichinomegata. This is consistent with the thickness of the crust in the SW and NE Japan arcs determined from seismic wave velocities (*e.g.*, KANAMORI, 1963).

The geotherms in NE and SW Honshu are similar to the pressure-temperature conditions for some of the metamorthic facies series by MIYASHIRO (1961). The geotherm in NE Honshu especially that near the volcanic front is close to but slightly to the lower temperature side of the pressure-temperature path for the low pressure/temperature type metamorphic facies series represented by metamorphism in the Abukuma plateau studied by MIYASHIRO (1958) and SHIDO (1958). On the other hand, the geotherm in SW Honshu is close to the intermediate pressure/temperature type represented by metamorphism in the Grampian Highlands, Scotland studied by BARROW (1893), TILLEY (1925) and CHINNER (1960) among others. Such similarities of the geotherms might be applicable to the tectonic and geological settings of these old metamorphic terranes.

CHEMICAL COMPOSITIONS OF THE LOWER CRUSTAL MATERIALS

The chemical compositions of the inclusions of the lower crustal rocks in the NE and SW Honshu are compared. The analyses of the gabbroic inclusions at Ichinomegata have been made by KUNO (1967), AOKI (1971) and FUKUYAMA (1985a) with the conventional wet chemical analysis and the XRF methods. The average chemical composition by wet chemical analysis of the mafic inclusions including gabbroic rocks, granulite and amphibolite is given in Table 2. The composition is low in SiO_2 and alkalies and high in Al_2O_3 and CaO, and is not close to those of any basalt. The analyses are enriched in plagioclase and hornblende components. However, none of these analyses shows normative corundum. Most of the analyses actually plot in the region between calcic plagioclase and hornblende (FUKUYAMA, 1985a), and TANAKA and AOKI (1981) showed that two of three gabbro inclusions analyzed have positive Eu anomalies. It is probable that most of the mafic inclusions were formed by the accumulation of hornblende and calcic plagioclase crystallized from hydrous basaltic magmas. Under lower crustal conditions, calcic plagioclase floats in anhydrous basaltic magmas (KUSHIRO and FUJII, 1977); however, the density of hydrous basaltic magmas with an H_2O content of 1.5 weight percent is less than that of calcic plagioclase with An > 60 (KUSHIRO, 1986a). Cumulates of hornblende gabbro can, therefore, be formed from hydrous basaltic magmas containing 1.5 weight percent H_2O even at the base of the crust. The chemical composition of the residual liquids after subtraction of the average composition of the mafic inclusions from the primary high-alumina basalt is calc-alkalic andesite. It is certainly possible that calc-alkalic andesite magma can be formed from high-alumina basalt magma by removal of amphibole, magnetite and plagioclase with or without clinopyroxene.

The chemical compositions of 18 gabbroic and granulitic inclusions in basalts in SW Honshu have been analyzed by MURAKAMI (1975). Their average chemical composition is given in Table 2. It is higher in SiO_2 and alkali and poorer in CaO and MgO than that of the inclusions from Ichinomegata. Six of the granulite inclusions are, however, high in Al_2O_3 relative to CaO and alkalies and contain significant amounts of normative corundum in their norm. As mentioned above, some granulite inclusions, which were not analyzed, contain aluminous phases such as garnet, kyanite and corundum. These inclusions and especially those containing latter two minerals would also have normative corundum. The presence or absence of alumina-excess inclusions is a distinct difference between the inclusions at Ichinomegata and those in the SW Honshu.

Table 2. Average chemical composition of deep-seated crustal rocks in NE and SW Honshu

	NE Honshu* (29)	SW Honshu† (18)
SiO_2	43.99	50.98
TiO_2	0.92	0.89
Al_2O_3	18.06	18.28
Fe_2O_3	4.62	4.87
FeO	6.38	4.43
MnO	0.16	0.22
MgO	10.91	5.73
CaO	13.18	10.74
Na_2O	1.40	3.10
K_2O	0.22	0.67
P_2O_5	0.16	0.09
Total	100.00	100.00

* KUNO (1967), AOKI (1970) and FUKUYAMA (1985a). XRF analyses are not included.

† MURAKAMI (1975). Numbers in parentheses are the numbers of analyses averaged.

Formation of excess-alumina rocks by magmatic processes is rather difficult. Partial melting of peridotite or gabbro does not generate alumina-excess liquids at least under anhydrous conditions in the pressure range 10–30 kbar. Under hydrous conditions, however, it is possible to produce alumina-excess liquids by fractional crystallization when the reaction plagioclase + orthopyroxene $\rightleftharpoons$ clinopyroxene + liquid takes place (KUSHIRO and YODER, 1972; ELLIS and THOMPSON, 1986). Alumina-excess calc-alkalic andesite and dacite may have been formed by such a reaction. KUNO (1950) observed a fractional crystallization trend toward normative corundum compositions in the hypersthenic rock series ($\approx$ calc-alkalic rock series) in the Izu-Hakone region. The amount of normative corundum in the calc-alkalic andesite and dacite is, however, a few percent at most. On the other hand, the amount of normative corundum in the granulites mentioned above is generally larger. In addition, most of the inclusions in the SW Honshu do not contain primary hydrous minerals and may have been formed under nearly anhydrous conditions. Some of them are high in SiO_2 and the compositions are rather similar to those of pelitic sediments. It is most probable that aluminous sediments were metamorphosed to granulite under the lower crustal conditions. MURAKAMI (1975) mentioned this possibility based on the presence of rounded zircon crystals in some of the granulite inclusions. It is, thus, most probable that the lower crust of SW Honshu consists of gabbroic and metamorphosed sedimentary rocks. Some of the gabbroic rocks have a two-pyroxene spinel assemblage, and were probably recrystallized under the granulite facies conditions, similar to those in the Ichinomegata region.

A MODEL FOR THE FORMATION OF LOWER CRUSTAL ROCKS

As mentioned above, most of the mafic inclusions at Ichinomegata were originally hornblende gabbro formed by accumulation from hydrous basaltic magmas. The original magma of the cumulates is probably hydrous high-alumina basalt magmas because the Quaternary basalts erupted near Ichinomegata are high-alumina basalts. The condition of generation of the high-alumina basalt magma is about 40 km deep and 1350°C in the presence of a small amount of H_2O (1–2 weight percent). As mentioned above, the density of hydrous tholeiitic magmas with H_2O contents greater than 1.5 weight percent is smaller than that of calcic plagioclase ($>An_{65}$) at 8 kbar (KUSHIRO, 1986a), indicating that calcic plagioclase sinks in basaltic magmas even near the base of the crust. Based on thermodynamic calculations, POWELL (1978) suggested that the gabbroic inclusions in St. Vincent, Dominica and St. Kitts where mineral assemblages are the same as those of the Ichinomegata gabbroic inclusions were formed at pressures between 6 and 8 kbar (20–30 km). The cumulates containing calcic plagioclase would have been formed at various depths within the crust in the temperature range 900–1000°C. Although some cumulates were preserved, others were crystallized to metamorphic rocks with different metamorphic facies upon cooling toward the stable geotherm. These processes are illustrated in Figure 7.

The crust in NE Honshu must have been thickened essentially by the input of basalt magmas from the upper mantle, as illustrated in Figure 8. The basalt magmas were fractionated to produce cumulates of gabbros and residual magmas of andesite, dacite and rhyolite compositions. Apparently no sedimentary rocks were involved in the development of the major part of the crust. Only in the shallow parts or near the surface, sedimentary rocks are involved, but they are products of recycling processes near the surface and would not contribute to the overall thickening of the crust in general. Remelting of the lower part of the crust may have produced granitic magmas as inferred from the intrusions of Tertiary granites in the NE Honshu. Even if it occurred, however, it should not contribute to the thickening of the crust. Near the coast of the Japan Sea, magmas of high-alumina basalt or alkali olivine basalt with higher H_2O contents are supplied from the upper mantle into the crust, whereas near the volcanic front, olivine tholeiite magmas with lower H_2O contents are supplied. The cumulates formed within the crust must be also different; more hornblende gabbros near the coast of Japan Sea and more pyroxene gabbro near the volcanic front. In the Hakone volcano, for example, some andesitic breccias contain many pyroxene gabbro inclusions. They often include inverted pigeonite which has never been reported in hornblende gabbros at Ichinomegata and other areas near the coast of Japan Sea. Apparently, the magmas from which pyroxene gabbros crystallized were higher in temperature and contain less H_2O.

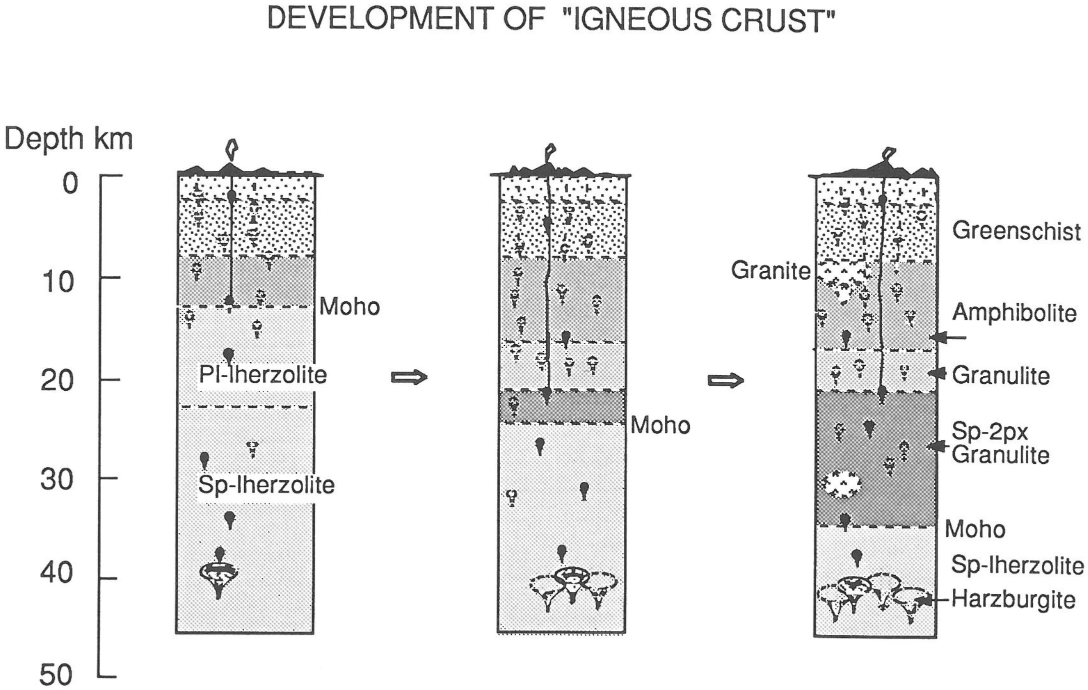

FIG. 8. Schematic pictures illustrating the development of 'igneous crust' in the volcanic zone of NE Japan and island arcs in general.

On the other hand, the deep-seated inclusions in SW Honshu would be partly of sedimentary origin as discussed above. Emplacement of the sedimentary rocks near the base of the crust must involve large scale tectonic movements. One possible mechanism is subduction of the oceanic plate, by which the sedimentary rocks as well as the volcanic rocks are accreted to the crust of SW Honshu. In the southern parts of SW Honshu (*i.e.*, southern Shikoku and Kyushu), the Shimanto group strata ranging in age from late Jurassic to early Tertiary are widely distributed. They are mainly sedimentary rocks with some basaltic rocks and are considered to have been accreted in association with subduction processes (*e.g.*, SUZUKI and HADA, 1979).

The evidence which may support the involvement of sedimentary rocks in the deep crust of the southern regions of SW Japan arc is that the Tertiary ilmenite-series granites, which are similar but not identical to the S-type granites (CHAPPEL and WHITE, 1974) or peraluminous granites, are distributed in these regions. On the other hand, the Tertiary magnetite-series granites, which are similar to the I-type granite, are distributed in the northern part of SW Honshu (ISHIHARA, 1977; TAKAHASHI *et al.*, 1980). It is suggested that these ilmenite-series granites were formed by remelting of the rocks of sedimentary origin or by reaction of basaltic magmas with these rocks in the lower part of the crust in this region (TAKAHASHI, 1986). On the other hand, magnetite-series granites were probably formed by remelting of igneous rocks or by fractional crystallization of basaltic magmas without significant interaction with sedimentary rocks.

In the island arcs where both magmatic activity and accretionary process take place, granite magmas of two different types (S and I types or ilmenite and magnetite series) would be generated; the I-type granites are formed mainly in the Quaternary volcanic zone and the S-type granites in the presently non-volcanic zone closer to the trench. ISHIHARA (1980) pointed out that the magnetite-series granites are generally distributed in the back arc basin side, whereas the ilmenite-series granites in the ocean side in island arcs, forming a double granite belt. The double granite or paired granite belts may be formed in matured island arcs within a limited time period. The paired granite belts appear to exist not only in the island arcs, but also in some parts in the continents such as SE Australia and the eastern part of China. Some of those might represent ancient island arc systems.

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APPENDIX

The melting experiments on the olivine tholeiite (IK85060803) from Ryozen district, NE Honshu have been made at pressures between 9.5 and 12.5 kbar and in the temperature range between 1290° and 1325°C under anhydrous conditions, using a solid-media, piston-cylinder apparatus. The piston-out method was employed. Temperature was measured with $Pt/Pt_{90}Rh_{10}$ thermocouples. Finely ground powder (<5 μm) of the rock was used as

Table 3. Results of runs on Ryozen olivine tholeiite

Pressure (kbar)	Temperature (°C)	Time (min.)	Results
9.5	1315	45	Ol + Gl
9.5	1305	60	Ol + Opx + Gl
9.5	1300	60	Ol + Opx + Gl
9.5	1290	150	Ol + Opx + Gl
10.5	1325	40	Gl
10.5	1315	60	Ol + Gl
11	1315	80	Ol + Opx + Gl
11	1315	420*	Ol + Opx + Gl
11	1306	60	Ol + Opx + Cpx(r) + Gl
11	1300	60	Ol(r) + Opx + Cpx + Gl
11	1292	60	Ol(r) + Opx + Cpx + Gl
11.5	1316	60	Opx + Gl
12.5	1325	60	Opx + Cpx(?) + Gl
12.5	1315	60	Opx + Cpx + Gl

Abbreviations: Cpx, clinopyroxene; Gl, glass; Ol, olivine; Opx, orthopyroxene; r, rare.

* Thus run was made in a graphite capsule which was sealed in a Pt capsule.

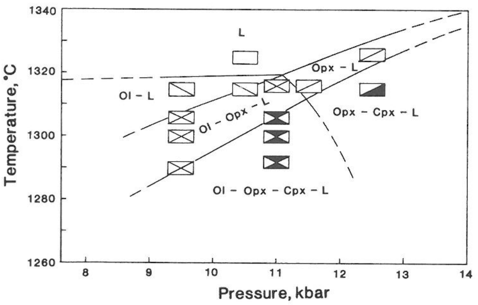

FIG. 9. Melting phase relations of olivine tholeiite (IK85060803) from Ryozen district, NE Honshu. The chemical composition is given in Table 1. Abbreviations: L, liquid; Ol, olivine; Opx, orthopyroxene; Cpx, clinopyroxene.

the starting material. Graphite capsule was used for all the runs. One critical run was made with a graphite capsule which was sealed in a Pt capsule for a longer duration. The results are shown in Table 3 and plotted in Figure 9. At pressures lower than 10.5 kbar, olivine is on the liquidus and above 11.5 kbar orthopyroxene is the liquidus phase. At 11 kbar both olivine (Fo_{89}) and orthopyroxene ($En_{89}Fs_{11}$) crystallize almost simultaneously on the liquidus at 1315°C. This run was made for both 80 and 420 minutes. The results of these runs were the same, except that the longer run showed growth of both olivine and orthopyroxene. At 11 kbar and 1306°C, olivine (Fo_{88}), orthopyroxene ($En_{88}Fs_{12}$) and clinopyroxene crystallize. The results indicate that the melt of this olivine tholeiite is in equilibrium with olivine and orthopyroxene at 11 kbar under anhydrous conditions. It is also indicated that the composition is close to an olivine-orthopyroxene-clinopyroxene cotectic under this condition.