9. Thermal history experienced by subducting sediments

9-1. Calculation of thermal process in the subducting lithosphere

Thermal evolution of subduction zone has been extensively investigated (e.g., Peacock, 1996; Iwamori, 1997). Studies hitherto mainly focus on the subduction shear zone. The subduction shear zone is a plane defined as the boundary plane between the subducting lithosphere and the mantle wedge. It is established from many two-dimensional numerical modeling studies that the subduction of cold oceanic plate rapidly cools the bordering mantle wedge. Inverted thermal structure is created around the subduction shear zone, and the steady state thermal structure is cool.

One of the objectives of previous studies is to elucidate the heat source for the volcanic magma formation in or beneath the mantle wedge. Despite the cooling underneath, crustal heat flux above the mantle wedge is higher than those at the other parts of the earth's surface. Peacock (1996) reviews various factors that affect the thermal structure of the subduction shear zone. Two of the most influential factors that heat the subduction shear zone are the frictional heat and the induced mantle convection in the mantle wedge. Peacock (1996: Figure 4D) shows the most possible temperature range for the subduction shear zone.

The estimated steady state thermal structure of the subduction shear zone is much cooler than the condition required for the epidote-amphibolite facies of the Sambagawa metamorphism. General P-T path for the Sambagawa metamorphism had been that the heating process for the high grade schists maintained until the early exhumation stage. In this case, the cool subducted sediments are able to achieve the epidote-amphibolite facies condition through the final stage of decompression and heating, (except for the problem that an unknown heat source is needed). Deduced P-T paths in this study only show heating and compression. It is suggested that the epidote-amphibolite facies condition was achieved during the subduction process, not exhumation. It must be examined whether the deduced pressure-temperature condition is feasible for the subducting sedimentary rocks.

The thermal structure of the subduction shear zone is not exactly what the subducting materials go through. It is a plate with certain thickness. Temperature of subduction shear zone only represents that of the top surface of the subducting layer. To determine the pressure-temperature path experienced by certain rock sample located deeper in the layer, heat transfer from the subduction shear zone must be considered.

Thermal evolution of a simple plate was numerically analyzed considering heat conduction (fig.9-1). A 10km-thick test layer was assumed,

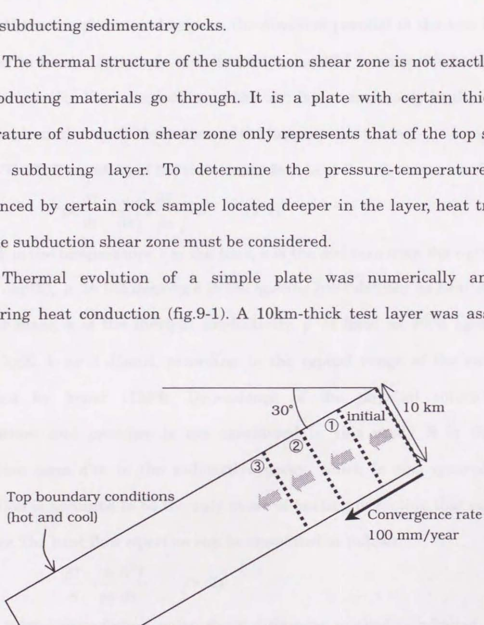

Fig.9-1. Calculation of the thermal evolution of the top layer of the subducting slab.

which represented the rocks on the top surface of the subducting lithosphere. Dip angle of the subduction zone was set to 30°. Convergence rate was supposed to be 100 mm/year, since the tectonic reconstruction for the time of the Sambagawa metamorphism suggested rapid subduction of the Izanagi plate toward the north (Wallis, 1998).

If the temperature change in the direction parallel to the test layer is assumed to be zero, a simple one-dimensional model is adequate to simulate the heat transfer. Heat conduction in the test layer occurs only in the vertical direction, from the top to the bottom of the layer or vice versa.

The full equation of the time-dependent heat flow is written as follows:

$$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) + S \qquad (9\text{-}1)$$

where T is the temperature, t is the time, x is the distance from the top surface (initial depth), ρ is the density, c is the specific heat defined as heat capacity per unit mass, k is the thermal conductivity. ρ is fixed as 3000 kg/m^3, c as 1000 J/kgK, k as 2 J/smK, according to the typical range of the constants tabulated by Spear (1993). Dependence of the physical constants on temperature and pressure is not considered in this study. S is the heat production term due to the radioactive decay, which is also ignored. Heat conduction is assumed to be the only cause of heating or cooling that occurs in the layer. The heat flow equation can be simplified as follows:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c} \frac{\partial^2 T}{\partial x^2} \qquad (9\text{-}2)$$

Numerical solution using finite difference method is adopted in this study (fig.9-2). The calculation consists of two operations:

(1) Displacement: the boundary temperature at the top surface of the test layer

is changed in response to subduction. The pressure changes accordingly.

(2) Heat conduction: the thermal structure within the test layer is allowed to diffuse.

Steps (1) and (2) were carried out iteratively until proper pressure was achieved. Time step for calculation, Δt, was set to 20,000 years, which allowed a displacement of 2 km parallel to the lithosphere, and a burial of 1 km (300 bar) for each time step. Depth step, Δx, was set to 100 m. Equations were solved with implicit method, using TDMA (TriDiagonal-Matrix Algorithm).

Given an initial thermal structure and certain boundary conditions, the vertical thermal structure of the test layer was calculated step by step. The initial temperature distribution of the layer was given as a steady state thermal structure. Two different heat fluxes were given as the bottom boundary conditions, which also defined the initial thermal gradients:

(cool-bottom): 70 mW/m^2 (35 °C /km, average heat flux of ocean floor).

(hot-bottom): 160 mW/m^2 (80 °C/km).

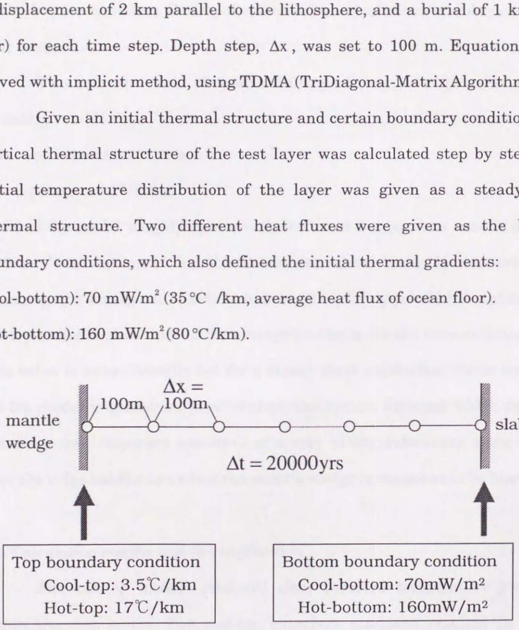

Fig.9-2. Finite difference model for the calculation of the heat conduction in the subducting sediments.

The temperature at the top boundary was fixed to 10°C. The heat flux for the cool-bottom model corresponds to that of the ocean floor of approximately 50 million years in age, according to GDH1 (global depth and heat flow) model by Stein and Stein (1992). The hot-bottom model corresponds to a 10-million-year-old ocean floor. The same heat flux was continuously given to the bottom boundary during the successive calculations of subduction and heat conduction.

Two extreme cases of temperature gradients were given as the top boundary conditions:

(cool-top): around 3.5 °C/km.

(hot-top): around 17 °C/km.

The cool-top model roughly agrees with the lower temperature case of Peacock (1996)'s "best estimate" for the subduction shear zone. It was estimated assuming the steady state subduction of 50-million-year-old lithosphere. The hot-top model is about half of the average geotherm for the oceanic lithosphere. This value is unrealistically hot for a steady state subduction shear zone. The hot-top model is presented here to show the hottest extreme, which probably simulates the temporary condition of a very young subduction zone, or just after the ridge subduction when the mantle wedge is supposed to be heated.

9-2. Calculation results and the implication

The hot-top models produced clear inverted temperature gradients within the test layers. The cool-top boundary condition resulted in rather overall heating of the layers.

The time series of the temperature conditions followed by rocks at certain distances from the subduction shear zone were examined. In combination with the depth informations, the experienced P-T paths were derived.

(1) (Cool-bottom) + (cool-top) model (fig.9-3)

This is the most feasible condition for an oceanic lithosphere of an age of 50 m.y. subducting under the steady state condition. The tested 10km-thick layer is warmed very slowly, so that it never passes through the epidote-amphibolite facies condition. The test layer remains cooler than around 300 °C until it reaches deep in the earth out of our sight.

(2) (Cool-bottom) + (hot-top) model (fig.9-4)

Unless the subducting oceanic plate is extraordinarily young, the shallower portion of the mantle wedge is supposed to be much cooler than this hot-top condition. This unrealistic boundary condition is given rather to create a case when the subducting rocks are heated from above and still the temperature reaches 500 °C within the depth of 30 km (9 kbar). It is demonstrated from this case that it is unrealistic for a subducting lithosphere of a moderate age to pass through the epidote-amphibolite facies condition.

The upper portion of the test layer is rapidly heated to create inverted thermal gradient. The rocks near the top surface were allowed to achieve the temperature of 500 °C or more before reaching to the depth of 30 km. The starting condition of the rocks is cool, so that they must be heated in a low dP/dT condition to achieve the epidote-amphibolite facies condition. The dP/dT obtained at the P-T condition of albite-biotite zone (520 °C, 9 kbar) will always

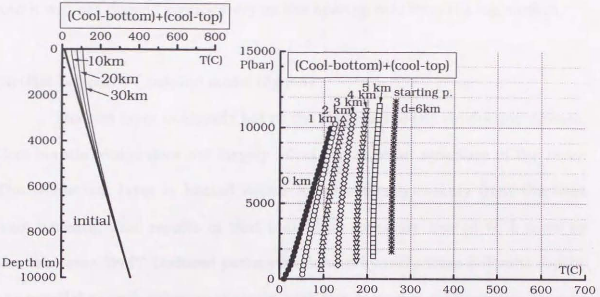

Fig.9-3. Thermal evolution of the test layer and the P-T paths for
(1) (Cool-bottom) + (cool-top) model.

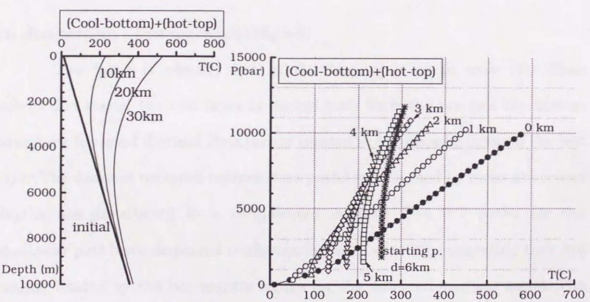

Fig.9-4. Thermal evolution of the test layer and the P-T paths for
(2) (Cool-bottom) + (hot-top) model.

be lower than that determined from garnet zoning in the previous chapters and it will not depend significantly on the heating rate from the top surface.

(3) (Hot-bottom) + (cool-top) model (fig.9-5)

The test layer is already hot at the initiation of the subduction process. Cool mantle wedge does not largely affect the thermal structure of the layer. The whole test layer is heated rather homogeneously, mainly from the heat from beneath. This results in that individual rocks are heated with more or less the same dP/dT. Deduced paths experienced by rocks from different depths are parallel to each other, in contrast with the dispersed configuration in case (2). The dP/dTs are much higher than those in case (2), and are concordant with the P-T paths derived from garnet zoning.

(4) (Hot-bottom) + (hot-top) model (fig.9-6)

The layer is already hot at the beginning as in case (3). When subduction starts, the test layer is heated both from the top and the bottom boundary. Inverted thermal structure is created in the upper portion of the test layer. The deduced pressure-temperature paths experienced by rocks at various depths are distributed in a complicated manner. The P-T paths for the shallower part have dispersed configuration as in case (2), suggesting they are mainly heated by the hot mantle wedge (or the subduction shear zone). The paths for the deeper starting points are roughly parallel to each other as in case (3), which imply that they are influenced by the high geotherm underneath.

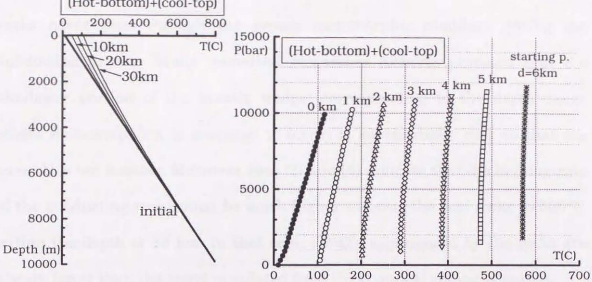

Fig.9-5. Thermal evolution of the test layer and the P-T paths for (3) (Hot-bottom) + (cool-top) model.

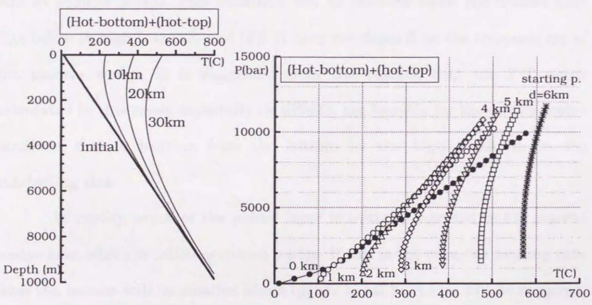

Fig.9-6. Thermal evolution of the test layer and the P-T paths for (4) (Hot-bottom) + (hot-top) model.

It is obvious from the results that the subducting sediments must be intensely heated either from the top or the bottom boundaries. Otherwise, the rocks never pass through the proper metamorphic condition during the subduction process. Many numerical researches hitherto proposed that the shallower portion of the mantle wedge (corresponding to the depth range where metamorphism is supposed to occur) is substantially cool, so that the case (2) is not feasible. Moreover, case (2) and (4) indicate that the heating rate of the subducting rocks must be much higher to bring the cool rocks to 500 °C within the depth of 30 km. In that case, dP/dTs experienced by the rocks are always lower than the trend calculated from the chemical zoning of garnet.

To achieve the starting conditions of the P-T paths deduced from garnet zoning (approx. 470 °C , 6 kbar), the rocks must be heated while they are still at shallow points. This condition can be realized when the crustal heat flux below is high (case (3) and (4)). It does not depend on the temperature of the mantle wedge. It is suggested from the results, that the P-T paths calculated in this study, especially its dP/dTs, are feasible for the metamorphic condition due to heating from the bottom by the high geotherm in the subducting slab.

In reality, much of the pelitic layer is initially accreted to the mantle wedge side, which is called accretion wedge. If this is the case, the heating rate from the bottom will be smaller. Much higher basal heat flux will be required, as the proposed ridge subduction (Iwamori, submitted), to bring the rocks into the epidote-amphibolite facies metamorphism. The above calculations represent the minimum estimates of heating rate. The temperature of the accretion wedge is largely controlled by the subducting plate, so that the above calculation will still be valid, except for the absolute value of heating.

10. Tectonic implication

10-1. Emplacement of the Iratsu metagabbro mass

From the spatial distribution of the garnet grains with composite zoning, it is clear that the formation of composite zoning is relevant to the tectonic blocks. It is most natural to explain the composite zoning as a result of the emplacement of the tectonic blocks.

It is suggested that the growths of garnet grains with normal zoning and those with composite zoning ceased in the same P-T condition. From the detailed analyses in the vicinity of the Iratsu metagabbro mass, there seemed to be no large discrepancy between the final temperatures recorded by the two types of garnet zoning. If the growth interruption recorded in the composite zoning corresponds to the emplacement, the event must have occurred while the environment was still on the heating and compression. Thus, it is concluded that the Iratsu metagabbro mass was incorporated in the Sambagawa schists during the subduction stage. After the emplacement, it is likely that the whole environment continued to heat and subduct that the garnet grains with composite zoning started growing again until the peak temperature.

Two important factors are legible from the composite zoning of garnet. Those factors help to define the characteristics of the event that corresponds to the emplacement of the Iratsu metagabbro.

Garnet growth was supposed to be interrupted by the emplacement, which not only prevented growing but also promoted resorption of the crystal. Deduced P-T histories in this study indicate that the temperature decreased during the resorption stage. Garnet formed under higher temperature may become unstable in lower temperature environment, therefore the cooling and the resorption are consistent with each other. It is suggested that the emplacement of the Iratsu metagabbro mass caused cooling of the surrounding schists.

The cooling obtained here seems inconsistent at a glance, considering that all the tectonic blocks were once metamorphosed under higher temperature conditions before the emplacement. In fact, most previous studies relevant to the tectonic blocks suggested that the tectonic blocks were hotter than the surrounding schists at the moment of emplacement. The Sebadani metagabbro mass was assumed to have been over 700°C just before the emplacement, which meant that the contact with the hot rock mass should have caused the surrounding basic rocks to develop "contact aureole". Omphacite grains observed in the aureole have grown in random direction, but not parallel to the schistosity. Takasu (1984) distinguished this texture from the schistosity-parallel omphacite, and called them prograde eclogite, meaning that they were produced by the high-pressure contact metamorphism. The feasibility of the contact metamorphism is recently in hot dispute. Aoya (1998) pointed out that the supposed total mass of the Sebadani rock mass is far too small to cause substantial thermal influence enough for the eclogitization of the surroundings. It is much more practical to think that the Sambagawa regional metamorphism is responsible for the development of the prograde eclogite. It is consistent with the result in this study that the Iratsu metagabbro did not heat the surrounding schists when it was incorporated in the Sambagawa metamorphic belt.

Another factor recorded in the composite zoning of garnet is the mechanical mixing of the schists. Composite zoning records two processes of prograde growths in each grain. The earlier growth is supposed to have grown before the emplacement, and the later growth formed after the event. There are samples that contain garnet grains with different chemical compositions exclusively for the earlier growth. The only possible explanation is the mechanical mixing of the schists during the time interval between the earlier and the later growths. The mechanism is also supported by the alternating layers of pelitic and basic appearances with a thickness of a few millimeters. It is suggested that the mechanical mixing was promoted during the garnet resorption stage, simultaneously with the emplacement of the Iratsu metagabbro. It is reasonable that the emplacement of such a large tectonic block caused ductile flow of rocks, which lead to the mechanical mixing of the surrounding schists with different bulk chemical composition. After the mixing, it is suggested that the matrix chlorite was quickly homogenized due to chemical diffusion. The later growth of the composite zoning occurred in equilibrium with the homogeneous matrix, resulting in the equivalent chemical compositions even for the grains that originated from different bulk rock chemistry.

The feature of the emplacement event recorded in the composite zoning is summarized as follows: (1) the emplacement did not result in heating of the surrounding schists, rather cooled them, (2) mechanical mixing of rocks with different bulk chemistry may have occurred in the vicinity of the tectonic blocks in response to the emplacement.

The cause of the cooling is yet uncertain. Though the simplest answer may be that the Iratsu metagabbro itself was cooler than the surroundings, it is not too feasible to assume a cool rock mass suddenly appear on the way of subducting sediments. Instead, cooling should occur corresponding to the ductile flow caused by the emplacement. If the schists with slightly different temperatures were forced to meet, cooling must be recorded in the schists with the higher temperature.

As discussed before, the composite zoning always formed onto the garnet with Ca-poor core. It is implied that the influence of the emplacement occurred selectively in the schists that contained garnet with Ca-poor normal zoning. If the Ca-rich and Ca-poor normal zoning represent the initial spatial difference between the schists, it is reasonable that the schists had different temperatures when they became together as they are observed today. From the fact that the cooling is recorded selectively in the Ca-poor garnet, it is suggested that the schists with the Ca-poor garnet had the higher temperature. It is known that the Ca-poor normal zoning is mainly distributed in the oligoclase-biotite zone, which is consistent with the above speculation that they represent the higher temperature schists. It is possible that the cooling recorded in the composite zoning was formed when the high temperature schists with Ca-poor garnet were forced to meet the cooler schists with Ca-rich garnet. The extensive ductile flow that caused the meeting of the rocks with different temperatures was probably due to the emplacement of the Iratsu metagabbro mass.

10-2. The Sambagawa metamorphism

The deduced P-T paths from garnet indicated minor heating and rapid compression. There was no evidence of simultaneous heating and exhumation, as previously noted. Zoning of grossular content in garnet was thought to be the evidence that indicated exhumation and heating at the same time. It was made clear from this study that the trend of grossular content does not necessarily indicate the pressure change.

The mechanism for the heating during exhumation was assigned to the relaxation of the thermal structure of the subduction zone. If the subduction zone is very young, its thermal structure may not be stable. The subducting cold plate will be continuously heated from the still hot surroundings even if it stops subducting and starts moving upward (Enami, 1994). Actually in the young subduction zone, the surrounding rocks keep on cooling because of the cold subducting lithosphere. It is shown from the numerical studies that the cold lithosphere moving into the mantle does not allow the surrounding mantle to recover its heat (Iwamori, 1997). If a rock mass stopped subducting and stayed at a certain depth, it will be successively cooled by the colder subsequent lithosphere. It is thus not feasible that the Sambagawa schists kept warming after they stopped subducting.

It is not necessary to assume such unrealistic heating processes if the derived P-T paths are adopted. There are still other observations that indicate decompression, but none of those are certain whether they occurred simultaneously with heating. It is possible that they were formed during the temperature decrease.

From the thermal calculation in the previous chapter, it was shown that the derived dP/dT was consistent with the heating from the subducting lithosphere. It was also suggested that to realize the epidote-amphibolite facies metamorphism, an enormous heat must be supplied from the bottom. This is consistent with the previous numerical simulation for the subduction zone, that points out that the temperature condition of steady state subduction zone is not enough to cause medium grade metamorphism (Iwamori, submitted). The Sambagawa metamorphism may be the product of the subduction of the lithosphere with very high crustal heat flux (i.e., subduction of an oceanic ridge).

When the sedimentary rocks are heated from the bottom, the deeper rocks will be heated more intensely. As a result, rocks from the deeper part will be subject to higher grade metamorphism. This is inconsistent with the previous model for the macroscopic structure of the Sambagawa metamorphic belt. One of the characteristic structures of the Samgabawa metamorphism is the inverted thermal structure found from the studies of the chemical zoning in minerals. Banno et al. (1986) pointed out that the difference of the chemical zoning in garnet from different metamorphic grade was explained in terms of the difference of pressure. Their forward calculation model implied that the P-T paths experienced by the higher grade rocks were relatively lower in pressure. It was shown from the chemical zoning of amphiboles that the higher grade rocks apparently lack the high pressure phase in their histories (Hara et al., 1990; Enami, 1994). These observations lead to the conclusion that the whole Sambagawa sequence represents the inverted thermal structure created at the subduction shear zone.

However, the comparison of pressure is only valid in relative terms. It only indicates that the oligoclase-biotite zone located shallower than the garnet zone "when they were at the same temperature". There is no evidence that they achieved the same temperature at the same time. Furthermore, the derived P-T paths for the albite-biotite zone never passes the temperature range for the garnet zone or the oligoclase-biotite zone. The high dP/dT suggests that the comparison at the same temperature will not be effective for the examination of the large-scale structure of the Sambagawa belt.

P-T paths are calculated from the representative chemical trends of garnet grains in the Sambagawa metamorphic belt (fig.10-1). The biotite-bearing system was assumed for grains in the oligoclase-biotite zone, the biotite-free system for the albite-biotite and the garnet zone. If the biotite-free system is applied, the P-T paths will be shorter (the starting point will be at higher pressure) but the shape of the overall trend will not change greatly. It is remarkable that the dP/dT of the derived P-T paths for the different metamorphic grades roughly agree with each other. The configuration of the three P-T paths shows good agreement with the calculated thermal process for the rocks with different depth, heated from the bottom (previous chapter). Although the oligoclase-biotite zone rocks located deeper, they were intensely heated that they experienced the same temperature at relatively shallow locations compared to the garnet zone rocks. It is suggested that the inverted thermal structure of the subduction shear zone is not necessary to explain the structure of the Sambagawa metamorphic belt.

Difference of the age of the subduction zone was also assigned as the cause of the difference in the recorded dP/dT (Enami, 1994). Materials subducted earlier into a young subduction zone will experience more heating. The oligoclase-biotite zone is supposed to have subducted first, reaching to the highest temperature. However, the difference in age is not a necessary condition to create the grades of the Sambagawa metamorphic belt. As seen in the figures shown in the previous chapter, it is possible to realize the three P-T paths simultaneously.

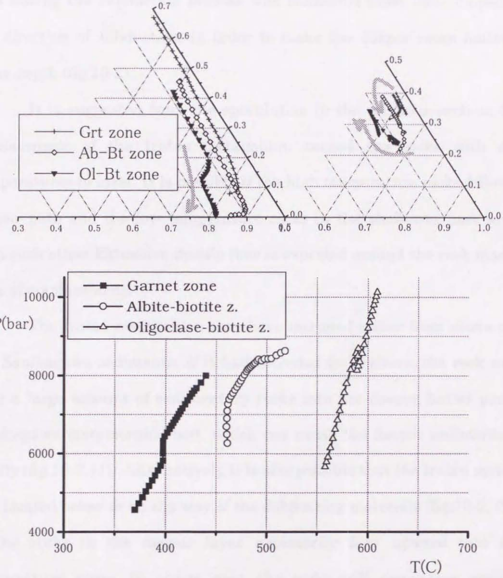

Fig.10-1. Chemical trends of the representative chemical zoning of garnet from each metamorphic zone and the derived P-T paths. The biotite-free system was applied to the garnet and albite-biotite zones, biotite-bearing system to the oligoclase-biotite zone.

Observations hitherto are consistent with the configuration that the higher grade schists of the Sambagawa metamorphic belt located in the deeper part during the subduction process. The isotherms must have dipped toward the direction of subduction, in order to make the deeper rocks hotter at the same depth (fig.10-2).

It is suggested from the speculation in the previous section, that the emplacement of the Iratsu metagabbro caused the rocks with different temperatures to meet. It is possible if the high temperature rocks following the deeper path and the low temperature rocks in the shallower part are mixed with each other. Extensive ductile flow is expected around the rock mass at the time of emplacement.

The Iratsu metagabbro may have intruded either from above or below the Sambagawa sediments. If it had intruded from above, the rock mass can drag a large amount of sedimentary rocks into the deeper, hotter part of the Sambagawa metamorphic belt, which can cause the deeper sediments to cool locally (fig.10-2, (1)). Alternatively, it is also possible that the Iratsu metagabbro was located below or on the way of the subducting materials (fig.10-2, (2)). Part of the rocks in the deeper layer necessarily flow upward into the low temperature zones. In either case, the rocks will experience cooling and mechanical mixing due to the emplacement of the tectonic block, which is consistent with the observations in this study.

It is up to the future research to determine which case is the truth. However, the case (2) seems more reasonable as far as speculating from our current knowledge. First, the tectonic blocks are concentrated at the same level within the stratigraphic sequence, namely the Upper Minawa Formation. It is

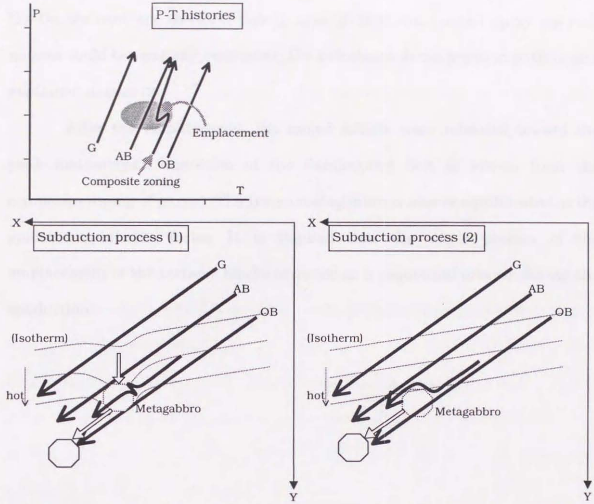

Fig.10-2. Summary of the derived P-T paths of the Sambagawa metamorphic belt and the two possible spatial configurations during the subduction process. (1): The tectonic block dragged the colder sediments into the deeper layer. (2): Part of the hotter sediments in the deeper layer were brought upward due to the tectonic block.

not likely to find them at similar locations if each exotic rock mass was brought in as the result of such large scale motion. It is more realistic to assume that the rock masses were rather static relative to the whole subducting sediments after they were incorporated in the Sambagawa belt. Secondly, the amount of the colder schists needed to cool the surroundings as assumed in case (1) may be unrealistically large. Thirdly, the observation suggests that the formation of the composite zoning in garnet was locally restricted in the narrow area around the tectonic blocks. The influence of cooling should be widely distributed in case

(1). On the contrary, the local flow in case (2) that was pushed up by the rock masses could be spatially restricted. The calculated decompression path is also explained in case (2).

After the emplacement, the cooled schists were reheated toward the peak metamorphic condition of the Sambagawa belt as shown from the composite zoning of garnet. The Iratsu metagabbro is also re-equilibrated at the epidote-amphibolite facies. It is implied that the whole process of the emplacement of the tectonic blocks occurred as a sequential process during the subduction.

Conclusion

Various patterns of garnet zoning found in the vicinity of the Iratsu metagabbro mass were analyzed in detail. Several distinct growth stages were recognized in the garnet grains. Non-equilibrium growth that promoted the formation of sector zoning was identified. The time period when the non-equilibrium growth occurred was known to be the final stage of the garnet growth.

Pressure-temperature paths were calculated from the garnet zoning using the differential thermodynamic method. The derived paths from normal zoning of garnet showed heating and compression. On the other hand, composite zoning indicated interruption and cooling in the midst of the growth. After the interruption, the grains indicated heating and compression for the second time until the rim. The interruption was supposed to be due to the emplacement of the Iratsu metagabbro.

It was suggested that tectonic block was incorporated into the Sambagawa pelitic schists during the subduction stage. It then moved together with the surrounding schists to experience the peak epidote-amphibolite facies metamorphism.

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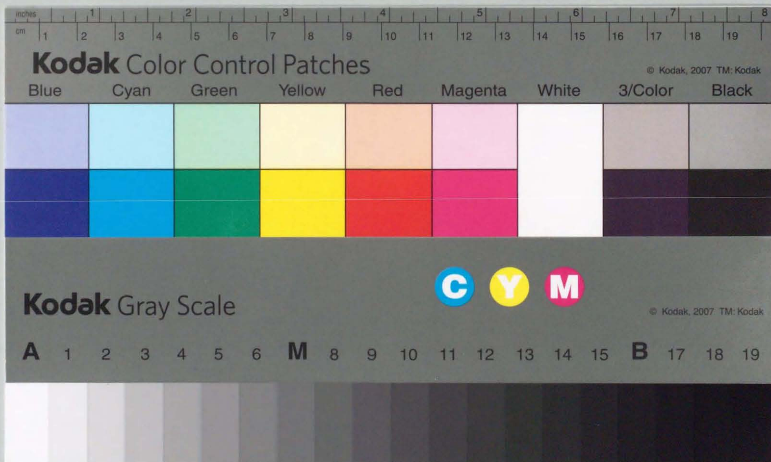
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