V. Macrorhythmic unit in the olivine cumulate of the Toba ultramafic complex : a direct evidence for boundary layer fractionation

1. Introduction

Crystallization occurs by heat loss from outer margin of a magma chamber. Since silicate melt usually is not eutectic composition, crystal mush is formed at the boundary between solidified rock and magma. The fractionation process caused by the movement of interstitial liquid from the marginal solidified zone between liquidus and solidus to the main chamber is named in-situ fractionation(Langmuir, 1989) or boundary layer fractionation (Nielsen and DeLong, 1992). The important mechanism of the boundary layer fractionation is ability of subtraction of such components that are not contained in liquidus phases in the magma chamber(Langmuir, 1989). Boundary layer fractionation can make fractionated magma which only contains primary phenocrysts.

Boundary layer fractionation has been discussed mainly by the numerical method to calculate best-fit melt for natural silicate melt. Tait(1988, 1989) and Turbeville(1992) discussed boundary layer crystallization by the xenolith in tephra. Because xenolith is often quenched, analyses of interstitial liquid is able to do. But in the studies of xenolith, there is lack of geological information. The problem of the numerical model is simple assumption of process in boundary layer. For the crystallization in the boundary layer, Langmuir(1989) assumed equilibrium crystallization and Nielsen and DeLong(1992) assumed fractional crystallization. In these modals, there is lack of discussion of the chemical and thermal gradient in boundary layer. These gradients are important for the

boundary layer fractionation because crystallizing minerals is affected by them. And they did not discuss movement process and mechanism of fractionated interstitial liquid.

Therefore it is very important to investigate cumulates for the evidence of the boundary layer fractionation. But there is a scarce direct evidence for the fact that cumulates were formed by boundary layer fractionation. Michael(1984) proposed in situ fractional crystallization for the Cordillera Paine granite. I will present some lines of evidence for that macrorhythmic unit in olivine cumulate of the Toba complex is caused by boundary layer crystallization. On the basis of petrology of those macrorhythmic unit, I will propose a model for boundary layer in which interstitial liquid is migrating.

2. Petrography of columnar section

The Toba ultramafic complex is characterized by layering of olivine cumulate and olivine clinopyroxene cumulate. In Fig.5-1, the locality of the outcrop for the columnar section is shown. The outcrop is located in a quarry along the western coast of the Sugashima island. The photograph of the outcrop is shown in Fig.5-2. Olivine clinopyroxene cumulate(wherlite and clinopyroxene gabbro; white part) overlies olivine cumulate(black part), which is overlain by another cycle of olivine-olivine clinopyroxene cumulates. The base of the lower olivine cumulate cannot be seen. Clinopyroxene gabbro intruded into wherlite. Xenoliths of wherlite are observed in clinopyroxene gabbros. The xenoliths are platy and a few meters long and several centimeters thick. Samples were collected by 1m intervals.

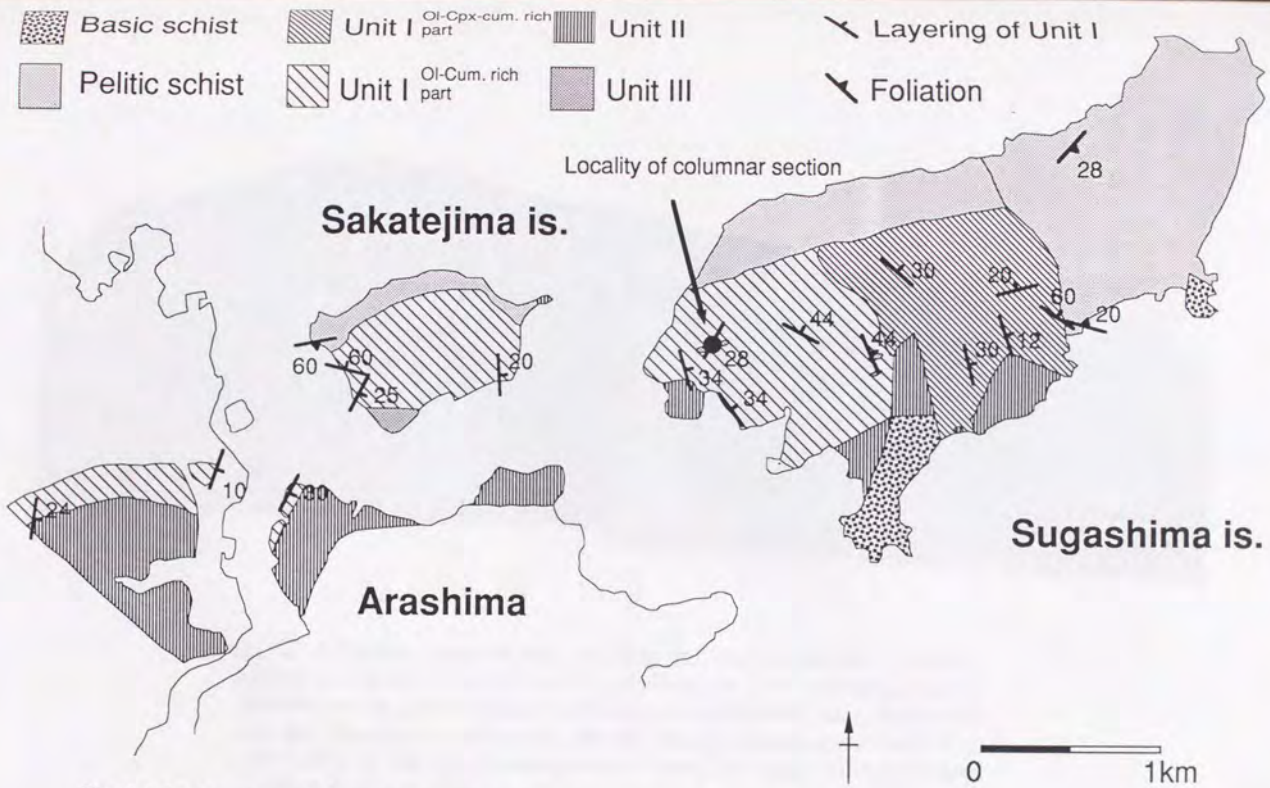


Fig.5-1 Index map of the columnar section. The columnar section is located on the western coast of the Sugashima island.

Fig.5-2 A photograph of the outcrop for the columnar section. Olivine clinopyroxene cumulate(wherlite and clinopyroxene gabbro: white part) overlies olivine cumulate(black part) and next olivine cumulate overlies the olivine clinopyroxene cumulate. The thickness of olivine clinopyroxene cumulate and clinopyroxene gabbro is about 20m.

Modal composition and texture

The modal composition and texture of olivine cumulate cyclically change. Olivine cumulate zone can be divided into 10 to 15 meters thick macrorhythmic unit(Irvine, 1982) by the modal composition of cumulus phases(Fig.5-3). The modal percent of the cumulus phases, olivine and spinel, is 80% at the bottom of the unit. It increases toward the top of the unit. At the top, the modal composition of cumulus phases is 95%. Ratio of hornblende in interstitial phases increases from the bottom to the top. Sometimes euhedral clinopyroxene is found at the top. The texture also changes as the modal composition increases. At the bottom of the unit, olivine is subhedral and elongated. The grain size of olivine is up to 2cm long. Poikilitic clinopyroxene, plagioclase and hornblende crystallized in interstitial space of olivine and spinel(Plate5-1A). At the top of the unit, olivine is equigranular and the grain size of olivine is up to 2mm long(Plate5-1B).

3. Mineral chemistry

Spinel

In the columnar section, chemical composition of spinel well correlates to the modal composition, although spinel in each thin section has wide chemical variation caused by interstitial liquid crystallization. Spinel enclosed in olivine is selectively analyzed. TiO_2 content and YFe value of spinel increase from the bottom to the top of the unit as the modal composition of cumulus phases increases(Fig.5-4). Typical unit is from 49 to 43m below from the top of the columnar section(Fig.5-4). The minimum TiO_2 content of spinel increases from 0.2wt.% at the bottom to 2.6wt.% at the top of the unit. The minimum YFe also increases from 0.21 to 0.25.

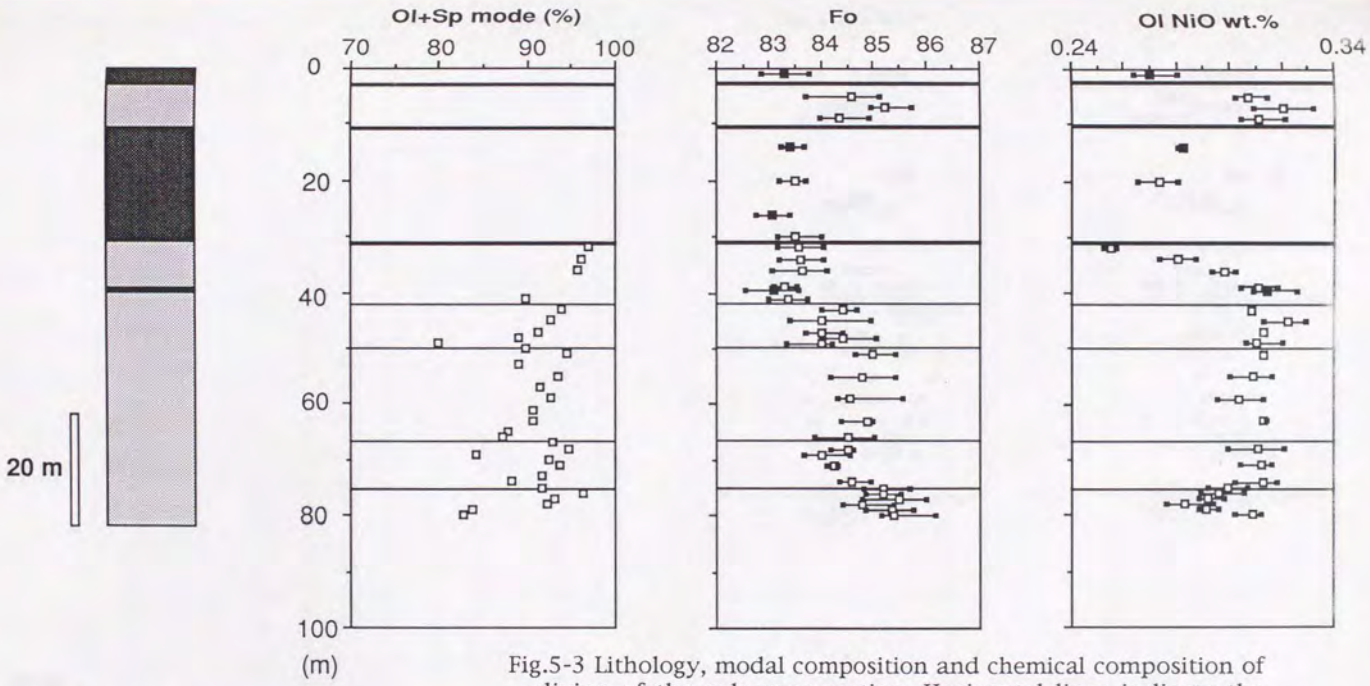


Fig.5-3 Lithology, modal composition and chemical composition of olivine of the columnar section. Horizontal lines indicate the boundary of macrorhythmic unit. Horizontal bold lines show the boundary between olivine cumulate and olivine clinopyroxene cumulate. Horizontal bar in column of olivine chemistry indicates the range in each thin section: open square; average composition in one thin section of olivine cumulate, filled square; average composition in one thin section of olivine clinopyroxene cumulate.

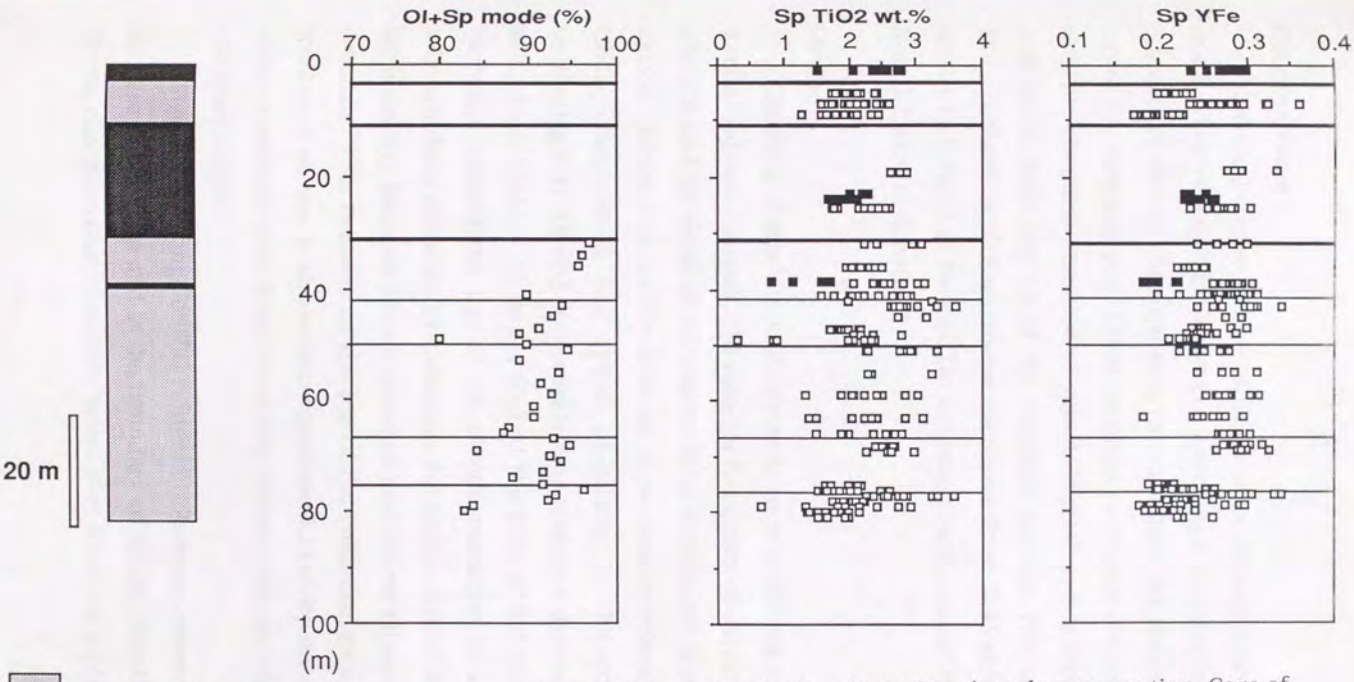


Fig.5-4 Chemical variation of spinel in the columnar section. Core of spinel enclosed in olivine was selectively analyzed. Chemical variation of spinel well correlates to the modal composition. The unit boundary defined by modal composition is shown by horizontal line.

Clinopyroxene

Chemical composition of clinopyroxene also correlates to the modal composition as in the case of spinel(Fig.5-5). Na_2O and TiO_2 contents of core of clinopyroxene increase from the bottom to the top of the cumulus pile. These chemical variations are consistent with the chemical variation of spinel. Typical unit is from 49 to 43m below from the top of the columnar section. The minimum TiO_2 content of clinopyroxene increases from 0.45wt.% at the bottom to 0.7wt.% at the top. The minimum Na_2O content increases from 0.2 wt.% to 0.4wt%.

Olivine

Chemical composition of olivine in each grain and each thin section is almost constant. The range of Fo content of olivine is up to 1.5mol% and the range of NiO content is up to 0.01wt.% in each thin section. Olivine composition does not show clear correlation to the modal composition and spinel chemistry in the columnar section(Fig.5-3). Olivine is relatively homogeneous thorough each unit. Fo content of olivine is 85.5 at the base of the outcrop. It decreases toward the top of the olivine cumulate as a whole, although there are some irregularities. Forsterite content is 83.5 at the boundary between olivine cumulate and olivine clinopyroxene cumulate, 32m below from the top of the columnar section. NiO content of olivine is almost homogeneous(0.31wt.%) through the olivine cumulate zone from 74 to 40m below from the top of the columnar section.

Significant change of NiO content of olivine is observed near the base of out crop and at the boundary of olivine cumulate and olivine clinopyroxene cumulate, below 31m from the top(Fig.5-3).

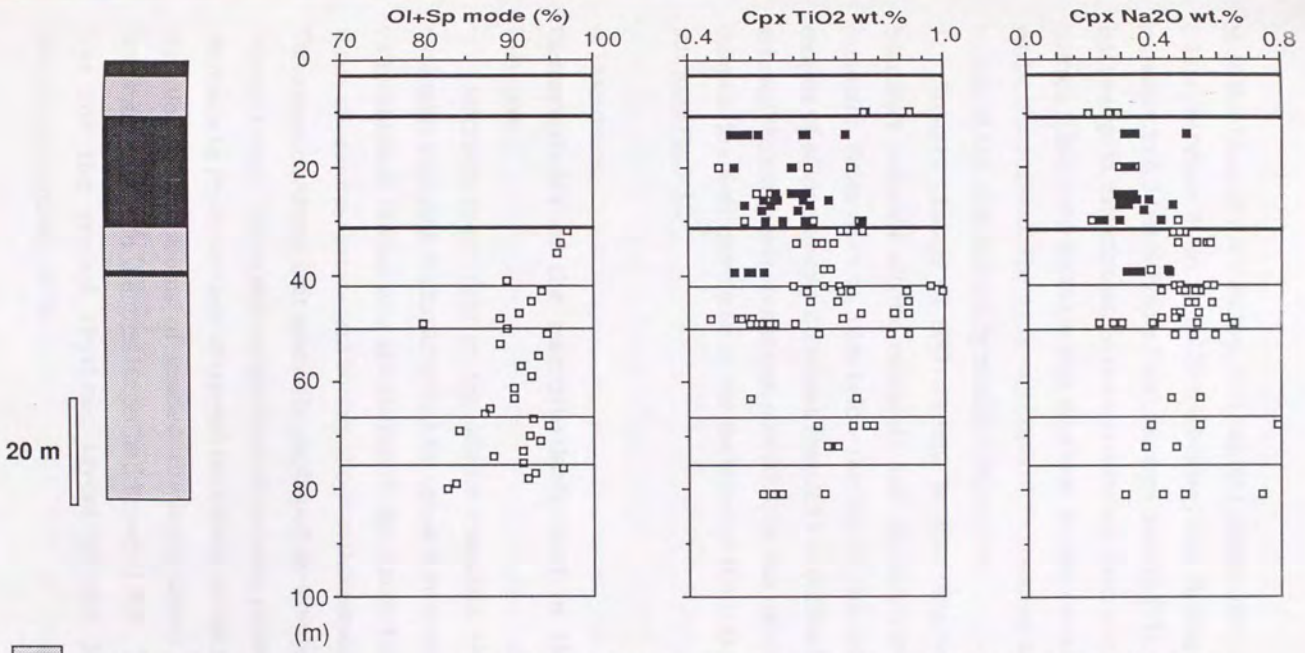


Fig.5-5 Chemical variation of clinopyroxene core in the columnar section: open square; interstitial pyroxene, filled square; cumulus clinopyroxene.

Near the base of the outcrop, NiO content olivine decreases from 0.31wt.%(below 80m) to 0.29wt.%(below 78m) through 2m and increases to 0.31wt.%(below 73m) through 5m(Fig.5-3). In spite of this change in NiO content, Fo content does not show corresponding change. This steep increase and decrease do not correlate to the modal composition. The minimum point of NiO content exists in the middle of the unit defined by modal composition.

Steeper change of NiO content is also observed at the boundary between olivine cumulate and olivine clinopyroxene cumulate. From 39m to 32m below the top of the column, NiO content of olivine steeply decreases from 0.31 to 0.25wt.%(Fig.5-3), although Fo content is almost constant(83.5) in this unit. The modal composition well correlates to the decrease of the NiO content in this unit(Fig.5-3).

4. Discussion

Characteristics of the macrorhythmic unit in the olivine cumulate

Macrorhythmic unit in the olivine cumulate of the Toba ultramafic complex is characterized by upward increase in modal composition of olivine plus spinel. Top of the macrorhythmic unit shows adcumulus texture and bottom shows orthocumulate texture. This macrorhythmic unit cannot be explained by simple fractional crystallization. The modal composition of cumulus phase generally decreases in rhythmic unit of layered intrusions. In the Skaergaard Intrusion, the bottoms of graded rhythmic layers are more orthocumulate than the tops(Wager and Brown, 1968). This is also true for the graded rhythmic layers of the Jimberlana intrusion(Campbell, 1978).

Petersen(1987) discussed the texture and chemical composition of partially solidified crystal pile. He pointed out that the top of the pile shows adcumulus texture and has refractory chemical composition and the bottom shows orthocumulate texture and fractionated composition. In the Toba complex, the texture of the unit is similar to this. However the spinel which occurs as a cumulus phase at the top of the pile has fractionated chemical composition and the spinel at the bottom has refractory composition(Fig.5-4).

Incompatible element enrichment

In macrorhythmic unit of the olivine cumulate, both the TiO_2 and YFe of spinel increase from the bottom to the top of each unit. Scowen et al.(1991) discussed that chemical composition of spinel embedded in olivine could be modified by lattice diffusion through the olivine grain. Their estimated diffusion coefficient is $1x10^{-11}$ cm^2/s for Al and Fe^{3+} and $6x10^{-13}$ cm^2/s for Ti and Cr at 1200°C. The variation of YCr of spinel is relatively small from the bottom to the top of the unit. This suggests that the variation of Ti is not caused by the lattice diffusion through olivine.

Order of magnitude of estimated diffusion coefficient of Ti and Cr through olivine is comparable to diffusion coefficient of Ni experimentally determined by Morioka(1981). Olivine is homogeneous not only in Forsterite content but also in NiO content(Fig.5-3). Therefore enrichment of TiO_2 and YFe in spinel cannot be explained by modification by an evolved interstitial liquid through cationic diffusion in olivine grain.

In Fig.3-9, distribution coefficient of TiO_2 between spinel and liquid was compiled from experiment of Roeder and

Reynolds(1991). Distribution coefficient is below unity at temperature higher than 1300°C and at 1200°C, distribution coefficient increases and becomes larger than unity if temperature becomes lower. At the top of the unit, the modal content of olivine is up to 95% and shows equigranular adcumulus texture. The crystallizing temperature of the spinel enclosed in core of olivine at the top should be higher than the bottom. Therefore chemical composition of spinel can be use for the indicator of the interstitial liquid composition.

The minimum TiO_2 content of spinel increases from bottom to top and the minimum TiO_2 content of the top is often higher than the maximum content of the bottom(Fig.5-4). This suggests the spinel enclosed in the core of olivine crystallized from the liquid which has comparable incompatible concentration to the interstitial liquid of the bottom. Incompatible element concentration of the liquid from which spinel crystallizes increases from the bottom to the top. Spinel at the top of the unit crystallizes after interstitial mineral of the bottom began to crystallize. Therefore the boundary of liquid-crystal mush interface moves upward.

Chemical composition of clinopyroxene also suggests increase of incompatible element. The Na_2O and TiO_2 contents of the core of clinopyroxene increase from the bottom to the top. Incompatible element in interstitial liquid also increases.

According to the chemistry of spinel and clinopyroxene, enrichment factor of incompatible elements can be estimated. These concentration for the core of spinel and clinopyroxene in the top of the unit is two to five times larger than that of the bottom.

Buffering of interstitial liquid by olivine

Chemical composition of olivine is relatively homogeneous through each unit. Fo and NiO do not change. They are probably buffered by olivine. Initial modal composition of interstitial liquid is about 30 to 10%. Incompatible element is not buffered by olivine and is enriched by two to five times. Then olivine/fractionated-liquid ratio is from 5 to 45.

Interstitial liquid can be buffered by cumulus phase if diffusion of certain element is high enough and mass of certain element in interstitial liquid is comparable or smaller to mass of the element transported through the interface from solid. These conditions may be satisfied in the Toba complex.

Buffering of interstitial liquid by cumulus phase is very important for boundary layer fractionation. The lower porosity, the smaller grain size and the smaller diffusion coefficient, the more effectiveness of buffering increases.

Model of macrorhythmic unit in the olivine cumulate

The above-mentioned characteristics of macrorhythmic unit in the olivine cumulate of the Toba complex can be explained by crystallization in boundary layer(Fig.5-6). The margin of the chamber, crystal mush is formed by the escape of heat. If there is enough thermal gradient in the crystal mush, the different phases can crystallize at the bottom and the top of crystal mush at the same time(Fig.5-6A). At the bottom of crystal mush, clinopyroxene and plagioclase crystallize in interstices of olivine and spinel and enrichment of incompatible element occurs. However, Fe/Mg ratio is probably buffered by abundant olivine. The fractionated interstitial melt has to be brought from the inner part of the crystal pile. The mechanism of upwelling is thought to be compositional

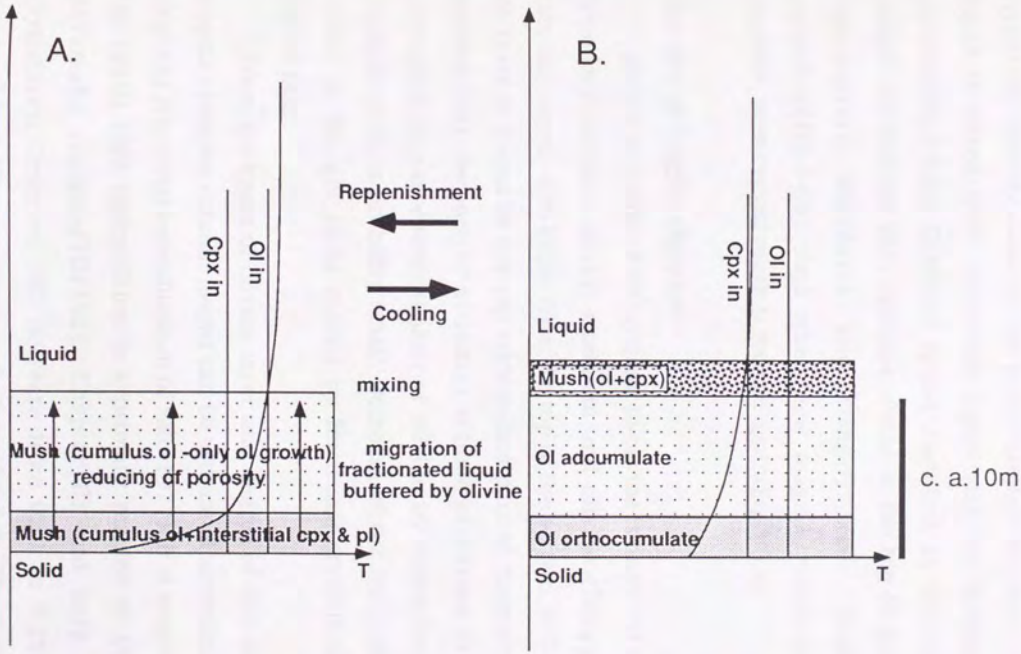


Fig.5-6 Model figure of the macrorhythmic unit in the olivine cumulate of the Toba complex. Heat loss through the floor is assumed. See text.

convection(Kerr and Tait, 1986). At the top of crystal mush, where crystal pile directly contacts with main chamber, the main chamber liquid is mixed with interstitial liquid rich in incompatible element(Fig.5-6A). Cumulus spinel enriched in incompatible element crystallizes with cumulus olivine at the top of pile. Then temperature decreases and clinopyroxene begins to crystallize(Fig.5-6B). And when new magma comes into the chamber, next crystal mush is formed again(Fig.5-6A).

The size of magma chamber

Abrupt decrease of NiO content in olivine is observed near the boundary between olivine cumulate and olivine clinopyroxene cumulate about 40m below from the top of the section. NiO content decrease is found in the top adcumulate part of macrorhythmic unit(Fig.5-3). Because of abundant volume of olivine to that of interstitial liquid, chemical shift of olivine by interstitial liquid crystallization is probably small. Decrease of the NiO content of olivine is thought to be caused by fractional crystallization of crystal pile.

From thickness of olivine layer and degree of NiO decrease, magma chamber column height can be estimated according to the model of fractional crystallization of Sato(1977). It is assumed that the initial melt composition is a primary magma of the Toba ultramafic complex(T071911, Chapter II) and only olivine crystallizes. Observed NiO decrease from 0.31 to 0.25wt.% is comparable to 5% crystallization of olivine(Fig.4-8). The thickness of the layer for decrease in NiO content is 5m and olivine modal composition is 95%. Then estimated column height is about 95m. This estimated thickness is about fifty times smaller than total

thickness of the Toba ultramafic complex. There is still possibility for stratified magma chamber(Huppert and Sparks, 1980). This column thickness is comparable to the melt thickness of the magma chamber of the MORB(Sinton and Detrick, 1992) and the Oman ophiolite(Browning, 1984).

VI. Origin of the olivine adcumulate in the Shimoina ultramafic complex, central Japan

1. Introduction

Compaction is thought to be very important mechanism for melt segregation in the upper mantle(McKenzie, 1984). When melt is segregated in the upper mantle, matrix is deformed by the buoyancy resulted from the density difference between crystal and melt. But the sample from alpine peridotites is not so useful to discuss deformation during melt segregation because of strong later deformation often imprinted by later tectonic movement and deformation may involve shear process, which complicates the process.

Cumulate is thought to be deformed more simple condition. Because shear stress is not so large and later deformation can often be neglected. Irvine(1980) proposed the compaction of cumulate to explain stratigraphic lag between olivine chemical variation and modal composition. Sparks et al.(1985) discussed efficiency of compaction. Shirley(1986) simulated compaction of cumulate by using the equation of McKenzie(1984) and estimated the viscosity of the matrix from the displacement length of the chemistry of the matrix.

In the Shimoina ultramafic complex, compacted cumulate can be observed. I will describe the deformation of cumulate and evaluate the efficiency of compaction. I will also discuss origin of adcumulate of the Shimoina ultramafic complex.

2. Geological setting

The Shimoina ultramafic complex is located in the western flank of the Akaishi Mountains, central Japan(Fig.2-1). The Shimoina ultramafic complex is one of the ultramafic masses of the Mikabu belt. The Mikabu belt is composed of accreted oceanic material. The Shimoina ultramafic complex represents the lowermost part of the accreted oceanic crust. In this area, the complex is in fault contact with host rocks. The host rocks are composed of pelitic schist and weakly metamorphosed basic volcanic rock. They are suffered from the Sambagawa metamorphism. The metamorphic grade of this district is from pumpellyite-actinolite facies to glaucophen schist facies(Watanabe, 1974). In the western part of this area, the Ryoke belt is distributed in fault contact by Median Tectonic Line with the Sambagawa belt. The eastern part of the Sambagawa belt is bounded by a fault, Todai Tectonic Line, and the Chichibu belt is distributed. Makimoto(1978) mentioned that the Shimoina complex is divided into peridotite-gabbro complex and hornblendite-gabbro complex. He also reported magnesian olivine, which is up to 92 mol% in Fo content.

3. Geology and petrography

The Shimoina ultramafic complex is divided into three units(Fig.6-1). Unit I is composed of ultramafic and mafic cumulate; Unit II, hornblende-rich sheet complex; Unit III, dikes intruding into Unit I. This division is similar to the Toba ultramafic complex. The original mineral of the Shimoina complex is partly altered by the Sambagawa metamorphism. Olivine is partly altered to serpentine and chlorite. Clinopyroxene is partly altered to

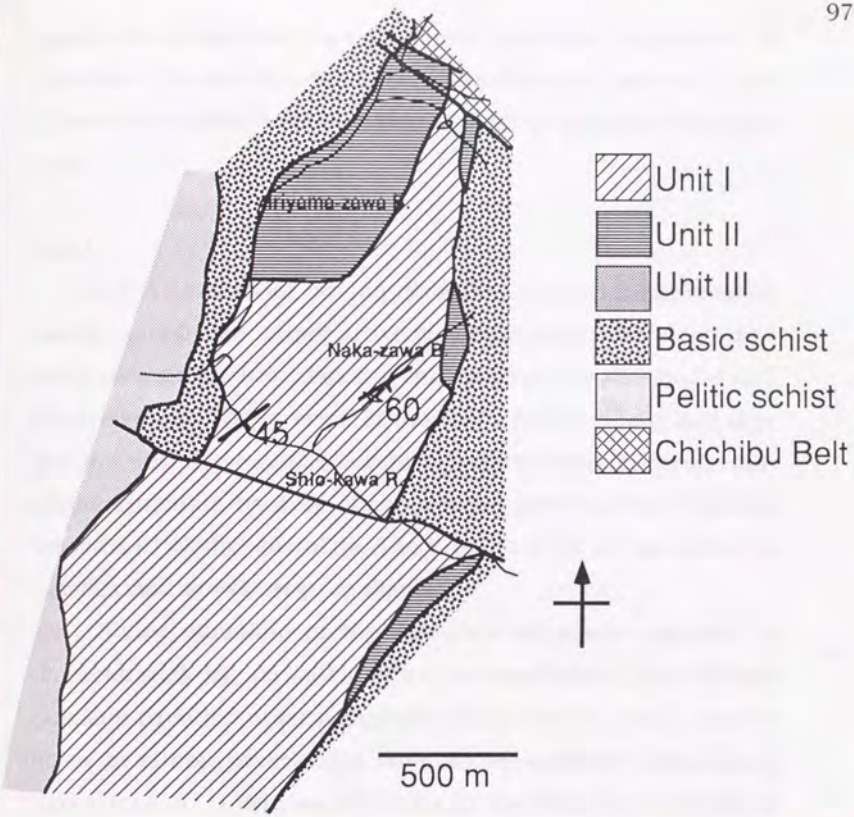


Fig.6-1 Geological map of the Shimoina ultramafic complex. Mainly based on the map of Makimoto(1978). Unit III is added unit.

amphibole. Plagioclase is completely altered to aggregate of grossular. The western fault boundary between host rock and ultramafic complex is observed in the outcrop along the Shiokawa river.

Unit I

Unit I consists of olivine cumulate, olivine clinopyroxene cumulate, olivine clinopyroxene plagioclase cumulate and clinopyroxene gabbro. Unit I is characterized by the modal and phase layering. The layering of the Unit I strikes NE-SW and dips east and west. Clinopyroxene gabbro is interpreted to intrude into olivine cumulate because clinopyroxene gabbro often includes xenoliths of olivine cumulate. The xenolith is up to one meter in diameter and shows irregular shape.

Olivine cumulate of the Shimoina ultramafic complex is characterized by its adcumulus texture(Plate6-1A). Olivine cumulate from the other complexes of the Mikabu belt is usually richer in clinopyroxene and often shows poikilitic texture(e.g. Nakamura, 1971). Olivine cumulate of the Shimoina complex is composed of olivine, spinel with small amount of clinopyroxene and rarely hornblende. The cumulus phases of olivine cumulate are olivine and spinel. The grain size of olivine is up to 3mm in diameter. Olivine locally shows undrouse extinction. Olivine has equigranular texture and typically shows dihedral angles of 120 degrees. The modal content of olivine ranges from 95 to 97%. Spinel shows different textures by its mode of occurrence. Spinel enclosed in olivine is euhedral and that occurs in interstices often shows planar shape. The grain size of spinel is up to 2mm in diameter. The modal content of spinel is up to 3.9%. Clinopyroxene occurs as

narrow vein up to 0.6mm in width(Plate6-2B). Hornblende is reddish brown and occurs in interstices of olivine grains.

Olivine clinopyroxene cumulate is composed of olivine, clinopyroxene, spinel, plagioclase and rarely small amount of hornblende(Plate6-1B). This rock type is heterogeneous in outcrop and modal content of plagioclase is abruptly changed. Plagioclase-rich layers up to 10cm thick are observed. The cumulus phases are olivine, spinel and clinopyroxene. Olivine is equigranular and up to 2mm in diameter. Modal content of olivine in plagioclase-free part is about 96%. Clinopyroxene is euhedral and up to 6mm long in diameter. It often includes fine platy opaque minerals. Modal content of clinopyroxene in plagioclase-free part is up to 6%. Spinel enclosed in olivine and clinopyroxene is euhedral while spinel observed in interstitial space is anhedral and shows irregular shape. The size of spinel is up to 1mm. Plagioclase is completely altered to aggregate of grossular. Hornblende is anhedral and rarely occurs along the boundary of olivine and plagioclase.

Olivine clinopyroxene plagioclase cumulate is composed of olivine, clinopyroxene, plagioclase and spinel(Plate6-2A). The difference to olivine clinopyroxene cumulate is modal content of plagioclase. It is relatively homogeneous in outcrop. The alteration of olivine clinopyroxene plagioclase cumulate is stronger than olivine cumulate.

Clinopyroxene gabbro is composed of clinopyroxene, plagioclase and minor amount of olivine. Olivine is completely altered to chlorite and deformed. Clinopyroxene is subhedral and up to 2mm long. Clinopyroxene is pale green in color and often includes platy opaque minerals. Plagioclase is completely altered to aggregate of grossular.

Unit II

Unit II is composed of hornblende-rich rocks; olivine hornblendite, hornblendite, hornblende gabbro and clinopyroxene hornblende gabbro. These are similar to the Unit II of the Toba ultramafic complex. Unit II is distributed in the margin of the ultramafic complex.

Olivine hornblendite is composed of olivine, spinel, orthopyroxene and hornblende. It shows porphyritic texture with phenocryst of olivine. Groudmass is composed of fine grained hornblende. Olivine is subhedral and the grain size is up to 8mm. It is partly or completely altered to serpentine or chlorite and tremolite. Orthopyroxene is subhedral and the grain size is up to 0.8mm. It is often altered to chlorite. Spinel is euhedral to subhedral and the grain size is up to 0.4mm. Zonal structure characterized by brown core and green rim is observed. Hornblende is pale brown and the grain size is about 0.1mm and sometimes up to 0.5mm.

Hornblendite and hornblende gabbro are composed of brown hornblende, plagioclase and ilmenite. Hornblendite and hornblende gabbro have remarkable foliation. Hornblende is subhedral and brown to green in color. The grain size of hornblende is up to 0.8mm. Ilmenite is subhedral and up to 0.1mm.

Clinopyroxene hornblende gabbro is composed of clinopyroxene, hornblende, plagioclase and ilmenite. Clinopyroxene is equidimensional and its grain size is up to 1.5mm. Coarse clinopyroxene has platy inclusions of opaque mineral. Hornblende is subhedral and the grain size is up to 0.6mm. Sometimes hornblende is poikilitic and includes clinopyroxene.

Unit III

Unit III is dikes which intrude into Unit I. The thickness is up to one meter. The rock type is olivine orthocumulate and hornblende gabbro.

Olivine orthocumulate is composed of olivine, spinel, clinopyroxene, plagioclase, orthopyroxene and hornblende. The cumulus phases are olivine and spinel. Modal content of cumulus phases is 54%. Olivine is euhedral and the grain size is up to 1.8mm. Spinel is euhedral and the grain size is up to 0.5mm. Clinopyroxene is poikilitic and occurs in interstices of olivine. Hornblende is anhedral and sometimes poikilitic. It is reddish brown in color and the grain size is up to 1.8mm. Orthopyroxene is anhedral and the grain size is up to 0.3mm. Plagioclase is completely altered to grossular.

Hornblende gabbro is composed of hornblende, plagioclase and ilmenite. Hornblende is subhedral and the grain size is up to 1.8mm. Ilmenite is subhedral to anhedral and the grain size is up to 0.7mm. Plagioclase is completely altered to grossular.

4. Mineral chemistry of Unit I

Olivine

Olivine in Unit I of the Shimoina complex is chemically homogeneous in each grain and sample. The range of Fo content is up to 1mol%. Most magnesian olivine is near the field of mantle olivine array(Takahashi et al., 1987). Fo content well correlates to MnO content(Fig.6-2). Fo content of olivine cumulate ranges from 92.5 to 86.8; NiO, from 0.43 to 0.27wt.%; MnO, from 0.12 to 0.23wt.%; CaO, from 0.29 to 0.01wt.%(Fig.6-2). Fo content of olivine clinopyroxene cumulate ranges from 88.8 to 84.5. ; NiO, from 0.31

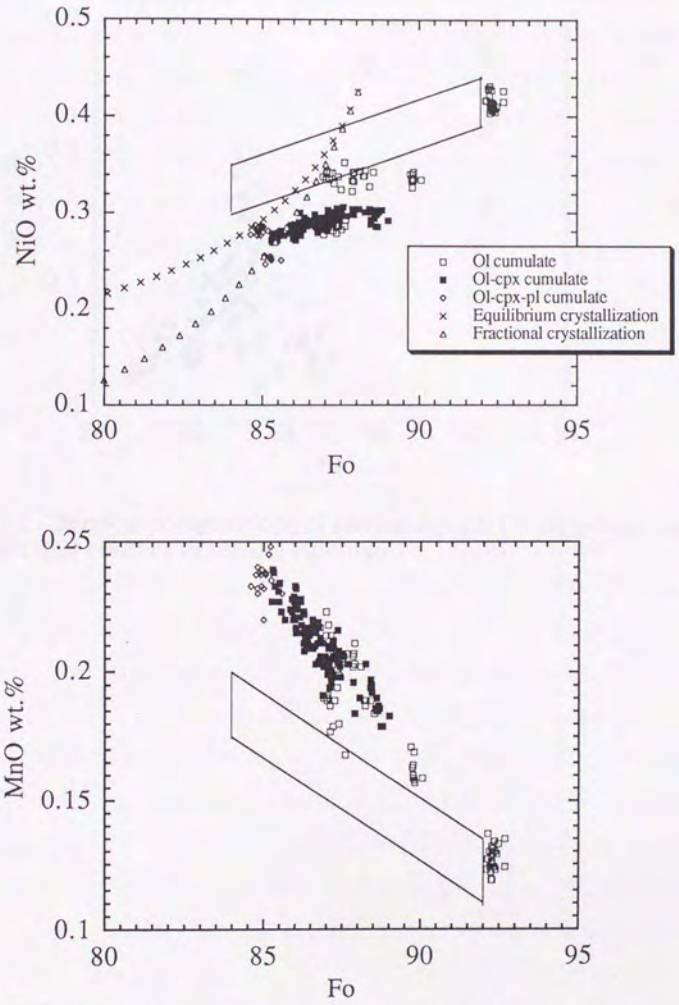


Fig.6-2 Chemical compositions of olivine in Unit I: open square; olivine cumulate, filled square; olivine clinopyroxene cumulate, open diamond; olivine clinopyroxene plagioclase cumulate. The box indicates the mantle olivine array of Takahshi et al.(1987). Calculated crystallization paths of olivine according to Sato(1977) is also shown. The initial composition is assumed to be T071911 of the Toba complex(Table2-2). Step for the calculation is 1%: open circle; equilibrium crystallization, closed circle; fractional crystallization.

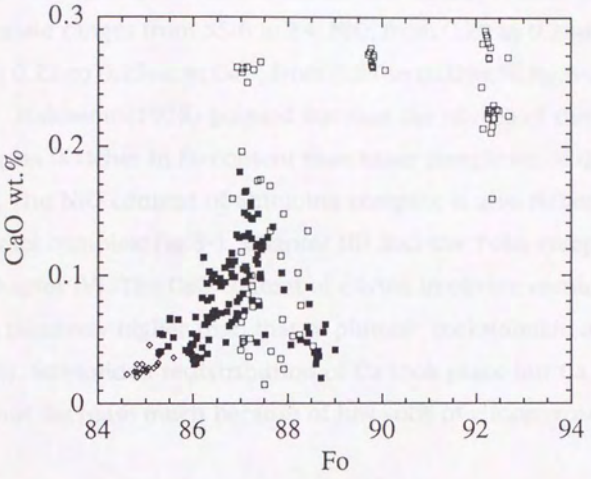


Fig.6-2 Chemical compositions of olivine in Unit I.(Continued) Note high CaO content in olivine cumulate.

to 0.27wt.%; MnO, from 0.18 to 0.24wt.%; CaO, from 0.17 to 0.02wt.%(Fig.6-2). Fo content of olivine clinopyroxene plagioclase cumulate ranges from 85.6 to 84; NiO, from 0.29 to 0.24wt.%; MnO, from 0.22 to 0.25wt.%; CaO, from 0.05 to 0.02wt.%(Fig.6-2).

Makimoto(1978) pointed out that the olivine of the Shimoina complex is richer in Fo content than other complexes of the Mikabu belt. The NiO content of Shimoina complex is also richer than the Mikkabi complex(Fig.3-1, Chapter III) and the Toba complex(Fig.4-1, Chapter IV). The CaO content of olivine in olivine cumulate(Fig.6-2) is relatively higher than that of plutonic rocks(Simkin and Smith, 1970). Subsolidus redistribution of Ca took place but Ca in olivine did not decrease much because of low vol% of clinopyroxene.

Spinel

Chemical composition of core of spinel in olivine is homogeneous in each sample. The range of TiO_2 content in one sample is up to 0.7wt.%. The variation in olivine clinopyroxene cumulate is wider than that of olivine cumulate. In Fig.6-3, chemical composition of spinel is plotted against Fo content of the host olivine. The overall variation of TiO_2 and YFe in Unit I is smaller than that for Unit I of the Toba ultramafic complex(Fig.4-4, Chapter IV). The TiO_2 and YFe do not largely change among olivine cumulate, olivine clinopyroxene cumulate and olivine clinopyroxene plagioclase cumulate. The YCr of spinel in olivine cumulate is higher than that in the others.

The YCr of spinel well correlates to the Fo content of the host olivine(Fig.6-3). It decreases as Fo content decreases. Chemical trend of the Shimoina ultramafic complex is resemble to Al-trend(Henderson, 1975), Cr-Al exchange is main vector of the trend.

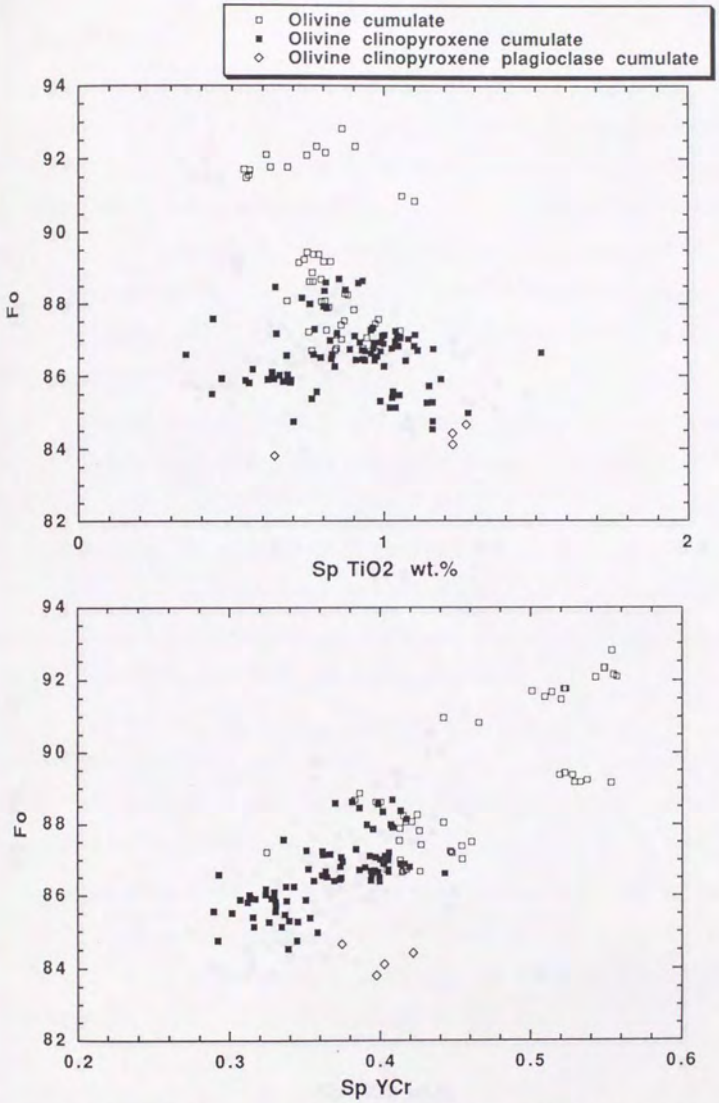


Fig.6-3 Chemical compositions of spinel core enclosed in olivine and coexisting olivine Fo content. Symbols are similar to those of Fig.6-2.

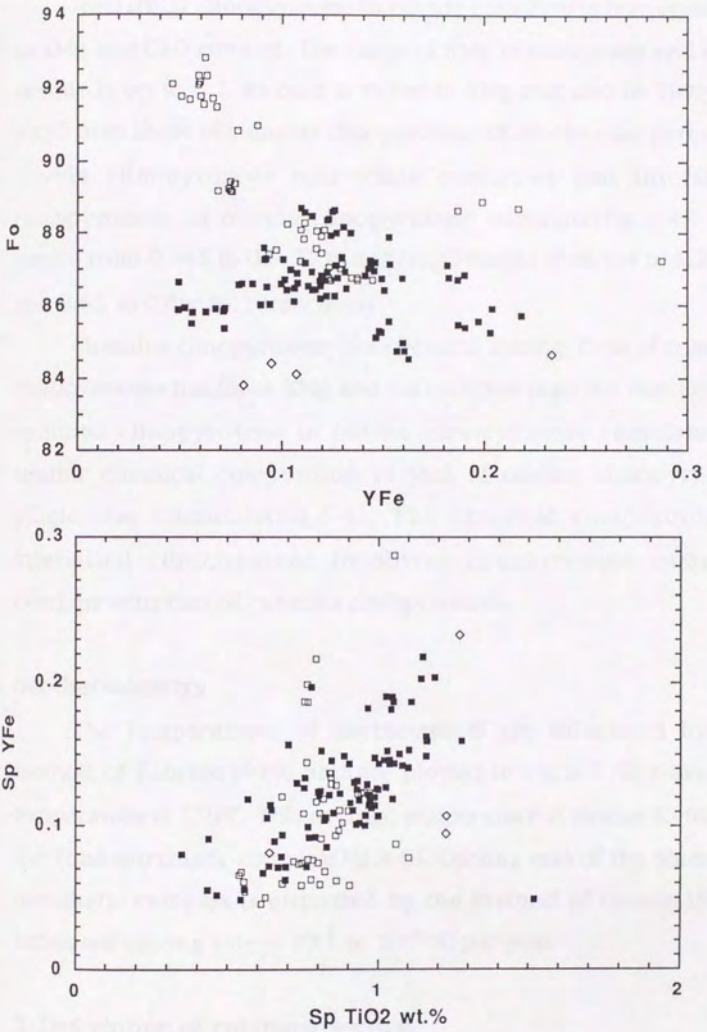


Fig.6-3 Chemical compositions of spinel core enclosed in olivine and coexisting olivine Fo content.(Continued)

Clinopyroxene

Interstitial clinopyroxene in olivine cumulate is homogeneous in XMg and CaO content. The range of XMg in each grain and same sample is up to 0.1. Its core is richer in XMg and also in TiO_2 and Na_2O than those of cumulus clinopyroxene of olivine clinopyroxene-olivine clinopyroxene plagioclase cumulates and interstitial clinopyroxene in olivine clinopyroxene cumulate(Fig.6-4). XMg ranges from 0.945 to 0.9. TiO_2 and Na_2O ranges from 0.4 to 1.2wt.% and 0.65 to 0.8wt.%, respectively.

Cumulus clinopyroxene has chemical zoning. Core of cumulus clinopyroxene has lower XMg and CaO content than the rim. Core of cumulus clinopyroxene in olivine clinopyroxene cumulate has similar chemical composition to that of olivine clinopyroxene plagioclase cumulate(Fig.6-4). The chemical composition of interstitial clinopyroxene in olivine clinopyroxene cumulate overlaps with that of cumulus clinopyroxene.

Geothermometry

The temperatures of olivine-spinel are calculated by the method of Fabriès(1979) and are plotted in Fig.6-5. The average temperature is 770°C. This average temperature is similar to that of the Toba ultramafic complex(Fig.4-6). Cooling rate of the Shimoina ultramafic complex is estimated by the method of Ozawa(1984). Estimated cooling rate is 10^{-1} to 10^{-3} °C per year.

5. Description of columnar section

In order to illustrate the variations from olivine cumulate to olivine clinopyroxene plagioclase cumulate, a columnar section was made along the Nakazawa branch(Fig.6-1). Makimoto(1978)

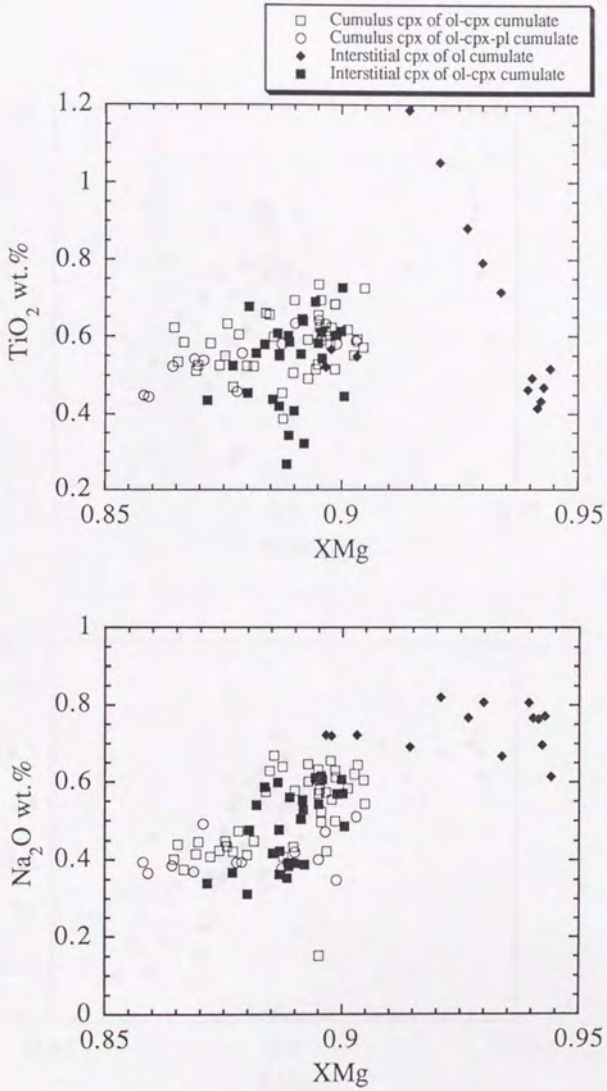
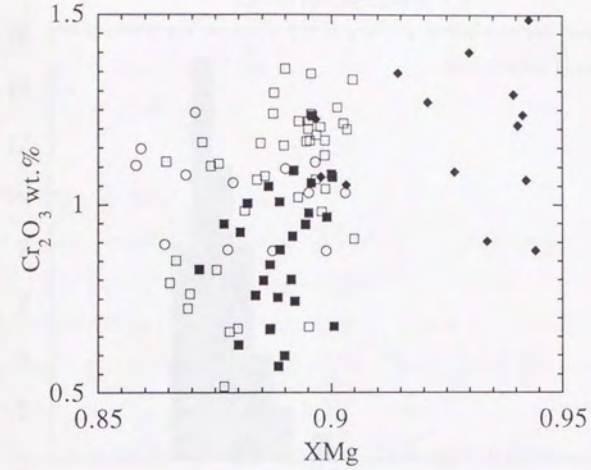


Fig.6-4 Chemical variation of clinopyroxene core of Unit I: open square; cumulus clinopyroxene of olivine clinopyroxene cumulate, open circle; cumulus clinopyroxene of olivine clinopyroxene plagioclase cumulate, filled diamond; interstitial clinopyroxene of olivine cumulate, filled square; interstitial clinopyroxene in olivine clinopyroxene cumulate.



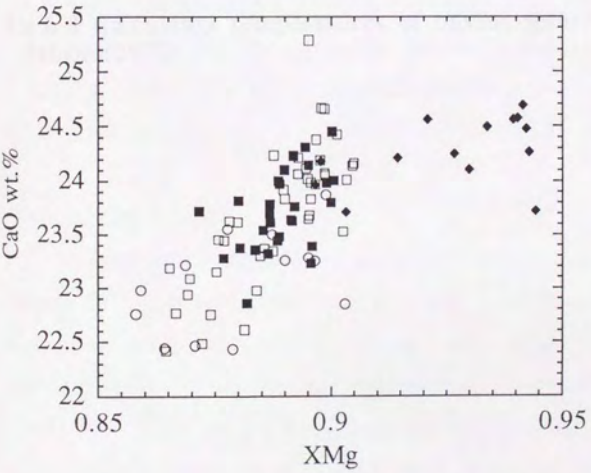


Fig.6-4 Chemical variation of clinopyroxene core of Unit I.(Continued)

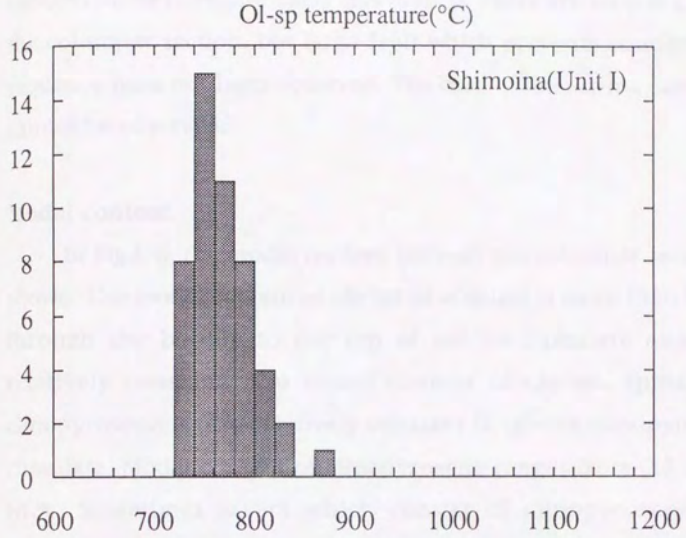


Fig.6-5 Calculated temperatures of olivine-spinel according to Fabriès(1979).

reported modal variation from olivine cumulate to olivine clinopyroxene cumulate along this branch. There are several gaps in the columnar section, but large fault which prevents stratigraphic sequence have not been observed. The base of the olivine cumulate cannot be observed.

Modal content

In Fig.6-6, the modal content through the columnar section is shown. The modal content of olivine plus spinel is more than 98.5% through the bottom to the top of olivine cumulate and it is relatively constant. The modal content of olivine, spinel and clinopyroxene is also relatively constant in olivine clinopyroxene cumulate. Modal content of clinopyroxene ranges from 0.8 to 2.5 wt.%. Sometimes layers which consist of clinopyroxene and plagioclase are observed in olivine clinopyroxene cumulate. Low modal composition of olivine + spinel corresponds to these layers(Fig.6-6). In the upper part of cumulus pile, the frequency of these layer increases.

Texture and fabric

Olivine fabrics of selected sample in the columnar section are shown in Fig.6-7. In the sample from the lower part of the columnar section(Plate6-1A), 96m below from the boundary between olivine clinopyroxene cumulate and olivine clinopyroxene plagioclase cumulate(Fig.6-6), a strong maximum of X-axes normal to foliation is observed(Fig.6-7A). Maximum of Y-axes and Z-axes are parallel to the foliation plane. In the middle part of the columnar section, 21m below from the boundary, maximum of X-axes is also normal to foliation plane(Fig.6-7B). Y-axes and Z-axes

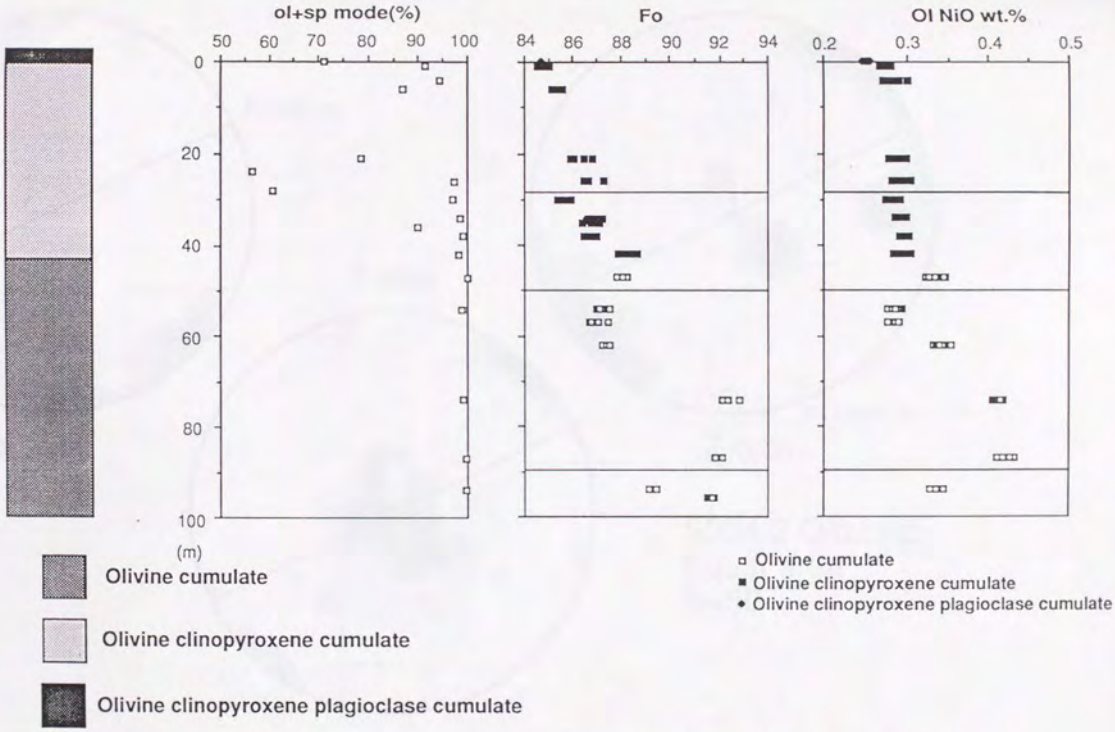


Fig.6-6 Lithology, modal content and chemical composition of olivine variation in the columnar section. Horizontal lines indicate the boundary of cyclic units defined by olivine chemistry.

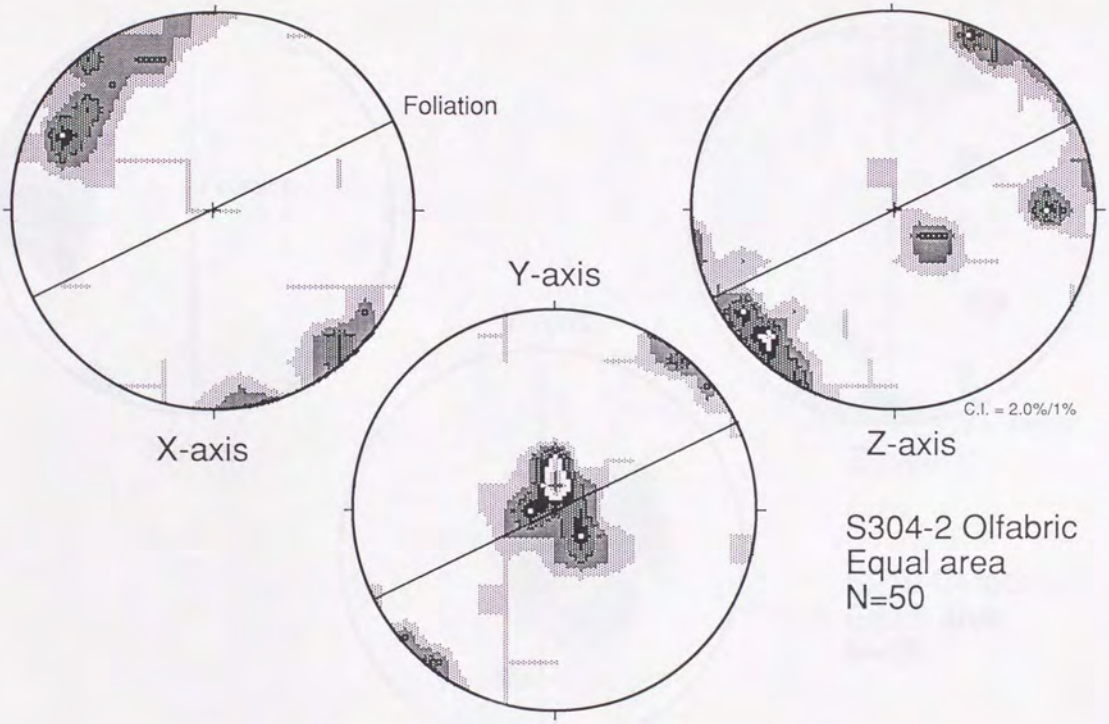


Fig.6-7A Stereo plot of petrofabric of olivine: S304-2. lower part of the columnar section(96m below from the boundary between olivine clinopyroxene cumulate and olivine clinopyroxene plagioclase cumulate.)

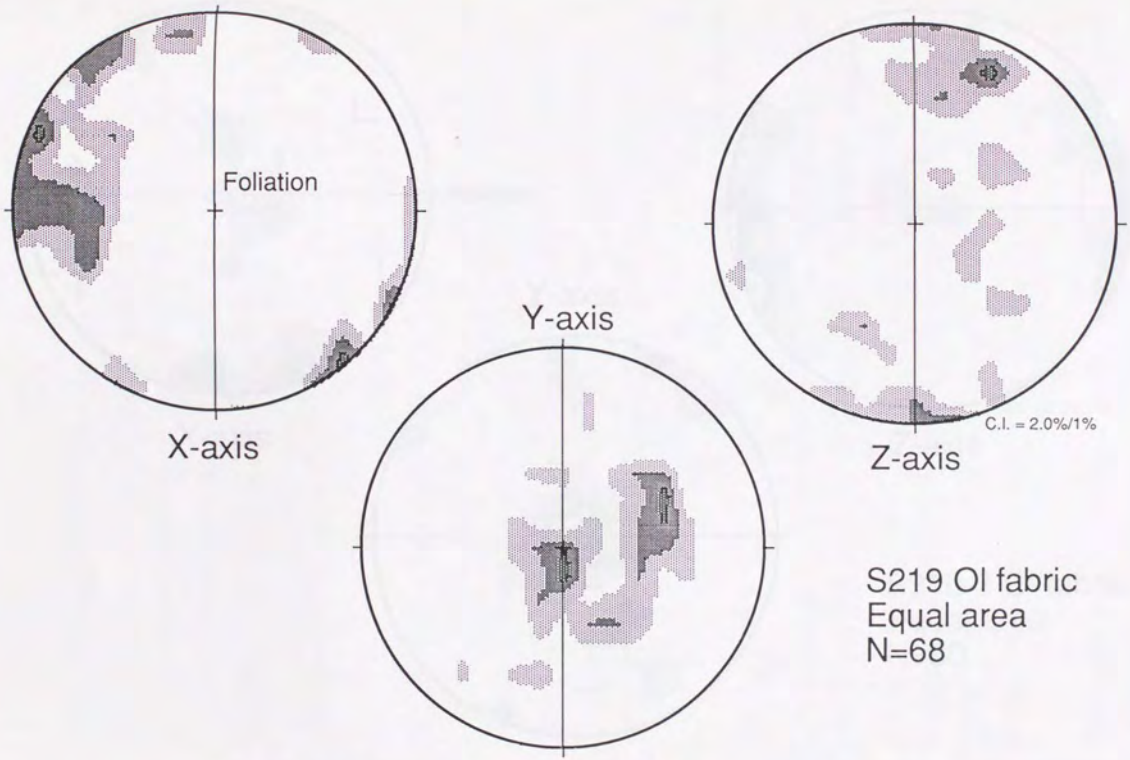


Fig6-7B Stereo plot of petrofabric of olivine: S219(21m below from the boundary).

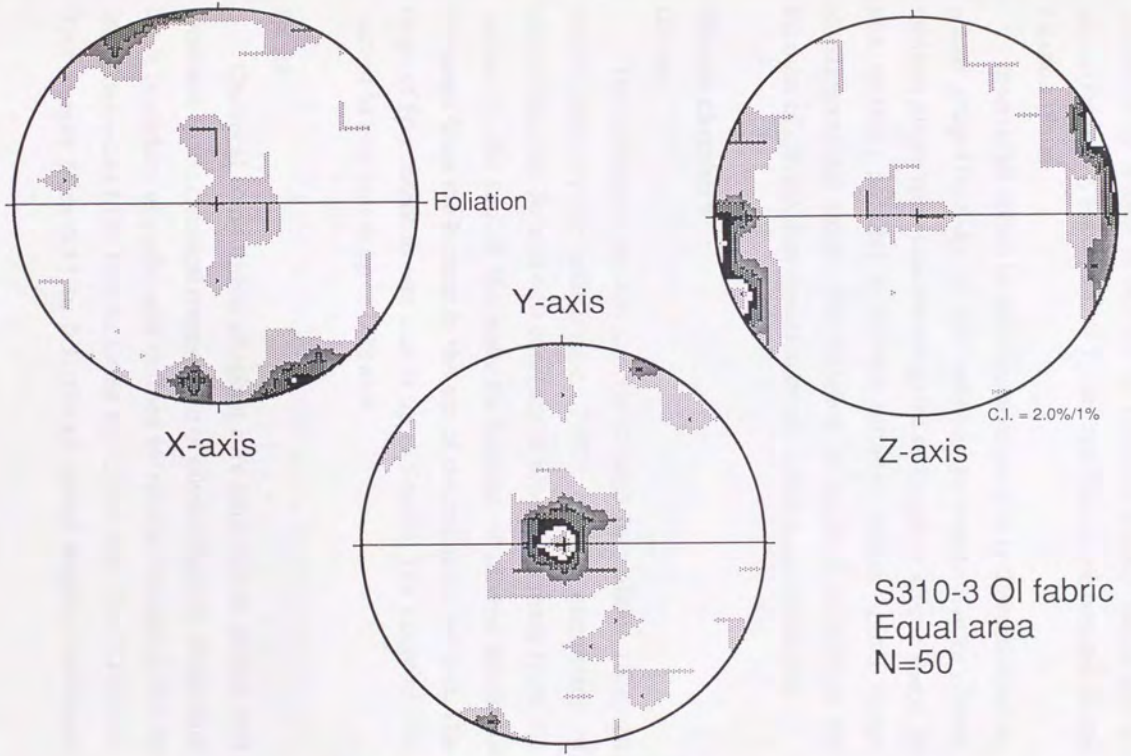


Fig.6-7C Stereo plot of petrofabric of olivine: S310-3(1m from the boundary)

show sub-girdle distribution. In the top of the columnar section(Plate6-2A), 1m below from the boundary, although maximum of X-axes is normal to foliation plane, but is not so strong(Fig.6-7C). Maximum of Y-axes and Z-axes are parallel to the foliation plane.

Interstitial spinel in the columnar section is characterized by planar shape(Fig.6-8). In thin sections perpendicular to olivine foliation plane, spinel shows elongated rectangle or ellipse shape. In thin sections parallel to olivine foliation plane, spinel shows equidimensional shape. The foliation of spinel is parallel to the foliation of olivine. The lineation of the spinel is not observed.

Mineral chemistry

Olivine

The columnar section can be divided into about 10 to 20 meter thick cyclic unit(Irvine, 1982) by the chemistry of olivine(Fig.6-6). Fo and NiO contents of olivine decrease from the bottom to the top of the unit. Fo content of olivine generally decreases from the bottom to the top of the columnar section. The range of Fo content in one unit is up to 5mol%. The range of NiO content in one unit is up to 0.13wt.%.

Spinel

Chemical composition of spinel core enclosed in olivine well correlates to the chemical composition of olivine(Fig.6-9). Horizontal bar is boundary of cyclic unit defined by olivine chemistry. YCr of spinel decreases from bottom to the top of the unit. The YCr in one layer ranges from 0.55 to 0.3. YFe of spinel slightly increases.

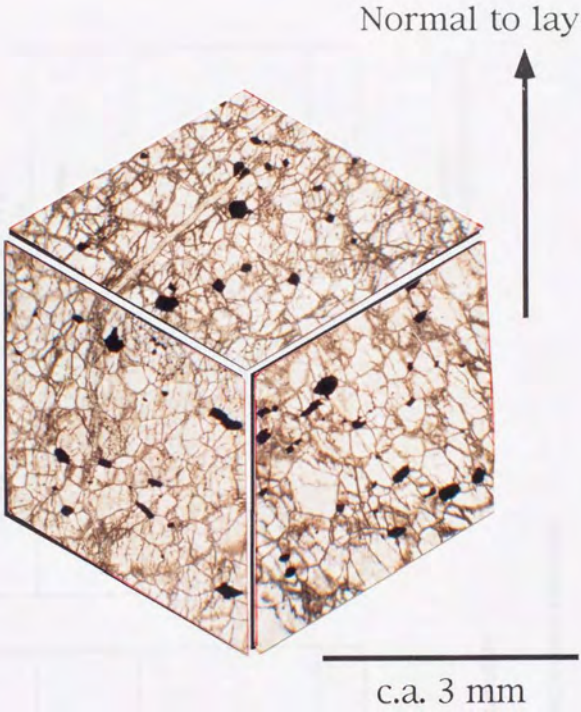


Fig.6-8 Three dimensional microphotograph of olivine cumulate. Plane light. S301.

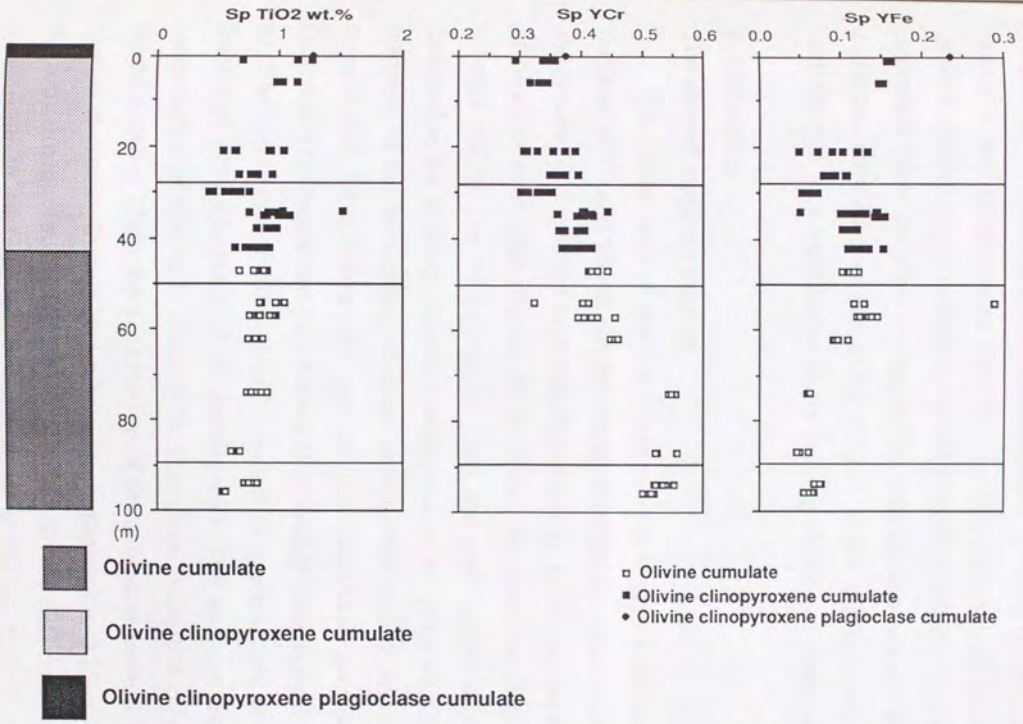


Fig.6-9 Chemical variation of spinel in the columnar section. Core of spinel enclosed in olivine is selectively analyzed. Horizontal lines indicate the boundary of cyclic units defined by olivine chemistry.

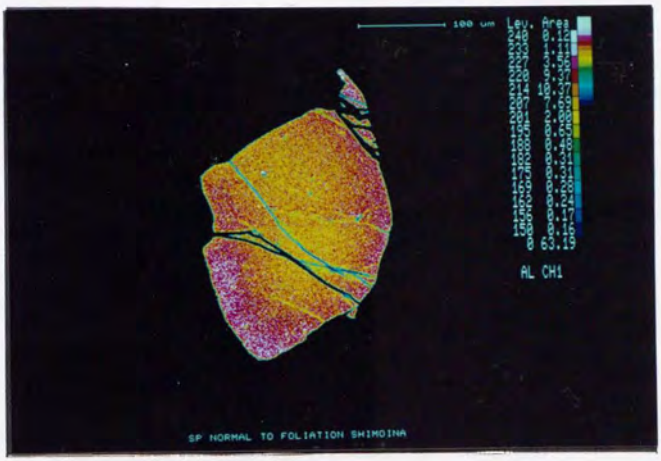
Interstitial spinel in the columnar section has chemical zoning. In Fig.6-10, concentration map of a spinel is shown. The thin section is parallel to foliation plane. Enrichment of Al along the rim of the spinel is well observed. In Fig.6-11, the line analyses of the same grain is shown. Al_2O_3 content of spinel increases and Cr_2O_3 content decreases from the core to rim. In the thin section normal to the foliation, only Al enriches along the rim in the direction of long axis(Fig.6-12). Cr enrichment in rim of long axis is not observed.

6. Discussion

The size of magma chamber

The cyclic unit of the columnar section is characterized by decrease of Fo and NiO in olivine. These decrease are interpreted as the product of fractional crystallization(Fig.6-2). From the thickness of olivine layer and degree of decrease, the magma chamber column height can be estimated. First the melt composition is assumed as the primary magma composition of the Toba ultramafic complex. At the base of the columnar section, NiO content decreases from 0.41(74m below the top of the columnar section)to 0.28wt.%(57m below the top) during 17m thick olivine layer(Fig.6-6). The decrease of olivine NiO content is comparable to 7% fractional crystallization of olivine(Fig.6-2). The average modal composition of olivine is about 97%. Therefore estimated column height is about 250m thick. At the top of the columnar section, NiO content decreases from 0.28(4m below from the top) to 0.25wt.%(at the top) during 4m thick. The decrease of olivine NiO content is comparable to 4% fractional crystallization of olivine(Fig.6-2). The average modal composition of olivine is 90%. Therefore estimated column height is about 110m thick.

A.



B.

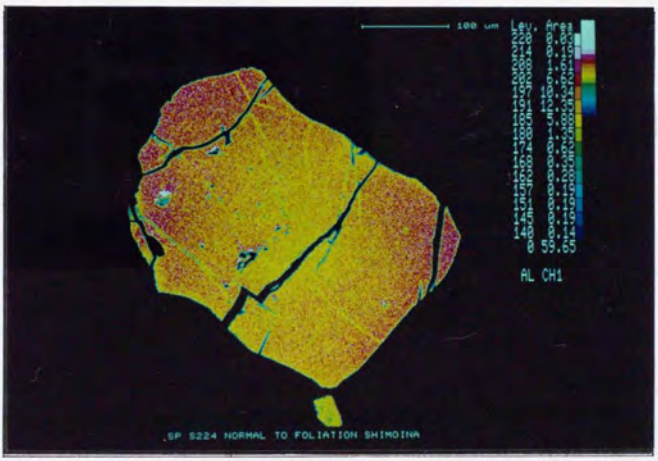


Fig.6-10 CMA map of interstitial spinel. The thin section is parallel to the foliation. Chemical zoning from this section is characterized by concentric increase of Al content to rim. A and B is in same thin section(S224)

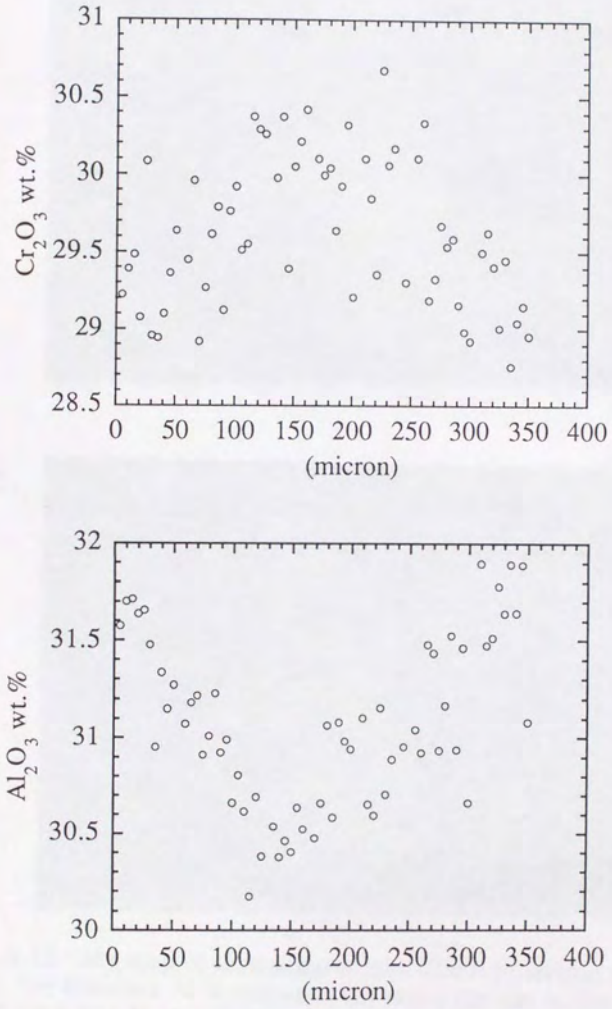


Fig.6-11 Line analyses of spinel as same as Fig.6-10A.

A.

B.

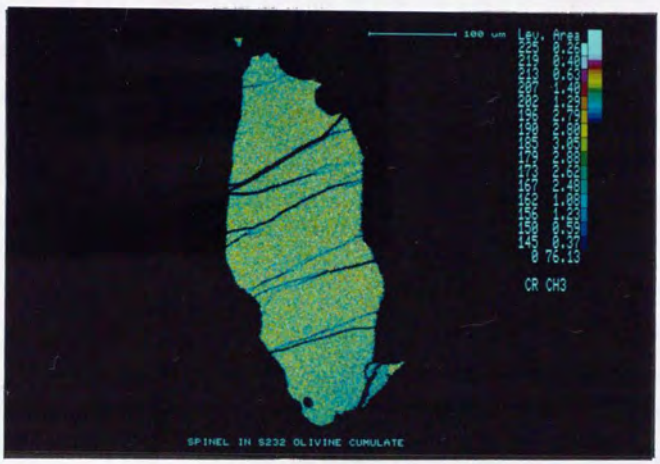


Fig.6-12 CMA map of interstitial spinel. The thin section is vertical to the foliation. Al is concentrated along the rim in the direction of long axis of spinel. Enrichment of Cr in compressional side is not observed.

Estimated column height is comparable to the column height of the Toba complex(Chapter V), the magma pocket of MORB(Sinton and Detrick, 1992) and the melt column height for the Oman ophiolite(Browning, 1984). The chamber depth for the Shimoina complex is not so thick as the total stratigraphic sequence of the complex. Melt filled space up to 1km thick is not required for accumulation of the olivine cumulate.

Origin of adcumulate in the Shimoina complex

Olivine cumulate of the Shimoina complex is characterized by adcumulus texture. Modal content of postcumulus phases is up to 1.5%. Textural equilibrium is well attained in the olivine cumulate. Decrease of NiO content in olivine generally can be explained by fractional crystallization (Fig.6-2). Spinel is poor in TiO_2 and YFe(Fig.6-3) and the range of the chemical composition in each thin section is narrower than the orthocumulates of the Toba complex(Chapter IV) and Mikkabi complex(Chapter III). Abundant interstitial liquid crystallization is not required to explain the chemical composition of the cumulus phases.

Crystal mush which is formed by crystal settling contains 40-50% of interstitial liquid(Wager et. al., 1960). If the olivine cumulate of the Shimoina complex is formed from crystal mush, with high initial porosity, some secondary processes are required. Compositional convection(Kerr and Tait, 1986) and compaction (McKenzie, 1984, 1987) is important postcumulus processes to reduce initial porosity. While it is widely believed that most cumulate rocks are formed by in situ crystallization at the floor and walls of the magma chamber(Campbell, 1978; McBirney and Noyes, 1979; Irvine, 1980). Therefore Campbell(1987) discussed that there

is no reason to assume that the initial porosity of cumulate rocks with low residual porosity was originally high and was subsequently reduced by a secondary process. If the olivine cumulate of the Shimoina complex is formed from crystal mush with low initial porosity, secondary processes is not needed.

According to above-mentioned mineralogical variation of the Shimoina complex, the layer thickness accumulated on the floor at once is up to a few tens of meters. Now mechanism, which controlled final porosity of this layer, is considered.

Compositional convection of cumulus pile is important mechanism, the effectiveness decreases as the porosity of the porous media decreases(Kerr and Tait, 1986). Sparks et al.(1985) pointed out that residual porosity of only 5% can be achieved by this mechanism if solidification velocity is 10^{-2} to 10^{-4} m/y. It is probable that the adcumulate of the Shimoina complex with maximum 1.5% postcumulus phase cannot be produced only by this mechanism.

A few tens meters thick layer with high initial porosity(30%) cannot be effectively compacted even in cooling time scale of large layered intrusion(Sparks et al., 1985). Compaction is thought to be not so useful to form the adcumulate of the Shimoina complex from initial high porosity.

In situ crystallization with low porosity(Campbell, 1987) is probably preferable mechanism for the adcumulate of the Shimoina complex. It can explain chemical composition of the cumulus phase with small effect of interstitial liquid.

Compaction of crystal pile

Although compaction does not work to form the Shimoina adcumulate from crystal mush with high initial porosity, typical result of compaction can be observed in the Shimoina ultramafic complex. Degree of chemical shifts of cumulus phase by interstitial liquid depends on the volume ratio of interstitial liquid to cumulus phase(Barnes, 1986). Small volume ratio of interstitial liquid to cumulus phase probably does not modify the chemical composition of cumulus phase so much. Compaction of the olivine cumulate with low initial porosity is considered now for the Shimoina complex.

In the Shimoina ultramafic complex, foliation plane can be identified by the olivine(Fig.6-7) and spinel shape fabric. Since strong lineation is not observed, its deformation condition may be different from tectonite(e.g. Ozawa, 1983). Foliation is probably due to simple compression. Lattice preferred orientation of olivine supports deformation of olivine. Strong maximum of olivine X-axes is observed in the lower part of the columnar section with weak maximum of Y and Z-axes(Fig.6-7). In the top, maximum of olivine X-axes is not so strong as in the lower part(Fig.6-7).

Chemical zoning of spinel for the Shimoina complex also supports deformation of the adcumulate. Spinel deformation in alpine peridotite has following characteristics (Ozawa, 1989). The spinel of alpine peridotite shows strong lineation shape fabric even included in olivine. The chemical zoning shows strong Al_2O_3 concentration in the rim of extension side and strong Cr_2O_3 concentration in the rim of compression side. Ozawa(1989) concluded that the mechanism of spinel deformation is diffusion creep. But in the Shimoina complex, spinel included in olivine shows euhedral shape and interstitial spinel is characterized by strong planar fabric. In the interstitial spinel of the olivine cumulate in the

Shimoina complex, Al enrichment along the rim in the direction of the long axis is observed, however Cr enrichment in the rim of long axis is not observed(Fig.6-12). These lines of evidence suggest deformation of the spinel in the Shimoina complex is caused by solution and precipitation with interstitial liquid.

Well developed textural equilibrium of the olivine cumulate in the Shimoina complex is probably attained under the existence of interstitial liquid because subsolidus textural equilibrium is slow process limited by grain boundary diffusion(Hunter, 1987). Solution and precipitation is a major mechanism for textural equilibrium under the above solidus. Cooper and Kohlstedt(1984) experimentally determined the viscosity of olivine aggregates with basaltic liquids. It is only 2-5 times smaller than similar melt-free experiment. They pointed out the mechanism of the deformation is pressure solution. Olivine fabric of the Shimoina complex, however, suggests that deformation mechanism of olivine is diffusion creep.

Upper part of the columnar section, clinopyroxene-plagioclase layers with up to 10cm thick are observed in olivine clinopyroxene cumulate. These layers are interpreted to be high porosity zone which can resist compaction because much time is required for compaction of high porosity layer. The frequency of these layers increases from the bottom of top of the columnar section. This is probably caused by interstitial liquid migration from the bottom to top.

Above consideration is summarized to the model figure(Fig.6-13). Cooling from floor is assumed. (1)Magma intruded into the magma chamber with vertical depth of a few hundreds meters. According to the cooling from the floor, thermal gradient is probably formed. In the bottom of the mush zone on the chamber

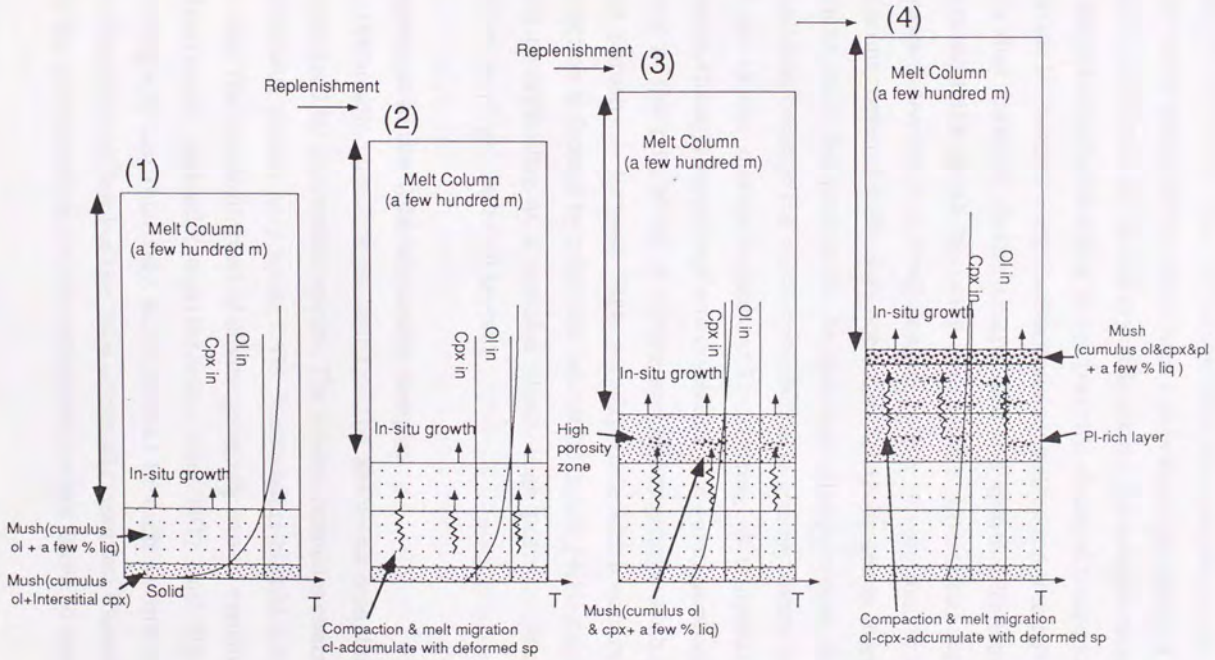


Fig.6-13 Model figure of crystallization, compaction and melt migration in crystal pile of the Shimoina complex. Cooling from floor is assumed. See text.

floor, olivine cumulate with interstitial clinopyroxene is formed which is not actually observed in the Shimoina complex. In the top of the mush zone, olivine mush with low porosity(probably a few percent) is formed by in situ crystallization. (2)Replenishment of the magma occurs. According to low porosity, chemical composition of olivine is changed along the fractional crystallization trend(Fig.6-2). In that mush of olivine, compaction and spinel deformation occurs and the mush becomes adcumulate. Interstitial liquid migrates, however it is small amount to the olivine matrix and significant chemical shifts does not occur. Relatively gentle thermal gradient may be preferable to prevent clinopyroxene from crystallizing because the modal composition of clinopyroxene is up to 1.5% in the olivine cumulate.(3)According to temperature decrease, clinopyroxene begins to crystallize as a cumulus phase at the top of the pile. Mush of olivine and clinopyroxene with low initial porosity is formed. High porosity zone which can resist compaction is formed by migrated interstitial liquid. (4)Plagioclase begins to crystallize as a cumulus phase. High porosity zone is solidified as plagioclase-rich layers.

Comparison to the Toba ultramafic complex

Ultramafic cumulate in Unit I of the Shimoina complex is characterized by adcumulus texture. The olivine cumulate contains postcumulus phases only up to 1.5%. Postcumulus hornblende is very rare. The chemical trend of olivine generally can be explained by fractional crystallization(Fig.6-2). The TiO_2 and YFe of spinel(Fig.6-3) are relatively homogeneous in each sample and lower than that of Unit I of the Toba ultramafic complex. Chemical shifts by interstitial liquid crystallization do not have so much

effect on the chemical composition of cumulus phases. The cyclic unit, up to a few tens of meters, can be defined by the chemical composition of olivine. Chemical zoning and fabric of spinel indicate compaction of the olivine cumulate. The estimated magma column depth for the chamber is about 110 to 250 meter.

On the contrary, ultramafic cumulate in Unit I of the Toba complex is characterized by orthocumulate texture. Small amount of hornblende commonly occurs as a postcumulus phase. Adcumulate with up to several meter thick is found on the orthocumulate, however it contains several percent of the postcumulus phases. Textural equilibrium does not completely achieve. No significant compaction does not have effect to decide the texture of the cumulate. The chemical composition of spinel is heterogeneous even in thin section scale(Fig.4-2, 4-3) and is probably affected by interstitial liquid. The chemical composition of olivine also can be explained by interstitial liquid crystallization(Fig.4-8). The macrorhythmic unit of the olivine cumulate, up to 15m, is characterized by upward increase of modal composition of olivine plus spinel and upward increase of incompatible elements in spinel and clinopyroxene. This macrorhythmic unit is probably caused by the crystallization in relatively steep thermal gradient. The estimated magma column depth for the chamber is about 100 meter.

The chemical and textural difference between the Shimoina complex and the Toba complex is caused by amount of interstitial liquid and its degree of crystallization. In the Toba complex, interstitial hornblende is commonly observed in olivine cumulate probably because interstitial liquid remains till temperature decreases to the point of hornblende crystallization. Fractionation of

interstitial liquid can occur. In the Shimoina complex, postcumulus minerals is rare in olivine cumulate probably because of low initial porosity and interstitial liquid migration by compaction before postcumulus phases begin to crystallize.

The controlling factor which makes two complexes different may be thermal gradient in the crystallizing mush. In the Toba ultramafic complex, thermal gradient several tens °C/m may be required to explain simultaneous crystallization of olivine at the top and clinopyroxene at the bottom of the layer up to 15m(Fig.5-6). In the Shimoina ultramafic complex, thermal gradient may be lower than several °C/m to explain very low volume of clinopyroxene in olivine cumulate(Fig.6-13).

In the Jimberana intrusion, orthocumulate and adcumulate is observed in same units(Campbell, 1987). At the margin of the intrusion, the units show orthocumulate texture. At the center of the intrusion, the units show adcumulus texture. The thickness of the units at the center of the intrusion is about ten times larger than that of the margin. However, there is no such large difference in the thickness of the layer between the Toba complex and the Shimoina complex.

Estimated crystallization pressure of Shimoina complex and the Toba complex is comparable because cotectic relations of olivine-clinopyroxene-plagioclase are observed in both of them. Nakamura(1971) discussed that the crystallization pressure of the Toba complex is below 10kb by using the cotectic relation. This conclusion holds according to the new experimental data(e.g. Gust and Perfit, 1987).

The difference in thermal gradient in the crystallizing mush is probably caused by the production rate of the magma. High

production rate of magma can maintain the temperature of the crystallizing mush high enough to prevent interstitial liquid from crystallization as a postcumulus phase. Replenishment of new magma may occur more frequently in the Shimoina complex.

VII. Concluding remarks

(1) Representative geological feature of ultramafic complexes of the Mikabu belt can be observed in the Toba ultramafic complex. It is divided into three units. Unit I is composed of olivine cumulate and olivine clinopyroxene cumulate. Unit II is a sill complex of hornblende-rich rocks and overlies Unit I. Unit III is composed of hornblende-rich rocks and occurs as dikes intruding into Unit I. Unit I is characterized by the alternation of olivine cumulate and olivine clinopyroxene cumulate. The layering mostly strikes northwest to southeast and dips to east. This trend is similar to the trend of foliation and sills of Unit II. Olivine cumulate in Unit I is characterized by orthocumulate texture. The primary magma for the Toba ultramafic complex can be estimated from the chemical composition of the dike from Unit III. It can coexist with mantle olivine and its MgO content is 14.4wt.%.

(2) An unequilibrated olivine orthocumulate in the Mikkabi complex is described to understand nature of interstitial liquid crystallization. Olivine has zonal structure characterized by decrease of Fo and NiO content which cannot be explained by fractional crystallization model. Chemical composition of spinel enclosed in olivine correlates to the distance to the rim of host olivine. TiO_2 and YFe of spinel increase as distance to the rim decreases. Spinel chemistry also correlates to enclosed minerals and spinel enclosed in postcumulus phases is relatively rich in TiO_2 and YFe. Clinopyroxene has chemical zoning and the rim of clinopyroxene has higher TiO_2 and Na_2O and lower XMg. XMg of clinopyroxene and other cumulus phases are not so low as expected from incompatible elements enrichment. These lines of evidence suggest that the Fe/Mg ratio of interstitial liquid of this olivine

cumulate is buffered by olivine while incompatible element is enriched by postcumulus crystallization.

(3) Wide chemical variation of spinel even in one thin section suggests abundant influence of interstitial liquid crystallization. Although olivine is now completely homogenized, gentle decrease of NiO content comparable to Fo content supports trapped liquid crystallization. High TiO_2 and Na_2O of interstitial clinopyroxene can also be explained by trapped liquid fractionation.

(4) Macrorhythmic unit of the olivine cumulate in the Toba complex is characterized by several to tens of meters scale units defined by upward decrease of postcumulus phases modal content and upward increase of incompatible elements in spinel and clinopyroxene. Chemical composition of olivine usually does not change significantly. This layering is a direct evidence of boundary layer fractionation. Fractionated interstitial liquid buffered by olivine migrates from the bottom and chemical composition of spinel and clinopyroxene is affected.

(5) The olivine cumulate of the Shimoina complex is characterized adcumulus texture and planar fabric of spinel in interstitial. Chemical composition of olivine and spinel may not be significantly affected by interstitial liquid crystallization. Cyclic unit can be defined by the chemical composition of the olivine and spinel. The melt column height required to form each units by fractional crystallization is estimated to be a few hundreds meters thick. Secondary reducing of porosity in the Shimoina complex may not have been occurred because time scale for compaction may be longer than the cooling time scale. In situ crystallization with low porosity is preferable for the Shimoina adcumulate. The crystal mush with low porosity is now deformed. Fabric and chemical

zoning of spinel and well attained texture equilibrium of olivine suggest that the mechanism of the deformation of the spinel is solution and precipitation. The chemical variation and texture of ultramafic cumulate in the Shimoina complex and the Toba complex are distinct because of amount of interstitial liquid and its crystallization degree. However, the size of the chamber is same order of magnitude. The difference is probably caused by the production rate of the magma. High production rate in the Shimoina complex can probably maintain the temperature in crystallizing mush high enough to prevent interstitial liquid from crystallizing.

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A.

B.

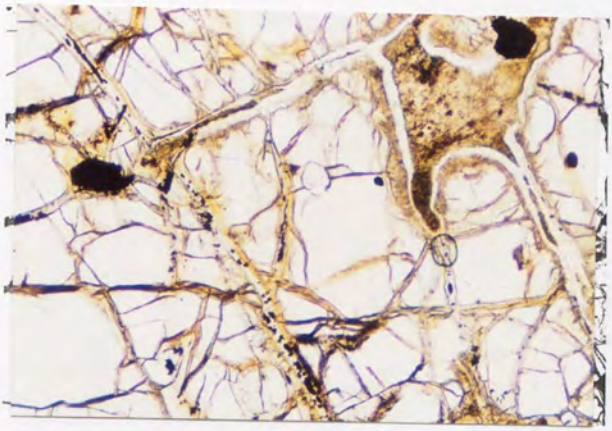
Plate2-1 A: Photograph of contact relationship between Unit I(green part), II(brown part of top of the mountain) and III(White vein part in Unit I). Central part of the Sugashima island. B: Olivine clinopyroxene cumulate(Clinopyroxene gabbro: white part) intrudes into olivine cumulate. Note platy angular block of olivine cumulate(black part) in olivine clinopyroxene cumulate(white part).

A.

B.

Plate2-2 A: Olivine cumulate of the Unit I. Note euhedral elongated olivine and interstitial postcumulus phases(Clinopyroxene, hornblende, plagioclase and phlogopite). T020410. Open nicol. B: Olivine clinopyroxene cumulate of the Unit I. T31253. Open nicol. The width of the photograph is c. a. 7mm.

A.



B.

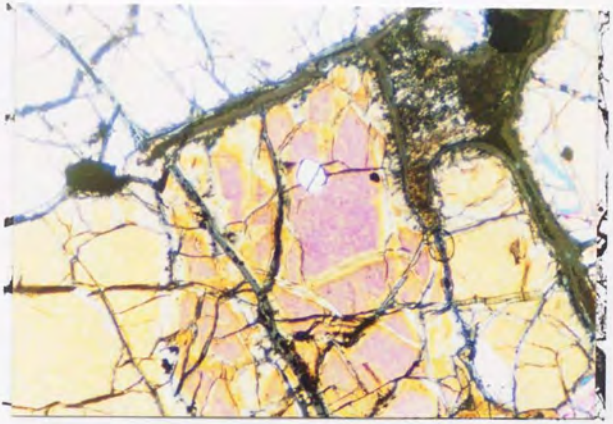
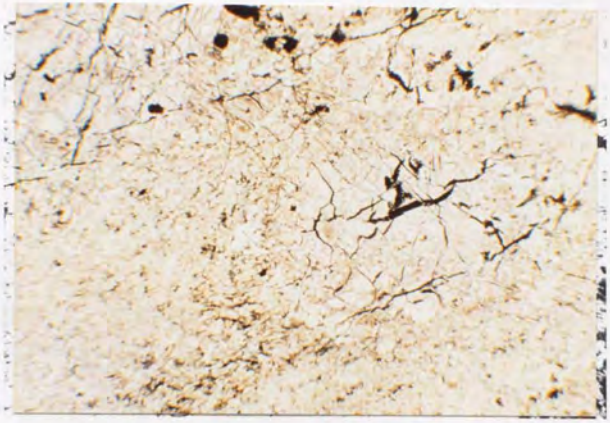


Plate2-3 Relict plagioclase in olivine in olivine cumulate of Unit I. the width of the photograph is c.a.1.4mm A; open nicol, B; crossed nicol.

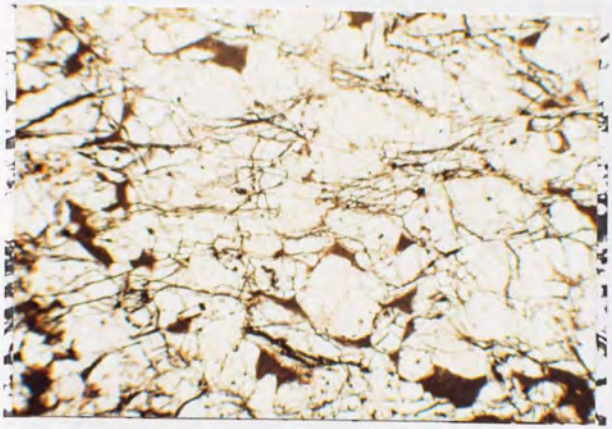
A.



B.

Plate2-4 A: Olivine hornblendite of the Unit II. T032711A. B: Hornblendite of Unit III. T071911. Chemical composition of this rock is primary magma of the Toba ultramafic complex. The width of the photograph is c. a. 7mm.

A.



B.

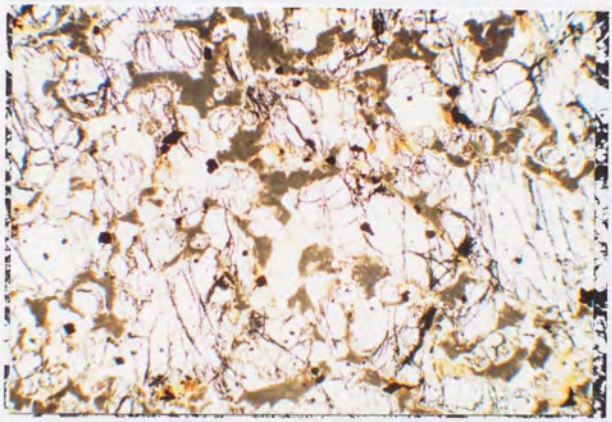
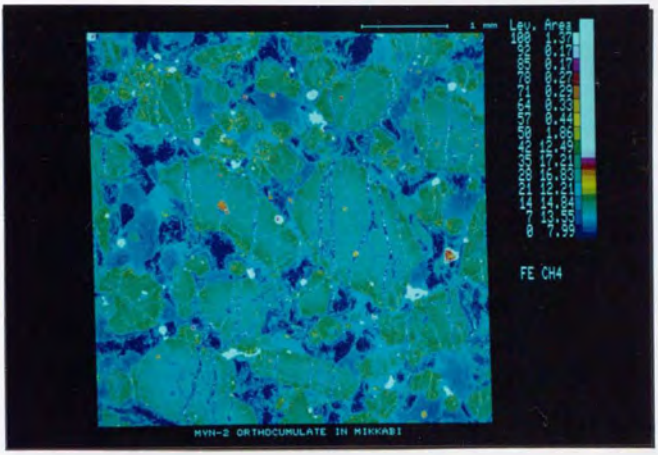


Plate3-1 A: Poikilitic clinopyroxene in olivine orthocumulate from the Mikkabi complex. B: Euhedral olivine and postcumulus phases(clinopyroxene, plagioclase and hornblende). The width of the photograph is c. a. 7mm.

A.



B.

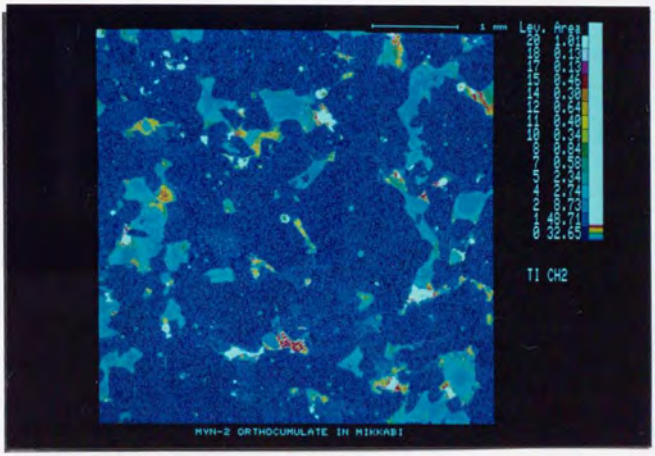
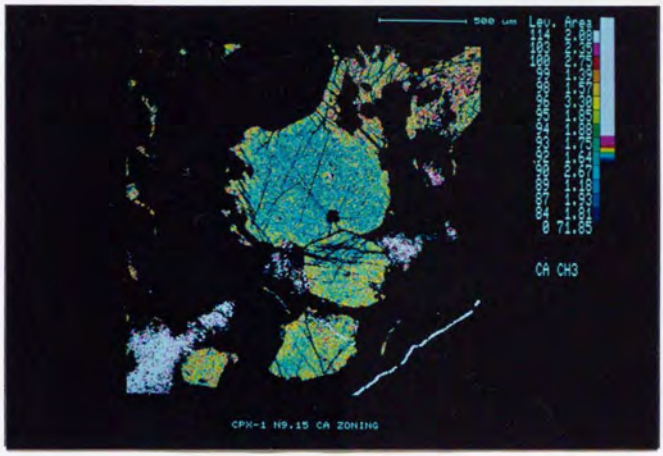


Plate3-2 CMA mapping of an unequilibrated olivine orthocumulate of the Mikkabi complex. A: Fe B: Ti

A.



B.

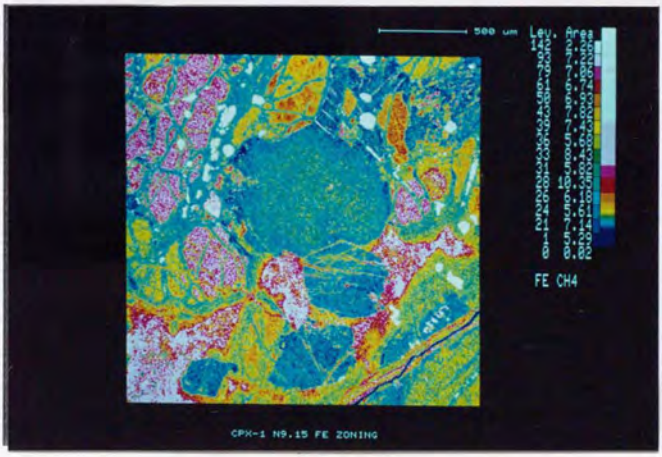
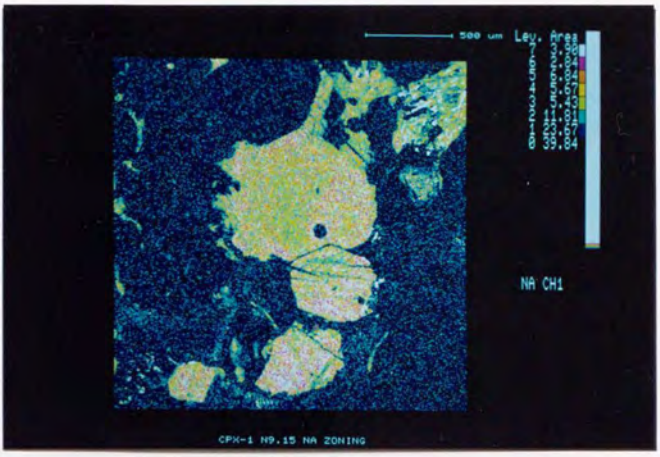


Plate4-1 CMA mapping of clinopyroxene in a olivine clinopyroxene cumulate of Unit I from the Toba ultramafic complex. A: Ca B: Fe. Note high CaO and low FeO concentration in rim and interstitial part of clinopyroxene.

A.



B.

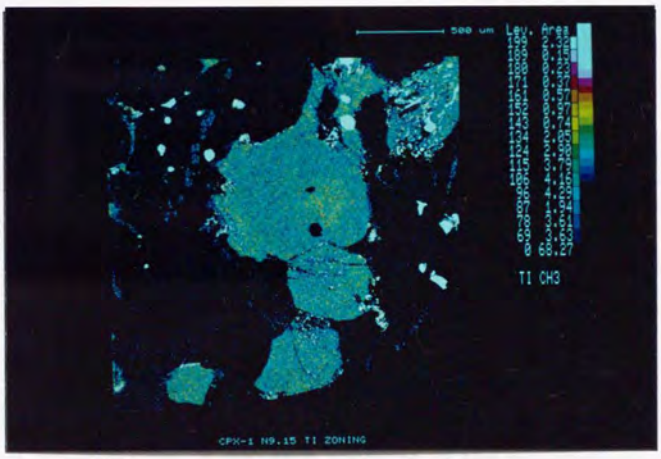
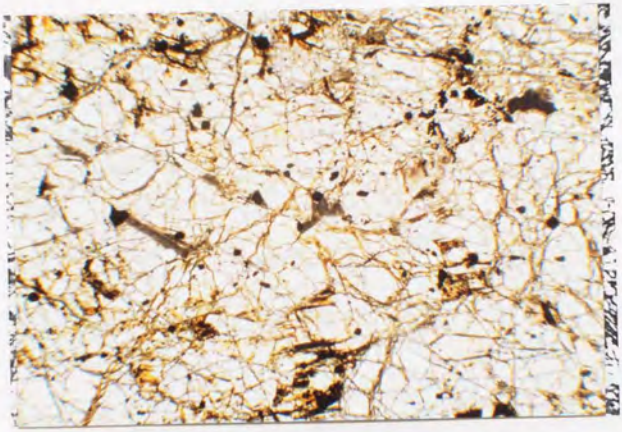


Plate4-2 CMA mapping of clinopyroxene in a olivine clinopyroxene cumulate of Unit I. A: Ti B: Na. Note high concentration of Na to the rim and interstitial part.

A.



B.

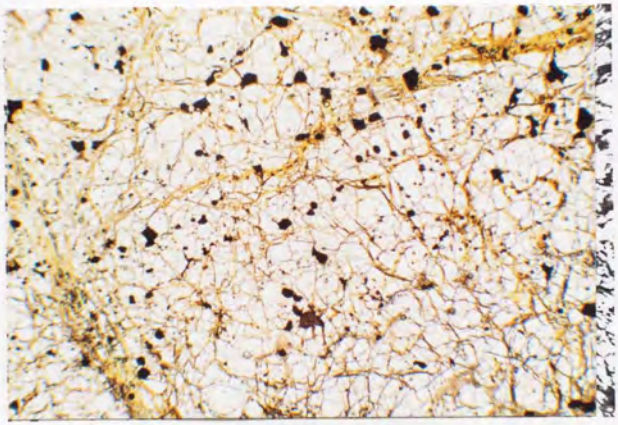
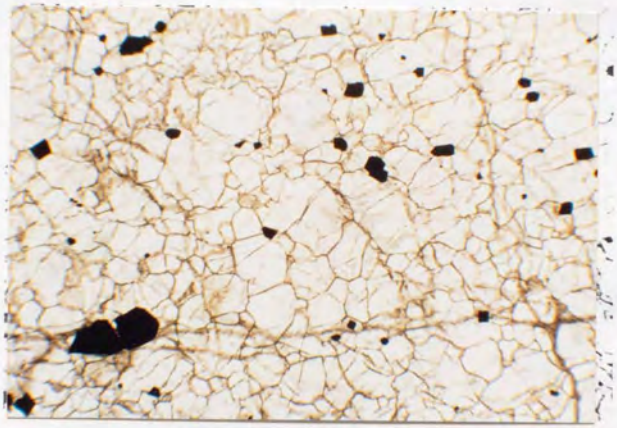


Plate5-1 Photographs of the thin sections of the macrorhythmic unit of olivine cumulate in the columnar section from the Toba ultramafic complex. A: Base of a macrorhythmic unit. B: Top of a macrorhythmic unit. Note abundant interstitial phases in A and texture equilibrium in B. The width of the photograph is c. a. 7mm.

A.



B.

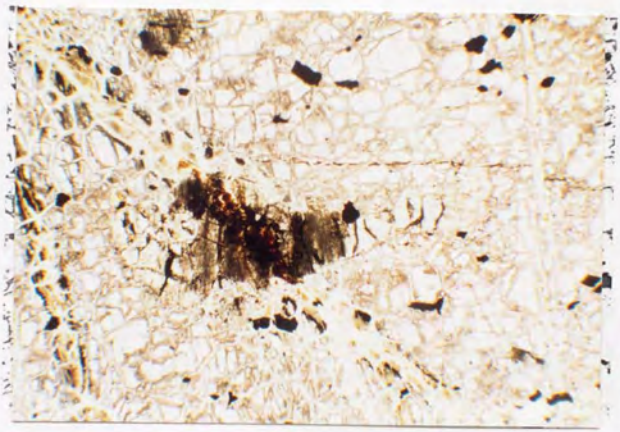
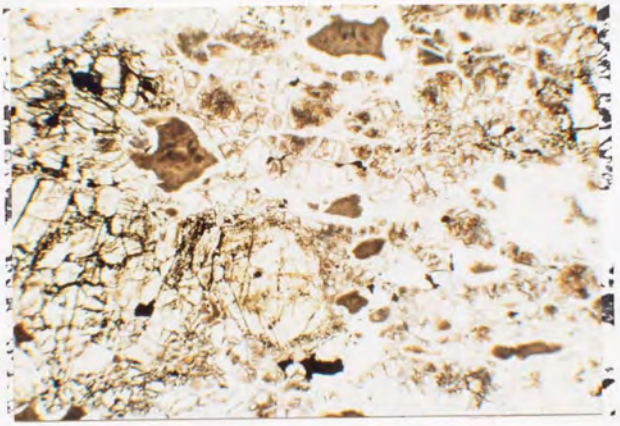


Plate6-1 A: Olivine cumulate of Unit I in the Shimoina complex. This thin section is vertical to the foliation. S304-2. Note well attained texture equilibrium. Base part of the columnar section. B: Olivine clinopyroxene cumulate of Unit I. S232. The width of the photograph is c. a. 7mm.

A.



B.

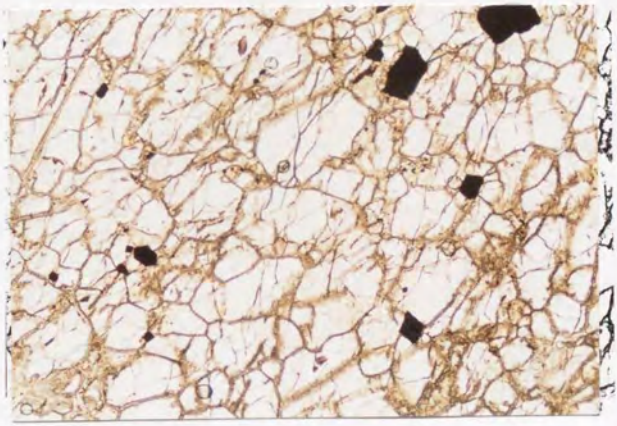
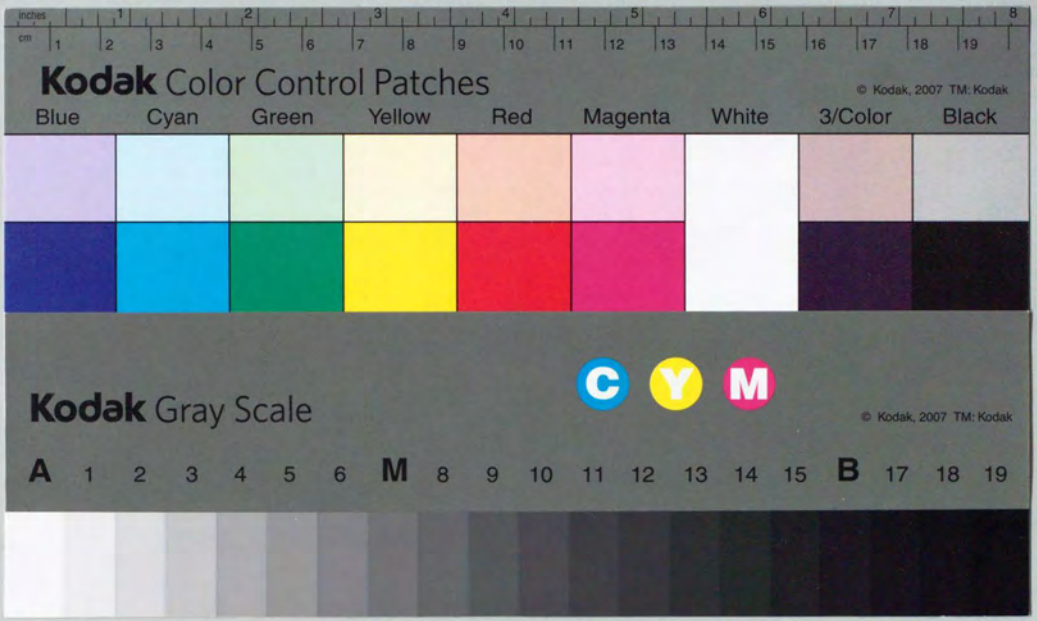


Plate6-2 A: Olivine clinopyroxene plagioclase cumulate in Unit I. This thin section is vertical to the foliation. S310-3. The width of the photograph is c. a. 7mm. B: Vein of clinopyroxene in olivine cumulate. S68. The width of the photograph is c. a. 3.5mm.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