Phase equilibrium modeling and P-T evolution of high-P/T Sambagawa Metamorphic rocks in Kanto Mountains, Central Japan

*Yusuke Kuribara[1], Toshiaki Tsunogae[2]

1.Graduate School of Life and Environmental Sciences, University of Tsukuba , 2.Faculty of Life and Environmental Sciences, University of Tsukuba

Sambagawa metamorphic belt, which extends about 800 km from east (Kanto Mountains) to west (East Kyushu Island), is regarded as an excellent example of high-P/T type metamorphic belt located at the northernmost edge of the Outer Zone of southwest Japan. The high-pressure rocks were probably formed by complex subduction-accretion processes in western Pacific region during Cretaceous (Isozaki and Itaya, 1990). Numerous petrological, geochronological and structural studies have been done on the belt particularly focusing on P-T evolution and tectonics, but they are mainly on the western part of the belt in Shikoku Island which metamorphic grade is higher than the eastern part. In contrast, only very few studies have been done on the Sambagawa metamorphic rocks in Kanto Mountains which corresponds to the eastern end of the belt. This study reports new petrological and P-T data of the Sambagawa pelitic schists from Kanto Mountains and compare the results with those of Shikoku Island. This is the first report of quantitative P-T path estimated for Sambagawa schist from this region based on phase equilibria modeling approach.
The studied pelitic schist is dark grayish, very fine- to fine-grained, well foliated, and contains phengite, hematite, chlorite, biotite, epidote, garnet, quartz, and plagioclase. Plagioclase is porphyroblastic and occurs as spots. Phengite defines major foliation of the rock. Garnet is fine grained (less than 30 microns) and almandine-rich in composition. It’s spessartine component decreased from core to rim, showing normal zoning. Although biotite could be a stable assemblage, it was probably completely replaced by chlorite due to later hydration event. Metamorphic P-T evolution of the rocks was evaluated using THERIAK-DOMINO ver.16.10.2012 software based on the chemical system Na_2O-CaO-K_2O-FeO- MgO-Al_2O_3-SiO_2-H_2O-TiO_2 (NCKFMASHT). The peak P-T condition of the rock was inferred from the stability field of the inferred peak assemblage (plagioclase + ilmenite + garnet + phengite + biotite + zoisite + quartz) as 580-630°C and 9-13 kbar, which is nearly consistent with the results of garnet-phengite geothermometry applied to the same sample. The event was followed by decompressional cooling toward a retrograde stage of 370-440°C and 1.4-5.5 kbar as inferred from a retrograde assemblage of plagioclase + ilmenite + chlorite + garnet + phengite + biotite + quartz. The peak condition is, however, about 100°C higher than the available P-T data of Fe-Mn rich nodule from the studied region (7-12 kbar and 460-540°C; Hirajima, 1995), but nearly consistent with the condition of Oligoclase-Biotite zone of the Sambagawa schists from Central Shikoku Island. The results of this study therefore suggest that the Sambagawa metamorphic belt in Kanto Mountains might have experienced a similar metamorphism with the belt in Shikoku. The Sambagawa metamorphic rocks in the two areas probably subducted to a similar depth and underwent similar high-pressure metamorphism.

Keywords: Sambagawa metamorphic belt, Phase Equilibria Modering, Pelitic schist, Peak P-T conditions, Kanto mountains

Geology of the Atogura Nappe of the Yorii-Ogawa district in the northeastern Kanto Mountains

*Akira Ono

Geology of the Atogura Nappe was studied in the Yorii-Ogawa district. The surveyed area is situated in the northeastern part of the Sanbagawa belt and is characterized by the wide distribution of Atogura (Atokura) Nappe. The results are shown in the attached figure. The geological map is partly based on the maps published before by the present writer [1, 2].

1) The Atogura thrusts were reported or supposed at locations a –e. In other localities the Atogura Nappe is in contact with pre-Miocene geological units by high-angle faults. Miocene deposits unconformably overlie the Atogura Nappe. Clasts of Ryoke metamorphic and granitic rocks are common in the Miocene deposits. The provenance of the clasts is the Ryoke Nappe tectonically superposed on the Atogura Nappe. The W-E geological section is figured on the basis of the assumption that the Ogawa Miocene sedimentary basin is a small half-graben.

2) The Atogura Nappe consists of various geological units. Large geological units are elongated in E-W directions. The large geological units are in contact with each other by high-angle faults. Many small tectonic blocks are distributed along the high-angle faults. Fault gouges and metasomatic rocks are accompanied by the high-angle faults. Prehnite is not found near the high-angle faults although prehnite is common in the Atogura Nappe.

3) Tectonic blocks of mid-Cretaceous Higo-Abukuma granitic and metamorphic rocks were found at many locations. Common rock-types are psammitic, calcareous and mafic metamorphic rocks. The metamorphic rocks exhibit variable metamorphic grades of amphibolite facies. Fusulinacean fossils are observed in some outcrops, but sillimanite- K-feldspar gneisses are exposed in a few outcrops.

4) Metamorphic rocks near the Kinshozan quartz diorite are usually described as Permian hornfels. It is however uncertain that all the metamorphic rocks are hornfels and were metamorphosed at Permian. Hence, the name of Shimonita metamorphic rocks is used here instead of Permian hornfels.

5) Acidic tuff and Higo-Abukuma granitic and metamorphic rocks are shown in the southernmost part of the Atogura Nappe. These rocks are members of the Kiroko greenstone mélange which mainly consists of Kiroko metamorphic rocks, serpentinite and various kinds of tectonic blocks.

6) Deformation and alteration are not observed at the boundary zone between tectonic blocks and Kiroko metamorphic rocks although prehnite veins and quartz-albite veins were formed in some tectonic blocks. The tectonic blocks did not suffer the Kiroko metamorphism.

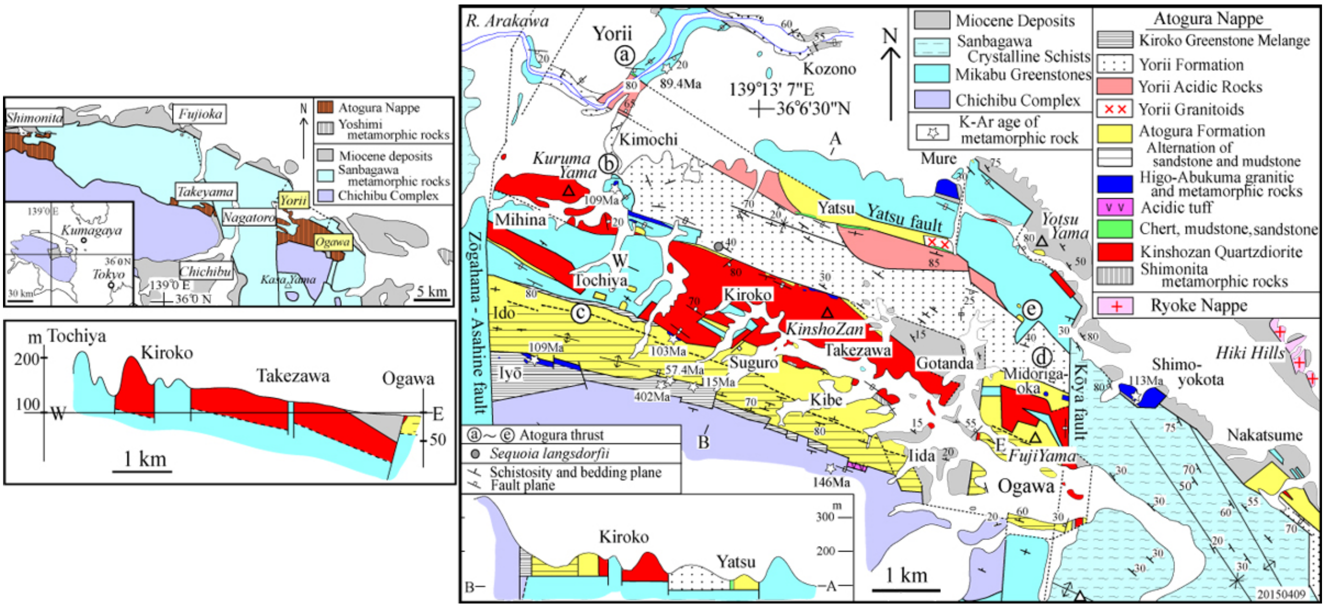
7) K-Ar whole-rock dating for the Kiroko metamorphic rock was carried out on a greenstone containing many small pelitic lenses. Secondary recrystallization of constituent minerals cannot be detected for the studied sample. The dating result is 57.4Ma. The result suggests that the Kiroko high-pressure type regional metamorphism occurred in early Paleogene.

8) Highly altered massive tonalites are exposed in the Tochimoto, Kibe district. They are tectonic blocks of the Kiroko greenstone mélange. As fine epidote and felsic minerals are recrystallized abundantly in the altered tonalites, it is often difficult to detect initial plutonic textures. K-feldspar is very small in amount. Hence, the tonalites appear to be plagiogranites.

9) Yorii acidic rocks mainly consist of early Paleogene pyroclastic rocks and porphylitic granites. These acidic rocks are believed to be formed very far from the subduction zone where serpentinites and the high-pressure-type Kiroko metamorphic rocks were exhumed. Hence, a considerable Nappe tectonics is supposed to take place before the formation of the Atogura Nappe.

[1] A. Ono, 2008, Abs. Japan Geosci. Union Meeting, G119-P002.
[2] A. Ono, 2013, Abs. Japan Geosci. Union Meeting, SGL41-P04.

Keywords: Atogura Nappe, Greenstone melange, Tectonic block, K-Ar dating, Nappe tectonics



Petrological and geochronological study of orthogneiss from the Tromsø Nappe in Scandinavian Caledonides

*Yasuhiro Monta[1], Takao Hirajima[1], Hideyuki Obayashi[1], Takafumi Hirata[1]

1.Department of Geology and Mineralogy, Graduate School of Science, Kyoto University

Orthogneiss is the predominant lithotype in ultra-high pressure (UHP) terranes in the world but it generally consists of low pressure metamorphic minerals of mainly amphibolite facies. However, extensive petrological studies succeeded to find several signs of UHP minerals from the county gneiss, and hence, most of the country gneiss shared the UHP metamorphism. The Scandinavian Caledonides were formed by collision between Baltica and Laurentia Cratons during Ordovician to Devonian, and are composed of several allochthons which have juxtaposed onto Precambrian cover. Evidences of UHP metamorphism are found from the Western Gneiss Region (WGR) in Lower Allochthon (Hacker et al., 2001), the Seve Nappe in Middle Allochthon (Majka et al., 2014), and the Tromsø Nappe in Uppermost Allochthon (Janák et al., 2013). In the WGR, UHP evidences occur widely in the NW part, however in the Seve and Tromsø Nappes UHP evidences are sporadic, so the areal extent of UHP metamorphism remains unclear. The Tromsø Nappe is mainly composed of eclogites, gneisses, schists and marbles. Krogh et al. (1990) estimated the peak *P-T* conditions of country gneisses and pelitic schists as 670-700 C and 1.5-1.7GPa during D_1 stage. After that, Janák et al. (2012) estimated the UHP metamorphic conditions of 720-800 C and 3.2-3.5 GPa using pseudosection analysis and conventional geothermobarometry for eclogite in Tromsdalstind. Janák et al. (2013) finally found microdiamond from garnet-rich carbonate-bearing gneiss in Tønsvika. However, UHP evidence has not been reported from the country gneiss and schists. In this study, we report mineral paragenesis and zircon U-Pb age of orthogneiss hosting UHP eclogites in the Tromsø Nappe. Studied sample was collected from large blocks of orthogneiss distributing on the ridge around N69°26′0″, E19°9′33″ (garnet-muscovite schist unit: Zwaan et al., 1998). Main constituent minerals are garnet, muscovite, plagioclase, alkali-feldspar, and quartz with minor amounts of kyanite, rutile, biotite, hornblende, epidote, chlorite, ilmenite, and zircon. The alignments of mica and plagioclase porphyroclast characterize the gneissose structure. The LA-ICP-MS U-Pb dating of zircon in orthogneiss gives the majority of the concordant ages between 470 and 420 Ma, and minor inherited ages of about 1500-1300 Ma and 800 Ma. The weighted mean $^{206}Pb/^{238}U$ age (± 2σ) of rim of zircon is 454.2 ±5.2 Ma (n=21). This age is consistent with metamorphic age of Tønsvika eclogites (452.1 ±1.7 Ma; Corfu et al., 2003) within error. Most of garnets with a few 10 to 100 μm diameter have Fe-rich compositions ($Alm_{0.68-0.74}Prp_{0.11-0.18}Grs_{0.10-0.18}Sps_{0.01}$). They include quartz, rutile, zircon, and rare kyanite as primary inclusions. Some of them have Ca-rich rim ($Alm_{0.63-0.68}Prp_{0.09-0.11}Grs_{0.20-0.26}Sps_{0.01}$) with a distinct chemical gap to the core. In some plagioclase, Ca-content decreases from the core (An=0.26-0.33) to the rim (An=0.17-0.28). Biotite commonly replaces rim of muscovite or occur as fine laths of a few 10 μm diameter, suggesting the secondary origin, while muscovite is relatively coarse grained {100-500μm diameter; Si=6.13-6.38 (O=22), TiO_2=0.17-1.34, X_{Fe}=0.28-0.50}. GASP geobarometer and Grt-Ms Fe/Mg exchange geothermometer give 450-500 °C and 1.1-1.2 GPa for the core-core pairs of garnet and plagioclase and 530-570 °C and 1.6-1.7 GPa for the rim-rim pairs of garnet and plagioclase, indicating the pressure increase is necessary for the rim formation. *P* condition estimated from the rim-rim pairs is consistent with D_1 stage (1.5-1.7 GPa) of the country gneiss in the same nappe (Krogh et al., 1990), but *T* condition obtained by the same pair is significantly lower than that of D_1, which may be caused by the modification of muscovite composition.

Keywords: UHP terrane, Caledonides, orthogneiss, Ziricn U-Pb dating

Deformation microstructures of metamorphic mafic rocks close to the boundary to the Tanzawa plutonic complex

*Tomoki Mizuno[1], Katsuyoshi Michibayashi[2]

1.Graduate School of Science, Shizuoka University, 2.Institute of Geosciences, Shizuoka University

The purpose of this study is to understand microstructural development of metamorphosed mafic rocks close to Tanzawa plutonic complex. Samples are collected from the southern region within 1 km from the boundary with Tanzawa plutonic complex. The mafic rocks consist mainly of amphibole and plagioclase with secondary minerals such as quartz and clinopyroxene. For microstructural analyses, we used well polished thin sections cutting perpendicular to the foliation and parallel to the lineation (i.e. XZ plane). Under a microscope, amphibole grains are well elongated. Plagioclase grains are polygonal and partly dynamically recrystallized.

Crystal-preferred orientations (CPOs) of both amphibole and plagioclase were measured. Amphibole CPOs commonly showed intense (100) [001] patterns. Plagioclase CPOs showed strong (001) [100] patterns in relativity monomineralic domains. In polymineralic domains where plagioclase and amphibole were coexisted, plagioclase CPOs showed remarkably weak (010)[001], (100)[001] patterns, or random patterns. Crystal orientations maps in amphibole dominant domains show that subgrains occur in amphibole grains. Some grain boundaries between amphibole grains are oriented perpendicular to the foliation. Cao *et al*. (2010 , JSG) showed that these grain boundaries were formed by dislocation wall resulting from dislocation creep. Therefore, we suggest that dislocation creep was dominant in deformation mechanism for amphibole. In polymineralic domains of amphibole and plagioclase, amphibole CPOs showed (100)[001] pattern, whereas plagioclase CPOs showed random patterns, where grain sizes are smaller than those with intense CPOs patterns in both amphibole and plagioclase. It suggests that grain-size sensitive creep may become dominant, as decreasing grain sizes of plagioclase due to the mixing with amphibole during deformation. As a consequence, the deformation mechanism could be switched from dislocation creep to grain-size sensitive creep during deformation in the metamorphic mafic rocks.

Keywords: dislocation creep, Tanzawa , CPO

Inconsistency between SEM image and Crystal orientation data obtained by SEM-EBSD systems

*Akira Miyake[1], Aki Takigawa[1,3], Yohei Igami[1], Shugo Ohi[2], Ryuta Nakamura[1], Akira Tsuchiyama[1]

1.Department of Geology and Mineralogy, Graduate School of Science, Kyoto University, 2.Faculty of education, Shiga university, 3.The Hakubi Center for Advanced Research, Kyoto University

Recently, a scanning electron microscope (SEM) equipped with electron back-scattering diffraction (EBSD) have become a strong and common tool to obtain the crystallographic information from minerals and various materials. SEM-EBSD can evaluate not only crystal orientations of individual crystals but also alignment property of crystal orientations in a wide area. For obtaining the crystallographic information by an SEM-EBSD system, we need a software program to detect and analyze EBSP (electron back-scattering diffraction pattern), which is generally developed by EBSD-detector venders or some laboratories.
El-Dasher et al. (2009) reported the possible inconsistencies between SEM images and crystal orientations obtained by SEM-EBSD systems. However, this crucial problem has not been widely known. In this presentation, we will report the result of experimental tests about this problem performed in our laboratory.
We carried out a series of experiments using our SEM-EBSD system consisting of JEM-7001F (JEOL) and HKL channel 5 (Oxford instruments). Single crystals of Si, corundum, and quartz with known crystal planes were used in the experiments. The crystal plane was set with its typical axis slightly tilted for easier analysis and discussion. Trigonal or orthorhombic crystals are more suitable for this test than that with the cubic crystals in order to avoid the confusion by equivalent orientations.
We confirmed the systematic inconsistency between SEM images and crystal orientations obtained by HKL channel 5. The orientation shown by HKL channel 5 was just consistent with the SEM image rotated by 180 degrees around the sample normal direction. The same inconsistency may occur in many SEM-EBSD systems in other laboratories. We will also report the cases for other combinations of SEMs and EBSD-detectors.

Keywords: SEM-EBSD, crystal orientation

Elastic wave velocity and microstructures of amphibolite gneisses

Kanta Koike[2], Hiroto Endo[4], Katsuyoshi Michibayashi[3], *Tohru Watanabe[1]

1.Gradudate School of Science and Engineering, University of Toyama, 2.Faculty of Science, University of Toyama, 3.Institute of Geosciences, Shizuoka University, 4.Graduate School of Science, Shizuoka University

Seismic velocity is one of the most important sources of information about the Earth’s interior. For its proper interpretation, we must have a thorough understanding of the dependence of seismic velocity on microstructural elements, including the modal composition, the crystal preferred orientation (CPO), the grain shape, the spatial distribution of mineral phases, etc. We have studied seismic velocities and microstructures of amphibole gneisses. Rock samples of amphibole gneisses were collected at Momose River (Yatsuo, Toyama Pref.). They are mainly composed of quartz (34-36vol.%), plagioclase (18-27vol.%) and hornblende (34-46vol.%). Quartz and plagioclase crystals are almost randomly oriented, while c-axes of hornblende crystals are strongly aligned parallel to the lineation and a-axes perpendicular to the foliation. A rectangular parallelpiped (the edge length ~ 40 mm) was made from rock samples for ultrasonic velocity measurements. Two faces are parallel to the foliation plane, and two faces perpendicular to the elongation direction. Velocity measurements were made under confining pressures of up to 180 MPa at room temperature. The pulse transmission technique was employed by using $Pb(Zr, Ti)O_3$ transducers with the central frequency of 2 MHz. Under the confining pressure of 180 MPa, the fastest compressional wave velocity was observed in the direction parallel to the lineation, and the slowest one in the direction perpendicular to the foliation. Velocities calculated with the VRH averaging scheme reasonably reproduce the measured velocities. The anisotropy in velocity is caused by the CPO of hornblende crystals, though the anisotropy due to aligned hornblende crystals is largely weakened by almost randomly oriented quartz and plagioclase crystals. The influence of the grain shape of hornblende on the anisotropy in velocity will also be discussed in our poster.

Keywords: amphibolite, gneiss, anisotropy, elastic wave velocity, crystal preferred orientation

Olivine megacrysts in mantle peridotites

*Akari Minamiyama[1], Yusuke Soda[1], Akihiro Tamura[1], Shoji Arai[1], Tomoaki Morishita[1]

1.Earth and Environmental Sciences Coarse, School of Natural System,Kanazawa University

Mineral grain size in the upper mantle affects many geological processes, such as mantle flow, fluid/melt migration and so on. Olivine grain size in the upper mantle conditions is generally less than 1 cm (Ave Lallemant et al, 1980; Karato, 2011). However, olivines, which are larger than 1 cm in grain size (olivine megacryst hereafter), often occur in peridotites. Therefore, understanding of the conditions of olivine megacrysts is critical to understand the upper mantle processes. In this study, peridotite samples with olivine magacrysts from the Horoman peridotite complex, Japan, and the Western Gneiss Region of Norway (WGR) are studied by crystallographic orientation analysis, ICP-MS and EPMA.

One peridotite sample is from MHL (Main Harzburgite-Lherzolite) suite in the Lower Zone of the Horoman peridotite complex. Olivine magacryst occurs subparallels to the foliation and looks darker than fine-grained olivines. Fine-giraned layer show porphyroclastic texture. Olivine megacryst and porphyroclast olivine in fine-grained layer developed subgrain boundaries and include lamellae of chromian spinel, clinopyroxene and amphibole.

Slip systems of olivine [001](100) and [100](001) are observed in the central part and the edge of olivine megacryst respectively, based on the U-stage measurements of subgrain boundaries and crystal orientations. Olivines in fine-grained layers show A-type fabric resulting from the dominance of [100](010) slip system (Jung et al., 2006). A-type fabric peridotite was reported in the Horoman peridotite complex and interpreted as the A-type fabric formed during uplifting of the Horoman peridotite complex from the upper mantle to the crust (Sawaguchi, 2004). Fine-grained olivine fabric near megacryst and slip system of olivine megacryst edge suggest that olivine megacryst would exist before the formation of A-type fabric in fine-grained layer.

Original olivine megacryst compositions before exsolution might relatively higher in Al, Cr, Na, Ti and Ca contents than fine-grained olivine. Adittion to this, presence of amphibole lamellae in olivine megacryst suggest that olivine megacryst was either originally hydrous olivine or hydrated after exsolution of unhydrous silicate minerals such as clinopyroxne. In the presentation, we will present results of chemical and structural observations of olivine megacrysts from the Horoman and WGR.

Metasomatic reactions at crust-mantle boundary in subduction zone: an example from Tomisato ultramafic body in the Tomisato area, central shikoku, Japan

*Ryosuke Oyanagi[1], Atsushi Okamoto[1], Masaoki Uno[1], Noriyoshi Tsuchiya[1]

1.graduate school of environmental studies, tohoku university

A large amont of element transfer could occur during the metamorphism along the subduction zone. Serpentinite, which was formed via hydration and/or metasomatic reaction of mantle peridotite, controls slab slip behavior (e.g., Peacock and Hyndman, 1999; Mizukami et al., 2014).
Si-metasomatism of mantle peridotite is discussed in $MgO-SiO_2-H_2O$ system (Manning, 1995, 1997). However, detailed analytical studies of on-land exposures of peridotites metasomatized by subduction-zone fluids are limited (e.g., Peacock, 1987; King et al., 2003). Therefore, the possible relationships between devolatilization reactions and related fluid and mass transfer are not clear.
In this study, we studied metasomatic reaction around a ultramafic body in the high pressure Sanbagwa metamorphic belt in Tomisato area, central Shikoku, Japan. Hereafter, we call this Tomisato ultramafic body. This ultramafic body is ~20m in size, and it is located at the garnet zone. The Tomisato ultramafic body is almost fully serpentinized (i.e., no olivine relict) and brucite is not observed. A lack of pyroxene relicts suggests the protolith of the Tomisato ultramafic body is dunite. Within the body, serpentinite has block-in-matrix or brecciated texture with fragments of fine-grained antigorite in coarse-grained matrix antigorite.
At north of the Tomisato ultramafic body, ultramafic rocks contact with basic rocks and veins of tremolite and talc was observed. On the other hand, at south of the Tomisato ultramafic body, ultramafic rocks contact with pelitic schist and vein of talc was observed. At the north boundary, reaction zone of Tremoite + Talc + Chlorite / Antigorite + Talc / Antigorite was observed. Tremolite and Talc zones were localized at ~80 cm and ~110cm from the contact, respectively. In contrast, at the south boundary, reaction zone of Antigorite + Talc / Antigorite was observed. Talc zone was observed ~80 cm from the boundary. Both boundaries are composed mainly of antigorite clasts embedded in a talc and/or tremolite veins, and matrix antigorite is not associated with these veins. These observations suggest that Si-metasomatic reaction occurred after block antigorite formation, and the mineralogy depends on the contact crustal rocks. We will discuss the timings of the Tomisato ultramafic body was taken in Sanbagawa metamorphic belt, metasomatic reaction, mass transport between crustal and mantle material, and possibility of hydrofracturing.

Keywords: crust-mantle boundary, metasomatism, serpentinite, Sanbagawa metamorphic belt, pelitic schist, basic schist

Estimation of Minimum Fe-Mg content for Plagioclase-Cordierite replacement

*Noboru Furukawa[1], Yoshikuni Hiroi[1], Yoichi Motoyoshi[2]

1.Graduate School of Science Chiba University, 2.National Institute of Polar Research

Conventional studies suggested that chemical compositions of metamorphic fluid consist of C-H-O-S system, and other elements such as Na, Ca, and Si are not transported with the fluid. These elements, however, do dissolve in the fluid in some instances, as exemplified by quartz-filled vein and as demonstrated by various studies of fluid inclusions. For example, in tonalitic granulite in Sri Lanka, plagioclase was substituted locally by cordierite.
We attempt to obtain the essential data about the element transport within the metamorphic fluid, by experimentally reproducing the chemical reactions that are responsible for element inflow and outflow. They include the solubility of mineral to the fluid, the chemical composition and concentration of the fluid, and their change in the pressure and temperature conditions. By utilizing this information, we should be able to limit the range of the chemical composition and concentration, and the P-T values.
This study has determined the minimum ratio of Mg/(Fe+Mg) and the minimum concentration of (Mg, Fe)Cl_2 for the plagioclase-cordierite replacement, by utilizing hydrothermal experiments. Because the ample amount of tonalitic-granulite specimen in Sri Lanka for this experiment is not available, we have used powdered specimens of anorthosite from the Natal region, South Africa, and chloride solution of Mg and Fe. These materials were sealed into gold capsule with or without CO_2 and were held at a pressure of 100 MPa and a temperature of 600 ℃ in autoclave for 130-400 hours. We have obtained the following results:
The minimum concentration of $MgCl_2$ for the plagioclase-cordierite replacement is approximately 0.08 mol/kg.
The minimum ratio of Mg/(Fe+Mg) for the plagioclase-cordierite replacement is approximately 0.2.
These minimum values derived above are not influenced by the presence of CO_2.
It is estimated that the Mg/(Fe+Mg) ratio of the fluid responsible for the plagioclase-cordierite replacement in the tornalitic granulite in Sri Lanka is approximately 0.2.

Formation of Corona around Corundum in the Lützow-Holm Complex, East Antarctica

*Yuki Mori[1], Takeshi Ikeda[2]

1.Department of Earth and Planetary Sciences, Graduate School of Science, Kyushu University,
2.Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University

Corona structures preserve both reactant and product minerals, which gives us information of its formation process including mass transformation. We investigated a corona structure in corundum-bearing ultramafic rocks in Akarui Point of the Lützow-Holm Complex, East Antarctica. The studied samples are composed mainly of calcium amphibole, plagioclase and corundum with minor biotite, spinel and sapphirine. The corundum grains are surrounded by the corona composed of spinel, sapphirine and plagioclase. These minerals are regularly arranged from corundum to the matrix. In the corona, cracks in spinel usually continue to sapphirine, but never extend further into plagioclase nor continue to corundum. We consider that the corona was produced by reaction between corundum and matrix calcium amphibole. Mass-balance in the CaO-MgO-Al_2O_3-SiO_2-H_2O system provides the following equation: corundum + spinel + calcium amphibole = sapphirine + plagioclase + H_2O-fluid. This equation shows spinel as reactant, which is inconsistent with the microstructure. This suggests that the corona was formed in an open system. We employed following additional assumption based on the microstructure. Continuity of cracks in spinel and sapphirine is indicative of former single phase. Provided that sapphirine was formerly spinel, corundum changed to spinel by supply of MgO from calcium amphibole. The remaining components in calcium amphibole may produce plagioclase, and excess SiO_2 would be released. After this reaction, significant amount of spinel was transformed to sapphirine due to supply of SiO_2. Alternatively provided that spinel was formerly sapphirine, corundum and calcium amphibole produced sapphirine and plagioclase. Similar to the former case, this reaction also released SiO_2. After that, sapphirine was partially transformed to spinel and released SiO_2. The net reaction based on both two cases is corundum + calcium amphibole = spinel + sapphirine + plagioclase + H_2O-fluid + SiO_2. This open-system reaction suggests that decrease of SiO_2-activity triggered the corona-forming reaction.

Keywords: corona, reaction microstructure, corundum, Lützow-Holm Complex

Petrological studies of high-grade paragneisses from Onzon and Thabeikkyin areas, central Myanmar

*Thu YE Kyaw[1], Masaki Enami[2]

1.Graduate School of Environmental Studies, Nagoya University, 2.Institute for Space-Earth Environmental Research, Nagoya University

The sigmoidal and elongated Mogok metamorphic belt extends for 1500 km from the Andaman Sea in the south to the eastern Himalayan syntaxis in the north and has variable metamorphic conditions throughout the belt. It lies at the western margin of Shan-Thai block and comprises high-grade metasedimentary rocks and metaigneous rocks with subduction-related granitoid intrusions. Previous radiometric studies, based on U-Th-Pb and Ar-Ar dating, concluded that an assembly of these high-grade metamorphic rocks was formed during Paleogene to early Neogene event that was caused by the collision of remnants of Gondwanaland with the Eurasian continent and subsequent underthrusting and collision of Indian plate with Eurasian plate. The metamorphic grade of the Mogok metamorphic rocks reaches upper amphibolite facies and granulite facies in some places.

Samples were collected from the middle segment of the Mogok belt, ~100 km north of the Mandalay region, where the geology is dominated by high-grade paragneisses overlain by various types of marbles and calc-silicate rocks trending toward the NE-SW and ENE-WSW directions. The marbles occur in massive or scattered blocks and are medium- to coarse-grained, showing polycrystalline texture. Their common mineral assemblage contains diopside, forsterite, chondrodite, garnet, phlogopite, and graphite, suggesting metamorphic grade up to upper amphibolite facies. In places, the marbles are intruded by biotite micro-granite, syenite, and pegmatite.

The paragneisses are medium- to coarse-grained and show well-banded gneissose texture defined by elongated layers of biotite, feldspar, and quartz. The matrix of the paragneisses is mainly composed of garnet, cordierite, biotite, plagioclase, K-feldspar, quartz, ilmenite, and rutile. Graphite and monazite are common accessory minerals. Sillimanite mainly occurs as inclusions within garnet. Most porphyroblastic garnet grains (> 3 mm) show retrograde zoning with increasing almandine {X_{alm} = Fe / (Ca + Mg + Fe + Mn) = 0.53 -0.58} and decreasing pyrope contents {X_{pyr} = Mg / (Ca + Mg + Fe + Mn) = 0.37 -0.43} towards the rim. Grossular (X_{gros} = 0.03) and spessartine (X_{sps} = 0.02) contents are low and fairly constant. Cordierite grains {X_{Mg} = Mg / (Mg + Fe) = 0.68–0.83} occur as the matrix phase, inclusions in garnet, and as pseudomorphs after garnet. Using garnet–biotite geothermometer and garnet–biotite–plagioclase–quartz (GBPQ) geobarometer, the matrix assemblage estimates pressures (P) and temperature (T) conditions of 0.5–0.8 GPa and 750–870°C. Biotite grains occur as an isolated phase in the matrix, inclusions in garnet, and a symplectic phase around garnet. Fluorine and chlorine contents are up to 0.6 wt. % and less than 0.1 wt. %, respectively. The Ti-in biotite geothermometer suggests 800° C or higher-temperature for the Ti-rich isolated biotite grains. Zr-in-rutile geothermometer gives temperature estimates of 750 –935°C (at P = 0.8 GPa), which are consistent with those estimated using a conventional geothermometer.

The samples analyzed in this study demonstrate that metamorphic conditions in the Mogok Belt reached 800°C or higher, implying wide distribution of granulite facies metamorphic rocks in the middle segment of the Mogok metamorphic belt.

Keywords: paragneiss, granulite, metamorphic conditions, Mogok metamorphic rocks, Myanmar

Deformation environment of the mylonite zone to the west of Shirakami Mountains, Northeast Japan

*Shunsuke Watanuki[1], Hidenori Saka[2], Takuto Kanai[1], Hideo Takagi[1]

1.Waseda University, 2.New Energy and Industrial Technology Development Organization

The N-S striking ductile shear zone (Takahashi, 2001; Fujimoto and Yamamoto, 2010; Sakai et al., 2012) along the western coastline of southernmost Aomori Prefecture is developed in the Cretaceous Shirakamidake granitic body (Katada and Osawa, 1964). This mylonite zone is called Shirakamidake mylonite zone (Fujimoto and Yamamoto, 2010). In this presentation, (1) detailed occurrence and microstructures are described, and (2) deformation environment is estimated on the basis of crystallographic preferred orientation (CPO) pattern of recrystallized quartz grains in the mylonitic rocks.

(1) The mylonite zone extends N-S for ~2 km with a width of ~600 m. The center of the mylonite zone with a width of ~200 m consists of ultramylonite and locally cataclasite overprinting ultramylonite. The foliation of the mylonites strikes mainly N-S and dips 40-80° to the east. The lineation plunges at 30-70° to the northeast. Asymmetric deformation microstructures (e.g. asymmetric pressure shadow) indicate sinistral normal shear as Takahashi (2001) already described.

(2) We measured CPO and grain size of recrystallized quartz in two transects across the mylonite zone using SEM-EBSD method. As a result, most fine-grained ultramylonite in the central part of the mylonite zone in both transects show a random CPO pattern and mean grain size of recrystallized quartz is about 8.5 μm. Other samples apart from central part of the mylonite zone show a type I crossed girdles and Y-maximum CPO pattern and mean grain size of recrystallized quartz is 13.1-198 μm. The former suggests that the diffusion creep was the dominant deformation mechanism from mean grain size of recrystallized quartz and CPO pattern (Passchier and Trouw, 2005), whereas the latter suggests that the dislocation creep took place at 350-450 °C which is switching temperature from type I crossed girdles to Y-maximum (Takeshita, 1996). From mean grain size of the most fine-grained sample with clear CPO pattern and estimated deformation temperature (about 400 °C), the differential stress is about 87 MPa using paleo-piezometer (Stipp and Tullis, 2003), and the strain rate is about 10^{-10} s^{-1} using flow law for dislocation creep (Hirth et al, 2001). On the other hand, the diffusion creep took place locally about 70 m thick ultramylonite zone after the formation of entire mylonite zone deformed by dislocation creep, because differential stress (<10 MPa) is estimated during diffusion creep using flow laws for dislocation creep and diffusion creep (Coble, 1963). The mylonite zone was therefore deformed by dislocation creep at about 400 °C, and subsequently diffusion creep took place locally in a center of the shear zone. At shallower depth, brittle deformation took place to form cataclasite locally.

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Keywords: Shirakami Mountains, Cretaceous granitic rocks, Mylonite, quartz CPO

Coexisting Omphacite-Diopside in Ab-CaCO3phases vein developed in Epidote-amphibolite olistolith in kamuikotan Metamorohic belt.

*Shusuke Kinoshita[1], Takao Hirajima[1]

1.Department of Geology and Mineralogy, Graduate School of Science, Kyoto University

Ca-Na pyroxene is a common mineral in eclogite and blueschist facies metamorphic rocks. Omphacite with an intermediate composition between jadeite and augite is considered to be a clinopyroxene group with ordered *P2/n* symmetry, because the cation partitioning and ordering in NaAl-CaMg substitution took place below the critical temperature. At further lower temperatures, two miscibility gaps were proposed between omphacite and *C2/c* sodium-rich augite, and omphacite and *C2/c* impure jadeite in the jadeite-augite binary system based on a thermodynamic theory and petrographic evidences (Carpenter, 1980). As natural Ca-Na pyroxenes generally incorporates Fe^{3+} as an aegirine component at various degrees, several phase diagrams of Ca-Na pyroxenes concerning with stability fields of *C2/c* and *P2/n* symmetries have been proposed in the jadeite-aegirine-augite ternary system based on a number of thermodynamic models (e.g. Carpenter, 1980; Holland, 1990; Green et al., 2007). As the low-temperature stability conditions of Ca-Na pyroxenes harm their synthetic study, thus it is necessary to justify the validity of proposed phase diagrams using natural samples. In this study, we report the petrology of omphacite and sodium-rich augite pair which was newly found from high-pressure mineral veins developed in an epidote amphibolite block collected from the Horokanai area in the Kamuikotan metamorphic belt, central Hokkaido. Shibakusa (1989) divided the metamorphic rocks in the Horokanai area into three zones, Zone I {lawsonite blueschist (BS) facies} to Zone III (epidote BS facies), based on the mineral assemblages of mafic rocks. Imaizumi (1984) reported the occurrence of epidote amphibolite blocks from the Horokanai pass area, which is located in Zone III of Shibakusa (1989), and he concluded that these blocks represent olistoliths within the Kamuikotan metamorphic rocks prior to the BS-facies metamorphism. We identified three kinds of metamorphic veins; 1) Pale green, 2) yellowish green and 3) white veins. The pale green vein is about 1 cm thick and its central part is mainly composed of Ca-Na pyroxenes, carbonate (aragonite and calcite) and albite, while apatite is partly developed in the outer part of the vein. Yellowish green veins and white veins are less than 1 mm thick and mainly composed of pumpellyite and albite, respectively. The composition of pumpellyite is identical to those of Zones II and III of Shibakusa (1989). Calcite is considered to have developed after the formation of aragonite, as aragonite is always surrounded by calcite. These observations suggest that the vein-forming conditions are about 250-350 °C and less than 7-10 kbar (*P-T* estimation for Zone II/III of Shibakusa, 1989). Most of Ca-Na pyroxenes occur as anhedral grains, ca. 1mm in length, in the central part of the pale green vein. They are composed of two domains, 20-100 μm in width, separated by straight boundary which can be easily identified by their different birefringence. The chemical composition of the two domains is omphacite ($Jd_{30-40}Acm_{15-25}Di_{38-55}$) and sodium-rich augite ($Jd_{4-8}Acm_{9-15}Di_{77-95}$), respectively, showing an obvious gap, probably between *P* lattice omphacite and *C* lattice sodium-rich augite. Tsujimori (1997) reported the coexistence of omphacite and sodium-rich augite in an omphacitite collected at the Osayama serpentinite mélange, Sangun-Renge belt. They are less Fe^{3+} contents compared with our data and are associated with pumpellyite. The results of our study and Tsujimori (1997) propose a miscibility gap between omphacite and sodium-rich augite at 250-350 °C, which is slightly wider than that proposed by Carpenter (1980) at 350 °C and there is a tendency that omphacite slightly prefers Fe^{3+} content rather than the coexisting sodium-rich augite.

Keywords: kamuikotan metamorphic belt, omphacite-diopside gao, aragonite

Metamorphic conditions of Gotsu blueschists in the Suo metamorphic belt, SW Japan

*Akira Takasu[1], Weimin Li[2], Kabir Md Fazle[1]

1.Department of Geoscience, Faculty of Science and Technology, Shimane University, 2.College of Earth Science, Jilin University, China

The Suo metamorphic belt in SW Japan is a representative of Jurassic accretionary terranes characterized by blueschist facies metamorphism of 160-230 Ma in metamorphic age (Nishimura, 1998). The metamorphic facies series of the Suo schists from pumpellyite-actinolite facies through glaucophane schist facies to epidote amphibolite facies (e.g. Nishimura, 1998). The Gotsu area in the Suo metamorphic belt is composed mainly of glaucophanic metamorphic rocks of blueschists and pelitic schists.
The metamorphism of the Gotsu blueschists is divided into three stages, i.e. pre-peak, peak and retrograde stages. The peak metamorphism of Gotsu blueschists is defined by porphyroblastic epidote, glaucophane, phengite, chlorite, hematite and titanite, suggesting epidote-blueschist facies conditions of 430-530 °C and 12-15.5 kbar.
The blueschists from the the Gotsu area and the Heilongjiang Complex, NE China suggest that both blueschists were formed within the same subduction system, which is related to the Paleo-Pacific plate subduction. This subduction event produced voluminous Jurassic accretionary complexes along the eastern margin of the Asian Continent.

Keywords: blueschist, Heilongjiang Complex, NE China, Suo metamorphic belt

The source rock age of Renge metamorphic rock in the Omi-area, Itoigawa city.

*Takumi Yoshida[1], Madhusoodhan Satish-Kumar[1], Hayato Ueda[1]

1.Niigata university

The Omi area located in the westernmost Niigata prefecture, is known for its LT/HP metamorphic rocks of Paleozoic age. Previous studies conducted in the Omi area reported that this area consist of serpentinite-melange, including LT/HP type metamorphic rocks and serpentinite. The highest metamorphic grade reported in this area is eclogite facies, which led to the demarcation of eclogite unit (EC-unit) and non-eclogite unit (N-EC unit) in the Omi area (Matsumoto et al., 2011). However, the tectonic evolution of metamorphic rocks in this area is not clear, especially, the relation between EC unit and N-EC unit is not clear. In this study, we present new result on the U-Pb zircon ages of high-pressure metamorphic rocks in EC unit and consider the tectonics of Paleozoic Japan.

The sample used for analysis is a Grt glaucophanite, occurring as a layer or lenticular form surrounded by politic schists (Grt-Ms schist). It comprises of euhedral~subhedral garnet porphyroblast (1-4mm) and large amount of euhedral glaucophane. Chlorite occurs in the altered domain. This sample contains a lot of zircon, which has bright rim and dark core under the CL image. About 200 zircon grains were hand picked and U-Pb analysis was carried out using an Agilent 7500a LA-ICPMS at Niigata University.

Off the 115 zircons analyzed, 34 spot gave concordant ages. Zircon core age is about 420-690Ma and the most prominent peak is seen in the range of about 450-460Ma. In contrast, some of the zircon core show about 1200-1460Ma.

The U-Pb results in this study (450-460Ma) are older than 280-340Ma of K-Ar age (Kunugiza et al., 2004) and 380Ma of eclogite metamorphism (Tsujimori, 2010). However, the sample has basaltic chemical composition. But it is hard to conclude that the protolith of this sample is basalt, because it contain large amount of zircon and those zircon shows a large spread of ages. Therefore it is necessary to examine the sedimentation history and tetonic evolution of the Omi area in more detail, which is ongoing.

Keywords: Renge metamorphic rock, U-Pb age

