

Analysis of metamorphic history recorded in garnet: A combined EBSD and EPMA study

ENAMI, Masaki^{1*}; NAGAYA, Takayoshi²

¹Center for Chronological Research, Nagoya University, ²Graduate School of Environmental Studies, Nagoya University

Pressure-temperature and deformation histories recorded in garnet grains in metapelites were analyzed with an effective combination of EBSD (Electron Backscatter Diffraction) and EPMA (electron-probe microanalyzer) data.

Sanbagawa metapelite (UKE04N07b):

This sample was collected from the eclogite-unit in the Besshi region, central Shikoku, which experienced the following successive metamorphic pressure-temperature path: prograde eclogite facies stage (1.7-1.9GPa/470-530 °C) → decompression and hydration reaction stage → prograde epidote-amphibolite facies stage (up to 1.0-1.1GPa/600-630 °C) (e.g., Kouketsu et al., 2014, IAR, 263-280). The main matrix phases are garnet, biotite, phengite, epidote, albite, quartz, and graphite. The analyzed garnet grain is composed of inner and outer segments formed in the eclogite and epidote-amphibolite facies stages, respectively. The inner segment ($\text{Alm}_{67-73}\text{Sps}_{3-10}\text{Prp}_{4-10}\text{Grs}_{16-21}$) contains paragonite and quartz with high residual pressure (up to 0.8-0.9GPa). The outer segment, which has Mn-poorer and Ca-richer composition ($\text{Alm}_{56-66}\text{Sps}_{0-10}\text{Prp}_{4-9}\text{Grs}_{26-36}$), mantles the inner segment in a compositional discontinuous change. The analyzed garnet grain seems to have grown as a single crystal, although it records a break in the growth period between the inner and outer segments. The EBSD data, however, implies that the garnet grain is composed of four domains with different crystallographic orientations, respectively, and misfits between these domains are 40-59 degrees. Sets of quartz grains included in garnet on both sides of the domain boundaries sometimes share the same crystallographic orientation (misfits are less than 1-6 degrees). The four domains are all composed of inner and outer segments. Thus, the EPMA and EBSD data suggest that the garnet grain studied was formed through the following process: prograde formation of polycrystalline garnet during the eclogite facies stage → resorption around the garnet grain and along the domain boundaries during exhumation → recrystallization of the outer segment and domain boundaries during the prograde epidote-amphibolite facies stage.

Mogok metapelite (S22b):

This sample was collected from an upper-amphibolite and granulite facies region in the Mogok metamorphic belt, northwest of Mandalay, Myanmar. The main matrix phases are garnet, biotite, plagioclase ($\text{An}_{43+/-4}$), K-feldspar, quartz, ilmenite, and graphite. Sillimanite occurs as inclusions in garnet. The peak metamorphic conditions are estimated at about 0.8GPa/800 °C (Maw Maw Win, personal communication, 2014). The garnet grain is separated into sub-grains of various sizes by resorption during the exhumation and cooling stages. Each sub-grain is mostly homogeneous, and shows a gradual increase of Mn and Fe and a decrease of Mg in the outermost margin ($\text{Alm}_{60-70}\text{Sps}_{1-3}\text{Prp}_{20-33}\text{Grs}_{5-7}$). Aggregates of biotite, plagioclase, and quartz fill the sub-grain boundaries, suggesting that the resorption stage progressed under the relatively high-temperature conditions of 0.2-0.4GPa/500-600 °C. The EBSD analysis shows that the sub-grains share the same crystallographic orientation (misfits are less than 1-4 degrees) and show no rotation or deformation. These data suggest that the sample has not experienced any dynamic deformation causing revolution of garnet grains after the resorption stage, and may have been exhumed under stationary conditions from at least 6-12 km of depths.

Keywords: EBSD, EPMA, garnet, metamorphic history

Metamorphism of dolomite-bearing eclogite in the Seba eclogitic basic schists, Sambagawa belt, central Shikoku, Japan

KABIR, Md Fazle^{1*} ; TAKASU, Akira¹ ; KISHIRA, Naohito¹

¹Shimane University

The Sebadani area is located in the Sambagawa metamorphic belt, Besshi district, central Shikoku. The Sebadani metagabbro mass and surrounding Seba basic schists (Seba eclogitic basic schists), and pelitic and siliceous schists occur in the area (Takasu and Makino, 1980; Takasu, 1984). Eclogitic mineral assemblages are sporadically preserved in both the Sebadani metagabbro mass and the Seba eclogitic basic schists (e.g. Takasu, 1984; Naohara and Aoya, 1997; Aoya, 2001). The Onodani eclogites are preserved within the Seba eclogitic basic schists, and they have a complex metamorphic history, with two different eclogitic metamorphic episodes (first eclogitic episode 530-590 °C/19-21 kbar; second eclogitic episode 630-680 °C/20-22 kbar) (Kabir and Takasu, 2010). The second eclogitic episode is similar to that of the Seba eclogitic basic schist of Aoya (2001) (610-640 °C and 12-24 kbar). The pelitic schists intercalated within the Seba eclogitic basic schists also underwent eclogite facies metamorphism of 520-550 °C and c. 18 kbar (Zaw Win Ko *et al.*, 2005; Kouketsu *et al.*, 2010).

The eclogites exposed in the northeastern part of the Seba eclogitic basic schists consist mainly of garnet, epidote, amphibole (glaucofane, barroisite, taramite, Mg-taramite, Mg-katophorite, edinite), omphacite (X_{Jd} 0.27-0.43), phengite (Si 6.5-7.1 pfu). Minor amounts of albite, carbonates (mostly dolomite and few calcite), rutile, titanite, biotite, chlorite and quartz. The schistosity is defined by preferred orientation of phengite, amphibole and epidote. Garnets are almandine-rich in composition, with a compositional zoning of increasing almandine (X_{Alm} 0.54-0.60), pyrope (X_{Prp} 0.07-0.13) and decreasing spessartine (X_{Sprs} 0.10-0.03) from core to rim. They contain inclusions of epidote, omphacite (X_{Jd} 0.27-0.41), dolomite, titanite and quartz. They also contain symplectite aggregates of barroisite/Mg-katophorite and albite. Omphacites in the matrix are zoned from pale green cores to colorless rims (X_{Jd} 0.27-0.43) and contain inclusions of epidote, and they are partly replaced by amphibole (barroisite/magnesiokatophorite) + albite symplectite. Amphibole in the matrix are zoned, barroisite/Mg-katophorite cores to edenite rims. Dolomites in the matrix are up to 0.5 mm across and they contain inclusions of omphacite, amphibole (winchite, barroisite, magnesiokatophorite), epidote, albite, calcite, rutile and quartz. A chemical zoning in dolomite is well defined by a continuous core-to-rim Mg increasing and Fe and Mn decreasing. Dolomites have mutual contact with eclogitic minerals of garnet, omphacite, barroisitic amphibole and phengite in the matrix.

Texturally abundant dolomites in the Seba eclogitic basic schists exposed in the northeastern part suggest X_{CO_2} fluid might stable in the eclogitic facies conditions. Supposing the peak metamorphic conditions are the same as the second eclogitic metamorphic episode of the Onodani eclogites (630-680 °C and 20-22 kbar), considerable amounts of CO_2 (X_{CO_2} 0.02-0.05) were included in metamorphic fluid during the peak metamorphism.

Carbonates are major constituents of the altered oceanic crust and of the sedimentary materials entering the orogenic cycle. Extensive experimental work on phase relationships in carbon-bearing systems reveals that carbonates are extremely stable up to mantle pressures and the transfer of carbon to the mantle wedge at subduction zones is linked to the extent of decarbonation and/or dissolution in aqueous fluids, or to the attainment of a carbonatitic solidus if a thermal relaxation occurs, e.g., upon subduction stagnation. Dolomite is a very common rock-forming mineral still waiting for further exploration and for innovative applications to the reconstruction of dynamic processes in the Earth's interior.

Keywords: Sambagawa metamorphic belt, eclogite, omphacite, dolomite, Seba basic schists

Unit division and metamorphic conditions of the Northern Chichibu belt in central Shikoku

ENDO, Shunsuke^{1*}

¹GSJ-AIST

There is a general consensus that part of the Northern Chichibu belt underwent the Sanbagawa metamorphism (i.e., Cretaceous high P/T metamorphism). However, the Sanbagawa belt proper represents metamorphosed Late Cretaceous accretionary complex, and thus tectonic implications of the Sanbagawa metamorphism in the Mikabu and N. Chichibu belts (Jurassic to Early Cretaceous accretionary complex) must be reconsidered. For this purpose, it is important to unravel metamorphic history of each unit within the N. Chichibu belt. The present study focuses on the Motoyama district of central Shikoku whereby primary structural relationship among the Sanbagawa, Mikabu and N. Chichibu belts are well preserved. I will report the results of geological mapping and petrological observation on ~200 metabasite samples from the Mikabu and N. Chichibu belts in the Motoyama district.

The N. Chichibu belt in the Motoyama district is composed of three units: the Kashiwagi, Kamiyoshida and Sumaizuku units, following to the unit terminology of Matsuoka et al. (1998). The Kashiwagi unit shows an interfinger relationship with the Mikabu ophiolitic unit, and they can be treated as the Mikabu-Kashiwagi unit. The Kamiyoshida unit overlays the Kashiwagi unit and is overlain by the Sumaizuku unit by south-dipping boundaries.

The Mikabu-Kashiwagi unit was unambiguously affected by the Sanbagawa metamorphism, and the occurrence of metamorphic aragonite (Suzuki & Ishizuka, 1998) suggests peak metamorphic pressures of >0.7 GPa at 300 °C. However, relatively low jadeite content in alkali pyroxene coexisting with quartz, and amphibole compositions (magnesian riebeckite to actinolite) in the presence of epidote suggest that the main stage of metamorphic recrystallization took place at lower pressure conditions.

Although the general trend of southward decrease in metamorphic grade has been inferred from the degree of metamorphic recrystallization and deformation structures, quantitative metamorphic conditions of the Kamiyoshida and Sumaizuku units have not been constrained. The Kamiyoshida unit is characterized by the occurrence of alkaline basaltic volcanic breccia with metamorphic minerals of magnesian riebeckite, calcite and stilpnomelane. Recently, jadeite has been discovered from quartz- and riebeckite-free metaigneous rocks in the Kamiyoshida unit. Decompression P-T path from 0.6-0.7 GPa, 300 °C to 0.4 GPa, 210-260 °C has been derived from zoned sodic pyroxene with a jadeite core and an aegirine rim (Endo, 2015).

The Sumaizuku unit is characterized by the occurrence of prehnite-pumpellyite-epidote-quartz veins in massive basalt and dolerite. No alkali pyroxene or Na amphibole is found. These observations appear to imply the lack of high-P/T metamorphism on this unit. However, lawsonite-pumpellyite-quartz veins were newly discovered from this unit. Lawsonite in the vein locally forms fine-scale Lws-Qz intergrowths with a prismatic outline, interpreted as pseudomorphs after laumontite. This texture suggests compression to >0.3 GPa at 200-250 °C. It is likely that prehnite-bearing veins formed during a decompression stage.

The N. Chichibu belt has long-term history in the accretionary wedge. Apparently gradual Sanbagawa metamorphism of the N. Chichibu belt may be related to exhumation-related metamorphism caused by underplating of new accretionary units in the Cretaceous subduction zone.

Keywords: Northern Chichibu belt, low-grade metamorphism, pressure-temperature history, jadeite, lawsonite

Study of geological structure and Paleogene kinematic history of the Fault system along the MTL, the west Shikoku.

KUBOTA, Yasu'uchi^{1*} ; TAKESHITA, Toru¹

¹Hokkaido University

For the long time span of the Paleogene period, the fault movement along the MTL (Median Tectonic Line) has not been fully clarified. Kubota and Takeshita (2008) inferred that Paleogene kinematic history of the MTL is divided to 63-58 Ma (Ichinokawa phase) and 45-25 Ma (Pre-Tobe phase), the pre-Tobe phase defined by N-S directed shortening, which is responsible for a large-scale folding of the Izumi Group and thrusting. The Okamura Fault, Kawakami Fault, and Iyo Fault distribute parallel to the trend of the MTL, and northern part of the MTL in the west Shikoku. We study the geological structure and the deformation structure of fault fracture zone for these faults.

The Okamura Fault has been recognized as active fault, and as right-lateral strike-slip faults (Ehime Prefecture 2001). And, Aoya et al.(2013) reported the development of left-hand en echelon folds along the Okamura Fault, and this study the folds with wavelength of ~500m of map scale and ~10m of outcrop scale. The fault fracture zone develops in alternating beds of sandstone and mudstone in the Izumi Group, The whole fault with ~25m width has been consisted of foliated cataclasite zone with ~15m width. Left lateral slip and top to the south movement sense by the observation of foliation structure. Furthermore, cataclasite zone with breccia and develops. It has been weakly foliation and shear band, partially remained bedding plane. The fault gouge 30-45cm thick develops at southern margin of fault fracture zone with foliation and shear band has shown movement sense of right lateral slip predominantly. Furthermore, in this study the deformation conditions had been discussed by the microscope observation of fault rocks. Further, the Kawakami and Iyo Fault had been the development of left-hand en echelon folds of map-scale along the Fault, and fault fracture with cataclasite zone with slip sense of left lateral slip and top to the south.

It indicates that the faults had been formed with movement sense of left lateral slip and top to the south. This movement period has been inferred the Paleogene according to the result of K-Ar age dating of the other faults in north of the MTL (Shibata et al. 1989), accordingly the movement is important data for clarify of Pre-Tobe phase of MTL.

Aoya, M.,Noda, A.,Mizuno, K., Mizukami, T., Miyachi, Y., Natsuura, H., Endo, S., Toshimitsu, S. and Aoki, M., 2013, Geology of the Niihama district. Quadrangle Series, 1:50,000, Geological Survey of Japan, AIST, 181p.(in Japanese with English abstract, 3P.);EHIME PREFECTURE 2001. Report on active faults in Ehime Prefecture, a summary-Investigation on the MTL fault systems in the northwestern part of Ehime Prefecture, the northern border of the Ishizuchi Mt. and the southern border of the Sanuki mountain range. pp. 47, Ehime Prefecture. (in Japanese).;Kubota, Y., Takeshita, T., 2008. Island Arc, vol. 17, p. 129-151.;SHIBATA K., NAKAJIMA T., SANGAWA A., UCHIUMI S. & AOYAMA H. 1989. K-Ar ages of fault gouges from the Median Tectonic Line in Shikoku. Bulletin of the Geological Survey of Japan 40, 661-71 (in Japanese with English abstract).

Keywords: Median Tectonic Line, Paleogene, kinematic history

Spatio-temporal fluctuation of garnet and cracks

TORIUMI, Mitsuhiro^{1*} ; FUKUYAMA, Mayuko²

¹JAMSTEC, ²Akita Univ.

In the previous papers of JpGU meeting (1), we studied the grain size distribution patterns of metamorphic garnet and albite in the banded metamorphic rocks with grain size grading. The average grain size increases with increasing distance across the banding but normalized distribution patterns of the grain sizes within the individual bands are very similar with each other. The banding structure should be derived from the unidirectional flow of metamorphic fluid with ionic diffusion, therefore suggesting that the growth conditions changed across the bands. It follows that the distribution patterns of grain size of garnet and albite display the summation of multiple simple distribution function such as Ostwald type or simply Gaussian, forming the lognormal to power law type.

In the plate boundary region, the metamorphic rocks also experienced frequent generation of small cracks with fluid and then occupied by minerals. However, the mechanical conditions controlling the crack formation and propagation must be fluctuated in terms of stresses, fluid pressure, temperature, and other parameters. Then, the observed frequency distribution of cracks filled with fluid and also minerals should show the summation of many simple distribution functions and it is approximately lognormal or power law. The fluctuation of the distribution patterns can be simply represented by drifts of mean and variant values with time and space.

In this paper, we would like to discuss the rapid growth of grains and cracks at the case of over - the critical fluctuations by drifts by means of stochastic resonance.

(1) Toriumi M. and M. Fukuyama, 2014, Grain size grading in the Liesegang banding of the plate boundary rocks. Proceeding of JpGU meeting 2014.

Keywords: size distribution, average and variance, spatio-temporal fluctuation, garnet, crack

Timescale of metamorphism and U-Pb ages of the Sanbagawa Metamorphic Complex

MIYAZAKI, Kazuhiro^{1*} ; WAKITA, Koji² ; DANHARA, Tohru³ ; IWANO, Hideki³ ; HIRATA, Takafumi⁴

¹GSJ AIST, ²Yamaguchi Univ., ³Kyoto FT, ⁴Kyoto Univ.

Timescale of high-pressure metamorphism is not well known, but is crucial for solid mass transport and fluid flux in the subduction zone. Here, we report timescale of high-pressure metamorphism for the Sanbagawa Metamorphic Complex in the area of 1:200,000 geological map of Matsuyama, western Shikoku, Japan.

We collected psammitic and pelitic rocks from the Iyo and Ozu units of the Sanbagawa Metamorphic Complex, weakly metamorphosed and non-metamorphosed Togano units of the southern Chichibu belt and non-metamorphosed Hanyama unit of the Shimanto belt. The samples are used for zircon U-Pb and phengite K-Ar dating. Histogram of detrital zircon U-Pb ages ($H(t_{zrn})$) of non-metamorphosed Togano unit is similar to $H(t_{zrn})$ of weakly metamorphosed Togano unit, and ages of the youngest cluster of detrital zircon U-Pb ages (t_{zrn-yc}) are 174.7 ± 1.9 Ma and 181.6 ± 1.4 Ma, respectively. The $H(t_{zrn})$ s of the Hanyama unit, Ozu unit and upper part of the Iyo unit are identical to each other. The t_{zrn-yc} s of the Hanyama and Ozu units, and the upper part of the Iyo unit are 111.3 ± 2.4 Ma, 110.3 ± 4 Ma, and 111.2 ± 2.9 Ma, respectively. This implies that protolith of the Ozu unit and the upper part of the Iyo unit, both units are a part of the Sanbagawa Metamorphic Complex, is the Hanyama unit of the Shimanto belt. On the other hand, the $H(t_{zrn})$ of the lower part of Iyo unit is quite different from those of the above-mentioned 3 samples, and the t_{zrn-yc} is 89 ± 1.0 Ma. The phengite K-Ar ages (t_{phn}) of the upper and lower parts of the Iyo unit are 83.8 ± 2.1 Ma and 86.9 ± 2.2 Ma, respectively.

Maximum value of the timescale of high-pressure metamorphism can be defined by the difference between the t_{zrn-yc} and the t_{phn} . The maximum value of the timescale for the upper part of the Iyo unit is 27 Myr, although that for the lower part of the Iyo unit is 2 Myr. Metamorphic zircon rims have grown around detrital zircon grains of the sample from the upper part of the Iyo unit suffered garnet zone metamorphism. Average of U-Pb ages of the metamorphic rims is 94.4 ± 1.2 Ma. It is inferred that the metamorphic zircon rim have grown at the peak temperature of the Sanbagawa metamorphism. Therefore, difference between the U-Pb age of the metamorphic rim and the t_{phn} should give minimum value of the timescale of the high-pressure metamorphism. The value is 11 Myr.

Results show that the timescale of high-pressure metamorphism ranges from <2Myr to 11-27 Myr in the same unit. The upper part of the Iyo unit suffered higher-grade metamorphism than the lower part of the Iyo unit. Numerical simulation of viscous fluids shows that lower viscosity part of metamorphic rocks, in which metamorphic dehydration reaction actively takes place, will be elongated by shear deformation, and intrude into lower-grade metamorphic rocks coming newly in the metamorphic field at deeper part of the subduction zone.

Keywords: Sanbagawa, metamorphism, metamorphic rock, zircon, U-Pb age

Heat transportation recorded in the southern part of the Hidaka metamorphic belt

SAKATA, Ryugen^{1*} ; OZAWA, Kazuhito¹

¹School of Science, The University of Tokyo

The earth's continental crust has granitic upper crust and gabbroic lower crust with andesitic average composition, which was developed by various magmatic processes driven by thermal and material transportation through the sub-continental crust-mantle boundary. There are three ways of heat transportation from the mantle to the crust with respective time and spatial scales: heat conduction, solid-state flow of the mantle and the crust, and magmatism. This study aims to evaluate the relative importance of these elemental mechanisms in an exhumed ancient arc crustal section, Hidaka metamorphic belt, Hokkaido, Japan.

Seismic wave tomography has revealed that the lithospheric mantle shows continuity to the shallow crustal level near the Hidaka Main Thrust, where the Horoman peridotite complex is exposed, suggesting shallow uplift of the upper mantle (Kita et al., 2012). The Horoman peridotite complex is shown to have undergone isothermal ascent with local heating up to <1GPa followed by rapid cooling (Ozawa, 2004), which could have heated the lower crust. Previous studies pointed out that basaltic magma frozen as gabbroic bodies caused crustal partial melting and melt transportation on the basis of geological and geochemical data (Osanai et al., 1991; Owada et al., 2003; Tagiri et al., 1988; Shimura et al., 2006). However, the role of mantle-derived heat and its transportation mechanism are still unclear.

Field survey was conducted along the Nikanbetsu river in the southern end of the Hidaka metamorphic belt. In the study area, a small peridotite body called Nikanbetsu mass is exposed on the west and a large tonalite body on the east. Metamorphic rocks are distributed in between them. The dominant lithology is banded garnet biotite gneiss intercalating <100m thick zone of mafic metamorphic rocks, which consists of amphibolite and mafic granulite with many leucocratic veins and layers. The banded garnet biotite gneiss shows remarkable foliation except for the one located near the Nikanbetsu mass.

We applied biotite-garnet Mg-Fe exchange thermometer (Ferry and Spear, 1978) for average chemical compositions of biotite and garnet in the banded garnet biotite gneiss and leucocratic veins including garnet and biotite in the zone of mafic metamorphic rocks. The results show a temperature decrease by ~100 °C within ~1km from the east of the peridotite mass to the west of the tonalite body with an exceptionally high value of 750 °C around the mafic metamorphic rocks. An application of biotite-garnet thermometer to the core and the rim of the largest garnet and the average value of biotite gives >900 and ~750 °C, respectively. The garnet zoning, occurrence of euhedral plagioclase with normal Na-Ca growth zoning, and weak foliation suggests partial melting of the rock followed by rapid cooling. We also applied two-pyroxene thermometer (Lindsley, 1983) for orthopyroxene coexisting with clinopyroxene in mafic metamorphic rocks with leucocratic veins. The calculated temperature ranges 1000~700 °C, which is due to a decrease in Wo content from the core to the rim suggesting rapid cooling.

Veins with various structure, morphology, and chemical composition suggest diverse processes during melt transportation, such as brittle failure of the host rock, permeable leakage to and reaction with the host rock, and differentiation and crystallization in the veins. Less differentiated veins may have records of a melt directly migrated from the deep crust, whereas differentiated veins may have records of partial melting of pelitic gneiss.

We detected a thermal gradient of ~100 °C/km from the Nikanbetsu mass, suggesting the mass acted as a heat source to affect the adjacent metamorphic rocks through heat conduction. We also detected a thermal gradient of $\gg 100$ °C/km around the zone of mafic metamorphic rocks generated by magma transportation overlapping the much gentler thermal gradient.

Keywords: Hidaka metamorphic belt, pelitic gneiss, peridotite, heat source, partial melting

Aqueous fluid activity in the MCT zone and its role in High Himalayan leucogranite formation, Dhankuta, Eastern Nepal

KAWAKAMI, Tetsuo^{1*} ; SAKAI, Harutaka¹ ; SATO, Katsushi¹

¹Graduate School of Science, Kyoto University

Significant aqueous fluid activity during the prograde to retrograde metamorphism in the footwall side of the Main Central Thrust (MCT) is observed in the MCT zone around Dhankuta, Eastern Nepal. A term 'MCT zone' in this study is used to represent the garnet to the kyanite zones developed in the footwall side of the MCT, where inverted metamorphism is observed. In the MCT zone, several evidences of continuous fluid activities during metamorphism and their movement cutting the schistosity can be observed.

The first and most important is the abundant quartz veins. They are found as sheared lenses in the MCT zone, and asymmetric textures show top-to-the-S sense of shear indicating the deformation during the MCT movement. In the kyanite zone, quartz veins contain mm- to cm-sized crystals of kyanite and minor plagioclase. Garnet and kyanite are coarse-grained only at the vicinity of the quartz veins, and in the staurolite and garnet zones as well, garnet tends to be coarser-grained around the quartz veins. These observations suggest that the aqueous fluid infiltration that formed the quartz veins took place at the prograde to peak stage of the metamorphism in the MCT zone.

Meta-dolostone in the kyanite zone is also a good indicator of H₂O movement. It is commonly almost completely metamorphosed to tremolite schist. In such rocks, radiated aggregates of tremolite form a flat, oval-shaped aggregate are arranged parallel to define the schistosity. Locally, such a tremolite arrangement discordantly cut the schistosity like a vein. In some meta-dolostones, dolomites are still preserved, and veins of tremolite discordantly cut the schistosity as well as stem out parallel to the schistosity. These observations indicate that SiO₂-bearing aqueous fluid infiltrated into the dolostone and reacted with dolomite to form tremolite, calcite and CO₂ along the vein and schistosity.

Tourmaline (Tur) is an important sink mineral of incompatible element B, and thus is often abundant in the environment where water-rock interaction took place. Unusually abundant Tur is locally found in metapelites of the MCT zone. It is localized in aluminous, muscovite-rich layers and can be formed through the input of external B into the appropriate whole-rock composition for Tur growth. Such a B-bearing fluid infiltration continued from the prograde stage because garnet with prograde chemical zoning includes abundant Tur crystals. B-bearing aqueous fluid infiltration continued in the post-peak stage as suggested by the presence of Tur-rich vein cross-cutting the schistosity. In the kyanite zone, Tur veins are found cutting the schistosity and/or stem out parallel to the schistosity. In such samples, although the B-rich fluid infiltration postdates schistosity formation, staurolite includes or partly overgrows the Tur crystals formed simultaneously with the Tur-rich vein, suggesting that the Tur vein was formed under relatively high-temperature condition slightly after the peak metamorphism.

These aqueous fluids are likely to have moved upwards through the veins to the MCT and to the Higher Himalayan Crystallines (HHC) where P-T conditions above water-saturated solidus of muscovite-bearing pelitic rocks are estimated. In the hanging wall side of the MCT in the Dhankuta area, patches of Tur-bearing leucogranites are found in the migmatitic Grt-Ms-Bt gneisses. One of these leucogranite samples gave the U-Pb zircon age of 25.9 +/- 2.3 Ma, and other gneiss sample from the same area gave U-Pb zircon age of ca. 17 Ma (Sakai et al. 2014). These ages are well consistent with the ages of High Himalayan leucogranites (HHL, Searle et al. 2010), which is commonly tourmaline-bearing, so segregation and extraction of these B-bearing melts is a likely process of the HHL formation. Therefore, input of aqueous fluids released from or passed through the MCT zone into the HHC can be an important process for the formation of HHL (e.g., Le Fort et al., 1981).

Keywords: aqueous fluid, quartz veins, tourmaline, partial melting, leucogranite, Himalayas

Garnet-hornblende vein formation and mass transfer by brine infiltration during upper amphibolite facies metamorphism

HIGASHINO, Fumiko^{1*}; KAWAKAMI, Tetsuo¹; TSUCHIYA, Noriyoshi²; SATISH-KUMAR, Madhusoodhan³; ISHIKAWA, Masahiro⁴; GRANTHAM, Geoffrey⁵

¹Kyoto University, ²Tohoku University, ³Niigata University, ⁴Yokohama National University, ⁵Council for Geoscience, South Africa

The importance of chloride brines during metamorphism is being increasingly recognized among various metamorphic fluids. This is because chloride brines can coexist with a CO₂-rich fluid under the granulite facies condition (Heinrich, 2007), has low a_{H_2O} , and acts as a powerful solvent not only for metals but also for various oxide and silicate minerals (Newton and Manning, 2010; Tropper et al., 2011). Therefore, chloride brines would play an important role in mass transfer especially when the pressure-temperature (P - T) conditions of metamorphism are around the wet solidus, because X_{H_2O} in the brine can control the melting/non-melting behavior of the rock (Aranovich et al., 2013).

In the Sør Rondane Mountains (SRM), East Antarctica where Late Proterozoic to Cambrian granulites are widely exposed, Cl-rich hornblende and biotite in mafic gneisses are locally but widely distributed for ca. 200 km (Higashino et al., under review). Formation mechanisms of these Cl-rich minerals can be different if the modes of occurrence of them are different. Therefore, this study deals with the Cl-rich hornblende-bearing garnet-hornblende (Grt-Hbl) vein which discordantly cuts the gneissose structure of a mafic gneiss in the Brattnipene area, and discuss the formation mechanism and mass transfer that accompanied the vein formation.

In the Grt-Hbl vein, Cl contents of hornblende and biotite, K content of hornblende, as well as the development of a Na-rich rim of plagioclase decrease with a distance from the vein center. Whole-rock composition analyses as a function of distance from the vein show mass imbalances around the vein, suggesting that the Grt-Hbl vein was formed through an open system process. Taking into account the possibility of partial melting, distribution of Cl between melt, aqueous fluid and minerals, and microstructural evidences of minerals, the Grt-Hbl vein was shown to have formed by the Cl-rich aqueous fluid infiltration. The Cl-rich aqueous fluid was possibly NaCl brine because whole-rock analyses showed that Na was added to the vein compared to the wall rock. We estimated that the Grt-Hbl vein was formed at ca. 700 °C and 0.70 GPa. This means that the NaCl brine infiltrated into the wall rock at the early stage of retrograde metamorphism in this area. The whole-rock analyses and fractional mass change values calculated according to Ague (2001) also revealed that the NaCl brine infiltration caused additions of Si, Ti, Al, Fe, Mn, Mg, Ca, Na, Li, Sc, V, Cu, Zn, Ge, Sr, Y, Ba, Pb, Bi, Th and U to the wall rock. These added elements are similar to those contained in previously reported brines which were present in mineral assemblages implying subduction metamorphism and implying metal segregation in hydrothermal systems (e.g., Heinrich et al., 1992; Philippot and Selverstone, 1991). The Grt-Hbl vein formed by the NaCl brine infiltration as shown in this study is a clear example that brine could move at least a few meters, and was playing a role in mass transfer at ca. 700 °C and 0.70 GPa in the lower crust of the continental collision setting.

Keywords: NaCl brine, trace elements, metasomatism, continental collision, Sor Rondane Mountains, Antarctica

Fluid activity during corona formation in ultramafic gneisses of Lutzow-Holm Complex, East Antarctica

IKEDA, Takeshi^{1*} ; SHIMADA, Asami¹

¹Kyushu University

In Lutzow-Holm Complex, East Antarctica, it is common that symplectic intergrowth of spinel, orthopyroxene and plagioclase occurs between garnet and hornblende in mafic to ultramafic gneisses. This reaction microstructure has suggested that the complex experienced decompression after peak of metamorphism. In contrast, this study found a corona that is composed of biotite and plagioclase around garnet in ultramafic gneisses. This study describes the mode of occurrence and discusses its significance.

Garnet in the centre of the corona shows convavo-convex shape. Some isolated grains of garnet also occur that have col-loded form. Biotite and plagioclase constituent of the corona are euhedral, in contrast to the common occurrence of symplectic intergrowth of spinel, orthopyroxene and plagioclase. Chemical composition of these minerals show almost constant range irrespective of distance from the garnet. Grain size of biotite in the corona represents lognormal distribution. The corona has a bulk composition equivalent to the sum of garnet and matrix plagioclase and biotite together with additional K₂O and H₂O.

These features suggest that K₂O-bearing H₂O fluid infiltrated during corona formation. Absence of the common symplectite in spite of the presense of hornblende in the matrix implies the fluid infiltration preceded the reaction to form symplectite. The shape and size distribution of corona minerals suggest that the corona minerals crystalized in a melt phase of which degree of supersaturation decreased with time. This study concludes that the complex experienced an infiltration of K₂O-bearing H₂O fluid at early stage after peak metamorphism, which caused partial melting and following crystallization with relative rapid cooling rate without significant annealing.

Keywords: corona, metamorphic fluid, Lutzow-Holm Complex

Interplay of irreversible reactions and deformation: a case of hydrofracturing in the system rodingite - serpentinite

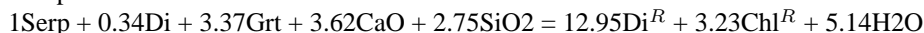
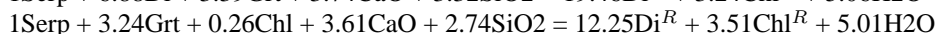
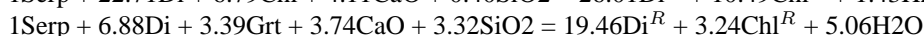
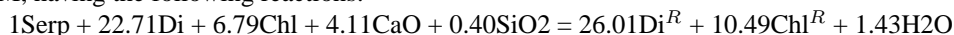
NISHIYAMA, Tadao^{1*} ; YOSHIDA, Chisato¹ ; MORI, Yasushi² ; SHIGENO, Miki²

¹Graduate School of Science and Technology, Kumamoto University, ²Kitakyushu Museum of Natural History and Human History

This paper examines hydrofracturing caused by reactions between rodingite and serpentinite during a regional metamorphism. Hydrofracturing is driven by rapid increment of fluid pressure, and therefore will be likely to occur in the contact metamorphic aureole due to rapid and irreversible reactions (Nishiyama, 1989). This paper aims to show the same type of hydrofracturing can occur even in the regional metamorphic terrane.

Rodingites occurs ubiquitously in serpentinite from the Nomo metamorphic rocks, western Kyushu, which is a Cretaceous accretionary complex of greenschist to epidote - amphibolite facies condition (Miyazaki and Nishiyama, 1989). Fukuyama et al. (2014) made geochemical and geochronological studies on these rodingites, and gave U-Pb age of zircons from the rodingites as 108 - 105 Ma. This study classified the rodingites into two types depending on the occurrence and the rock texture: vein type and dyke type. Mineralogy of both types of rodingites are almost the same, consisting of diopside, garnet (grandite), chlorite, vesuvianite and titanite with rare occurrence of epidote and pumpellyite. Both vein-type and dyke-type rodingites are associated with reaction zones between serpentinite. Tremolite veins commonly develop from the reaction zone into serpentinite, representing hydrofracturing associated with the formation of the reaction zone. A conspicuous feature is that perovskite occurs in some reaction zones consisting mainly of diopside and chlorite, whereas titanite is common in rodingites. The reaction perovskite + SiO₂ = titanite indicates the condition poorer in SiO₂ in the reaction zone. We investigated the reaction relation between rodingites and serpentinites using the singular value decomposition (SVD) technique (Fisher, 1989). Constant solid volume is assumed during the formation of the reaction zone because of lack of ductile deformation in the reaction zone. The condition of constant solid volume is incorporated into the SVD analysis as was firstly done by Yuguchi et al. (2015).

The seven component system CaO - SiO₂ - Al₂O₃ - Fe₂O₃ - FeO - MgO - H₂O is considered. Antigorite (serpentinite), diopside, garnet and chlorite (rodingite), and diopside^R and chlorite^R (reaction zone) are considered. The superscript R denotes minerals from the reaction zone, because they also occur in the rodingite but have different compositions. We took the following strategy to find the reaction relation. First we tried to find reaction relations which hold the conservation of pseudoquaternary components CaO - SiO₂ - AF (Al₂O₃ + Fe₂O₃) - FM (FeO + MgO) among the mineral assemblage, but we got no reaction relation. Next we omitted CaO as an inert component from the system, and consider reaction relations that hold conservation of pseudoternary SiO₂ - AF - FM components, then we got three reactions consuming CaO and evolving H₂O. This strongly suggests increment of fluid pressure associated with the progress of the reactions. We have further examined the system AF - FM, having the following reactions:



All of these reactions consumes SiO₂ and CaO, and evolves H₂O. This relation holds if we take any linear combination of above reactions. When we consider the perovskite formation from titanite in the reaction zone, reactions in the system AF-FM are preferable, because SiO₂ liberated by the titanite breakdown will be consumed by the above reactions in the system AF - FM.

Keywords: rodingite, serpentinite, hydrofracturing, irreversible reactions, singular value decomposition

Construction of Raman geothermobarometer using aluminosilicate minerals in garnet porphyroblast

KOUKETSU, Yui^{1*} ; TAGUCHI, Tomoki²

¹Geochemical research center, Graduate School of Science, The University of Tokyo, ²Graduate School of Environmental Studies, Nagoya University

In recent years, the development of geothermobarometer applying Raman spectroscopy has been actively examined. Several studies report the detection of new information of the metamorphic history that was difficult to obtain using conventional thermodynamic approaches. Especially, the “quartz Raman barometer” that can constrain the metamorphic condition using Raman peak shifts of quartz inclusions in garnet porphyroblasts show remarkable achievements in the Sambagawa belt. However, quartz transforms to coesite or β -quartz under the ultrahigh-pressure or high-temperature conditions, respectively, and applicable geological zone is limited. In the present study, we focused on aluminosilicate minerals, sillimanite and kyanite, in garnet porphyroblasts and examined whether the metamorphic condition can constrain using these Raman spectra as with quartz Raman barometer.

First, we calculated the relation between the metamorphic P - T condition and residual pressure using the elastic moduli of sillimanite, kyanite, and garnet. As a result, the residual pressure of sillimanite in garnet is independent of pressure condition, and depends on only temperature condition. On the other hand, the residual pressure of kyanite in garnet depends on pressure condition rather than temperature condition. Next, we measured the natural samples of sillimanite and kyanite inclusions in garnet porphyroblasts. Ultrahigh-temperature and high-pressure metamorphic rocks were measured; Garnet-Sillimanite gneiss collected from Rundvagshetta, Lutzow-Holm Complex in eastern Antarctica, and Kyanite-Quartz eclogite collected from Besshi region, Sambagawa belt in central Shikoku. The Raman spectra of sillimanite inclusions in garnets of Garnet-Sillimanite gneiss show characteristic peaks at around 962 and 1182 cm^{-1} , and these peaks shift to high wavenumber side of around 4 to 5 cm^{-1} . The Raman spectra of kyanite inclusions in garnets of Kyanite-Quartz eclogite show characteristic peaks at around 325 and 486 cm^{-1} , and these peaks shift to high wavenumber side of around 1 cm^{-1} .

The residual pressures were estimated to be 0.8 GPa for sillimanite and 0.3 GPa for kyanite using previously reported experimental data of aluminosilicate minerals. The residual pressure value of sillimanite inclusions in ultrahigh-temperature metamorphic rocks is converted to the metamorphic temperature of around 1000 $^{\circ}\text{C}$, and this result is consistent with previous studies. On the other hand, the residual pressure of kyanite inclusions is calculated as negative value with increasing metamorphic pressure, but measured values in high-pressure metamorphic rocks of the Sambagawa belt are positive. The elastic modulus of kyanite selected in the present study seems to have some problems, but it's expected to be solved by improving the equation of state of kyanite. These results indicate that Raman spectra of aluminosilicate minerals are useful to estimate metamorphic condition for high- to ultrahigh-pressure and -temperature metamorphic rocks.

Keywords: Raman geothermobarometer, sillimanite, kyanite, garnet, high-temperature metamorphic rock, ultrahigh-pressure metamorphic rock

Metamorphic evolution of ultrahigh-pressure rock revealed by residual pressure of SiO₂ inclusion in garnet

TAGUCHI, Tomoki^{1*}; ENAMI, Masaki²; KOUKETSU, Yui³

¹Graduate School of Environmental studies, Nagoya Univ., ²Center for Chronological Research, Nagoya Univ., ³Graduate School of Science, The Univ. of Tokyo

Residual pressures are generated in metamorphic host minerals and sealed inclusions due to the difference of their physical properties. If the residual pressure recorded in a host mineral or inclusion could be quantitatively analyzed, it would provide useful data for the estimating the crystallization conditions of the host phase and the metamorphic pressure-temperature (P-T) history. Enami *et al.* (2007, AM, 1303-1315) proposed a method to estimate the residual pressure recorded in quartz inclusions in garnet using a frequency shift in the Raman spectrum of quartz (quartz-Raman barometry). Kouketsu *et al.* (2014, AM, 433-442) calculated the relationship between the residual pressure of quartz inclusions in garnet and the P-T conditions of the garnet crystallization stage under α -quartz stable conditions and proposed a novel method to constrain the metamorphic P-T conditions. As quartz-Raman barometry is independent of the thermodynamic model, this technique could be a powerful tool to determine the evolution of progressive metamorphism. However, the quartz-Raman barometry cannot be applied to ultrahigh-pressure (UHP) metamorphic rocks formed under coesite-stable conditions, at least in principal. That said, quartz inclusions trapped by garnet under quartz-stable conditions may preserve the information preserve the effects produced during the early stages of prograde metamorphism. In this study, we examine the metamorphic evolution of a UHP metamorphic rock can deduced from the residual pressure of quartz inclusions in garnet.

The samples studied were collected from the Yangzhuang region of the Sulu UHP metamorphic belt, eastern China. Although coesite has not been reported from in Yangzhuang samples, quartz-pseudomorph after coesite has been reported, and coesite stability conditions of 2.7-3.5 GPa/660-830 °C are estimated for the peak metamorphic stage (Enami and Nagasaki, 1999, IAR, 459-474). These results suggest that the Yangzhuang samples might record the prograde P-T path from quartz to coesite stability.

Garnet grains in the Yangzhuang samples were divided into inner (Alm₄₉₋₅₄Prp₁₆₋₂₈Grs₂₁₋₂₉Sps₁, $X_{Mg} = 0.22-0.36$) and outer (Alm₄₅₋₅₂Prp₁₈₋₃₁Grs₂₃₋₂₉Sps₁, $X_{Mg} = 0.29-0.41$) segments, the boundary between the two defined by discontinuous changes in grossular content. In the inner segment, the SiO₂ phases are all α -quartz, and quartz-pseudomorphs after coesite and any radial cracks around the quartz inclusion are not observed. Residual pressures retained by the quartz inclusions systematically increased with decreasing grossular content from the crystal center to the margin in the inner segment and indicated a value of 0.9 GPa. Metamorphic pressure, estimated by an inverse calculation based on the measured residual pressure, implies that the quartz inclusions were trapped at pressure conditions just below the quartz/coesite transition. In the outer segment, quartz-pseudomorphs after coesite with radial cracks in the surrounding host garnet were observed. Coesite was identified for the first time in this region as an inclusion in a kyanite grain from the outer segment. The occurrence of coesite in the Yangzhuang sample supports the P-T conditions previously estimated by conventional geothermobarometry. These results suggest that (1) quartz inclusions in the inner segment were trapped by garnet under quartz-stable conditions, avoided phase transition to coesite at the peak metamorphic stage, and still preserved P-T information gained during the early stage of prograde metamorphism and (2) SiO₂ inclusions in the outer segment were included as coesite; and most of these translated into quartz and released their residual pressure during exhumation. These results suggest that the quartz-Raman barometry is a useful tool for determining P-T conditions at an early prograde stage even in the case of UHP metamorphism.

Keywords: quartz, residual pressure, quartz-Raman barometry, ultrahigh-pressure rock, Sulu belt

Examination of extrusion model of Himalayan metamorphic belt by study of exhumation process of metamorphic nappe

SAKAI, Harutaka^{1*} ; IWANO, Hideki² ; DANHARA, Tohru²

¹Department of Geology, Kyoto University, ²Kyoto Fission-Track Co. Ltd.

A ductile extrusion model explains that metamorphic core of the Himalaya, called the Higher Himalayan Crystallines (HHC), was originated by ductile channel flow of partially melted mid-crust from beneath the Tibetan plateau. No definite evidence of the model has yet been documented that shows the melted mid-crust extruded to form the HHC though many numerical models were proposed and their simulation was performed.

We performed thermochronological study of the HHC nappe by means of zircon and apatite fission-track dating in order to examine the extrusion model on the basis of emplacement and cooling history of the HHC nappe, which extensively covers the Lesser Himalayan autochthon ranging in width of 80 to 120 km. As the results, we could have revealed the emplacement history of the nappe, which has strong constraints on the extrusion model: the HHC of more than 10 km thick extruded on the ground at 15-14 Ma, and advanced to the SSW with the rate of 3-4 cm/yr retaining hot condition more than 300 °C . The nappe finally terminated its movement at 11 Ma. Early Miocene foreland basin sediments on the top of the Lesser Himalayan autochthon have undergone weak metamorphism after covering of hot nappe at 11-10 Ma. Both metamorphic nappe and the underlying foreland basin sediments cooled down below 240 °C by 10 Ma and below 110 °C by 8 Ma. The metamorphic nappe laterally cooled down toward the NNE from its front at the rate of ca. 1cm/yr, and root zone area of the nappe reached 240 °C by 4 Ma and 110 °C by 1 Ma. One more constraint is that estimated P-T condition is consistent from the nappe front to the root zone: maximum temperature is around 750 °C and maximum pressure is 11-12kb.

Under these constraints, we examined the disposition of the HHC nappe before its extrusion, considering width of nappe as 80 km and inclination angle of metamorphic belt as 20 degree. After simple calculation of position of root zone of nappe under 12kb, it is concluded that root zone was located at 53 km to the north of the front of partially melted mid-crust of Tibet and seated 39 km in depth. It indicates that the HHC nappe must have been originated from partially melted mid-crust of Tibet.

Keywords: extrusion, nappe, fission-track dating, zircon, Himalayan metamorphic belt, Lesser Himalaya

Late Cretaceous detrital zircon from the Eclogite unit of the Sanbagawa belt: implications for exhumation tectonics

ENDO, Shunsuke^{1*}

¹GSJ-AIST

Eclogite facies rocks in the Sanbagawa belt can be classified into two types: 1) coarse-grained mafic-ultramafic complex such as the Iratsu body, and 2) surrounding fine-grained mafic, pelitic and siliceous schists. The former type has poly-phase metamorphic history with an early metamorphic stage in Early Cretaceous (c. 116 Ma), whereas the latter type has short-term history of a Late Cretaceous (c. 90 Ma) subduction-exhumation cycle (Wallis et al. 2009 JMG; Endo et al. 2012 Lithos; Aoya et al. 2013 Geology). However, there is another proposal that entire the high-grade Sanbagawa belt underwent peak metamorphism at Early Cretaceous (120-110 Ma) followed by pervasive retrograde recrystallization during Late Cretaceous (90-80 Ma)(Okamoto et al. 2004 Terra Nova; Aoki et al. 2009 Lithos; Itaya et al. 2011 JAES). To solve the controversial views in geochronology of the high-grade Sanbagawa belt, this study use detrital zircon geochronology to place constraints on the depositional ages of eclogitic pelitic schists at the trench. Zircon grains were separated from two pelitic schist samples from the oligoclase-biotite and albite-biotite zones in the Besshi area of central Shikoku. The sample localities belong to the Eclogite unit (Mouri & Enami 2008 Geology; Kouketsu & Enami 2010 IAR). Separated zircon grains exhibit oscillatory-zoned detrital cores and very thin metamorphic rims on CL images. LA-ICP-MS U-Pb dating of detrital zircon from the oligoclase-biotite and albite-biotite zone samples yields weighted mean ages of the youngest group as 101.7 ± 1.6 Ma (n=12, youngest grain: 94.4 ± 4.8 Ma) and 94.2 ± 2.5 Ma (n=9, youngest grain: 87.6 ± 4.6 Ma), respectively. Zircon rims from the two samples yield metamorphic ages of 90.0 ± 4.1 Ma (n=4) and 86.9 ± 5.7 Ma (n=1), respectively. These results reconfirm Late Cretaceous accretionary complex origin of the eclogite-facies region except for the coarse-grained mafic-ultramafic bodies. Late Cretaceous (c. 90 Ma) subduction of voluminous metasedimentary rocks to great depth (~70 km) resulted in formation and subsequent buoyancy-driven rapid exhumation of the Eclogite unit (consisting of the coarse- and fine-grained types) in the Sanbagawa belt.

Keywords: Sanbagawa belt, eclogite, pelitic schist, zircon, U-Pb age

Metamorphic formation of arrested charnockite in Sri Lanka: significance of bulk composition and mass transformation

YAMASAKI, Yukiko^{1*}; IKEDA, Takeshi¹; MOTOYOSHI, Yoichi²; HIROI, Yoshikuni³; PRAME, Bernard⁴; TSUNOGAE, Toshiaki⁵

¹Kyushu University, ²National Institute of Polar Research, ³Chiba University, ⁴Geological Survey of Sri Lanka, ⁵Tsukuba University

Arrested charnockite, that represents granulite facies mineral assemblage, occurs in several decimeters scale within amphibolite facies gneisses. The gneissosity in the gneiss becomes, in general, obscure toward center of charnockite. This suggests that the gneiss was metamorphosed into charnockite in local scale. The local charnockitization may be caused by fluid influx and/or partial melting or difference of local bulk composition (e.g. Newton et al., 1980; Hiroi et al., 1990; Burton and O'Nions, 1990; Ravindra Kumar, 2004; Endo et al., 2012, 2013). This study described mode of occurrence of arrested charnockite in Sri Lanka, and reveals cause of metamorphic formation of arrested charnockite. Mass transformation during charnockitization was also discussed.

Arrested charnockite in Sri Lanka occurs as a number of patches in Hbl-Bt gneiss. The modal abundance of minerals in both rocks indicates that the elements transformed between melanocratic and leucocratic parts. The elements constituent of Bt in leucocratic part moves to melanocratic part, and those of Pl, Ksp and Qtz of melanocratic part, instead, move to leucocratic part. The modal abundance of Bt of leucocratic part in Hbl-Bt gneiss decreases into the charnockite near the boundary. This suggests that mass transformation also be caused across the boundary.

The formation of Opx can be described by the following two reactions,

Ti-rich Bt + Qtz = Ti-poor Bt + opx + Ilm + Ksp + H₂O and

Ti-rich Hbl + Qtz = Ti-poor Hbl + Opx + Ilm + An + Ab + Ksp + H₂O.

These reactions suggest the possibility that the fluid influx and/or the partial melting produced arrested charnockite. However, similar chemical composition of apatite in both rocks implies that there is no positive evidence to support the above possibility. The pseudosection modeling of mineral assemblage in NCKFMASHTO system shows that the local difference of bulk composition is responsible for the local charnockitization.

Keywords: Sri Lanka, Arrested charnockite, Hornblende-biotite gneiss, Mass transformation, Pseudosection

Metamorphism of garnet amphibolite from the Neldy Formation, Makbal area in the Kyrgyz Northern Tien-Shan, Kyrgyzstan

KASYMBEKOV, Adil^{1*} ; TAKASU, Akira¹ ; KABIR, Md fazle¹ ; BAKIROV, Apas² ; SAKIEV, Kadyrbek²

¹Shimane University, Japan, ²Institute of Geology, Academy of Science, Kyrgyz Republic

The Makbal Complex in the Kyrgyz Northern Tien-Shan is one of several HP/UHP metamorphic complexes in the Tianshan orogenic belt located in the western segment of the CAO. The metamorphic rocks exposed in the Makbal district are divided into the Akdzhon and the Scharkyrak Groups based on their metamorphic conditions (Tagiri and Bakirov, 1990). The metamorphic sequence of the Akdzhon Group in the Northern Tien-Shan is divided into two contrasting metamorphic formation the structurally lower Makbal Formation and the upper Neldy Formation. The Neldy Formation is mainly composed of pelitic schists (garnet chloritoid-bearing schist, garnet-phengite schist) and chlorite-carbonate rocks along with minor metaquartzites, marbles and amphibolites. Garnet amphibolites occur in the pelitic schists as lenses or blocks up to 50m across. Eclogites are preserved in the core of the garnet amphibolite bodies (Togonbaeva *et al.*, 2010).

The garnet amphibolites are crops out in the Neldy Formation is composed mainly of amphibole (Brs, Mhb, Act, Fprg, Fts, Ts), garnet and chlorite with small amounts of quartz, epidote and albite. Accessory minerals are biotite, paragonite, muscovite, oligoclase, titanite, ilmenite and calcite. A schistosity is defined by preferred orientation of amphibole (Brs, Mhb), chlorite and biotite. The garnets occur as porphyroblasts up to 1.4 mm in diameter, which show distinct compositional zoning, in which X_{Sps} (0.22-0.04) decreases, X_{Alm} (0.34-0.63) and X_{Grs} (0.30-0.64) increase, and slightly increases X_{Prp} (0.01-0.03) from the core to the rim. The core of garnet contains inclusions of epidote, titanite, ilmenite, calcite and quartz. The rim of the garnet contains inclusions of amphibole (Act, Mhb), chlorite (X_{Mg} 0.37-0.42), epidote (X_{Ps} 0.13-0.25), quartz and also contain polyphase inclusions of muscovite + chlorite + epidote and chlorite + paragonite + epidote + oligoclase ($An < 18$), although some of them are connected outside with cracks. Box-shaped polyphase inclusions of paragonite+epidote±chlorite±muscovite±oligoclase suggest a possibility of pseudomorphs after lawsonite. Porphyroblastic garnets are sometimes replaced by amphibole (Fprg, Ts), chlorite (X_{Mg} 0.46-0.52) and epidote (X_{Ps} 0.13-0.23) along rim and cracks. Amphiboles in the matrix show a zoning with Mg-hornblende and actinolite (Na_B 0.15-0.48 pfu) core, barroisite (Na_B 0.50-0.63 pfu) mantle, and Mg-hornblende and tschermakite (Na_B 0.18-0.46 pfu) rim. Amphiboles replacing the garnets have a zoning with barroisite (Na_B 0.62-0.65 pfu) core and ferrotschermakite, ferropargasite and Mg-hornblende (Na_B 0.11-0.48 pfu) rim.

Based on the texture and mineral composition, two metamorphic events have been distinguished from the garnet amphibolites. The prograde to peak stage of the first metamorphic event is characterized by core to rim of the porphyroblastic garnets and inclusion minerals therein (i.e. amphibole, epidote, chlorite, biotite, paragonite, titanite, ilmenite, calcite and quartz). The peak metamorphic conditions are probably stable in the epidote-amphibolite facies. The retrograde stage is characterized by chlorite, which replaces the porphyroblastic garnets. The prograde stage of the second metamorphic event is characterized by barroisite core of the amphiboles and epidote replacing the garnets. The peak stage is characterized by fracture connected inclusions of muscovite and oligoclase and tschermakite and ferropargasitic amphibole developed at the rim of the amphiboles replacing the garnets, probably suffered amphibolite facies metamorphic conditions. The retrograde stage is characterized by albite and quartz in the matrix.

The petrological study suggests that the garnet amphibolites probably suffered metamorphism events of (i) high-pressure epidote amphibolite facies and (ii) amphibolite facies. These metamorphic events are related to the tectonics of the oceanic plate subduction and subsequent continental collision.

Keywords: Garnet amphibolite, Makbal Complex, Neldy Formation, amphibolite facies, Kyrgyz Northern Tien-Shan

Geothermobarometry of the Mogok pelitic gneisses from the Sagaing area, Central Myanmar

Maw Maw Win^{1*} ; ENAMI, Masaki² ; KATO, Takenori²

¹Graduate School of Environmental Studies, ²Center for Chronological Research

The amalgamation of continental blocks that drifted from the northeastern margin of Gondwanaland from Late Paleozoic to Cenozoic formed the present landmass of eastern and southeastern Asia (e.g., Metcalfe, 2011). Myanmar is tectonically divided into eastern and western provinces by the Sagaing Fault, which is a 1200-km-long right-lateral strike-slip fault. The eastern province consists of the Sibumasu (Shan-Thai) Block and the western province consists of the West Burma Block and the Indo-Burma ranges. Both the Sibumasu and West Burma Blocks belong to the Sundaland. For the present study, samples were collected from the Mogok metamorphic belt (MMB), which borders the eastern province along the western edge forming a sigmoidal structure. It is 50 km wide and extends southwards from the eastern Himalayan syntaxis in the north to over 1500 km, where it joins the high-grade metamorphic belts of northern Thailand.

Our study area is situated at the central part of the MMB, north of Sagaing, and is bound by two parallel N-S trending ridges — Sagaing Ridge in the east and Minwun Ridge in the west. These two-parallel ridges are separated by the Sagaing fault valley, which varies in width from 0.5 to 1 km. Metamorphic rocks exposed in this area include gneisses, marbles, calc-silicates, schists, and amphibolites. Detailed mineralogical and petrological studies were conducted on garnet-biotite gneisses taken from the Sagaing Ridge (S30a, S26, S22a & b, and S39 from north to south). CHIME monazite ages indicate three possible crystallization events during the Paleogene period: 48.0 ± 2.4 , 37.1 ± 0.8 and 27.6 ± 0.6 Ma (2-sigma level). The common mineral assemblages are garnet, biotite, plagioclase, and quartz with minor amounts of rutile, ilmenite, graphite, apatite, monazite, and zircon. Additionally, the sample S30a contains prismatic sillimanite in the matrix. In sample S26, garnets contain fibrolite inclusions and the matrix consists of prismatic sillimanite. The samples S22a and b contain fibrolite inclusions in garnet and K-feldspar matrix. In the sample S39, spinel occurs as inclusions in garnet. Garnet grains are mostly homogeneous and exhibited high Mn content and low Mg content locally at the grain boundaries: $\text{Alm}_{63-67}\text{Prp}_{28-30}\text{Sps}_3\text{Grs}_{4-5}$, $\text{Alm}_{55-72}\text{Prp}_{20-38}\text{Sps}_{1-5}\text{Grs}_{4-5}$, $\text{Alm}_{59-65}\text{Prp}_{30-35}\text{Sps}_{1-2}\text{Grs}_{5-7}$, $\text{Alm}_{58-63}\text{Prp}_{30-33}\text{Sps}_1\text{Grs}_{4-6}$, $\text{Alm}_{62-72}\text{Prp}_{17-28}\text{Sps}_{1-3}\text{Grs}_{6-10}$ in samples S30a, S26, S22a & b, and S39, respectively. Biotites were texturally categorized as (i) inclusions in garnet, (ii) isolated grains in matrix (iii) symplectitic aggregate with plagioclase around the garnet grains, and (iv) in veins through the garnet grains. Biotite inclusions and biotite content in matrix contain 5.6 wt% and 2.0 wt% of TiO_2 and F, respectively. Spinel contains 4.9 wt% ZnO and its X_{Mg} [=Mg/(Mg+Fe²⁺)] and Y_{Al} [=Al/(Al+Fe³⁺+Cr)] values are about 0.35 - 0.40 and 0.95, respectively.

The garnet-biotite geothermometer and two geobarometers characterized by garnet-biotite-plagioclase-quartz and garnet-plagioclase-sillimanite-quartz equilibria were employed for the pressure/temperature (P/T) estimations of the samples collected from Sagaing. Three groups of datasets were used for the calculations: (1) biotite and plagioclase inclusions and their garnet host, (2) garnet core along with biotite and plagioclase matrix, and (3) symplectite and garnet rim. The estimated equilibrium P/T conditions were 0.3 - 0.7 GPa/580 - 700 °C and 0.6 - 0.9 GPa/780 - 880 °C for the inclusion and matrix assemblages, respectively. Symplectitic assemblages around the garnets exhibit equilibrium conditions at 0.2 - 0.3 GPa/580 - 610 °C. The high TiO_2 content of the biotite grains coexisting with rutile and/or ilmenite indicate a temperature of crystallization of 800 °C, when the Ti content of biotite is used as the geothermometer as proposed by Henry et al. (2005).

Keywords: CHIME monazite ages, P-T conditions, pelitic gneisses, Mogok metamorphic belt, Myanmar

Petrological studies of spinel and quartz-bearing paragneiss from Zayetkwin-Onzon area, central Myanmar

Ye Kyaw Thu^{1*} ; ENAMI, Masaki²

¹Graduate School of Environmental Studies, Nagoya University, ²Center for Chronological Research

The Mogok Metamorphic Belt (MMB) extends for over 1450 km, from the Andaman Sea to the eastern Himalayan syntaxis along the western margin of the Shan-Thai block. This belt is mainly composed of high-grade metamorphic rocks, from upper-amphibolite facies to granulite facies, and younger intrusions. Previous studies concluded that an assemblage of the high-grade metamorphic rocks formed during a Paleogene regional metamorphic event that was caused by collision or underthrusting of the Indian microcontinent with the Eurasian continent. The study area is situated in the middle part of the MMB, 100 km north of Mandalay, and is mainly composed of paragneisses overlain by marbles and calc-silicate rocks. These lithologies are intruded by quartz syenite, biotite-granite, and pegmatite. The marbles and calc-silicate rocks are mainly composed of diopside, forsterite, phlogopite, spinel, graphite, and chondrodite, which record upper amphibolite facies equilibria. Paragneisses are mainly garnet-biotite gneisses with intercalations of biotite gneisses and leucogneisses, and show general NE - SW foliation. Paragneiss samples studied are medium- to coarse-grained, well-banded, and show porphyroblastic and gneissose texture. Most of them contain garnet, biotite, plagioclase, quartz, sillimanite, and K-feldspar with a minor amount of graphite, ilmenite and monazite. Porphyroblastic garnet grains are 2 - 5 mm in diameter, and contain numerous inclusions of biotite, plagioclase, quartz, and sillimanite. Biotite grains occur as four-generation phases, an inclusion phase in garnet, an isolated phase in the matrix, a symplectitic aggregate around garnet, and a vein phase replacing cracks in the garnet.

Coexisting spinel and quartz are newly found in a garnet-biotite gneiss collected from the Zayetkwin-Onzon area. This sample contains porphyroblastic garnet and cordierite, and biotite, plagioclase, quartz, and graphite in the matrix. Spinel and sillimanite coexisting with quartz, plagioclase, biotite, and ilmenite occur only as inclusions in cordierite. Spinel is a Zn-poor spinel-hercynite solid solution with $X_{Mg} [= \text{Mg}/(\text{Mg} + \text{Fe}^{2+})] = 0.34 - 0.35$, $Y_{Al} [= \text{Al}/(\text{Al} + \text{Fe}^{3+})] = 0.97 - 0.99$, $\text{TiO}_2 = 0.0 - 0.2$ wt%, and $\text{ZnO} = 1.8 - 2.3$ wt%. The matrix assemblage gives pressure/temperature estimates of 0.7 - 0.8 GPa/780 - 840 °C using a garnet-biotite geothermometer and garnet-biotite-plagioclase-quartz geobarometer. Biotite grains in the spinel-bearing sample and associated paragneisses contain a distinctly high TiO_2 content of up to 6.9 wt% (0.39 per formula unit for O = 11), which probably progressed mainly because of the $\text{Ti} \diamond \text{R}_{-2}$ substitution (R is the sum of divalent cations and \diamond represents vacancy in the octahedral sites). The fluorine content is up to 2.0 wt%, and the chlorine content is less than 0.1 wt%. The Ti-rich biotite suggests temperatures of 800 °C or higher if Ti is employed in the biotite geothermometer, as proposed by Henry et al. (2005).

The occurrence of a spinel-quartz-cordierite-sillimanite assemblage in the Zayetkwin-Onzon sample and the high-temperature estimates of around 800 °C suggest granulite facies equilibrium of the Mogok metamorphic rocks. Orthopyroxene-bearing garnet-gneisses were reported from the Mogok area, about 80 km NE of the Zayetkwin-Onzon area (Yonemura et al., 2013). These data suggest wide distributions of granulite facies metamorphic rocks in the northern part of the MMB.

Keywords: spinel, paragneiss, P-T conditions, Mogok Metamorphic Belt, Myanmar

Olivine megacrysts in the Horoman Peridotite Complex, Hokkaido, northern Japan

MINAMIYAMA, Akari^{1*} ; SODA, Yusuke¹ ; HAMADA, Morihisa² ; MORISHITA, Tomoaki¹

¹Kanazawa University, ²Japan Agency for Marine-Earth Science and Technology

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 Lallemand et al, 1980; Karato, 2011). However, olivine, which is larger than 1 cm in grain size (olivine megacryst hereafter), often occurs in peridotites. Therefore, understanding of the characteristic of olivine megacrysts is crucial to investigate a possibility of the formation of megacrysts in the upper mantle conditions. In this study, peridotite samples with olivine megacrysts from the Horoman peridotite complex, Japan, are studied by crystallographic orientation analysis, FT-IR analysis, EPMA. Especially, we focused on the change of crystal and subgrain boundary orientation by deformation

Peridotite samples are from MHL (Main Harzburgite-Lherzolite) suite of Takahashi (1991) in the Lower Zone of the Horoman peridotite complex (Niida, 1984). Olivine megacryst, which is often darker in color than fine-grained olivines, occurs subparallel to the foliation. Fine-grained layer shows porphyroclastic texture. Olivine megacryst and porphyroclast olivine in the fine-grained layer develop subgrain boundaries and include lamellae of chromian spinel, clinopyroxene and amphibole.

Slip systems of olivine [001](100) and [100](001) are estimated 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). Crystal orientation of fine-grained olivines near megacryst show transitional characteristics in olivine fabric between the megacryst and the fine grains.

Structural hydroxyl species are not observed by FTIR in both olivine megacryst and olivine grains in fine-grained layer. There are no differences in the Fo content and NiO wt% between olivine megacryst and fine grains by EPMA.

Presence of amphibole lamellae in olivine megacryst suggest that olivine megacryst had existed under wet condition. Fine-grained olivine fabrics near megacryst and slip system of olivine megacryst edge suggest that olivine megacryst had existed when A-type fabric of olivines forms in fine-grained layer. A-type fabric peridotite was reported in the Horoman peridotite complex and interpreted that the A-type fabric formed during uplifting of the Horoman peridotite complex from the upper mantle to the crust (Sawaguchi, 2004).

Consequently, olivine megacryst had existed under water-rich condition in the upper mantle followed by A-type fabric formation in the fine-grained layers during uplifting of the Horoman peridotite complex from the upper mantle.

Keywords: olivine megacrysts, Horoman peridotite, CPO

Elastic wave velocity and microstructures of Hida gneisses

KOIKE, Kanta^{1*} ; WATANABE, Tohru¹

¹Department of Earth Sciences, University of Toyama

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. For its complexity, the influence of the spatial distribution of mineral phases has been poorly understood. In this study, we focus on a layered structure seen in gneisses. We are studying elastic wave velocities and microstructures in Hida gneisses.

Rock samples of Hida gneisses were collected at Kubusu River (Yatsuo, Toyama Pref.). A rectangular parallelepiped (the edge length~40 mm) was made from rock samples. Two faces are parallel to the foliation plane, and two faces perpendicular to the elongation direction. Preliminary velocity measurements were made at room conditions by the pulse transmission technique using Pb(Zr, Ti)O₃ transducers with the resonant frequency of 2 MHz. One compressional wave velocity and two shear wave velocities were measured in each of three orthogonal directions. Two shear waves propagating in one direction oscillate in mutually orthogonal directions. The fastest compressional wave velocity (5.91 km/s) was observed in the direction parallel to the elongation, while the slowest (5.51 km/s) perpendicular to the foliation. When a shear wave propagated along the foliation plane, it showed slightly higher velocity for oscillating along the foliation than for oscillating perpendicular to the foliation plane.

However, these velocity values cannot be compared with microstructures, because they must be affected by pores in rock samples. We are now conducting velocity measurements under confining pressures of up to 180 MPa to remove the influence of pores. The relationship between velocity under confining pressures and microstructures will be presented in our poster.

Keywords: gneiss, seismic velocity, anisotropy, microstructure, CPO

Relation of the Tsukiyoshi Fault and orientation distribution of microcracks in the borehole MIU-3 core in Mizunami City

OHTANI, Tomoyuki^{1*}; YOKOI, Kosuke¹; OKAZAKI, Kazunari¹; NISHIMURA, Yuki¹; KOJIMA, Satoru¹; KUBOSHIMA, Koji²; SASAO, Eiji²

¹Gifu Univ., ²JAEA

The orientation measurement of microcracks was performed using the borehole core penetrating a fault to clarify the relation of the microcrack distribution pattern near a fault. The studied borehole is MIU-3 drilled by Japan Atomic Energy Agency (JAEA). The MIU-3 borehole is 1014 m length and penetrates the Tsukiyoshi fault at the depth of 707 m. The host rock of the Tsukiyoshi Fault is the Late-Cretaceous Toki Granite. The Tsukiyoshi Fault trends E-W and dips about 70 degree to the south. The sense of shear is mainly reverse after the deposition of the Miocene Mizunami Group, although the evidence of normal and strike-slip was also reported based on the texture analysis of the fault rocks (Niizato, 2003).

Seven granite samples from the MIU-3 borehole were used for this study. Sampling depths are 496 m, 623 m, 662 m, 698 m, 755 m, 851 m and 996 m. Four samples from the hanging wall are coarse-grained granite, and three samples from the footwall are medium-grained granite. Attitude of microcracks developed in quartz grains in the granite are measured by the method of Vollbrecht et al. (1991), which is performed under the optical microscope with the universal stage using three perpendicular thin sections. The target of measurement is healed and sealed microcracks. Open microcracks are excluded from measurement because of the possibility of artificial formation during drilling.

From the occurrence of the microcracks, the formation of healed microcracks is probably prior to that of sealed microcracks. From the orientation measurement, the preferred orientations of the healed microcracks are subhorizontal to gentle dip and N-S strike with steep dip in all depths, and moderate dip except 496 m depth. As healed microcracks with moderate dip strikes E-W in 623 m depth and N-S in 662 m depth, their preferred strikes are different among the samples. The preferred orientations of the sealed microcracks are subhorizontal to gentle dip, N-S strike with steep dip and E-W to WNW-ESE strike with steep dip in most depths. The concentration of N-S and E-W strikes with moderate dip is also recognized in the samples of 698 m and 755m, which are located near the fault.

As described above, both healed and sealed microcracks with moderate dip appears near the fault. Moore and Lockner (1995) revealed the microcrack pattern from an experimental study to generate shear fracture in laboratory. The microcracks that were formed during the experiment are principally tensile cracks of which orientations reflect the local stress field: those formed prior to the nucleation of the fault are roughly parallel to the cylinder axis, whereas those generated in the process zone make angles averaging 30 degree to the overall fault strike (and 20 degree to the cylinder axis). The appearance of microcracks with moderate dip near the Tsukiyoshi Fault shows that the preferred orientation of microcracks near the natural fault is also different from that far from the fault. The zone of the sealed microcracks with moderate dip is thinner than that of the healed microcracks. The microscopic features show that the formation of the healed microcracks is prior to that of the sealed microcracks, so that the thicker zone of the healed microcracks with moderate dip was developed in the intact granite at the earlier stage of the faulting history, and thinner of the sealed microcracks was in the weak fault zone which has repeated rupturing and healing at the later.

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Keywords: microcracks, orientation distribution, Tsukiyoshi Fault, borehole MIU-3 core

Numerical model for subduction zone dynamics

ISHII, Kazuhiko^{1*}

¹Graduate School of Sciences, Osaka Prefecture University

I present a numerical model for subduction zone dynamics. This model is composed of upper and lower continental crust, upper and lower oceanic crust, mantle lithosphere and asthenosphere, seawater and air. The model includes various processes such as the subduction and deformation of oceanic plate, the deformation of mantle wedge and continental crust, the metamorphic processes in the subducting oceanic crust (eclogitization and dehydration) and the mantle wedge (serpentinization), the reduction of effective frictional coefficient due to increase in fluid pressure, melting of peridotites, permeable flow of melt and aqueous fluids, and temperature-dependent solid flow of mantle peridotites with water- and melt-induced weakening. The final goal of this modeling is to understand (1) the coupling depth and strength of the plate interfaces, (2) the mechanism for exhumation of metamorphic rocks, (3) the processes and conditions for the accretion and tectonic erosion, and (4) the deformation and stress distribution in the arc crust.

Keywords: subduction zones, numerical model, strength of plate interfaces, exhumation of metamorphic rocks, crustal deformation and stress, accretion and tectonic erosion

Kondo theory for spherical shells tectonics

KIKUCHI, Kazuhei^{1*} ; NAGAHAMA, Hiroyuki¹

¹Department of earth science, Tohoku University

Buckling phenomenon in spherical shells of the lithosphere in subduction zone is studied by spherical shell tectonics. We show a similar relationship between Batdorf parameter for length of the slab and normalized hydrostatic pressure (Kikuchi and Nagahama, 2015). Length of the slab is approximately proportional to the length of the arc and thickness of the lithosphere. However, spherical shells tectonics cannot give us the curvature with high order strain of buckling equation for the lithosphere. On the other hand, Kondo (1955) used the concept of Riemannian geometry in yield and buckling of the curved material. So, by Kondo theory, we derive a buckling equation of spherical shells for the curvature in the lithosphere.

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Kondo, K. (1955) Theory of Metaphorical Plates and Shells, RAAG Memoirs, Vol. I, (ed). K. Kondo, pp. 47- 60.

Keywords: Spherical shells tectonics, Kondo theory

Radiolarian fossils and crystal growth of metamorphic minerals in low-grade metamorphic rocks

ONO, Akira^{1*}

¹None

Radiolarian fossils are commonly found in weakly metamorphosed slates and siliceous rocks of the Atogura Nappe and Chichibu Complex on the basis of the observation by using a loupe. Pelitic schists and Kashio mylonites from the Ryoke belt of the Takato-Hase region were also examined to elucidate the existence of radiolarian fossils. The results were reported before [1]. In the present article, radiolarian fossils in thin sections are described in relation to metamorphic grade and crystal growth of minerals.

Radiolarian fossils of a siliceous slate of the Atogura Nappe

A siliceous slate in a chert block exposed in the Yatsu, Yorii town was studied. Figure A shows radiolarian fossils observed under an optical microscope. Many white ring structures are filled with fine colored minerals. Ring structures become indistinct when concentrations of internal colored minerals are low. The concentrations of colored minerals, chlorite and opaque minerals are often low in the central parts of the ring structures. In this case a broad dark ring structure of fine-grained colored minerals is formed. White and dark ring structures are considered as traces of radiolarian fossils. Similar textures are recognized in metamorphic rocks formed under fairly high temperatures. An example is shown in Figure B which is a muscovite-biotite schist exposed in Takato town, Ina city, Nagano Prefecture.

Metamorphic grade and radiolarian fossil

The Ryoke metamorphic belt of the Takato-Shiojiri area is divided into three zones; chlorite-biotite zone, biotite zone and sillimanite zone. Metamorphic temperature increases in this order. Radiolarian fossils were confirmed under an optical microscope in the chlorite-biotite zone, but it was unable to recognize radiolarian fossils in the biotite and sillimanite zones. Recently, however, many small white rings (Figure B) were recognized by using a loupe and usb microscope for biotite schists near the sillimanite isograd. The ring structures are traces of radiolarian fossils which are preserved in spite of the existence of large biotite, muscovite, plagioclase and quartz. The preservation of the ring structures is mainly due to the existence of very small carbonaceous materials within the ring structures (Figure C). The small grain sizes of the carbonaceous materials suggest the slow rates of crystal growth and transportation of carbonaceous materials under relatively low metamorphic temperatures. Carbonaceous materials of pelitic Ryoke gneisses, however, considerably grow up in the sillimanite zone of the Takato area. Therefore it is almost impossible to recognize relics of radiolarian fossils in the sillimanite zone.

Mineral growth and radiolarian fossil

A large metamorphic tectonic block is distributed in the northern part of the Kiroko greenstone melange of the Atogura Nappe. Psammitic metamorphic rocks are common in the tectonic block. Many small ring structures of approximately 40-100 μ m in diameter are recognized by using a loupe for a siliceous psammitic rock. The siliceous rock is mainly composed of quartz and small amounts of fine brown minerals which are not identified yet. Quartz crystals larger than 100 μ m are common. The fine brown minerals are distributed forming circular structures and broad dark ring structures within quartz crystals according to the observation by using an optical microscope. Fine brown minerals were included in quartz crystals during the crystal growth of quartz crystals. Shapes of radiolarian fossils were partly preserved in spite of high-temperature metamorphism.

[1] A. Ono, 2012, Abs. Geol. Soc. Japan, Meeting, R4-P-24, p.228.

Keywords: Radiolarian fossil, Metamorphic temperature, Recrystallization

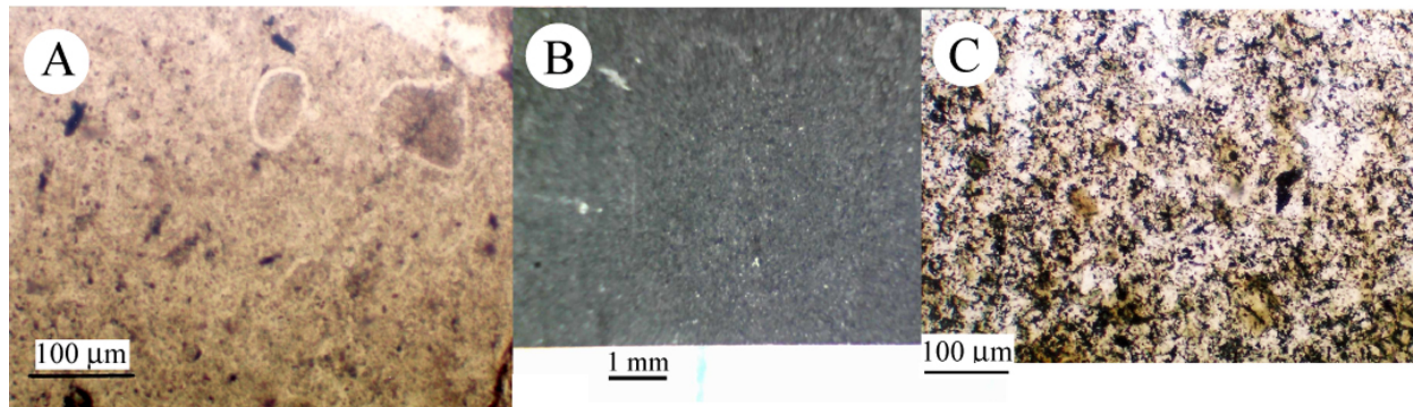
SMP43-P14

Room:Convention Hall

Time:May 24 18:15-19:30

A Siliceous slate

B and C Biotite-muscovite schist



Metamorphic P-T evolution of the eclogitic pelitic schists in the Sambagawa belt, central Shikoku, Japan

TAKASU, Akira^{1*} ; KABIR, M.f.¹

¹Shimane University

The Seba area in the Sambagawa metamorphic belt is located in the central part of the Besshi district, central Shikoku, and it is composed of the Sebadani metagabbro mass and surrounding Seba basic schists. Eclogitic mineral assemblages are sporadically preserved in both the Sebadani metagabbro and the Seba basic schists (Takasu, 1984; Aoya, 2001). Pelitic schists are intercalated within the Seba eclogitic basic schists, and they consist mainly of quartz, phengite, chlorite and garnet minor amounts of epidote, amphiboles (sodic, sodic-calcic and calcic-amphibole), omphacite, albite, biotite and carbonaceous matter. Rutile, titanite, calcite, chloritoid, K-feldspar, tourmaline, apatite and zircon are occasionally present as accessories. Amphiboles in the matrix sporadically grow oblique to the main schistosity. These amphiboles are strongly zoned, with glaucophane core, barroisite/Mg-katophorite mantle and edenite/actinolite rim.

Three distinct metamorphic events are identified from the pelitic schists. These are (i) precursor metamorphic event, (ii) first high-pressure metamorphic event, and (iii) second high-pressure metamorphic event. The precursor metamorphic event (i) is defined by calcic amphibole (pargasite, Mg-hornblende and taramite) and muscovite (Si 6.05-6.13 pfu) inclusions in the core of the garnets. These minerals suggest relatively high-temperature metamorphic conditions such as high-temperature portions of the epidote amphibolite or the amphibolite facies. The prograde path of the first high-pressure metamorphic event (ii) is from the epidote?blueschist facies, passing through the epidote?amphibolite facies, to reach peak metamorphic conditions in the eclogite facies. P-T pseudosection (MnNCKFMASHO model system) was calculated and compositional isopleths suggested the peak metamorphic conditions of 640?660 °C and 21?23 kbar. The prograde metamorphic conditions were also obtained as 460 °C and 8 kbar.

Aoya (2001) suggested a prograde path of the Seba eclogitic basic schists that garnet and omphacite growth mainly occurred during the decompression stage after the pressure peak. During garnet cores growing pressure and temperature increased, and during garnet rim and omphacite growing temperature continuously increased whereas pressure decreased. According to the present study both omphacite and garnet grew under the conditions of temperature and pressure increasing. During decompression amphibole+albite±less-jadeite omphacite symplectites developed after omphacite, suggesting both pressure and temperature decreased into epidote amphibolite facies conditions after the peak metamorphism. The second high-pressure metamorphic event (iii) is defined by distinctly zoned amphiboles suggesting a prograde crystallization of the amphiboles from blueschist facies to epidote amphibolite facies conditions, and it is probably correlated with the metamorphism of non-eclogitic schists surrounding the eclogite bodies (Aoya, 2001; Kabir and Takasu, 2010).

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Keywords: Sambagawa, eclogite, P-T pseudosection, garnet, Besshi, Seba

Electron Probe Microanalyser and Laser Raman analyses of reaction textures in breccia veins, Tokunoshima, SW Japan

SADAKANE, Takeyoshi^{1*} ; YAMAMOTO, Hiroshi¹ ; UEDA, Shuro² ; TERABAYASHI, Masaru³

¹Graduate School of Science and Engineering Kagoshima University, ²Dia Consultants CO.,Ltd, ³Department of Safety Systems Construction Engineering, Kagawa University

Dark colored veins have been recognized in metamorphic body of Akirigami river in the western Tokunoshima, the Amami Islands (Ueda *et al.*, 2012). This Dark colored veins are filled with breccia, microbreccia and fine-grained matrix derived from fault activity. Those matrices include circular opaque minerals which show bright rims and very dark cores under reflection microscope. The element concentration mapping by Electron Probe Microanalyser shows that bright rims consist mostly of Ti and dark cores are Ca-rich. Laser Raman Spectroscopic mapping differentiates that the small anatase grains (Ti rim) enclosing calcite (Ca - rich core). The circular opaque minerals are not found from host rocks (peltic - psammitic schists) and titanite is the only Ca - Ti bearing mineral phase in the host rocks. These observations indicate that the titanite-breakdown reaction operated during or shortly after injection of ultracataclastic veins under temperatures around 200 °C (e.g., Chakhmouradian, 2004) or higher.

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Keywords: Laser Raman Spectroscopy, Ryukyu arc, Tokunoshima, Kagoshima Prefecture