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Construction of Raman geothermobarometer using aluminosilicate minerals in garnet porphyroblast

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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 ℃, 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

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Metamorphic evolution of ultrahigh-pressure rock revealed by residual pressure of SiO_2 inclusion in garnet

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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 ℃ 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 ($Alm_{49-54}Prp_{16-28}Grs_{21-29}Sps_1$, X_{Mg} = 0.22-0.36) and outer ($Alm_{45-52}Prp_{18-31}Grs_{23-29}Sps_1$, X_{Mg} = 0.29-0.41) segments, the boundary between the two defined by discontinuous changes in grossular content. In the inner segment, the SiO_2 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) SiO_2 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

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

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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 ℃ . 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 ℃ by 10 Ma and below 110 ℃ 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 ℃ by 4 Ma and 110 ℃ 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 ℃ 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

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

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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$\pm$1.6 Ma (n=12, youngest grain: 94.4$\pm$4.8 Ma) and 94.2$\pm$2.5 Ma (n=9, youngest grain: 87.6$\pm$4.6 Ma), respectively. Zircon rims from the two samples yield metamorphic ages of 90.0$\pm$4.1 Ma (n=4) and 86.9$\pm$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

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

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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 + H_2O and

Ti-rich Hbl + Qtzz = Ti-poor Hbl + Opx + Ilm + An + Ab + Ksp + H_2O.

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

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

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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 CAOB. 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 devided 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 chlorotoid-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, oligioclase, 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 + olgioclase (An $<$18), although some of them are connected outside with cracks. Box-shaped polyphase inclusions of paragonite+epidote$\pm$chlorite$\pm$muscovite$\pm$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

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

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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 $\pm$ 2.4, 37.1 $\pm$ 0.8 and 27.6 $\pm$ 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: $Alm_{63-67}Prp_{28-30}Sps_3Grs_{4-5}$, $Alm_{55-72}Prp_{20-38}Sps_{1-5}Grs_{4-5}$, $Alm_{59-65}Prp_{30-35}Sps_{1-2}Grs_{5-7}$, $Alm_{58-63}Prp3_{0-33}Sps1Grs_{4-6}$, $Alm_{62-72}Prp_{17-28}Sps_{1-3}Grs_{6-10}$ 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+Fe^{2+})] and Y_{Al} [=Al/(Al+Fe^{3+}+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 - 0.7GPa/580 - 700 ℃ and 0.6 - 0.9GPa/780 - 880 ℃ for the inclusion and matrix assemblages, respectively. Symplectitic assemblages around the garnets exhibit equilibrium conditions at 0.2 - 0.3GPa/580 - 610 ℃. The high TiO_2 content of the biotite grains coexisting with rutile and/or ilmenite indicate a temperature of crystallization of 800 ℃, 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

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

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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} [= Mg/(Mg + Fe^{2+})] = 0.34 - 0.35, Y_{Al} [=Al/(Al + Fe^{3+})] = 0.97 - 0.99, TiO_2 = 0.0 - 0.2 wt%, and ZnO = 1.8 - 2.3 wt%. The matrix assemblage gives pressure/temperature estimates of 0.7 - 0.8 GPa/780 - 840 ℃ 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 $Ti\diamondsuit R_{-2}$ substitution (R is the sum of divalent cations and $\diamondsuit$ 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 ℃ 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 ℃ 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

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

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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, 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 magacrysts 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 magacryst, which is often darker in color than fine-grained olivines, occurs subparallels 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

SMP43-P10 Room:Convention Hall Time:May 24 18:15-19:30

Elastic wave velocity and microstructures of Hida gneisses

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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 parallelpiped (the edge length$\sim$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 $Pb(Zr, Ti)O_3$ 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

SMP43-P11 Room:Convention Hall Time:May 24 18:15-19:30

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

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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 course-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

SMP43-P12 Room:Convention Hall Time:May 24 18:15-19:30

Numerical model for subduction zone dynamics

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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

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Kondo theory for spherical shells tectonics

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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.

Kikuchi, K. and H. Nagahama (2015) Batdorf parameter for the spherical shells tectonics, EGU General Assembly Conference Geophysical Research Abstracts Vol. 17.
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

Japan Geoscience Union Meeting 2015
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SMP43-P14 Room:Convention Hall Time:May 24 18:15-19:30

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

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[1]None

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 radiolarians 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 40-100μm 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 100μm 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

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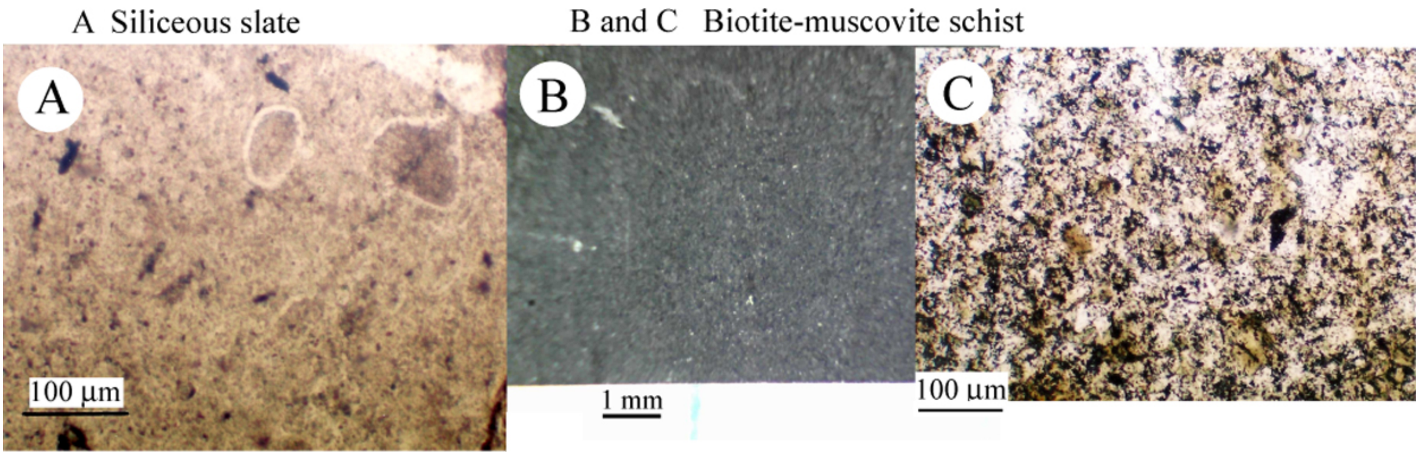

Japan Geoscience Union Meeting 2015
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SMP43-P15 Room:Convention Hall Time:May 24 18:15-19:30

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

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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 ℃ and 21?23 kbar. The prograde metamorphic conditions were also obtained as 460 ℃ 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

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SMP43-P16 Room:Convention Hall Time:May 24 18:15-19:30

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

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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 - psammitc 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 ℃ (e.g., Chakhmouradian, 2004) or higher.

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