The core of garnet porphyroblasts in the garnet-sillimanite gneiss from Skallevikshalsen, Lützow-Holm Complex, East Antarctica, includes Cl-rich (>0.3wt%Cl) biotite and nanogranite/felsite inclusions (former granitic melt). These are estimated to be stable at >1.2 GPa and 820-850 °C. Rare occurrence of matrix biotite suggests almost complete consumption of pre-existed matrix biotite during prograde to peak metamorphism. Brine infiltration during prograde to peak metamorphism is supported by Cl-rich scapolite described in previous studies [e.g., 1]. Brine infiltration and progress of continuous biotite-consuming melting reactions were probably responsible for elevating the Cl content of biotite.

In situ electron microprobe U-Th-Pb dating of monazite and the in situ LA-ICPMS U-Pb dating of zircon in the garnet-sillimanite gneiss revealed that both monazite and zircon has the ‘older age population’ with ca. 650-580 Ma and the ‘younger age population’ with ca. 560-500 Ma. The REE and trace element pattern of one of the P-rich patches in the garnet core is different from the P-rich garnet rim. The isotope mapping of the same patch by LA-ICPMS revealed that the patch is also observed as a domain depleted in $^{51}$V, $^{89}$Y, $^{165}$Ho, $^{166}$Er, $^{169}$Tm, $^{172}$Yb, and $^{175}$Lu. Clear difference in $^{51}$V concentration between the patch and the rim of the garnet suggests that this patch is not a continuous part from the garnet rim, but is likely a relic of preexisting garnet. Kyanite included in the patch suggests that medium- to high-pressure type metamorphic rock was the precursor. Presence of the older age population (ca. 650-580 Ma) monazites in Skallevikshalsen and Skallen [2] also suggest that rocks in these areas experienced polymetamorphism, and resetting by the ca. 560-500 Ma metamorphic event was incomplete. Taking into account the presence of Cl-rich biotite inclusions in garnet, infiltration of brine accompanied by partial melting is one probable event that took place at ca. 560-500 Ma in the Skallevikshalsen area, and part of the monazite possibly recrystallized by this brine infiltration.

References: [1] Satish-Kumar et al., 2006, JMG. [2] Hokada and Motoyoshi, 2006, Polar Geosci.
Possible process of microstructure formation around Cl-rich mineral-bearing vein under upper amphibolite facies conditions

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Fluids in the crust play important roles in heat and mass transfer. Evidence for the presence of fluids in the deep crust is recorded as fluid inclusions or as hydrous minerals. Existence of brines in the deep crust is recently recognized in addition to CO₂-rich fluids (e.g., Newton et al., 1998; Shmulovich & Graham, 2004). Brines have higher solubility of minerals and lower viscosity and wetting angle than CO₂-rich fluids. This makes it possible to induce mass transfer along grain boundaries over vast distances on the km scale (e.g., Harlov, 2012), while it is difficult to be preserved in rocks as fluid inclusions. Therefore, it is important to establish microstructural indicators of the presence of brine in order to understand the distribution and role of brine in the crust.

This study deals with about 1 cm-thick garnet-hornblende (Grt-Hbl) vein that discordantly cuts the gneissose structure of garnet-orthopyroxene-hornblende (Grt-Opx-Hbl) gneiss from Brattipenne, Sor Rondane Mountains (SRM), East Antarctica. The Grt-Hbl vein is likely to have been formed from the wall rock, because the continuous gneissose structure is preserved as arrangements of biotite inclusions in the vein-forming Grt. With distance from the vein center, Cl concentration of Hbl and biotite (Bt), K content of Hbl, and thickness of Na-richer rim of plagioclase (Pl) decrease and become constant at a few cm away from the vein center. These compositional changes imply that the Grt-Hbl vein was possibly formed by NaCl-KCl-bearing fluid or melt infiltration. The P-T conditions for the vein formation is estimated to be ca. 700°C and 0.7 GPa, using geothermobarometers.

In this study, Zr is confirmed as immobile during the Grt-Hbl vein formation by almost constant bulk rock Zr content with distance from the vein (Higashino et al., 2015). Using Zr as an immobile element, the mass balance analysis was performed based on the fractionation mass change value (Ague, 2003). The bulk rock chemical variation with distance from the vein was evaluated. As a result, elements which are compatible to alkali-chloride-rich fluid (Keppler, 1996) were added to the wall rock rather than melt compatible and chloride-free-fluid compatible elements (Keppler, 1996). This supports that the Grt-Hbl vein was formed by brine infiltration.

In addition to Na, K and Cl concentrations, some trace element concentrations of constituent minerals gradually decrease or increase with distance from the vein center and become constant. It is important to note that distances where the trace element concentrations become constant are dependent on elements, and not on mineral species. These decreasing/increasing trends show diffusion-like profiles with distance from the vein. Trace element zoning within each grain is small, and almost negligible compared to chemical variation with distance from the vein. However, Pl preserves discontinuous zoning in terms of anorthite content. Discontinuous boundary between Pl rim and mantle implies that the brine infiltration caused dissolution-reprecipitation process. The preserved sharp mantle-rim boundary compared to flat zoning profile of trace elements would be
explained by the sluggish NaSi-CaAl interdiffusion compared to the lattice diffusion of trace elements (e.g., Grove et al., 1984; Cherniak, 1995). It is likely that the brine infiltrated through the grain boundaries and altered the rim composition of minerals. Therefore, microstructure indicating dissolution-reprecipitation process, such as stepwise zoning of anorthite content of plagioclase, coexisting with Cl-bearing minerals may become an indicator of passage of brines. Field mapping of these microstructures would have a potential to unravel the large-scale distributions and movement of brines in the lower crust.

Keywords: brine, metasomatism, dissolution-reprecipitation, continental crust
U-Pb zircon ages younger than regional metamorphism obtained from gneissosse granitoids in the Mikawa area, Ryoke belt

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The Mikawa Belt is composed of high-temperature low-pressure metamorphic rocks and granitoids formed in the late Jurassic, and records magmatic activity along the eastern margin of the Asian continent. In the Mikawa Belt, gneissic granitoids are intruded continuously from the time of regional metamorphism [1], allowing observation of the long-term spatial-temporal variations in magmatic activity accompanied by the subduction of oceanic plateaux [1].

Gneissic granitoids in this area are divided based on rock type and intrusion relationship [2]. Among them, the gneissic gneisses associated with the ancient gneissic granitoids, such as the Shinya Tonnal granite and the Tatsukawa granite, are widely distributed in the area and are thought to have formed as a result of the heat source of the metamorphic rocks [3]. This is also supported by CHIME monazite ages (Mikawa metamorphic rocks, 102-98 Ma; Shinya Tonnal granite, about 95 Ma; Tatsukawa granite, about 91 Ma) [1] and the fact that most of the ancient gneissic granitoids are found to be distributed below the metamorphic rocks.

However, in the Mikawa Belt, gneissic granitoids in the Nishino region show U-Pb zircon ages that are younger than CHIME monazite ages by about 10 Ma [4]. The results of this study show that gneissic granitoids can be dated by LA-ICP-MS analysis.

The samples used in this study are from two Shinya Tonnal granite bodies and three Tatsukawa granite bodies. All of the samples show a gneissic structure that is consistent with the surrounding metamorphic rocks. The Fukuoka granite body is intruded into the most metamorphosed zukoku, azumaite of the area [5]. The Asami granite body is intruded into the quartz-feldsparite gneiss of the area [6]. These two granite bodies are not intruded into the metamorphic rocks.

For the above 6 samples, the U-Pb zircon ages obtained by LA-ICP-MS analysis are 77.5±0.6 Ma and 77.1±0.6 Ma for the Fukuoka granite body, and 81.1±1.0 Ma for the Asami granite body. The U-Pb zircon ages obtained for the Nishino granite body are 98.9±0.9 Ma and 99.4±0.9 Ma. These ages are interpreted to be the solidification ages of their respective rocks.

In the Fukuoka granite body, 92.2±6.0 Ma old CHIME monazite ages have been reported [1], which are younger than the U-Pb zircon ages obtained in this study. The difference in CHIME monazite ages and U-Pb zircon ages is still unclear.

The U-Pb zircon ages obtained for the Asami granite body are consistent with the CHIME monazite ages of the metamorphic rocks (102-98 Ma) [1], while the U-Pb zircon ages obtained for the Fukuoka granite body are younger than the CHIME monazite ages of the metamorphic rocks (87.4±0.2 Ma; 87.1±0.5 Ma) [7]. Therefore, it is unclear whether the gneissic gneisses intruded during the peak metamorphic period or whether the gneissic gneisses were intruded after the peak metamorphic period. Further, the U-Pb zircon ages of the Fukuoka granite body are younger than the CHIME monazite ages of the metamorphic rocks. Therefore, it is unclear whether the metamorphic rocks were intruded after the peak metamorphic period.

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Keywords: Ryoke belt, LA-ICP-MS, U-Pb zircon dating, Gneissose granitoid

[7] Nakajima et al., 2013, SHRIMP Workshop講演要旨.
領家帯は白亜紀の火山弧直下で形成されたのか？
Did the Ryoke belt form beneath the Cretaceous volcanic arc?

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西南日本のテクトニクスを論ずる上で大きな問題となるのが、白亜紀低温高圧型変成帯である三波川帯と高温低圧変成帯である領家帯が中央構造線を境に接している関係である。三波川帯は沈み込み帯の変成岩であり、領家帯は火山弧の地殻中下部で形成されたと考えられている。両者の間にarc-trench gapが存在したはずであり、その距離は今日の島弧-海溝系から考えて100km程度であったと推定される。そのように離れて存在していた両者を接合させるに至ったテクトニクスはどのようなものであったのか？それが本講演で議論する問題である。この問題に新たな切り口を与えたのが、Ito et al. (2009)である。彼らは地震波探査により西南日本の地殻構造を解明した。その結果、驚くべき事実が明らかになった。それはSSP（Seto Subsurface Prism）と称された領家帯のプリズム構造である。SSPは幅60km、深さ20kmに達する二等辺三角形の断面を示すプリズムで、南は中央構造線で三波川帯と接し、北は内帯のナップ群に漸移するように見える。このSSPの実態は地表では領家帯ならびに山陽帯の花崗岩類と変成岩類である。地下においても同様であると考えて良いであろう。中国・四国地方の領家帯は、南側（四国側）において塩基性岩が多く花崗岩中に産し（Nakajima et al., 2004など）、北側（山陽側）において産し、その変成度は北から南に増加する（Nakajima, 1994; Ikeda, 2004など）。領家帯の花崗岩類はチタン鉄鉱系列に属し、山陽帯から山陰帯へ向かって磁鉄鉱系列の花崗岩へと変化する（Ishihara, 1977）。従来の考えでは、領家帯は現在の中国地方に想定される白亜紀火山弧の地殻中下部で形成されたとされていた（Nakajima, 1994など）。講演ではその考えの矛盾を示す。以下では、領家帯の形成場に関してIto et al. (2009)の地殻構造断面に基づく新たな仮説を提示する。SSPの形態は、北米西岸のGreat Valley forearc basinに酷似している。SSPは本来、前弧堆積盆に相当する場所の堆積物であって、それが部分溶融によって花崗岩を形成したのではないか、というのが新たな仮説の骨子である。すなわち、領家帯は現在の位置（かつての前弧積層）においてin situに形成されたのではないか、という考えである。領家変成岩の原岩は、ジュラ紀付加体であることが知られているから、付加体の形成過程において、木村（1998）が議論したようなout-of-sequence thrustによって付加体の厚化が起こり、それは側方に発達して火山弧周辺でナップを形成するとともに、前弧においては厚い堆積層となったと推定される。SSPはそのようにして形成された前弧堆積層に相当する場所の厚い堆積物であると考えられる。部分溶融の熱源は、放射性壊変による熱と、領家帯南部に貫入している塩基性岩の熱が考えられる。このように堆積物の部分溶融によって領家変成岩が形成されたとする考えは、領家変成岩の大半がI-タイプであるという事実と矛盾するように見える。しかし領家変成岩の大半はチタン鉄鉱系列に属し、還元的な環境下で形成されており、堆積物の部分溶融や同化が花崗岩の形成に大きく寄与している可能性は高い。変成岩の形成圧力を考えると、現在の地表に露出している領家変成岩は、地下約15km程度まで埋没していたことが推定される。すなわち、現在のSSPよりさらに15km程度深い前弧堆積層に存在していたことが示唆される。そのように厚い堆積層は、下位の三波川帯の岩石に圧力をかけ、その上昇に寄与した可能性がある。また厚い堆積層はやがてアイソスタシーを保つために浮力によって隆起し、その上部が浸食削除されて、現在の変成岩が露出するに至った可能性がある。Ikeda, T. (2004) CMP, 146, 577-589. Ishihara, S. (1977) Mining Geol., 27, 293-305. Nakajima, T. (1994) Lithos, 33, 51-66. Nakajima, T. (2004) Trans. Royal Soc. Edinburgh, 95, 249-263. 木村（1998）地質学論集、50、131-146.

キーワード：領家帯、火山弧、対の変成帯
Keywords: Ryoke belt, volcanic arc, paired metamorphic belt

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粘性流体が浮力上昇する場合に形成される地殻スケールのパターンと、白亜紀中頃の北部九州における高温型変成帯と同時期に形成された地殻岩石の分布形態との比較を行った。地殻スケールの粘性流体シミュレーションでは、粘性流体浮力上昇パターンが、粘性率及び密度コントラストが小さい場合はダイヤピル状に、大きい場合は枝分かれした岩脈状になった。両者の遷移領域では、岩脈状と瘤状からなるパターンが出現する。このパターンはストックあるいはパソリス状深成岩体と類似している。シミュレーションでは下底部をゆっくり水平移動させている。粘性率及び密度コントラストが小さく、ダイヤピル上昇速度が水平移動速度と同程度の場合、水平方向へ引き延ばされた変成帯様の構造が形成された。このように、粘性率及び密度コントラストが大きくなるにつれ、浮力上昇する粘性流体のパターンが変成帯様、ダイヤピル状、瘤-岩脈状、岩脈状へと変化した。

一方、白亜紀中頃の北部九州の地層岩体分布から以下のことが言える。1)地殻浅部から深部（〜25km）まで、周防変成岩（智頭変成岩相当も含む）が分布していた。2)大量の珪長質深成岩パソリスが深度10km前後で周防変成岩に貫入している。3)北部九州南部の大牟田地域では、周防変成岩を原岩とし、深度20-25 kmで形成された高温型変成岩が露出している。4)北部九州北部では関門層群中に珪長質火山岩が挟在する。上記2)及び3)のジルコンU-Pb年代は107-97 Ma（珪長質深成岩類）と105.1±5.1 Ma（高温型変成岩）である（宮崎ほか、2014）。今回、関門層群珪長質火山岩のジルコンU-Pb年代測定を行い、111.6±0.8 Ma（桜野亜層群）と106.3±0.7 Ma（下関亜層群）の年代を得た。白亜紀中頃の北部九州では、火山岩噴出を伴う堆積盆、深成岩パソリス、高温型変成帯の形成が同時期に起こっていたことを示している。

高温型変成帯、パソリス状深成岩体、堆積盆堆積物に挟在する火山岩はいずれも、地殻深部からメルト、マグマ、メルト・固体の混合体が上昇してきたものである。シミュレーションの結果から、地殻深部でのメルトと固体岩石の分離が進まない場合は、粘性率及び密度コントラストが小さく、変成帯様の構造を生じながら部分溶融した変成岩がゆっくり上昇する。すなわち、火山弧から海溝側へのマントルの水平移流に引きずられて北部九州地殻深部に広範囲に高温型変成帯が形成されていた可能性が示唆される。一方、メルトと固体岩石の分離が進んだ場合、パソリス状深成岩体の貫入、あるいは岩脈状に上昇し火山岩として噴出する。シミュレーションでは、低密度低粘性流体の岩脈状上昇パターンを生じることが、その場合、粘性流体地殻の変形速度は極端に速くなる。実際の地殻はそのように速く塑性変形できない。現実的には、マグマが周囲の地殻を脆性破壊し、岩脈として上昇すると考えられる。加えて、巨大なパソリス形成域や高温型変成帯上昇域周囲には、地表面の相対的下降域が形成されると予想される。北部九州北部の関門層群はそのような下降域（堆積盆）に堆積した可能性がある。

引用文献：宮崎ほか（2014）日本地質学会第121年学術大会，講演要旨，p.70。

キーワード：地殻、変成帯、粘性流体、北部九州、高温型変成岩

Keywords: Crust, Metamorphic belt, Viscous fulids, Northern Kyushu, High-temperature metamorphic rocks
ざくろ石のケリファイト化に伴う物質移動ーその2: 内部応力によって生じた変成分化?

Material transfer in kelyphitization of garnet (part 2): metamorphic differentiation caused by the internal stress?

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ざくろ石が分解してケリファイトに転移するとき、長距離物質移動によりバルク組成が元のざくろ石から変化することはよく知られた現象である。このことからケリファイト化は物質の出入りを伴う開放系の反応であると従来考えられていた。我々はかつて、局所的にはバルク組成が変化するもののケリファイト全体平均組成としてはざくろ石組成に一致する、累帯構造を有するケリファイトを報告し、閉じた系における物質移動の例として報告した（小畑, 2014）。本講演では同じ素材を用いてこの変成分化のメカニズムをより具体的に考察する。エッセンスは体積増加反応と応力の進行によって生じると考えられる内部応力および応力勾配にある。使ったサンプルはスペインロンダ岩体に産するざくろ石輝巖（サンプル、R410）である。岩石はざくろ石、Alに富んだ斜斜輝石（Cpx）、斜長石（Pl、An60）と少量の石英からなるマフィックグラニュライトである。ざくろ石を置き換えるように発達するケリファイトは斜方輝石（Opx）、スピネル（Sp）、Pl、Cpxからなる細粒集合体（シンプレクタイト）であるが次の様な同心円的組成累帯構造を示す。すなわち内側は、Opx、Sp、Plからなり、組織的には斜長石マトリクス中に繊維状のOpxが整然と並んだマトリクス中にSp-Opxシンプレクタイトがバッチ状に散在するという2重構造を示す。外側はこのSp-Opxシンプレクタイトパッチの占める割合が多くなり斜長石は存在しなくなる。この外側に偏在するSp-Opxシンプレクタイト部には、局所的に極端に細粒のSp-Cpx-Opxシンプレクタイトが発達する。加えてSp-Opxシンプレクタイトの粗化した部分には少量のCpxも産する。これら様々な缶を含むケリファイトについては、電子線マイクロプローブで拡大ビーム径（3, 10ミクロン）を使い分けてバルク組成を求めたところ、内側のパルクはざくろ石組成よりもSi、Al、Caに富み、Mg、Feに乏しく、外側のSp-Cpx-Opxシンプレクタイト部の組成はその逆であり、両者を適当な比に混ぜると、Na以外は元のざくろ石組成に一致させることができるということが分かった。ざくろ石の分解反応は全体として

Grt → Opx + Cpx + An + Sp (1)

であるが、局所的には元素の出入りを伴う二つの交代反応（metasomatic reaction）の組み合わせで考えられるすることを示す。具体的には、ざくろ石分解反応はケリファイトとざくろ石境界部の第1反応前線で起きるはずであるが、これは固体ケリファイト殻に囲まれているので体積の自由増加は許されないので、応力の増大と物質の流出が起こることが考えられる。内側から外に向かって移動する成分は外周の第2の反応前線で再び反応して前にできていた斜長石を消費しSp-Cpx-Opxシンプレクタイトを形成したと考えられる。講演ではケリファイトのローカルパルク組成に基づいて各部における交代反応と物質移動を導出し、このような物質移動と変成分化は反応の進行によりケリファイト内に発生した応力と応力勾配によって引き起こされたという新しいモデルを提示する。

キーワード：ケリファイト、ざくろ石、物質移動、変成分化、内部応力、ロンダかんらん岩
Keywords: kelyphite, garnet, material transfer, metamorphic differentiation, internal stress, Ronda peridotite

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Determination of channel CO$_2$ contents in random cordierite crystals using Raman spectroscopy

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Cordierite is a common metamorphic mineral, which entraps volatiles such as CO$_2$, H$_2$O in its channel, consisting of six-membered rings of (Al, Si)O$_4$. Carbon dioxide is orientated linearly along the a-axis in cordierite channel, and therefore the peak intensity of CO$_2$ at 1383 cm$^{-1}$ obtained from Raman spectroscopy varies considerably depending on the crystal orientation of cordierite. Kaindl et al. (2006) has shown that the Raman spectral intensity of CO$_2$ band in crystallographically oriented cordierite grains can be used to estimate the CO$_2$ contents. These previous studies suggested the importance of applying a correction on the effect of crystal orientation for the determination of intrinsic contents of CO$_2$ in randomly oriented cordierite crystals. The purpose of this study is to reveal the relationship between Raman spectral patterns and crystal orientation of cordierite, and to construct a new method for the determination of CO$_2$ content in cordierite using Raman spectroscopy.

For the identification of crystal orientation of cordierite, euhedral cordierite crystals, from the volcanic ash deposit in the Takiga swamp, Gunma Prefecture, Japan were used to prepare crystallographically oriented thin sections, and examined in detail using micro-Raman spectroscopy. In addition, to examine the effect of crystal orientation to the intensity of CO$_2$ for its determination, two cordierite samples were analyzed. One is cordierite crystal from a pelitic cordierite-bearing from gneisses in the Kerala Khondalite Belt (KKB), southern India, and the other is a standard cordierite with known CO$_2$ contents (SH). Since Raman spectral intensity also depends on polarization of the incident laser, Raman spectra were obtained by rotating the sample at an interval of 10°. The crystal orientation of cordierite was cross-checked by using 5-axis universal stage and conoscopic figures.

Raman spectral patterns obtained for (001), (100) and (010) crystallographic planes change cyclically with the polarization of incident laser. We selected six peaks of cordierite (1: 554 cm$^{-1}$, 2: 575 cm$^{-1}$, 3: 670 cm$^{-1}$, 4: 970 cm$^{-1}$, 5: 1010 cm$^{-1}$, 6: 1180 cm$^{-1}$) for a detailed analysis. The intensity of peak-5 and peak-6 changed systematically when compared with other peaks, and so these peaks were used for the identification of crystal orientation. The intensity of peak-3 did not change and we used it as a normalizing peak for instrumental intensity variations. The intensity ratio of peak-5/peak-3 versus intensity ratio of peak-6/peak-3 ($I_5/I_3$ vs. $I_6/I_3$) in (001), (100) and (010) plane showed a linear relation. The value of other oriented cordierite crystals and random ones fell within this range. Therefore, it is possible to identify the crystal orientation of cordierite using the relation of $I_5/I_3$ vs. $I_6/I_3$. The cyclic patterns can be expressed mathematically using a combination of sine curves, where it is possible to determine the crystal orientation. Furthermore, the peak intensity of CO$_2$ for SH cordierite with known CO$_2$ contents also showed cyclic variations, similar to the periodicity of the peak-6 in the crystallographically oriented crystals. Accordingly, using the mathematical expression we could retrieve the maximum
peak intensity of CO$_2$ at 1383cm$^{-1}$ from a random crystal, which was then used for determining the CO$_2$ contents of unknown cordierite crystals.

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キーワード：堇青石、ラマン分光法、結晶方位、CO2定量
Keywords: Cordierite, Raman spectroscopy, Crystal orientation, CO2 determination
変成岩中の炭質物の見かけの格子面間隔d002とラマンR2パラメータの相関
Correlations between the apparent interlayer spacings d002 and the Raman R2 parameters of carbonaceous matters in metamorphic rocks

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堆積岩中の炭質物の格子面間隔d002は、変成程度の指標としてこれまで多くの研究がなされてきた。Itaya (1981)は、三波川帯の満見川に沿って変成度の上昇とともに見かけのd002値が減少することを指摘し、高見・西村（2000）は、広島県弥栄峡の玖珂層群中の炭質物の見かけのd002が、広島型花崗岩との接触境界に向けて減少すると報告している。また、千々和ほか（1993）も、山口県須佐地域の須佐層群中の炭質物の見かけのd002が、高山はんれい岩との接触境界に向けて減少すると述べている。一方で、Beyssac et al.（2002）は、炭質物のラマンスペクトルのR2パラメータを用いた地質温度計、T（℃） = -445 R2 + 641, を提案し、上記満見川沿いの三波川帯の変成温度解析を行った。

本研究では、上記3地域の変成岩中の炭質物のR2パラメータの測定を行い、上記の研究で報告された見かけのd002との比較を行った。その結果、R2パラメータは岩石ごとに標準偏差が大きいものの、その最頻値とd002は、R2 ≤ 0.75かつd002 < 3.60の範囲で良い相関を示すことが明らかとなった（Fig. 1）。

この相関は単純な双曲線関数、(R2 - a) (d002 - b) = k、で近似される。従って、これまで多く測定されてきた見かけのd002に対して、T（℃） = -445 (k / (d002 - b) + a) + 641で示される温度スケールを当てはめることが出来る。上記の条件を満たす全ての地域のデータでは、R2の漸近値（a）とd002の漸近値（b）およびkの値は、それぞれ0.95, 3.26, -0.064である（R² = 0.94）。また、満見川地域ののみでは、それぞれ0.96, 3.28, -0.058（R² = 0.94）、弥栄地域のみでは、それぞれ0.89, 3.27, -0.046（R² = 0.97）となるが、須佐地域ではほとんどの炭質物が上記の条件を満たさないため、これらを求めることは出来ない。

Beyssac et al.（2002）の地質温度計の適応可能範囲はR2 < 0.7であるため、上記の相関を地質温度計として使用するには、ほとんどの炭質物などのデータの回帰から求めた満見川地域のパラメータセットを用いた方が良い。

キーワード: 炭質物、d002、ラマン R2
Keywords: carbonaceous matter, d002, Raman R2
Fig. 1 Correlations between $d_{002}$ and $R^2$ of CMs in the A Semi (circle), Yasaka (square) and Susa (triangle) areas.
Preliminary results of the CM Raman geothermometry of the Kebara Formation and the proximal areas in the Kii Peninsula

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The Outer Zone of Southwest Japan in the Kii Peninsula is composed of the Sanbagawa metamorphic belt, the Mikabu belt, the Chichibu belt, the Kurosegawa belt, and the Shimanto belt from the north to the south (Kurimoto, 1986). In the Shimizu-Misato area of the Wakayama prefecture, components of above-mentioned five belts are exposed and the Mikabu belt disappears in the eastern part, where the Kebara Formation is exposed between the Sanbagawa metamorphic belt and the Chichibu belt. One of petrologic characteristics of the Kebara Formation is a common occurrence of lawsonite in both meta-mafic rocks and metapelites (Hada, 1967; Kurimoto, 1986; Tomiyoshi & Takasu, 2009), although surrounding geological units are free from lawsonite. Therefore, the attribution of the Kebara Formation is a lasting question for the researchers of the Kii Peninsula. Since thermodynamic approach for the low-grade metamorphic rocks has some difficulties, we applied carbonaceous material (CM-) Raman geothermometer for the metapelitic rocks of the Shimizu-Misato area including the Kebara Formation, Mikabu belt, Sanbagawa belt, Chichibu belt, and Shimanto belt, following the procedure of Kouketsu et al. (2014), which is developed for the low-grade metamorphic rocks covering 165-400 deg. C. We obtained a mean temperature of 318 deg. C for the Kebara Formation, which is comparable with that of the neighboring unit of the Mikabu belt (320 deg. C). On the other hand, the Sanbagawa belt of the Shimizu-Misato area shows the average temperature of 291 deg. C, which is slightly but evidently lower value within an apparent distance of a few kilometers. Temperatures obtained from the Chichibu belt of the relevant area yields about 283 deg. C, and the Shimanto area does the lowest of 212 deg. C. The estimated temperature of the Kebara Formation is equivalent to that of the Sanbagawa belt of the Ise area, eastern Kii Peninsula (316 +/- 5 deg. C: Ueno, 2001), which shows a gap with that of the Sanbagawa metamorphic belt of the Shimizu-Misato area. This temperature gap suggests that the Kebara Formation and the Sanbagawa metamorphic belt of the Shimizu-Misato area are not a coherent unit but in tectonic contact with each other. This fact is also suggested by the geochronological data: K-Ar/Ar-Ar age data of the Kebara Formation have a range of 103-89 Ma (Isozaki et al., 1992; Kurimoto, 1993; de Jong et al., 2000) while those in the Sanbagawa metamorphic belt of the Shimizu-Misato area mostly range 85-72 Ma with a few exceptions (Kurimoto, 1993; Kurimoto, 1995; Kurimoto, 2013). Compared to the Sanbagawa metamorphic belt in the study area, the metamorphic temperature and geochronological data of the Kebara Formation is similar to the Mikabu belt. The similarity in the CM-Raman geothermometry in addition to the previously investigated geochronological data possibly suggest that the Kebara Formation is correlated with the Mikabu belt.

Keywords: carbonaceous material Raman geothermometer, the Kebara Formation, the Sanbagawa belt, the Mikabu belt
Pressure-temperature-time dependence of structural evolution of CM to graphite: Implication for fast graphitization in metamorphic terrain

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The structural evolution of carbonaceous material (CM) to graphite is one of the most important thermal indicators for geological regimes of very low to medium metamorphic temperature. The process sensu stricto depended not only on peak metamorphism but also lithostatic pressure, tectonic deformation and catalytic effects. Some studies argued that the pressure dependence during graphitization was one of the most important factor to recrystallize from CM to graphite (e.g. Beyssac et al. 2003). However, the natural and experimental studies regarding the pressure dependence on graphitization are very limited.

We report here new experimental data on the structural evolution of CM to graphite at various pressures of 0.5 to 8 GPa at 1200 degree C for 1 hour. Natural CMs extracted from sedimentary rocks in the Shimanto accretionary complex and the Hidaka metamorphic belt transformed its morphology and crystallinity with increasing pressure. Both the starting materials were converted to a graphitic structure above 2 GPa, suggesting either the termination of crystal growth or only sluggish growth. Based on the results of pressure dependence, we compared the relation between the effective activation energies and experimental pressures by combining our results with previous studies. It was found that the effective activation energy empirically decreases with increasing pressure. The pressure dependence was given by:

\[ E_a = -71.66 \ln(P) + 789 \quad (R^2 = 0.98) \]

Thus we are able to express the effective activation energy \( E_a \) at any pressure conditions using the above regression curve. Combining the previous experimental data on thermal dependence of graphitization (Nakamura et al. 2015), the structural evolution of CM can be expressed by three different factors of pressure \( P \), metamorphic temperature \( T \) and duration \( t \):

\[ f(P, T, t) = C_{\text{min}} + (C_{\text{max}} - C_{\text{min}}) / \left\{ 1 + [ \frac{(A \exp(-71.66 \ln(P) + 789)/RT)/t]}{h} \right\} \]

where \( C_{\text{min}} \) and \( C_{\text{max}} \) are respectively the maximum and minimum values of each parameter, \( A \) the intercept of the Arrhenius plot, \( R \) the gas constant, and \( h \) is the reaction rate of the sigmoid function (named as the “Hill coefficient”). Based on the equation combining the thermal and pressure dependences, we attempted to extrapolate to the low-temperature condition (300-1000 degree C) at the pressures of 0.1 to 1 GPa (Fig.1). Detailed results between natural and experimental data will be discussed in the presentation.

Reference: Beyssac et al. (2003) EJM. Nakamura et al. (2015) AGU fall meeting abstract.
The chemical composition of minerals is generally controlled by several factors such as $P$-$T$ conditions and bulk composition. Barroisite (Brs) is an intermediate amphibole between glaucophane and tschermakite and its ideal chemical formula is \((\text{NaCa})\text{Mg}_3\text{Al}_2(\text{Si}_7\text{Al})\text{O}_{22}(\text{OH})_2\). In the Sambagawa belt of central Shikoku, Brs is reported from the higher grade zones, such as the Grt and Ab-Bt zones, and eclogite units. On the other hand, sodic-amphibole, winchite (Wnc), and actinolite (Act) are common in the lower grade zones such as the Chl to Grt zones and the Mikabu belt. In this study, we report the first finding of Brs in metabasite from the Kebara Formation in the NW Kii Peninsula, and discuss its significance. The Kebara Formation is an E-W trending geological unit, 5x1 km, exposed between the Sambagawa and Chichibu belts (Kurimoto, 1986). The Kebara Formation is mainly composed of metapelite with minor amount of lenses or layers of metabasite and siliceous schist (Kurimoto, 1986). Mineral assemblages reported from the Kebara Formation are quartz + albite + chlorite + phengite + lawsonite + calcite in metapelite and lawsonite + pumpellyite + actinolite or sodic-amphibole + pumpellyite + sodic pyroxene + epidote in metabasite (Kurimoto, 1986; Tomiyoshi & Takasu, 2005, 2009). These mineral assemblages are stable from a high-$P$ part of the pumpellyite-actinolite (PA) facies to a low-$P$ part of the epidote-blueschist facies. Although the Kebara Formation is regarded as the Mikabu belt (Kurimoto et al., 1998; Makimoto et al., 2004), its main lithology differs from that of other areas in the Mikabu belt. Brs-bearing metabasite was collected from a continuous, 30m-long outcrop along the Takino-gawa in the SW part of the Kebara Formation. The outcrop exhibits a change from metabasite in the north to metapelites in the south. The main foliation shows ENE-WSW strike and steeply dip to the south. Brs-bearing metabasite, more than 70 cm in thickness, occurs at the transition between metabasite- and metapelitic-dominated parts, and its main foliation is consistent with that of the surrounding rocks. Brs-bearing metabasite consists of mm-thick blue-green epidote-rich layers alternating with blue amphibole-rich layers. The blue-green layers are mainly composed of epidote, amphibole, chlorite, white mica, albite, and quartz with minor amount of titanite and apatite. The blue layers contain sodic pyroxene in addition to the above mentioned minerals. Many amphibole grains show a distinct zoning pattern characterized by a Brs core, a sodic amphibole mantle, and a Wnc rim with distinct compositional gap. In some amphibole grains, sodic amphibole and Wnc repeatedly appear at the margin of Brs. Various zoning types of amphibole were reported in the Sambagawa belt: Brs-hornblende(-Wnc)-Act from the Grt and Ab-Bt zones in the Asemi-gawa and Dozan-gawa areas, Brs-sodic amphibole-Wnc/Act from the Ab-Bt zone in the Saruta-gawa area (Otsuki & Banno, 1990; Y. Banno, 2000; Okamoto & Toriumi, 2004). Most of these zoning patterns are attributed to $P$-$T$ changes during the exhumation stage, i.e., a decompression with a significant cooling path in the Saruta-gawa area (Y. Banno, 2000) and an isothermal decompression path at an early stage of the exhumation in the Asemi-gawa and Dozan-gawa areas (Okamoto & Toriumi, 2004). The amphibole zoning pattern identified in this study is similar to that of the Saruta-gawa area except for the lack of hematite. This fact suggests that the study samples experienced the epidote-amphibolite facies prior to the PA facies. Multiple recrystallization can be explained by so-called Yo-Yo subduction
as reported in the Italian Western Alps (e.g. Rubatto et al., 2011).

キーワード：バロワ閃石、御荷鉾帯、毛原層、紀伊半島、苦鉄質変成岩、ヨーヨーサブダクション
Keywords: barroisite, the Mikabu belt, the Kebara formation, Kii Peninsula, metabasite, Yo-Yo subduction
北海道旭川市周辺の神居古潭変成岩のテクトニクスの再検討：ジルコンU-Pb年代と流体移動による接触変成作用

Appraisal of the tectonics of the Kamuikotan metamorphic rocks around the Asahikawa City, central Hokkaido: Zircon U-Pb ages and contact metamorphism by fluid migration

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北海道中央部に分布する神居古潭変成岩は中生代白亜紀の低温高圧型の変成岩であり、その北方延長はロシアのサハリン島に分布するとされている。Sakakibara and Ota(1994)は、その岩相、変成度、変成年代に基づいて、神居古潭変成岩を6つのユニットに区分し、それらを変成鉱物組合せにより3つの変成圧力タイプに分類した。各タイプごとの地温勾配と白雲母のK-Ar年代および40Ar-39Ar年代は、高圧1（HP1）の場合、地温勾配G = -10℃/km, 108-145 Ma、高圧2（HP2）の場合、G = -13℃/km, 91-107 Ma、高圧中間群（HI）の場合、G = -20℃/km, 50-84 Maである。近年報告されたジルコンU-Pb年代（Okamoto et al., 2014）によると、石狩川沿いのパンケホロナイ(Pk)ユニット（115-120 Ma）の方が、春志内（Hr）ユニット（100 Ma）よりわずかに古い砕屑性ジルコン年代を示していることが明らかになった。一方、石狩川の支流沿いのPkユニットから80 MaのジルコンU-Pb年代も報告されている（Nagata et al., 2015）。しかしながら、旭川市西方の神居古潭峡谷周辺のユニット区分・変成圧力タイプの分類にはいくつかの疑問が残されている。まず、各ユニットは本来スラストシートとして分布しているが、それらの年代分布は一定方向性を示さず、乱雑な分布を示している。次に、HIタイプに分類されるPkユニットのK-Ar年代とHP2タイプに属するHrユニットの年代が70-85 Maで重なっており（Okamoto et al., 2015）、砕屑性ジルコン年代よりも圧力タイプの分類とは合わない。三つ目に、隣接した試料の白雲母K-Ar年代が大きな年代差を示し、最大で数千万年の幅を持っている。以上の疑問と先行研究をまとめると、Sakakibara and Ota(1994)により定義されたPkユニットは、少なくともHrユニットに似た古いユニットとより若いユニットの2つのユニットに分けられる可能性がある。

本研究では、神居古潭変成岩のPkユニットが分布する石狩川、石狩川の支流、オロエン川およびパンケホロナイ川において、岩石学的、構造地質学的観察を行い、泥質変成岩や苦鉄質変成岩の変成鉱物組合せについて検討した。石狩川沿いの古いユニットは泥質および苦鉄質片岩、石灰質片岩、チャート起源の石英片岩から構成されていることに対し、南側の若いユニットは泥質及び苦鉄質片岩で構成されている。特徴的な変成鉱物としてローソン石が古いユニットでは産するが、若いユニットでは存在しない。これらの事実は、以前定義されたPkユニットは古いユニットと若いユニットに分けられるという考えを支持している。若いユニットの中でも、石狩川の支流沿いの苦鉄質岩中にはパンペリー石が産する一方、オロエン川沿いの苦鉄質岩中にはエピドートが産する。これらは、後者の地域の変成温度が前者の地域よりも高いことから、両地域の白雲母K-Ar年代（Iwasaki et al., 1995; Ota, 1999）は、後者の方が前者よりも傾向を示し、再結晶白雲母が後者の地域で優勢であると考えると、先述の変成温度の違いと矛盾しない。これらの温度と年代の空間的不均質は、流体の移動が起因であることを強く示唆し、流体に起因する接触変成作用の不均質を反映している可能性がある。

キーワード：神居古潭変成岩、テクトニクス、流体移動、ジルコンU-Pb年代、白雲母K-Ar年代、変成鉱物組合せ

Keywords: Kamuikotan metamorphic rocks, tectonics, fluid migration, zircon U-Pb ages, white mica K-Ar ages, metamorphic mineral assemblages
Metamorphic evolution of eclogites in the Alag Khadny metamorphic complex, Lake Zone, SW Mongolia

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The eclogite-bearing Alag Khadny metamorphic complex in the Lake Zone, SW Mongolia located in the central part of the Central Asian Orogenic Belt, consist mainly of orthogneisses which interleaving with marbles including lenses of garnet-chloritoid schists of Maykhan Tsakhir Formation. Eclogites occur as lenses or boudins in orthogneisses and marbles, and their peak metamorphic conditions have been estimated as 590-610°C and 20-22.5 kbar (Stipska et al., 2010). Garnet-chloritoid schists occur as lenses or layers within marbles, which lie in contact with eclogite bodies showing distinct lower P-T conditions than eclogite (Javkhlan et al., 2013).

Glaucophane-bearing and amphibolitized eclogite consists mainly of garnet, clinopyroxene, sodic, sodic-calcic and calcic amphiboles (Gln, Brs, Fprg, Ts, Fts, Fe/Mg-Hbl, Act) with subordinate amounts of epidote, phengite (Si 6.51-7.11 pfu), plagioclase, K-feldspar, chlorite, rutile, titanite and quartz. Garnets display a prograde zoning (Sps 9-1, Prp 5-19, Grs 27-31, -20), and the core of the garnets contains polyphase and discrete inclusions of amphibole (Trm, Prg, Ts) and plagioclase (An 37), and also contains aegirine-augite/omphacite (Jd 14-21), epidote, K-feldspar, rutile and titanite. The rim of the garnet contains omphacite (Jd 27-46), barroisite, phengite, epidote and rutile. Omphacite (Jd 27-46) in the matrix are zoned, increasing jadeite content from core to rim (Jd 27-46). Omphacites are partly replaced by symplectite of diopside/aegirine-augite/omphacite (Jd 25), Mg-hornblende and plagioclase (An 18). Amphiboles in the matrix are zoned with glaucophane core through barroisite mantle to Mg-hornblende rim, and the others are actinolite/barroisite core and hornblende to tschermakite rim coexisting with large plagioclase (An 18), which contains fragments of barroisitic amphibole and garnet.

Alag Khadny eclogites experienced multiple metamorphic events, i.e. precursor metamorphic event of relatively high-T/P metamorphism of amphibolite facies prior to eclogite metamorphism represented by pargasite/tschermakite and plagioclase (An 17) inclusions in the core of the garnets. The minerals in the matrix are representative of eclogitic metamorphism and the prograde path pass through the epidote-blueschist facies to the eclogite facies. P-T pseudosections were calculated in the NCKFMASHO model system and compositional isopleths of garnet suggest the peak metamorphic conditions of the eclogite as 590-620°C and 21-22 kbar and retrograded into 510-540°C and 9-11 kbar in the epidote-amphibolite facies. Zoned amphiboles in the matrix (Act/Brs core Hbl to Ts rim) and associated large plagioclases suggest another prograde metamorphism of medium-P conditions. Peak eclogitic metamorphic conditions are similar to those of Stipska et al. (2010), and they correspond to subduction type metamorphic conditions with lower geothermal gradient (8°C/km). Subsequent medium-P metamorphism together with garnet-chloritoid schists (560-590°C/10-11 kbar; Javkhlan et al., 2013) took place in the higher geothermal gradient (19-20°C/km), and this metamorphic event is correspond to continental collision type metamorphism.

⁴⁸Ar/³⁹Ar muscovite ages in the eclogites (543±3.9 Ma) within marbles and garnet-chloritoid schists (537±2.7 Ma) were determined (Stipska et al., 2010). K-Ar ages for eclogites (c. 600 Ma) within orthogneisses have been obtained by Javkhlan et al. (2014). These ages are interpreted as the exhumation ages for the eclogites and the garnet-chloritoid schists.
Keywords: eclogite, pseudosection modelling, garnet-chloritoid schist, Maykhan Tsakhir Formation, Lake Zone, SW Mongolia
Formation of secondary olivine after orthopyroxene during serpentinization: Evidence from the Hantaishir ophiolite, western Mongolia

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Serpentinization plays a crucial role on global water circulation, and causes significant decrease in density and seismic velocity of mantle peridotite. Typically, it advances along slow-spreading ridges, in bending faults during the onset of subduction zone, and wedge mantle in the subduction zone. Serpentine minerals brought into deep part of subducting zone, are broken down to release H₂O, which is thought to associate with intermediate-depth earthquakes and arc magmatism. Secondary olivine, which is usually interpreted to be formed by dehydration of serpentine, has been reported in several serpentinites from subduction zone. Recently, Plümper et al., (2012) found that a novel texture of the secondary olivine which formed after orthopyroxene via bastite formation. Although the hydration and dehydration processes of ultramafic rock are important on the H₂O budget within the subduction zone, the detail mechanism of secondary olivine formation is still poorly understood. In this study, we investigate serpentinization processes of ultramafic rocks from the Hantaishir ophiolite in Mongolia, and propose a new mechanism for secondary olivine formation after orthopyroxenes.

The Hantaishir ophiolite is located within the Central Asian Orogenic Belt (CAOB). It is located at the north of the Main Mongolian Lineament in the western Mongolia. The ophiolite composed of ultramafic rocks, pyroxenites and gabbro, sheeted dikes, pillow lavas, and pelagic sediments is strongly sheared and thrusted, but well-preserved ophiolitic sequence is partly preserved. It contains two ultramafic complexes, the Taishir and the Naran massifs. Geochemical study of igneous rocks indicates suprasubduction-zone origin (Matsumoto and Tomurtogoo, 2003).

Eighteen ultramafic rock samples were analyzed in detail by using optical microscope, EPMA, and raman spectroscopy. Most of the ultramafic bodies are intensively deformed, and completely serpentinized. Three samples in Naran massif preserve olivine as well as serpentines, spinel, magnetite, and brucite. Serpentine in these samples shows three occurrences; First one is fine-grained lizardite as a mixture with brucite in veins of primary olivine, Second one is chrysotile veins, cutting the all textures, and Third one is antigorite, which dominantly exists in matrix. We found the primary and secondary olivine. Primary and secondary olivine show contrasting Mg#, the former (0.92-0.93) and the latter (0.94-0.98). A plot Mg# of primary olivine vs Cr# (0.70-0.82) of spinel suggests that the ophiolite was formed at fore-arc setting within the subduction zone. It is noted that some secondary olivine exists as fine-grained aggregates. This aggregate looks replace large grain aligned fractures filled with antigorite which shows relatively high Al- and Cr-content. These observations suggest that secondary olivine aggregate was originated from orthopyroxene. Based on the similar textures, Plümper et al., (2012) suggested that bastite is formed after orthopyroxene and then a dehydration reaction occurs to the secondary olivine. In contrast, our sample does not the evidence for formation of bastite, and the secondary olivine and antigorite look formed at the similar stage. Therefore, we propose that the secondary olivine is directly formed by silica-releasing reaction after orthopyroxene, and the releasing silica is reacted with primary olivine to produce antigorite. In this mechanism, the secondary olivine could be formed during the hydration stage within subduction zone.

Keywords: microtextural-chemical evolution, Mg-rich secondary olivine
Backarc-like characteristics and their spatial distributions within serpentinized peridotites in the Mineoka belt, Boso peninsula

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We studied chemical compositions and crystal-preferred orientations of serpentinized peridotites in Mineoka belt, Boso peninsula, Honshu island, Japan. The chemical compositions of both olivine and spinel are in the range of the olivine-spinel mantle array of Arai (1994, Chemical Geology). Spinel Cr# can be divided into two groups: high Cr# (0.5-0.6) and low Cr# (0.3-0.4). Moreover, we found that olivine crystal-fabrics in these peridotites have two types along with the two chemical compositions: A type with the low Cr# to the west and D type with the high Cr# to the east of the Mineoka belt. The chemical compositions are compatible with those of Parece Vela Rift (Ohara et al., 2003, G3). We suggest that the peridotites in the Mineoka belt could be derived from backarc environment and they have not so dismembered at present, since both structural and petrological characteristics are correlated to their spatial distribution in the Mineoka belt.

Keywords: Mineoka belt, peridotite, chemical composition of mineral, olivine crystallographic orientation
Komperito-like growth of metamorphic minerals and microprobes of metamorphic fluid flow

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Grain growth of the metamorphic process is basically governed by precipitation from grain boundary thin fluid film and dissolution of preexisting minerals. Morphology of metamorphic minerals appears as a variety between euhedral and anhedral shapes, although it sometimes shows the irregular shape likely to amoeboid but not to dendrite. Amoeboid grains of garnet and albite are very common in the regional metamorphic rocks and are considered as unstable growth by coupling of growth from thin film of boundary solution and fluid flow along the thin film.

The similar grain growth from thin film of flowing solution reveals the Konpeito of sucrose and hails which show the spherical ball having many rounded horns (spikes). Such feature is considered to be derived from growth instability from flowing boundary fluid film (1).

In this paper, I will talk about the occurrence of Kompeito-like grains of garnet, albite, and quartz in the regional metamorphic rocks and discuss the robustness of the spacing of rounded horns on the cross section. He also suggests the possibility of microprobes of metamorphic grain boundary fluid flow inferred from the instability of Kompeito-like growth of these metamorphic minerals.

(1) Sakai I., and Y. Hayakawa, 2006, JPSJ, 75, 10, 104802

Keywords: Konmpeito-like growth, metamorphic minerals, grain boundary fluid