北海道旭川市周辺の神居古潭変成岩における上昇時の流体移動による重複変成作用

Metamorphic overprint of the Kamuikotan metamorphic rocks by fluid migration during exhumation around Asahikawa City, central Hokkaido, Japan

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Subduction zone is a place where fluid cycling occurs from surface through the lithosphere to the lower mantle of the Earth. However, for high-P/T metamorphic rocks in intermediated depths of subduction zone, fluid migration associated with metamorphism remains unclear. The Kamuikotan metamorphic rocks in northern Japan are the typical high-P/T metamorphic rocks in the world, formed by subduction during Early Cretaceous to early Eocene (Sakakibara and Ota, 1994). Around Asahikawa City, they have evidence implying thermal overprint which might have been caused by fluid migration. Kamuikotan metamorphic rocks in study area show relatively high geothermal gradient (Sakakibara and Ota, 1994), spatially heterogeneous distribution of K-Ar ages (Ota *et al.*, 1993; Ota, 1999; Iwasaki *et al.*, 1995) and pervasive development of quartz veins while high-P/T mineral assemblages recording prograde metamorphism were only locally preserved. The purpose of this study is to reappraise the tectonics of the Kamuikotan metamorphic rocks in respect of metamorphic overprint by fluid flow during exhumation. In this study, we conducted petrographic and mineralogical analyses for mafic rocks and Raman spectroscopy of carbonaceous material for pelitic rocks to elucidate the spatial center and effect of the thermal overprint. The mafic rocks contain lawsonite, pumpellyite along the Ishikari River, glaucophane, pumpellyite, actinolite and Na-pyroxene along the branch of Ishikari River, and epidote, actinolite along the Orowen River from north to south. chlorite exists in all of the analyzed metabasites. Six pelitic rocks were analyzed to infer the peak metamorphic temperature by using Raman CM geothermometer (Kouketsu *et al.*, 2014). The metamorphic temperature estimated from full width at half maximum of D1-band is approximately 313˚C from the Ishikari River, 300˚C from the branches of Ishikari River, 351˚C from the Orowen River, and 325˚C from the Pankehoronai River areas from north to south. Glaucophane and lawsonite are restrictively distributed in the northern part of this area and the overgrowth of actinolite on alkali amphibole indicates the Kamuikotan metamorphic rocks underwent metamorphic overprint (greenschist facies at 58 Ma; Ota, 1999) during exhumation. It is inferred that the effect of fluid migration was most intense around the Orowen River area within the study area. Further research is needed to determine the origin of fluid.

キーワード：神居古潭変成岩、テクトニクス、流体移動、変成岩の上昇、重複変成作用、ラマン分光法
Keywords: Kamuikotan metamorphic rocks, tectonics, fluid migration, exhumation, metamorphic overprint, Raman spectroscopy

EBSD analysis on coexisting omphacite and diopside found in aragonite-calcite vein form the Horokanai area, Kamuikotan metamorphic belt, Hokkaido

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Ca-Na pyroxenes are common in high pressure metamorphic rocks. While most of them have C2/c space group, omphacite (Omp), the intermediate composition between jadeite (Jd) and diopside (Di), has P2/n space group, because of cation ordering in M1 sites (Mg, Fe and Al), and M2 sites (Ca and Na). Two miscibility gaps are reported between Jd and Omp, and Omp and Di, as a result of the ordering (Carpenter 1980b), which takes place below the critical temperature ~750˚C (Carpenter, 1980b). In addition, degree of the ordering in Omp decreases as the Fe (II) and Fe (III) contents increase, and finally, Fe-rich Omp has disordered C2/c space group (Carpenter, 1980b; Cámara et al., 1998). Matsumoto & Hirajima (2005) proposed a possible phase boundary between the P and C lattice in eclogite facies rocks (~700˚C) based on natural and synthetic data of Carpenter and Smith (1981), Cámara et al. (1998) and Boffa Ballaran et al. (1998), i.e., P lattice field for less Fe (III) (< 15%) Omp. However, Carpenter (1980a) reported P lattice space group for Fe (III)-rich (>20%) Omp in an epidote-blueschist collected from the Franciscan Complex. These data suggest the P lattice field also expands with the decrease of metamorphic temperature.
In this study, we report possible space group of coexisting Omp and Di found from a pale green vein in the Horokanai area of the Kamuikotan metamorphic belt. Shibakusa (1989) subdivided the relevant area into three zones, from zone I (Lawsonite-BS facies) to zone III (Epidote-BS facies) with the increase of grade. The host rock of the pale green vein is an epidote amphibolite, collected from the amphibolite block at the Horokanai Pass. The sample is mainly composed of epidote, Ca-amphibole and rutile which are partly replaced by muscovite + chlorite, Na-amphibole and titanite, respectively, suggesting the BS-facies overprinting on the epidote amphibolite as described by Imaizumi (1984). A pale green vein (~1 cm width), white veins (~1 mm width) and yellowish green veins (~1 mm width) are developed in the studied amphibolite. The pale green vein mainly consists of Omp, Di, calcite, aragonite, albite and apatite. White veins consist of calcite, aragonite and albite. Yellowish green veins consist of pumpellyite and chlorite. All aragonites are surrounded by calcites. Furthermore, the composition ranges of vein forming minerals are equivalent to those of zone II or zone III of Shibakusa (1989), thus the vein-forming conditions can be estimated as 250-350 ˚C and 7-10 kbar.
Ca-Na pyroxenes in the pale green vein show the wavy extinction and their grain sizes are of ~0.5 mm and growth faces dominantly lie parallel/perpendicular to the c axis. EBSD analysis suggests that Omp and Di constituting the hour-glass texture have the same orientation with the phase boundary parallel to the c axis. Three domains are recognized in Omp based on the contrast of back scatter electron (BSE) image, strongly correlated with Al/Ca contents. Their domain boundaries are curved and diffused and banding structures with ~1 μm width are observed in Omp domain in BSE image. The banding structures with ~1 μm width are also observed in Di. In spite of the existence of micron-scale zonings in Omp and Di, EPMA analysis gave Jd30-40Acm15-25Di38-55 for Omp and Jd4-8Acm9-15Di77-95 for Di. This compositional gap between Omp and Di is almost identical to those reported by Carpenter (1980a) and Tsujimori (1997) for BS facies (~300˚C) conditions.
Fe (III) component of Omp analyzed in this work is almost the same as the composition reported by

Carpenter (1980a) pointed out P lattice space group for Omp with Fe (III) rich (~20 %) based on TEM study. However, Kikuchi patterns obtained from our Omp with similar Fe (III) content with the Omp of Carpenter (1980a) are best fit to C2/c Di. Further study is needed to evaluate the ferric component effect on the space group of the Omp.

キーワード：オンファス輝石、秩序状態、神居古潭帯
Keywords: omphacite, ordering state, Kamuikotan belt

神居古潭帯江丹別峠地域の変成分帯の再検討
Revisiting of metamorphic zonal mapping in the Etambetsu Pass area, the Kamuikotan belt, Hokkaido.

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沈み込み帯におけるローソン石の形成・消滅過程は沈み込み帯での流体活動を考察する上で重要な要素である。沈み込む過程でローソン石が分解する変成帯の一つである三波川変成帯において、Yoshida et al. (2015)は地下15－60kmで変成した岩石中に捕獲された流体包有物は海水並の高Cl濃度とともに高Li/Cl比（>0.001）を示し、それらはスラブ由来とされる有馬型熱水の特徴の一つ (風早ほか, 2014）と一致することを見出した。上記の特性が沈み込み帯流体の普遍性であるか否を検討するためには、他の低温高圧型変成帯での検証が必要である。

北海道の神居古潭変成帯幌加内－江丹別地域もその一つである。Shibakusa (1989)は、I帯(ローソン石青色片岩相)からIII帯(緑簾石青色片岩相)へと変成度が上昇する変成分帯を提案した。その一方で、今泉(1984)や小俣・渡辺(1992)達は“III帯はテクトニックブロックであり周囲の変成岩とは不連続である”との考えを提示した。さらに、皆川・平島（2012）や平島ほか（2016）はShibakusa (1989)のII帯において、緑簾石とアルカリ角閃石で構成される主片理面を包有して成長しているローソン石を発見し、Shibakusa(1989)が提案した累進変成作用の考え方に疑問を提示した。さらに、Sakakibara & Ohta (1994)は幌加内－江丹別－峡谷地域の変成岩の白雲母のK-Ar年代に基づき、形成年代が最も古い幌加内ユニット（135－120Ma）、美瑛春志内ユニット（115－100Ma）、年代が最も若い斑渓幌内ユニット(80-50Ma)との分帯を提案した。この様に当該地域の形成史については未だに統一的な見解が得られていないのが現状である。

本報告では、道道72号線の江丹別峠から南北にそれぞれ約3kmの範囲で採集した試料のlow-variantな変成鉱物組み合わせの空間変化に基づいて、新たな変成分帯を提示する。この調査範囲はShibakusa (1989)のI帯とII帯、Sakakibara & Ohta (1994)の美瑛春志内ユニットと幌加内ユニットに相当している。

当該地域の主岩相は泥質変成岩でチャートや塩基岩が層状・レンズ条に産する。主片理面の走向は東西性で南北にそれぞれ40度程度ばらつくが、主として、北側に10－45度程度傾斜している。調査対象の大半の岩石にローソン石が認められるが、緑簾石は調査地域の北端約1kmの範囲に限られる。緑簾石の認められる地域はShibakusa (1989)のII帯、あるいは、Sakakibara & Ohta (1994)の幌加内ユニットに相当し、緑簾石が出現しない地域は、Shibakusa (1989)のI帯、Sakakibara & Ohta (1994)の美瑛春志内ユニットに相当する。

石英、アルバイト、緑泥石を含む塩基性変成岩中において、緑簾石が出現しない地域では、Lws+Napx±Pmpの組合せが卓越し、ローソン石青色片岩を特徴づける鉱物組合せである、Lws＋Namp＋Pmp、あるいは、Lws＋Namp +Napxは、II帯との境界付近にのみ出現する。同様の鉱物組み合わせ変化は、九州黒瀬川帯の箱石地域で認められており、このような鉱物組合せの変化は、Ca-Al-Fe3-(Fe+Mg)の4成分系において、以下の吸水反応が累進的に進行したことによって説明されている(Sato et al., 2017)： Pmp+Napx＋Chl = Lws + Namp＋H2O （１）

この新知見は、江丹別峠付近の、Shibakusa (1989)のI帯とSakakibara & Ohta (1992)の美瑛春志内ユニットは、Lws+Napx+Pmp亜帯とLws+Namp亜帯に区分でき、見かけ上位に向かって変成圧力が上昇したことを示唆している。

江丹別峠北方の緑簾石を含む試料に卓越する鉱物組み合わせは、Ep+Namp+Pmp+Lws+Chl（7/16）で、他に２試料ずつにEp+Lws+NampとEp+Namp+Pmpを認めた。これらの組み合わせはEp +Pmp+Chl = Lws +Namp＋H2O （２）の反応の周辺で安定である。Sato et al (2017)が提案したPetrogenetic gridでは、上記２つの反応の安定領

域の間には温度圧力ギャップが存在する。従って、江丹別峠のローソン石帯と緑簾石帯は構造接触関係にあると考えるのが妥当で、本研究結果は、今泉(1984)、小俣・渡辺(1992)、Sakakibara & Ohta (1992)達の考えを支持する。

キーワード：変成分帯、ローソン石青色片岩、神居古潭帯
Keywords: metamorphic zonal mapping, Lawsonite blueschist, Kamuikotan belt

紀伊半島北西部毛原層から見出された異地性岩体の多様性と分布
The extent and variety of exotic rocks identified from the Kebara Formation, NW Kii Peninsula

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The metamorphic zoning in the regional metamorphic belt can be defined as area in which a particular mineral or suite of minerals is predominant or characteristic(s) reflecting the original rock compositions, the pressure and temperature of formation, and the duration of the metamorphism (e.g., Jackson, 1997). If we found rocks with some of different nature to the metamorphic zoning, the earth scientists generally try to consider its reason and it becomes a long term controversy in some case, e.g., the origin of tectonic blocks of blueschist and/or eclogite in direct contact with greywacke or serpentinite in the Franciscan complex (e.g. Colman and Lanphere, 1971).
Metabasites with barroisite (Brs) + epidote (Ep) assemblage, which is stable under higher-*T* (>450 ºC: Kato and Hirajima, 2017), have been recognized in the SW part of the Kebara Formation (KF), the southern margin of the Sanbagawa belt, NW Kii Peninsula, of which peak metamorphic temperatures for pelitic rocks, which are main lithotype of the KF, are <340 ºC estimated by the stability conditions of diagnostic minerals (Tomiyoshi and Takasu, 2009) and by the Raman spectra of carbonaceous material (RSCM) geothermometer (Yoshida et al., 2016). This study describes the mode of occurrence and mineralogy of metamorphic rocks exposed nearby the Brs-bearing metabasites and discusses its tectonic significance.
Brs-bearing rocks are identified from a metabasite layer in N-S striking 30 m-long outcrop. The dominant schistosity in the outcrop strikes ENE-WSW and dips steeply to the south, which is consistent with that of the main schistosity in the KF. No clear fault-bounded contact is observed in the outcrop. Following three rock types are recognized in this layer; A) weakly schistose metabasite rich in relict pyroxene, B) metamorphosed mixtures of volcaniclastic materials and pelagic sediments characterized by distinct schistosity and the high modal amount of phengite accompanying with relict pyroxene, and C) basic schist whose schistosity is mainly defined by the arraignment of amphiboles, Ep and chlorite (Chl).
A/B) type rocks occupy the northern half of the out crop and most of them contain pumpellyite (Pmp) + Chl + Ep assemblage, which is the identical assemblage with the previous report (Kurimoto, 1986), suggesting the Pmp-actinolite facies metamorphism.
C) type rocks mostly occupy the southern half of the outcrop and they can be distinguished into two types based on the composition of amphibole: C1) Brs-Ep schist and C2) glaucophane (Gln)-Ep schist.
C1) type rocks are recognized from two parts; i.e., from more than 2.5 m and 70 cm thick layers. The mineral assemblage and the zoning structure of representable minerals of the 2.5 m thick layer are identical with those in 70 cm layer as reported in Kato and Hirajima (2017).
C2) type rock is recognized from 7 m thick layer exposed to the north of the 2.5 m thick Brs-Ep schist. All analyzed Gln are rich in Al content [$Y_{Fe} = Fe^{3+} / (Al + Fe^{3+}) = 0.00 – 0.30$] with constant Fe-Mg ratio [$Fe^{2+} / (Mg + Fe^{2+}) \sim 0.40$], and some grains are rimmed by actinolite. Ep is Fe^{3+}-rich composition ($Y_{Fe} = 0.27 – 0.34$). Al content of Gln associated with Ep increases with the metamorphic grade (e.g. Hosotani & Banno, 1986), and those of C2 type rock are equivalent to or higher than those in the garnet zone of the Sanbagawa belt in central Shikoku, suggesting the higher-*T* than 350 ºC.

These data indicate that most basic schists in the southern half of the outcrop underwent higher-*T* metamorphism than those of the KF. Such occurrence of these basic schists can be interpreted as tectonic blocks or olistostromes, because the irreversible nature of RSCM geothermometry suggests that the pelitic schist of the KF never experienced temperatures higher than ~350 ºC. Further geological and geochronological studies are requested to interpret the origin of these exotic rocks, which will shed a light on the material cycling in the shallower part of the subduction zone.

キーワード：異地性岩体、毛原層、三波川変成帯
Keywords: exotic rock, Kebara Formation, Sanbagawa metamorphic belt

On the origin of high temperature metamorphism within a magmatic arc: the case of the Cretaceous Ryoke belt (Japan)

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Magmatic arcs, located at convergent plate boundaries, are sites of crustal deformation, widespread plutonism and high temperature (HT) metamorphism. Our task is to reveal how these intricate events relate in space and time, and how heat transfers and large-scale tectonics contribute to the genesis of HT conditions within the arc crust.
The Ryoke belt (Japan) is a ca. 800 km-long association of Cretaceous magmatic and metamorphic rocks which gives direct access to the upper-middle crust of a former continental arc setting. Across the belt, a regional HT metamorphic gradient is defined by paragenetic zones that lie parallel to the main foliation of metamorphic rocks and gneissose granitoids. This gradient is opposed to localized contact metamorphic aureoles that are ascribed to later, massive plutons. By summarizing structural/petrological observations and new U–Pb zircon ages obtained in the western (Yanai) and central (Aoyama/Mikawa) parts of the Ryoke belt, we try to constrain the origin of HT metamorphism within this former magmatic arc.
(1) Deformation across the belt was polyphase, with distinct episodes of horizontal extension and shortening (Yanai), or of variable intensity (Mikawa; Adachi & Wallis, 2008).
(2) Metamorphic mineral growth, when correlated with the deformation history, appears to have been polyphase as well. Importantly, pre-tectonic porphyroblasts are observed in both areas. Syn-tectonic assemblages, assuming they were not reoriented by deformation, define the regional gradient while post-tectonic minerals are frequent.
(3) The reported U–Pb zircon ages of HT metamorphic conditions decrease from west (~100 Ma, Yanai) to east (~90 Ma, Aoyama; Kawakami *et al.*, 2013 / ~87 Ma, Mikawa; Nakajima *et al.*, 2013), indicating that the so-called regional metamorphic event was diachronous.
(4) With respect to HT metamorphism, some granitoid intrusions are older; these are usually the shallowest plutons that are not only gneissose but also massive (Skrzypek *et al.*, 2016).
(5) Although some gneissose plutons are broadly coeval with HT metamorphism (Yanai), some others can be significantly younger (Mikawa; Takatsuka *et al.*, 2017).
(6) The latest stage of voluminous plutonic activity was also diachronous and occurred without apparent deformation; its age decreases from west (~80 Ma, Yanai) to east (~70 Ma, Mikawa; Takatsuka *et al.*, 2016).
The upper-middle arc crust clearly experienced heating before, during and after the main phase of regional deformation. The importance of heat advection by granitoids is obvious; we may additionally suggest that the oldest, shallow intrusions potentially acted as a hot lid which facilitated the thermal maturation of the crust. However, we emphasize that regional HT metamorphism is not always spatially and temporally associated with plutonism. This underlines the role of heat conduction, the source of which can be found at the base of the crust where prolonged HT conditions and partial melting are needed to sustain the protracted magmatic activity (105–80 Ma, Yanai; 99–70 Ma, Mikawa). Therefore, there must have been a large-scale process (oblique ridge subduction or lateral mantle upwelling?) which was able to generate diachronous HT conditions along the base of the arc crust. Yet, was it the same process which led to the much younger, magmatic flare-ups associated with relative tectonic quiescence?

References:
Adachi & Wallis, 2008. *Island Arc*, 17, 41–56. Kawakami et al., 2013. *Contrib. Min. Pet.*, 165, 575–591.

Nakajima *et al.*, 2013. *Geol. Soc. Japan Meeting Abstract Vol.,* 51. Skrzypek *et al.*, 2016. *Lithos*, 260, 9–27. Takatsuka *et al.*, 2016. *Geol. Soc. Japan Meeting Abstract Vol., 68*. Takatsuka *et al.*, 2017. *Island Arc*, submitted.

Keywords: magmatic arc, high temperature metamorphism, Ryoke belt

浮力による高温型変成帯の上昇
Rising of a high-temperature metamorphic belt due to buoyancy

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白亜紀の高温型変成作用で特徴付けられる領家(深成変成)コンプレックス（以下領家コンプレックス）は日本列島を東西に約1000km連続する．最近，領家コンプレックスの西方延長と考えることができる高温型変成岩を北部九州大牟田地域で発見した．ここでは三畳紀の高圧型周防(変成)コンプレックスを原岩として高温型変成岩が形成されている(Miyazaki et al., submitted)．大牟田地域の高温部は広くミグマタイトが分布する．地質温度圧力計による低温部と高温部の圧力差は地質学的に現在観測できる層厚の違いでは説明できず，低温部とミグマタイトが発達する高温部の間で変成帯の薄化が起こっていたと推定された(Ikeda et al., accepted)．

高温型変成帯の下部では部分溶融が起きており，メルトが存在していたはずである．また，高温型変成帯下部における片理に調和的に貫入する花崗岩類も変成作用の応力場でのメルトから固結を意味する．メルトは固体岩石より密度が小さく，それ自体浮力により上昇する．しかし，珪長質メルトは大きな粘性のために容易には固体岩石から分離して上昇できない．従って，メルトと固体岩石の混合体が上昇を開始する可能性が指摘できる．

この可能性を探るため，密度差のある粘性流体の上昇シミュレーションを行った．シミュレーションでは地殻をホスト粘性流体と仮定した．周囲より密度が小さい上昇粘性流体を部分溶融した高温型変成帯に見立てた．ホスト粘性流体と上昇粘性流体の密度差だけを考えた場合，上昇粘性流体はダイアピルとして上昇できる．しかし，温度勾配がある場合，上昇粘性流体は途中で冷却され，ホスト粘性流体との密度差がなくなった時点で上昇はストップしてしまう．シミュレーションの結果，下底において絶えず上昇粘性流体が生産されれば，下底にあった粘性流体は浮力を失ったあとも上昇できることが分かった．浮力を失ったあとの粘性流体は，垂直方向の圧縮と水平方向の引っ張りにより薄化が起こる．シミュレーションの結果は，部分溶融した高温型変成帯が薄化を伴いながら地表付近まで上昇できることを示している．この機構が成り立つためには，地殻下部で数10 Myrの間，メルトを生成できるようなエネルギーの供給が必要となる．北部九州では112-98 Maの間に火成作用が継続したことが深成岩，火山岩のジルコンU-Pb年代測定から推定される．高温型変成帯の浮力による上昇を起こすだけのエネルギーのインプットが北部九州では起こっていた可能性を指摘できる．

キーワード：高温型変成帯、上昇、領家
Keywords: high temperature metamorphic belt, rising, Ryoke

九州中央部肥後変成岩（白亜紀高温低圧型変成岩）の超高圧変成作用の新証拠

New evidence of ultrahigh-pressure metamorphism in the Cretaceous low *P/T* metamorphic terrane, Higo Metamorphic Rock, Central Kyushu, Japan

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九州中央部に位置する白亜紀高温低圧型変成岩である肥後変成岩からダイヤモンド・石墨集合体（DGA : diamond-graphite aggregate）を発見した．DGAには３つの産状がある．一つはスピニフェックス様組織を示す変成カンラン岩中のクロミタイトに含まれる包有物であり，これについてはすでに報告した（Nishiyama et al, 2014）．今回新たに泥質片麻岩中のザクロ石に含まれる包有物として，また含ザクロ石角閃岩中の鉱物としてDGAを見出した．マイクロダイヤモンドを含むクロミタイトについては，mantle migration model (Arai, 2010)が提唱されており，その産出のみでは変成岩全体が超高圧変成作用を受けたことの証拠にはならない．しかし，今回泥質片麻岩と含ザクロ石角閃岩からDGAが発見されたことにより，肥後変成岩が超高圧変成作用を受けた後，白亜紀の高温低圧変成作用を重複して受けたことが明らかになった．なおDGAを確認したすべての薄片はダイヤモンドペーストを用いずに作成（Al_2O_3ラッピングシート使用）し，カーボン蒸着はしていない．

問題の泥質片麻岩は，甲佐岳周辺（川越・平・坂谷）の3か所で確認した．いずれも菫青石・ザクロ石帯（Obata et al., 1994; Miyazaki, 2004）に属する．これらの岩石中のザクロ石は肉眼で見ても，黒色のコアとピンク色のマントルから構成される二重累帯構造を示す．この種のザクロ石は肥後変成岩分布地域の各地で産するが，同一露頭においても，層の違いで単一累帯構造のザクロ石と二重累帯構造のザクロ石を産することが多く，その産出条件は全岩化学組成にも依存していると推定される（石丸ほか，2015）．DGAはザクロ石のコアに10 μm程度の粒子として産し，板状の形態を示すものが多い．マントルには産しない．金蒸着によるEDS分析ではCが確認され，ラマンスペクトルでは1335 cm^{-1}のダイヤモンドのバンドと1580cm^{-1}(Gバンド）ならびに2680cm^{-1}(S1バンド)の石墨のバンドを示す．この特徴は西彼杵変成岩中のDGAと酷似している．ただし，ダイヤモンドのバンドの波数が西彼杵変成岩中で1330 cm^{-1}であるのに対し，やや高波数側にシフトしている．また西彼杵変成岩中のDGAが1 μm程度のものが多いのに比べ，やや粗粒である．またSEM-SXES法により，これらの粒子は場所によりsp^3とsp^2が混在していることが確認され，ダイヤモンドと石墨の混合物であると判断した．

ザクロ石コアにはルチルの包有物が放射状に含まれているが，コース石は確認できていない．またマントルには石英の包有物が含まれている．

含ザクロ石角閃岩は砥用町川越の沢に産するもので，長径1m, 短径50 cmほどの岩塊として泥質片麻岩中に産する．一見転石のようにも見えるが，この20年間，度重なる洪水にも拘らず動いていないので，露頭と判断している．角閃石（マグネシオホルンブレンド）と黒雲母を主体とし，少量の斜長石を含む．局所的に径数mmのザクロ石を含んでいる．ザクロ石はアルマンディン質でX_{Mg} = 0.16，X_{Ca} = 0.17であり，累帯構造を示さず均質である．このザクロ石は周囲からシンプレクタイト（斜方輝石＋アノーサイト）に分解している．シ

ンプレクタイトの斜方輝石は多くの場合，緑泥石に変質しているが，変質を免れた組成はX_{Mg} = 0.47のフェロシライトである．Alの含有量は0.02 apfu程度と少ない．ザクロ石・角閃石温度計は450 °C程度の温度を，ザクロ石・斜方輝石温度計は640 °C (500 MPa)～670 °C (1GPa)程度の温度を示す．このことは450 °C程度の温度で平衡にあったこの岩石が，200 °C程度の温度上昇を経験し，これによりザクロ石が分解してシンプレクタイトを形成したと推定される．DGAはこのシンプレクタイト中に100 μm程度の粒状物質として産する．ザクロ石中には産しない．金蒸着によるEDS分析ではCが確認され，ラマンスペクトルでは1335 cm^{-1}のダイヤモンドのバンドと1580cm^{-1}(Gバンド）ならびに2680cm^{-1}(S1バンド)の石墨のバンドが確認される点は，泥質片麻岩中のDGAと全く同じである．SEM-SXES法により，これらの粒子は場所によりsp^3とsp^2が混在していることが確認され，ダイヤモンドと石墨の混合物であると判断される点も同じである．

以上，4カ所の2種の岩石からDGAが確認されたことから，肥後変成岩が超高圧変成作用を受けた後に白亜紀の高温低圧型変成作用を受けたことは確実と思われる．ただし，コース石がなぜ見つからないのかは理解できず，今後の検討課題である．肥後変成岩の重複変成作用に関してはOsanai et al. (2006)の先駆的研究がある．彼らは変成カンラン岩に伴うサフィリングラニュライトを発見し，250 Maの超高温変成作用の可能性を指摘した．今回，DGAを含むザクロ石コアがいつ形成されたのか，年代学的情報はない．この点も検討課題である．

キーワード：肥後変成岩、超高圧変成作用、ダイヤモンド石墨集合体、ラマンスペクトル、軟X線分光法
Keywords: Higo Metamorphic Rock, ultrahigh-pressure metamorphism, diamond-graphite aggregate, Raman spectrometry, Soft X-ray emission spectrometry

Inverted Metamorphism across the Main Central Thrust constrained by metamorphic P-T condition, western Himalaya, India

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Evolutionary signatures of active mountain building tectonic process as a consequence of collision between Indian plate and Tibetan plate are well preserved in the Himalayan metamorphic rocks. Southward thrusting of high grade metamorphic rocks (amphibolite to granulite facies) of Greater Himalayan Sequence (GHS) over low grade (greenschist facies) Lesser Himalayan Sequence (LHS) cause an inverted metamorphic field gradient across Main Central Thrust (MCT) (Arita, 1983; Vannay and Hodges, 1996). A geological map of the study area along Madhmaheswar Ganga valley, Rudraprayag district, Uttarakhand, India is prepared. In order to understand the inverted metamorphism in the study area, it is important to analyze how *P-T* conditions inferred from the phengite chemistry and garnet zoning pattern change with increasing structural level across the MCT. In this study area, hangingwall block of north-easterly dipping MCT mainly consists of paragneiss with intrusive body of leucogranite within the lower GHS (~1.5 km thickness) and footwall is generally termed as MCT Zone (~4 km thickness) comprised of augen gneiss and micaceous quartzite with some intercalations of amphibolites. An inverted Barrovian sequence is persistent from biotite zone through garnet zone upto kyanite zone where garnet-in isograd lies just beneath the MCT.

In this study, chemical analysis including garnet line profile and elemental map for major elements such as Ca, Fe, Mn, Mg and composition of matrix minerals is carried out by electronprobe microanalyser. Further, we have employed average *P-T* method (Holland & Powell, 1994) by using Thermocalc program (ver. 3.36) for thermobarometry. Garnets from uppermost MCTZ and lowermost GHS are characterized by growth zoning with consistently decreasing X_{Mn} content (from core to rim) suggesting the grain growth during burial with increasing *P* and *T* (Spear *et al.*, 1990). On the other hand, most of the garnet porphyroblasts in the lower GHS exhibit flat profile of X_{Mn} with little increase of it at rim. So, this kind of diffusional zoning profile signify retrograde reaction during exhumation and cooling of the lower GHS rocks (Florence & Spear, 1991). Higher rate of diffusion of major elements at higher elevated temperature than that of growth zoning cause homogeneous distribution of these elements. Tschermak substitution [$(Mg, Fe2+)^{vi}$, $Si^{iv}=Al^{vi}$, Al^{iv}], between solid solution end members of dioctahedral micas is good indicator of metamorphic condition (Guidotti, 1984). In low grade metamorphic rocks, phengite composition changes from celadonite-rich mica towards idealized muscovite composition with increasing temperature (Guidotti and Sassi, 2002). Decrease of octahedral Fe+Mg content with increasing tetrahedral Al content in the order of 1 a.p.f.u. (11 oxygen basis), towards structural high, indicate the extent of tschermak substitution from biotite zone to kyanite zone. However, there is an abrupt decrease of Fe+Mg and Si content at the base and top of the MCTZ which could support the presence of Munsiari thrust and MCT, respectively. Peak *P-T* condition of 594 ±19 ˚C and 9.4 ±1 kbar is estimated from garnet + quartz + chlorite + plagioclase + biotite + muscovite ±ilmenite assemblage in uppermost MCTZ rocks. In contrast, lowermost GHS experienced peak *P-T* condition of 687 ±31 ˚C and 11.9 ±1.2 kbar attained by the peak metamorphic assemblage of garnet + quartz + plagioclase + muscovite + biotite ±kyanite ±ilmenite ± rutile. Thus, it is estimated that a steep inverted pressure gradient of 16.4 ±1.3 kbar km^{-1} persist between uppermost MCTZ sample and lowermost GHS sample which could suggest that MCT activity exhumed GHS from deeper level than MCTZ rocks. Further, it has to be determined whether very low Si

concentration in phengites in direct proximity to the major thrusts correlate with the effect of low-*P* or high-*T*.

Keywords: Himalayan metamorphic rocks, Main Central Thrust, Inverted metamorphism, Tschermak substitution, Peak P-T conditions

Metamorphic process of the Tromso Nappe in the Scandinavian Caledonides based on P-T-t history of felsic gneiss

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Zircon grains have a potential to retain UHP minerals as inclusions, such as Coe and Jd, from the later stage overprint (e.g., Tabata et al., 1998). Therefore, the comprehensive study on Zrn is a potential tool to determine the exact spatial distribution and the formation timing of UHP belt. The Scandinavian Caledonides formed by continental collision between Laurentia and Baltica during the Ordovician to the Devonian, and are composed of a stack of several nappes. The Tromsø Nappe is traditionally ascribed to the Uppermost Allochthon (i.e., the uppermost tectonostratigraphic unit in the Caledonian nappe stack), containing abundant eclogites and ultramafic rocks within the host felsic gneisses, schists, marbles and calcsilicate rocks. UHPM conditions were reported from eclogites at two localities (Tonsvika and Tromsdalstind) as well as Dia-bearing gneiss hosting UHP eclogite at Tonsvika (e.g., Ravna & Roux, 2006; Janák et al., 2013). However, the country rocks hosting eclogites and peridotites have not been investigated in detail with respect of P-T conditions except of older work by Krogh et al. (1990). Therefore, we carried out petrological and Zrn geochronological study on felsic gneiss from Holmevatn, where Cr-rich eclogite and garnet peridotite were investigated previously (Ravna et al., 2006; Janák et al., 2015), recording P-T conditions up to 2.8 GPa and 800˚C, close to UHPM. Felsic gneiss shows an augen texture characterized by cm-size Pl porphyroclasts in the gneissose matrix mainly composed of micas, mm-size Grt and Qtz. Si-content and Mg# of Ms are homogeneous in each grain (6.14-6.41 for O=22 basis and 0.60-0.74, respectively). X-ray mappings of representative Grt grains show a zoning structure, such as Ca-poor (Grs9-15) and inclusion-rich (including Ky) inner-core, Ca- and inclusion-poor outer-core and Ca-rich rim (Grs18-26). The Ca-rich rim is absent from the most grains of Grt. Outline of inner core shows an irregular shape, suggesting that some garnet was partially resorbed before the outer-core formation stage. Most Pl grains show a zoning from Ca-rich (An26-33) core to Ca-poor (An15-25) rim. The Zrn grains also show zoning structures composed of oscillatory zoned core, thin dark mantle and bright rim in CL image, and include Qtz, Ms, Bt and Ap in the core. The LA-ICPMS U-Pb Zrn dating gives the concordant ages of 2800-950 Ma for the core and 490-430 Ma for the rim. The Zrn core shows high Th/U ratio (> 0.10), the HREE over LREE and Ce positive and Eu negative anomaly, suggesting the magmatic origin (e.g., Hoskin & Ireland, 2000). The Zrn rim shows low Th/U ratio (< 0.10), depleted HREE and negative Eu anomaly, suggesting the metamorphic origin in the Pl stability field. The age spectra of the Zrn core are similar to those of the East Greenland Caledonides (e.g., Watt et al., 2000), suggesting the studied rock could be derived from the Laurentia but also detrital zircons from the Laksefjord and Gaisa Nappes indicating Baltican origin (e.g. Gee et al. 2017). The Zrn rim ages overlap with the previous report of Corfu et al. (2003) using ID-TIMS (e.g., U-Pb Zrn age of 452.1 +/- 1.7 Ma from eclogites and U-Pb Ttn ages of 451-448 Ma). Zr-in-Rt thermometry and GASP barometry give 640-700˚C and 1.5-1.7 GPa for the Grt and Pl cores. The same thermometry and Grt-Hbl-Pl-Qtz barometry give 550-570 C and 1.1-1.2 GPa for the rim pairs. The P-T conditions of the Grt core stage are similar to those of D1 stage in metapelite reported by Krogh et al., (1990). Above mentioned results from conventional thermobarometry

and zircon composition suggest that felsic gneiss probably did not experience UHPM, but crystallization of metamorphic zircon during exhumation cannot be excluded (e.g. Kohn et al., 2015). Moreover, all analyzed inner–rims of garnet (Grs18–20) show no Eu anomaly, suggesting formation in the absence of Pl, at eclogite facies conditions.

キーワード：カレドニア造山運動、U-Pbジルコン年代、REEパターン
Keywords: Caledonian Orogeny, U-Pb zircon age, REE pattern

Amorphous SiO_2 phase in a pseudomorph after coesite in garnet of a Su-Lu ultrahigh-pressure eclogite

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Coesite has been identified in continental collision-related metamorphic rocks and serves as a critical indicator of ultrahigh-pressure (UHP) metamorphism. Coesite grains and their pseudomorphs effectively preserve geological and mineralogical information, which is useful for understanding the exhumation process of UHP belts. Although the pseudomorphs after coesite included in robust phases are generally composed of polycrystalline α-quartz grains, occurrences of K-feldspar in these pseudomorphs have also been reported. The mineralogical data of polyphase pseudomorphs are insufficient, and their origins are not well understood.
By using a Focused Ion Beam (FIB) system, Transmission Electron Microscopy (TEM), and Raman spectroscopy, pseudomorphs after coesite in a garnet of a Sulu UHP eclogite obtained from Yangzhuang, Junan region, eastern China, were carefully examined in this study. Anomalous pseudomorphs consisting of amorphous SiO_2 (APSI) and K-bearing fibrous phases were noted; the existence of an APSI phase in UHP rocks has not been reported previously. In this presentation, we report on the crystal chemical features and nano-textural characteristics of the pseudomorph.
The eclogite sample includes garnet porphyroblasts mostly 1 mm in diameter or larger. These garnet grains are composed of inner and outer segments with the boundary marked by discontinuous changes in the grossular content. The pseudomorphs occur within only the outer segment of the host garnet, and radial cracks have developed in the garnet around them. These pseudomorphs are divided into darkly colored and transparent areas under plane-polarized light, which are dominant mainly at the core and in the marginal parts, respectively. The transparent area is composed of fine-grained α-quartz crystals. The darkly colored area consists of fine-grained aggregates of an SiO_2 phase and a fibrous phase including K and Mg. The Raman spectra of the SiO_2 phase in the darkly colored area do not show definitive Raman bands. The fibrous phase has a broad Raman spectrum and does not show a distinctive Raman band.
The TEM observation of a cross-section of the pseudomorph shows that the internal structure consists of a worm-like SiO_2 phase and fibrous parts. The selected area electron diffraction (SAED) analyses of most parts of the worm-like SiO_2 phase did not show diffraction spots, suggesting a non-crystalline state. In addition, the SAED analysis of fibrous minerals shows weak ring patterns with corresponding d-values of approximately 4.8, 4.3, and 2.5 Å. According to these d-values and Energy Dispersive X-ray Spectrometry (EDS) analysis data, the fibrous minerals were identified as polycrystalline sheet-silicates (KFSS). This study also discusses the origin of the pseudomorph consisting of APSI and KFSS phases and implications on the behavior of metamorphic fluid during the retrograde stage

キーワード：コース石の仮像、非晶質SiO2相、蘇魯超高圧エクロジャイト、TEM観察
Keywords: Pseudomorph after coesite, Amorphous SiO2 phase, Su-Lu UHP eclogite, TEM observation

Spacial distribution of garnet associated with foliation in the Sanbagawa metamorphic rocks, Kanto Mountains, Japan

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Reconstruction of the local thermal structure within metamorphic rocks are important since the thermal structure shows the deformation regime during the exhumation of the terrain. The deformation regime of the Sanbagawa metamorphic rocks of the Kanto Mountains have long been controversial, whether it is one plastic continuous body or it is composed of several parts separated by faults or thrusts. One of the key must lie in the area where apparent isograd is outcropped. Most of the Nagatoro area is categorized as the zone I by Hashimoto et al. (1992), which is the lowest metamorphic grade zone and is equivalent to the Chlorite Zone defined in the Shikoku Area of the Sanbagawa Metamorphic Belt. Zone I is defined by the mineral assemblage without garnet. Appearance of garnet is the index of zone II, which is the second lowest metamorphic grade zone defined in this area. Several outcrops in this area are known as being the zone II rocks since they show the mineral assemblage including garnet. Hashimoto et al. (1992) interpreted the appearance of garnet as being the result of the brittle structural deformation such as faults and thrusts. In that case, the local occurrence of garnet means that the area shows discontinuity in metamorphic grade, and the discontinuity results from juxtaposition of different grade rocks through some thrusting. However, raman spectrometry of the carbonaceous material indicated no gap in the metamorphic temperatures between the samples with and without garnet from the same outcrop. In this study, spacial distribution of garnet within an outcrop several tens of meters long was determined.
Mineral assemblage was quartz, plagioclase, muscovite, chlorite. Not all the samples had garnet, calcite, titanite, and zoisite. Carbonaceous material was also included in many of the samples. 36 of the 55 samples included garnet in its mineral assemblage. Garnet grains were small, most of them with diameters 50 to 100 micrometers. Most of the garnet grains were euhedral and were found within the relatively mafic layers within the pelitic metamorphic rocks which were mostly composed of muscovite. Chlorite was often associated with garnet.
Occurrence of garnet was not at random, but seemed to form groups with lenticular or tabular distribution. The lens (if it was a lens) was subparallel to the foliation, which is known to be subparallel to the lithologic boundary in this area. Spacial distribution of garnet occurrence seemed to form lenticular or tabular groups subparallel to the lithology.
Chemical analyses of garnet using EPMA showed that the garnet grains were normally zoned, exhibiting euhedral growth of the crystal. Mn (spessartine) content was quite high (<50 Xsps). Some of the grains lacked part of the outermost rim, indicating resorption of garnet grains, but not in large amount. No evidence of large retrograde metamorphism was found. It is explained that the garnet grains started to grow during the last stage of the prograde metamorphism. Those cores were formed and started to grow but the growth did not last long because the grains are all so small compared to the proper garnet grains from the garnet zone.
The sharp euhedral chemical zoning profile indicates that the garnet grains were not kept hot for long time. Spacial distribution of garnet was probably controlled by the lithology parallel layers, namely the bulk rock chemistry.
Reference
Hashimoto et al. (1992) Journal of the Geological Society of Japan. 98, 953-965.

キーワード：garnet、bulk rock chemistry、distribution
Keywords: lithology, Sanbagawa metamorphic belt, temperature

珪線石のAl/Si秩序度に着目した最高変成温度の推定
Estimation of maximum metamorphic temperature from Al/Si-order parameter in sillimanite

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The polymorphs of Al_2SiO_5 (andalusite, kyanite, sillimanite) are valuable for metamorphic rocks as indicators of pressure and temperature. Moreover, crystal structure and micro-texture of sillimanite can provide more detailed information about thermal history. For example, Raterron *et al.* (2000) observed the micro-textures in sillimanite, which were formed by the partly transformation to mullite ($Al_2(Al_{2+2x}Si_{2-2x})O_{10-x}$, $x \cong 0.17–0.59$) at high temperatures. Furthermore, Zen (1969) and so on suggested that Al/Si-distribution in TO_4 tetrahedra of sillimanite should become continuously disordered with adding temperature. Although this Al/Si-disordering, in particular, has a possibility of a powerful geothermometer, the quantification of Al/Si-order parameter has been never succeeded. Recently, Igami *et al.* (JpGU, 2016; 2017) successfully determined the Al/Si-order parameter from micrometric region by HARECXS (High Angular Resolution Electron Channeling X-ray Spectroscopy, *e.g.* Soeda, 2000) method using TEM-EDS and obtained the relationship between the Al/Si-order parameter and temperature. In this study, HARECXS experiment was applied to natural sillimanite from metamorphic rocks, and the maximum metamorphic temperature of analyzed sillimanite was estimated.

Analyzed samples were sillimanite from Rundvågshetta, Lützow-Holm Complex, East Antarctica (sample No. RVH92011102A), and that from Mt. Riiser-Larsen, Napier Complex, East Antarctica (sample No. TH96123009). Both regions are assumed to be the UHT metamorphic regions (*e.g.* Kawasaki *et al.*, 2011; Hokada, 2001). No characteristic textures were observed in these sillimanite by optical microscope and SEM. Ultrathin sections were prepared from these sillimanite using focused ion beam (FEI Quanta 200 3DS or Helios NanoLab 3G CX), and then observed and analyzed by TEM-EDS (JEOL, JEM-2100F, JED-2300T).

In RVH92011102A, no characteristic textures were observed, and HARECXS analysis showed that the Al/Si-order parameter converged on ~ 0.88. In TH96123009, on the other hand, abundant anti-phase boundaries (APBs) were observed, and HARECXS analysis showed that the Al/Si-order parameter slightly converged on around 0.90, but widely distributed ranging from ~ 0.6 to ~ 0.9.

Generally, Al/Si-order parameter are assumed to have the lowest value at the peak temperature and to become somewhat higher during cooling. The HARECXS results of RVH92011102A implies that the peak temperature is > 1000 ℃ by comparison with those of experimentally heat-treated sillimanite (Igami *et al.*, 2016; 2017). This temperature is consistent with previous estimates (*e.g.* Kawasaki *et al.*, 1993; 2011; Harley, 1998; Fraser *et al.*, 2000). On the other hand, the lowest Al/Si-order parameter obtained from the HARECXS results of TH96123009 is ~ 0.65, and this value implies that the peak temperature is much higher than RVH92011102A. However, this low Al/Si-order state is thought not to be formed by stoichiometric disordered sillimanite and to be formed by the transformation from mullite + SiO_2 to sillimanite, because mullite has similar framework with sillimanite and its Al/Si-distribution is disordered. The APBs observed in TH96123009 is also thought to be formed at the same time. Therefore, the peak temperature of this sillimanite is assumed to be above the transition temperature between sillimanite and mullite + SiO_2, ~1200 ℃. This result provides further constraint on previous estimates, > 1100 ℃ (Harley

and Motoyoshi, 2000; Hokada, 2001).

キーワード：珪線石、Al/Si秩序度、地質温度計、ナピア岩体、高角度分解能電子チャネリングX線分光法、透過型電子顕微鏡
Keywords: sillimanite, Al/Si-order parameter, geothermometer, Napier Complex, HARECXS, TEM

Pressure dependence of structural evolution of CM: Implication for fast graphitization in subduction zone

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We report here new kinetic experiments in the pressure range of 0.5 to 8 GPa at 1200˚C for 10 min to 24 hours. Natural CMs extracted from sedimentary rocks in the Shimanto accretionary complex (SM) and Hidaka metamorphic belt (HMB) changed their morphology and crystallinity with increasing pressure. The time-pressure relations of each crystal parameter by X-ray diffraction and micro-Raman spectroscopy demonstrated sigmoidal transformations from an amorphous to a graphitic structure, suggesting the pressure-induced recrystallization at constant temperature (1473 K). Utilizing the relationship between log rate constant (ln$k$) and pressure (atm), we obtained the activation volumes of −22~− 44 cm^3/mol during graphitization using a power rate model and a Johnson-Mehl-Avrami-Kolmogorov model. Combining the activation volumes and data on Nakamura et al. (2017), the structural evolution of CM based on experimental kinetic model can be expressed by three different factors of pressure P(MPa), metamorphic temperature T (K) and duration t (min):
$f(P, T, t) = C_{min} + (C_{max} - C_{min}) / \{1+[((-22P+286686)/RT)/t]^h\}$,
where C_{min} and C_{max} are the maximum and minimum values of each parameter, respectively, A is 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”). It is thus possible to calculate the progress of graphitization at any P-T-t conditions during metamorphism. Utilizing the kinetic model, we tried to compare the experimental model based crystallinity of CM with natural metamorphic P-T-t conditions. In the case of Hidaka metamorphic belt, the natural CMs along the field P-T path of HMB proceeded structural evolution of CM from around 350 ˚C and form a graphite at around 450 ˚C. On the other hand, calculated structural evolution of CM started to recrystallize at around 400 ˚C, and form graphite at over 500 ˚C in a duration of ca.10 million years. Although there still exist some factors for fully understanding the natural structural evolution of CM to graphite, the experimental kinetic model can be applicable as a thermal indicator in a wide range of P-T conditions between 0.5 and 2 GPa at 400~800 ˚C. The most important implication of our finding is that natural CM in crust has proceed fast recrystallization from an amorphous to a graphitic structure by temperature and pressure compared with the laboratory at 1 atm. Our data provide a new kinetic model for not only geothermometry but also geospeedometry and geobarometry in subduction zone.

キーワード：炭質物、石墨化、化学反応速度論、高温高圧実験
Keywords: Carbonaceous material, Graphitization, Chemical kinetics, HPHT experiments

Progressive mélange formation during subduction: The Makimine mélange in the Shimanto accretionary complex of eastern Kyushu, southwest Japan

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Mélanges are commonly observed in accretionary complexes. However, the origin of mélange has remained controversial. Detailed field and microstructural studies of the Makimine mélange in the Late Cretaceous Shimanto accretionary complex of eastern Kyushu have revealed the progressive mélange formation during north-northwest directed subduction at the thickly sedimented convergent margin. The mélange preserved the ocean plate stratigraphy composed of basalt slabs in the argillaceous matrix, brown tuff, and mixed sandstone and mudstone, in ascending order. The mélange was imbricated at least two times possibly due to a duplex underplating after subduction. Early deformation in the mélange was recorded in the upper part of thrust sheets and is marked by mixing and layer-parallel shear of partially lithified sandstone and mudstone, resulting in the sandstone blocks in the mudstone matrix with mud intrusions and disaggregated sandstone blocks. These features suggest the deformation under elevated pores pressure beneath the décollement. Late deformation in the mélange occurred in middle to lower parts of thrust sheets and is characterized by stretching, and layer-parallel extension and shear of lithified sediments under the operation of pressure solution creep, resulting in development of stretching lineation, boudined layers, and composite planar fabrics with pressure solution seams. Basalt slabs were incorporated into the mélange during late deformation. Kinematic indicators consistently show the north-northwest directed shear from early to late deformation that is perpendicular to the general strike of the mélange. Overall, the mélange recorded the margin-perpendicular subduction-related deformation, with its distribution and deformation mechanisms spatially and temporary changed with depth.

蛇紋岩メランジの作り方　ー北海道三石蓬莱山の例ー
A recipe of serpentinite melange in Mitsuishi Horaisan, Hokkaido.

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高圧変成岩塊を含む蛇紋岩メランジは，プレート境界で形成され上昇してきたと考えられる．しかし，プレート境界でどのような構造を持っていたか，それは地表まで上昇する間に保存されているのかは，充分に検討されていない．本発表では，北海道神居古潭帯の三石蓬莱山蛇紋岩メランジの産状観察に基づき，その形成過程を考察する．

蓬莱山メランジは，角閃岩類やアンチゴライト蛇紋岩，塊状の蛇紋岩～かんらん岩のブロックを多産する．ざくろ石角閃岩から見積もられるピーク変成条件はおよそ650℃ 1.1 GPaと，沈み込み帯としてはかなり高温な部類に属する．当メランジは，ボニナイトを伴う160 Maの軍艦山オフィオライトの構造的下位に隣接するため，角閃岩類は高温ウェッジマントル下に沈み込んだスラブの断片と推察される．以下に，産状や組織観察から推定される形成過程を記す．

ステージ1（緑簾石角閃岩相）：ウェッジマントル下に緑簾石角閃岩化したスラブが沈み込む．変形はスラブ（緑簾石角閃岩）に集中し片理を形成したが，かんらん岩はほとんど変形しなかった．

ステージ2（緑簾石曹長石角閃岩相）：角閃岩は部分的に後退変成を受ける．かんらん岩にはアンチゴライトの脈が生じたほか，部分的に塊状アンチゴライト岩となる．角閃岩には網状剪断面が生じ，ブロック化が進行．角閃岩に外接するかんらん岩を置換して，アクチノライト岩が生じる．かんらん岩中にもアンチゴライト片岩やトレモライト岩の網状剪断面が形成される．この時期はかんらん岩や角閃岩の内部はほとんど変形せず，反応縁やこれを起源とする網状剪断面沿いに歪が集中した．

ステージ3（青色片岩相）：角閃岩中にアルカリ角閃石が生じる．この時期のかんらん岩の状態は不明．角閃岩は変形しなかった．コヒーレントな青色片岩ユニットが底付けし，メランジは既にスラブから離れていたと推定される．

ステージ4（極低変成度）：かんらん岩が低温蛇紋石化．角閃岩ブロックの周縁部は低温の反応縁を生じる．かんらん岩は低温蛇紋石化し，塊状のブロック部と葉片状の剪断帯（現在の基質）に分化．

各ステージでの岩石組織から，主要な歪を担ったのは，ステージ１では角閃岩，２ではアクチノライト岩やアンチゴライト片岩，３？～４では蛇紋岩と考えられる．ステージ１～２では，かんらん岩や角閃岩の岩塊ないしスラブが，薄い反応縁起源の剪断帯（アクチノライト岩）を介してスタックした構造をとっていたと推定される．蛇紋岩を基質とする現在の姿はプレート境界で形成されたものではなく，上昇・冷却後の二次的な特徴と思われる．

キーワード：蛇紋岩メランジ、沈み込み帯、アクチノ閃石岩
Keywords: serpentinitei melange, subduction zone, actinolite rind

南西インド洋海嶺Prince Edward Transform 断層のかんらん岩ウルトラマイロナイト～トランスフォーム断層下マントルの含水剪断変形～
Peridotite ultramylonites derived from Prince Edward Transform fault, Southwest Indian Ridge: evidence of hydrous shearing in the lithospheric mantle

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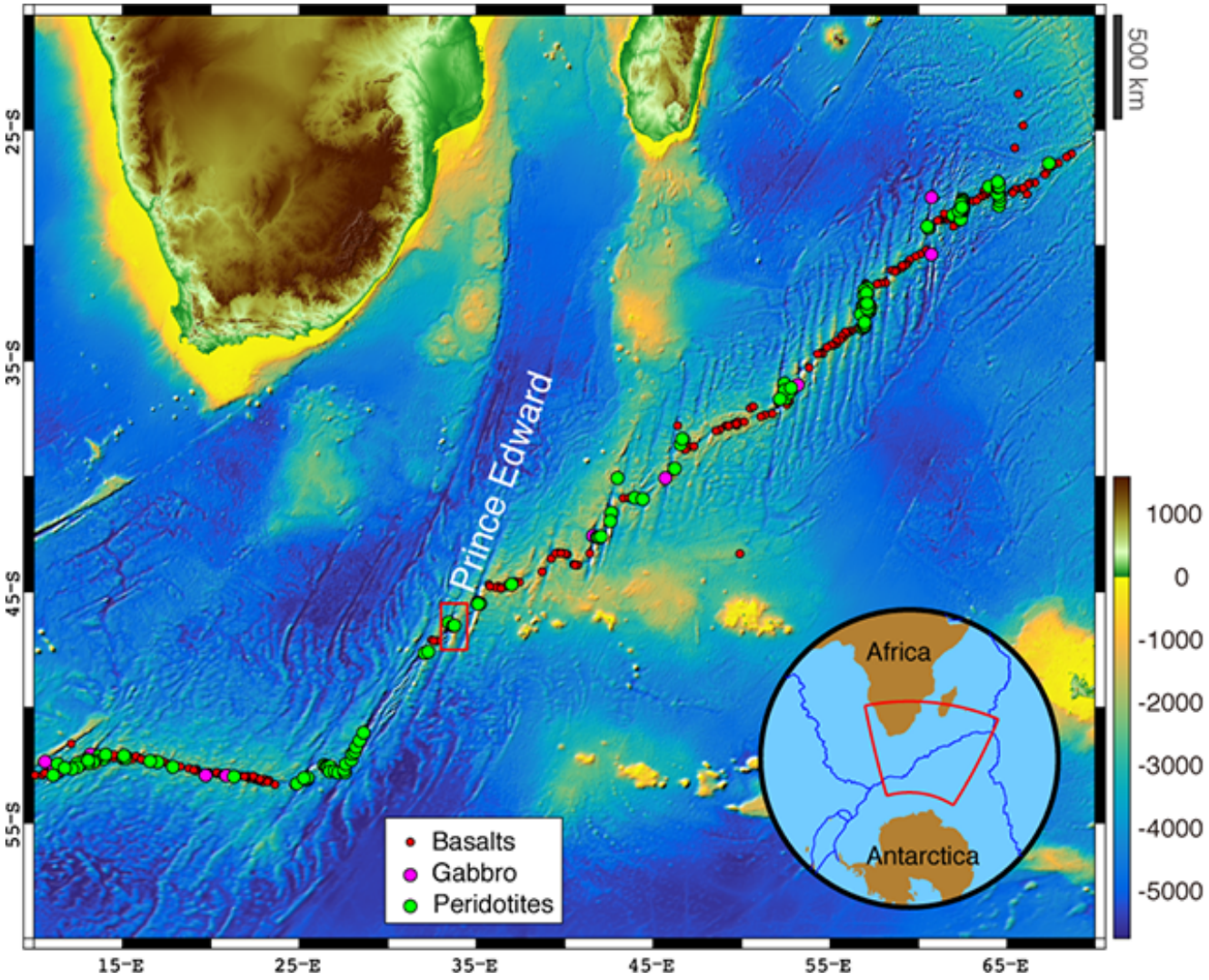
南西インド洋海嶺はインド洋の3つの海嶺の会合点であるロドリゲス三重点の南西に位置し，世界的にも拡大速度の遅い超低速拡大海嶺である．本研究では，1983年のPROTEA5航海において南西インド洋海嶺のプリンスエドワードトランスフォーム断層で採取されたかんらん岩21試料の微細構造解析を行った．

本研究に用いたかんらん岩にはかんらん石，斜方輝石，単斜輝石，スピネルが含まれ，一部角閃石を含む試料も存在した．EPMAによる主要元素組成分析の結果，ほとんどの試料の組成がマントル起源のかんらん岩であることが分かった．角閃石にはトレモライトとmagnesiohornblendeが存在することが分かった．

薄片観察から本研究に用いた21試料は，それぞれの微細組織に基づいてほとんどの部分が粒径3~5μmの細粒基質からなるウルトラマイロナイト，粗粒結晶と細粒基質からなる不均質な組織の試料，カタクレーサイト，蛇紋岩化が進行した試料の4通りに分類できた．これらのうち，ウルトラマイロナイトと不均質な組織の試料の組織から，角閃石はかんらん岩の変形前か変形開始初期に形成されたと考えられる．不均質な試料には，輝石やスピネルのブーディン構造が見られるものがあった．角閃石を含むかんらん岩の結晶方位ファブリックはB，Eタイプ，角閃石のないかんらん岩の結晶方位ファブリックはA，Dタイプであった．

上記の結果は，トランスフォーム断層下のマントル流動が水の影響を受けていた可能性を示している．また，トランスフォーム断層からマントルへ水の移動が起こっていることが示唆される．



環伊豆地塊蛇紋岩帯葉山ー嶺岡帯かんらん岩の構造岩石学的特徴とIBM前弧かんらん岩との類似性

Petrophysical characteristics of peridotites in Hayama-Mineoka belt of Cirmum-Izu serpentinite zone and their similarities to IBM fore arc peridotites

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We present petrophysical characteristics of serpentinized peridotites obtained from Hayama belt in Miura peninsula and Mineoka belt in Boso peninsula. The peridotites are dominantly harzburgites with minor lherzolite. Olivine grain sizes within the peridotites are ranged from coarser grains (>3mm) to medium grains (~1mm) and show undulose extinctions as well as kink bands. Orthopyroxene grains have exsolution lamellae. The chemical compositions of both olivine and spinel are in the range of the olivine-spinel mantle array of Arai (1994). Spinel Cr# can be divided into two groups: high Cr# (0.5-0.6) and low Cr# (0.3-0.4). Olivine crystal-fabrics in these peridotites were also divided into two groups: D type (Fablic Index Angle (FIA): 71˚-84˚) and A (AG) type (FIA: 34˚-59˚). Moreover, the two groups of olivine crystal-fabrics are directly related to chemical compositions of spinel: D type with the high Cr# and A type with the low Cr#. The peridotites of D type with high Cr# are similar to those in Izu-Bonin forearc peridotites. The peridotites of A type with low Cr# have similar physico-chemical properties to abyssal peridotites or those in Oman ophiolite. With the other geological evidences such as older basalt occurrences, we argue that the peridotites of A type with low Cr# might be possibly derived from the oceanic crust before subduction initiation.

キーワード：環伊豆地塊蛇紋岩帯、葉山-嶺岡帯、かんらん岩
Keywords: Cirmum-Izu serpentinite zone, Hayama-Mineoka belt, peridotite

Global seismicity dynamics - dimension reduction analysis of global seismicity

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Huge amounts of global seismicity data along the plate boundaries are very critical to understand the global mechanics of the plate motion together with relative velocity and subduction geometry. Especially, the continuous time series of seismicity of the subduction zone is of great importance to reconstruct the dynamical behavior within the several to several tens year global plate motion. In this paper, I would like to propose the new global seismicity dynamics based on the data-driven machine learning method using truly global seismic data stored in the international seismic database of USGS and ERI.
Recent studies of global seismic activity in the subduction zones reveals the repeating nature of the intermediate sized earthquakes, correlation of slow slip events, low frequency tremor, and normal earthquake , and correlated truncation of several asperities of the plate boundary. Further, it has been suggested that there is some degree of correlation between differential stress acting on the plate boundary and b value of the plate boundary seismicity, supporting that the correlation between buoyancy force of the plate and b value of seismic statistics appears weak. In the region of low b value statistics, the giant earthquake occurred a little bit frequently rather than the other region.
The global surveys of plate boundary seismicity were concerned with mainly the relations among occurrence of giant earthquake, slab characteristics, and the plate motion or the subduction geometry. It suggests that the physical model of subduction is possibly reconstructed by several to several tens examples of plate boundary characteristics. However, it seems to be obvious that huge amounts of seismicity data along the plate boundary zones including many seismicity time series now accumulating with time are most important data to reconstruct the global mechanics of plate motion.
In this paper, I would like to clarify the mechanical behavior of the truly global seismicity in the plate dynamics using the whole seismic data of the plate boundary. The method used here is the dimension reduction in which the observed seismicity vectors defined by time dependent number density of seismic spikes in the given volume of the plate boundary zone of the whole earth are uniquely projected on the low dimensional principal subspace of characteristic base vectors. Those characteristic base vectors are classified into two types; one is the aftershock seismicity of the world wide giant earthquakes, and the other is the strong correlation of plate boundary deformation. In this study, it is suggested that the mode of the latter changed repeatedly within ten years from quite period to murmured one.

キーワード：全地球地震活動解析、次元圧縮、プレート連動
Keywords: global seismicity analysis, dimension reduction, correlative plate motion

