Japan Geoscience Union Meeting 2013
(May 19-24 2013 at Makuhari, Chiba, Japan)

SMP43-P01 Room:Convention Hall Time:May 24 16:15-17:30

Thermodynamic equilibrium for fluid-dominant metamorphic systems

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Classical metamorphic petrology has generally considered chemical equilibrium only among solid phases, but not among solid phases and aqueous species in the intergranular fluid (aqueous solution). It has been implicitly assumed that the chemistry of fluid is entirely buffered by the coexisting minerals. On the other hand, hydrothermal chemistry has modeled that the generation and extinction of the minerals are mostly controlled by the aqueous chemistry in the coexisting water. In most cases, however, the formulation in hydrothermal systems has treated minerals only as pure components but not as solid solutions (e.g. Reed 1983; Henley 1984). In this study, we develop the unified thermodynamic model that seamlessly integrates both the classical concept of metamorphic petrology and the concept of hydrothermal chemistry. The incorporation of the amount of water and chemistry of the aqueous species into the theory of the metamorphic equilibria enables us to investigate the water-rock interaction in metamorphism and metasomatism. In the numerical modeling, the rock shows a wide variety of mineral assemblages according to the amount of water, or the water/rock ratio, even in the same pressure, temperature and bulk-composition conditions. With the increase of water, the number of phase decreases and eventually the system becomes bimineralic or monomineralic. The present model will be the basis for the future study of the various reaction textures such as the formation of the metamorphic banding and the pseudomorphic replacement.

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Change of modal abundance of mafic minerals during formation of arrested charnockite in Sri Lanka

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Arrested charnockite occurs as a number of patches with lenticular to ovoidal shapes in hornblende-biotite gneiss in central Sri Lanka. Yamasaki et al. (2012) tentatively proposed the following reactions to produce orthopyroxene based on compositional difference of hornblende and biotite between charnockite and surrounding gneiss.

Ti-rich biotite + quartz = Ti-poor biotite + orthopyroxene + ilmenite + alkari feldspar + H_2O

Ti-rich hornblende + quartz = Ti-poor hornblende + orthopyroxene + ilmenite + anorthite + albite + alkari feldspar + H_2O.

These reactions suggest that orthopyroxene is produced under the condition of low-H_2O activity in the interstitial fluid. However, it is still unclear where the formation of charnockite began and how the reactions proceeded with time. Although gneissic structure in the surrounding gneiss becomes obscure at interior of charnockite, it can be traced into the near-boundary charnockite. Therefore information before charnockitization have been possibly preserved in charnockite. This study describes variation in modal abundance of hornblende, biotite and orthopyroxene in both rock-types.

Modal abundance of hornblende and biotite in gneiss decreases with decreasing the distance from charnockite. The modal abundance of hornblende and biotite at a point 12cm apart from charnockite is 7.9% and 6.9%, respectively, which decreases to 5.0% and 5.5%, respectively, at the boundary. This abundance decreases discontinuously to 1.7% and 4.1%, respectively, in the charnockite next to the boundary, and further decreases to 0.06% and 1.9% at the interior of the charnockite. The amount of orthopyroxene in charnockite is almost constant at 3.3%.

Biotite occurs both in leucocratic and melanocratic parts in gneiss, in contrast, biotite is absent in leucocratic part in charnockite. Orthopyroxene occurs in melanocratic part or its extension.

Provided that the small amount of hornblende and biotite in central part of charnockite were due to progress of orthopyroxene-forming reaction, the amount of orthopyroxene increases toward the center of charnockite. This prediction contradicts the observation. If the amount of hornblende and biotite before charnockitization tends to decrease toward the present center of charnockite, similar progress of the orthopyroxene-forming reaction in the charnockite would leave hornblende and biotite of which amount decreases toward the centre. This hypothesis is consistent with the fact. This indicates that the orthopyroxene-forming reaction initiated at the hornblende- and biotite-poor part, i.e., leucocratic part.

Keywords: Sri Lanka, arrested charnockite, hornblende-biotite gneiss

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Microstructure of corona of garnet amphibolites from the Lutzow-Holm Complex, East Antarctica

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Corona is a microstructure that any mineral or its aggregate surrounds another mineral. This suggests that corona was formed by the reaction between the interior mineral and the matrix minerals. Estimating this reaction, enables us to know which component transferred and how temperature and pressure changed. Microstructure of constituent mineral in the corona also provides duration of reaction and strain of rocks. In this study, we described the microstructure, crystal size distribution of biotite in the corona and chemical composition of constituent minerals of a corona from the Lutzow-Holm Complex, East Antarctica.

Geological outline

In the Lutzow-Holm Complex, metamorphic grade increases from amphibolites facies in the northeast to granulite facies in the southwest. The granulite facies metamorphic rocks are widely distributed throughout East Ongul Island. The rock types are mainly garnet gneiss and hornblende gneiss. Ultramafic rocks occur as thin layers in garnet gneiss. The ultramafic rocks analyzed in this study are composed mainly of hornblende and porphyroblasts of garnet. Corona structure occurs between garnet and hornblende.

Microstructure

In the matrix, hornblende-rich domain and plagioclase-rich domain occur. Both domains consist of hornblende, plagioclase, brown biotite, and orthopyroxene. Garnet porphydroblast (about 15mm diameter) occurs in the hornblende-rich domain and locally shows concavo-convex shape (around 0.5mm). Garnet (long axis 0.10-0.45mm) that is rounded and irregularly shaped locally occurs at the extension of embayed part. The corona consists mainly of plagioclase and green biotite, and occurs around the outer edge of garnet. Crystal size of green biotite increases with increasing the distance from garnet. In immediate proximity to garnet, biotite occurring at the embayed part of garnet has the long axis that orientates at right angles to garnet.

Crystal Size Distribution

We measured area of all biotite grains(about 3300 grains) in the corona, using image analysis soft(image J) and calculated projected area diameter. We obtained the crystal size distribution for three domains(1,2,3 domains according to the distance from garnet) identified by naked eye. The mode of crystal size distribution is smaller than average and gently decrease on the coarse-grained side as compared with the fine-grained side. The crystal size distribution of 2and 3 is similar to lognormal distribution. 2 has high standard deviation relative to 3.

Chemical composition

Garnet has homogeneous interior and trim that shows higher Fe and lower Mg than the interior. Orthopyroxene in the corona has higher Al and lower Si and Fe+Mg than orthopyroxene in the matrix. Plagioclase in the matrix shows chemical zoning Xan=0.38~0.46 from core to rim. In contrast, plagioclase in the corona has chemical zoning Xan=0.65~0.84. Biotite in the corona has higher Al and lower Si, Ti and K+Na than biotite in the matrix.

Discussion

The crystal size distribution of biotite in the corona resembles to lognormal distribution, suggesting that biotite maintained continuous nucleation and growth with reduced rate of nucleation, during corona formation. Thus this suggests that recrystallization didn't take place significantly despite high temperature condition. Bulk composition of the corona, estimated from mode and chemical composition of minerals, has higher K and lower Fe than bulk composition of the matrix, deduced from chemical composition of garnet, hornblende and plagioclase. This suggests that K is supplied from the outside and Fe is leached through fluid during corona formation.

Keywords: East Antarctica, Lutzow-Holm Complex, corona

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SHRIMP U-Pb zircon dating of garnet gneiss from the Lutzow-Holm Complex at Langhovde, East Antarctica

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The Lutzow-Holm Complex of East Antarctica is one of Pan-African metamorphic terranes that formed as a part of the East Gondwana supercontinent amalgamation. The LHC is considered to have experienced a typical clockwise pressure-tempereture-time path, as indicated by the presence of relict kyanite and staurolite inclusions within garnet and plagioclase in sillimanite-rich pelitic granulites and the development of reaction textures characteristic of near-isothermal decompression in mafic to ultramafic rocks (e.g., Hiroi et al., 1991). The timing of peak regional metamorphism within the sillimanite stability field is constrained to be 520-550 Ma by SHRIMP U-Pb dating on zircon (Shiraishi et al., 1994).

Hiroi et al. (2008) found magmatic andalusite in garnet-bearing pegmatite for the first time from the granulite facies Langhovde area of the LHC. The andalusite-bearing pegmatite intrudes garnet-biotite-sillimanite gneiss, and between them, garnet gneiss that does not contain both andalusite and sillimanite is sometimes formed. In order to constrain the timing of andalusite formation, we performed an ion microprobe (SHRIMP) dating of zircons in the garnet gneiss, and obtained an apparent population of U-Pb ages at ca. 525 Ma, that is almost contemporaneous with the timing of peak metamorphism in the LHC. We discuss the significance of the zircon U-Pb age from the garnet gneiss.

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Keywords: antarctica, granulite, Langhovde, andalusite, zircon, Lutzow-Holm Complex

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Palaeo stress analysis using microboudinage structures of tourmaline within metacherts in East Pilbara Terrane

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Granite emplacement is the key process for generation of continental crust during Archaean. We analysed microstructures of tourmaline grains embedded within metacherts in the aureole around the Mount Edgar Granitoid Complex in east Pilbara, Western Australia. The aim of this study is to evaluate stress and strain with respect to progressing deformation in the aureole during the metamorphism in relation to the granite emplacement. The shape preferred orientation of tourmaline grains on the foliation surface revealed that the intensity of lineation depicted by the value of k ranges from 0.6 to 5.4. Higher values of k occur in an area which is previously called sinking zone by several authors. As many tourmaline grains exhibit microboudinage structures, we performed the microboudine analysis for palaeostress analysis. The estimated palaeodifferential stress ranges from 3.9 to 9.2 MPa. The sample with the highest palaeodifferential stress came from the locality $<$10 m from the contact between the granite and the greenstone belt. The palaeodifferential stress in the sinking zone is 7.2-9.2 MPa, while that far from the contact is 3.9 MPa. We discuss the relationship between the palaeodifferential stress and the k value in the poster.

Keywords: microboudinage structure, granite-greenstone belt, metachert, differential stress

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Modeling shear wave anisotropy in forearc regions: implications for distribution of antigorite and olivine CPO fabrics

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In the upper mantle it is generally thought that the crystal preferred orientation (CPO) of olivine forms by plastic deformation related to solid-state mantle flow. The presence of olivine CPO is one of the main causes of the seismic azimuthal and polarization anisotropy observed in the upper mantle. This link means seismic anisotropy can be used to investigate the flow patterns in the mantle. An important proviso is that there has to be good knowledge of the distribution and type of olivine CPO.

Thermodynamic modeling combined with results of deformation experiments can be used to predict the distribution of different types of CPO patterns in the forearc mantle (e.g. Kneller et al 2008). However, it has also been proposed that topotactic growth of olivine on aligned antigorite may also be an important process in the formation of B-type olivine CPO (Nagaya et al., 2012). This mechanism predicts B-type Ol CPO may be much more widespread in the wedge mantle than CPO formed by deformation alone.

Many forearc regions show an unusual pattern of seismic anisotropy with the fast direction perpendicular to the plate movement direction. One explanation of this observed seismic anisotropy is that the wedge mantle of these regions is characterized by a B-type olivine CPO patterns that characteristically have an a-axis concentration parallel to the intermediate principle axis of strain. The anisotropy observed in NE Japan (s-wave splitting with a time delay of ˜0.1 sec) can be explained by the presence of B-type olivine CPO (Katayama and Karato, 2006).

Olivine is the dominant mineral in the mantle, but forearc mantle of subduction zones also consists of significant amounts of hydrous minerals, in particular antigorite, that have much high anisotropy (for olivine Vp=24%, Vs=18%; for antigorite Vp=46%, Vs=66%). Relatively thin layers of antigorite-rich rock may therefore also have a strong influence on the seismic anisotropy. S-wave splitting with large-time delays greater than 1 second seen in the Ryukyu arc may be due to the presence of antigorite with a CPO that has a strong alignment of the c-axes perpendicular to a steeply dipping subduction zone (Katayama et al., 2009).

Modeling seismic anisotropy is a potentially useful way to place constraints on the types and distribution of different CPO patterns in the forearc mantle. We develop an approach used by Kneller et al. (2008) including a 3D analysis of ray paths and apply it to investigate proposed models of antigorite and olivine CPO distribution in the wedge mantle of NE Japan and the Ryukyu arc. The anisotropy of antigorite has only recently been determined and it has not yet been incorporated in such models. Our model combines two recently developed Matlab toolkits: MTEX (Hielscher & Schaeben, 2008; Mainprice, 2011) and MSAT (Walker & Wookey, 2012). We apply this model to the Ryukyu and NE Japan subduction zones and examine its potential to constrain the distribution region and type of olivine and antigorite CPO in these two wedge mantle.

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Keywords: antigorite, olivine, crystal preferred orientation (CPO), topotaxy, MTEX & MSAT, seismic anisotropy

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Minerals on the verge of fracturing: fluid inclusions observed in minerals within kink bands

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Sambagawa metamorphic belt is a high pressure intermediate type metamorphic belt exposed along the south-west Japan. The peak pressure condition of the metamorphism is known at least to be 0.4 to 0.5 GPa at the lowest metamorphic grade rocks (chlorite zone). Outcrops of the chlorite zone rocks of the Sambagawa metamorphic belt in Chichibu, Saitama prefecture, often show abundant veins. Veins are the evidence of how the rocks have cracked and deformed during exhumation, most likely at the seismic depth. This study first investigated the orientation of veins and kink-bands found in an outcrop of the chlorite zone rocks. The similarity of their orientation indicated that at least some of the kink-bands are possibly the predecessor of the cracks and veins. Several kink-bands gradually changed into veins, which seems to support the view. Observation of the thin sections of the rocks in and out of one of the kink-bands revealed that quartz contained fluid inclusions in a large amount within the kink-band (between the two axial planes of the kink-band). Most of the fluid inclusion bubbles were were aligned in the similar orientation as the axial plane. More than a hundred lines of fluid inclusion bubbles were observed in a 0.5 $*$ 0.5 mm2 area between the two axial planes of the kink, whereas very few fluid inclusion was observed in quartz outside the kink-band. It is possible that the alignment of the fluid inclusions in quartz shows the beginning of the brittle deformation in rocks quenched. Kink bands observed in the outcrops of the Sambagawa metamorphic rocks in Chichibu (Saitama, Japan) may exhibit the minerals on the verge of fracturing.

Keywords: Sambagawa metamorphic belt, crack, vein, kink band, fluid inclusion

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On the genesis and evolution of serpentinite melange in the Mitsuishi-Horaisan area of the Kamuikotan Zone, Hokkaido.

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The Mitsuishi-Horaisan area is one of the typical localities of serpentinite melange with high-grade metamorphic rocks in the Kamuikotan high-P/T metamorphic zone. It is thus expected that the serpentinite melange records condition and evolution of deep subduction zone. Here we discuss genesis and evolution of the serpentinite melange.

Pre-Tertiary in this area comprises an array of high-P/T accretionary complex, ophiolite, and serpentinite melange from NE to SW. These together are overlain by Miocene sediments, and tightly folded to form an anticline. Foliation of serpentinite melange matrix does not show any structure of the fold axis, and thus are probably formed during or after the folding.

Amphibolite blocks consist of garnet-epidote amphibolite and epidote amphibolite. The latter also occasionally contain pseudomorphs and trace relics of garnet. Amphiboles commonly show a compositional zoning from (I) actinolite core via (II) hornblende or barroisite mantle and (III) actinolite rim 1, to (IV) sodic amphibole rim 2. Stage I amphiboles contain relic inclusions of titanite. Stage II amphiboles co-occur with rutile +- ilmenite, garnet or its pseudomorphs, oligoclase or albite and muscovite +- biotite. Stages III and IV amphiboles are associated with titanite, albite, phengite, and chlorite. Sodic pyroxene also occurs in the stage IV. This zoning suggest heating from the greenschist (I) to amphibolite (II) facies and subsequent cooling via the greenschist facies again (III) to the blueschist facies(IV). Geothermobarometry on garnet amphibolites suggested conditions of 560-670 degC, ~1.1 GPa for the stage II.

The amphibolite blocks are commonly mantled by actinolite or tremolite rocks with chlorite or talc, regarded as reaction rind in contact with serpentinites. Sodic amphiboles rimming tremolite suggest that the contact reaction (i.e. fragmentation of amphibolites and juxtaposition with ultramafic rocks) precedes the stage IV.

Ultramafic rocks are primarily classified into (a) antigorite rock, (b) peridotite and massive serpentinites with mesh texture of low-temperature serpentines, and (c) foliated serpentinite mainly of chrysotile. Some massive serpentinite contains antigorite, which generated prior to low-temperature serpentinization, implying that olivine co-existed with antigorite in early stages. Antigorite rocks occasionally contain diopside in addition to common occurrences of carbonates. These occurrences suggest that peridotite first heterogeneously hydrated to produce antigorite peridotite and antigorite rocks. This stage is compared to the amphibolite stages II-III. Low-temperature serpentinization may have occurred in or after the amphibolite stage IV.

Metamorphic sequence of the amphibolites is characterized by early heating under high geothermal gradient from the greenschist (I) to amphibolite (II) facies, juxtaposition with serpentinite (II-III), and subsequent cooling without significant decompression (III-IV) to the blueschist facies. The stage IV condition is common with the major Kamuikotan schists. Contemporaneously, peridotite first experienced a high-temperature hydration mixing with amphibolite fragments at depths of 30-40 km. Later, olivine was extensively hydrated to be mesh textures of low-temperature serpentines during or after the stage IV.

In Hokkaido, subduction zone jumped from the Oshima Belt in the west to the Kamuikotan Zone in the earliest Cretaceous as the Horokanai Ophiolite was emplaced. Amphibolites in serpentinite melanges are the first products since the new subduction zone initiated. It is difficult to explain high thermal gradients and subsequent near-isobaric cooling for amphiboltes in the scheme of thermally stable subduction zone. Whereas subduction initiation and transition to more matured low subduction geotherm potentially explain them. If so, serpentinite blocks in the study area could be fragments of the very juvenile wedge mantle being hydrated for the first time.

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Tectonic blocks in the Kamuikotan metamorphic rocks with distinct P-T paths, Etanbetsu-Horokanai district, Hokkaido

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The Kamuikotan metamorphic rocks are known as typical high-*P/T* type metamorphic rocks formed at a convergent boundary. One the other hand, in the study area, the Horokanai ?Etanbetsu district, while accretionary sediments suffered a high-*P/T* type metamorphism, amphibolites formed by an intermediate-*P/T* type metamorphism also occur as tectonic blocks, which later suffered the same high-*P/T* type metamorphism as the sediments did (Watanabe et al., 1986). In order to argue about the metamorphic history and tectonics of these amphibolites, it is important to estimate the temperature and pressure changes (*P-T* paths) during metamorphism strictly. Furthermore, it is necessary to analyze deformation structures, which recorded a motion of metamorphic rocks. Accordingly, in this research, we have analyzed mineral assemblages in these amphibolites, and conducted micro-chemical analyses of compositional zoning in amphiboles from these rocks with an EPMA. Further, we have analyzed the pressure and temperature conditions which the amphibolite experienced based on a thermodynamic calculation (i.e. pseudosection). As a result, amphiboles which constitute the amphibolites can be divided into 7 types in terms of compositional zoning in amphiboles. Type I amphibole is characterized by the compositional zoning from actinolite core to glaucophane rim. Therefore, it can be inferred that greenschist facies metamorphism was overprinted by blueschist facies metamorphism. Here, we inferred that no cooling was experienced in the amphibolites during the poly-metamorphism, because neither pumpellyite nor lawsonite which is expected to form at high pressure and low temperature conditions was not formed. Therefore, it is thought that this sample only experienced the pressure increase without cooling during the poly-metamorphism. Type II amphibole is characterized by the compositional zoning in amphiboles from magnesiohornblende core indicating amphibolite facies metamorphism through actinolite mantle indicating greenschist facies metamorphism to glaucophane rim indicating blueschist facies metamorphism. Therefore, a *P-T* path such as pressure increase after cooling is suggested. Type III is characterized by the compositional zoning in amphiboles from tschermakite core to glaucophane-magnesioriebeckite rim. It is inferred from compositional zoning in garnet that both temperature and pressure increased in the garnet amphibolite, which was followed by blueschist facies metamorphism inferred by the compositional zoning in amphibole. Therefore, in this area, there are at least three different types of amphibolites which show different *P-T* paths. Since these three types of amphibolites show different overall paleo-geothermal gradients based on the compositions of amphiboles, we inferred that the paleo-geothermal gradient decreased from low-*P/T* (or intermediate-*P/T*) type to high-*P/T* type during the poly-metamorphism, which is best represented by the compositional zoning of type II amphibole. These facts could indicate that the paleo-subduction zone was cooled, and three different types of amphibolites which may have been formed at different paleo-geothermal gradients in different ages, were later assembled as tectonic blocks with different temperature-pressure-time paths in the Horokanai-Etanbetsu district.

Keywords: the Kamuikotan metamorphic rocks, high-P/T metamorphism, tectonic blocks, pressure-temperature path, compositional zoning in amphiboles

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Serpentinite textures and mode of hydration along the ancient subduction zone beneath the Horokanai Ophiolite, Hokkaido,

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Along convergent plate boundaries, the mantle peridotites are serpentinized as water fluids are supplied from the subducted slab. Because serpentinites are less frictional than peridotites, it might play an important role on the deformation characteristics and seismic activities. However, there are still poor observations on the ways how water is supplied and how hydration proceeds in deep subduction zones.

Serpentines of mantle origins occur in contact with a metamorphic rock of oceanic plate origins crop out in the Horokanai area located 30km to the northwest of Asahikawa, Hokkaido. It is prospective that contact relations between, and element transports across the plate boundary of a deep part of the subduction zone is preserved. In this study, field mapping and sampling were made mainly along two routes, which traverse the boundary between the serpentines and the metamorphic rocks. By optical and electron microscopy, occurrences of serpentinites and related minerals and reaction textures are here described.

The serpentinite body is dominated by low-temperature serpentinites occasionally with relic olivine, opx, spinel, and rarely cpx. Antigorite more commonly occurs in parts close to the metamorphic rocks, accompanied by reaction rocks such as talc and/or carbonate rocks. In olivine-antigorite serpentinites, antigorite typically occurs penetrating olivine and opx along with their grain boundaries. Trace amounts of talc instead of antigorite occurs along the grain boundaries between olivine and opx in an antigorite-free peridotite. These occurrences suggest that percolation along grain boundaries was a major mode of water supply in the mantle, as well as by hairline cracks indicated by antigorite serrate veins.

Some antigorite serpentinites also contain diopside and tremolite useful to estimate metamorphic temperature. Several types of reaction textures are observed: (a) opx is surrounded by tremolite corona with secondary olivine at their tips, and (b) simplectic Ol + Cpx + Atg + Mag pseudomorphs presumably after tremolite. Retrogressive hydration from amphibole peridotite to antigorite serpentinite is supposed by these textures. Water supply might have been heterogeneous and intermittent because textures of incomplete hydration are not uncommon.

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Compositional zoning and inclusions of garnet in Sanbagawa metapelites from the Asemigawa area, central Shikoku

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Chemical zoning and inclusions in garnets record valuable information for estimating the pressure-temperature (P-T) history of metamorphic rocks. Metamorphic garnet grains in Sanbagawa metapelites usually record a bell-shaped profile of Mn (normal zoning), suggesting that they were formed by nucleation and continuous growth with increasing temperature during the Sanbagawa metamorphism (Sakai et al., 1985). In contrast, garnet grains in metapelites around eclogite bodies in the Besshi area usually have composite zoning, showing discontinuous growth between the grain's core and mantle boundary, and are reported as resorption-overgrowth zoning by Takasu (1986). In the Asemigawa area, some rare garnet grains in metapelites show reverse zoning (Itaya, 1978) and sector zoning (Inui, 2010) in addition to the normal zoning.

We re-examined the metamorphic P-T history of the metapelites in the Asemigawa area, based on the zoning of garnets, composition and parageneses of garnet inclusions, and residual pressure recorded by quartz grains inclusions in garnets. Thirty-four samples were collected from different metamorphic zones of the garnet (Grt), lower albite-biotite (Ab-Bt), oligoclase-biotite (Ol-Bt), and upper albite-biotite zones along the Asemigawa region from south to north.

Most garnet grains show normal zoning. However, garnet grains from the lower Ab-Bt zone have composite zoning. The composite zoning of garnet is defined by the discontinuous variation in Mn content at the core-mantle boundary. The two types of zoned garnet grains have different inclusion assemblages, as follows: (1) Normal zoning: Qtz (quartz), Ttn (titanite), and micro multi-phase inclusions of Pg (paragonite) + Phg (phengite); and (2) Composite zoning comprising (a) Core: Rt (rutile), Ttn, Cz (clinozoisite), Gln (glaucophane), and (b) Rim: Qtz and Ttn.

Quartz inclusions in the garnets in samples from the Grt, Ol-Bt, and upper Ab-Bt zones preserve a residual pressure compatible to that of the epidote-amphibolite facies. In contrast, the samples from the lower Ab-Bt zone record higher residual pressure than those from the other zones.

These results suggest that the metapelites in the lower Ab-Bt zone were likely recrystallized under relatively higher-pressure metamorphic conditions than others in the Asemigawa area.

Keywords: garnet, compositional zoning, residual pressure, quartz-Raman barometer, Sanbagawa metamorphic belt

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SMP43-P12 Room:Convention Hall Time:May 24 16:15-17:30

Preliminary 2-D thermal modeling of Proterozoic granulite: a case study of structurally controlled exhumation

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Deep continental crustal rocks undergone granulite-grade of metamorphism are exposed at the orogenic belts. Mesoproterozoic Eastern Ghats Granulite belt is one such polymetamorphosed and polydeformed terrain. The unique character of this belt is the occurrence of ultrahigh temperature metamorphosed granulites on a regional-scale where the peak metamorphism is estimated to be in excess of 1000 ^{o}C at ~8-10 kbars. The reason(s) for such extreme thermal conditions at the deeper parts of the Proterozoic orogen and an appropriate geotectonic setting for such extreme high heat flow are still eluding the geoscientists. Moreover, the exhumation processes and rates of exhumation are one of the least studied areas for the deep interiors of such extremely hot orogen.

Proper structural and petrological assessments, particularly exhaustive analysis of pressure-temperature-deformation-time evolutionary history of Eastern Ghats Granulite belt pave the path to look for exhumation histories. This belt is known to be anisotropic and domainal in terms of isotopic signatures and tectonothermal histories. The domain 2 of this orogenic belt presents the best-studied section showing an overall anticlockwise P-T path evolution with three to four deformation and metamorphic events in an overall possible accretionary orogenic set-up. Regional-scale structural studies along the Vishakhapatnam-Araku transect of domain 2 show imprints of superposed deformation at high angle producing domal structures. Three such large-scale domes are arranged from south-east (Madudavada mega-sheath) to north-west (Anantagiri dome and domal structure near Araku).

The present study is based on the occurrence of aluminous granulite with sapphirine-spinel-aluminous orthopyroxene-cordierite-sillimanite-garnet-biotite-quartz-feldspar near the boundary of the "Maduravada mega-sheath". Fe-Mg compositional profiles of porphyroblastic garnet adjacent to orthopyroxene, and that with adjacent retrograde biotite (fluorine-Ti-Mg-rich) show development of zoning only in the latter case. Geothermometric calculations indicate formation of biotite at ~875 ^{o}C during the early cooling, followed by the formation of compositional zoning in adjacent porphyroblastic garnet. In an earlier study, we estimated an anomalously fast cooling rate from this zoning profile of garnet *i.e.*, 12 to 25 ^{o}C/Ky, which is several order higher than the normal thermal relaxation rates reported from younger orogenic belts. In the present study, we have tried to formulate a preliminary two-dimensional numerical thermal model using rapid upheaval of deep crust in a compressional tectonic setting through a domal structure having near-vertical foliation planes. The model calculation is based on an initial thermal condition similar to that of known old continental crust having a steady-state geotherm on 100 km wide area with depth of 35 km. An already perturbed geotherm of 900 ^{o}C at the lowermost part is then folded up in an antiformal parabolic shape, more or less in the fashion of a diapiric upheaval. The 2-D conductive cooling is then assumed and cooling rates have been calculated at different places from the boundary of the upheaved portions, i.e., 0 to 1.25 km at a depth of 5 km from the surface. We use a finite volume method with an implicit time integration to solve the thermal conduction equation with a radiogenic heat source decaying with the depth. The initial cooling rates of ~10-20 ^{o}C/Ky is estimated to be achieved near the boundary with non-linear subsequent decay, similar to the recorded cooling rate from the Fe-Mg zoning profile in the studied rock. The thermomechanical consequence of such deep crustal flow process in presence of partial melt in the overall perspective of the Proterozoic orogen is being checked, in addition to the plausibility of such high degree of thermal relaxation rate.

Keywords: Deep crustal UHT granulites, Anomalously high thermal relaxation rate, 2-D thermal model and crustal flow

SMP43-P13 Room:Convention Hall Time:May 24 16:15-17:30

Subduction conditions estimated from the P-T paths for the Sambagawa metamorphic rocks

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Petrologically derived P-T conditions for high P/T-type Sambagawa metamorphic rocks show lower P/T ratio than numerically modeled typical steady state temperature distribution along the surface of subducting slab. To explain this discrepancy, several authors have proposed the idea of subduction of very young slab that may involve a subduction of spreading ridge (Iwamori, 2000; Aoya et al., 2003; Okudaira & Yoshitaka, 2004). I examined the thermal effects of ridge subduction on both subduction- and exhumation-stage PT-path by a two-dimensional thermal calculation. The results show that PT-path for eclogite and lower-grade metamorphic rocks can be reproduced by a subduction and exhumation of rocks just before the ridge subduction.

Garnet-bearing ultramafic rocks in the Higashi-akaishi perodotite show progressive PT-path up to UHP condition with high dP/dT ratio (Enami et al., 2004). A numerical calculation shows that this PT-path can be explained by a mantle wedge dragged down by the subducting oceanic slab with older age (>20 Ma) and fast (>10 cm/yr) subduction rate.

These two results indicate that UHP and lower-grade metamorphisms are occurred different time and different subduction conditions.

Keywords: plate subduction, Sambagawa metamorphic rocks, P-T path, thermal modeling

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Reaction and structural development of antigorite serpentinite in the Higashi-akaishi ultramafic body, Sambagawa belt

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Serpentinization of mantle wedge is a key process controlling fluid flux across subduction boundaries. In order to model progressive serpentinization and its effect on subduction system, it is important to understand mechanism of the fluid-rock reactions in open system. For direct information on the kinetic reactions, we made field observations on antigorite (Atg) serpentinite in the Higashi-akaishi ultramafic body in the Sambagawa belt.

Schistosed Atg serpentinite develops at the lower half of the body. Modal proportions of Atg to olivine (Ol) show a bimodal distribution representing an interlayering between Ol-rich (5-20% Atg) and Atg-rich (30-60% Atg) layers. Such layering can be seen in scales of several mm to 20 meters. Each layer is generally distinctive but local gradual decrease of Atg proportion in a single unit indicates the direction of fluid transport from bottom to top. Veins and network structures of Atg connect these strongly foliated parallel layers with the hydrous mineral.

Brucite (Brc) and magnetite (Mag) are found in highly serpentinized layers. However, there is no concentration of Brc and Mag in the outcrops and strain shadows are filled by Atg or carbonate indicating extraction of Mg and Fe is minor during serpentinization. Mineral chemistry of Atg and Ol suggests re-distribution of Ni and Fe during serpentinization. These observations indicate that Atg formation is owing to an additional SiO2 dissolved in aqueous fluids. Minor Brc and a small amount of Mag can be explained by a reaction involving SiO2.

These observations indicate that discontinuous layers with high concentrations of Atg represent fluid pass ways supplying SiO2 and H2O required for serpentinization of peridotite. Syn-deformational serpentinization causes strong schistosity defined by parallel alignment of platy Atg. Such foliated layers probably enhanced channelized fluid flow and, as a result, formation of Atg. This positive feedback is considered as a major mechanism to increase the amount of Atg in the Ol-rich Higashi-akaishi body. It is also indicated that contributions of interconnecting channels were important for advancing of serpentinization front into the mantle wedge.

Keywords: serpentinization, structural development, reaction

SMP43-P15 Room:Convention Hall Time:May 24 16:15-17:30

U-Pb zircon age of low-pressure/high-temperature metamorphic rocks from the Kurosegawa tectonic zone, South-west Japan.

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The Kurosegawa Tectonic Zone distributed from Kyushu to Kanto Mountains, characterized by serpentinite melange. The serpentinite melange contains various types blocks such as sedimentary rocks, granite, high-temperature amphibolite- to granulite-facies rocks and high-pressure/low-temperature metamorphic rocks.

The variation of U-Pb detrital zircon age clusters in pelitic schist from Itsuki area in Kyushu, Toba area in Kii Peninsula, and quartzite from Anan area in Shikoku are mostly similar in each area. These results might indicate that the pelitic schists and the quartzite from three areas were derived from similar hinterland.

Meanwhile, the U-Pb zircon ages of garnet-clinopyroxene granulite from Tsubokinohana area and amphibolite from Hashirimizu area in Kyushu are 447+/-3 Ma and 449+/-4 Ma, respectively. According to texture and Th/U ratios of analyzed zircon grains, the estimated U-Pb zircon ages from low-pressure/high-temperature metamorphic rocks may indicate protolith ages of these metamorphic rocks. In addition, the U-Pb zircon age of glaucophanite, which represent to form the gabbro, from Engyoji area in Shikoku shows 447+/-5 Ma. This U-Pb zircon age may also indicate protolith age. At present, protolith ages of metamorphosed mafic rocks in the Kurosegawa Tectonic Zone are considered to concentrate between the Silurian and the Cambrian.

Keywords: Kurosegawa Tectonic Zone, U-Pb zrn age

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The Kiroko greenstone melange of the Atokura Nappe in the Yorii-Ogawa district, central Japan

Akira Ono[1]*

[1]None

The Atokura Nappe is distributed in the Yorii-Ogawa district of the northeastern margin of the Kanto Mountains. The Kiroko greenstone melange is exposed in the southern margin of the Atokura Nappe. The greenstone melange is composed of Kiroko metamorphic rocks, serpentinite and various tectonic blocks. The tectonic blocks are considered to be captured by the Kiroko metamorphic rocks and serpentinite in the course of their rises toward shallow crust. K-Ar datings for the Kiroko greenstone melange were carried out for two samples by the present writer. The Kiroko-M sample is a greenstone. The Iyo-mus sample is a biotite-garnet-muscovite schist which is exposed in Iyo, East Chichibu village.

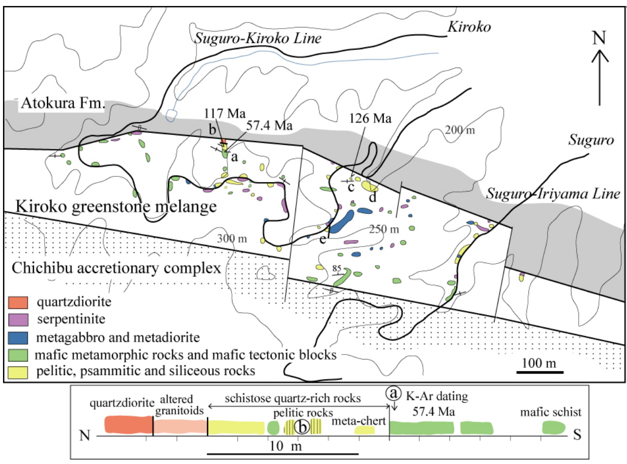
The Kiroko-M sample was made from several hand specimens. Lenticular portions with various colors such as pale-green, gray, white and black are observed for the hand specimens (Figure 1). The lenticular portions are of about 1-3cm in length and less than 5mm in thickness. Radiolarians are rich in white siliceous parts although they are also common for other portions. Black pelitic lenses are composed of fine actinolite, chlorite, white mica, quartz and carbonaceous material. The small white mica has a great impact on the K-Ar age of the Kiroko-M sample.

Pelitic metamorphic rocks of the Kiroko greenstone melange were previously described as slates or mudstones. Recrystallizations of minerals are good in spite of the low metamorphic temperature. Preferred orientation of muscovite is clear in many cases. The sizes of muscovite grains depend on each rock sample. It is very small in some cases. Two kinds of muscovite with respect to grain sizes are observed for all the studied samples. Larger muscovite grains are considered to be detrital ones. Secondary minerals are hardly observed although quartz veins are present frequently.

K-Ar dating was carried out for two pelitic rocks, Kiroko-P and Suguro-P. The results are 117Ma and 126Ma, respectively (Figure 1). Considering the common occurrences of detrital muscovite grains, the measured K-Ar ages are considerably older than cooling ages of metamorphic minerals.

Mid-Cretaceous granitic and metamorphic rocks are tectonic blocks of the early Paleogene Kiroko greenstone melange. The Kiroko metamorphic rocks and serpentinite exhumed to the shallow crust where mid-Cretaceous granitic and metamorphic rocks were distributed. The mid-Cretaceous granitic and metamorphic rocks were largely transported toward an oceanic plate before 60Ma and were situated at the margin of the Paleogene forearc region where the exhumation of high-pressure type metamorphic rocks took place. Similar tectonic shortenings occurred after 60Ma in the forearc region of Southwest Japan. The formation of the Atokura Nappe is an evidence for the tectonic contraction.

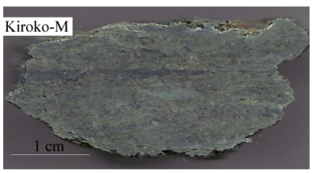
Keywords: greenstone melange, Atokura Nappe, slate, K-Ar dating, detrital white mica



	Sample	Age (Ma)	^{40}Ar rad (scc/g x10^{-5})	^{40}Ar rad (%)	K (%)
(a)	Kiroko-M	57.4± 1.4	0.047 0.046	83.5 75.7	0.21 0.20
(b)	Kiroko-P	117 ± 2.9	1.60 1.64	96.6 96.7	3.45 3.45
(c)	Suguro-P	126 ± 3.0	0.963 0.973	94.2 93.7	1.91 1.92
(x)	Iyō-mus	109 ± 2.7	3.04 3.01	95.1 94.1	6.94 6.92

M: mafic schist, P: pelitic rock, mus: muscovite

$\lambda_{\beta} = 4.962 \times 10^{-10}$/yr , $\lambda_{\varepsilon} = 0.581 \times 10^{-10}$/yr
^{40}K/K=0.01167 atom% Geospace Science CO.,LTD.



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Zircon LA-ICP-MS U-Pb dating of metamorphic rocks from Sor Rondane Mountains, East Antarctica.

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Sor Rondane Mountains, East Antarctica, has been considered to locate inside of the collision zone between West Gondwana and East Gondwana (e.g., Meert, 2003; Jacobs and Thomas, 2004). This area is composed by greenschist- to granulite-facies metamorphic rocks and various plutonic rocks that intrude to metamorphic rocks (Osanai et al., 1992). The Sor Rondane Mountains has been divided into Northeastern (NE) terrane and Southwestern (SW) terrane, based on variety of the constituent rocks and metamorphic process (Osanai et al., in press). The NE terrane consists of unit A and unit B. Metamorphic rocks from the unit A are amphibolite-facies, and from the unit B are granulite-facies (unit B). Metamorphic rocks from unit B show the ages of magmatism at 1130-890 Ma and 800-790 Ma (partial melting), granulite-facies metamorphism at 750-700 Ma and 640-600 Ma, and amphibolite-facies metamorphism (retrograde) at 580-520 Ma (Osanai et al., in press). By contrast, the SW terrane has granulite-facies metamorphic rocks in unit C, greenschist- to amphibolite-facies metamorphic rocks in unit D, and metatonalite (unit D'). Metamorphic rocks of the unit C, D and D' show the ages of syn-magmatism and magmatism at 1190-950 Ma, magmatism at 770-750 Ma (e.g., Nakano et al., 2012), metamorphism at 700 Ma (Hokada et al, 2013), granulite-facies metamorphism at 640-600 Ma, amphibolite-facies metamorphism (retrograde) at 580-520 Ma (Osanai et al., in press). Amount of geochronological data has been reported from the Sor Rondane Mountains. However, their collected areas were limited mainly in central part and eastern part. In this study, we analyzed 25 samples (2 samples from unit A, 12 samples from unit B, 5 samples from unit C and 6 samples from unit D) mainly from the unknown areas to reveal more detailed tectonic evolution of the Sor Rondane Mountains.

In the unit A, zircon ages in metapelites (Grt-Bt gneiss) yield 1070-780 Ma from detrital zircon and 640-630 Ma from metamorphic rim. Those in metamorphosed felsic or intermediate rocks (Hbl-Bt gneiss) yield 1180-1030 Ma, which is interpreted as the ages of magmatism. In the unit B, range of zircon ages in metapelites (mainly Grt-Bt gneiss and Opx-Bt gneiss) is 610?2900 Ma. Especially, the age cluster of 660?610 Ma are interrupted as metamorphic age, and other age groups were analyzed from detrital zircon. Metamorphosed felsic or intermediate rocks (Bt gneiss) consists 1050-840 Ma igneous zircon age and 670-570 Ma metamorphic zircon age. In the unit C, zircon ages in metamorphosed felsic or intermediate rocks (Hbl-Bt gneiss and Bt gneiss) yield 1000-920 and 870-730 Ma with minor 730-710, 570 Ma. Zircon ages at 1000-920 and 870-730 Ma are interpreted as magmatic age, on the other hand, ages of minor 730-710, 570 Ma may be interpreted as metamorphic age. Zircon ages of metamorphosed mafic rocks (Grt-bg. Bt amphibolite) yield 810-760 Ma as magmatism age, and 640 and 610-570 Ma as metamorphic age. Those in calcsilicate metamorphic rock (Hbl-Cpx rock) yield ca. 760 Ma. In the unit D, detrital zircon ages in metapelites (Grt-Bt gneiss and Ep-Chl-Ms schist) are dated at 1120-930 Ma. The variety of zircon age clusters in metamorphosed felsic or intermediate rocks (St-bg. Grt-Bt gneiss and Bt-Hbl gneiss) is 1150, 1050-1010, 950-800 Ma and 720 Ma. Zircon ages, ranging 1150?800 Ma, are interpreted as magmatism age, in contrast, zircon age of 720 Ma may be interpreted as metamorphism. Range of detrital zircon ages in calcsilicate metamorphic rock (Bt-Ep-Hbl rock) is 980-780 Ma.

In comparison with geochronological data of the NE terrane and the SW terrane, the detrital age cluster of >1800 Ma is recognized in unit B, characteristically. Difference in detrital zircon ages suggests that these two terranes would be derived from different hinterlands. We also could recognize that both terranes have similar igneous ages from felsic, intermediate and mafic metamorphic rocks.

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Electron microprobe age dating of monazite from the meta-sedimentary rocks, central-eastern Madagascar

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Madagascar is situated within the interior of the Neoproterozoic East African Orogen (EAO; Stern, 1994) that marks the join between East and West Gondwana. The Betsimisaraka Unit exposed on the eastern margin of EAO experienced Neoproterozoic-Early Paleozoic metamorphism and deformation. Monazites from biotite gneiss in the Betsimisaraka Unit, sillimanite-biotite gneiss and kyanite-biotite-muscovite schist, and garnet-sillimanite gneiss in the Antananarivo Block were dated by the field emission Electron microprobe. The ages and zoning characteristics varied between the samples, but the U-Th-Pb monazite data confirm that at least Early Paleozoic (Cambrian) metamorphic events are recorded in the area.

Monazites from the Betsimisaraka Unit are subhedral to anhedral, and occur both as inclusions within biotite porphyroblasts and the matrix. Analyzed grains gave ages from 400 to 610 Ma with the 500 Ma age being dominant. Compositional zoning in monazites from samples in the Masora Block demonstrates complex growth relationships. Monazites are subhedral to anhedral, and yield two distinct ages. The cores of monazite grains give ages of ca. 930 Ma whereas the rims of grains generally give ages of ca. 500 Ma. A second sample from the Masora Block contained subhedral to anhedral monazite grains both within biotite and matrix minerals. Analyzed grains gave ages ranging from 450 to 550 Ma with the 510 Ma age being dominant. Discontinuous zoning in monazites from sample in the Antananarivo Block demonstrates complex growth relationships. Monazites are anhedral and yield two distinct ages. The cores of monazite grains give age of ca. 2500 Ma whereas the rims of grains generally give ages of ca. 490 Ma.

The occurrence of monazites suggests that Cambrian-Ordovician history is preserved within metamorphosed equivalents in the central-eastern Madagascar. The monazite data support the previous monazite ages in central-southern Madagascar reported by Giese et al. (2011) and requires re-evaluation of tectonic model of Gondwana formation along the eastern margin of EAO.

Keywords: Gondwana, central-eastern Madagascar, EPMA monazite dating, meta-sedimentary rocks

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Some characteristics of isochemical kelyphite in garnet peridotites, Czech Bohemia

Masaaki Obata[1*], Kazuhito Ozawa[2], Kosuke Naemura[2], Akira Miyake[1]

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Isochemical kelyphite that is formed by isochemical breakdown of garnet has been known to occur in olivine-free mafic xenoliths such as garnet pyroxenites or granulites in volcanic rocks. We reported an occurrence of isochemical kelyphite (kelyphite II:Opx+Sp+Plagioclase) from garnet peridotite from Czech Boldanubian Zone (Obata et al, Mineralogy and Petrology, 2013). This presentation illustrates some important petrographic characteristics and discuss their significance. It occurs within ordinary kelyphite (kelyphite I: Opx+Cpx+Sp), which indicates the formation of kelyphite I preceeded kelyphite II.The characteristics of the Czech isochemical kelyphite (kelyphite II) are as follows. (1) kelyphite II is asymmetric, i.e., it develops only on one side of garnet. (2) mineralogical transitions zones are defined between kelyphites I and II. (3) another thin hydrous kelyphite (kelyphiteIII: Amp+Sp+Pl) separates the kelyphite II and relict garnet. (5) while no topotaxic relationship is found between pyroxene and spinel in the kelyphite I, a good topotaxic relationship occurs in the middle of the kelyphite II. These are new features that have not been recognized from previous isochemical kelyphites (from xenoliths) and are considered to bear important information regarding the processes of transformation from kelyphite I to kelyphite II formations and they are expected to occur in other orogenic peridotites. A preliminary report of such isochemical kelyphite is also presented from the Ronda peridotite, Spain.

Keywords: kelyphite, symplectite, garnet peridotite, Czech, Bohemia

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Talc flow layer tectonics :a new concept of globe

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[1]non

Many of the theories of plate tectonics are disputable. It is not comprehensible that the low velocity layer in the upper mantle is interpreted as the partial melting. The caldera chain (Iida, 2011b) was proposed as a new concept of magmatism that is possible to be in place of the existing concepts consisting of the hot spot, plume, and subduction zone magmatism. According to the new concept, all magmas except the kimberlite are expected to be generated in the crust or uppermost mantle, and the upper mantle is considered to be much cooler than the current theory.

Talc could be stable in the considerable depth. It is estimated that the talc bearing flow layer (TFL) underlying the plates is the cause of the plate drift and isostasy. The North American ice sheet centered in the Hudson Bay is surrounded by a belt of large lakes. The belt rose in the ice age by the outward migration of the flow material from the center, and turned to sink with the melting of ice sheet. Such a reverse movement of surrounding zone indicates the relatively thin flow layer underlying the crust.

The considerable portion of oceanic plate is serpentinized prior to subduction. The dehydration of serpentine metamorphoses both the plate itself and adjacent mantle into TFL that migrates upward along the lower surface of the plate represented by the lower side of the double seismic plane. Such metamorphism and two-way movement makes the speedy subduction possible. The plate bends and then becomes straight again to subside. It is considered that such plastic deformation is realized by the fractured and surpentinized rocks and surrounding mobile TFL.

The TFL below the oceanic plate migrates toward the mid-oceanic ridge to become the raw materials for the plate. In the subduction zone the oceanic plate enveloped by TFL subsides with the density difference that is the power source for the whole system. The mid-oceanic ridge is in the passive tension field where the oceanic plate is formed by the magma generated with the pressure reduction. The ridge ranges at right angles to the tension direction. The continent is cut by the caldera chain (CC) that moves irregular in shape. In order to fit the shape the ridge is dislocated by the transform faults. The CC that split the Pangaea has migrated for 600 million years from south to north. The current tip of the CC is located at the eastern end of the Gakkel ridge in the Arctic sea.

The zonal geologic structure parallel to the trench is common in the edge of continental crust adjacent to the subduction zone. The caldera tends to be formed in the soft and thin crust rather than hard and thick crust. Accordingly the CC tends to be formed in parallel with the trench. When the large scale CC which magma originates from the TFL is formed along the edge of the continent, the CC becomes the cutting line for the separation of the marginal part. The TFL in the surrounding area flows into the gap to supply the material for the new oceanic crust. The island arch and the marginal sea are formed with such process. The CC concentrically migrates in the new oceanic crust due to its thinness, the marginal sea spreads itself. The movement of the TFL toward the marginal sea makes the TFL below the island arch thin to depress the land. The transgression happened in Japan in the mid-Miocene at the time of the Japan sea spreading could be explained by the process.

The TFL and the CC are the individual tectonics severally. These two are proposed as the new concepts that are totally different from the existing concepts of the earth.

Keywords: continental drift, caldera chain, island arch, marginal sea