Petrology and metamorphic evolution of the ultramafic rocks in the Eoarchean Isua supracrustal belt: Implications to Archean geodynamics

Dissertation Abstract

Petrology and metamorphic evolution of the ultramafic rocks in the Eoarchean Isua supracrustal belt: Implications to Archean geodynamics

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Abstract

The 3.8-3.7 Ga Isua supracrustal belt (ISB) in southwestern Greenland contains discontinuous chains of ultramafic rock bodies within amphibolite facies volcanic and sedimentary sequences. The ultramafic bodies in the western limb of ISB (Lens A and Lens B) that were interpreted to have lesser effects of metamorphism and deformation are the focus of this. In Lens B, Ti-rich humite-type minerals (titanian chondrodite and titanian clinohumite) occur as accessory phases in these ultramafic rock bodies forming patches within olivine. The host olivine contains abundant magnetite inclusions and high forsterite content (Fo=96-98) with variable MnO and NiO contents indicating a metamorphic origin as a result of deserpentinization rather than primary igneous features. The intergrowth relationship between Ti-Chn and Ti-Chu formed as a result of breakdown during decompression. The discrete Ti-Chu grains suggest a retrograde path from high-pressure (2.6 GPa) to lower pressure (1.6 GPa) within the antigorite stability field (630-660°C). The overall petrological and geochemical features of the 3.8-3.7 Ga ISB ultramafic rocks reached eclogite facies conditions following deserpentinization. However, Lens A (south of Lens B) exhibit contrasting textural and geochemical signatures (Fo=89-92 and less varying MnO and NiO contents). Spinel-clinopyroxene symplectites in olivine in Lens A exhibit textural and chemical composition that is similar to this formed by dehydrogenation-oxidation of hydrous olivine and possibly humite layers in olivine. The Eoarchean Lens B metadunites exhibit features suggestive of HP metamorphism followed by retrograde metamorphism, which are petrological features that can be explained by deep burial followed by rapid exhumation, comparable to modern subduction zone channels, though the extent of actual subduction remains enigmatic. On the contrary, Lens A shows minimal metamorphic imprints. Lens A shows contrasting mineralogical composition and texture compared to Lens B suggesting a difference in the P-T path or exhumation history.

1. Introduction

The mantle temperature during the Hadean-Archean eon (ca. 3 Ga) was about 200-250°C hotter than the present-day conditions. The lithosphere was mainly formed by tectonomagmatic differentiation (Sizova et al., 2010). The unstable portions of the crust are detached by eclogite dripping and delamination. Plate tectonics transitional phase occurred during the Archean-Proterozoic (3 Ga-1 Ga) wherein squishy-lid tectonics evolved developed towards plate-tectonic-like. The modern-style plate tectonics began operating at ca. 1-0.5 Ga as a result of the more advanced cooling mantle, formation of rigid plates, rise of continents and increase erosion that served as subduction lubricant (Sobolev and Brown, 2019). The Isua supracrustal belt (ISB) is a 35-km arcuate belt located within the Eoarchean terranes which are composed of 3.9-3.6 Ga Amıtsoq gneiss and 2.8 Ga Ikkattoq gneiss. In some areas, low-strain and alteration-free pillow lavas are exposed suggesting that original lithological relationship and chemical features can still be observed in the ISB (Appel et al., 1998).

1.2. ISB metamorphism: details from supracrustal lithologies

The ISB can be subdivided into 5 domains based on lithologic packages. Garnet morphology and composition in pelites suggest several growth generations. The eastern part of the western limb of the ISB falls under Domain IV. Several domains in the ISB (Domains II-V) record two garnet growths which correspond to metamorphic events (average age 3.74 Ga). Two domains (Domain II and IV) record a younger garnet growth. The younger garnet is linked to the 2.8 Ga metamorphic event (Gruau et al., 1996; Frei et al., 1999) which is both recorded in Domains III and IV also. Garnet-biotite pairs suggest that temperature conditions of above 610°C for the early metamorphic event (3.74 Ga) and a lower temperature range (550-570°C) for the younger metamorphic event (2.8 Ga) (Rollinson, 2002). There are few metamorphic studies in ISB focusing on ultramafic rocks. Metamorphosed ultramafic rocks were reported and described by Dymek et al. (1988) from the southern train of the western limb of ISB.

1.3. Metamorphism of ultramafic rocks

Low-grade metamorphism of ultramafic rocks is typically dominated by serpentine minerals: lizardite, chrysotile and antigorite. Serpentine minerals replace olivine and pyroxene in the ultramafic rocks. The breakdown of serpentine at higher temperatures is marked by the appearance of secondary olivine, pyroxene and amphibole (Spear, 1993). Spinel, though regarded as resistant, also record metamorphism at various metamorphic grade (Barnes and Roeder, 2001). The hydration of olivine and pyroxene forms serpentine±brucite±magnetite. Serpentinization is also responsible for introducing fluid mobile elements (FMEs) such as B, Sr and Cs Cs (Hattori and Guillot, 2003; Scambelluri et al., 2004).

The dehydration of serpentine is also referred to as deserpentinization (Arai, 1975; Khedr and Arai, 2012). Olivine formed through such process contains abundant magnetite inclusions and has higher forsterite contents above 93, low-variable NiO and high MnO contents (Arai, 1975; Nozaka, 2003). Elements that are mobile under high fluid conditions such as B and Li also tend to be detectable in metamorphic olivine (McCaig et al., 2018). Ultramafic rocks in the $MgO-SiO_2-H_2O$ system have limited thermobarometric indicators. Accessory phases such as the titanium-rich humite group of minerals have been recently described in detail in terms of PT stability (Shen et al., 2015). In the absence of garnet, such phases are very useful in reconstructing the PT history of ultramafic rocks. The Al-content and Tschermak's substitution in antigorite has also been used in constraining pressure (Padrón-Navarta et al., 2013).

In southern West Greenland, complex metamorphic imprints are observed in some of the ultramafic bodies outside ISB. The Mesoarchean Ulamertoq peridotite body in the adjacent Akia terrane shows characteristics that suggest varying metamorphic PT conditions. Chromitites with reverse zoned chromites (Mg-Al increase coupled with Cr-Fe decrease from core to rim) are hosted within olivine+orthopyroxene+magnesiohornblende+phlogopite dunitic rock and could be possibly metamorphosed up to upper amphibolite facies. The compositional zonation in chromites may be ascribed to subsolidus equilibration with surrounding Al-rich phases such as amphibole and orthopyroxene. Another type, homogeneous chromites, are hosted in olivine-clinopyroxene-tremolite peridotite, and could be metamorphosed at a lower metamorphic grade (greenschist to lower amphibolite facies), or have retrogressed more extensively (Guotana et al., 2018). The ultramafic rocks in the Ulamertoq peridotite body exhibit strong metasomatic and metamorphic features which could also be the case in the other ultramafic rocks in southern West Greenland including the ISB ultramafic rocks.

2. Methodology

Thin sections of representative samples from ISB Lens A and Lens B were prepared. Rock slabs from the hand specimen were cut. Lapping and polishing of rock slabs were done using 200, 400, 800, 100 and 300 SiC powder grits and finally with a 1 µm diamond polishing solution. A Nikon Eclipse LV100 Pol polarizing petrographic microscope was used in the detailed observation of the thin sections.

The major-element compositions of mineral phases were obtained using a JEOL JXA-8800 electron probe microanalyzer (EPMA) at the Kanazawa University. The analyses were carried out using operating conditions of 20 kV accelerating voltage, 20 nA beam current, and a 3 µm beam diameter. Natural and synthetic standards were used for the analysis and results were corrected using ZAF (Z=atomic number, A=absorption, F=characteristic fluorescence) correction method using JEOL JXA-8800 software.

Mineral rare earth element (REE) and trace element concentrations were analyzed using a Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) (Agilent 7500S equipped with MicroLas Geolas Q-plus laser system; Agilent Technologies, Santa Clara, CA, US) at the Kanazawa University was used to analyze the concentrations of rare earth element (REE) and trace element compositions of major and minor phases. An ablating spot size of 50 µm in diameter at a repetition rate of 6 Hz was used in each analysis point. External reference material was NIST SRM 612 and data reduction was facilitated using ^{29}Si as the internal standard, using the SiO_2 content obtained by EPMA.

The serpentine minerals were identified using micro-Raman system (HORIBA Jobin Yvon, LabRam HR800) equipped with a 532 nm Nd:YAG laser (Showa Optronics Co., Ltd, J100GS-16) and an Olympus BX41 optical microscope at the Kanazawa University.

The whole-rock compositions of representative Lens A and B metadunites were determined at the National Museum of Nature and Science in Tsukuba, Japan. Crushed and powdered samples were prepared using rock slabs of the representative samples. The loss on ignition (L.O.I) was determined by igniting 0.4000$\pm$0.0004 g of powdered samples at 1025ºC for 4 hours. The difference with the weight prior and after ignition determines the L.O.I. Lithium tetraborate flux (10 to 1 sample dilution) was used in preparing the glass beads. Pressed pellets (4.0-5.0g) were prepared using a 12-ton force for trace element geochemistry. The major and trace element compositions were measured using an X-ray fluorescence spectrometer (RIGAKU ZSX Primus II) following a method described in (Sano et al., 2011).

3. Isua supracrustal belt ultramafics: Lens B

Lens B (located north of Lens A) is one of the ultramafic bodies in the northern portion. Lens A and B also exhibit Lens B belongs to the few ultramafic lenses in ISB which is interpreted to have retained primary magmatic features (Friend and Nutman, 2011; Kaczmarek et al., 2016). Lens B contains titanian chondrodite and titanian clinohumite which implies a high-pressure origin (Yamamoto and Akimoto, 1974). In the earlier works, these ultramafic lenses were interpreted as metasomatized and deformed metaperidotites from an olivine±pyroxene protoliths (Dymek et al., 1988; Rosing et al., 1996; Furnes et al., 2007).

4.1. Sample description

Most of the samples are olivine dominated with varying degrees of serpentinization. In this study, samples will be referred to as metadunites and serpentinites to refer to the samples from Lens B. Olivine porphyroblasts in Lens B metadunites are characterized by a dusty core and clear rim. The brownish dusty olivine contains abundant opaque inclusions, mainly magnetite. Opaque inclusions are minor or absent in the clear olivine which envelopes the dusty olivine. Lizardite cuts both the dusty and clear olivine. Antigorite occurs as inclusion, coarse blades around olivine porphyroblasts and as interlocking grains in the groundmass. The coarse blades antigorite and groundmass antigorite are compositionally similar. The antigorite inclusions have lower Al_2O_3 wt.% contents. Titanian clinohumite (Ti-Chu) and titanian chondrodite (Ti-Chn) occur as accessory phases that are associated with the dusty olivine. In some portions, Ti-Chu and Ti-Chn are intergrown. Chromite grains are heavily zoned with Cr-rich cores and feritchromite-magnetite rim. Magnesite replaces olivine and serpentine phases and preserves the original outline of the grain. Stichtites, Cr-hydrotalcites, replaces magnesite and several grains Ni-sulfides are also present.

3.2. Mineral chemistry

The olivine in Lens B metadunites are highly forsteritic (Fo=96-98) and are not typical of mantle olivine. The NiO and MnO contents of the dusty olivine (0.45-0.70, 0.18-0.59 wt. %) are higher values relative to the clear olivine (0.36-0.55, 0.08-0.25 wt. %). Olivine porphyroblasts show detectable amounts of B, Li and other FMEs (U, Pb, Sr, Cs and Ba). The Lens B humite-group minerals are characterized by high TiO_2 contents (Ti-Chu=2.42-5.86 wt.%; Ti-Chn=7.72-9.22 wt.%; XTi=0.2-0.48). The Ti-Chu and Ti-Chn XMg range from 0.97-0.98 which is comparable to the host olivine. The Lens B humite-group minerals are generally almost fluorine-free which is different from those occurring in the nearby Ulamertoq peridotites (Nishio et al., 2019). In chondrite-normalized trace and rare-earth element diagrams, the humite-group minerals show enrichment in Ti, Nb, Ta, and Zr. The Isua Ti-Chu and Ti-Chn show elevated LREE and HREE patterns with distinctly low concentrations of MREE.

4. Metamorphic imprints on Lens B metadunites

The high forsterite and MnO contents are chemical features that are associated with metamorphic olivine from deserpentinized ultramafic protolith (Arai, 1975; Khedr and Arai, 2012). The highly variable NiO contents could be ascribed to the absence of talc, presence of Ni-sulfides and deserpentinization degrees which all could have effects in the NiO content of the olivine (Menzel et al., 2018). In the Isua metadunites, Ti-Chn is commonly intergrown with Ti-Chu. The Ti-Chn occurs as dark orange grains mantled by light-orange Ti-Chu. The intergrowth relationship suggests the instability of Ti-Chn during retrograde metamorphism and subsequent reaction with olivine and antigorite to form Ti-Chu. It was observed though that Ti-Chn reacts away at 2.5 GPa and below. It is, however, possible to form Ti-Chu from Ti-Chn in a Ti-rich system (presence Ti-rich phases) at lower pressure conditions (below 2.5 GPa). The abundance of magnetite replacing the chrome spinel is considered as the Ti source that formed the Ti-rich humites. The breakdown of Ti-Chn to Ti-Chu is also observed at lower pressures (~1.6 GPa) in a Ti-rich system (ilmenite-bearing) (Scambelluri and Rampone, 1999; Shen et al., 2015). The absence of ilmenite and rutile suggests a lower pressure limit of 1.6 GPa and an upper limit of 2.6 GPa within the antigorite stability field (~650°C) (Engi and Lindsley, 1980; Shen et al., 2015).

5. PT path of Lens B metamorphism

The dunitic protolith underwent hydration during an early serpentinization event forming serpentine and magnetite. The magnetite network within olivine porphyroblasts is interpreted as relict of the mesh texture of the earlier serpentinization. The serpentinization and formation of magnetite are associated with lower-grade metamorphism around greenschist facies (Evans, 2008). The subsequent prograde event caused deserpentinization and formation of the dusty olivine. The dehydration and fluids released could have mobilized Ti to form Ti-rich humite group of minerals which are closely associated with the dusty olivine. The fluctuation of fluid infiltration and high-temperature serpentinization forming magnetite-free antigorite could have preceded the clear olivine formation. The zonation observed in Cr-spinel with increasing Fe^{3+} from core to rim is also comparable to the typical alteration from low-grade to upper amphibolite facies with increasing ferric iron contents from low- to high-grade (Barnes and Roeder, 2001). Antigorite blades postdate the lizardite veinlets which are cutting both the dusty and clear olivine. The groundmass and blade antigorites are compositionally similar and formed under the same event. The carbonation could have occurred twice replacing direct olivine porphyroblasts as shown in the magnesite pseudomorph after olivine and irregular magnesite replacing antigorite blades in the groundmass. These features can be explained by deep burial and subsequent exhumation which is similar to modern-day subduction.

6. Lens A dunitic rocks

Spinel-pyroxene symplectites in olivine is commonly observed in terrestrial, meteorites and lunar samples (Mikouchi et al., 2000; Khisina and Lorenz, 2015). The formation of intergrown spinel and silicate phases such as diopside is ascribed to exsolution from olivine as a result of oxygen fugacity and pressure-temperature shifts (Mikouchi et al., 2000). The geologic events triggering such mechanisms are still being debated. This study reports, for the first time, the oriented spinel-pyroxene symplectite within olivine from Lens A ultramafic body in Isua supracrustal belt (ISB), southern West Greenland. Symplectites in olivine occur as spinel-pyroxene intergrowths that contain elements that are typically present as trace amounts such as Cr, Ca, Al, Ti, V and Mn, some of which in high-valence state (e.g. $Cr^{3+}$and Fe^{3+}). Lens A olivine does not show the two subdomains similar to those observed in Lens B. The entire olivine grain exhibits brownish color and contains oriented symplectite inclusions. The symplectites in the olivine are clinopyroxene-spinel intergrowths that from dendritic platelets. Lizardite veinlets are absent and antigorite mainly occurs as blades around olivine and inclusion. The olivine from Lens A has lower forsterite content (89-92) compared to Lens B, NiO content ranges from 0.4-0.6 wt% and MnO values from 0.1-0.18 wt%. The total olivine Ca (0.2 wt%) and Cr contents (0.05 wt%) is not anomalously high for typical olivine. Clinopyroxene is mainly diopside and characterized by Mg#=0.94-0.97, CaO=22.88-24.93 wt.%, and Cr_2O_3=0.2-0.71 wt.%.

Spinel-clinopyroxene symplectites in olivine in Lens A exhibit textural and chemical composition that is similar to this formed by dehydrogenation-oxidation of hydrous olivine and possibly humite layers in olivine.

7. Conclusions

The Eoarchean Lens B metadunites exhibit features suggestive of HP metamorphism followed by retrograde metamorphism, which are petrological features that can be explained by deep burial followed by rapid exhumation, comparable to modern subduction zone channels, though the extent of actual subduction remains enigmatic. On the contrary, Lens A shows minimal metamorphic imprints. Lens A shows strong difference in mineral composition and texture compared to Lens B suggesting a difference with respect to the P-T path or exhumation history.

8. References

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令和 2 年　8月　7日

学位論文審査報告書（甲）

1．学位論文題目（外国語の場合は和訳を付けること。）

Petrology and metamorphic evolution of the ultramafic rocks in the Eoarchean Isua supracrustal belt: Implications to Archean geodynamics (原太古代イスア表成岩帯中に産する超苦鉄質岩体の火成一変成履歴：太古代地球ダイナミクスへの貢献)

2．論文提出者　(1) 所　属　自然システム学　専攻

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3．審査結果の要旨（600～650字）

本論文はグリーンランドに露出する世界最古級（30-38億年前）の地質帯中に産する超苦鉄質岩類試料を解析した結果である。これまで，周囲の変成岩類の研究は多くなされており，超苦鉄質岩石類の研究も行われてはいたが情報が断片的であり，本論文では，特に，38 億年前の地質帯であるイスア表成岩帯中の代表的な２岩体を詳細に検討し，30 億年前の地質帯中の類似岩石群らの研究も行った上で，その特徴，違いをはじめて明らかにし，太古代のテクトニックセッティングについて議論したものである。論文内での新しい知見・論点は以下の 3 点である。（1）イスア表成岩帯中 Lens B 岩体から，エクロジャイト相に達するような変成作用を受けた履歴が残されていることを明らかにしたこと，（2）イスア表成岩帯中 Lens A 岩体は，Lens B と近接しているにも関わらず変成履歴が異なり，火成岩として形成された時の情報を有し，含水メルトからの結晶化した可能性が高いこと，（3）上記の 2 点から，太古代では現在のプレートテクトニクスに類似するテクトニクスが既に起きていた可能性を強く示唆したことである。8 月 7 日に学位論文審査委員会を開催し，Guotana 君が提出した博士学位請求論文を合格と認め，博士（学術）の学位を授与するに値すると判断した。

4．審査結果　(1) 判　定（いずれかに○印）　合　格　・　不合格

(2) 授与学位　博　士（学術）