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イスア地域のイトサック片麻岩の地質年代の再検討
Reappraisal of geochronology of the Itsaq Gneisses in the Isua area

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地球は生命が生息し、またプレートテクトニクスに伴う火成活動や地震活動が起きている、活動的な天体である。それらの生命の起源やプレートテクトニクスの開始は、一般に初期太古代や冥王代にまで遡るとされている。しかし、太古代の地質体は極めて稀で、カナダ・アカスタ片麻岩体、西グリーンランドイトサック片麻岩体、カナダ・ラブラドル・サグレック岩体やヌブアギツック帯に限られる。特に、イトサック片麻岩体のイスア表成岩帯からは約 38 億年前のプレートテクトニクスの地質学的証拠や生命の痕跡が報告されており、その詳細な年代決定は極めて重要である。

最近のイスア地域の花崗岩質片麻岩体中のジルコンの U-Pb 年代の研究によれば、イスア表成岩帯より北部の地域は約 3700 Ma、一方、南部は約 3800 Ma の年代をもつとされている。Nutman et al. (2009) は、この年代の相違を南北の片麻岩ブロック（テレーン）が別々に生成し、それらが衝突・合体したということで説明し、その境界はイスア表成岩帯中にあり、チャート層がその縫合帯であるとした。特に、いくつかの先行研究では北部において 3700 Ma 以前の大陸地殻や物質は存在せず、南側とは別のテレーンであることが強調されたが、 表成岩中には最も古いもので 3950 Ma に達する片麻岩よりも古い年代を示すジルコンが見つかっていることや、リサイクルの影響を考慮していないと言った点から、その年代分布について再考の余地がある。また、現在の沈み込み帯では片麻岩の原岩である花崗岩が数億年にわたり間欠的に生成しており、古生代の付加体中に中生代前期、中期、新生代前期、新生代末期の花崗岩が極めて狭い範囲で貫入している地質体が随所に見られ、花崗岩の年代分布の違いは必ずしも異なるテレーンを必要としない。

本研究では、カソードルミネッセンス（CL）観察で片麻岩中から分離したジルコンを火成起源、変成起源と残存鉱物起源に分類し、それらのジルコンの U-Pb 年代を局所 ICP-MS によって決定した。

イスア北部から片麻岩 3 個、南部から片麻岩 2 個を採取し、ジルコンを分離した。北部の試料のうち 2 試料は表成岩との境界部、1 試料は片麻岩体中央部から採取した。南部の試料はともに表成岩との境界部から採取した。南部の試料のうちの 1 試料はジルコンを殆ど含んでいなかった。分離されたジルコンは東京工業大学のカソードルミネッセンス（CL）像解析を用いてジルコンの内部組織を観察し、京都大学の LA-ICP-MS を用いて U-Pb 年代を測定した。CL 観察では、oscillatory zoning が残存しているものや、中心部と周縁部で明確に構造が異なるものが北部と南部のジルコンに共通して見られたが、北部のジルコンは南部のジルコンに比べて全体的に像が暗くなる傾向があった。北部の境界部と中心部の試料のジルコンの Pb-Pb 年代は明瞭な違いは見られず、ともに約 3660~3750Ma（年代分布のピークは約 3720Ma、最古の年代は 3759 ± 56Ma）となり、concordia 図上では約 0Ma と約 3710Ma を結ぶ discordia 上にプロットされた。一方、南部の試料は約 3750~3800Ma の Pb-Pb 年代をもち (年代分布のピークは約 3770Ma)、concordia 図上では、約 0Ma と約 3785Ma を結ぶ discordia 上にプロットされた。しかし、これらの discordia が変成年代を示唆しているとは考えにくい。また、北部と南部の両方の試料において、ジルコン内部の中央部と周辺部とで、Pb-Pb 年代に明瞭な違いは見られなかった。また、ジルコンの U や Th の濃度と CL 発光には明瞭な相関がみられ、暗い部分ほど U や Th に富むという傾向が見られた。この特徴はメタミクト化によると考えられる。

以上の結果をまとめると、北部と南部の片麻岩の年代は先行研究と一致するものの、先行研究では重視されなかったジルコン内部の中央部と周縁部で年代差が見られないと言った特徴やジルコンの化学組成との相関と年代や CL 像との相関が明らかになった。今後、Pb ロスによるジルコンの U-Pb 年代の若返りの問題やこれらの花崗岩先駆物質の起源物質の推定を行う。

キーワード: 前期太古代, イスア表成岩帯, カソードルミネッセンス
Keywords: Early Archean, Isua Supracrustal Belt, Cathodoluminescence

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西オーストラリア・ピルバラクラトンの海洋底玄武岩中の黄鉄鉱四種硫黄同位体比から制約する太古代海底下の微生物活動
Microbial activity below Archean seafloor constrained by 4 sulfur isotopes analysis of pyrite in ca. 3.5 Ga basalts from

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Microbial sulfate reduction is one of the most ubiquitous metabolisms on Earth [Canfield, 1998]. In modern environment, it is well known that microbial sulfate reduction takes place below seafloor [e.g. Kallmeyer et al., 2012]. Aoyama et al. [2014] showed microbial sulfate reduction takes place not only in quiescent seafloor (i.e. non-hydrothermal), but also in active hydrothermal system. On the other hand, the oldest evidence of microbial sulfate reduction has been reported from ca. 3.5 Ga Dresser Formation, Western Australia by using quadruple sulfur stable isotopes analyses of sulfate and sulfide minerals related to hydrothermal environment [Ueno et al., 2008; Shen et al., 2009]. However, the isotopic compositions of sulfides and sulfate minerals through history show small isotopic fractionation (~20 ‰) before the rise of oxygen (c. 2450 Ma), possibly because of low sulfate concentration in the Archean seawater ($<200\ \mu M$) [Habicht et al., 2002]. Microbial sulfate reduction below Archean seafloor might have yield larger sulfur isotopic fractionation owing to enhanced sulfate concentration. In order to test this scenario, we analyzed quadruple sulfur isotopic compositions of pyrite grains (from 10 to 40 μg) of seafloor basalts. For studying isotopic variation within sample, we used newly developed micro-fluorination technique.

The observed variations within each rock have positive correlations between the d34S and D33S, and negative correlations between the d34S and D36S, suggesting these trends are derived from mixing or fractionation. Pyrite within silica dykes penetrating seafloor basalts, which are the most plausible end-member within pyrite in basalts, however, cannot explain the observed variations. On the other hand, the slope of the observed D36S/ D33S (-9.3) and large variations within small volume rocks (~10 ‰) suggest microbial sulfate reduction took place in Archean hydrothermal system. The observed intensive d34S depletions only in Unit-I, and mass dependent compositions imply the substrate sulfate was different from Archean seawater suggested by bedded barite in upper part of the Unit-I. Thus the Archean hydrothermal system may have host microbial activity by enhanced sulfate.

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In-situ iron isotope analysis of pyrites in ˜3.7 Ga sedimentary protoliths from the Isua supracrustal belt

In-situ iron isotope analysis of pyrites in ˜3.7 Ga sedimentary protoliths from the Isua supracrustal belt

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The timing of the emergence of life remains one of the principal unresolved questions in the Earth sciences. Putative relicts of microorganisms in the Eoarchean (ca. 3.6-3.85 Ga) high-grade metamorphic terranes do not preserve morphological evidence for early life, but some relicts can be identified by their geochemical signatures created by metabolic processes. Among the oldest rocks of sedimentary origin (ca. 3.8 Ga) occur in the Isua supracrustal belt (ISB), southern West Greenland; these have undergone metamorphism up to the amphibolite facies. Despite intense metamorphism, the carbon isotope compositions of graphite clots from the Isua metasedimentary rocks suggest biological carbon fixation and provide the oldest evidence for this biological process. Microbial dissimilatory iron reduction (DIR) is considered to be an early form of metabolism. The microbial DIR produced $Fe^{2+}{}_{aq}$ with a lower δ^{56}Fe value from a precursor Fe^{3+}-bearing iron mineral. However, δ^{56}Fe values lower than -1 ‰ are not found in sedimentary rocks prior to about 2.9 Ga. Here, we report in-situ iron isotope analysis of pyrites in sedimentary rocks from the ISB, using a near infrared-femtosecond-laser ablation-multicollector-ICP-MS (NIR-fs-LA-MC-ICP-MS). A large variation of δ^{56}Fe values from -2.41 to +2.35 ‰, was documented from 190 points within pyrite grains from 11 rock specimens, including those interpreted to be banded iron-formations (BIF), chert, amphibole-rich chert, quartz-rich clastic sedimentary rocks, mafic clastic sedimentary rocks, carbonate rocks and conglomerates. We found that the distribution of δ^{56}Fe values depends on the lithology, whereas there is no correlation between their δ^{56}Fe values and the metamorphic grade. The δ^{56}Fe values of pyrites in BIFs range from +0.25 to +2.35 ‰, indicating partial oxidation in the deep ocean. Especially, the high δ^{56}Fe values, up to +2.35 ‰, suggest that the BIF was formed through interaction of ferruginous seawater with a highly alkaline hydrothermal fluid under anoxic conditions. Pyrite grains in a conglomerate, carbonate rocks, mafic clastic sedimentary rocks, and amphibole-rich cherts show negative δ^{56}Fe values around -1.5 ‰, down to -2.41 ‰, pointing to microbial DIR in the Eoarchean shallow sea. In addition, the relatively low δ^{56}Fe values of pyrites in the shallow water sediments suggest anoxic, anoxygenic photoautotrophic iron oxidation in the photic zone.
Keywords: Eoarchean, Isua supracrustal belt (ISB), pyrite, microbial dissimilatory iron reduction (DIR)

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ノースポール地域とイスア表成岩帯の玄武岩のSr、Nd同位体系から推定される太古代マントルの組成多様性
Compositional diversity of Archaean mantle estimated from Sr and Nd isotopic systematics of basaltic rocks in North Pole

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Two types of oceanic basalt, mid-ocean ridge basalt (MORB) and oceanic island basalt (OIB), have large variations in chemical and isotopic compositions, suggesting the compositional heterogeneity of the mantle by the differentiation process related to the material recycling. This research aims at revealing the timing which the crust-mantle recycling system has been established in the early Earth, and how it transforms into the present-day style through the time, based on geochemical analyses of the Archean basalts from the North Pole and the Isua regions.

The North Pole region (~3.5 Ga), located in the central Pilbara Craton, northwestern Australia, and the Isua Supracrustal Belt (~3.8 Ga), southwestern Greenland, represent the Archaean accretionary complexes. In these areas, the Archaean MORBs and OIBs have been identified on the basis of their occurrence and oceanic plate stratigraphy, which have a possibility to record the old mantle recycling system and differentiation events.

We have analyzed trace element and $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ isotopic compositions of MORBs and OIBs in North Pole (NP MORBs and NP OIBs), and those in Isua Supracrustal Belt (ISB MORBs and ISB OIBs). Concerning the North Pole basalts, we have also analyzed the igneous clinopyroxenes (cpx) to evaluate the effect of the post-igneous alteration or metamorphism by examining the partitioning of elements between the cpx and whole rock.

The trace element compositions of NP MORBs and OIBs are roughly similar to each other in REEs composition. A relatively small variation of NP MORBs and OIBs can be reproduced by 5-35 % melting of the primitive mantle. On the other hands, ISB MORBs and OIBs exhibit distinct geochemical characteristics, and can be reproduced by ~15 % to ~35 % melting of the D-DMM (or more depleted mantle) and ~5 % to ~25 % melting of the primitive mantle, respectively. These results suggest that the source mantles of NP MORBs and OIBs were similar, whereas the source mantles of ISB MORBs and OIBs were different in chemical composition.

The Sr isotopic compositions of both NP basalts and ISB basalts are largely scattered, and the isochron age is inconsistent with previous studies. Furthermore, the trace element pattern shows spikes in Rb and Sr, and as for NP basalts, partitioning of these elements between cpx and whole rock (or estimated melt) is in a disequilibrium relation. From these evidences, the Rb-Sr system seems to have been disturbed by post-igneous alteration or metamorphism.

On the contrary, the Nd isotopic compositions of both NP basalts and ISB basalts are thought to show the original properties, based on the evidences of the equilibrium partitioning of REEs and the well-defined isochron age consistent with previous studies. The initial εNd values of NP MORBs and OIBs are similar to each other and show a slightly negative values, whereas those of ISB MORBs and OIBs are systematically different, which is consistent with the REE variation as mentioned earlier. Based on these geochemical data, we propose the following model to explain the temporal variation in composition of the Archaean mantle; (i) $>$3800 Ma; recycling of plate material and melting occurred quite actively and therefore the mantle was highly differentiated to produce MORB and OIB from different sources, (ii) 3460-3800 Ma; mantle-crust mixing events occurred, and the compositional variation of the mantle became smaller, (iii) at 3460 Ma; differentiation-recycling system restarted, and volcanic rocks (including MORBs and OIBs) have rather primitive composition, representing the homogenized mantle, and (iv) $<$3460 Ma; mantle heterogeneity gradually develops in the material recycling system, generating the compositional differences between MORB and OIB again. This model requires a drastic event for homogenization at the stage (ii), and may provide a new insight into the crust-mantle evolution system and its physical model.

Keywords: Archaean mantle, Nprth Pole, Isua, oceanic basalt, mantle diversity