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研究成果の概要（和文）：酸素同位体比を用いて水-岩石反応のモデル化を行い、岩石の形成過程と変成作用における水の影響を明らかにした。ヒマラヤの超高圧変成岩中ジルコンの酸素同位体比を測定した。岩石試料から３つの形成段階、（1）火成起源の原岩、（2）超高圧変成作用、および（3）後退変成作用（加水反応）を識別できた。δ-18Oの値に基づいて原岩形成時のマグマは天水由来の熱水の影響を受けたこと（低いδ-18O値）と、当時のインド大陸は寒冷気候（南部高緯度）であったことが示唆される。また、超高圧変成作用に伴って形成されたジルコンのδ-18Oは再平衡に達している。成果はLithosとGondwana Researchに掲載された。

研究成果の概要（英文）：Water-rock interaction modeling was done using the oxygen isotope in the natural rocks to understand the tectonic evolution and the effect of metamorphism. Samples from the Himalayan ultrahigh-pressure (UHP) metamorphic rocks were investigated. Three stages: (1) magmatic protolith (igneous zircons), (2) UHP stage (coesite-bearing rocks), and (3) retrogressed stage (hydration reactions) were recognized. δ-18O values were lower in magmatic (negative in metamorphic zircons), compared with the mantle values (+5~7 per mil) indicate the protolith were hydrothermally altered by meteoric water interactions when Indian plate (part of Himalaya from where the samples were investigated) was experiencing cold climate (southern high latitudes) when the protolith rocks were forming. Later after it drifted northward, subducted to mantle depth and suffered UHP metamorphism, the δ-18O were re-equilibrated. The results are published in international journals such as Lithos and Gondwana Research.

研究分野：地質学

キーワード：ジルコン　年代　岩石　酸素同位体　変成作用　火成岩

１．研究開始当初の背景

Oxygen is the most abundant element on earth with its three stable isotopes of ^{16}O (99.763%), ^{17}O (0.037%) and ^{18}O (0.199%). Because of the higher abundance of ^{16}O and its greater mass difference with ^{18}O, the $\delta^{18}O$ (delta O-18: measure of the ratio of ^{18}O:^{16}O) provides important information on the oxygen isotope fractionation in the earth processes at the interior (magmatism, metamorphism,) and on the surface (weathering, alteration). Especially, ^{18}O (< 0.2% in abundance) in earth is a significant geochemical tracer to understand nature of the magma source, hydrothermal alteration by sea or fresh (meteoric) water and extent of water-rock interaction during subduction/exhumation-related metamorphic processes. Bulk earth has a uniform value of $\delta^{18}O$ ca. 6‰ (parts per thousand) and most mantle-derived rocks (basalts and gabbros) show a narrow range ca. +5.7±0.3‰ (Hoefs, 2009).

Eclogites (metamorphic rocks composed mainly of garnet and omphacite with minor phengite/quartz/rutile/zircon) form by high-grade metamorphism of basalts or gabbros. They usually have $\delta^{18}O$ values equal to mantle ca. +5.7‰, if altered have much wider range ca. 3 to +12‰ (Alt et al., 1986). However, eclogites having negative $\delta^{18}O$ values are rare. So far, two localities of ultrahigh-pressures (UHP) eclogites (coesite-bearing rocks subducted to mantle depth > 100 km) in the world have been known with negative $\delta^{18}O$ (1) Dabie-Sulu in eastern China (Fu et al. 2013), and (2) Kokchetav in Kazakhstan (Masago et al. 2003). Kaghan Valley in Himalaya is the 3rd locality where negative $\delta^{18}O$ values were discovered from the UHP eclogites (Rehman et al., 2014). The negative $\delta^{18}O$ values were likely resulted from the meteoric water-rock interaction in the protolith (Panjal trap basalts: Rehman et al. 2013) in southern high latitudes (60°S) with glacial environment. During the India-Asia collision in Eocene the protolith rocks were subducted to mantle depth, underwent UHP metamorphism and exhumed to earth surface where some rocks (least retrogressed) preserved the protolith-inherited negative $\delta^{18}O$ values and $\delta^{18}O$ in retrogressed rocks partially reset by hydration. To quantify water-rock interaction in the magmatic protoliths and to evaluate the effect of metamorphism on $\delta^{18}O$, an in-situ $\delta^{18}O$ study (within thin sections with known textural features) was proposed. Rehman et al. (2014) showed that fresh UHP eclogites yielded negative $\delta^{18}O$ (－2.25 to －1.44‰) values, amphibolitized eclogites (+1.66 to +4.24‰) and amphibolites (+5.84 to +5.91‰). The protoliths of these eclogites were the Permian Panjal Trap basalts, but **(1) why** not all eclogites have identical values, is an enigma. Moreover, if fresh eclogites (unaltered) are the true representative of protoliths, then **(2) how** they acquired such low or negative $\delta^{18}O$ values, and **(3) what** was the effect of subduction- and exhumation-related metamorphism on these rocks?

Meteoric water hydrothermal alteration modifies $\delta^{18}O$ to lower or negative values, hence protolith of the Himalayan eclogites were hydrothermally altered. However, it needed confirmation whether the negative $\delta^{18}O$ values were protolith-inherited (magmatic source) or caused by later processes. In-situ $\delta^{18}O$ study provides the answers to these issues.

２．研究の目的

Purpose of the research was to determine the water-rock interaction for the tectonic evolution of the Indian plate. In Permian extensive volcanism (Panjal trap basalts) occurred on India when it was part of Gondwana. After the break-up of Gondwana India moved northward, collided with Asia in the Eocene and the rocks of the Indian plate experienced ultrahigh-pressure metamorphism. This collision and exhumation resulted in the gigantic Himalayan mountain range. Through the study of oxygen isotope paleoclimate, tectonic position and water-rock interaction during the magmatic and metamorphic events have to be determined.

３．研究の方法

In-situ $\delta^{18}O$ analyses of

(1) Magmatic zircons (to evaluate the magma source),

(2) Metamorphic zircons, garnet and omphacite (to find the link of $\delta^{18}O$ with metamorphism), and

(3) Amphibole and epidote (to understand the behavior of $\delta^{18}O$ on retrograde metamorphism).

In-situ $\delta^{18}O$ analyses conducted on minerals (within thin sections with preserved geological textures) provide understanding on the mechanism of water-rock interaction/ hydrothermal alterations. The $\delta^{18}O$ values in igneous zircons (within eclogites) provide information of the magmatic source. The $\delta^{18}O$ values in peak-stage metamorphic minerals (metamorphic zircon, garnet, omphacite) and exhumation-related retrograde stage minerals (amphibole, epidote) lead us to quantify the effect of late-stage processes on $\delta^{18}O$. The proposed project on the Himalayan eclogites increased our understanding on the geologic/tectonic evolution of Himalayan orogeny and its paleoclimate. Comparative studies on metamorphic rocks of other orogenic belts (e.g. Sanbagawa HP eclogites in Japan and Bohemian UHP eclogites in Germany) will also confirm the proposed model.

Sample preparation was mainly done at Kagoshima University (KU) and in-situ $\delta^{18}O$ analyses were carried out at SIMS Lab of the University of Wisconsin, USA (J. Valley & Noriko Kita's Lab). Due to limited amount of funds and high price of the machine-use ($3600/day), all the planned analytical work was not done, however, main target (magmatic and metamorphic zircons) was accomplished.

In addition, field work and sample collection were done in the Sanbagawa metamorphic belt, Shikoku where students also participated in the field survey and used the samples for their graduation research. However, it was not possible to carry out field survey in the Bohemian massif, Germany, because of the limited budget.

４．研究成果

Major target of the project was to understand the the mechanism of water-rock interaction/ hydrothermal alterations in magmatic and metamorphic rocks using in-situ $\delta^{18}O$ analyses. Zircons were separated from the Himalayan eclogites and dated for U-Pb age using the LA-ICP-MS. In addition, the same dated spots were further analyzed for Lu-Hf isotope to understand their source rock. The geochemical, textural and U-Pb age data revealed two populations of zircons (1) magmatic zircons crystallized in Permian (Panjal Trap magmatism) and (2) metamorphic zircons grown during Eocene (India-Asia collision-related metamorphism). Hafnium isotope results from these zircons suggest their mantle source for magmatic ones and recrystallization of metamorphic zircons from the magmatic zircons with complete geochemical resetting. The results were published in International impact factor

Journal (Rehman et al., 2016). Some other publications were also made in collaboration (list shown below). Knowing the magmatic and metamorphic zircons, we conducted in situ $\delta^{18}O$ analysis on the known domains using SIMS at the University of Wisconsin, USA. The in situ $\delta^{18}O$ analysis confirmed that magmatic source was hydrothermally altered by the meteoric-water rock interaction and the values were re-equilibrated in metamorphic zircons during UHP metamorphism. The results provide significant understanding on the tectonic setting, paleoclimate and effect of metamorphism on the $\delta^{18}O$ values. The achievements were published in international Journal (Rehman et al., 2018). Some of the works, previously planned, were not accomplished or had to modify due to lack of funding. However, in parallel, similar petrological and geochemical works were done and the results were published in international journals or presented at international conferences (see list below).

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５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　8 件）

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〔学会発表〕（計　8 件）

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〔図書〕（計　0 件）

〔産業財産権〕

○出願状況（計　0 件）

名称：
発明者：
権利者：
種類：
番号：
出願年月日：
国内外の別：

○取得状況（計　0 件）
名称：
発明者：
権利者：
種類：
番号：
取得年月日：
国内外の別：

〔その他〕
ホームページ等：
http://ris.kuas.kagoshima-u.ac.jp/html/100005058_en.html

６．研究組織

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