

## 論文の内容の要旨

### 論文題目

# **A chronological study of differentiated meteorites: elucidation of crustal evolution and accretion history of protoplanets**

(分化隕石の年代記録を用いた  
原始惑星の地殻進化・天体衝突史の解明)

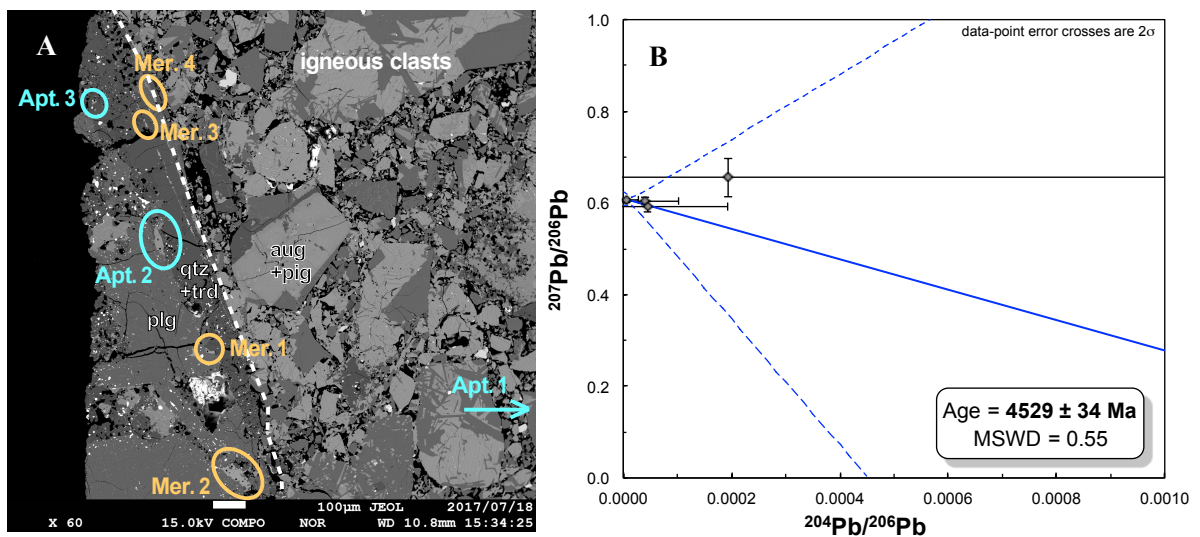
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Elucidation of the planetary formation process is a long-standing issue in planetary science. Scarcity of the surviving small bodies (planetesimals ~ protoplanets) makes it difficult to reveal the early history. Rocky small bodies with sizes up to 100s–1000 km are considered to have been common in the early solar system. However, most of them were lost to date. Meteorites from the ancient differentiated bodies, (i.e. differentiated meteorites), are valuable recorders of past evolutionary processes of the protoplanets, including igneous crystallization of the primary crusts, thermal metamorphism, hydrous alteration, and/or impact brecciation<sup>e.g. [1][2]</sup>. This study aims to reveal the planetary evolution histories from the meteoritical records. Especially, I focus on Vesta and Vesta-like protoplanets

In the present study, I investigate the meteoritical samples from asteroid 4–Vesta (eucrites; Chapter 2), and those from Vesta-like unknown body (mesosiderites; Chapter 3). Co-authors and I previously established *in-situ* U-Pb dating protocols of extraterrestrial phosphates using NanoSIMS 50 (Koike et al., 2014; 2016). In the present work, I have also established *in-situ* Hf-W dating protocols of meteoritical zircon (reported in Koike et al., 2017; Chapter 3). Taking advantages of the *in-situ* techniques, I have analyzed the U-Pb and Hf-W records of these samples, which indicate the ancient histories of their parent protoplanets.

In Chapter 2, I investigate the crustal metamorphic history of asteroid 4-Vesta. Vesta, a large ( $R \sim 280\text{km}$ ) rocky body in the main asteroid belt, is the only surviving differentiated protoplanet currently known. Their crustal samples are known to be available as the common meteoritical groups (howardites-eucrites-diogenites; HEDs). Eucrites, the largest group in HEDs, are basaltic composition rocks, which represent Vesta's crusts. A number of previous studies investigated their mineralogy, geochemistry, and chronology, and proposed their complicated histories e.g. [3]. *In-situ* U-Pb dating were previously conducted on zircons in several eucrites [4]–[6], which indicate high-temperature ( $\geq 900^\circ\text{C}$ ) thermal process at 4554 Ma. The U-Pb systems in Ca-phosphates (apatite [ $\text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH})$ ]) provide moderately robust thermo-chronometer, which records thermal events at typical temperature ranges of  $\sim 450$ – $600^\circ\text{C}$  [7]. In order to understand the complicated history of Vesta's crusts, it is important to investigate various chronological records with *in-situ* techniques, and compare them to each other. The goal of this study in Chapter 2 is to reveal the crustal metamorphic history of Vesta at moderate temperatures (ca.  $600^\circ\text{C}$ ), by *in-situ* U-Pb dating of phosphates in basaltic eucrites.

I have analyzed four basaltic eucrites (Juvinas, Camel Donga, Stannern, Agoult) and an anomalous basaltic achondrite (Ibitira). Three of the five (Juvinas, Camel Donga, Stannern) are severely brecciated by impacts, whereas the others (Agoult, Ibitira) are unbrecciated. From apatite in Agoult, a precise  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  age of  $4522 \pm 11\text{ Ma}$  is determined. Similar  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  age at ca. 4530 Ma is also obtained from apatite in Juvinas (Fig.1). This ca. 4530 Ma period is significantly younger than the igneous age of  $\geq 4560\text{ Ma}$ . It is inferred that Vesta's crust experienced either the slow cooling from earlier thermal events, or additional moderate reheating (ca.  $600^\circ\text{C}$ ) at 4530 Ma. In contrast, merrillite in the same Juvinas samples has a



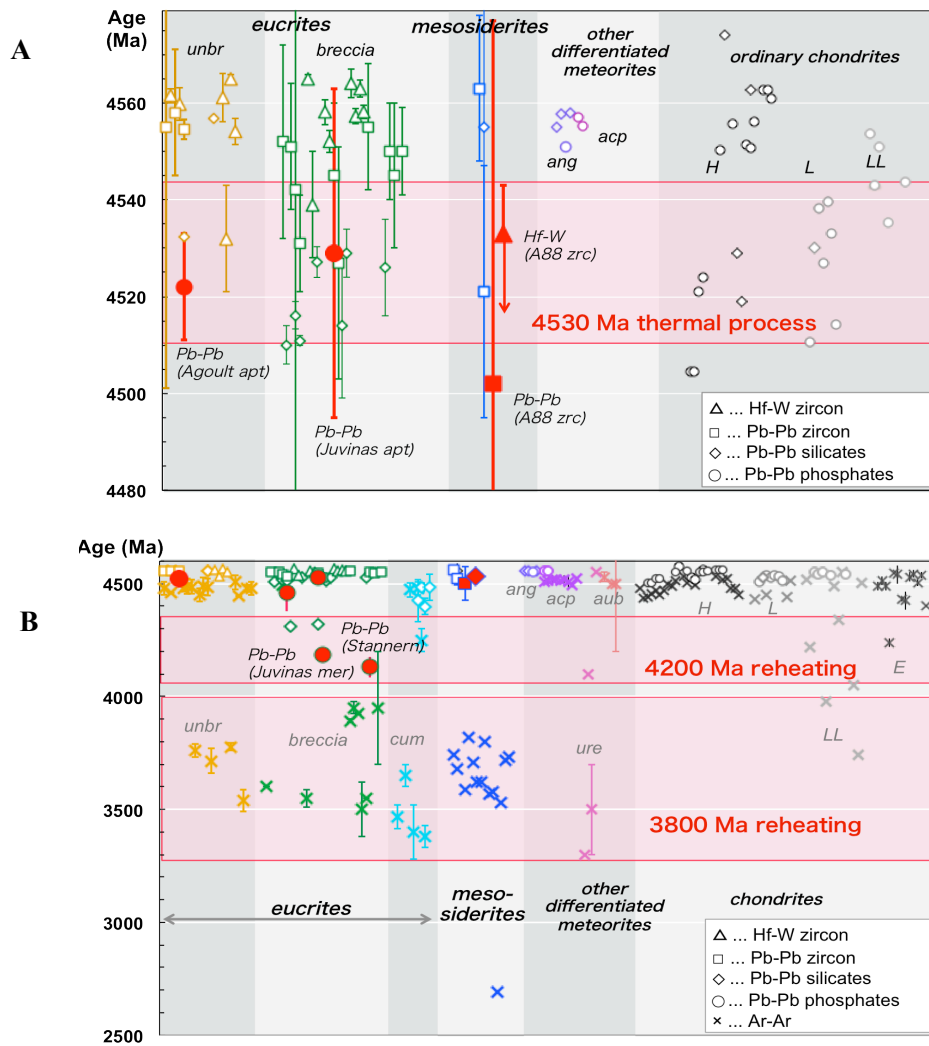
**Fig. 1.** (A) BSE image of the Juvinas phosphates. (B)  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  isochron of the Juvinas apatite.

significantly younger  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  age of ca. 4200 Ma, suggesting its U-Pb system was completely reset at the later impact reheating with partial remelting. This study is the first report that has identified the local disturbances of the U-Pb systems in phosphates from the single sample, owing to the *in-situ* methods. The  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  age of another brecciated eucrite, Stannern, is also as young as 4130 Ma. The other breccia, Camel Donga, has the disturbed U-Pb system around ~4500–4400 Ma. Partially remelted textures in these brecciated samples, especially in Juvinas, suggest that reheating temperatures at the 4200 Ma event(s) may have locally exceeded the melting points of basalts (~1060°C). Consequently, it is inferred that Vesta suffered the intense impacts with brecciation and partial remelting during ca. 4200 Ma.

In Chapter 3, I investigate the impact and reheating history of the mesosiderites parent body (MPB). Mesosiderites are unique mixtures of brecciated silicates (~50wt%) and Fe-Ni metals (~50wt%). The silicate parts are similar to eucrites in their mineralogy, geochemistry and isotopic compositions <sup>e.g.</sup> [8][9], suggesting similar parent bodies for the two. Nasa's Dawn mission did not identify mesosiderite-like regolith on the surface of Vesta. Hence, MPB is likely to be the past Vesta-like protoplanet (not exactly Vesta itself), which may not exist today. Although formation process of mesosiderites is still enigmatic, their silicates-metal mixing should have occurred during impact(s) and subsequent reheating(s) [10]–[12]. Records in mesosiderites are valuable hint for the collisional destruction and/or accretion processes of protoplanets in the early solar system. However, little is uncovered for these meteorites. The goal of this study in Chapter 3 is to reveal the MPB evolutionary history, from chronological constraints of the high-temperature events recorded in the mesosiderite zircons.

I have conducted *in-situ* U-Pb and Hf-W dating on a single zircon grain in Asuka 882023 (A88) mesosiderite, using NanoSIMS 50. Its  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  age is calculated as  $4502 \pm 75$  Ma, while its  $^{182}\text{Hf}$ - $^{182}\text{W}$  age is  $4532.8 \pm 9.6$  Ma. Both U-Pb and Hf-W systems are likely to have recorded timing of the zircon formation in A88. Considering textural and geochemical features, the zircon in A88 may have crystallized secondarily at the thermal metamorphism at 4540–4500 Ma ('4530 Ma'), distinctly later than the crustal formation of MPB at  $\geq 4560$  Ma. The silicates-metal mixing may have occurred at the same time or earlier. Although exact timing of the mixing is controversial, it is clear that MPB crusts suffered high temperature metamorphism during 4530 Ma. A plausible interpretation is that the primary crusts on MPB and metallic core in impactor(s) were mixed during the 4530 Ma impact, subsequently reheated to produce the secondary zircon. It is inferred the evolution processes of protoplanets were active at this stage. The main part of Chapter 3 is reported in Koike et al. (2017).

Finally, I summarize the present chronological knowledge from eucrites and mesosiderites, along with literature data of various meteorites. From comparison of the various chronological records, it is inferred that Vest and Vesta-like protoplanets experienced thermal events at (I) ca. 4530 Ma, (II) ca. 4200 Ma, and (III) 3800 Ma (Fig. 2). The event (I) can be both internal thermal metamorphism and impacts. The later (II) and (III) should be impact reheating. The event (II) was identified from the U-Pb systems in phosphates and silicates from several eucrites, while the event (III) was recorded in their K-Ar systems. Future investigations of additional extraterrestrial samples will enable the further discussion.



**Fig. 2.** Age comparisons with various meteorites. References are in the main text. (A) Pb-Pb (zircon, apatite, silicates) and Hf-W (zircon) ages. (B) Pb-Pb, Hf-W, and Ar-Ar. records.

Refs: [1] Mittlefehldt, 2014; [2] Wadhwa, 2014; [3] Yamaguchi et al., 1996; [4] Misawa et al., 2005; [5] Zhou et al., 2013; [6] Iizuka et al., 2015; [7] Cherniak et al., 1991; [8] Clayton & Mayeda, 1996; [9] Greenwood et al., 2015; [10] Rubin & Mittlefehldt, 1993; [11] Scott et al., 2001; [12] Haba et al., 2017