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Major and trace elements of zircons from basaltic eucrites: Implications for the formation of zircons on the eucrite parent body

Makiko K. Haba [a,b,*], Akira Yamaguchi [a], Kenji Horie [a], Hiroshi Hidaka [c]

[a] National Institute of Polar Research, Tachikawa, Tokyo 190-8518, Japan
[b] Geochemical Research Center, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[c] Department of Earth and Planetary Systems Science, Hiroshima University, Higashi Hiroshima, Hiroshima 739-8526, Japan

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The major and trace elements in zircons obtained from basaltic eucrites Yamato [Y]-75011, Y-792510, Y-82082, Asuka [A]-881467, Juvinas, and Stannern were determined using an electron microprobe analyzer and a sensitive high-resolution ion microprobe, and the formation of zircons on the parent body was discussed. The maximum sizes of zircon grains in each sample are likely to be related to its metamorphic grade. The least-metamorphosed basaltic eucrite Y-75011 contains zircons with sizes of a few µm. Conversely, the highly metamorphosed basaltic eucrites Y-792510 and A-881467 include zircons larger than 20 µm. The relationship between the maximum grain size and metamorphic grade suggests that the formation process of zircons is related to metamorphic events. The Zr/Hf ratios of the zircons found in this study show a wide variation (31.6–71.7), as compared to the chondritic values (Zr/Hf = 32.8–34.3) and bulk basaltic eucrites (34.0–34.7). The Zr/Hf ratios of the zircons from Y-792510 and A-881467 are relatively constant, whereas those of the zircons from Y-82082, Juvinas, and Stannern show large variations. The rare earth element (REE) content in the zircons from Y-792510 and A-881467 is given by La = 0.1 × CI and Lu = 1000 × CI. On the other hand, the zircons from Stannern show higher REE content (La = 0.1–1 × CI and Lu = 1000–10 000 × CI) than those from Y-792510 and A-881467. The most reliable REE data of a large zircon from A-881467 show no Ce anomaly and a distinct negative Eu anomaly. Therefore, it is presumed that the zircons formed under reducing condition in which Ce^{3+} was stable. The melt compositions coexisting with the studied zircons suggest that the zircons from highly metamorphosed eucrites might react with the REE-enriched melt derived from partial melting of the mesostasis region during metamorphism.

1. Introduction

Zircon has strong resistance to mechanical and chemical breakdown over long periods and is well known to be host of incompatible elements, such as U, Th, Hf, and rare earth elements (REE) (Sawka, 1988; Bea, 1996; O'Hara et al., 2001). Although zircon is a common accessory mineral in terrestrial rocks, zircon in meteorites from asteroids is very rare. Such zircons have been observed in an H5 chondrite, mesosiderites, and basaltic eucrites (e.g., Ireland and Wlotzka, 1992; Misawa et al., 2005). Among asteroidal meteorites, zircon is the most common in basaltic eucrites. The average Zr content in 16 basaltic eucrites is 66 ppm (Barrat et al., 2000, 2007), which is much higher than that of 15 chondrites (6 ppm) (Münker et al., 2003). The high Zr content probably promoted zircon crystallization in basaltic eucrites.

Most eucrites have basaltic composition and several of them represent lavas or shallow intrusions from a differentiated parent body, possibly asteroid 4 Vesta (Consolmagno and Drake, 1977; Binzel and Xu, 1993). It has been suggested that eucrites comprise the topmost part of the eucrite parent body (EPB) (Takeda, 1997). Basaltic eucrites have been classified into three chemical groups (main group–Nuevo Laredo-trend, Stannern-trend, and residual), depending on the whole-rock molar Mg/(Mg + Fe) ratio and the incompatible elements (Basaltic Volcanism Study Project, BVSP, 1981; Warren and Jerde, 1987; Yamaguchi et al., 2009). The formation processes of the Stannern-trend eucrites and their relationship with the main group–Nuevo Laredo-trend eucrites have been unclear. Recently, Barrat et al. (2007) suggested that the chemical composition of the Stannern-trend eucrites could be explained by contamination of the main group-trend eucritic magma derived from partial melting of the asteroidal crust. The residual eucrites are basaltic eucrites that experienced varying degrees of partial melting (Yamaguchi et al., 2009).

Many isotopic studies have been conducted using long- and short-lived geochronometers to understand the evolutionary

* Corresponding author at: Geochemical Research Center, University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan. Tel.: +81 3 5841 8376; fax: +81 3 5841 4119.
E-mail address: kikuchi@eqchem.s.u-tokyo.ac.jp (M.K. Haba).

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Table 1
Characteristics of basaltic eucrites and their zircons analyzed in this study.

Sample	Sub-number	Monomict or polymict	Metamorphic grade or texture[a]	Chemical group[b]	Maximum size (μm)	Shape
Yamato-75011	,112-2	polymict	type 1	Stannern	5	irregular, thin veinlet rim of ilmenite and baddeleyite
Yamato-82082	,53	polymict	type 4	main group	10	irregular
Stannern		monomict	type 4	Stannern	15	irregular
Juvinas		monomict	type 5	main group	15	irregular, and subrounded
Yamato-792510	,71	monomict	type 6	main group	20	irregular, and subrounded
Asuka-881467	,54	monomict	granulitic	main group	30	subrounded

[a] Metamorphic grade of each basaltic eucrite is classified according to Takeda and Graham (1991). Because the metamorphic grade of A-881467 does not fit the classification in Takeda and Graham (1991), we call it "granulitic" as reported in the previous works (e.g., Yamaguchi et al., 1997; Floss et al., 2000).

[b] Chemical group of basaltic eucrites is classified into main group–Nuevo Laredo-trend (main group), Stannern-trend (Stannern), and residual eucrites (Basaltic Volcanism Study Project, BVSP, 1981; Warren and Jerde, 1987; Yamaguchi et al., 2009).

history of the EPB (e.g., Carlson and Lugmair, 2000). The presence of some nuclides from the decay of now extinct radionuclides, ^{53}Mn ($T_{1/2} = 3.7$ Ma), ^{60}Fe ($T_{1/2} = 2.6$ Ma), and ^{26}Al ($T_{1/2} = 0.7$ Ma), in several eucrites indicate that differentiation of the EPB took place within only a few Myr after the start of the solar system (Shukolyukov and Lugmair, 1993; Lugmair and Shukolyukov, 1998; Srinivasan et al., 1999; Nyquist et al., 2003; Bizzarro et al., 2005; Wadhwa et al., 2009; Quitte et al., 2011). U–Pb, Sm–Nd, Rb–Sr, and ^{244}Pu–Xe systematics of basaltic eucrites have indicated the crystallization of primitive magma at ∼4.55 Ga and disturbance and reset of isotopic systems in some eucrites (Unruh et al., 1977; Manhes et al., 1984; Chen and Wasserburg, 1985; Carlson et al., 1988; Nyquist et al., 1997; Tera et al., 1997; Miura et al., 1998). A majority of basaltic eucrites have experienced complex thermal histories such as post-crystallization thermal metamorphism (e.g., Duke and Silver, 1967; Mason et al., 1979; Takeda and Graham, 1991; Yamaguchi et al., 1994, 1996, 2001; Bogard and Garrison, 2003) and late impact events (Bogard and Garrison, 2003). These thermal events could modify the isotopic systems and result in persistently unanswered questions regarding the precise timing and duration of magmatic activity on the EPB.

In situ U–Pb and ^{182}Hf–^{182}W analyses of zircons from basaltic eucrites have been performed by secondary ion mass spectrometry (SIMS). The average ^{207}Pb–^{206}Pb age of zircons from five basaltic eucrites (Yamato [Y]-75011, Y-792510, Asuka [A]-881388, A-881467, and Padvarninkai) was 4554 ± 7 Ma, which is indistinguishable from the average U–Pb age (4552 ± 9 Ma) of the same samples (Misawa et al., 2005). Recently, Zhou et al. (2013) have reported the average ^{207}Pb–^{206}Pb age of 4541 ± 11 Ma and the U–Pb concordia age of 4525 ± 24 Ma for zircons from five basaltic eucrites (Béréba, Cachari, Caldera, Camel Donga, and Juvinas). Furthermore, ^{182}Hf–^{182}W systematics revealed that eucritic zircons crystallized within 6.8 million years after metal–silicate differentiation (Srinivasan et al., 2007). These ages suggest that the zircons could provide geochronological constraints on the evolution of their protoplanet.

In this study, we report major and trace elements of zircons from six basaltic eucrites that have different metamorphic grades. Then, we discuss the geochemical characteristics and formation processes of zircons that underwent various degrees of metamorphism on the EPB. These considerations are important to understand the thermal histories of the EPB by relating them to the ages determined using zircons from the basaltic eucrites.

2. Sample descriptions

Six basaltic eucrites (Y-75011, Y-792510, Y-82082, A-881467, Juvinas, and Stannern) were used in this study. The sub-number, monomict or polymict, metamorphic grade, and chemical group of the samples are summarized in Table 1. The metamorphic grade classification proposed by Takeda and Graham (1991) was followed. Juvinas and Stannern (falls) have not experienced the terrestrial weathering (e.g., Mittlefehldt and Lindstrom, 2003). They were selected not only to understand the geochemical characteristics of the zircons but also to evaluate possible effect of terrestrial weathering.

Y-75011 is a polymict and a Stannern-trend eucrite. The majority of clasts in Y-75011 are classified as type 1 that is characterized by fast-cooled textures, mesostasis-rich basalt, and extensively zoning of pyroxene (Takeda and Graham, 1991). It has been reported that Y-75011 has the most unequilibrated fragments (Nyquist et al., 1986; Takeda and Graham, 1991). Y-82082 is a polymict and main group–Nuevo Laredo-trend eucrite. Y-82082 was classified as type 4 in this study on the basis of the pyroxene compositions that show remnant Ca–Mg zoning (Takeda and Graham, 1991; Yamaguchi et al., 1996). The REE contents of Y-82082 indicate that Y-82082 might have experienced terrestrial weathering during its storage in Antarctic ice (Miura, 1995). Stannern is a monomict and Stannern-trend eucrite. It fell in Jihomoravsky, Czech Republic, in 1808. The textures of Stannern show ophitic to subophitic clasts and a little remnant Ca–Mg zoning of pyroxene (Takeda and Graham, 1991). Stannern is classified as type 4 (Takeda and Graham, 1991). Juvinas is a monomict and main group–Nuevo Laredo-trend eucrite. It fell in Rhose-Alpes, France, in 1821. The textures of Juvinas show breccias composed of fine- to coarse-grained subophitic and ophitic lithic clasts. Juvinas has been classified as type 5 (Takeda and Graham, 1991). Y-792510 is a monomict and main group–Nuevo Laredo-trend eucrite. Y-792510 has been classified as type 6 that is characterized by slowly cooled clasts and recrystallized mesostasis region (Takeda and Graham, 1991; Nyquist et al., 1997). A-881467 is a monomict and main group–Nuevo Laredo-trend eucrite. A-881467 shows a granulitic texture that was highly metamorphosed at ∼1000 °C (Yamaguchi et al., 1997). Because the metamorphic grade of A-881467 cannot fit the classification of Takeda and Graham (1991), A-881467 has been described as a granulitic eucrite (e.g., Yamaguchi et al., 1997; Floss et al., 2000).

3. Analytical methods

3.1. Electron microprobe analysis

Slices of each sample were mounted on an epoxy resin disk and polished with 1/4 μm diamond paste. The thin sections were examined using an electron microprobe analyzer (EPMA) (JEOL JXA 8200) at the National Institute of Polar Research, Tokyo (NIPR). Zircon was identified by elemental mapping of Zr Lα and Si Kα using EPMA. Baddeleyite (ZrO_2) was also found in Y-75011 and Juvinas. Scanning electron microscope (SEM) (JEOL JSM5900LV) at NIPR was used to obtain back-scattered electron (BSE) image and cathodoluminescence (CL) image of individual grains. In this study, the chemical heterogeneity of the zircons did not observe in CL images. Over one hundred zircon grains were found in the samples,