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Trace element composition and U-Pb age of zircons from Estherville: Constraints on the timing of the metal-silicate mixing event on the mesosiderite parent body

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Abstract

Mesosiderites are a group of stony-iron meteorites, which are thought to be the result of mixing of silicates with Fe-Ni metal. In this study, we combined textural observations with geochemical and chronological studies of two zircon grains found in the Estherville mesosiderite. One of the zircons (Zrc1) occurs with pyroxene, plagioclase, troilite, and silica, and the other (Zrc2) is located at a boundary between Fe-Ni metal and a silicate part mainly composed of pyroxene and plagioclase. The textural observations demonstrate that Zrc1 is relatively homogenous, whereas Zrc2 is composed of at least two chemically distinct domains. Trace element analyses of Zrc2 resolve large concentration gradients within this single grain with variations that are an order of magnitude for rare earth elements (REE) and two orders of magnitude for U and Th. The lowest trace element concentration in Zrc2 is more than an order of magnitude lower than those of lunar and eucritic zircons. However, it is similar to those of Zrc1 and a zircon from the Vaca Muerta mesosiderite. The calculated REE composition of the melt in equilibrium with Zrc2 shows that Zrc2 and perhaps also Zrc1 did not crystallize from a melt that was produced by fractional crystallization of the primary magmatic mineral assemblages. The zircons with low REE, U, and Th concentrations can be interpreted to have formed in a residual melt after incorporation of large amounts of REE, U, and Th into secondary phosphate minerals, which formed during the metal-silicate mixing event. The large concentration gradients observed in Zrc2 suggest significant heterogeneities in the melt from which the zircon crystallized. Alternatively, either mixing or diffusion between a relict zircon and a newly formed zircon could explain the observed concentration gradients. However, the REE patterns of Zrc2 cannot be explained by mixing or diffusion between the two distinct generations of zircons. These considerations suggest that Zrc1 and Zrc2 formed during a high-temperature reheating event, which is probably related to the metal-silicate mixing event. The weighted average ^{207}Pb-^{206}Pb age obtained by SIMS from both zircons is 4521 ± 26 Ma (2σ). This

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age is younger than that of a primary magmatic zircon from Vaca Muerta (4563 ± 15 Ma) and probably corresponds to the timing of the metal-silicate mixing event or a later impact event.

Keywords: Zircon; Mesosiderite; Trace elements; U-Pb chronology

1. INTRODUCTION

Mesosiderites are polymict breccias composed of roughly equal amounts of silicates and Fe-Ni metal. The silicate parts are composed of basaltic, gabbroic, and orthopyroxenitic clasts. Their petrology and oxygen isotopic compositions are similar to those of Howardite-Eucrite-Diogenite (HED) meteorites (McCall, 1966; Mittlefehldt, 1979; Ikeda et al., 1990; Kimura et al., 1991; Rubin and Mittlefehldt, 1993; Clayton and Mayeda, 1996; Greenwood et al., 2006). The Fe-Ni metal parts show chemical composition similar to that of IIIAB iron meteorites (Hassanzadeh et al., 1990). Results of previous chronological studies on mesosiderites indicate that the mesosiderite parent body (MPB) experienced a complex thermal history. The initial melting and differentiation of the MPB occurred within several million years after solar system formation (Schönbächler et al., 2002; Wadhwa et al., 2003; Bizzarro et al., 2005). Rubin and Mittlefehldt (1993) and Stewart et al. (1994) suggested that the MPB experienced significant crustal melting within 100–150 Ma after solar system formation, which possibly took place in association with the metal-silicate mixing event that formed mesosiderites. The original silicate components could have mixed with molten Fe-Ni metal during this stage (Hassanzadeh et al., 1990). The MPB may have also suffered from localized impact events that occurred 4.5–3.9 Ga ago (Murthy et al., 1977; Brouxel and Tatsumoto, 1990, 1991; Stewart et al., 1994) and collisional disruption and reassembly about 3.9 Ga ago (Bogard et al., 1990; Bogard and Garrison, 1998). Much later, mesosiderites were excavated from the MPB $\leq$ 0.1 Ga ago (Begemann et al., 1976; Albrecht et al., 2000; Bajo and Nagao, 2011).

A well-constrained age for the metal-silicate mixing event is vital to improve our understanding of the formation process of mesosiderites, which has been debated over the past decades. The U-Pb systematics of Estherville show that one component of the silicate fraction preserves the primary formation age with a ^{207}Pb-^{206}Pb age of 4555 ± 35 Ma and a U-Pb age of 4560 ± 31 Ma, while other components record a younger event with a ^{207}Pb-^{206}Pb age of 4422 ± 50 Ma and U-Pb age of 4437 ± 11 Ma (Brouxel and Tatsumoto, 1990, 1991). These ages indicate that the U-Pb system of Estherville was not reset after 4.37 Ga. In addition, three silicate clasts from Vaca Muerta and one from Mt. Padbury yielded ^{147}Sm-^{143}Nd ages of 4.48 ± 0.19 Ga, 4.48 ± 0.09 Ga, 4.42 ± 0.02 Ga, and 4.52 ± 0.04 Ga, respectively (Stewart et al., 1994). The data show that the Sm-Nd system of the silicate clasts was not reequilibrated after 4.40 Ga. Another constraint on the timing of the metal-silicate mixing was obtained from ^{53}Mn-^{53}Cr isotopic systematics of silicate clasts from Vaca Muerta (Wadhwa et al., 2003). The ^{53}Mn-^{53}Cr data indicate that the equilibration of the clasts must have taken place > 20 Ma after solar system formation, perhaps during the metal-silicate mixing event. Although the U-Pb, Sm-Nd and Mn-Cr data suggest that the metal-silicate mixing occurred 20–170 Ma after solar system formation, the age still spans a large range of 150 million years. Analysis of silicate clasts and/or minerals that can be demonstrated to have formed or were equilibrated during the metal-silicate mixing event could provide more precise age constraints for this mixing event. Also, it is necessary for the sample to have remained a closed system for the applied chronometer during later reheating events.

Accessory zircon ($ZrSiO_4$) was previously found in asteroidal meteorites including basaltic eucrites (e.g., Misawa et al., 2005; Roszjar et al., 2011; Zhou et al., 2013; Haba et al., 2014), mesosiderites, and H5, L5, and LL3–6 chondrites (e.g., Ireland and Wlotzka, 1992; Roszjar et al., 2014). Zircon has strong resistance to thermal resetting under dry conditions compared to other minerals in meteorites. In addition, it is suitable for U-Pb and Pb-Pb dating owing to its moderate to high U content and virtually no initial Pb. U-Pb and Pb-Pb dating of meteoritic zircons has been performed employing secondary ion mass spectrometry (SIMS) because the grain size of the zircons is generally smaller than a few tens of micrometers. ^{207}Pb-^{206}Pb ages of zircons from basaltic eucrites cluster around ~4550 Ma (Misawa et al., 2005; Zhou et al., 2013), with a few younger ages as low as 4530 Ma (Zhou et al., 2013; Hopkins et al., 2015). The older ages are interpreted to represent the crystallization age of extrusive lavas on the parent body of eucrites, while the younger ages are considered to correspond to the timing of reheating or impact events.

U-Pb dating of one zircon from the Vaca Muerta mesosiderite yielded a ^{207}Pb-^{206}Pb age of 4563 ± 15 Ma (2σ) (Ireland and Wlotzka, 1992). This old zircon has been recognized as a relict zircon that formed in the silicate part before the metal-silicate mixing event. In contrast, recent studies of eucritic zircons propose that their formation could be associated with sub-solidus metamorphic events (Haba et al., 2014; Roszjar et al., 2014; Iizuka et al., 2015). Haba et al. (2014) measured major and trace elements of zircons from six basaltic eucrites having different metamorphic grades and suggested that the zircons from highly metamorphosed eucrites could have formed during a sub-solidus reheating event. Subsequently, Iizuka et al. (2015) revealed that zircons in Agoult, which is a highly metamorphosed and unbrecciated basaltic eucrite, formed from a reaction between Zr released from ilmenite and silica during a sub-solidus metamorphic event 4554.5 ± 2.0 Ma ago. The bulk sample and ilmenite from Vaca Muerta have