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The W isotope composition of eucrite metals: constraints on the timing and cause of the thermal metamorphism of basaltic eucrites

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Abstract

Basaltic eucrites formed as lava flows at or near the surface of asteroid Vesta. After crystallization, most eucrites were affected by thermal metamorphism, the timing and cause of which are enigmatic. We present Hf–W data for magnetic (largely metal) and non-magnetic fractions (mostly silicates and oxides) from six basaltic eucrites that allow the first direct dating of this thermal metamorphism. All metals have high W contents and show excesses in the abundance of ^{182}W (between 2 and 16 ϵ_W) relative to the initial ϵ_W of the whole-rock isochron ($\epsilon_W \sim -0.5$), indicating a late re-mobilization of radiogenic W from silicates into metal. The Hf–W ages of metal formation/re-equilibration in five out of six eucrites agree and give a weighted average of 16±2 Myr after mantle–crust differentiation in Vesta, corresponding to an 'absolute' age of 4547±2 Myr when using the H chondrite Ste. Marguerite as an absolute time marker. Hf–W isotopic closure in metal from Stannern occurred 0.5–3.6 Myr after mantle–crust differentiation, which is significantly earlier than in the other eucrites. The different whole-rock and non-magnetic fractions from Bouvante, Ibitira and Juvinas plot along the eucrite whole-rock isochron but are not collinear with their respective metal fractions. Thus, metal and silicates in eucrites have not been in complete W isotopic equilibrium, indicating that the Hf–W metal ages correspond to a short re-heating rather than a magmatic event. Based primarily on age comparison, the temperature required for W diffusion from silicates into metal is estimated to be at least ~600 °C, similar to the peak metamorphic temperatures deduced from diffusion profiles in eucritic pyroxenes. The Hf–W ages of metal formation/re-equilibration, therefore, provide the first direct age constraints on the thermal metamorphism that affected almost all eucrites. The ~16 Myr time gap between mantle–crust differentiation and metal formation/re-equilibration indicates that the thermal metamorphism cannot be related to differentiation of a magma ocean into layers or rapid burial of early crust. Impacts instead must have provided the energy for re-heating of early-erupted basalts. Given that five out of six eucrites studied here exhibit identical Hf–W ages, the thermal metamorphism may have been caused by a large impact on Vesta. The Hf–W systematics in Stannern were not affected by this event, indicating that Stannern is derived from a different part of Vesta's crust than the other examined eucrites. Ar–Ar ages for unbrecciated and brecciated eucrites [Bogard and Garrison, Meteorit. Planet. Sci. 38 (2003)

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669–710] are ~50 Myr and more than ~450 Myr younger than the Hf–W metal ages, reflecting later impact-induced heating events that caused resetting of Ar–Ar ages but did not affect the Hf–W systematics.

Keywords: eucrites; thermal metamorphism; W isotopes; Vesta; impacts

1. Introduction

Basaltic eucrites are meteorites that formed as a result of igneous activity on a small planet, probably the asteroid Vesta [1]. Eucrites have magmatic textures similar to those of terrestrial and lunar basalts, indicating formation as lava flows at or near the surface of Vesta [2]. As a result of rapid cooling near the surface, the pyroxenes in terrestrial and lunar basalts are chemically zoned. In contrast, pyroxenes in most eucrites show no chemical zoning and contain exsolution lamellae, indicating slow cooling and/or a prolonged thermal metamorphism after crystallization from a melt [2,3]. In addition to this thermal overprint, most eucrites are brecciated as a result of impacts [4–6], prompting some authors to suggest that the thermal metamorphism is related to impact heating [4,7]. Other authors, however, attribute the thermal metamorphism on Vesta to slow cooling after differentiation of a magma ocean into layers [8] or burial of early crust by rapid successions of extensive lava flows [3]. These scenarios imply that the thermal metamorphism took place during or shortly after mantle differentiation and crust formation on Vesta at ~4564 Ma [9,10]. In contrast, impact heating may have occurred at a later time as, for example, recorded by relatively young Ar–Ar ages of ~4.1 to 3.5 Ga [5,6,11,12]. Thus, direct dating of the thermal metamorphism is essential to determine the processes and heat sources that ultimately caused this high temperature overprint.

All eucrites contain at least some metal (typically <0.5%), which formed either during crystallization or later metamorphism [13]. The low Ni contents of these metals exclude a meteoritic origin by impacts on the surface of Vesta. The Camel Donga eucrite has the highest metal contents among eucrites and the metal in this meteorite evidently formed by reduction of FeO and FeS during thermal metamorphism [14]. The time of metal formation and/or redistribution of W between metal and silicate can be constrained with the extinct ^{182}Hf–^{182}W isotope system that has proven useful in dating metal-silicate separation processes in the early solar system [15–18]. Hafnium is lithophile, whereas W behaves moderately siderophile, resulting in a fractionation of Hf from W during metal-silicate separation. Metals contain virtually no Hf, such that they preserve the W isotope composition acquired at the time of metal formation and/or redistribution of W between metal and silicate. In contrast, the high Hf/W silicates will evolve to more radiogenic ^{182}W/^{184}W ratios and thus can be used to construct isochrons with the comparatively unradiogenic metals. We present Hf–W data for magnetic (largely metal) and non-magnetic (mostly silicates and oxides) fractions of six basaltic eucrites that allow the first direct dating of the thermal metamorphism of eucrites. The selected samples include the brecciated eucrites Bereba, Bouvante, Camel Donga (two fragments), Juvinas (three fragments) and Stannern, as well as the unbrecciated eucrite Ibitira.

2. Analytical methods

Samples were cleaned with steel-free abrasives and in an ultra-sonic bath, leached in 0.05 M HNO_3 for a few minutes and powdered in an agate mortar. Metal-silicate separation was performed using a hand magnet. Silicate dust adhering to the metal grains was removed by repeated crushing of the magnetic fractions in ethanol. Some non-magnetic fractions were further purified by alternately grinding the powder in an agate mortar and removing the remaining metal grains with a magnet. The pyroxene separate from Juvinas was purified using heavy liquids. About 200–500 mg of the whole-rock samples and non-magnetic fractions were dissolved in 60 mL Savillex® vials at 180 °C on a hotplate using $HF–HNO_3–HClO_4$ (5:3:2). Between 0.1 and 2 mg of the metal separates were dissolved in 15 mL Savillex® vials with aqua regia at 120 °C on a hotplate. After digestion, the samples were dried and