THE W ISOTOPE COMPOSITION OF EUCRITE METALS: CONSTRAINTS ON TIMING AND CAUSE OF THE THERMAL METAMORPHISM OF EUCRITES. T. Kleine¹, K. Mezger¹, H. Palme² and C. Münker¹,
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Introduction: Eucrites are meteorites of basaltic composition that formed as a result of igneous activity on a differentiated parent body, which generally is considered to be asteroid 4 Vesta [e.g., 1]. After formation at or near the surface of Vesta most eucrites have been affected by thermal metamorphism [e.g., 2], the timing and origin of which is enigmatic. In addition to the thermal overprint, eucrites show evidence for shock deformation, brecciation, and melting that are related to impacts on the surface of Vesta [e.g., 3]. This has led some to suggest that the thermal metamorphism is related to heating by these impacts [e.g., 3, 4], the timing of which has been constrained by K-Ar ages to ~4.1–3.5 Ga [5,6]. However, other authors attribute the thermal metamorphism to deep burial in the parent body [7,8].

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The major differentiation of Vesta’s mantle has been dated to within the first ~5 Myr of the solar system [9,10], and models describing the thermal overprint of eucrites to be the result of magma ocean crystallization that are related to impacts on the surface of Vesta [e.g., 3]. This has led some to suggest that the thermal metamorphism is related to heating by these impacts [e.g., 3, 4], the timing of which has been constrained by K-Ar ages to ~4.1–3.5 Ga [5,6]. However, other authors attribute the thermal metamorphism to deep burial in the parent body [7,8].

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Most eucrites contain small amounts of metal, which either formed during magma crystallization or by reduction of oxidized Fe in pyroxenes during thermal metamorphism [11]. The time of formation of these metals can be constrained using the extinct $^{182}$Hf-$^{182}$W isotope system (half-life = 9 Myr) that is well suited for dating metal-silicate differentiation processes in the early solar system [e.g., 10]. We present Hf-W data for metal and silicate fractions of the eucrites Bereba, Bouvante, Camel Donga, and Juvinas that for the first time allow direct dating of the thermal metamorphism of eucrites.

Results: The Hf-W data for metal and non-metal separates as well as whole-rocks were obtained following the procedure outlined in [10,12]. The $^{182}$W/$^{184}$W ratio of a sample is reported in $\varepsilon_W$ units, which is defined as the deviation of the $^{182}$W/$^{184}$W ratio of a sample from the terrestrial value in parts per 10,000. All metal separates have low Hf/W ratios of <0.1 and show radiogenic $^{182}$W/$^{184}$W ratios of ~11 $\varepsilon_W$ (for Bereba and Bouvante) or ~16 $\varepsilon_W$ (for Camel Donga and Juvinas). The whole-rock and non-metal fractions of the studied eucrites have high Hf/W ratios (usually between 20 and 30) and $\varepsilon_W$ values between ~15 and ~25, and, thus, can be used to construct isochrons. Three fractions of Juvinas and two fractions of Bouvante plot on or close to the eucrite whole-rock isochron reported in the literature [10,13]. Two fractions from Bereba and one fraction from Camel Donga, however, plot significantly off the whole-rock isochron and the Hf/W ratios and $\varepsilon_W$ values of these samples are intermediate between those of the metals and the samples plotting on the whole-rock isochron.

Discussion: The Hf-W data for metal and non-metal fractions as well as whole-rock samples reveal two distinct trends in a plot of $\varepsilon_W$ vs. $^{180}$Hf/$^{184}$W. One of these trends corresponds to the whole-rock isochron reported previously [10,13]. This isochron gives the age of the major mantle differentiation in Vesta and is 4563.2 ± 1.4 Ma [10]. The second trend is defined by the metal separates and some silicate fractions of Bereba and Camel Donga. The elevated $\varepsilon_W$ values of the metals indicate a late re-mobilization of radiogenic W from silicates into metal. The most likely reason for this re-mobilization is thermal metamorphism that affected almost all eucrites and may have resulted in the formation of metals by reduction of Fe in pyroxenes [11]. The high abundance of metal in Camel Dong is almost certainly the result of thermal metamorphism. This has led some to suggest that the thermal metamorphism is related to heating by these impacts [e.g., 3, 4], the timing of which has been constrained by K-Ar ages to ~4.1–3.5 Ga [5,6]. However, other authors attribute the thermal metamorphism to deep burial in the parent body [7,8].

Even if metamorphism did not lead to reduction of FeO in silicates of some eucrites, redistribution of W into magmatically formed metal must have occurred, as evident from the extremely high W content in eucrite metals [14,15]. Moreover, igneous metals are expected to plot on the low Hf/W end of the eucrite whole-rock isochron, which clearly is not the case as all eucritic metals have higher $^{182}$W/$^{184}$W ratios than metal formed during eucrite crystallization. The W isotope composition of the metal, therefore, reflects the W isotope composition of the sample at the time of thermal metamorphism. The presence of two distinct trends in a plot of $\varepsilon_W$ vs. $^{180}$Hf/$^{184}$W indicates that the metals have not been in isotopic equilibrium with the whole-rock during the life-time of $^{182}$Hf. This is particularly evident from the Hf-W data for one of the silicate fractions of Juvinas, which, despite its higher Hf/W ratio, has a less radiogenic $\varepsilon_W$ value than the metal from Juvinas.

In order to interpret the Hf-W data for the metals in a chronological sense, the Hf/W ratio and $\varepsilon_W$ value of the host phase of the metal must be known. Since
almost all eucrites have Hf/W ratios between 20 and 40, it is reasonable to assume that the metals formed from a reservoir with such a Hf/W ratio. With this assumption the metals from Bereba and Bouvante must have formed between 4546 and 4560 Ma and those from Camel Donga and Juvinas between 4500 and 4555 Ma. Provided that the Hf/W ratios of Camel Donga and Juvinas are slightly higher than those of Bereba and Bouvante, all metals could have formed contemporaneously between 4546 and 4555 Ma. It is thus clear that the thermal metamorphism of eucrites must have occurred at least ~10 Myr later than the major mantle differentiation in Vesta, and, thus, cannot be related to magma ocean crystallization or rapid burial of crust. Moreover, the thermal metamorphism occurred too late to be driven by decay of short-lived \(^{26}\text{Al}\) or \(^{60}\text{Fe}\). Therefore, heating by impacts is the most plausible cause for the thermal metamorphism. These impacts occurred earlier than those that are responsible for the resetting of K-Ar ages ~4.1–3.5 Ga ago, implying that the later impacts were not energetic enough to reset the Hf-W system.