^{39}Ar-^{40}Ar Ages of Eucrites and the Thermal History of Asteroid 4-Vesta.

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Summary. New Ar-Ar ages of several cumulate and unbrecciated eucrites cluster at ~4.48 Gyr. We suggest that this age cluster was produced by interruption of eucrite metamorphism within the Vesta parent asteroid by a giant impact, which excavated and rapidly cooled these meteorites. We see no evidence for younger formation ages of the cumulate eucrites, as previously proposed.

Introduction. Several observations indicate that the eucrite parent asteroid is relatively large and is probably 4-Vesta. First, most eucrites were extensively metamorphosed to temperatures ≥800°C (1,2). This heating probably occurred as a consequence of early, deep burial, either through differentiation of a molten crust into layers (3) or very rapid accumulation of deep (15-25 km) layers of basalt (4). Second is the observation that asteroid 4-Vesta shows a reflectance spectrum similar to those of eucrites (5). Many smaller asteroids with similar spectra (i.e., vestoids) were apparently derived from Vesta by impacts and have orbital parameters that approach those orbital resonances thought to be "gateways" for perturbing objects into Earth-crossing orbits (6,7). A third reason is the observation that almost all K-Ar ages of eucrites were partially or totally reset ~4.1-3.4 Gyr ago, and Rb-Sr and Pb-Pb ages of some eucrites were disturbed, as a result of large multiple impacts that also brecciated most eucrites (8). Because relatively large craters are required to produce sufficient heat to reset isotopic chronometers, and because such extensive age resetting is not observed in most other meteorites types, this argues for a relatively large parent asteroid, such as 4-Vesta

Evidence in some eucrites for decay products of extinct, short-lived nuclides (e.g., ^{26}Al, ^{53}Mn, ^{60}Fe) and of old Pb-Pb model ages (9,10) argue that most eucrites formed very early, >4.555 Gyr ago. Yet, 14 younger, but variable Pb-Pb and ^{147}Sm-^{143}Nd isochron ages have been reported for four cumulate eucrites and three basaltic, unbrecciated eucrites (10,11). These ages range over ~4.40-4.55 Gyr (Fig. 1).

New Ar-Ar Results. We measured ^{39}Ar-^{40}Ar ages of six eucrites classified as cumulate and 11 eucrites classified as unbrecciated. Our rationale in studying these eucrites is that they may have escaped the impact heating that affected brecciated basaltic eucrites (8), and thus give information about the early thermal history of the eucrite parent body. Three cumulate and two unbrecciated eucrites give relatively young ages of 3.4-3.7 Gyr. These Ar-Ar ages were reset by later impact heating, in spite of the apparent lack of textural evidence for impact brecciation of the meteorites. However, Ar-Ar ages of the other eucrites cluster at ~4.45-4.51 Gyr, with an average value of 4.48 ±0.02 Gyr (Fig. 1). The most precisely determined ages of two cumulate and four unbrecciated eucrites give an even tighter grouping of 4.48 ±0.01 Gyr. This age is identical to the Pb-Pb whole rock isochron for cumulate eucrites reported by (11). Below we evaluate three possible explanations for the overall distribution of Ar-Ar, Pb-Pb, and Sm-Nd ages (Fig. 1).

Young Formation. From their U-Th-Pb study, Tera et al (11) suggested that the cumulate eucrites actually formed at later times, and possibly on a different parent body. In their model of the possible thermal history of Vesta, Ghosh and McSween (12) concluded that 100 Myr after formation, much of the deep interior of Vesta would remain above 1100°C (the upper ~15 km above ~400°C), which might permit late eucrite formation. However, arguments can be made against late cumulate formation. Recent ^{176}Lu-^{176}Hf data (13) suggest comparable ages for several cumulate and basaltic eucrites, and as we note above, at least some basaltic eucrites formed very early. In addition, of the three cumulate eucrites with the youngest Pb-Pb and Sm-Nd ages (i.e., <4.46 Gyr), the Pb-Pb and Sm-Nd ages of one (Sera de Magé) may have been partially reset by impact heating, which occurred at the time of its Ar-Ar age of ~3.4 Gyr. The other two cumulates (Moama and EET87520) have Pb-Pb ages that are younger than either their Ar-Ar or Sm-Nd ages, and the uncertainty in the Pb-Pb age of one of these (Moama) is sufficiently large (±92 Myr) that it overlaps both the Ar-Ar and Sm-Nd ages (which agree with each other within their uncertainties). Further, if the observed spread in Pb-Pb and Sm-Nd ages (Fig. 1) reflects young formation, why do the Ar-Ar ages group more tightly, and why are the Sm-Nd ages of cumulate EET87520 and unbrecciated Caldera older than the Ar and Pb ages? Thus, we reject young formation times as the sole explanation for the age distribution in Fig. 1.

Metamorphism. If the eucrite parent body remained hot internally for a significant period (12) and if both cumulate and basaltic eucrites were metamorphosed at considerably depth in that body (3,4), then we might expect isotopic chronometers to have remained open for a considerable period of time after actual eucrite formation. As isotopic diffusion stopped in the cooling environment, closure of these chronometers is expected to occur at a different time for each chronometer (generally Sm-Nd before Pb-Pb, before K-Ar) and possibly at a different time for each meteorite. Additional support for a slowly cooling environment is the observation of variable fission ^{244}Pu-^{136}Xe ages of ~4.56-~4.46 Gyr among 22 eucrites, including two cumulate and three unbrecciated (14,15). However, if this were the sole explanation for younger ages, we might expect each meteorite to give ages in the decreasing sequence of Nd>Pb>Ar. Because diffusion loss of Ar occurs so readily, we certainly would not expect the tight grouping of Ar-Ar ages (Fig. 1).

Early Impacts. We believe that the strong clustering of Ar-Ar ages of cumulate and unbrecciated eucrites is not accidental, but rather dates some widespread event on the parent body. We suggest that the slightly younger ages were produced by a combination of metamorphic heating at depth and a very large impact on Vesta, which excavated these meteorites to the surface, rapidly cooled them, and quenched their isotopic chronometers. We suggest that this impact occurred ~4.48 Gyr ago and caused closure of all K-Ar ages, which were open until that time. The somewhat older Sm-Nd ages for a few of these eucrites (Fig. 1) can be explained if these chronometers had already closed prior to this impact. In their multidiscipline study of EET90020, Yamaguchi et al (16) concluded from mineral textures that this unbrecciated eucrite formed at the surface and later was metamorphosed at depth to grade 5. Then, while at a temperature of ~870^{o}C, it was briefly heated above the subsolidus temperature of ~1060^{o}C, causing partial melting; and finally cooled rapidly at several ^{o}C/day. These authors suggested that this partial melting event was responsible for resetting the Sm-Nd and Ar-Ar ages, as well as apparent disturbance of the Rb-Sr and Mn-Cr systems. They further suggested that this reheating event was the formation on Vesta of a very large impact crater ~4.50 Gyr ago, which excavated relatively hot material from considerable depths.

Vesta apparently possesses several very large impact craters. The largest crater is ~460 km in diameter and ~13 km deep, and a second is ~160 km in diameter (17). Spectral studies suggest that these craters have excavated deeper material richer in pyroxene and olivine (17,18). These large craters may be the source of the Vestoids (6) or an associated dynamical family of smaller asteroids (19). These smaller asteroids may be the more immediate source of eucrites that fall on Earth (7). If the immediate parent bodies of cumulate and unbrecciated eucrites were ejected as small asteroids from Vesta ~4.48 Gyr ago, this might explain how these eucrites escaped Ar-Ar age resetting during the later impact bombardment (8).

References. (1) Takeda & Graham 1991 *Meteoritics 26*, 129; (2) Mittlefehldt et al 1998 *Reviews in Mineralogy, Vol. 36, Planetary Materials*; (3) Ikeda & Takeda 1985 *Proc. 15th LPSC* C649-C663; (4) Yamaguchi et al. 1996 *Icaurs 124*, 97; (5) McCord et al. 1970 *Science 168*, 1445; (6) Binzel & Xu 1993 *Science 260*, 186; (7) Sykes & Vilas 2001 *Earth Planets Space 53*, 1077; (8) Bogard 1995 *Meteoritics 30*, 244; (9) Srinivasan et al. (1999 *Science 284*, 1348; (10) Carlson & Lugmair 2000 *Origin of the Earth and Moon* 25; (11) Tera et al.1997 *Geochim. Cosmochim. Acta 61*, 1713; (12) Ghosh & McSween 1998 *Icarus 134*, 187; (13) Blichert-Toft et al. 2002 *Meteor. Planet Sci. 37*, A19; (14) Shukolyukov & Begemann 1996 *Geochim. Cosmochim. Acta 60*, 2453; (15) Miura et al. 1998 *Geochim. Cosmochim. Acta 62*, 2369; (16) Yamaguchi et al. 2001 *Geochim. Cosmochim. Acta. 65*, 3577; (17) Thomas et al. 1997 *Science 277*, 1492; (18) Gaffey 1997 *Icarus 127*, 130; (19) Zappala et al. 1995 *Icarus 116*, 291.