^{39}AR-^{40}AR DATING OF UNUSUAL EUCRITE NWA 011: IS IT FROM VESTA?

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Introduction: Basaltic meteorite NWA-011 is similar to eucrites in many aspects, but its oxygen isotopic composition lies far off the oxygen fractionation line defined by eucrites (1). It was suggested that NWA011 may have derived from a different parent body from that of eucrites (1), which are thought to derive from the asteroid Vesta. Some other eucrites also show small anomalous oxygen compositions (2). This suggests that for all eucrites to derive from Vesta, it must be compositionally inhomogeneous. Some workers have speculated whether early, large impactors on Vesta might have contributed the anomalous oxygen (2, 3).

Prior Chronologies: Nyquist et al. (3) reported a ^{147}Sm-^{143}Nd isochron age of 4.46 ±0.04 Gyr for NWA-011. This age is younger than the formation time of some other eucrites (4), but it is similar to radiometric ages for several cumulate and unbrecciated basaltic eucrites (4, 5). The ^{39}Ar-^{40}Ar ages of most eucrites were strongly disturbed or reset by impact heating, primarily ~4.1-3.4 Gyr ago (5). No other class of meteorite is known to display frequent impact resetting of Ar-Ar ages in this time period. Impact resetting of Ar-Ar ages requires heating by relatively large events. These are attainable on relatively large parent bodies such as Vesta, whereas large impacts would disrupt smaller parent bodies (6). If NWA-011 shows major resetting of its Ar-Ar age in the range of ~3.4-4.1 Gyr, that could be an argument for an origin from Vesta. On the other hand, if NWA-011 indicates no impact resetting of its Ar-Ar age, or age resetting at a very different time, that may or may not be consistent with a Vesta origin, as some eucrites also do not show age resetting over ~3.4-4.1 Gyr.

Korotchantseva et al (7) found significant effects of terrestrial weathering in an Ar-Ar analysis of NWA-011 WR. These included adsorbed terrestrial Ar and recoil redistribution of ^{39}Ar (produced during neutron irradiation), which transferred part of the ^{39}Ar produced in low-temperature phases to sites releasing at higher temperature. With increasing extraction temperatures, their Ar-Ar age spectrum rises from an age of ~0.8 Gyr to ~3.9 Gyr, then decreases to ~3.3 Gyr in the last ~25% of the age spectrum. The authors suggest a crystallization age of >3.2 Gyr and a thermal event at 0.8 Gyr. However, it is hard to evaluate the effects of recoiled ^{39}Ar on the age spectrum at higher temperature.

New Ar-Ar Age Data: We made ^{39}Ar-^{40}Ar analyses of two samples of NWA-011 that were specially treated in an effort to reduce or eliminate weathering products. These products primarily occur on grain surfaces and act as the source of most of the recoiled ^{39}Ar that affects the age spectrum at higher temperatures. We treated a whole rock (WR) sample of NWA-011 with dithionite citrate bicarbonate, which is very effective at removing some weathering products. A second sample was separated into mineral fractions for dating by other chronometers (3). The separated feldspar, which still exhibited some discoloration of grain surfaces, was then leached with dilute nitric acid (0.5 N for 15'). The ^{39}Ar-^{40}Ar age spectra for the treated WR and feldspar samples are shown in Figs. 1 & 2, respectively.

The Ar-Ar age spectrum of NWA-011 WR rises from an age of ~1.1 Gyr to an age of ~3.3 Gyr at ~80% ^{39}Ar release, then decreases to an age of ~3.1 Gyr. The K/Ca ratios in the first few extractions are only slightly elevated over the nearly constant ratio of ~0.006 for 20-75% ^{39}Ar release. Only the first extraction shows an elevated ^{36}Ar/^{37}Ar indicative of adsorbed terrestrial Ar. These characteristics indicate that the chemical treatment removed much of the K-rich weathering product observed in the WR analysis by (7). The slight decrease in age over ~85-98% ^{39}Ar release (even more pronounced in the data of 7) coincides with a large drop in K/Ca ratio and is likely produced by release of some ^{39}Ar recoiled into pyroxene grain surfaces. As weathering phases were largely removed in our WR sample, the source of this recoiled ^{39}Ar was probably feldspar. An isochron plot of the first few extractions (~0-30% ^{39}Ar release) displays no linearity to indicate a two component mixture of terrestrial Ar and a constant age. In contrast, the analysis by (7) gave such a linearity consistent with an age of ~0.8 Gyr for several low temperature extractions showing elevated K/Ca ratios. These differing observations suggest that the 0.8 Gyr "age" is associated with terrestrial weathering products and may not be real.

The Ar-Ar age spectrum of the NWA-011 feldspar separate shows significant effects of weathering products in the first 30% of the ^{39}Ar release. These include much higher K/Ca ratios compared to 40-100% of the ^{39}Ar release, much greater loss of radiogenic ^{40}Ar, and significant amounts of adsorbed terrestrial Ar. Using the ^{36}Ar/^{37}Ar ratio to correct for terrestrial Ar, the first few extractions give an age near zero, but terrestrial Ar is absent by the 625^{o}C extraction (32-35% ^{39}Ar release). Apparently, the chemical treatment used on the WR sample was much more effective in removing terrestrial weathering products than was mineral separation of feldspar and its acid etching. In spite of this, the feldspar gives a more interpretable age, because ^{39}Ar recoil effects are apparently absent. Across ~30-75% of the ^{39}Ar release, the Ar-Ar age shows a steady rise characteristic of diffusive loss of ^{40}Ar. Above ~75% ^{39}Ar release, nine extractions define an age plateau with a mean value of 3.145 ±0.034 Gyr. Because the feldspar separate was quite pure, little pyroxene exists to lower the K/Ca ratio at higher temperatures or to act as a catcher of recoiled ^{39}Ar and lower the age spectrum (c.f. Figs. 1 and 2). It seems reasonable to conclude that this feldspar plateau age of 3.15 Gyr is the time of last major Ar degassing of NWA-011. However, it is somewhat puzzling that, whereas the high temperature data of all three NWA-011 analyses (Figs. 1&2 and ref. 7) give comparable ages of ~3.2 Gyr, the two whole rock analyses give higher maximum ages at intermediate temperatures of ~3.3 Gyr (Fig.1) and ~3.9 Gyr (ref. 7). These higher ages may have been caused by weathering.

Origin of NWA-011: Although terrestrial weathering of NWA-011 causes its Ar-Ar age to be difficult to determine, this Ar-Ar age could be an important clue to the meteorite's origin. Most eucrites show impact reset Ar-Ar ages over the time period of ~3.4-4.1 Gyr ago (5), whereas essentially no other meteorite type is known to show significant impact resetting of Ar ages in this time period. This observation has been attributed to the relatively large size of the eucrite parent asteroid, Vesta (6). If NWA-011 possessed an Ar-Ar age in this time range, that would be consistent with a Vesta origin. In addition, the cosmic-ray (space) exposure age of ~25 Myr for NWA-011 is close to a peak in CRE ages observed in many other HED meteorites (8). However, if the time of major Ar degassing of NWA-011 is really 3.15 Gyr, as indicated by the feldspar data, then it shows an age younger than that generally observed for eucrites (~3.4-4.1 Gyr). In this case, the chronology link between NWA-011 and Vesta is weaker. Whatever the origin of NWA-011, either from Vesta or some other parent body, impact resetting of its Ar-Ar age long after parent body formation suggests a relatively large impact and probably a relatively large parent body.

References: (1) A. Yamaguchi et al., *Science 296*, 334, 2002; (2) U. Wiechert et al., *Goldschmidt Conf.* A834, 2002; (3) L. Nyquist et al., *MAPS 38*, A59, 2003; (4) Carlson & Lugmair, *Origin of Earth & Moon*, 2000; (5) Bogard & Garrison, *MAPS 38*, 669, 2003; (6) Bogard, *Meteoritics 30*, 244, 1995; (7) Korotchantseva et al., *LPSC XXXIV*, #1575, 2003; (8) Wakefield et al., *LPSC XXXV* #1020, 2004.