CHRONOLOGY OF THE EUCRITE NORTHWEST AFRICA 8661: A RECORD OF ANCIENT VOLCANISM ON VESTA.

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Introduction: Eucrites are members of the Howardite-Eucrite-Diogenite clan of meteorites which originate from the asteroid Vesta [1]. They are basaltic or gabbroic samples composed primarily of pigeonite and plagioclase. The chronology of eucrite formation has been extensively investigated with long-lived and short-lived chronometers ([2] and references therein). However, a significant challenge in unraveling the precise timeline of basaltic volcanism on Vesta is that most eucrites have undergone extensive thermal metamorphism. As such, eucrites are typically highly equilibrated and most chronometers are affected to varying degrees by this secondary processing. This has made it challenging to obtain reliable concordant crystallization ages using multiple chronometers for these samples.

Here we report the petrography and chronology of an atypically unequilibrated eucrite Northwest Africa (NWA) 8661, and discuss the implications for the timing of ancient volcanism on Vesta. Specifically, we have applied three high-resolution chronometers to determine the formation age of this eucrite, i.e., the relative ^{26}Al-^{26}Mg ($t_{1/2}$ = 0.705 Ma) and ^{53}Mn-^{53}Cr ($t_{1/2}$ = 3.7 Ma) chronometers as well as the absolute Pb-Pb (^{238}U $t_{1/2}$ = 4460 Ma and ^{235}U $t_{1/2}$ = 704 Ma) chronometer.

Methods: Electron microprobe analyses were performed at UCLA using, for most phases, 15 nA current and a fully focused beam (except for plagioclase, where a 3 nA current and a beam defocused to 4−5 μm was used). A single bulk rock fraction (~600 mg), free of fusion crust or any visible terrestrial alteration was processed for the Al-Mg, Mn-Cr and Pb-Pb investigations under clean laboratory conditions at ASU and ANU. A ~30 mg chip from this bulk sample (WR1) was crushed and digested in concentrated HNO_3:HF, then brought into solution in 3% HNO_3. A total of ~300 mg was processed to obtain two plagioclase (Plag A, B) and two pyroxene (Px A, B) mineral separates for the Al-Mg and Mn-Cr analyses after careful crushing, sieving, and hand-picking. These separates were also digested in HNO_3:HF and then brought into solution in 3% HNO_3. A ~5% aliquot of each sample solution was reserved for determining Al/Mg and Mn/Cr ratios.

The Mg was purified (>99% recovery) and then the isotopic composition was analyzed following methods described in [3]. The Cr was purified from the matrix cuts obtained during the Mg chemistry. The Cr was purified (~90% recovery) and the isotopic composition was analyzed following methods described in [4].

For the Pb-Pb analyses, another ~10 mg chip from the bulk sample (WR2), one plagioclase separate, and 13 pyroxene separates were prepared and processed at ANU using methods similar to [5]. A ~200 mg chip (distinct from the ~600 mg chip processed for Al-Mg, Mn-Cr and Pb-Pb analyses) was additionally processed for the determination of the $^{238}U/^{235}U$ ratio following [6].

Petrography: NWA 8661 is an unbrecciated non-cumulate eucrite with a medium-grained subophitic texture with equant pyroxenes and lathy plagioclases up to 3 mm long. Irregular-shaped, interstitial vesicles, up to 1 mm across, occupy ~3 vol.% (Fig. 1).

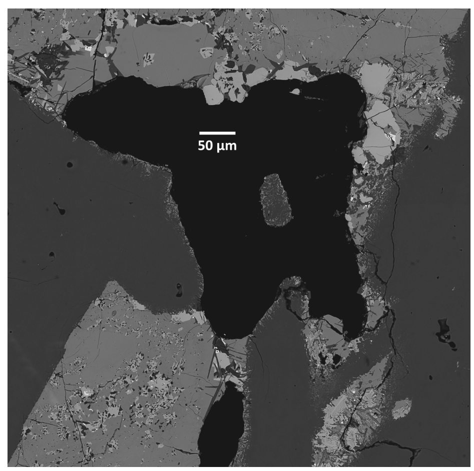

Figure 1. Backscattered electron image of NWA 8661, showing a large vesicle (black) surrounded mainly by plagioclase (dark grey) and late-stage ferroan pyroxene (light grey, intergrown with various late-stage minerals).

Saharan weathering is scarcely detectible in this eucrite. This eucrite is to an exquisite degree unaffected by thermal metamorphism. Pyroxenes lack SEM-discernible exsolution features. Mesostasis areas retain their original igneous forms as extremely fine-grained intergrowths. “Cloudy” inclusions are rare in both pyroxene and plagioclase. The pyroxene zonation resembles that of other unequilibrated eucrites (e.g., Bluewing 001 [7]) by fanning out from an initial core composition of $En_{61}Wo_{6.7}$ toward increasingly ferroan and Wo-diverse compositions in the general direction of En_8Wo_{32}. Plagioclase An content averages 80.0 (range 69-88) mol.%. Given the unequilibrated nature of this eucrite, NWA 8661 is an ideal candidate for investigating the chronology of basaltic volcanism on Vesta.

Results of Isotopic Analyses: Radiogenic excesses in ^{26}Mg and ^{53}Cr are expressed as μ^{26}Mg* and μ^{53}Cr*, respectively where the µ-notation indicates the parts per million (ppm) deviation relative to a terrestrial standard.

^{26}Al-^{26}Mg Systematics: The ^{26}Al-^{26}Mg internal isochron for NWA 8661 is defined by a bulk sample (WR1), a pyroxene separate (Px A), and two plagioclase separates (Plag A, B). This isochron yields a $^{26}Al/^{27}Al = (4.29 \pm 0.61) \times 10^{-7}$ with an initial $\mu^{26}Mg^*_0 = 18.6 \pm 9.6$ ppm (MSWD = 2.4).

^{53}Mn-^{53}Cr Systematics: The ^{53}Mn-^{53}Cr internal isochron for NWA 8661 is defined by a bulk sample (WR1), two pyroxene separates (Px A, B) and two plagioclase separates (Plag A, B). This isochron corresponds to a $^{53}Mn/^{55}Mn = (3.38 \pm 1.02) \times 10^{-6}$ with an initial $\mu^{53}Cr^*_0 = 10.1 \pm 19.5$ ppm (MSWD = 0.9).

Pb-Pb Systematics: A regression that includes the most radiogenic fractions ($^{206}Pb/^{204}Pb > 50$) yields a Pb-Pb internal isochron age of 4563.44 ± 1.11 Ma. This age is calculated using the measured $^{238}U/^{235}U = 137.808 \pm 0.011$ for NWA 8661.

Discussion: Relative to the D'Orbigny angrite age anchor [8-11], the ^{26}Al-^{26}Mg and ^{53}Mn-^{53}Cr internal isochrons for NWA 8661 give model ages of 4563.45 ± 0.30 Ma and 4563.6 (+1.9/-1.4) Ma, respectively. These ages are concordant with each other, and are additionally concordant with the Pb-Pb age of 4563.44 ± 1.11 Ma (Fig. 2). These data represent the first report of concordant, high-resolution internal isochron ages for any eucrite. Also shown in Fig. 2 are the ^{26}Al-^{26}Mg and ^{53}Mn-^{53}Cr model ages of NWA 8661 using other age anchors, i.e., the ungrouped achondrite NWA 6704 [12,13] and CAIs [14-18]. In each case, the ^{26}Al-^{26}Mg and ^{53}Mn-^{53}Cr model ages are concordant with each other, and also agree with the Pb-Pb age within the errors. It is noted, however, that while the ^{26}Al-^{26}Mg model ages relative to D'Orbigny [8], NWA 6704 [12] and the CAI B4 from the NWA 6991 CV3 [17] all agree with each other, the ^{26}Al-^{26}Mg model age relative to the Efremovka CAI 22 E [14] appears ~0.5-1 Ma younger than the other ^{26}Al-^{26}Mg model ages.

NWA 8661 seems to have avoided the fate of most other non-cumulate eucrites in light of its petrologic characteristics as well as the chronologic constraints discussed here. This implies that at least some regions on the Vestan surface largely escaped thermal and impact related metamorphism. Alternatively, NWA 8661 may have been ejected during an early basin-forming event prior to large-scale metamorphism on the Vestan crust.

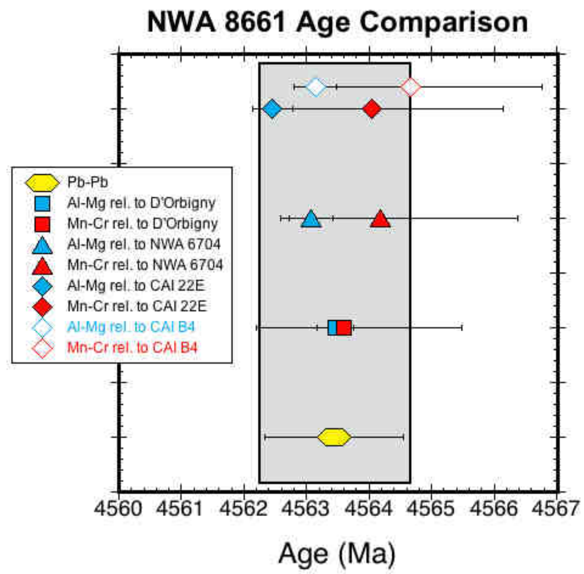

Figure 2. This plot shows the absolute Pb-Pb age and relative ^{26}Al-^{26}Mg and ^{53}Mn-^{53}Cr ages of NWA 8661. The relative ages are shown anchored to D'Orbigny (squares), NWA 6704 (triangles), and CAIs (diamonds) [8-18].

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