Evidence for burial metamorphism on Vesta from Pb–Ar chronology of the Agoult eucrite

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Introduction: Eucrites represent mafic crust likely on Vesta that has a complex geologic history involving magmatism, metamorphism, impact processing, and metasomatism. They include basaltic and gabbroic lithologies which are indicative of rapid crystallization of lava flows or shallow intrusions and slow crystallization of lower crustal magma chambers, respectively. Most of basaltic eucrites underwent thermal annealing causing Mg-Fe-Ca diffusion and exsolution of pyroxene (i.e., equilibration), demonstrating ubiquitous crustal metamorphism at temperatures ranging from ~700 to 1000 ˚C [1,2]. Yet, the mechanism for driving the metamorphism remains controversial, with hypotheses of impact heating [1,3], crustal burial accompanied by heating from the hot interior [2], annealing by younger superjacent lavas as well as intrusions [4], and combination of these [5]. To provide new constraints on the nature and cause of the metamorphism and, by implication, on the geologic history of Vesta, here we present a combined Pb and Ar isotope chronology of a granulitic eucrite Agoult that is considered to represent a region within the basaltic crust where significant recrystallization has proceeded during the metamorphism [6]. The U–Pb ages of zircon and apatite in Agoult were previously determined to be 4554.5 ± 2.0 Ma [7] and 4521 ± 11 Ma [8], respectively. Combining the results of the previous and present studies, we estimate the cooling rate and, by extension, the burial depth of the granulitic eucrite.

Methods: *Pb isotopic dating.* Pyroxene-rich, plagioclase-rich and whole-rock fractions of Agoult were analyzed for Pb isotopes. The multi-step acid washing technique described by [9] was applied: 1st-step with 0.5 N HNO_3 and 2nd-step with 6 N HNO_3 and 6 N HCl. All acid washes and residues were spiked with a mixed ^{202}Pb-^{205}Pb-^{229}Th-^{233}U-^{236}U tracer before digestion. Pb was separated using anion exchange resin AG1x8 200–400 mesh, following the method of [9]. The Pb isotopic ratio measurements were performed on MAT 261 and TRITON plus TIMS at the Australian National University. Instrumental mass bias was corrected for based on the measured ^{202}Pb/^{205}Pb.

Ar isotopic dating. Plagioclase grains of Agoult were analyzed for Ar isotopic dating, following the protocol described by [10]. The sample aliquots were loaded into an aluminum disc and irradiated for 25h in the Hamilton McMaster University nuclear reactor. The Ar isotopic analysis was carried out using a 110 W Spectron laser system at the Western Australian Argon Isotope Facility, Curtin University. The ages were calculated using the ^{40}K decay constant of [11].

Results: *Pb isotopic data.* In a plot of ^{207}Pb/^{206}Pb v.s. ^{204}Pb/^{206}Pb, acid washes and residues of Agoult define a line passing through the primordial Pb isotopic composition of [12]. Residues gave more radiogenic Pb than acid washes. The residues of plagioclase-rich fractions yielded a precise Pb-Pb isochron age of 4534.21 ± 0.85 Ma (Fig. 1), while those of pyroxene-rich and whole-rock fractions defined scattered array. The residues of plagioclase-rich fractions gave a weighted model ^{207}Pb/^{206}Pb age of 4533.93 ± 0.73 Ma, consistent with the isochron age. The model ages of residues for pyroxene-rich and whole-rock fractions are 4530–4525 Ma. The trace element data further reveal that acid residues contain oxide minerals that were originally included in plagioclase or pyroxene grains and survived the acid washing. Accordingly, the isochron age of the plagioclase-rich fractions is interpreted as reflecting the timing of U-Pb system closure in oxide minerals of Agoult. Furthermore, the youngest model ages of 4524.5 ± 1.3 Ma (MSWD = 1.8) is interpreted as the best representative of the timing of pyroxene U-Pb system closure.

Ar isotopic data. Among the five Agoult plagioclase aliquots, four defined ^{40}Ar/^{39}Ar age plateaus. The plateaus of two plagioclase fractions include 100% ^{39}Ar and yield relatively imprecise ages of 4536 ± 49 Ma (MSWD = 0.37; P = 0.97) and 4519 ± 33 Ma (MSWD = 0.5; P = 0.94) due to the small quantity of material analysed (single grains),

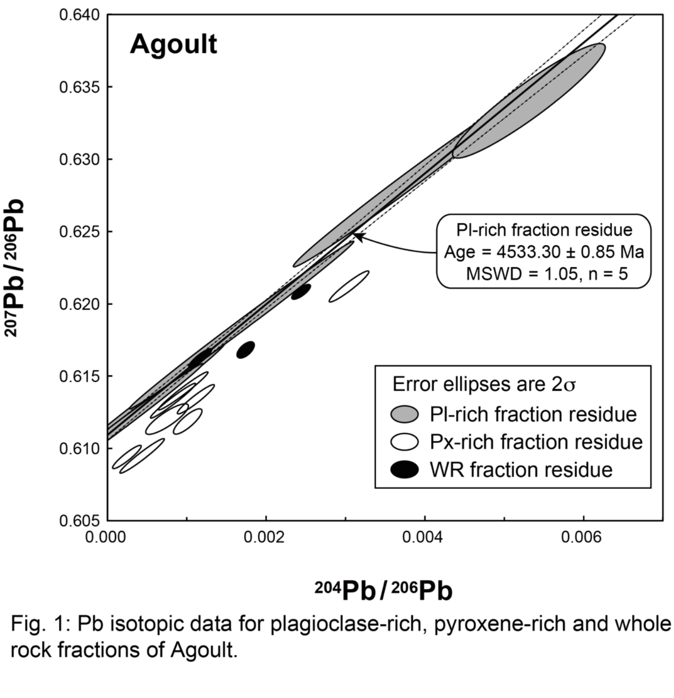

Fig. 1: Pb isotopic data for plagioclase-rich, pyroxene-rich and whole rock fractions of Agoult.

whereas those of other two fractions include 71% and 76% ^{39}Ar and provide much more precise ages of 4484 ± 13 Ma (MSWD = 0.7; P = 0.66) and 4500 ± 12 Ma (MSWD = 1.2; P = 0.26), respectively (Fig. 2). Here, taking only the two most precise ages, we calculate a preferred weighted mean age of 4493 ± 9 Ma (n = 2; P = 0.07).

Discussion: Similar, but distinguishable isotopic ages have been determined for individual minerals of Agoult: $^{207}Pb/^{206}Pb$ ages of 4554.5 ± 2.0 Ma for zircon [7], 4533.30 ± 0.85 Ma for oxide minerals, 4524.5 ± 1.3 Ma for pyroxenes, and 4521 ± 11 Ma for apatite (after [8], recalculated using the $^{238}U/^{235}U$ value of 137.794) and $^{40}Ar/^{39}Ar$ age of 4493 ± 9 Ma for plagioclase. Considering that Agoult exhibits a granulitic texture reflecting significant recrystallization, this age variation may reflect differential closure temperatures of the individual chronometers during a single prolonged metamorphic event. To evaluate this possibility, the isotopic ages are plotted against the closure temperatures for the chronometers (Fig. 3). We have calculated the Pb closure temperatures using the formalism of [13] for spherical geometry. For the calculations, we tentatively used a cooling rate of 10 ˚C/Ma. The plot shows a correlation, supporting the view that the variable isotopic ages of different minerals in Agoult reflect the successive closure of the chronometers during cooling from the thermal maximum in a metamorphic event, rather than discrete thermal events. The slope of the correlation corresponds to an average cooling rate of 10 ˚C/Ma. Note that the slope, i.e., the resultant estimate of cooling rate, is insensitive to the initial assumption of cooling rate for the closure temperature calculations, because the choice of a different cooling rate causes similar shifts in the calculated closure temperatures of the individual chronometers. This finding, together with the relict subophitic texture in Agoult [6], requires its rapid igneous crystallization at or near the surface followed by significant burial to a depth where a slow thermal relaxation can be realized during the metamorphism. Given that the cooling proceeded by thermal conduction, and assuming a thermal diffusivity of 1–4 × 10^{-7} m^2/s [14] and a constant surface temperature of -190 ˚C [15], the burial depth is estimated to be 10–20 km. Thus, our results provide evidence for burial metamorphism on the parent body, Vesta.

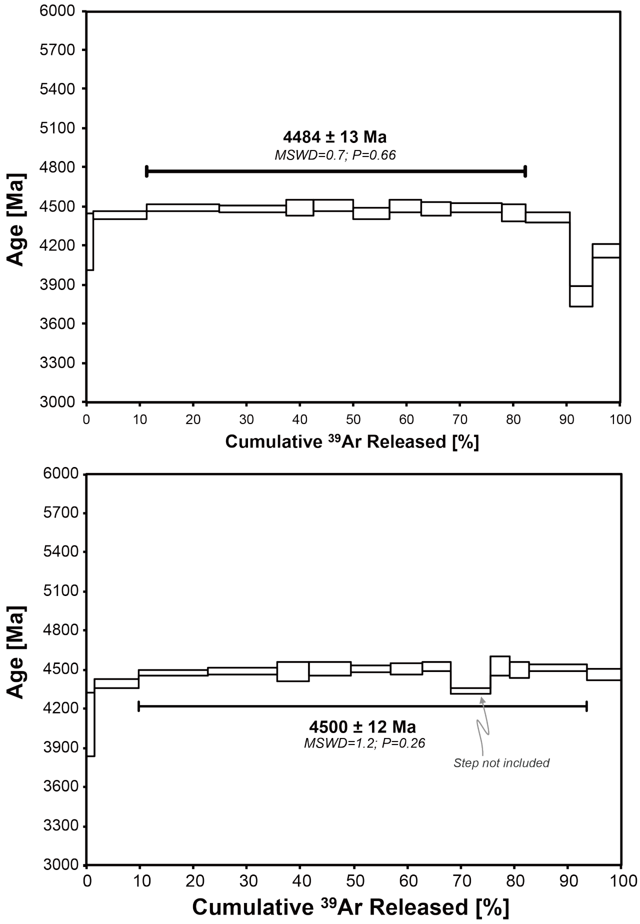

Fig. 2: Ar isotopic age spectra of two Agoult plagioclase fractions.

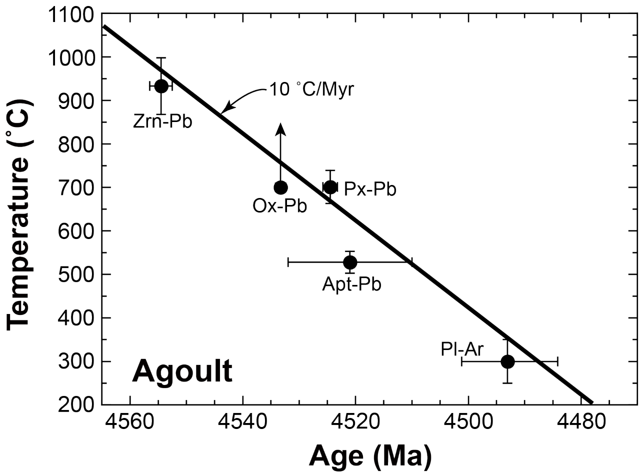

Fig. 3: Plot of Pb and Ar ages for minerals from Agoult v.s. the estimated closure temperatures of individual chronometers.

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