EARLY SOLAR SYSTEM CHRONOLOGY: SIMULTANEOUS ACCRETION OF DIFFERENTIATED AND METAMORPHOSED ASTEROIDAL CLASTS AND CHONDRULES?

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Introduction: The idea that certain meteorites represent samples of "second-generation" parent bodies (daughter asteroids) formed after collisional destruction of "parent" planetary bodies has been discussed earlier (e.g., [1-3]).

Recent results of isotopic dating studies (^{182}Hf-^{182}W, ^{26}Al-^{26}Mg; (e.g., [4-7]) and the increasing number of igneous and metamorphosed fragments observed in (primitive) chondrites (e.g. [8-11]) provide strong evidence that accretion and differentiation of planetesimals pre-dates the formation of primitive chondrite parent bodies.

Some very primitive chondrites (Adrar 003, Acfer 094) contain unusual fragments that seem to have undergone high-grade thermal metamorphism. Within the ordinary chondrite breccias AdzhiBogdo and Study Butte clasts with igneous textures occur (granitoidal and andesitic fragments). These objects may represent clasts of precursor planetesimals and indicate mixing of achondritic fragments and chondritic components. Al-Mg isotope systematics can be used to obtain their relative ages. Here, Al-Mg isotope data for several of these fragments are presented.

Analytical Method: Polished thin sections of Acfer 094, Adrar 003, Adzhi Bogdo and Study Butte were studied by optical microscopy, scanning electron microscopy (SEM), and with an electron microprobe.

Magnesium isotope ratios and Al/Mg ratios were measured by secondary ion mass spectrometry (SIMS). Two granitoid fragments from Adzhi Bogdo, which have feldspar grains that are > 20 μm in size, were analyzed with the CAMECA IMS 3f ion microprobe at St. Louis. A 17 keV $^{16}O^-$ primary beam of ~ 3.0 nA was focused into a 10-15 μm spot. The secondary Mg ions were collected with an electron multiplier (EM) in peak jumping mode with a mass resolving power of ≈ 3500. For all other inclusions the NanoSIMS ion probe at St. Louis was used. A $^{16}O^-$ primary ion beam of ~30-50 nA and 10 keV energy (2-4 μm in diameter) was used to generate positive secondary ions for the analysis. Typical mass resolving power was ~4000. Magnesium isotopes were measured in a peak jumping mode, while Al^+ was detected simultaneously (multi-detection mode).

Results: Acfer 094 is a unique, type 3 carbonaceous chondrite, which appears to be a mineralogically pristine rock that escaped thermal metamorphism and aqueous alteration. This meteorite contains numerous fragments that seem to be highly metamorphosed (Fig. 1a). The ^{27}Al/^{24}Mg ratios of plagioclase in these metamorphic fragments are in the range of 24 – 74, which unfortunately is quite low, making it difficult to detect radiogenic ^{26}Mg for small ^{26}Al/^{27}Al ratios. The Mg isotopic compositions of these fragments are normal within experimental uncertainties. No evidence for radiogenic ^{26}Mg was observed. Upper limits for ^{26}Al/^{27}Al range from 6.6 x10^{-6} to 1.2 x 10^{-5}. It is unclear whether the fragments never had any ^{26}Al or had their ^{26}Al clock reset during thermal metamorphism. However, upper limits imply that metamorphism of these inclusions postdates the formation of CAIs by at least 1 – 2.5 Ma.

Adrar 003 is an LL(L)3 chondrite, whose unequilibrated character was recognized immediately [12]. Several apparently metamorphic fragments were observed among other constituents (Fig.1b). Some of them represent metamorphosed, type 6 fragments that still contain relics of barred-olivine chondrules. None of the 4 analyzed metamorphic fragments show clear evidence for ^{26}Mg excess but the limits on (^{26}Al/^{27}Al)$_0$ permitted by the data are not particularly tight. The Al/Mg ratios in measured plagioclases are low (ranging from 32 to 97) and result in large uncertainties for the inferred limits on ^{26}Al/^{27}Al. Upper limits range from 8.2×10^{-6} to 2.4×10^{-5}. The possibility that all evidence of once existing ^{26}Al was destroyed by parent-body metamorphism after accretion can be excluded, because Adrar 003 escaped thermal metamorphism. The lack of evidence for ^{26}Al can be due to the metamorphic overprint of these fragments on the precursor parent body. These results demonstrate that Adrar 003 accreted rather late (at least 2.2 Ma after CAIs), in spite of its primitive nature.

Adzhi Bogdo contains pyroxene-rich fragments with achondritic textures, and alkali-granitoids (Fig. 1c; [13]). The alkali-granitoids primarily consist of K-feldspar and SiO_2-phases. Most likely, these fragments formed from a melt. The analyzed orthoclase grains in two of these granitoid fragments have quite high ^{27}Al/^{24}Mg ratios (1350 – 2330), but no ^{26}Mg excess was detected. Upper limits on the ^{26}Al/^{27}Al ratio are 6×10^{-7} and 5×10^{-7}, respectively. These limits refer to the ^{26}Al/^{27}Al ratio at the time when the rocks had cooled enough for Mg-diffusion to have ceased, which must have been at least 4.8 Ma after CAIs formed.

Among other components Study Butte (H3-6) contains one fragment with an andesitic bulk composition [14]. This fragment (Fig. 1d) has an igneous texture, distinctly different from the textures of chondrules or lithic clasts from this meteorite. Plagioclase in this fragment has fairly high $^{27}Al/^{24}Mg$ ratios, in the range from 2230 to 6600. Four distinct feldspar grains were measured but no ^{26}Mg excesses above the experimental uncertainties could be detected. The upper limit on $(^{26}Al/^{27}Al)_0$ is 1.2×10^{-6}, indicating that this clast did not cool until at least ~ 4 Ma after CAIs formed.

Conclusions: No clear evidence of radiogenic ^{26}Mg could be found in any of the studied fragments and 2σ upper limits for $^{26}Al/^{27}Al$ range from 5.6×10^{-7} to 2.4×10^{-5}. The possibility that evidence for ^{26}Al was destroyed by parent-body metamorphism after formation is not likely, because other constituents of these primitive chondrites do not show any metamorphic features. Since final accretion of a planetesimal must have occurred after formation of its youngest components, formation of the parent bodies of Acfer 094 and Adrar 003 and the mixing process and the lithification of the regolith breccias Adzhi Bogdo and Study Butte must thus have been relatively late (i.e. after most ^{26}Al had decayed). The absence of ^{26}Mg excess in the igneous inclusions does not exclude ^{26}Al from being a heat source for planetary melting. In large, early formed planetesimals, cooling below the closure temperature of the Al-Mg system may have been too late for any evidence for live ^{26}Al (in the form of ^{26}Mg excess) to be retained.

In summary, this study adds to the growing evidence that chondritic meteorites represent the products of a complex, multi-stage history of accretion, parent body modification, disruption and re-accretion.

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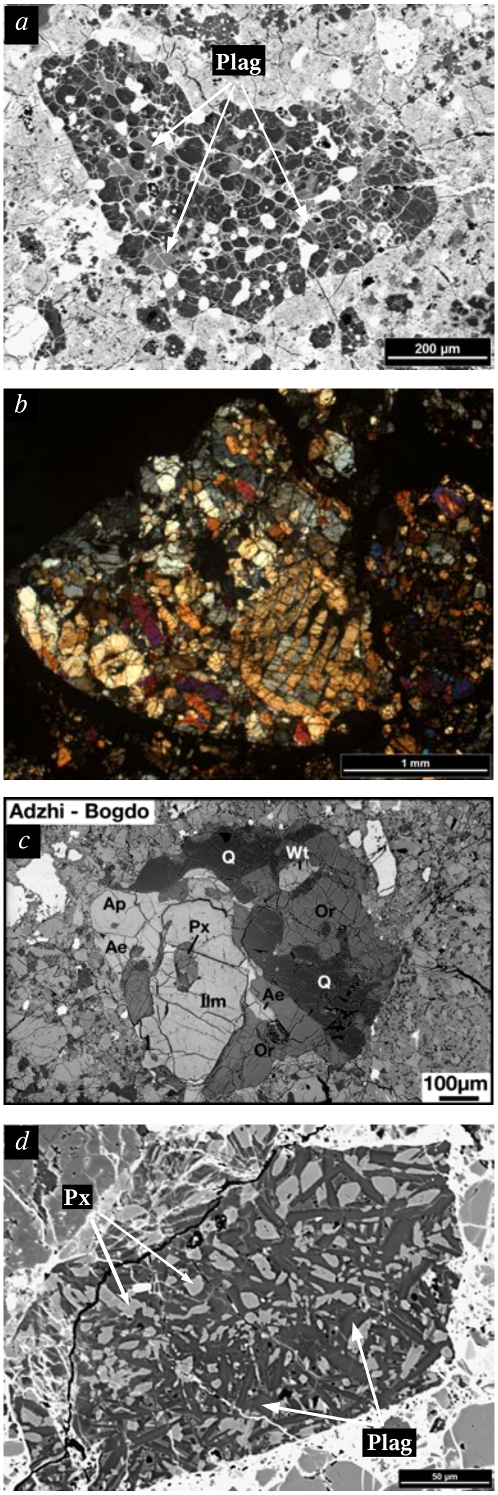

Fig. 1. Backscattered electron and transmitted light (b) images of metamorphic fragments from Acfer 094 (a) and Adrar 003 (b), a granitoidal clasts from Adzhi Bogdo [15] (c), and an andesitic fragment from Study Butte (d); Plag=plagioclase, Px=pyroxene, Ilm=ilmenite, Ap=apatite, Or=orthoclase, Q=quartz, Wt=whitlockite, Ae=aenigmatite.