Mixing in the early Solar System as evidenced by the quenched angrite meteorites. B. G. Rider-Stokes[1], R. C. Greenwood[1], A. Yamaguchi[2], M. Anand[1], V. Debaille[3], L. F. White[1], S. Goderis[4], I. A. Franchi[1], T. Mikouchi[5] & P. Claeys[4]. [1]The Open University, Milton Keynes, MK7 6AA, UK. (ben.rider-stokes@open.ac.uk). [2]National Institute of Polar Research, Tachikawa, Tokyo, Japan. [3]Université Libre de Bruxelles, Brussels, Belgium. [4]Department of Chemistry, Vrije Universiteit Brussel, Brussels, Belgium. [5]Department of Earth and Planetary Science, The University of Tokyo, Japan.

Introduction: An empirical timeline for the assembly, differentiation and mixing of protoplanetary bodies is essential to understanding the formation and evolution of the early Solar System. Angrite meteorites are a group of alkali-depleted achondrites that are derived from the earliest differentiated planetesimals that accreted inward of Jupiter's orbit (c. 5.2 AU), providing a unique insight into the earliest inner Solar System processes [1,2].

Recent oxygen isotope analyses of angrites redefined the angrite fractionation line (AFL) to Δ^{17}O -0.064 ± 0.018 ‰ (2σ), supporting the proposition that angrites originate from a separate parent body to the HED meteorites [3]. However, this study also revealed more positive values in the newly classified quenched angrite NWA 12320 (Δ^{17}O -0.017 ± 0.004 ‰ (2σ)) [3]. Mineralogically, NWA 12320 is similar to the majority of quenched angrites, however, it contains very few unmolten relic olivine grains in comparison.

In this study we investigate the oxygen isotopic compositions of unmolten relic olivine grains and 'matrix' fractions in the quenched angrites: NWA 12320, Asuka 12209 and Asuka 881371. Additionally, olivine grains were investigated using electron backscatter diffraction (EBSD).

Methods: Individual olivine and matrix fractions from Asuka 12209, Asuka 881371, and NWA 12320 were separated and their triple oxygen isotope composition was determined at The Open University by laser-assisted fluorination [4,5,6].

A small chip of NWA 12320 was embedded within a 1-inch round epoxy mount and coated using a Safematic CCU-010 Compact Coating Unit (<5 µm). The mount was then subsequently investigated using a Zeiss Crossbeam 550 SEM with an Oxford Instruments Symmetry 2 EBSD detector at The Open University. High resolution Energy Dispersive X-Ray Spectroscopy (EDS) smart-mapping was collected using an Oxford Instruments Ultim Extreme and an Oxford Instruments Ultim Max detector. The sample was tilted to 70° and an electron beam was used to generate EBSD "maps", consisting of electron backscatter diffraction patterns (EBSPs) acquired at step-sizes ranging from 0.4 to 1 µm. The beam conditions used for both EDS and EBSD analyses comprised an incident beam ranging between 1-2 nA current and a 20 kV accelerating voltage at a working distance of 12 mm.

Results: The matrix of NWA 12320 has a bulk Δ^{17}O value of −0.024 ± 0.037 ‰ (2σ) and being the major component in this sample, dominates the bulk value. Similarly, the matrix of Asuka 12009 and Asuka 881371 also reveal less negative Δ^{17}O values of -0.003 ± 0.002 ‰ (2σ) and -0.003 ± 0.011 ‰ (2σ), respectively, plotting significantly higher than the bulk angrite meteorites (Figure 1). The Δ^{17}O values of the olivine grains in NWA 12320, Asuka 12209 and Asuka 881371 on the other hand, reveal Δ^{17}O values of -0.068 ± 0.009 ‰ (2σ), -0.067 ± 0.008 ‰ (2σ) and -0.065 ± 0.033 ‰ (2σ) respectively, similar to the newly redefined AFL [3] (Figure 1).

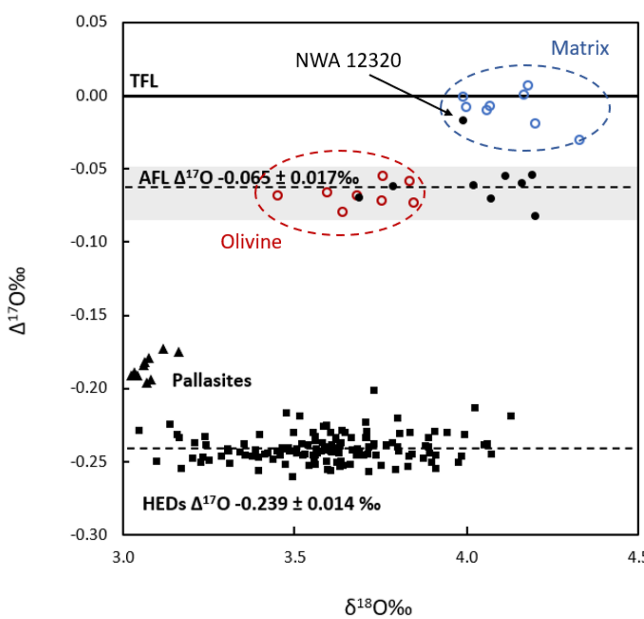

Figure 1: Recent bulk-rock angrite analyses [3] (closed black circles). Note the less negative NWA 12320 plotting closer to the TFL in comparison to other angrites. Olivine grains (open red circles) and matrix fractions (open blue circles). Main group pallasites and HED meteorites displayed for comparisons [6].

EBSD analyses of olivine grains revealed two populations of olivine grains, those that demonstrate granular textures indicative of recrystallization and those that reveal no deformation nor evidence of recrystallization (Figure 2).

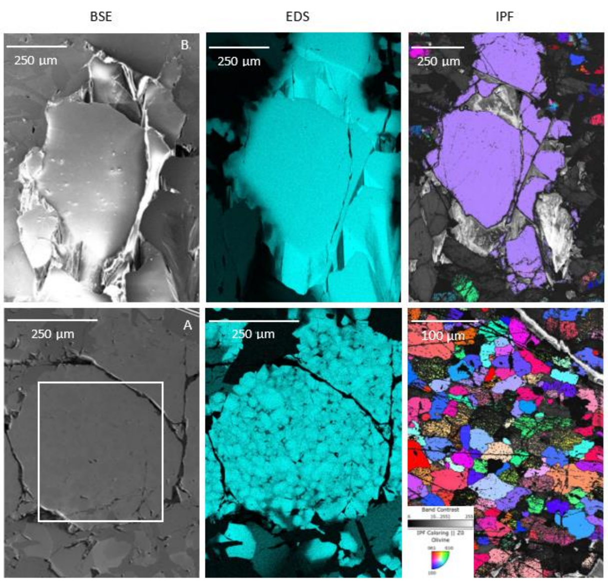

Figure 2: Backscatter electron image (BSE), Mg energy dispersive X-Ray spectroscopy map (EDS) and inverse pole figures (IPF) of two generations of olivine grains. The top panel displays the undeformed and unaltered grains, while the bottom panel reveals the granular texture, indicative of recrystallization.

Discussion: Granular textures, as seen in the olivine grains within NWA 12320 (Figure 2), have also been reported in the urelite JaH 422 and the howardite JaH 556 [7,8]. These meteorites have been interpreted as impact-melt rocks with the olivine grains representing unmolten relics of their precursor material [8]. Interestingly, JaH 556 similarly displayed slight oxygen isotopic variations between the bulk-rock and matrix fractions [8]. Based on this disequilibrium and siderophile element variations it was suggested that the impactor material that caused JaH 556 to melt and recrystallize was an ordinary chondrite [8].

This textural evidence could suggest that at least some olivine grains in NWA 12320 remained as relict material and were affected by high temperature processes on the APB. While magmatic activity could be the cause of these textures, the oxygen isotopic disequilibrium between the relict olivine grains and matrix shown in this study could not be induced by such a mechanism.

We therefore favor the hypothesis that NWA 12320, Asuka 12209 and Asuka 881371 have an impact-melt origin, with the matrix representing crystallized material induced by an impact event and the olivine grains representing relict material of the original angrite parent body (APB).

Based on the significant difference in $\Delta^{17}O$ values, it is likely that the impactor formed in a different region of the protoplanetary disk in relation to the APB. The impactor must have had a positive $\Delta^{17}O$, perhaps related to the ordinary chondrites or the highly positive angrite-like fragments identified the CH3 carbonaceous chondrite 'Sayh al Uhaymir 290' [9].

Summary: The quenched angrite meteorites reveal an oxygen isotopic disequilibrium between the matrix and olivine grains, which suggests the mixing of two bodies sourced from differing locations in the Solar System extremely early in Solar System history (< 4 Myr after the formation of calcium-aluminum-rich inclusions). Structural investigations of olivine grains revealed granular textures indicative of recrystallization, suggesting some olivine grains remained as relict material and subsequently affected by high temperature events. We interpret our findings in terms of angrite meteorites representing impact-melt rocks rather than shallow magmatic intrusions, recording evidence of impact-driven mixing. This mixing may have taken place in response to the inward migration of giant planets (as envisaged in the Grand Tack model [10]) and hence would represent the earliest isotopic evidence for planetary migration in the early Solar System.

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