

THE HISTORY OF HYDROGEN IN THE EARLY INNER SOLAR SYSTEM AS RECORDED IN ANGRITE METEORITES. B. G. Rider-Stokes¹, M. Anand^{1,2}, L. F. White¹, A. Stephant^{1,3}, I. A. Franchi¹, X. Zhao¹, M. J. Whitehouse⁴, R. C. Greenwood¹ & A. Yamaguchi⁵. ¹The Open University, Milton Keynes, MK7 6AA, UK. (ben.rider-stokes@open.ac.uk). ²Department of Earth Sciences, The Natural History Museum, London, SW7 5BD, ³Istituto di Astrofisica e Planetologia Spaziali – INAF, 00111 Rome, Italy, ⁴Department of Geosciences, Swedish Museum of Natural History, SE-104 05 Stockholm, Sweden. ⁵National Institute of Polar Research, Tachikawa, Tokyo 190-8518, Japan.

Introduction: The timescales, mechanisms and source(s) of water delivery (with the term ‘water’ hereafter referring to OH, H and H₂O) to the inner Solar System remains an active area of study. At present, two prevailing models for the origin of inner Solar System water exist: 1) Early presence of isotopically CM-like H (and associated N) in the inner Solar System prior to the separation of the non-carbonaceous (NC) and carbonaceous chondrite (CC) reservoirs at ≤ 1 Ma after CAI formation and 2) the influx of volatile-rich materials from the outer Solar System due to the growth and/or migration of Jupiter [1]. Angrite meteorites represent ancient Solar System materials that accreted sunward of Jupiter’s orbit, and are thus ideally situated to help constrain the timing and source(s) of volatile delivery to planetary bodies in the inner Solar System [2].

An oxygen isotopic disequilibrium has been revealed in the quenched (rapidly-cooled) angrite meteorites, implying an impact melt origin [3]. However, the olivine ‘xenocrysts’ appear to be relict grains that survived impact melting [3]. Furthermore, it is considered that the impact melting event is caused by the gravitational excitement resulting from the growth and/or migration of Jupiter [3]. It is therefore plausible that the impacting material may have originated from the outer Solar System.

In this study we present δD values and H₂O abundances of silicate minerals (olivine and pyroxene) in the quenched angrite meteorites to determine if any variation exists between the relict olivine grains and groundmass of the quenched angrites. This in turn will test whether or not the angrites accreted CM-like H prior to large scale impact mixing or if an influx of volatile-rich material was caused by this gravitational excitement. Furthermore, we present δD values and H₂O abundances of silicate minerals (olivine and pyroxene) in the plutonic (NWA 4801), intermediate (NWA 10463) and dunitic (NWA 8535) angrites to investigate the history of H in the angrite parent body (APB).

Methods: All polished samples investigated in this study were pressed into indium mounts to re-

duce background H. Secondary ion mass spectrometry measurements of D/H and H/O ratios, calibrated as H₂O concentrations, in olivines and clinopyroxenes were performed on the Cameca NanoSIMS 50L at Open University following established procedures [4,5] using San Carlos olivine to monitor background H. Asuka 881371 (paired with Asuka (A) 12209) and NWA 4801 have published cosmic ray exposure (CRE) ages [6,7] that are used in correcting for spallation using a production rate of cosmogenic deuterium [8]. NWA 12320 is corrected for the maximum recorded CRE age of quenched angrites [9], while NWA 8535 and NWA 10463 are corrected assuming a CRE age of ~26 Ma and ~54 Ma, respectively, following the protocols of [5].

We used the CAMECA IMS 1280 ion probe located at the NordSIMS facility in the Swedish Museum of Natural History in Stockholm, Sweden for ²⁰⁸Pb-²⁰⁷Pb-²⁰⁶Pb-²⁰⁴Pb analysis on phosphates within NWA 8535 and NWA 12320 following established procedures [10].

Results: All δD values and H₂O abundances of silicate and phosphate minerals are presented in Table 1.

	Sample	Mineral	H ₂ O	2SD	D	2SD	N
Average	Asuka 12209	Olivine	4.8	1.9	-126.8	300.4	59
Average	Asuka 12209	Pyroxene	5.4	0.7	174.3	175.2	8
Average	NWA 12320	Olivine	5.1	4.0	668.7	758.7	25
Average	NWA 12320	Pyroxene	6.2	2.6	1275.9	233.5	10
Average	NWA 12320	Phosphate	2551.7	1141.9	450.3	446.2	13
Average	NWA 10463	Olivine	28.1	3.2	-200.9	40.1	8
Average	NWA 10463	Pyroxene	44.3	19.1	-154.3	50.2	5
Average	NWA 10463	Phosphate	106.3	23.4	389.3	352.2	2
Average	D’Orbigny	Phosphate	2405.5	729.3	875.5	432.4	16
Average	NWA 4801	Olivine	6.7	0.4	-210.2	243.2	9
Average	NWA 4801	Pyroxene	8.0	4.3	-278.4	115.4	9
Average	NWA 8535	Olivine	8.0	1.6	486.1	346.3	10
Average	Asuka 12209	Relict Olivine	4.8	1.7	-137.3	140.2	47
Average	Asuka 12209	Olivine in Groundmass	5.0	1.3	-86.4	185.0	12

Table 1: All reported δD values and H₂O abundances from this study.

Based on regression through Canyon Diablo troilite (CDT) Pb isotope composition, NWA 8535 yields a Pb-Pb isochron date of 4515 ± 30 Ma, with a MSWD of 0.111, while regression through Stacey & Kramers (SK) modern terrestrial Pb isotope composi-

tion indicates an identical date of 4517 ± 31 Ma, with a MSWD of 0.16. Based on regression through CDT, NWA 12320 yields a Pb-Pb isochron date of 4572.1 ± 9.4 Ma, with a (MSWD) of 1.07, while regression through SK modern terrestrial Pb isotope composition yields a similar date of 4575.2 ± 9.7 Ma, with a MSWD of 1.3.

Discussion: Unlike oxygen isotopic compositions, the δD values and H_2O abundances of relict olivine grains and olivine present in the groundmass within A 12209, demonstrate values that are indistinguishable from one another (e.g. Table 1 & Figure 1).

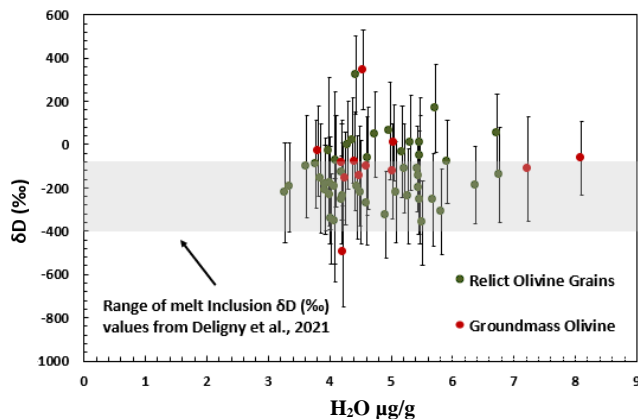


Figure 1: Plot of δD (‰) vs H_2O ($\mu g/g$) in relict and groundmass olivines in A 12209.

This would imply that the APB had acquired a CC-like H composition prior to impact melting/mixing and that the impactor was either dry or had similar H isotopic compositions to the APB. The age of NWA 12320, which overlaps with the most ancient quenched angrites (NWA 1670; 4564.39 Ma [11]), suggests that the APB accreted a CM-like H composition extremely early in the inner Solar System.

To better constrain the evolution of H in the early inner Solar System, we determine a chronological constraint on the dunitic angrite, NWA 8535. Unshocked phosphates (and surrounding phases) provide an age of 4515 ± 30 Ma. The upper most limit of this range is chronologically distinct from the youngest plutonic angrite (Angra Dos Reis; 4556.6 Ma [11]). Therefore, angrite formation and evolution spans the first 50 Ma of inner Solar System history.

A 12209, NWA 4801 and NWA 10463 all demonstrate similar δD values compared to the range of melt inclusions within Mg-rich olivines (Figure 2) [1]. Although, the high H and terrestrial-like δD values in NWA 10463 could be a result of terrestrial weather-

ing. NWA 12320 on the other hand, reveals more positive δD values, which may be indicative of degassing. NWA 8535 also exhibits slightly more positive δD values, however, the lack of radical variations suggests that the APB did not experience extensive addition from H rich impactors. We suggest the more positive values of NWA 8535 represent prolonged degassing of the angrite melt.

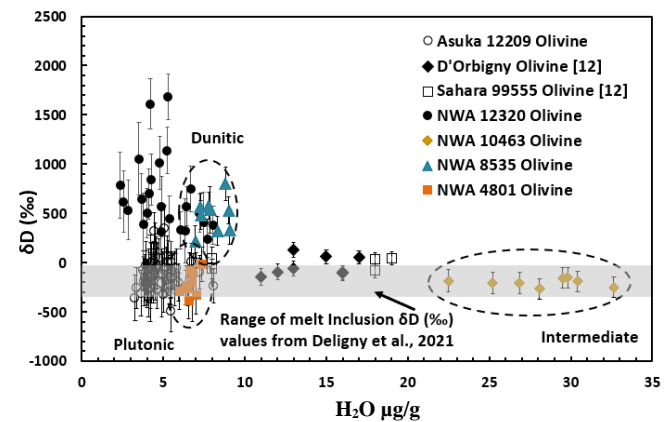


Figure 2: Plot of δD (‰) vs H_2O ($\mu g/g$) in olivine within angrite meteorites. D'Orbigny and Sahara 99555 data from [12].

Conclusions: Based on the lack of variation between the relict olivine grains and olivine present within the groundmass in the two quenched angrites analysed in this study, we suggest that the APB accreted the majority/all of its water extremely early in the Solar System history and certainly prior to experiencing any impact mixing/melting. Moreover, based on the evolution of H on the APB, we propose that the APB did not suffer from late water addition through impacts. Our findings therefore support the proposition that an early presence of isotopically CM-like H existed in the Solar System prior to the separation of the NC and CC reservoirs at ≤ 1 Ma.

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