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ORIGIN OF OPAL (HYDRATED SILICA) IN POLYMICHT UREILITES. H. Downes^{1,2}, A. D. Beard¹, I. A. Franchi³, R. C. Greenwood³. ¹Centre for Planetary Sciences and Dept. of Earth and Planetary Sciences, Birkbeck University of London, London, UK (h.downes@ucl.ac.uk), ²Dept. of Earth Sciences, Natural History Museum, London, UK; ³Planetary and Space Sciences, Open University, Milton Keynes, MK7 6AA UK.

Introduction: We previously reported the occurrence of fragments of opal ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) in several internal chips of an Antarctic brecciated polymict ureilite Elephant Moraine (EET) 83309 [1,2]. Here we present the results of a NanoSIMS oxygen isotope study of these opals with the aim of understanding their origin. The opals occur mainly as clasts up to $300\mu\text{m}$ in longest dimension and often show banding (Figure 1). The bands are often terminated at adjacent clasts, suggesting that the opal was not formed in situ but pre-dates the brecciation.

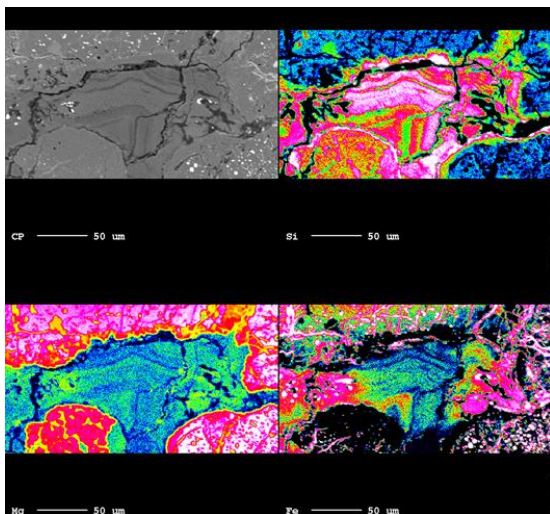


Figure 1. Top left: back-scatter electron image of a banded opal clast in EET 83309,50. Top right: Si X-Ray map of same clast. Bottom left: Mg X-Ray map. Bottom right: Fe X-Ray map. Scale bar = $50\mu\text{m}$. False color images: reds/pinks represent high elemental concentrations; blues/greens represent low concentrations.

Opal also occurs as thin rims around the ureilitic mineral suessite (Fe_3Si) (Figure 2), and often contains inclusions of schreibersite ($(\text{Fe},\text{Ni}_3)\text{P}$). It shows no relationship whatsoever with terrestrial weathering veins or rims (Figure 3), although one piece of opal has been found in contact with ureilitic olivine, surrounded by a terrestrial weathering rim.

Opal is extremely rare in meteorites. Although one occurrence of opal is reported as a cavity infill in the highly weathered Wolf Creek iron meteorite [3], it has not been reported as a weathering product in any other meteorite. However, opal-A has recently been identi-

fied in the ~ 1300 Ma old Martian meteorite Nakhla [4] where it was interpreted as being a product of extraterrestrial aqueous alteration.

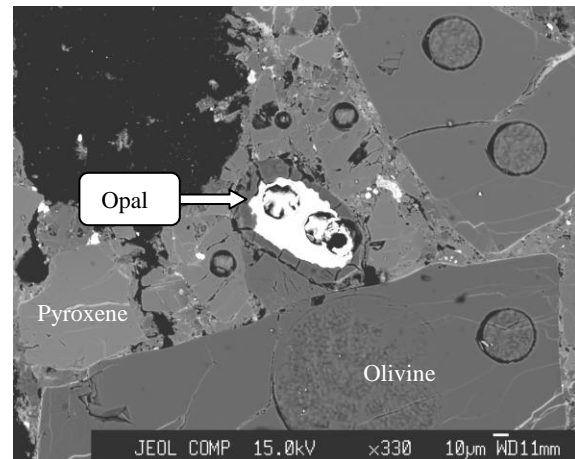


Figure 2. Back-scatter electron image of opal surrounding suessite in polymict ureilite EET 83309,49. Suessite is bright mineral in center of field of view; opal is thin ($10\mu\text{m}$) dark rim (arrowed). Other minerals include ureilitic olivine and pyroxene. Circular structures are laser pits. Scale bar = $10\mu\text{m}$.

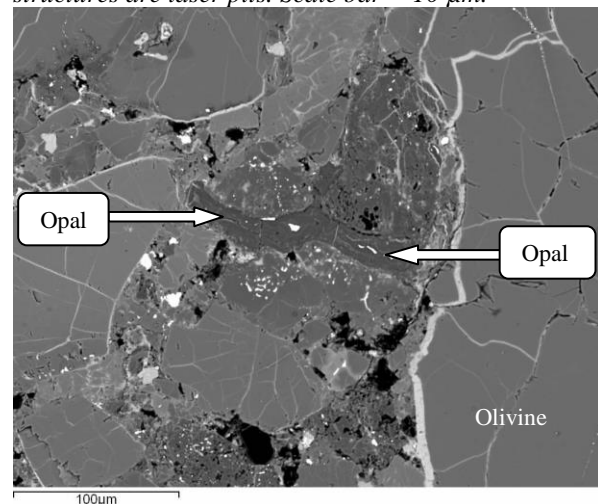


Figure 3. Back-scatter electron image of EET 83309,52 with an elongated clast of opal (dark object at center of field of view, arrowed), with embedded schreibersite. The opal is unrelated to terrestrial weathering rims (brighter linear features, e.g. crossing from bottom to top of image to the right of the opal clast). Major minerals include ureilitic olivine and less abundant pyroxene. Scale bar = $100\mu\text{m}$.

Opal variety and composition: XRD analysis (K. Howard pers. comm.) suggests that the opal is of the amorphous variety opal-A, although it appears to be undergoing some degree of recrystallization (Figure 1). The largest opal clast has a composition of approximately 65.5 wt% SiO₂, 6 wt% FeO and <1 wt% MgO, but compositions vary from 60 to 76 wt% SiO₂. Analytical totals are always low (67-82 wt%), indicating a substantial quantity of water in the opal.

Oxygen isotopes: In order to determine the oxygen isotope composition of the opal in the ureilite using the Cameca NanoSIMS 50L at the Open University, an opal standard was required. A biogenic silica standard [5] was not considered appropriate. Therefore a piece of unbanded opal hosted in a volcanic rock from the Faeroe Islands (BM 1907,568) was acquired from the Natural History Museum mineral collection and four ~2mg chips were analysed using a laser-assisted fluorination technique, also at the Open University. They yielded the following average values: $\delta^{18}\text{O} = 30.06 \pm 0.36\text{‰}$ (2σ) and $\delta^{17}\text{O} = 15.68 \pm 0.20\text{‰}$ (2σ).

NanoSIMS measurements were conducted using the methods described by [6]. Repeated analyses of the opal standard showed excellent reproducibility with $\delta^{18}\text{O}$ values $\pm 1.0\text{‰}$ (2σ) and $\delta^{17}\text{O} \pm 1.5\text{‰}$. Two separate opal clasts were analysed. The results for the opal clasts from the polymict ureilite are within error of the Terrestrial Fractionation Line (Figure 4) and spread along a line from a point close to the ureilite field towards lower $\delta^{18}\text{O}$ values.

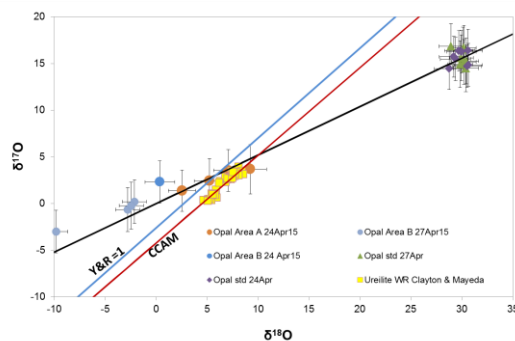


Figure 4. Oxygen isotope results for opal clasts from polymict ureilite EET83309,50 (orange and blue symbols), together with data for terrestrial opal standard (green and purple symbols) and ureilite bulk rock data (yellow symbols) from [7]. Black line = Terrestrial Fractionation Line.

Discussion: Our petrographic observations (Figures 1-3) strongly suggest that the ureilitic opal was formed prior to the final brecciation event on the

ureilite parent body and prior to terrestrial weathering, and therefore has an extraterrestrial origin. However the oxygen isotope composition of the ureilite opal analysed in this study all plot within error of the Terrestrial Fractionation line with a mean $\Delta^{17}\text{O}$ value of 0.6 ± 0.8 (2 SE)‰.

Opal is known to exchange water readily with the environment. Terrestrial opal has variable, but generally ¹⁸O-rich oxygen (~19 to 38‰) whereas the ureilitic opal $\delta^{18}\text{O}$ values are more ¹⁸O-poor. Antarctic water can have $\delta^{18}\text{O}$ ca. -40 to -50‰, so it is possible that the trend observed in the ureilite opal may reflect interaction with terrestrial water. There is a high abundance of water in the analysed opal (18-33 wt%), readily facilitating isotopic exchange with the Antarctic environment, even at low temperatures. The equilibrium fractionation factor between water and opal is $\approx 40\text{‰}$ at temperatures applicable to Antarctica [8,9] and therefore the measured values are consistent with a terrestrial origin for the O-isotope signature. The variation in $\delta^{18}\text{O}$ observed in the ureilitic opal may be the result of partial isotopic exchange between the opal (which initially had a ureilitic oxygen isotope composition) and Antarctic water. Alternatively, the isotopic composition of the Antarctic water may have evolved during interaction with the opal and reaction with the rest of the meteorite.

Hydrated amorphous silica (i.e. opal) has also been identified in abundance on the surface of Mars [10,11] where it has been formed at low temperatures (ca 0°C) and by acid alteration of silicate minerals [12]. A similar low temperature hydrothermal asteroidal origin for the fragments of opal in EET83309 cannot be ruled out. Based on the evidence provided, an extraterrestrial origin for the ureilitic opal is more likely than a terrestrial weathering origin.

References: [1] Beard A D et al., 2009. 72nd Annual Meteoritic Society Meeting, Abst #5027. [2] Beard A D et al., 2011. 74th Annual Meteoritic Society Meeting, Abst #5088. [3] White J S Jr et al., 1967. American Mineralogist 52, 1190-1197. [4] Lee et al., 2015. MAPS 50, 1362-1377. [5] Chaplignin B et al., 2011. GCA 75, 7242-7256. [6] Starkey NA et al., 2013 GCA 105, 73-91. [7] Clayton R N and Mayeda T K 1988. GCA 52, 1313-1318. [8] Kawabe I, 1978. GCA 42, 613-621. [9] Kita I et al, 1985. Nature 314, 83-84. [10] Rice M S et al., 2010. Icarus 205, 375-395. [11] Tosca N J and Knoll A H, 2009. EPSL 286, 379-386. [12] McAdam A C et al., 2008. J G R 113, E08003.