MICROSTRUCTURAL GEOCHRONOLOGY OF LUNAR FELDSPATHIC BRECCIA NORTHWEST AFRICA 10272: A MAJOR EVENT AT ~3.48 GA IN THE LUNAR CRUST?

S. Schuindt[1] , J. R. Darling[1], L. G. Staddon[1], W. H. Schwarz[2], J. Dunlop[1], L. F. White[3], C. D. Storey[1] and K. T. Tait[4,5]. [1]School of Environment, Geography and Geoscience, University of Portsmouth, UK; *Sheila.schuindt@port.ac. [2]Institute of Earth Sciences, Heidelberg University, Germany. [3]School of Physical Sciences, Open University, UK. [4]Department of Earth Sciences, University of Toronto, Canada, [5]Royal Ontario Museum, Toronto, Canada.

Introduction: Lunar breccias provide exceptional insights into the geological diversity of the lunar crust, and can provide constraints on the timing and nature of lunar differentiation, magmatism, impact bombardment and regolith evolution. Meteoritic breccias samples offer broader geographical, and potentially geological, sampling than currently available returned samples [1]. Geochronology of breccia components can be highly challenging, especially where a high proportion of clasts are mineral fragments; precluding mineral isochron approaches. However, U-bearing accessory minerals offer a powerful approach to resolving the timing of formation of breccia components, if the effects of secondary shock metamorphism and/or thermal events can be disentangled [2].

Baddeleyite and zircon are widespread accessory phases in achondrites and can be employed as both robust chronometers and shock-metamorphic indicators [3,4]. Baddeleyite (monoclinic ZrO_2) is particularly important, as it occurs in a wide-range of mafic magmas that do not crystallize zircon and is a highly sensitive recorder of extreme thermal and shock events. This is due to phase transformations to and from metastable tetragonal (t-ZrO_2) or cubic (c-ZrO_2) polymorphs at very high temperatures and orthorhombic (o-ZrO_2) polymorphs at pressures >3.3 GPa [5]. The discovery of baddeleyite with cubic phase heritage (>2300 °C) in an unshocked Apollo troctolite implies that secondary reworking of the lunar crust may have been widely driven by impact melt sheets [6].

In this study, we combined microstructural and U-Pb isotopic analysis of baddeleyite grains to characterize the magmatic, shock metamorphic and thermal history of the lunar breccia meteorite NWA 10272.

Sample and Methods: NWA 10272 is a feldspathic breccia composed predominantly by angular clasts of plagioclase, pigeonite, olivine, orthopyroxene, augite, fayalite and silica polymorphs [7]. The studied thin section is accession number M57546 of the Royal Ontario Museum (Figure 1). It shows irregular and angular clasts, in which monomineralic clasts, matrix-supported, are dominant. The monomineralic clasts are primarily composed of plagioclase, orthopyroxene, and clinopyroxene. There are also lithic clasts representing a range of lithologies that include ophitic basalts, granular anorthosites, a syeno-granite with graphic texture, and also a few glassy clasts.

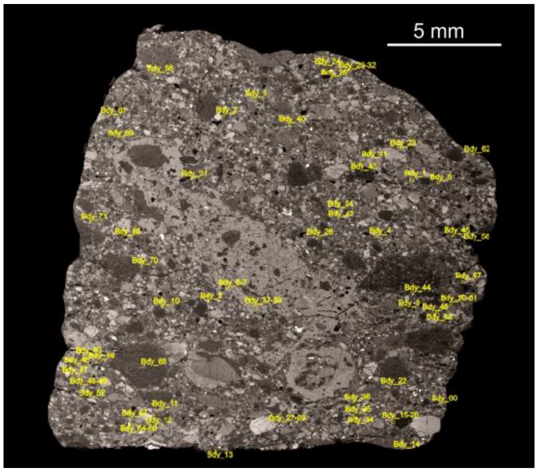

Figure 1: NWA 10272 thin section. BSE image showing the variety of clasts and the locations of all 71 identified micro-baddeleyite grains.

Many clasts preserve their igneous textures (e.g. basalts in Figure 2), while others show impact related textures, as deformed lamellae in ortho- and clinopyroxene, along with glass in matrix, that permeates the clasts and porosities, mimicking the melt (Figure 2), and also the presence of maskelynite.

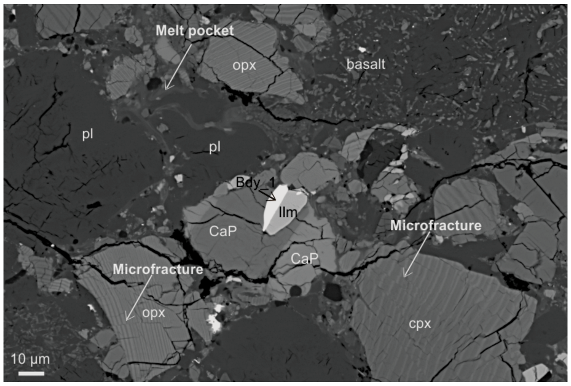

***Figure 2:** Example BSE image of NWA 10272 clasts and matrix, including deformed pyroxenes (opx, cpx) and a melt pocket surrounding plagioclase (pl).*

Baddeleyite grains were located by a combination of a backscattered electron (BSE) imaging and energydispersive X-ray spectroscopy (EDS) mapping. Microstructural data were collected using an Oxford Instruments Nordlys Nano electron backscatter diffraction (EBSD) detector (50-80 nm step size) after polishing using 50 nm alumina suspension. Diffraction patterns were captured and indexed online on an Oxford Instruments Aztec software. After acquisition, all data were processed off-line using HKL Channel 5. All the electron microscope data were collected on the Zeiss EVO MA10 LaB6 scanning electron microscope (SEM) housed at the University of Portsmouth (UoP).

U-Pb geochronology on baddeleyite grains within both clasts and the matrix was undertaken by Secondary Ion Mass Spectrometry (SIMS), using a CAMECA IMS 1280-HR at the Heidelberg University (HIP), using a ~5 µm O^- primary beam (~500pA) with oxygen flooding increasing the Pb^+ yield and a duration of ~40 min for each analysis (MRP: ~5000). The thin-section was cast in an epoxy mount along with the Phalaborwa baddeleyite and FC4 reference materials. Instrumental operating conditions and data reduction followed the protocols described in [8,9].

Results and Discussion: Seventy one baddeleyite grains (1 to 46 µm in longest axis) were found, with 55% of these located in clasts; as inclusions in ilmenite, pyroxene and plagioclase. The grains show extreme nanoscale structural variability (Figure 3). Features include partial preservation of magmatic twins, domains with orthogonal orientation relationships that reflect phase transformations from t-ZrO_2 or o-ZrO_2 polymorphs, cryptocrystalline domains with quasi-amorphous zirconia (at the length scales of EBSD analysis), and orientation relationships consistent with reversion from a cubic precursor (as [6]).

Twelve baddeleyites were selected for SIMS analysis; based upon the size and position of the grains (matrix or clast) and representing the microstructural states described above. The analysis yielded a narrow range of $^{207}Pb/^{206}Pb$ dates from 3.45 to 3.53 Ga (Figure 4). Given the heterogeneity of clasts and the high microstructural variability of baddeleyites analyzed, such as grains showing evidence for shock (quasi-amorphous), evidence of extreme high-temperature (reversion from cubic) and evidence for igneous crystallization (twinning), such a narrow time interval (80 Myr) in this sample was not expected. Importantly, it is unlikely that the measured ages all reflect a single major resetting of the U-Pb system, due to the partial preservation of magmatic twins and other microstructures that are not associated with major Pb-loss in other highly-shocked achondrites [e.g. 10]. As such, this period must include significant magmatism, impact events and extreme thermal events, such as impact melt sheet formation, that can account for baddeleyite with reversion from a cubic precursor (>2300 °C; [6]).

In any case, these results show that other important events may remain to be discovered in lunar breccias and highlighted the importance of multidisciplinary approaches to better constrain them.

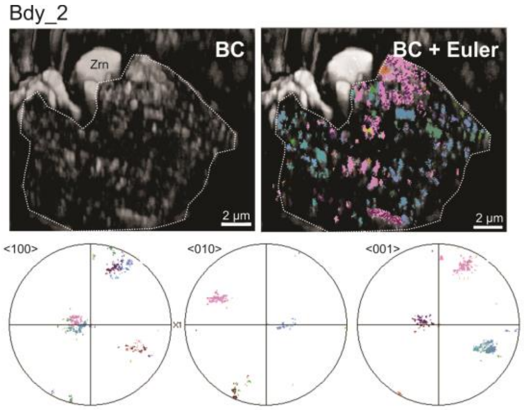

Figure 3: *Band Contrast (BC), Euler maps and pole figures from baddeleyite grain 2. Bdy_2 shows quasi-amorphous and an orthogonal relationship that can be seeing on the pole figure, suggesting reversion from t-ZrO_2 or o-ZrO_2.*

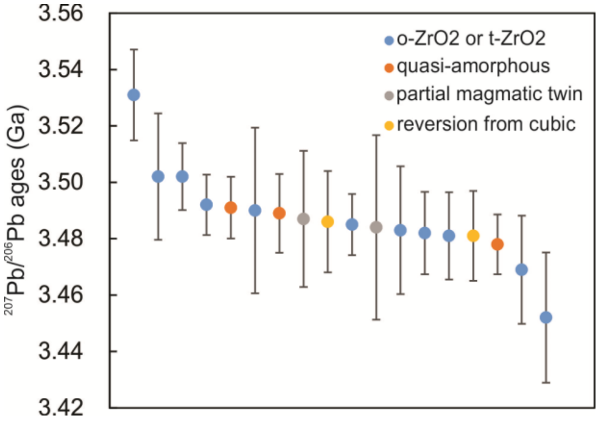

Figure 4: *$^{207}Pb/^{206}Pb$ ages distribution of baddeleyite grains (2σ uncertainties) showing a narrow range of dates not linked to the microstructure feature.*

References: [1] Korotev R. L. (2005) *Geochemistry, 65, 4*, 297-346. [2] Nemchin A. A. (2008) *GCA, 72, 2*, 668-689. [3] Timms N. E. et al. (2017) *Earth-Sci Rev 165*,185–202. [4] White L. F. et al. (2018) *Geology 46*, 719–722. [5] Takagi S. et al. (2020) *GRL, 47*. [6] White L. F. et al. (2020) *Nature Astronomy*, 1-5. [7] Bouvier et al. (2017) *Meteoritical Bulletin, 104*. [8] Chamberlain K.R. et al. (2010) *Precambrian Research, 183*, 379–387. [9] Schmitt A. K. (2010) *Chemical Geology 269*, 386–395. [10] Darling J. R. et al., (2016) *EPSL, 444*, 1-12.