PLAGIOCLASE IN REGOLITH BRECCIAS: CRITICAL TOOLS FOR DECIPHERING THE SHOCK HISTORY OF THE LUNAR HIGHLANDS. J.F. Pernet-Fisher; K.H. Joy; D.J.P. Martin. School of Earth, Atmospheric, and Environmental Sciences, University of Manchester, Oxford Road, Manchester, M13 9PL, UK. (john.pernet-fisher@manchester.ac.uk).

Introduction: Understanding how minerals are modified during impact related shock represents an important 'first-order' question that has implications for understanding impact structures on all terrestrial bodies within the Solar System. Here, we characterise the shock history of anorthositic clasts within a suite of Apollo 16 and lunar-meteorite regolith breccias to understand the formation and impact modification history of the ancient lunar highlands.

Clasts within regolith breccias provide critical geological insights into lunar bedrock lithologies, such as the highland anorthosites and Mg-suite lithologies [e.g., 1,2]. This is particularly pertinent for lunar meteorite breccias, which are currently our best means of directly sampling highland material from outside of the Apollo and Luna landing sites. It is, therefore, important to establish whether these clasts are chemically 'pristine' (i.e., unmodified since crystallisation), or whether they have had their chemistry altered by secondary processes such as shock-metamorphism prior to subsequent geochemical interpretations. Indeed, it has been suggested that shock-metamorphism can significantly modify, to varying extents, both major- and trace-element mineral chemistry [3].

To characterise effects of impact shock in highland lunar samples, we report cathodoluminescence (CL) imaging and FTIR spectra for plagioclase crystals within polymineralic clasts and as individual mineral fragments contained within regolith samples. We focus specifically on plagioclase as it is a good shock indicator mineral due to the significant crystalline structural modification that occurs during shock compared with other igneous minerals [4].

Methods: The SEM-CL images (and BSE images) were acquired using a JEOL JSM-6400 SEM with an Oxford cathodoluminescence system. The optical microscope-CL imaging (OM-CL) was acquired using a CITL 8200 mk 3 cold CL system coupled to a transmitted-light microscope. The FTIR spectra were acquired using a Perkin-Elmer FTIR microscope in reflectance-mode equipped with a liquid nitrogen cooled MCT array detector. A spectral range from 650 to 4000 cm^{-1} was acquired using a spatial resolution of 25 µm integrating measurements over 64 measurements. Plagioclase major-element chemistry was determined on the same FTIR spots using a Cameca SX100 electron microprobe following the same procedure as detailed by [5].

CL imaging: During impact, shock will distort and disorder plagioclase lattice structures, resulting in the emission of characteristic colours during OM-CL imaging and variable luminescence during SEM-CL imaging. Green-yellow emissions (e.g., large clast at left; Fig. 1c) generally represents unshocked plagioclase; variation in the intensity of these emissions in terrestrial plagioclase is controlled by Mn substitution within the M site [6]. By contrast, blue (e.g., Fig. 1f) and orange/red emissions (e.g., plagioclase fragment at lower right; Fig. 1c) are interpreted to reflect structural modification of plagioclase. Specifically, blue emissions results from disordered Al-O-Al clusters reflecting extensive lattice defects [7]; whereas, orange/red emission have been reported to reflect vitrification of plagioclase into maskelynite [8].

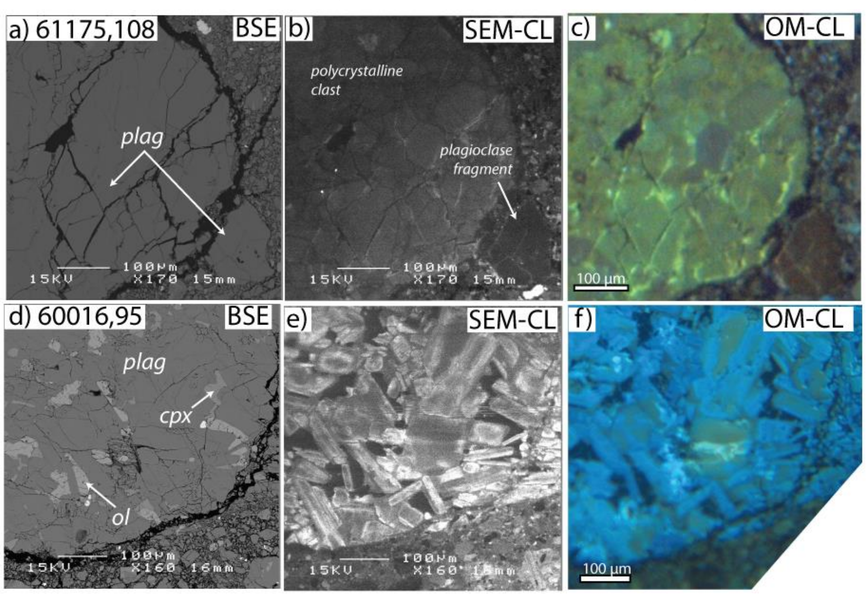

Figure 1: BSE, SEM-CL, and OM-CL imaging for polycrystalline clasts within Apollo 16 breccias 61175,108 and 60016,95. Mafic minerals (bright intensities in BSE) do not luminesce due to high-Fe content. The complex crystalline nature of these clasts are clear in the CL images. Clast in sample 61175,108 displays predominantly green/yellow emission characteristic of an unshocked plagioclase. Sample 60016,95 clast displays predominantly blue emission characteristic of highly shocked plagioclase.

Within all samples studied here, individual plagioclase mineral fragments and polycrystalline plagioclase clasts are typically characterised by green-yellow and orange emissions during OM-CL imaging coupled with relatively darker and less variable intensities during SEM-CL imaging, commonly lacking zoning (Fig. 1a-c). For the most part, crystals within polymineralic clasts (i.e., plag + ol + cpx bearing clasts) are characterised by strong blue emissions during OM-CL imaging and bright variable intensities during SEM-CL imaging. CL zoning is more common within these clasts, typically ranging from orange/dull cores and blue/bright rims in individual minerals (Fig, 1d-f). Red emissions are rarely observed within the suite of samples investigated here. Only two polymineralic clasts from 61175,108 contain crystals that display dark red emissions.

In order to quantify to what extent structure defects (i.e., blue emissions) are controlled by impact shock and to what extent orange/red emissions reflect maskelynisation, FTIR reflectance spectra can be used to further quantify the maximum shock-damage experienced by individual plagioclase crystals.

FTIR spectra: The mid-IR reflectance spectra of plagioclase display systematic changes with increasing shock pressure [4; Fig. 2]. Thus, well-defined correlations between FTIR spectral features (such as band depths) of experimentally shocked plagioclase chips and their known peak shock pressure intensities can be used as to estimate shock pressure in natural mineral systems [4]. Here, we use the relationship of decreasing band depth between ~940 cm^{-1} and ~1100 cm^{-1} and increasing shock from the dataset of [4] (see [10] for further details).

The FTIR spectra for plagioclase crystals that display green/yellow OM-CL emissions confirm the unshocked nature of these crystals, yielding calculated shock pressures < ~5 GPa (scale of S1 according to the meteorite shock classification scheme of [9]). By contrast, measured spectra for known maskelynite crystals yield shock pressures > ~30 GPa (scale of S5 according to the classification scheme of [9]), and display red OM-CL emissions, consistent with the observations of [8]. Plagioclase crystals that display orange and blue OM-CL emissions display FTIR spectra that are intermediate between 'unshocked' plagioclase and maskelynite spectra. Shock-pressure estimates of these samples suggest that the orange OM-CL emission reflects lesser degrees of shock compared to plagioclase crystals that display blue OM-CL emission. This indicates that a fundamental structural change occurs to plagioclase which has witnessed ~15 GPa of shock pressure, resulting in a change of OM-CL emissions.

Conclusions: Plagioclase bearing clasts within Apollo 16 regolith breccias typically display smaller ranges of shock pressures (<4 GPa to ~15 GPa) compared to lunar meteorite regolith breccia samples (~5 to ~30 GPa, [4]). Importantly, this study has identified ferroan anorthosite clasts in some regolith breccias that have been classified as being 'pristine' (e.g., 66035; [11]), do display some evidence for shock damage. Overall, we highlight FTIR and CL-imaging techniques as important tools during the characterisation of lunar breccias, particularly when determining whether geochemically 'exotic' clasts such as Mg-anorthosite clasts [12] (purported to represent a key component of the farside lunar highlands), are indeed geochemical pristine or if they have undergone significant shock modification and compositional equilibration [1, 13].

References: [1] Gross J. et al. (2014) *EPSL*, 388, 318-328. [2] Russell S. S. (2014) *Phill. Trans. R. Soc.* A 372. [3] Crozaz G. & Wadhwa M. (2001) *GCA*, 65, 971-978. [4] Johnson J. R. (2002) *J. Geophys. Res.*, 107(E10), 5073. [5] Joy K. H et al. (2015) *MaPS*, 50, 1157-1172. [6] Götze J. et al. (1999) *Am. Min.* 84, 1027-1032. [7] Petrov I. et al. (1993) *Am. Min.*, 78, 500-510. [8] Sippel R. F. & Spence A. B. (1970] *Proc. Apollo 11 LPS*, GCA, Suppl. 1, Levinson A.A. (ed), Pergamon, New York, 2413-2426. [9] Rubbin A. E. et al. (1997) *GCA*, 61, 847-858. [10] Martin D. J. P. et al. (2016) *this meeting*. [11] Warren P. H (1993) *Am. Min.*, 78, 360-376. [12] Takeda H. et al. (2006) *EPSL*, 247, 171-184. [13] Warren P. H. (2012) *2nd Conference on the Lunar Highlands* #9034.

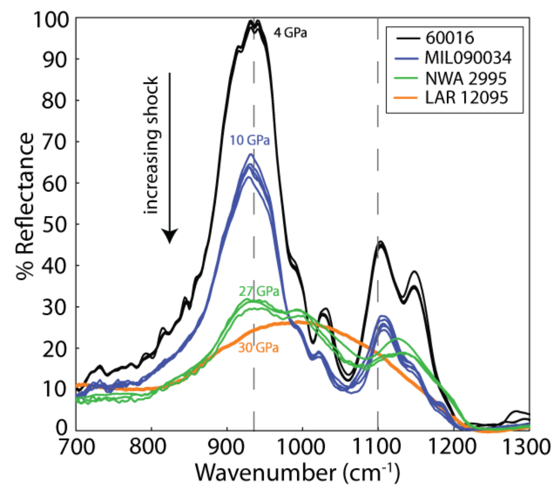

Figure 2: FTIR reflectance spectra for a select range of plagioclase crystals within different planetary materials (Moon and Mars), illustrating the differences in reflectance spectra with increasing shock pressure. Increasing shock is evidenced by a general smoothing of spectrum (e.g. in martian meteorite LAR 12095, which contains extremely shocked 'maskelynitised' mineral).