USING QUANTITATIVE MICRO-FTIR SPECTROSCOPY TO CHARACTERISE THE SHOCK HISTORY OF FELDSPATHIC LUNAR METEORITES MILLER RANGE 090034, 090070 AND 090075.

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Introduction: Lunar meteorites Miller Range (MIL) 090034, 090070 and 090075 are feldspathic regolith breccias [1]. The three meteorites have similar bulk compositions and were found within close proximity in Antarctica, leading to the conclusion that they were launch grouped (i.e., pieces of the same material ejected from the lunar surface) [1-3].

The meteorites are composed of feldspathic impact melt breccia clasts, melt veins, and minor amounts of mafic mineral fragments [2]. Anorthite crystals hosted within impact melt breccia clasts in each sample are compositionally similar (An_{95-99}) suggesting that they were sourced from similar types of precursor highlands rocks (i.e. ferroan and magnesian anorthosite) [1]. However, as each impact melt clast has likely been reworked multiple times prior to lithification, they have been subject to varying levels of shock. Here we report the results of an investigation into variation of shock effects using FTIR spectra and cathodoluminescence images, with the goal that these techniques can be integrated to better understand the shock history of these samples, in addition to the impact bombardment history of the lunar highlands.

Methods: Thick sections (090034,27, 090070,25, and 090075,21) were analyzed using a Perkin-Elmer Spotlight 400 FTIR Spectrometer at the University of Manchester. This instrument has a cooled-MCT detector and a high-resolution mapping unit (1000 to 6 µm aperture size range, 0.1 cm^{-1} accuracy) that was used to collect spectra and high-resolution spectral datacube maps from minerals and clasts in each of the meteorites. Each data point in this study was collected with a 25 µm aperture size where 32 repeat scans were co-added per measurement. Chemical analyses were carried out using a Cameca SX100 Electron MicroProbe Analyser at the University of Manchester. Analysis points are co-located with the FTIR spectral analysis points to directly compare composition and spectral signal. Optical microscope cathodoluminescence (OM-CL) was carried out with a CITL8200 mk 3 cold CL system coupled to a transmitted-light microscope [4].

Spectral analysis: Within polished sections, individual minerals can be identified by their unique IR spectral Reststrahlen Band patterns – the reflectance and absorbance bands situated between 7 and 15 µm in the mid-infrared region of the spectrum [5]. As such, relatively unshocked minerals within the meteorites, such as olivine, pyroxene and plagioclase, are identifiable using their FTIR spectrum. Anorthite plagioclase has a Christiansen Feature (CF – the point of lowest reflectance) position of 1221 cm^{-1} (8.19 µm) compared to 1192 cm^{-1} (8.39 µm) for pyroxene and 1117 cm^{-1} (8.95 µm) for olivine. The CF position increases in wavelength from plagioclase to olivine; a correlation due to composition that is consistent with previous studies of CF position [6].

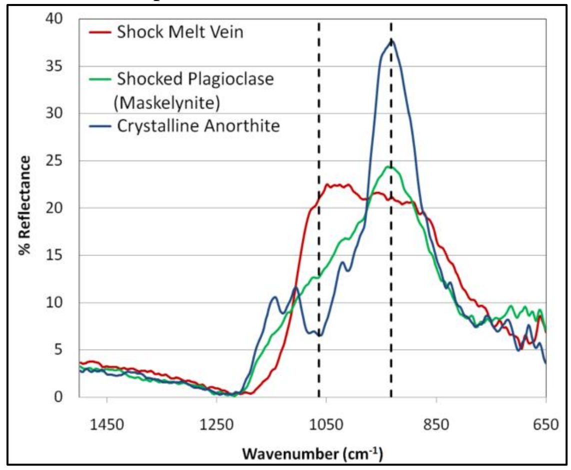

Figure 1 (above) and Table 1 (below) – FTIR spectra of crystalline anorthite, shocked plagioclase (maskelynite) in contact zone and shock melt vein in MIL 090034. The locations of these points are denoted by red circles in Figure 2B, and their oxide compositions are shown in Table 1 (below). Differences in shock result in different spectral patterns, quantified by the ratio of the 1064 cm^{-1} (9.40 µm) and 932 cm^{-1} (10.73 µm) bands (black vertical dashed lines).

Oxide wt%	Crystalline Anorthite	Maskelynite in contact zone	Shock Melt Vein
SiO_2	43.76	43.62	44.77
Al_2O_3	36.06	36.25	32.39
K_2O	0.02	0.02	0.04
Na_2O	0.34	0.35	0.36
MgO	0.08	0.03	2.23
CaO	19.71	19.61	18.2
FeO	0.22	0.13	2.40
Sum	100.19	100.02	100.38
An#	96.9	96.8	96.3
Mg#	39.3	29.1	62.3

Impact shock effects: In MIL 090034, feldspathic phases of similar composition show different spectral features due to changes in internal structure caused by shock and *in situ* melting (Fig. 1). The first reflectance bands to lose spectral resolution (and to disappear, resulting in overall peak broadening) are situated around 1150 cm^{-1} (8.70 µm) and are representative of Al-O-Si bonds within the plagioclase crystal. Impact-induced shock preferentially disrupts AlO_4 tetrahedra due to Al-O bonds being weaker than Si-O bonds [7].

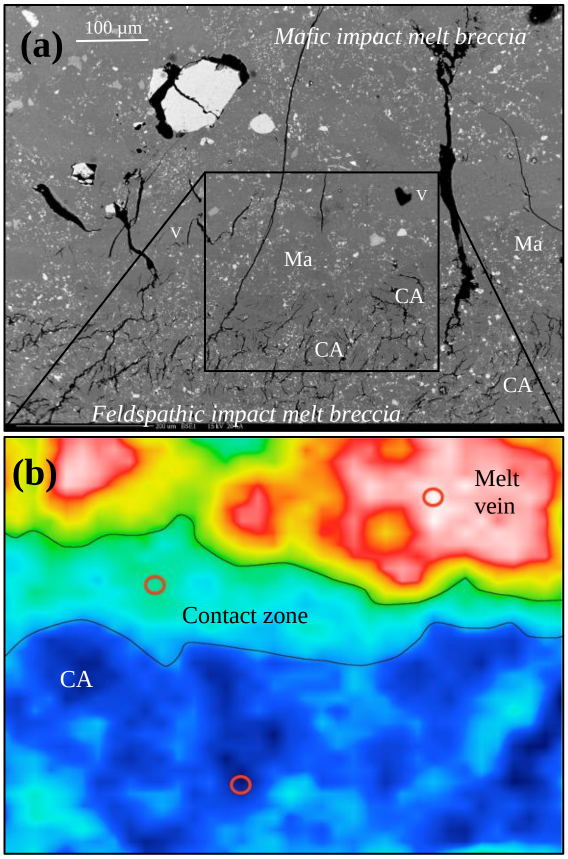

Figure 2 – (a) Back-scattered electron image of an area of MIL 090034, showing crystalline anorthite (CA) in an impact melt breccia clast, a shock melt vein (V) and the shocked plagioclase (Ma) in the contact zone in between. The box shows the area highlighted in (b). (b) False-colored map showing the 1064 and 932 cm^{-1} ratio. Crystalline anorthite is blue, contact zone is light blue/cyan green, and shock melt vein is yellow/red. Lighter areas within the crystalline anorthite show areas of fractures and more mafic phases. Red circles represent the locations of spectra shown in Fig. 1.

Quantification of plagioclase shock levels using FTIR spectra: Quantifying the spectral differences between shocked and unshocked plagioclase is important for existing and future mid-infrared studies of planetary surfaces e.g. the MERTIS instrument that will study Mercury's surface from aboard the Bepi-Colombo spacecraft [8]. With increasing levels of lattice disorder, the intensity of the absorption band at 1064 cm^{-1} (9.40 µm) increases relative to the main Si-O reflectance band at 932 cm^{-1} (10.73 µm) (Figs. 1 and 2b). As such, the ratio of these two band positions (1064/932 cm^{-1}) results in low values for crystalline anorthite of 0.31 ± 0.07 compared to the shock melt vein: 0.92 ± 0.08 (where each value represents an average of ~30 measurements and uncertainty equals 1 st. dev.). Plotting between these regions, with a ratio of 0.65 ± 0.05, is shocked plagioclase in the contact zone.

Anorthite crystal: Anorthite crystals hosted in a feldspathic impact melt breccia clast have both Al-O and Si-O reflectance bands indicating a peak shock pressure of <10-15 GPa. This is consistent with OM-CL investigations of shocked plagioclase that detect a structural change in anorthite at ~15 GPa [4]. Reduced Al-O band intensities may indicate more highly shocked crystalline anorthite (up to 25 GPa).

Shocked plagioclase: Shocked plagioclase phases hosted in the contact zone display a strong Si-O reflectance band at 932 cm^{-1} (10.74 µm), but no Al-O bands. Their texture and composition indicate transformation to maskelynite. Therefore, peak shock pressures can be estimated to be between 25 GPa and 45 GPa [9].

Shock melt vein: The shock melt vein is more mafic than the surrounding mineral components (Table 1). Its spectra consist of a broad, arching peak between ~1060 and 860 cm^{-1} (9.4 - 11.6 µm) and display significantly lower reflectance values than the crystalline anorthite (Fig. 1). This represents complete disorder of the crystal lattice as a result of melting.

Shock history of the Miller Range lunar meteorites: The concentration of variably shocked crystal fragments within the feldspathic impact melt breccia clasts confirm that multiple impact events have reworked this material prior to lithification and ejection. The presence of shock melt veins in close proximity to unshocked material indicates that the propagating shockwave may have been concentrated into thin lenses in between clasts that reached at least 45 GPa, causing localized *in situ* melting of this interstitial material (possibly regolith) [9]. The maskelynite in the contact zone between the melt vein and impact melt clast indicates a shock-level of 25-45 GPa. However, the large fraction of crystalline anorthite mineral clasts found throughout the samples suggests a low average shock level experienced during residence in the lunar crust: <10-15 GPa.

Comparing the three meteorites: MIL 090075 has the greatest concentration of shock melt veins, with MIL 090070 having none (in the sections viewed), indicating that MIL 090075 experienced the highest levels of shock throughout its history.

Conclusions: Micro-FTIR spectroscopy and CL imaging [4] can be used to distinguish between shocked and unshocked varieties of plagioclase in the lunar meteorite samples studied here. Future work includes a more detailed quantitative analysis of the spectra and comparison to definite shock values, along with a similar study with mafic mineral fragments.

References: [1] Korotev R. et al. (2011) LPS XLII #1999. [2] Martin D. J. P. and Joy K. H. (2014) 77th MetSoc, #5191. [3] Zeigler R. A. et al. (2012) LPS XLIII, #2377. [4] Pernet-Fisher J. F. et al. (2016) LPS XLVII *#1499* [5] Pieters C. M. and Englert P. A. J. (1993) Remote Geochemical Analysis [6] Conel J. E. (1969) *Geophys. Res. 74 (6)*, 1614–1634. [7] Williams Q. (1998) *Geophys Mono 11, AGU*, 531-543. [8] Hiesinger H. et al. (2010) *PSS 58, 144-165.* [9] Rubin A. E. et al. (1997) *GCA, 61*, 847-858.