RAMAN STUDY OF MODERATELY TO STRONGLY SHOCKED FEATURES IN LUNAR ANORTHITE FROM APOLLO 16 MISSION T. Xie[1], G. R. Osinski[1, 2], S. R.Shieh[1], C. M. Pieters[2]. [1]Dept. of Earth Sciences / Institute for Earth and Space Exploration, University of Western Ontario, 1151 Richmond Street, London, ON, Canada, N6A 5B7 (txie23@uwo.ca, gosinski@uwo.ca, sshieh@uwo.ca), [2]Brown University, Dept. Earth, Environmental, and Planetary Sciences, Providence, RI, 02912 USA (Carle_Pieters@brown.edu)

Introduction: Earth's moon, our nearest neighbour, records and preserves a rich and extended geological history and key information about fundamental processes that shape planetary crusts such as impact cratering events. Lunar regolith, soil, and rock samples brought back to Earth by the Apollo missions have been instrumental in developing our understanding of lunar mineralogy and geological evolution [1]. Understanding shock effects in lunar anorthite (Ca-rich plagioclase), the principal component of anorthosite and most common crustal mineral on the Moon, is key to unravelling the early evolution of the Moon and terrestrial planets in the solar system. However, as we stand on the edge of a new era of lunar exploration, it is notable that there are relatively few systematic study of shock effects in lunar anorthite using modern analytical techniques. Here, we investigate shock features in lunar anorthite from the Apollo missions using traditional optical microscopy and modern Raman spectroscopy.

Methodology: Sixteen polished thin sections from lunar samples returned by Apollo 16 were used in this study (Table 1). Mainly anorthosite, with some gabbro, basalt, impact melt rock, and breccia, were specifically selected to collect the widest possible range of optical deformation induced by shock events. All the lunar anorthite used here has a composition of $An_{89–99}$ [2].

Table 1. List of Apollo 16 lunar sample selected for this study and their origin information (LM: Lunar Module; *marked samples not investigated in our recent published work [3]).

Sample#	Origin	Rock type
60015,114	~30m from LM	Anorthosite
60025,230	~15m from LM	Anorthosite
60055,30*	Station 10	Anorthosite
60215,13 60215,68*	Station 10	Anorthosite breccia
60618,4	~70m from LM	Anorthosite
67075,41	North Ray Crater	Anorthosite (F)
67415,113	North Ray Crater	Anorthosite (N)
67746,12	North Ray Crater	Anorthosite (N)
67936,23	North Ray Crater	Impact melt
67975,85	North Ray Crater	Fragmental breccia
68035,6	Station 8	Anorthosite
69955,27 69955,29	Station 9	Anorthosite
61016,549* 61016,550*	East rim of Plum Crater	Anorthosite

Optical petrography was used to separate samples into broad categories of shock levels. A Renishaw InVia Reflex Raman Spectrometer with a 514 nm wavelength laser was used to collect Raman spectra of target features. The spectrometer was calibrated using silicon crystal and spectra were collected using confocal 50X/100X objectives, ranging from 126 to 2000 cm^{-1} with 1800 g/mm grading. The collecting time of the spectra has an average of 180s, and the baselines were removed using built-in software WiRE.

Results: A variety of shock features recording low to moderately to strongly shocked levels in lunar anorthite from Apollo 16 samples were documented in this study (summarized in Table 2). While low shock features were observed in nearly all of the thin sections, moderately to strongly shocked features like planar deformation features (PDFs) and diaplectic glass were only seen in 3 of them. Raman spectra of these shock features were systematically collected [3] and Raman spectra from anorthite in 60215,68 (~An_{97}[4]) was used as unshocked to weakly shocked reference (as marked in Fig 2). The two most intense Raman peaks occur near 500 cm^{-1} are diagnostic for anorthite and assigned to T-O-T stretching modes [5].

Table 2. Summary of shock features in lunar samples.

Shock Stage	Shock features
S1 Unshocked	Sharp optical extinction, little irregular fractures
S2 Weakly shocked	Deformed twins, slightly undulatory extinction
S3 Moderately shocked	Heavily undulatory extinction, planar features, PDFs, partially isotropic
S4 Strongly shocked	Diaplectic glass
S5 Very strongly shocked	Glass

Undulatory extinction is commonly seen as moderately shocked feature. Comparing Raman spectra from undulatory extinction in 61016, 549 (Fig 1A, B, #1 in Fig 2) to the unshocked reference, band broadening, reduction of intensities, and loss of lattice mode bands were observed. These obvious changes in Raman features suggest microstructural deformation and loss of crystallinity.

The most diagnostic indicator of moderate shock levels is the presence of PDFs. While PDFs have been proposed to form in plagioclase feldspar and reported in early works with Apollo samples as "shocked-induced lamellae" of low refractive index and low or no birefringence [6], more recent work was not able to document any unequivocal PDFs in both lunar and terrestrial plagioclase samples [3,7]. This could be due to misidentification in early work and/or the presence of pre-existing planes of weakness such as fine twin planes, exsolutions and alterations.

Interestingly, among all the thin sections studied here, a few sets of PDFs were observed in 61016,549 (~An_{96}[8]) (Figs. 1C – F). The presence of PDFs here was confirmed by the isotropic appearance under cross polarized light (spot 4 in Fig. 1F) and the Raman spectra (#4 in Fig 2). Similar as the one (#5 in Fig. 2) from diaplectic glass (Figs. 1G, H), the spectrum (#4 in Fig. 2)) collected from the fine planar features (4 in Figs. 1E,F) indicate amorphous nature of the target, confirming them being PDFs.

As the diagnostic feature of strongly shocked level, diaplectic glass was observed in 69955, 27, 69955, 29 and 61016, 549. Raman spectra of diaplectic glass (spot 5 in Figs. 1 G, H, #5 in Fig 2) no longer shows the narrow Raman peaks from well-crystallized tectosilicate structure, but consist of two broad peaks indicating amorphization: the first broad peak centered around 500 cm^{-1} suggesting short-range variability and long-range disorder; the second broad peak centered around 1000 cm^{-1} suggests the increased amount of nonbridging oxygen.

Conclusion: Raman features are efficient in differentiating amorphous areas from crystalline plagioclase, making it efficient in identifying diagnostic shocked features, such as PDFs and diaplectic glass. This makes Raman spectroscopy a useful tool for purposely selecting moderately to strongly shocked samples to study in lab and/or return in future lunar missions. The results of this study can help the interpretation of Raman data of impact materials from past and future exploration missions and demonstrate the utility of Raman spectroscopy for documenting and selecting samples for future lunar missions.

References: [1] Hiesinger H. et al. 2006. Reviews in Mineralogy and Geochemistry 60(1):1 – 82. [2] Papike J. et al. 1991. Cambridge: 121–181. [3] Xie T. et al. 2021. Meteoritics & Planetary Science 56(9): 1633-1651. [4] McGee J. J. 1993. J. Geophys. Res.98, 9089-9105. [5] Sharma S.K. et al. 1983. American Mineralogist, 68: 1113- 1125. [6] Short N. M. 1970. Proc. Lunar Sci. Conf. 1: 865–871. [7] Pickersgill A. E. et al. Meteoritics and Planetary Science 50:1851–1862. [8] Meyer C. 2009. 61016 Lunar Sample Compendium.

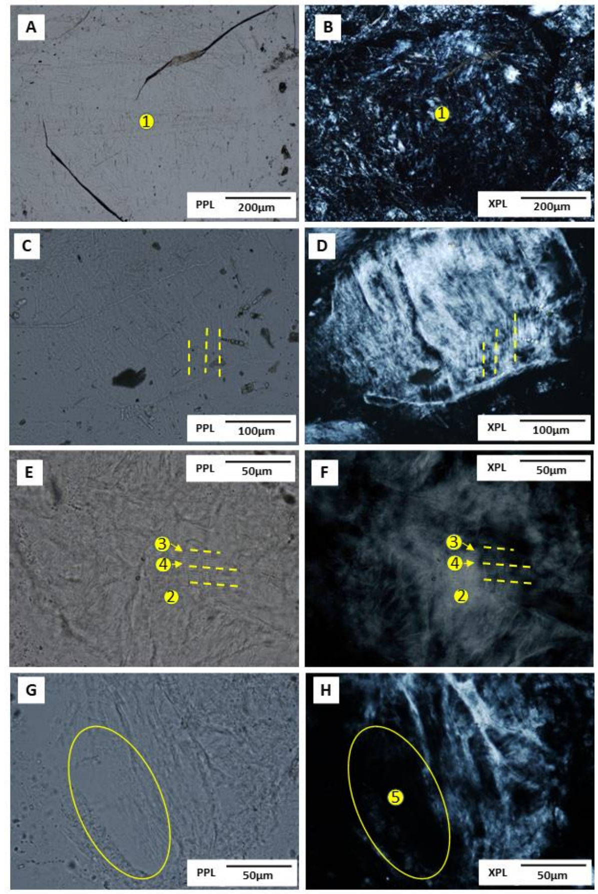

Figure 1. Photomicrographs of moderately to strongly shocked features in lunar sample 61016,549. PPL= Plane polarized light; XPL= Cross-polarized light. A, B): heavily undulatory extinction; C, D, E, F): sets of PDFs, indicated by dash lines; G, H): diaplectic glass.

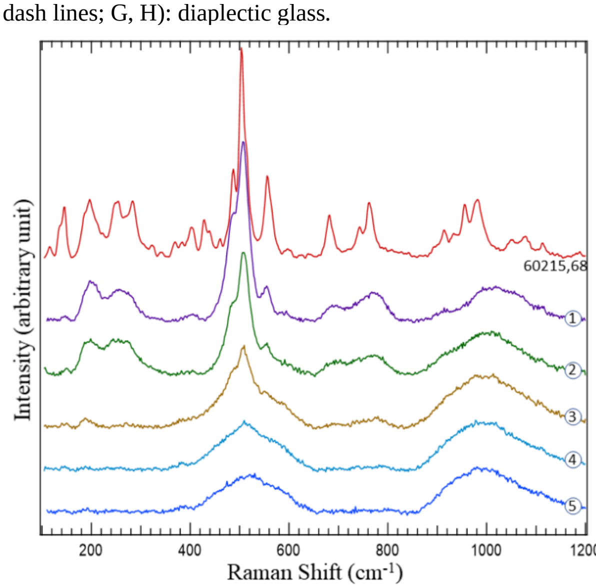

Figure 2. Raman spectra from shock features marked in Figure 1 from 61016,549; the spectrum from 60215,68 is used as reference for unshocked anorthite.