CHARACTERISATION OF A TERRESTRIAL LOW-IRON PINK SPINEL AS AN ANALOGUE TO SUPPORT THERMAL INFRARED OBSERVATIONS OF THE MOON. C. M. Marriner[1], K. L. Donaldson Hanna[1], N. E. Bowles[1], T. C. Prissel[2], C. R. M. Jackson[2], L. Cheek[3], S. W. Parman[2], C. M. Pieters[2], P. J. Isaacson[4], and B. T. Greenhagen[5]. [1]Atmospheric, Oceanic & Planetary Physics, University of Oxford, Clarendon Laboratory, Oxford, OX1 3PU, UK. [2]Dept. of Geological Sciences, Brown University, Providence, RI, USA. [3]Astronomy Department, University of Maryland, College Park, Maryland, USA. [4]HIGP, University of Hawaii, Manoa, Hawaii, USA, [5]Jet Propulsion Laboratory, Pasadena, CA, USA. (Corresponding Author: marriner@atm.ox.ac.uk)

Introduction: The Moon Mineralogy Mapper (M^3) onboard the Chandrayaan-1 spacecraft has identified a new lunar rock type in small exposures across the lunar surface [e.g. 1-4]. These small exposures are spectrally dominated by Mg-Al spinel and appear to be associated with regions of thinner crust and/or the inner rings of basins like the inner ring of the farside Moscoviense basin [1], and in the central peak of Theophilus crater (in Nectaris basin [2,3]). This association indicates that the Mg-Al spinel likely originated in the lower crust/upper mantle before excavation to the surface during impact event(s) [1-4], however exposed lithologies suggestive of a mantle origin have not been observed thus far [4]. In addition, these Mg-Al spinel exposures appear to be associated with feldspathic material, including identifications of pure crystalline plagioclase units nearby, with no observable mafic silicate signature in the spectra [4]. This is a distinguishing feature, as all spinel-bearing samples recovered from the Moon are associated with significant proportions of olivine +/- pyroxene. Thus, this new rock type has been termed a pink spinel anorthosite [1,2].

The Fe bearing Mg-spinel-rich rock types are identified spectroscopically in the near infrared (NIR) by a prominent absorption band near 2 µm and a lack of a 1 µm absorption band [1-4]. Recent studies have shown that spinels synthesized in the lab that contain <5 wt. % FeO (high Mg) do not exhibit an absorption band near 1 µm in their NIR spectra suggesting the Mg-spinels on the lunar surface may be low in FeO [5] and contain <5% mafic materials (e.g. pyroxene and olivine) [1]. Furthermore, lab experiments have suggested Mg-spinel anorthosites may have formed during melt-rock interactions between Mg-suite magma and anorthositic crust, implying Mg-spinel anorthosites may be an uncollected member of the Mg-suite rocks [6].

NIR data can be used to uniquely identify exposures of Mg-spinel anorthosites as well as estimating the FeO content of the Mg-Al spinel. Due to the non-linear nature of mixing in the NIR, it is difficult to determine the abundance of feldspathic material (plagioclase) in the Mg-spinel anorthosite exposures, however the linear nature of mixing at the thermal infrared (TIR) wavelengths allows for the estimation of plagioclase abundance [e.g. 7]. Terrestrial and synthetic spinel samples must first be characterized at TIR wavelengths under simulated lunar conditions before comparing resultant spectra to observations of Mg-spinel anorthosite exposures by the Diviner Lunar Radiometer Experiment (Diviner) onboard the Lunar Reconnaissance Orbiter (LRO) [8] (see Figure 1).

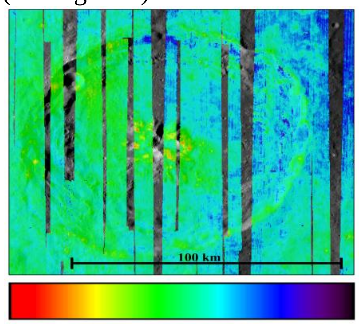

Figure 1. Diviner CF map [8] of Theophilus crater overlaid on a LROC WAC albedo image. Colour scale: red = 7.85 µm and blue/violet = 8.5 µm.

In this study, we first analyse a rough pink spinel gemstone from Sri Lanka using a scanning electron microscope (SEM) using energy-dispersive X-ray spectroscopy (EDX) and an electron microprobe (EMP) to confirm its low FeO content (< 5 wt.% FeO) making it a suitable lunar analogue. Particulate samples of the pink spinel gemstones are processed and measured at TIR wavelengths under simulated lunar conditions in the Lunar Environment Chamber at the University of Oxford's Planetary Spectroscopy Facility. These laboratory measurements will be the first in characterizing lunar-like spinels across TIR wavelengths in an effort to understand current (Diviner) and future observations of Mg-spinel anorthosite exposures on the lunar surface like those in Moscoviense Basin and Theophilus crater (see Figure 1) [8].

Methodology: The rough spinel gemstones were ground into particulates using a mortar and pestle (Figure 2). The largest grains were chosen to verify the elemental homogeneity of the sample using the FEI Quanta 600 FEG at the University of Oxford's Nanofabrication and Electron Microscopy facility. The chamber, under high vacuum, produced charging on the surface of the spinel grains as they are non-conducting. To minimalize charging, water was introduced and the chamber put on a low vacuum (0.08 torr). Several locations on the grains were chosen for spectral analysis at a magnification of 2002x. To reduce charging, an 11kV lifetime for 120 seconds was chosen. Then for the final analysis of each grain a higher 20kV lifetime for 300 seconds was chosen to obtain a higher resolution spectrum. A sample spectrum from the SEM results can be seen in Figure 3 where the peaks for the species are identified.

The Cameca SX-100 EMP at the Brown University Geological Sciences Electron Microprobe Research Facility was used to analyse 20 different locations across a pink spinel gemstone to determine the mineral's composition as well as the homogeneity of the spinel sample. Average composition is given in Table 1.

The particulate pink spinel samples will be ground and sieved further to produce sample material with particle sizes < 25 μm, which is similar to the range of particle sizes that dominate the optical properties of the lunar surface [9]. Fine particulate samples will be measured across thermal infrared wavelengths (5 – 25 μm or 400 – 2000 cm^{-1}) under simulated lunar conditions in the Lunar Environment Chamber at the University of Oxford [10]. The near-surface conditions of the Moon are simulated in a vacuum chamber that is capable of maintaining pressures < 1×10^{-4} mbar. Samples are heated from below to 450K using sample cup heaters and the vacuum chamber is cooled to temperatures < 150K using a liquid nitrogen cooled radiation shield. To simulate incident solar radiation on the lunar surface, a solar-like lamp illuminates the samples, heating the surface of the sample. Radiation emitted from the sample is reflected into a Brüker FTIR spectrometer.

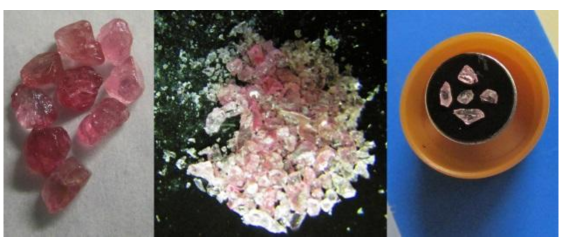

Figure 2. (Left) Rough pink spinel gemstones. (Centre) Crushed pink spinel sample. (Right) Largest grains for SEM EDX analysis.

Compositional Results: EDX analysis indicates the sample contains a large abundance of O, Mg, and Al detected shortward of 2KeV over several spectra (see Figure 3). Longward of 2KeV no iron was detected in the sample above the background noise. The C-peak present in the sample is due to an adhesive tab used during analysis and not inherent to the sample (this was confirmed during EMP analyses).

EMP analyses confirm the sample is nearly pure, stoichiometric $MgAl_2O_4$ spinel with < 0.2% FeO (see Table 1). The distinct pink colour is produced by traces of Cr_2O_3. Therefore, both techniques agree, and confirm, that this is pink spinel with a low-Fe content of <1%, and is thus an excellent terrestrial sourced lunar analogue for ongoing experiments.

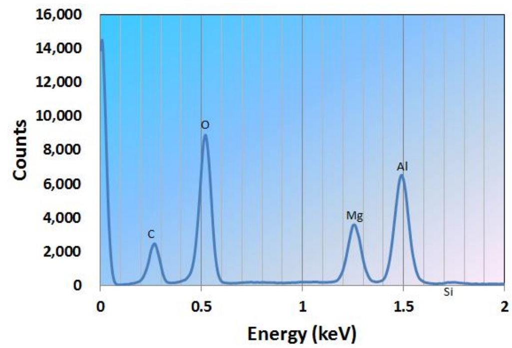

Figure 3. Spectrum (11kV for 120s) of the terrestrial pink spinel analysed in the SEM using EDX.

Table 1. Average of points analysed (EMP).

Molecule	Average Abundance (%)
MgO	28.7 ± 0.2
Al_2O_3	72.1 ± 0.4
SiO_2	0.057 ± 0.019
CaO	0.0025 ± 0.0026
TiO_2	0.013 ± 0.005
Cr_2O_3	0.14 ± 0.09
MnO	0.007 ± 0.004
FeO	0.15 ± 0.02

Ongoing/Future Work: Lunar analogues like the low-Fe pink spinel sample in this study as well as a suite of well-characterized, synthesized spinel samples of varying Fe- and Cr- abundance will be measured across TIR wavelengths under simulated lunar conditions. These spectral measurements of spinel under simulated lunar conditions will be the first of their kind and will compared with spinel spectra measured under Earth-like conditions in an effort to characterize spectral changes due to the lunar environment. In addition TIR spectra of spinel measured under lunar conditions will be compared to Diviner observations of Mg-spinel anorthosite exposures like those in Moscoviense Basin and Theophilus crater to provide initial estimates of the abundance of plagioclase in these spinel-rich regions. Understanding the spinel-to-plagioclase ratio in these exposures could provide new insight into magmatic processes involved in spinel-production and the petrogenesis of spinel lithologies on the Moon.

References: [1] Pieters C.M. et al., (2011), *JGR*, 116, E00G08. [2] Dhingra D. et al., (2011), *GRL*, L11201. [3] Lal D. et al., (2012), *JESS*, 121, 847-853 [4] Pieters C.M. et al., (2013), LPSC44, 2545. [5] Jackson C.R.M. et al., (2012), LPSC43, 2335. [6] Prissel T.C. et al., (2012), LPSC43, 2743. [7] Ramey M.S. and Christensen P.R. (1998), *JGR*, 103, 577-596. [8] Greenhagen B.T. et al., (2011), *AGU*, P13D-1694. [9] Pieters C. M. et al., (1993), *JGR*, 98, 20817020824. [10] Thomas I. R. et al., (2012) *Rev. Sci. Instrum.*, 83(12), 124502.