Demonstrating TEMMI: A Three-Dimensional Exploration Multispectral Microscopic Imager on Geologic Materials. N.R.E. Segal[1], G. R. Osinski[1], P. Dietrich[2], L. L. Tornabene[1], A. B. Coulter[1], M. Daly[3], M. Doucet[4], A. Kerr[2], M. Robert[4], M. Talbot[4], A. Taylor[2], M. Tremblay[4], [1]Centre for Planetary Science and Exploration, Western University Canada, London, ON, Canada N6A 5B7 (gosinski@uwo.ca), [2]MDA Space Missions, 9445 Airport Road, Brampton, ON, Canada L6S 4J3, [3]Centre for Research in Earth and Space Science,York University, Toronto, ON, Canada, [4]INO, 2740 Einstein, Quebec, Canada G1P 4S4.

Introduction: High-resolution microscopic imagers are a valuable and necessary component for surface missions to Mars and the Moon [1-5]. Microscopic images provide *in situ* micro-scale information which allows samples to be classified, and placed into a geological context and framework. The following abstract summarizes a demonstration of the capabilities of the Three-Dimensional Exploration Multispectral Microscopic Imager (TEMMI) (Fig. 1) on geologically relevant materials, including recent contributions the instrument made to the 2014 joint Collaborative Research and Training Experience (CREATE) and Canadian Space Agency (CSA) Mars Sample Return Analogue Mission.

Fig. 1. TEMMI mounted on the arm of the Mars Exploration Science Rover (MESR) along with the Mini-Corer sampling tool (Mars Yard at the CSA in St. Hubert, Quebec).

TEMMI Design and Specifications: The CSA designed and developed TEMMI in association with two industrial partners, MacDonald, Dettwiler and Associates Ltd. (MDA) and the National Optics Institute (INO), along with three investigative academic partners: Western University, the University of New Brunswick and York University [6-8]. For maximum effectiveness and versatility TEMMI has three different operating modes: 2D colour, 3D and Ultraviolet (UV).

To create a 2D image, TEMMI is equipped with eight Light-Emitting-Diode (LED) lights. Seven covering the wavelength range of the visible and the near infrared (VNIR) part of the electromagnetic spectrum, from 455 nm to 850 nm, and one in the UV range (365 nm) [9]; these are used to derive a "true" colour composite image and allow 7-point VNIR spectral analysis. Diagnostic absorptions in the VNIR short of 1 µm are specifically sensitive to outer-shell electron transitions in transition metal cations, especially iron (Fe) [10]. As such, the TEMMI 7-point VNIR spectra may be used to discriminate ferrous (Fe^{2+}) and ferric (Fe^{3+}) iron-bearing minerals common to the Moon and Mars (e.g., Fig. 2).

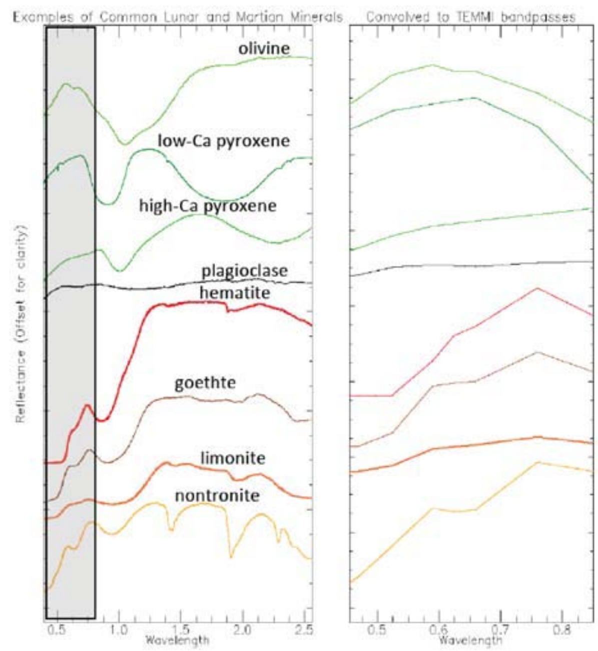

Fig. 2. Left: selected minerals common to the Moon and/or Mars from the USGS VNIR spectral library. The gray box indicates the spectral wavelength range covered by TEMMI's seven-point spectra. Right: the same minerals resampled to the seven TEMMI VNIR LEDs.

A 3D surface is derived by projecting a Moiré pattern onto the surface of the sample and mathematically calculating a 3D point cloud associated with the distortion of the pattern. The point cloud has a lateral resolution of 5µm and a vertical resolution of 2µm [9]. A 3D colour composite is derived by overlaying the 2D colour image onto the point cloud.

Utilizing a wavelength of 365nm, the UV mode allows identification of fluorescence in a sample. Fluorescence may be indicative of mineralogy and some biosignatures. As such, it augments other information and data, collected by other instruments with respect to characterizing the sample.

Two imaging modes define the parameters for 2D imaging, for both 2D colour and UV. The high-resolution mode provides a field-of-view (FOV) of 5.7 x 2.1 mm^2 with ≤ 5µm optical resolution (2.2µm pixel resolution) while the low-resolution mode provides a FOV of 5.7 x 4.3 mm^2 with optical resolution≤ 10µm (4.4µm pixel resolution). The nominal working distance of TEMMI is 25mm, which is adjusted by an internal focusing stage that positions the microscope on a range from -20 to +5 relative to its initial position. The 20 µm native depth-of-field (DOF) can be extended using focus stacking [9].

Demonstration: The purpose of integrating TEMMI into the academic/scientific community is to test its imaging capabilities and validate its contribution to geological investigations on planetary surfaces. Furthermore, such testing and validation on a suite of geologically relevant samples provides an opportunity for the academic/scientific community to provide feedback with respect to the further development of the TEMMI prototype into a flight-ready instrument.

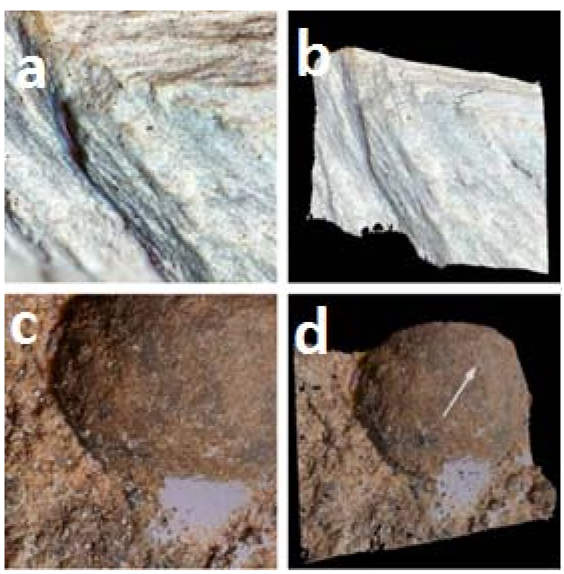

Fig. 3. a) and c) Low-resolution colour image (4.3 x 4.3 mm). b) and d) 3D perspectives of the same images from a) and c) draped on their derived 3D models [6].

Fig. 3 shows a set of images of two impactites (a shatter cone and a melt-bearing rock) including low-resolution color images (Fig. 3a and 3c) and a screenshot of 3D color composite images (Fig. 3b and 3d). The micro morphologies become quite apparent in these samples by utilizing TEMMI's focus stacking capabilities along with the 3D mapping. Fig. 3a and Fig. 3b are TEMMI images of the surface of a shatter cone – the only macroscopic indicator of the high shock deformation for an impact event [11]. The characteristic conical and striated "horse-tail" structures captured by TEMMI are a diagnostic feature of shatter cones. The conical nature of the shatter cone, relevant to the proper identification of such a feature, is under-appreciated in the 2D image, but is easily recognized in the 3D. Fig. 3c and Fig. 3d show a spherical, concretion-like feature in a melt-bearing rock that is reminiscent of the hematite-rich Martian 'blueberries' that were discovered by the Opportunity Rover in Meridiani Planum on Mars [12]. Like the shatter cone, the spherical nature of the putative concretion is not clear in the 2D image, but is easily discerned in the 3D.

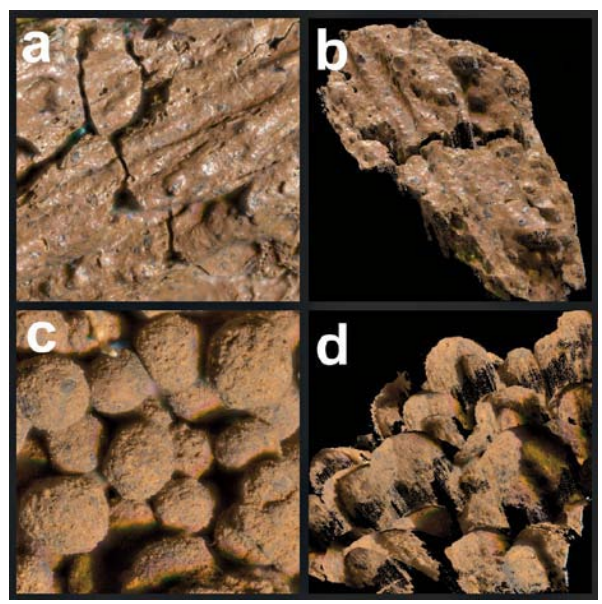

Fig. 4. a) and c) low-resolution colour images (4.3 x 4.3 mm) of a volcanic scoria and phosphorite oolites, respectively. b) and d) 3D perspectives of the same images from a) and c) draped on their derived 3D models

Fig. 4 shows a compilation of TEMMI images of two additional samples – a highly oxidized and glassy volcanic scoria (Fig. 4a and 4b) and phosphoritic oolites (Fig. 4c and 4d). Fig. 4a and 4c show the final iteration of 2D colour images stacked with 150 layers at 0.025mm and 100 layers at 0.025mm, respectively. Fig. 4b and 4d show the 3D perspective images of the two samples. TEMMI captures well the dimensions (both

2D and 3D) of the ~1-2 mm spherulitic oolites [13].

The images taken by TEMMI in Figs. 3 and 4 may be analogous to features and structures that may be found in a Martian and/or Lunar environment. As such, the high-resolution, multi-wavelength, and 3D capability of TEMMI may prove invaluable for determining the geologic histories of the materials investigated by future roving missions.

UV Imaging: Corundum (Al_2O_3) is a known fluorescent mineral. As seen in Fig. 5, the mineral corundum is shown to fluoresce under TEMMI's UV LED illumination at 365 nm (Fig. 5b).

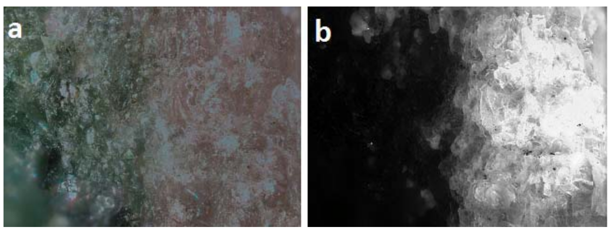

Fig. 5. TEMMI 2D colour and UV images of corundum in zoisite. a) A low-resolution colour image (5.7 mm x 4.3 mm). b) Same image taken with just the UV wavelength at 365nm.

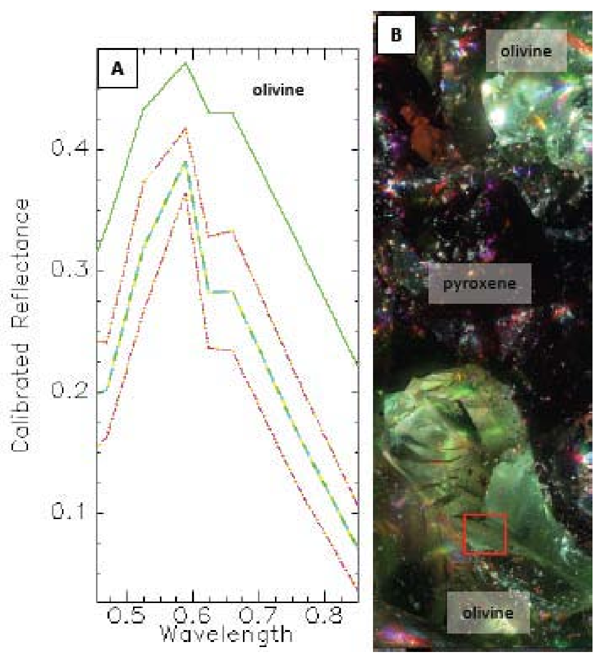

Fig. 6. TEMMI basaltic xenolith spectra and 2D col-our image. (a) An image-derived 7-band TEMMI spectrum (green dashed line) matched with a lab-collected olivine spectrum (green solid line) from the USGS VNIR mineral spectral library (solid lines). Both a single pixel spectrum (extracted from the red box in (b)), as well as an averaged spectrum utilizing up to 9,558 pixels from the same grain (standard deviations plotted in red) were spectrally consistent and had the highest weighted score/match for olivine spectra contained in the USGS library. The olivine grain shown in (b) has dimensions of ~275x425 pixels.

Reflectance Spectroscopy: Calibrated multispectral reflectance data acquired by TEMMI allows for the discrimination of known minerals within a sample. As demonstrated in Fig. 6, TEMMI-acquired spectra are matched with lab-collected olivine spectrum from the USGS mineral spectral library of 481 minerals [14]. Visual inspection as well as spectral angle mapping (SAM), spectral feature fitting (SFF), and Binary Encoding (BE) was used to obtain the best-matched results [15]. A darker phase in the sample (Fig 6b), known to be orthopyroxene, was not well constrained spectrally due to low signal-to-noise as a consequence of under-exposure of this naturally dark phase. Adjustments of the exposure and implementation of a High Dynamic Range (HDR) function have yet to be tested with this sample and may yield positive results.

Analogue Mission Deployment: The most recent demonstration of the TEMMI prototype involved rover arm-mounted operations on the CSA's Mars Exploration Science Rover (MESR) platform as part of the 2014 CREATE-CSA Mars Sample Return Analogue Mission that took place August 11-22. During the mission, TEMMI provided valuable context for sample collection by complementing both X-Ray Fluorescence (XRF) and Raman spectral data, and aiding with the documentation of collected samples. Fig. 7 shows the TEMMI image of the Mars Yard "regolith" sand, interpreted to be quartz-rich and is consistent with XRF data showing a high silica content and Raman data indicating peaks indicative of quartz.

Fig. 7. A low-resolution colour image of "regolith" sand (5.7 mm x 4.3 mm) aquired on SOL3 of the CREATE-CSA Mars Sample Return Analogue Mission.

Future Work: Ruggedizing the mechanical design and advancing the electronic design towards flight are important steps towards a flight design. Updated software and hardware are required to reduce the image acquisition and processing time. Also, further laboratory investigations, including testing the HDR imaging capabilities (e.g. dealing with a sample with mixed light and dark phases – such as the sample from Fig. 6b) and another analog mission, which incorporates TEMMI's full range of capabilities are forthcoming.

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References: [1] Edgett, K. S. et. al. (2012) *Space Science Reviews 170, 1-4, pg 259-317*. [2] Edgett, K. S. et. al. (2009) *Work-shop on the Microstructure of the Martian Surface*, 5-5.[3] Farmer, J. D. et. al. (2011) *AGU Fall Meeting 2011*, Abstract #P33D-1786. [4] Nuñez, J. I. et. al. (2010) *2010 GSA Denver Annual Meeting*. [5] Tunstel, E. et. al. (2002) *Automation Congress, vol. 14, pg. 320-327*. [6] Coutler, A. B. et al. (2002) *International Workshop on Instrumentation for Planetary Missions*, Abstract #1081. [7] Preston, L. J. et. al (2011) *GAC/MAC -MAC/AMC -SEG -SGA Joint Annual Meeting.* [8] MDA TEMMI User Guide. [10] Burns (1993) In Remote Geochemical Analysis: Elemental and Mineralogical Composition, 329. [11] Amir Sagy et. al. (2002) *Nature 418, 310-213*. [12] Mahaney, E. C. et al (2008) *AGU Fall Meeting*, Abstract #P33B-1440. [13] http://coastal.er.usgs.gov/navassa/geology/ [14] Clark, N. et al. (2007) USGS digital spectral library splib06a: USGS, Digital Data Series 231. [15] Kruse A. et al. (1993). Remote sensing of environment, 44, 145-16