HYPERSPECTRAL CHARACTERIZATION OF THE FLAKSTADØY ANORTHOSITIC COMPLEX (LOFOTEN ISLANDS, NORWAY) AS ANALOG SITE OF LUNAR HIGHLANDS: PRELIMINARY RESULTS. R. Chirico[1], R. Pozzobon[1] and M. Massironi[1], [1]Department of Geosciences, University of Padua (Via Giovanni Gradenigo, 6, 35131 Padova PD, rita.chirico@unipd.it)

Introduction: In recent years, progress in space exploration technology, with a primary focus on identifying prospective landing sites for both robotic and human missions, has sparked renewed interest and created new opportunities for comprehensive lunar research. Numerous investigations have been conducted on the reflectance spectra of lunar highland regions, including analyses of rock samples collected during Apollo missions. However, only a restricted number of studies have been performed by satellite- and laboratory-based hyperspectral sensing of terrestrial lunar analogues [1,2]. This study aims to perform a spectral mineralogical characterization of the Proterozoic anorthositic suite of the Flakstadøy basic complex, exposed in the Lofoten Islands archipelago, off the northwest coast of Norway [3–5]. The site shares many geological features and genetic aspects with plagioclase-rich lunar highlands rocks, making it a valuable example to be studied as an analogue. Furthermore, the rocks in this region are well-exposed due to Quaternary glaciations and limited vegetation cover [6], making the site an ideal target for optical remote sensing applications.

Geological Setting: The archipelago is composed of Meso- to Neoarchaean gneisses, intruded about 1.8–1.7 billion years ago [4], by an extensive magmatic suite. This suite includes a sequence of anorthosite, leucogabbro, leucotroctolite, troctolite, and norites, as well as associated rocks such as orthopyroxene-bearing monzonite and granites (i.e., mangerites and charnockites) [3,6]. It originated within the deep crust of the Baltica continent prior to its merging into the Rodinia supercontinent (~1300-1000 Ma, [3]). The genetic processes involved polybaric fractional crystallization comprising initial crystallization at depth (crust-mantle boundary) and intrusion as anorthositic crystal-rich mush, followed by intrusions of margerites and charnockites [4]. These mirror the formation of the lunar primordial crust, where Fe-anorthositic rocks segregated from the early magmatic ocean, succeeded by subsequent intrusions of Mg- and alkali-suites [7].

Materials and Methods: The spectral characterization and sample-based mapping of minerals rely on their diagnostic responses within the Visible Near to Shortwave Infrared (VNIR-SWIR, from 450 to 2500 nm) regions, to be used as a basis for conducting remote mapping by means of satellite hyperspectral/multispectral sensors (e.g., the 30m/pixel German EnMAP and the 40cm to 7.5m/pixel WorldView-3 missions).

Laboratory-based Hyperspectral Data. The Laboratory-based hyperspectral involves cut-rocks analyzed with high spectral resolution (270 VNIR and 166 SWIR spectral bands) and high spatial resolution (averaging 200-300 µm) Headwall Photonics Nano- and Micro-Hyperspectral cameras. These cameras cover a spectral range from the VNIR (400-1000 nm) to the SWIR (900 - 2500 nm), respective-ly.

Pre-processing and feature extraction. The preprocessing steps include cross-track illumination correction (sample-based), noise suppression using the Minimum Noise Fraction, and clipping of noisy bands. The hyperspectral data were processed using a multiple feature extraction workflow, focusing on spectral parameters after continuum-removal, such as the relative abundances (absorption band depth) and compositions (absorption wavelength position) of specific minerals, including plagioclase and Fe-Mg minerals (i.e., pyroxene, olivine, epidote, micas). In this preliminary stage, the focus is on four samples representative of plagioclase-rich rocks from the anorthosite-troctolite group, prominently exposed in the area (Fig. 1 a-d). Outcomes include sample-scale mineral distribution maps and the design of a spectral library to refine remote sensing surveys. Validation of results involves integrating data from diverse sources, including mineralogical and micro-geochemical analyses through Optical Microscopy and SEM-EDS.

Results: The results reveal a mineralogical association primarily defined by plagioclase (Na-Ca plagioclase with local exsolution of K-feldspar) as the main phase. Variable amounts of olivine, ortho- and clinopyroxene (opx and cpx) are present, along with epidote, biotite, and white mica/clay minerals, as alteration phases. Ubiquitous presence of Fe-Ti oxides (ilmenite and magnetite) is observed, both as coarser crystals and very small inclusions within the plagioclase. Spectral responses indicate diverse alteration phases in the anorthosite samples. Plagioclase spectra are generally featureless, exhibiting a pronounced negative slope (i.e., reduction in reflectance) towards longer SWIR wavelengths. Shallow absorption bands at 1400 nm, 1900 nm, and between 2196 and 2200 nm suggest alteration (due to H_2O and Al-OH vibrational modes; Fig.1 a, c - ROI 2). In more altered portions, these features become more prominent, along with a wide feature between 2200 and 2235 nm and an absorption band at 2350 nm (Al-OH and Mg-OH vibrational modes; Fig. 1 a, c – ROI 5).

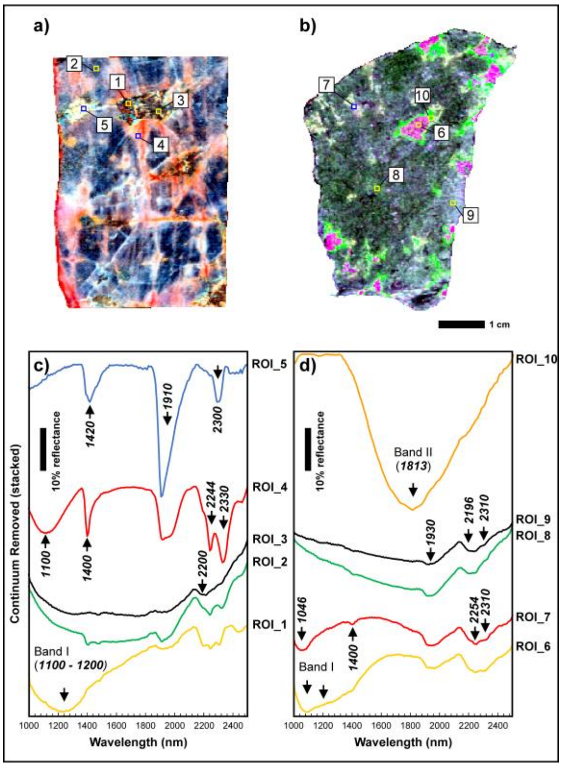

Figure 1: a, b) ST2b (left) and LON10 (right) samples, representing specimens of anorthosite and troctolite, respectively, from the study area, depicted in false-colour images after continuum removal to better highlight the spectral variability of the different mineralogical phases present. a) R: 1593 nm, G: 1190 nm, B: 1027 nm; b) R: 1813 nm, G: 1305 nm, B: 2254 nm. c, d) Spectral signatures in the SWIR region (from 1000 to 2500 nm) obtained after continuum removal of the identified endmembers, corresponding to the numbered squares (Region of Interest=ROI) in Figures 1a and 1b. The main absorption features discussed in the text are highlighted with black arrows and expressed in nanometers

Mafic minerals are present in minor amounts, shown by features related to crystal field transitions due to Fe^{2+} in octahedral M1 and/or M2 sites in silicates (such as olivine, opx and cpx) [8]. Opx features at approximately 950 nm and 1890 nm (Band I and Band II, [8]) indicate a higher Mg composition. Olivine remnants, observed in one anorthosite sample, are defined by a broad absorption (Band I) from ~1100 to ~1200 nm (Fig. 1 a, c – ROI 1), also showing features at 2196, 2244 and 2310 nm due to alteration minerals. Fe-Epidote exhibits major absorption features in the longer wavelength SWIR region at ~2254 nm and 2340 nm (Fig. 1 a, c – ROI 4). Troctolite samples are characterized by Na-Ca plagioclase with more diffuse K-feldspar exsolutions. It is less altered compared to anorthosite samples, as shown by shallow or absent H_2O-OH-bearing phases-related features (at ~1400 and ~1900 nm) (Fig. 1 b, d – ROIs 8, 9). The spectral signatures show a pronounced negative slope toward SWIR longer wavelengths. Preserved olivine is characterized by a well-defined Band I feature, displaying typical asymmetry towards longer wavelengths (~1300 nm) and the 1200 nm flattening. It is surrounded by a Mg-richer opx rim (avg. MgO 15.5 wt%, avg. FeO 13.7 wt%) delineated by Band I and Band II features at 950 and 1813 nm, respectively (Fig. 1 b, d – ROIs 6 and 10). Dark micas, when present as alteration, are shown by absorption features at ~2254, 2310-2330 and ~2390 nm (Fig. 1 b, d – ROI 7).

Based on this initial analysis, plagioclase is defined by the absence of the absorption feature in the ~1200 nm region. This is consistent across both the investigated rock types (anorthosite and troctolite) and correlates with micro-geochemical analysis, revealing either very low or undetectable FeO content, generally falling below the detection limit. This differs from findings in other complexes, such as The Stillwater complex [2].

Despite being preliminary, this spectral characterization of terrestrial Anorthosite-Troctolite-Norite complex, renowned for sharing genetic features with the lunar primordial crust, serves as a valuable contribution to enhancing and validating insights gained from remote sensing analyses. It represents a starting point to better understand the evolution of these geological environments, with implications for potential future lunar remote and rover missions on lunar highlands. Moreover, these findings lay the groundwork of an upcoming field survey in the re-gion and a valuable product for future ESA PANGAEA astronaut training sessions in this location [6].

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