WEATHERING OF MOON SOILS, AS SEEN FROM THE FELDSPATHIC BRECCIA NORTHWEST AFRICA 11273 METEORITE, AS THE FIRST STEP FOR PLANT CULTIVATION. J. Huidobro*[1], I. Población[1], F. Alberquilla[1], J.M. Madariaga[1], L. Coloma[1], J. Aramendia[1], C. García-Florentino[1], J. Martinez-Frias[2], K. Castro[1], and G. Arana[1], [1]Dep. Anal. Chem., University of the Basque Country (UPV/EHU), 48940 Leioa, Spain (jennifer.huidobro@ehu.eus, juanmanuel.madariaga@ehu.eus), [2]Institute of Geosciences IGEO, Madrid, Spain

Introduction: Future plant cultivation in the Moon will require using amended (nutrients, organic matter and water) Lunar soils as demonstrated recently [1]. But first, the soils must be treated to transform the anoxic environment (reduced redox potential) to an oxic one in order to avoid the presence of harmful reduced ions that could be released after amending the soils. To select the most adequate amending compounds, the chemical transformation of the Lunar soils must be understood and the respective chemical reactions must be modelled.

As part of this research program, the weathering of the Northwest Africa (NWA) 11273 Lunar meteorite (felspathic breccia) has been studied. NWA 11273 was approved 17 Oct 2017 as Lunar Meteorite [2]. It was excavated from a site near Tindouf, Algeria. It has a geochemistry composed of olivine ($Fa_{8.7-59.7}$, FeO/MnO = 89-111, N = 4), pigeonite ($Fs_{28.8}Wo_{11.2}$, FeO/MnO = 56), HCP ($Fs_{15.3}Wo_{40.9}$, FeO/MnO = 44), orthopyroxene exsolution lamella ($Fs_{34.0}Wo_{2.7}$, FeO/MnO = 56), augite ($Fs_{16.8}Wo_{41.7}$, FeO/MnO = 62) and plagioclase ($An_{95.9-96.5}Or_{0.2}$, N = 2). Bulk-rock composition of NWA 11273 showed similarities to other Lunar highlands meteorites [3].

In addition to finding the minerals indicated by the Meteoritical Society, anorthite ($CaAl_2Si_2O_8$), olivine (Fa_{9-60}), pigeonite (clinopyroxene), augite (orthopyroxene), chromite ($FeCr_2O_4$), Ti-Cr-Fe spinel, kamacite (Fe:Ni>90:10 alloy), taenite (35:65<Fe:Ni<80:20 alloy) and troilite (FeS) were found [2]. Other minerals, such as zircon and ilmenite, were identified in a recent work using micro-Raman spectroscopy [4]. Zircon was detected as shocked zirconite suffering a pressure ~20 GPa [4]. All these can be considered primary minerals showing a complete anoxic environment during the cooling of the magma.

Soils derived directly from these rocks are poor in weathered minerals and cannot be used for cultivation processes. Before performing accelerated weathering experiments, a careful analysis of the sample was designed aiming to detect weathered phases formed after the long period that the NWA 11274 was buried in the soils of Tindouf. To realize this aim, the analyses were conducted using Raman spectroscopy (point-by-point and image), Energy dispersive X-Ray Fluorescence microscopy and image (μ-EDXRF) and Scanning Electron Microscopy with Energy Dispersive Spectroscopy (SEM-EDS).

Results and discussion: To visualize the distribution of the elements present in the recovered NWA 11273 sample from Tindouf soils, μ-EDXRF image was performed on the whole surface of the meteorite. Fig. 1 shows such distribution of elements for side A, being side B equivalent. The high intensity areas of Al coincide with the anorthite crystals and with the medium intensity areas of Ca, as expected, and Sr. The distribution of Fe, Mg, Mn, Ti and Cr do not follow one mineral phase but several mixed minerals are present in the maps with high and medium intensity signals of these elements. The voids left by these elements are filled by Al (and Ca, Sr) confirming plagioclase, olivine and pyroxenes as the bulk of the NWA 11273.

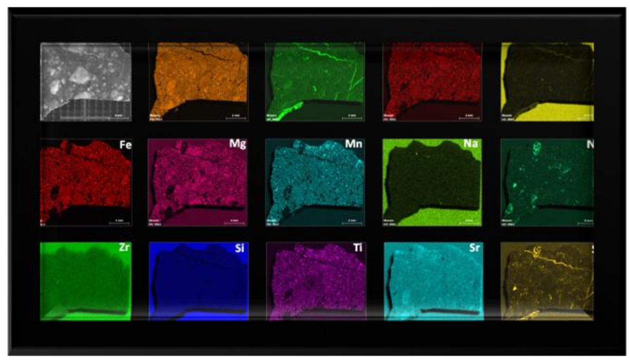

Figure 1. Micro-XRF image of detected elements distributed in NWA 11273 surface

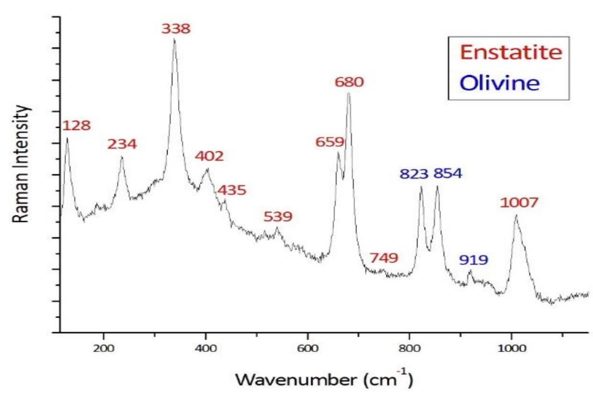

Fig. 2 Raman spectrum obtained in the border of an olivine grain

However, some hot spots of Fe do not coincide with other elements. The hot spots of Zr do not coincide with other elements suggesting the distribution of zirconite. The important presence of Ni (as kamacite in the low intensity hot spots coincident with Fe ones, and as taenite in the high intensity hot spots with low Fe) must be highlighted; some hot spots of Ni also coincide with sulfur suggesting the presence of NiS.

In the surface of olivine grains, enstatite was detected as observed in Fig. 2. Enstatite ($MgSiO_3$) is not a mineral phase of the Moon mineralogy and must be considered a weathering of bulk olivine (Fa9) in slightly oxidized environment.

The two olivine bands are consistent with a slightly enriched Fe olivine (Fa15 from [5]) with regard to the original Fa9 one. Thus, a possible reaction is:

$$(Mg_{0,91}Fe_{0,09})_2SiO_4 + O_2 \rightarrow 0.4\ MgSiO_3 + 0.6\ (Mg_{0,85}Fe_{0,15})_2SiO_4 + 0.4\ MgO + O_2$$

without a net consumption of oxygen, or this one

$$(Mg_{0,91}Fe_{0,09})_2SiO_4 + 0.03\ O_2 \rightarrow 0.8\ MgSiO_3 + 0.2\ (Mg_{0,85}Fe_{0,15})_2SiO_4 + 0.68\ MgO + 0.06\ Fe_2O_3$$

In the same border of olivine grains, quartz and hematite were observed, together with olivine, as observed in Fig. 3. The two olivine bands are consistent with a slightly depleted Fe olivine (822 and 853 cm^{-1} is consistent with Fa20 from [5]) with regard to the original Fa40 one. And the presence of quartz and hematite would suggest a oxidative degradation of a more enriched Fe olivine.

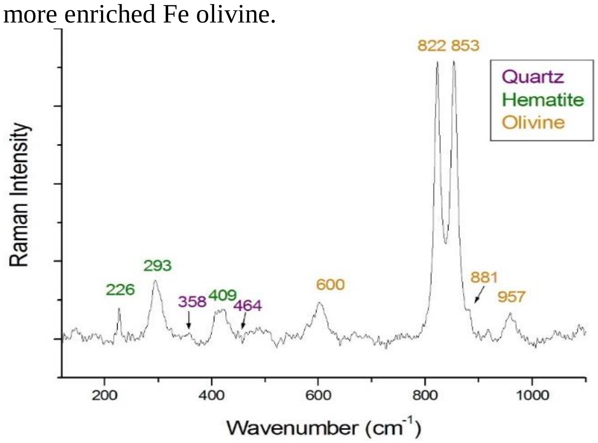

Fig. 3 Raman spectrum obtained in the border of an olivine grain

A possible weathering reaction could be:

$$4\ (Mg_{0,60}Fe_{0,40})_2SiO_4 + 0.5\ O_2 \rightarrow 3\ (Mg_{0,80}Fe_{0,20})_2SiO_4 + SiO_2 + Fe_2O_3$$

here the initial $(Mg_{0,60}Fe_{0,40})_2SiO_4$ olivine is completely transformed to the minerals showed in the spectrum.

With these two oxidative reactions, where water does not take part although an aqueous medium is always required, three important minerals for plant cultivation, MgO, SiO_2 and Fe_2O_3 have been formed, remaining an important amount of olivine to generate Mg- and Fe-rich phyllosilicates.

Another important oxidative weathering reaction detected was the transformation of ilmenite in anatase and hematite, as seen from several Raman spectra with the three minerals present simultaneously. The oxidative weathering of ilmenite:

$$4\ FeTiO_3 + O_2 \rightarrow 4\ TiO_2 + 2\ Fe_2O_3$$

is thermodynamically possible in the usual pH range for plant cultivation. Thus, a possible source of hematite is coming from the reaction.

Conclusion: All those described weathered compounds (MgO, SiO_2, TiO_2 and Fe_2O_3) have been formed from the original minerals in the feldspathic breccia NWA 11273 and are expected to be formed when Lunar regolith is oxidised as a previous step for plant cultivation. Remaining olivine, pyroxenes and plagioclase are sources for phyllosilicate formation when acidic attack is applied in oxidizing conditions. Moreover, the NWA 11273 has another three important oligoelements, Mn, Cr and Ni that will be present in the Lunar regolith coming from feldspathic breccia rocks.

The described major original minerals in NWA 11273 [2-4] are quite close to the minerals described for the LZS-1 Lunar basaltic soil simulant [6], dominated by Ca-rich plagioclases, high-Ca pyroxenes, Mg-rich olivines (mean Fo70) and Fe-Ti-Cr oxides. This clear parallelism between NWA 11273 and LZS-1 simulant will help to perform high scale experiments for habitability with the simulant and confirm then at low scale with the NWA 11273 materials.

Next experiments will be developed to detect if the weathered oxides described previously for NWA 11273 are found in the LZS-1 Lunar soil simulant [6] using Raman spectroscopy. Then, searching for soluble ions and their concentrations in NWA 11273 and LZS-1 materials will be conducted to confirm the parallelism between NWA 11273 and LZS-1. Finally, acidic oxidative tests will be performed to detect new mineral phases and released compounds in both materials.

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References:

[1] A.-L. Paul, et al. (2022) *Nature Comm. Biol., 5,* 382. [2] *Met. Bull. No. 106* (2018). [3] X. Zeng et al. (2020) *Met. Plan. Sci., 55,* 36-55. [4] J. Huidobro, et al. (2021) *ACS Earth Space Chem., 5,* 1333-1342. [5] I. Torre-Fdez, et al. (2023) *J. Raman Spectrosc., 54,* DOI: 10.1002/jrs.6485. [6] F. Alberquilla, et al. (2022) *Sci. Rep., 12, 1647*0.