POSSIBLE LL CHONDRITE PROJECTILE IN LUNA-16 SOIL SAMPLES. S. I. Demidova[1], R. Merle[2], G. G. Kenny[2], A. A. Nemchin[2,3], M. J. Whitehouse[2], F. Brandstätter[4], Th. Ntaflos[5], [1]Vernadsky Institute of Geochemistry and Analytical Chemistry, Moscow, Russia, demidova.si@yandex.ru; [2]Swedish Museum of Natural History (NRM), Stockholm, Sweden, [3]Curtin University, Perth, WA, [4]Natural History Museum (NHM), Vienna, Austria; [5]Vienna University, Austria

Introduction: Regolith covering the lunar surface is expected to be heavily reworked as a result of meteorite bombardment, with accompanying mixing, melting and evaporation of both the target and projectile materials. Nonetheless, it is reasonable to expect that some traces of the latter may survive in the regolith. Here we report the results of a mineralogical and chemical study of a fragment found in Luna-16 soil, suggesting its possible origin from a LL chondrite.

Samples and Methods: A polished thick section of Luna-16 soil fragments (sample 1639, fraction >200 µm) was investigated using optical microscopy followed by chemical characterization of the mineral phases using a Cameca SX100 (Vienna University) and JEOL JXA-8530F microprobes (NHM). Fe-Ni metal and sulfide were studied using a Jeol JSM 6610-LV SEM (NHM). Element maps and bulk chemical composition were acquired using a FEI Quanta FEG 650 SEM (NRM).

Results: A small (~200x300 µm), compositionally unusual, metal-rich fragment (#443) of Luna-16 soil originally consisted of silicate and metal portions. While a significant volume of metal was lost during polishing, the silicate part (180x200 µm) (Fig. 1) has been studied in detail. This silicate part represents a medium-grained rock consisting of subhedral olivine (~55 vol%) and low-Ca pyroxene (~25 vol%) with minor interstitial glass (~5 vol%) sometimes surrounded by external radiating fractures. In places, olivine was dissolved in the glass, forming a convoluted boundary between both phases. A Fe-Ni-metal - sulfide vein (2-5 µm in thickness) crosscuts the clast, expanding into melt pockets up to 10-50 µm in size. In addition, abundant small fractures and areas filled with troilite are common in the fragment. In a large troilite pocket, small rounded Fe-Ni metal grains (up to 4 µm in size) are unevenly distributed within a band-like zone and are also ubiquitous in the fractures (Fig. 1). Troilite and metal comprise the remaining 15 vol% of the rock. Accessory minerals are Ti-Al chromite and merrillite.

The mineral chemistry of major silicates is shown in Fig. 2. Olivine varies in composition from Fo_{71} to Fo_{75}. Its FeO/MnO (49-58) is not common for lunar olivines (60-120, mean 89+/-0.3 (1σ) [1]) (Fig. 3). Some grains are enriched in Ni (NiO up to 0.3 wt%). Pyroxene is represented by a low-Ca variety ($En_{73-77}Wo_{1-2}$) with low TiO_2, Cr_2O_3, Al_2O_3 not exceeding 0.1-0.2 wt%. FeO/MnO (30-34) is also lower than in lunar low-Ca pyroxenes (30-80, mean 54+/-0.3 (1σ) [1]) (Fig. 4). Fe,Mg-rich feldspathic glass has a highly variable composition. It is enriched in alkalis (1-2 wt% K_2O and 2-6 wt% Na_2O) and generally has low major elements totals. A single plagioclase has a Na-rich composition ($An_{12}Ab_{84}$). Fe-Ni metal grains contain 12-24 wt% Ni and ~1 wt% Co. Their Ni/Co ratio (0.04-0.09) is close to chondritic (0.05) [2]. Troilite is slightly enriched in Ni (0.8 wt%). The bulk chemistry of the fragment corresponds to an ultramafic composition enriched in alkalis and Fe,Ni,S.

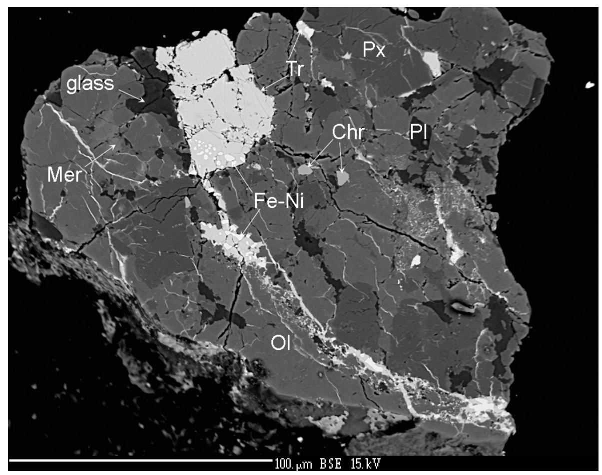

Fig. 1. BSE image of Luna-16 soil fragment #443

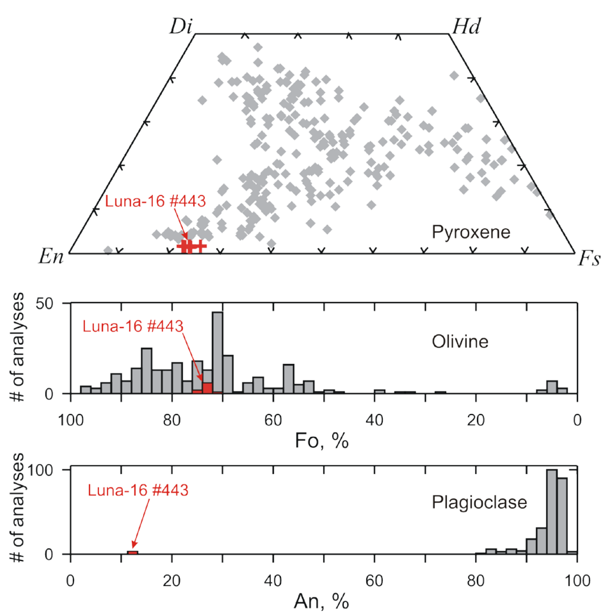

Fig 2. Chemical compositions of pyroxene, olivine and plagioclase of Luna-16 samples.

Discussion: Low FeO/MnO ratios in olivine and pyroxene along with a number of mineralogical and compositional features of the clast #443 clearly distinguish it from known lunar rocks, suggesting it is of non-lunar origin. Mineralogy, mineral chemistry, and proportion of the phases indicate that #443 is most likely a fragment of a LL chondrite [3] (Fig. 5). On a Fa in olivine versus Fs in low-Ca pyroxene diagram, the fragment does not exactly match the ordinary chondrite (OC) trend, but plots in close proximity to the LL group (Fig. 6). In addition, the fragment contains a higher amount of sulfide than commonly seen in OC [4] but the clast may not be representative of the parent lithology. However elevated sulfide contents have been observed in some L, LL and unequilibrated OCs [4,5]

Textural characteristics indicate that the fragment #443 could be either a product of impact melting of a chondritic precursor or a preserved chondrule fragment. The abundance and the geometrical complexity of metal - sulfide veins with expansion in the melt pockets as well as the nearly ubiquitous transformation of plagioclase to glass and reaction of olivine with the glass points to the heavy shock experienced by the rock, corresponding to shock metamorphism stages S4-S6 according to [6]. The features mentioned above appear at pressures more than 30-35GPa [6]. Post-shock temperature could reach 988-1500ºC [6,7].

It was previously suggested the projectiles on the Moon are dominated by chondritic material, however non-chondritic impactors are also possible [e.g. 8]. Rare finds of both chondritic [9-12] and non-chondritic [13,14] fragments have been reported in lunar samples. However, OC material is not common among them. A detailed study of Apollo 16 breccias has shown that a carbonaceous chondrite (CC) impactor is preferable [12]. The find of OC relict material in Luna-16 soils, reported here, expands the range of known lunar projectiles and gives new possibilities for studying the impact history of the Luna-16 site.

References: [1] Nazarov M.A. et al. (2009) *LPSC 40,* #1059. [2] Warren P.H. (1993) *Am. Min. 78,* 360-376. [3] Dunn T. L. et al. (2010) *Meteoritics & Planet. Sci., 45,* 135–156. [4] Dunn T. L. et al. (2010) *Meteoritics & Planet. Sci., 45,* 123–134. [5] Jilly-Rehak C.E. et al. (2016) *Chemie der Erde, 76,* 111–116. [6] Stoffler D. et al. (1991) *GCA, 55,* 3845-3867. [7] Rubin A.E.. (2004) *GCA, 68,* 673–689. [8] Haskin L., Warren P. (1991) In *Lunar sourcebook*, 357-475 [9] Zolensky M. E. (1997) *Meteoritics & Planet. Sci., 32,* 15-18. [10] Rubin A. E. (1997) *Meteoritics & Planet. Sci., 32,* 231-247. [11] Day J. M. D. et al. (2006) *GCA, 70,* 5957-5989. [12] Joy K. et al. (2012) *Science, 336,* 1426-1429. [13] Joy K. et al. (2014) *Meteoritics & Planet. Sci., 49,* 677-695. [14] Zeng X. et al. (2018) *Meteoritics & Planet. Sci., 53,* 1–21.

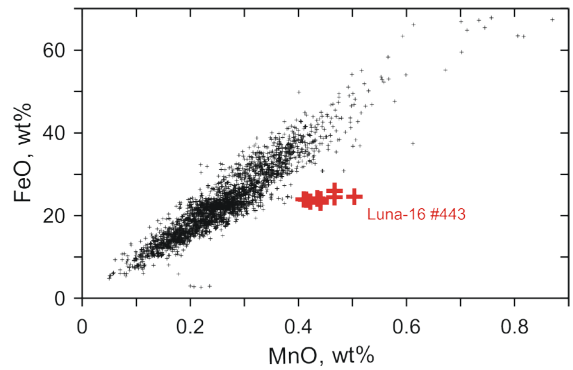

Fig. 3. FeO vs MnO contents (wt%) in lunar olivines

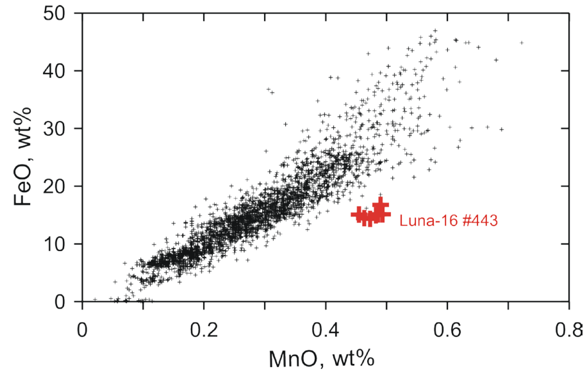

Fig. 4. FeO vs MnO contents (wt%) in lunar pyroxenes

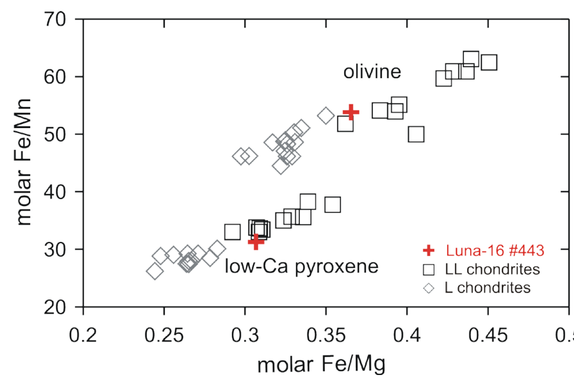

Fig. 5. Molar Fe⁄Mn versus Fe⁄Mg ratios for olivine and low-Ca pyroxene in L and LL chondrites (average values) [3]

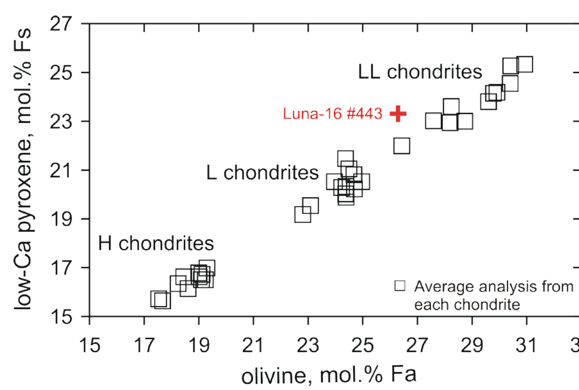

Fig. 6. Olivine (as mol% Fa) versus low-Ca pyroxene (as mol% Fs) in the H, L, and LL chondrites (average values) [3]