MINERALOGICAL EVIDENCE FOR THE ACTIVITY OF LUNAR WATER. S. I. Demidova[1], M. A. Nazarov[1], F. Brandstätter[2], and Th. Ntaflos[3] [1]Vernadsky Institute of Geochemistry and Analytical Chemistry, Kosygin St. 19, Moscow 119991, Russia, demidova.si@yandex.ru; [2]Naturhistorisches Museum, A-1014 Vienna, Austria; [3]Department für Lithosphärenforschung, Universität Wien, Althanstrasse 14, 1090 Wien, Austria.

Introduction: Traces of water have been documented in lunar glasses, phosphates and inclusions in olivine [e.g.,1-3]. The studies suggest that water could be an important component of lunar magmas. However, no mineralogical evidence has been reported for aqueous alteration of lunar rocks. Here we report on two peculiar objects in the Dhofar 302 and Dhofar 961 lunar highland meteorites. The texture and composition of the objects indicate that they were formed from a serpentine precursor.

Methods: The objects were found during a routine study of lunar meteorite thin sections by traditional methods of optical microscopy, ASEM, and EMPA. Mineral phases were analyzed using the Cameca SX-100 microprobe of the Vienna University.

Results: Both Dho 302 and Dho 961 are feldspathic impact melt breccias although Dho 961 contains certainly a KREEP component [4,5].

In Dho 302 the object (#1) of interest (Fig. 1) has a rounded shape and a size of 30x40 µm. It occurs in a glassy melt of anorthositic composition. The object shows mosaic extinction and a very fine vermicular texture consisting of two phases. The phases are too small for a quantitative analysis but ASEM study suggests that they are orthopyroxene and olivine. In bulk composition the object is very high in MG# (Table 1) and corresponds to a formula of $Mg_{2.9}Fe_{0.1}Ca_{0.1}Si_{1.9}Al_{0.1}O_7$.

In Dho 961 there is an olivine fragment (object #2) of 370x370 µm in size with a unique texture and composition (Fig. 2). The fragment contains parallel orientated pyroxene lamellae and an accessory Ca-Al-Si phase. The object exhibits zonation that is present in chemical composition and mineral modes. The modes of the core are (vol.%) ~55 olivine, ~44 orthopyroxene, <1 the Ca-Al-Si phase. In the rim the modes are (vol.%) ~63 olivine, ~35 pyroxene, ~2 the Ca-Al-Si phase. The olivine has undulatory extinction.

In the core olivine is Mg-rich and very uniform in composition (Fo_{84}, Fe/Mn ~ 80). Interestingly, the olivine contains P_2O_5 (0.4-0.5 wt.%). Phosphorian olivine was described in some terrestrial rocks and meteorites [6-10] but it has never been reported in lunar rocks. The P enrichment is considered usually as a result of disequilibrium rapid crystallization of olivine from P-rich melts [6-8]. In the outer part the olivine is richer in Fe (Fo_{68-70}), poorer in P_2O_5 (0.1-0.3 wt.%), and has much higher Fe/Mn ratio (~111) than olivine in the core. Pyroxene of the core is enstatite ($En_{90}Wo_1$ Fe/Mn = 71) but in the outer part its composition gradually changes from $En_{72-77}Wo_{4-7}$ to $En_{54}Wo_{24}$ (Fe/Mn ~ 50). No P was detected in the pyroxenes.

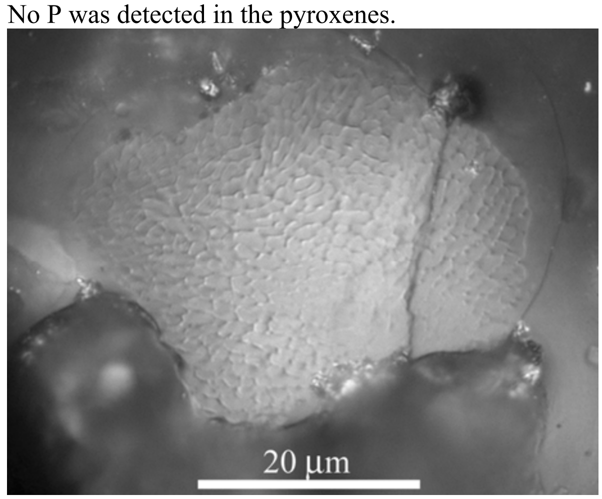

Fig. 1. Foto of object #1 in Dho 302, reflected light, oil immersion.

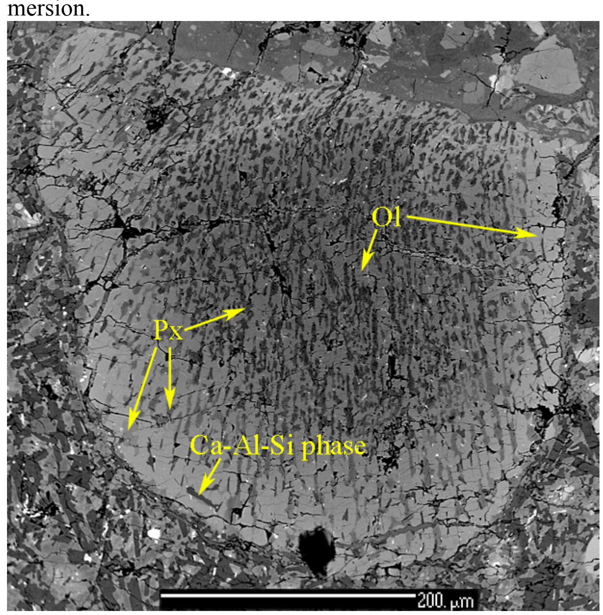

Fig. 2. BSE image of object #2 in Dho 961.

The Ca-Al-Si phase analyzed in the outer part is close to plagioclase in composition (An_{81-89}) but contains Ti, Cr, P, and shows some deviation from feldspar stoichiometry. These findings suggest that the Ca-Al-Si phase is a glass. It is also interesting that there are very tiny inclusions containing Ti, Cr, P, Fe, S, REEs and Zr in the Dho 961 object. The bulk composition of the core of the Dho 961 object calculated from mineral chemistry and mineral modes is given in Table 1 and corresponds to a formula of $Mg_{2.5}Fe_{0.4}Si_{2.0}O_7$.

The Dho 961 object occurs in an impact melt clast that has the composition of olivine norite. The clast contains rare olivine porphyroclasts set within a subophitic matrix consisting of plagioclase and pyroxene: olivine (Fo_{55-64}, Fe/Mn ~ 107), plagioclase ($An_{91-96}Or_{0.1-0.8}$), pyroxene ($En_{54-68}Wo_{8-12}$ Fe/Mn ~ 60). No P-bearing phases in the clast were found except for one small olivine grain (Fo_{55}) that contains 0.18 wt.% P_2O_5 but no pyroxene lamellae.

Table 1. Bulk composition of the Dho 302 and 961 objects

	SiO_2	MgO	Al_2O_3	CaO	Cr_2O_3	TiO_2	MnO	FeO	P_2O_5	∑	MG#
#1	46.4	48.5	1.7	1.2	0.16	0.52	0.02	1.7	-	100.1	98
#2	47.3	39.1	0.7	0.4	0.17	0.18	0.14	11.0	0.24	99.3	86

#1 – Dho 302 object; #2 – Dho 961 object

Discussion: The bulk composition of the Dho 302 and Dho 961 (core) objects is very close to dehydrated serpentine ($Mg_3Si_2O_7$) and therefore, they very likely have been formed from a serpentine precursor. Compositionally, there is some deviation of the outer part of the Dho 961 object from serpentine. This can be related to reaction of the object with the surrounding melt. Significantly, the Dho 302 and Dho 961 objects have pyroxene-olivine exsolution textures which could be attributed to the breakdown of a precursor phase but not to crystallization from a melt. In the latter process orthopyroxene forms usually coronas around olivine grains. Experimental studies show that serpentine is not a stable phase at high temperatures. At a high pressure of 2.1±0.2 GPa serpentine loses H_2O and transforms to an olivine+enstatite mixture at ~720°C [11]. This reaction was described in terrestrial rocks but the exsolution textures, which are similar to those in the Dho302 and 961 objects, were not reported [12]. Changing in P-T conditions and minor element contents result in appearance of mineral associations with talc, chlorite, tremolite and others. [13].

Serpentine is a common mineral of CI, CM and CR carbonaceous chondrites occurring in fine intergrowths with other phases. In general, chondritic serpentines are Fe-rich and, therefore, are completely different in MG# from the Dho 302 and 961 objects. In addition, the objects have lunar Fe/Mn ratios and contain Na-poor feldspathic glass that is atypical for chondrites. Therefore, we conclude that the serpentine precursor of the objects should be of lunar origin.

Serpentinization is a common process of aqueous alteration of terrestrial olivine-bearing rocks. The prominent chemical differences between the Dho 302 and 961 objects point to serpentinization of different lunar source rocks. In contrast to the simple Dho 302 object, a serpentine precursor of the Dho 961 object should be formed in a KREEP-bearing source. Indeed, computer modeling of crystallization of the melt surrounding the object demonstrates that the olivine core is out of equilibrium with the melt. Therefore, the Dho 961 object is an olivine xenocryst, the outer part of which reacted with the melt. Additional evidence for the xenolithic nature of the olivine is the absence of P in the reacting melt. However, it's not clear whether the reaction with KREEP was related to the aqueous alteration or not. Apparently, one can suggest that dehydration of lunar serpentine could be connected with impact reworking of lunar rocks. However dehydration of the Dho 302 and Dho 961 serpentine precursors should not take place in their host melts because there are no textural evidences, e.g. high porosity, for water losses from the objects. Probably, the dehydration occurred in a hot ejecta blanket accompanied by recrystallization that led to compact textures of these objects.

The findings of the Dho 302 and Dho 961 objects point to possible activity of water during lunar petrogenesis. An estimation of the degree of serpentinization of the lunar rocks is not possible yet. Probably, serpentinization took place in local areas because only two findings give evidence for the process. However, it can be suggested that the rarity of these objects could be also related to a deep-seated occurrence of serpentinized lunar rocks which cannot be easily excavated by impact processes.

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