LUNAR MANTLE SPINEL IN DHOFAR 1528 ? Axel Wittmann[1], Randy L. Korotev[1], and Bradley L. Jolliff[1], [1]Dept. Earth & Planetary Sciences, Washington University, St. Louis, MO 63130, axel.wittmann@yahoo.com.

Introduction: Cratering mechanics indicate that the largest lunar impact basins should have excavated target rocks from the lunar mantle [1,4]. Candidate lithologies are Mg-spinel-bearing rocks that also contain Al-rich low-Ca pyroxene and forsteritic olivine. So far, this assemblage has only been found in Apollo samples 15445 and 73263,1,11 [5,6]. Magnesian spinel assemblages have recently received a renaissance of scientific interest due to remote sensing observations [7,8] that suggest the presence of magnesian spinel lithologies associated, and perhaps excavated by, large impact craters that formed in thin lunar crust.

Recovered in Oman in 2009, Dhofar 1528 is a 213 g stone that contains spinel (H. Haack in [9]). It is the most magnesian lunar meteorite among those having Sc >6 ppm or Al_2O_3 <30 wt% [10,11]. We studied a 46 mm^2 petrographic section of Dhofar 1528 by optical microscopy and electron microprobe analysis to explore the origins of some of its components.

Results: *Petrography.* Dhofar 1528 is a vitric melt rock that contains abundant lithic clasts [9]. A glassy melt matrix embeds up to 2 mm dark, clast-rich, microcrystalline melt bodies that show plastic deformation, and angular mineral and rock clasts. These clasts comprise granular, poikilitic lithologies with troctolitic and gabbroic mineral modes, a K-rich feldspathic phase, and possible basalt. Up to 1.5 mm fragments of monomineralic feldspar, pyroxene, and olivine ($Fo_{63,83–95}$) dominate the mineral clast content. Silica, magnesian spinel, chromite, ilmenite, Fe-Ni metal, troilite, and zirconolite are minor to accessory mineral clast phases.

We found 11 magnesian spinel assemblages in our thin section (Fig. 1) with ~10 to 680 µm individual spinel grains. Three of the four largest spinel fragments show euhedral shapes and one of them is an anhedral intergrowth with plagioclase. Cores of these spinel crystals are homogenous but most have <5 µm thick rims in contact with impact melt that are enriched in Fe relative to Mg. The two most Mg-rich spinel assemblages are components of ophitic clasts, indicating they grew from an impact melt that crystallized laths of plagioclase ($An_{99.8–99.9}$), skeletal pyroxene and subhedral, 10 µm spinel (Mg# 92–96). These highly magnesian melt-phenocryst spinels are distinct from a main group of spinels with rims of $Mg_{0.66–0.76}Fe_{0.22–0.32}$, cores of $Mg_{0.78–0.83}Fe_{0.15–0.21}$, and $Al_{0.88–0.96}Cr_{0.04–0.12}$. This main group of spinel assemblages includes Al-rich low-Ca pyroxene (En_{90}; 4.5–6.1 wt% Al_2O_3), olivine ($Fo_{87–88}$), and plagioclase ($Ab_{3–4}An_{94–97}Or_{0.0–0.1}$).

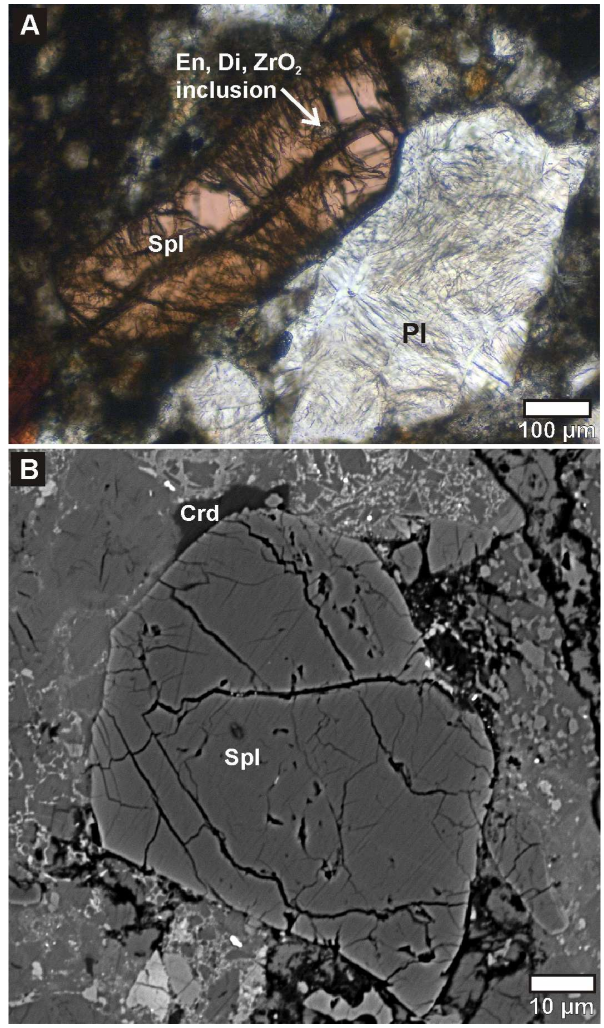

Fig. 1. Spinel assemblages in Dhofar 1528.
A – largest spinel (Spl) grain with Al-rich low-Ca pyroxene (En), diopside (Di) and ZrO_2 inclusion, intergrown with plagioclase (Pl); linear polarized light. B – euhedral spinel (Spl) clast, intergrown with cordierite (Crd); back-scattered electron image.

The largest spinel grain contains a 45×25 µm inclusion of low-Ca pyroxene (En_{90}, 6 wt% Al_2O_3) and diopside, and a <1 µm ZrO_2 crystal. Other spinels are intergrown with $Fo_{87–91}$ olivine, and a 15 µm cordierite crystal [$K_{0.09}Ca_{0.02}Mg_{1.95}Fe_{0.12}Al_{4.07}Si_{4.87}O_{18}$] (Fig. 1B).

Three spinels have lower MgO and higher FeO and/or lower Al and higher Cr than the main group spinel assemblages; their assemblages include low-Ca pyroxene ($En_{80–85}$) with 1.1–2.5 wt% Al_2O_3, olivine (Fo_{90}), and plagioclase ($Ab_{2.6–5.1}An_{96–97}Or_{0.0–0.3}$).

We evaluated equilibrium criteria [12] for the low-Ca pyroxene-spinel-olivine crystals that occur in assemblages. Using mineral pairs that could have been in equilibrium, we modeled equilibration conditions for the core compositions of the two spinel groups that are not melt phenocrysts [6]. We found that 7 main group assemblage spinels could have equilibrated at depths ≥29–46 ± 4 km at 840–900°C.

Discussion: *Characteristics of spinel assemblages in Dhofar 1528:* The scarcity of magnesian spinel in lunar rocks, the compositional similarities of spinel fragments, and the complementary forsterite and Al-rich low-Ca pyroxene grains in Dhofar 1528 suggest a common petrogenesis. Sizes and shapes of some of the spinel grains indicate they likely crystallized as cumulates, similar to Apollo spinel troctolite 67435,14 [13]. Thermodynamic calculations suggest that assemblages of magnesian spinel, Al-rich low-Ca pyroxene, forsterite ± plagioclase can record pressure and temperature conditions commensurate with depths in the lunar mantle [5,6,14,15]. To our knowledge, only clasts in Apollo samples 15445 [6,12,16] and 73263 [5] contain such assemblages (and they are compositionally very similar to some of the assemblages in Dhofar 1528!). A minimum depth of equilibration of 26 km has been estimated for these mineral assemblages in the Moon [6]. Assemblages of forsterite and magnesian spinel intergrown with cordierite, and phase relationships were used to deduce a lower crustal provenance for the stability of these assemblages [14,17]. We suggest that the cordierite crystal in Dhofar 1528 formed from a reaction with magnesian spinel and impact melt. Cordierite is known as an igneous phase in terrestrial impact melts [18,19]. Alternatively, metamorphic phase equilibria cause spinel and Al-rich low-Ca pyroxene to react to forsterite and cordierite in the system MgO-Al_2O_3-SiO_2 at pressures ≤2.5 kbar and temperatures of 800–900°C [6,14]. If the spinel-diopside-Al-rich low-Ca pyroxene intergrowth in Fig. 1 represents an equilibrium assemblage, it would indicate a minimum pressure of 5 kbar [15,20] that corresponds to a depth of ~100 km in the Moon.

Excavation speculation: Cratering mechanics suggest that the largest lunar impact basins excavated target rocks from the lunar mantle [1–4]. The crater that excavated the deep-seated spinel lithology was larger than a complex crater. The central uplifts of such craters on the Moon originated from depths down to ~35 km and reach final diameters of 200 km [1]. Thus, some of the spinel assemblages could have been parts of a lunar complex crater's central uplift. On the other hand, to excavate material from a depth of >29 km, a minimum transient cavity diameter of 200 km is required [2], which corresponds to a final crater diameter of at least ~400 km [1,21]. Thin (≤30 km thick) regions of the lunar crust typically correspond to areas of incompatible element enrichments [22,23]. Association with incompatible element-enriched phases may suggest that the spinel assemblages of Dhofar 1528 were sourced from (below?) regions of such thin crust. Moreover, if the spinel-diopside-Al-rich low-Ca pyroxene assemblage (Fig. 1A) formed at a depth ≥100 km, it could have only been excavated during the formation of the largest known lunar impact basin [3].

Genetic interpretation: We favor an endogenous origin for the main group of Dhofar 1528 cumulate spinels in the Moon's upper mantle or lowermost crust. The most magnesian lunar spinels indicate formation as phenocrysts in small–scale impact melt volumes. None of the spinel-bearing assemblages in Dhofar 1528 are pure magnesian spinel and anorthite, thus, they do not represent the lithologies that were spectroscopically identified on the surface of the Moon [7,8].

Conclusions: We report the first magnesian spinel, Al-rich low-Ca pyroxene, forsterite, and cordierite from a lunar meteorite; this assemblage could have originally crystallized at depths ≥29–46 km, making it representative of a plausible lunar mantle rock.

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