SHALLOW CRUSTAL ORIGINS FOR SPINEL-BEARING LITHOLOGIES ON THE MOON: A PERSPECTIVE FROM THE LUNA 20 MISSION. S.B. Simon[1,2], C.K. Shearer[1,3], S.E. Haggerty[4], D. Moriarty[5,6], N. Petro[5], J.J. Papike[1], and Z. Vaci[1]. [1]Institute of Meteoritics and Dept. Earth and Planetary Sci., Univ. of New Mexico, Albuquerque, NM 87131, [2]Field Museum of Natural History, Chicago, IL,[3]Lunar and Planetary Inst., Houston, TX 77058, [4]Florida Intl. Univ., Miami, FL, [5]Goddard SFC, Greenbelt, MD ,[6]Univ. of Maryland, College Park, MD. (sbs8@unm.edu)

Introduction: The Russian Luna 20 mission returned samples in 1972 from the noritic Hilly and Furrowed Terrain [1] approximately 200 km south of the inner ring of the Crisium basin [2]. The sampling site is 33 km north of the edge of Mare Fecunditatis. The Luna 20 samples may contain clues to the depth of material excavated by Crisium-forming impact.

Spinel (s*ensu stricto*)-bearing crustal lithologies have long been recognized in the Apollo sample collection. However, such lithologies are rather rare and individual samples are small in mass (< 1 g). It has been inferred since the early 1970s that these lithologies (e.g., spinel cataclasites) were excavated during basin-forming events from the deep lunar crust to upper mantle [3-10]. Past studies and the present one have identified numerous spinel-bearing lithologies within the Luna 20 sample suite. Here, we examine those lithologies, compare mineral assemblages and spinel chemistries to those of other lunar samples, and deduce models for the petrogenesis of spinel-bearing lithologies (processes, conditions of formation) in both the Crisium region and the Moon in general.

Methods: Polished thin sections of material sieved into the 250-500 µm size fraction (parent split is 22003) and allocated to NASA were studied. Sections were carbon-coated and examined with a TESCAN LYRA3 scanning electron microscope (SEM) operated at 15kV. Quantitative energy-dispersive analyses and elemental X-ray maps were obtained with an IXRF silicon drift energy-dispersive X-ray detector running Iridium Ultra software. Quantitative wavelength-dispersive analyses were obtained with a fully automated JEOL 8200 electron microprobe operated at 15kV, using synthetic glass and natural mineral standards. Spinel analyses were plotted on the modified Johnston prism using the Spinel Web software of [11].

Results: The sections contain a total of 166 particles, of which 31 contain spinel. Of these, 10 are crystalline magmatic rocks, 16 are impact melt rocks (e.g., impact melt breccias, including two fragments found in agglutinates), and the other 5 are fused soil or devitrified glass fragments. The spinel-bearing lithic fragments are plagioclase-rich but not modally spinel-rich, which is typical of spinel-bearing lithologies found among the Apollo samples (e.g., [12]). None of these Luna 20 spinel-bearing lithologies have the high modal abundance of Mg-Al spinel (approximately 30%) of either the "pink-spinel" lithologies predicted from orbital data [10,13,14] or found in the unique lunar meteorite ALHA 81005 documented by [12]. Most spinels in the present samples are anhedral and <20 µm across. Representative images of spinel-bearing samples are shown in Simon et al. [15,16]. Compositions range from nearly pure $MgAl_2O_4$ to chromian ulvöspinel [15,16].

Petrography of Spinel-bearing Lithic Fragments. The spinel-bearing plutonic rocks examined in this study belong to the Mg-suite, based on their plagioclase compositions (anorthite contents) and Mg#s (Mg/(Mg+Fe)) of mafic silicates [3]. Of these ten samples, seven are troctolitic (i.e., olivine is the dominant mafic silicate), two are gabbroic anorthosites, and one is a feldspathic basalt. Mafic grains are typically less than 50 µm across, plagioclase <200 µm.

Impact melt rocks are common in lunar regoliths with large highland components. The spinel-bearing ones in the present suite typically have relatively coarse plagioclase clasts and relict-looking Mg-Al spinel grains in a finer (10–20 µm) matrix of plagioclase, pyroxene, and olivine. The fine textures of the matrices indicate rapid cooling, and they are generally composed of plagioclase laths with interstitial olivine ± pyroxene. Like most of the spinel-bearing igneous rocks, olivine is much more abundant than pyroxene in the impact rocks. It was also noted by [17] that in many Luna 20 lithic fragments, olivine is the dominant or even the only mafic silicate, especially in spinel-bearing fragments.

Impact-produced lithologies may contain multiple generations of olivine, plagioclase, and/or spinel. More Mg-rich olivine is observed to be large and anhedral, whereas smaller, euhedral (well-formed, with sharp, easily recognized faces), and zoned Fe-rich olivine is closely associated with spinel. Relict plagioclase clasts are anhedral to subhedral, whereas finer-grained plagioclase occurs as abundant laths with interstitial Fe-rich, calcic pyroxene, and as elongate crystals radiating from mineral surfaces, as seen in the backscattered electron image shown in Fig. 1. In some samples, Cr-rich spinel is anhedral and appears to be relict while Mg-Al spinel is more well-formed and in equilibrium with pyroxene of the host rock.

Discussion: The Luna 20 mission returned much less material than the successful Apollo missions, yet the L-20 sample suite contains a variety of lithologies from which we can gain insights into lunar petrogenesis.

Implications for the origin of magmatic spinel-bearing lithologies. Although the Mg-Al spinel stability field has been experimentally shown to expand at high pressure [12,14,18-20], the textures of the present spinel-bearing igneous samples suggest that they are not products of crystallization at high pressure. Their fine grain sizes and the fineness of pyroxene exsolution lamellae are consistent with relatively rapid cooling and thus shallow depths. High-pressure assemblages, such as low-Ca pyroxene + spinel [12] are not observed, and modeling of the Crisium impact event indicates that material composing the outer portions of its ejecta blanket may have had relatively shallow origins [21].

A way to generate spinel-bearing melts that is petrologically sound and consistent with constraints from remote sensing is through assimilation of ferroan anorthositic crust by Mg-rich, mantle-derived magmas [12,14,22,23]. This process can produce melts in the spinel stability field [12,14,23] that will have a crystallization sequence like that inferred for spinel troctolites. In addition, this process would destabilize previously crystallized olivine, resulting in resorption features, as observed in many of the present samples.

Implications for the formation of spinel-bearing impact melt lithologies. Our observations suggest that an exogenic origin, as suggested by [24], may be appropriate for some of these samples, but a meteoritic component is not necessary. The stability of Mg-Al spinel in these low-pressure, relatively quickly cooled melt systems provides some insights into the role of the plagioclase component in the petrogenesis of Mg-Al spinel in both magmatic and impact-produced lithologies. The backscattered electron (BSE) image of the impact melt breccia shown in Fig. 1 illustrates this. The relict mineralogy, plagioclase (An_{94-96}), olivine (Fo_{79-89}), and Cr-Fe spinel (56 wt% Cr_2O_3, 23 wt% FeO) is representative of a troctolitic anorthosite (i.e., an Mg-suite sample). The impact melt component crystallized to fine plagioclase laths (An_{93-95}), with interstitial olivine (Fo_{82}) and pyroxene ($En_{64}Wo_6Fs_{30}$), with accessory Mg-Al-dominated spinel and local, euhedral, relatively Fe-rich (Fo_{71-82}, Fig. 1) olivine. The crystallization sequence appears to be plagioclase (radiating from relict grains) $\Rightarrow$ olivine and spinel $\Rightarrow$ fine grained intergrowth of pyroxene and plagioclase. If the plagioclase radiating from the surface of relict olivine is analogous to that in mare basalts such as Apollo 15 quartz-normative basalts (e.g., 15499), these textures could represent rapid cooling (10°C/hr) of a plagioclase-oversaturated melt [25,26].

Conclusions:

1. Lunar Mg-Al spinels are products of both magmatic and impact processes.
2. Spinel-bearing magmatic samples are members of the Mg-suite and the spinel in these assemblages crystallized in relatively shallow crustal environments.
3. Assimilation of plagioclase-rich crust by a mantle-derived, olivine-saturated magma is the best way to account for our observations.
4. Impact processes can produce spinel-bearing feldspathic assemblages. A target rock such as anorthositic troctolite, for example, should yield lithologies with plagioclase and spinel.
5. Even a relatively small, robotically collected regolith core from a single location provides insights into a diverse array of lunar petrologic processes.

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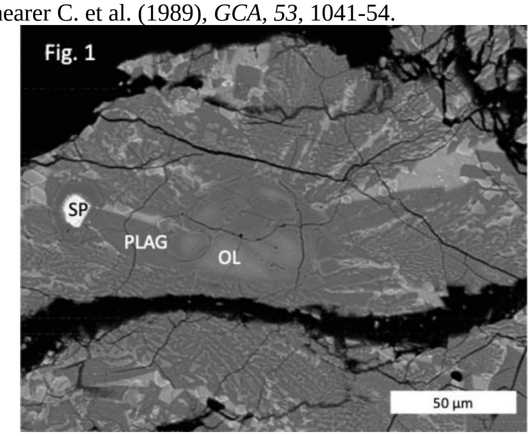

Fig. 1. BSE image of L-20 an impact melt rock fragment showing relict Cr-rich spinel (SP), and plagioclase (PLAG) laths that nucleated on relict olivine (OL).