THE EVOLUTION OF THE LUNAR CRUST II. A MULTI-PERSPECTIVE APPROACH TO UNDERSTANDING THE ORIGIN OF SPINEL-BEARING LITHOLOGIES AT THE LUNA 20 LANDING SITE.

S. B. Simon[1,2], C. K. Shearer[1,2,3], S. E. Haggerty[4], J. J. Papike[1,2], N. E. Petro[5], D. P. Moriarty[5,6], and Z. Vaci[1,2]. [1]Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, [2]Dept. of Earth and Planetary Sciences, Univ. of New Mexico, Albuquerque, NM 87131, [3]Lunar and Planetary Institute, Houston TX 77058, [4]Earth & Environmental Sci., Florida International Univ., Miami, FL 33155, [5]NASA Goddard Space Flight Center, Greenbelt, MD 20771, [6] Universities Space Research Association, Columbia, MD 21046. sbs8@unm.edu.

Introduction: 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 [1-9]. Studies of lunar meteorites have revealed several unique spinel-bearing assemblages [e.g., 10]. More recently, a new lunar rock type rich in Mg-Al spinel and plagioclase, with limited Mg-rich olivine and pyroxene, was identified with near-infrared reflectance spectroscopy by the Moon Mineralogy Mapper instrument (M^3) during the Chandrayaan-1 mission. At least 23 regions containing exposures of this lithology have been identified. The individual regions are on the scale of 100s of meters and have a global distribution geologically associated with regions of crustal thinning [e.g., 9]. Several of these locations are in the highlands terrain surrounding the Crisium basin. In particular, the spinel location associated with Macrobius crater (lat 21.3, long 46.1) within the noritic Hilly and Furrowed Terrain [11,12] is associated with the Crisium basin-forming event. Potentially, the Crisium event excavated deep crustal and upper mantle lithologies. The Luna 20 mission returned samples from the noritic Hilly and Furrowed Terrain [11]. We are examining crystalline lithologies returned by the Luna 20 mission [12] within the context of orbital observations. Past studies and the present one have identified numerous spinel-bearing lithologies within the Luna 20 sample suite. Here, we examine those lithologies, compare the mineral assemblages and spinel chemistries to other lunar sample data (Apollo, meteorites), and deduce models for the petrogenesis of spinel-bearing lithologies (processes, conditions of formation) in both the Crisium region and the Moon in general.

Analytical Approach: Thin sections of sieved material (250-500 μm) collected from the Luna 20 site and allocated to NASA were examined and integrated with data collected during consortium studies in 1973 [13]. Imaging and analyses were performed with a TESCAN LYRA3 scanning electron microscope and a JEOL 8200 electron microprobe, respectively, both at the University of New Mexico.

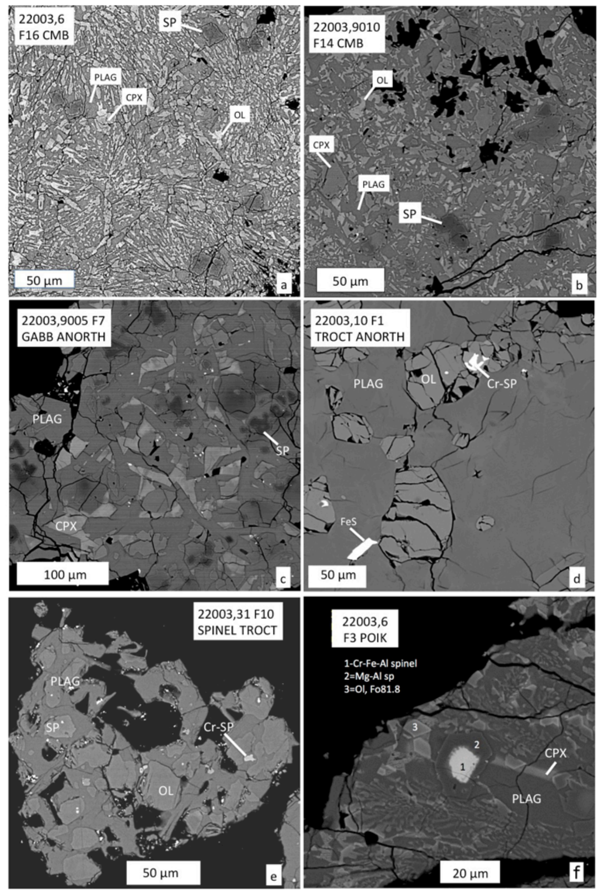

Fig. 1. Backscattered electron images of spinel-bearing lithic fragments. a, b: Crystalline melt breccias (CMB) with Mg-Al spinel; c: Gabbroic anorthosite with Mg-Al spinel; d: Troctolitic anorthosite with Cr-rich spinel; e: Spinel troctolite with Cr-rich and Mg-Al spinel; f: Cr-Fe-Al spinel (1) enclosed in subhedral Mg-Al spinel (2) in a poikilitic CMB. CPX=clinopyroxene; PLAG=plagioclase; OL=olivine; SP=spinel; Cr-SP=Cr-rich spinel.

Results: Of 166 particles examined, 31 contain spinel; of these, 12 are impact melt rocks (e.g., Fig. 1a,b,f) and 13 are true igneous rocks (e.g., Fig. 1c,d,e). All are feldspar-rich but not modally spinel-rich, which is typical of spinel-bearing lithologies among Apollo samples [10] and unlike the one found in ALHA 81005 [10]. Spinel was also found in fused soil particles and devitrified glass. Spinel grain sizes are mostly <20 μm.

Most occurrences are anhedral. Compositions range from nearly pure $MgAl_2O_4$ to chromian ulvöspinel. Fe-Mg and Cr-Al relationships are illustrated in Fig. 2. Contents of Fe are strongly anticorrelated with Mg, and Cr is strongly anticorrelated with Al. Cr-rich grains are richer in V than Cr-poor grains. Spinel in spinel troctolites is relatively Cr-poor and Al-rich, as previously reported [e.g. 13]. Cr-rich ulvöspinel is more common in plutonic than in impact melt rocks (Fig. 2), and its composition is similar to previously reported L-20 Cr-usp compositions [13-15]. One melt rock has Cr-spinel enclosed in Mg-Al spinel (Fig. 1f). The range of literature data for L-20 igneous rocks is illustrated in Fig. 3.

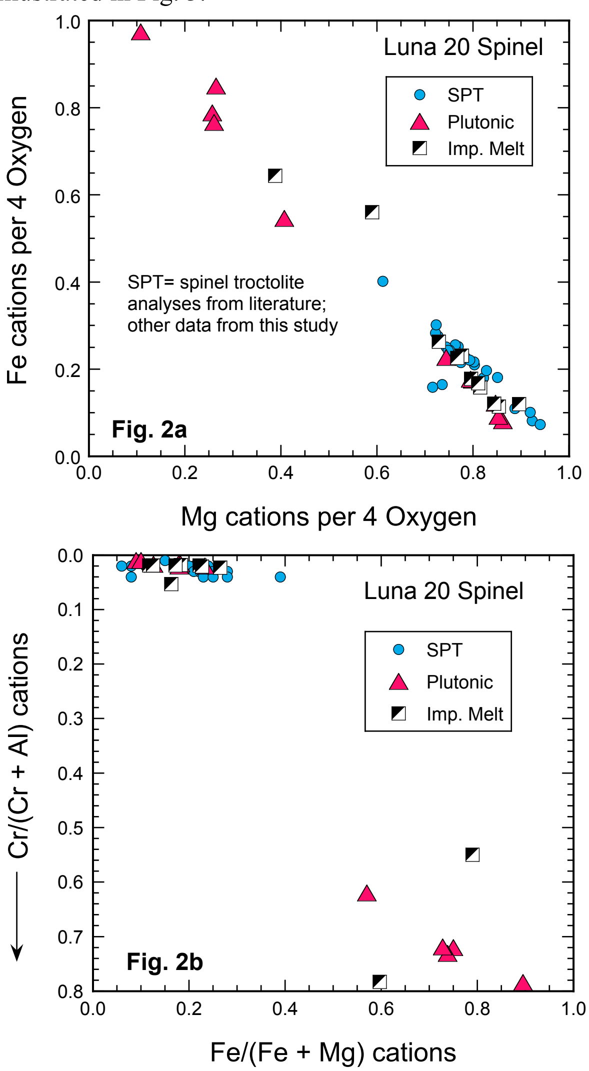

Fig. 2. Spinel compositions in Luna 20 plutonic and impact melt rock lithic fragments. Most spinels are either Mg-, Al-rich or Cr-, Fe-rich.

Discussion: *Crystal Chemistry of Lunar Spinels:* Spinel in mare basalts is dominated by the $FeCr_2O_4$-Fe_2TiO_4-$FeAl_2O_4$ components, with the principle substitution $Fe^{2+} + Ti^{4+} \leftrightarrow 2(Cr,Al)^{3+}$. Generally, spinel in mare basalt (e.g., A-12, A-15) is zoned from early chromite toward ulvöspinel. In this typical mare crystallization path Mg^{2+} and Al^{3+} decrease. Although the chromite component is important in many Highland lithologies (e.g., troctolites), in many of the present samples the $MgAl_2O_4$ component is dominant.

Conditions of formation: Plagioclase-rich impact melt rocks are an important type of spinel-bearing lithology in the region. In these impact lithologies there are preserved remnants of target rock spinel, mostly embayed, relict Mg-, Al-rich grains (Fig. 1a,b), or Cr-rich grains rimmed by Mg-Al spinel (Fig. 2f) in a sequence that is the opposite of mare basalt trends. Presence of Mg-Al spinel does not necessarily require an origin in lower crust-upper mantle P-T environments as has been previously suggested [e.g. 8]. Many of the rock textures, with fine grain sizes and pyroxene free of exsolution lamellae, imply a relatively shallow crystallization environment, like that favored by [10]. The occurrence of spinel in both impact and magmatic rocks has important implications for geologic interpretation of the pink spinel lithologies identified via remote sensing.

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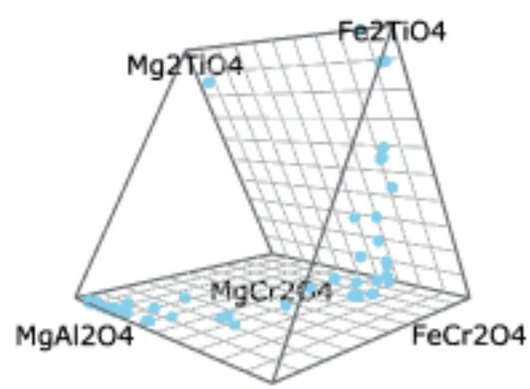

Figure 3. The range of published spinel compositions from Luna 20 samples [13-15]. Plotted using method of [16].