WHERE IS THE LUNAR MANTLE AND DEEP CRUST AT CRISIUM? PLACING THE LUNA 20 SAMPLES WITHIN THE CONTEXT OF THE CRISIUM BASIN-FORMING EVENT.

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Introduction: The Crisium basin provides a unique lunar terrain for examining crustal structure of the Moon and the role of basin-forming processes in crustal evolution. Orbital, geophysical, and sample (Luna 20) data offer a variety of perspectives. The initial remote sensing studies of the Crisium region provided initial constraints on the composition of the rings of Crisium and variability in the adjacent crust [e.g., 1-3]. Analyses of Chandryaan-1 Moon Mineralogy Mapper instrument (M^3) and Spectral Profiler data from Kaguya identified olivine (Fo_{90-65}) along the rim of the Crisium Basin that has been interpreted to represent materials excavated from the upper mantle-lower crust, igneous intrusions, or impact melt sheets [4-7]. Further interpretation of the M^3 data led [8] to conclude that the lithologies at the inner rim of Crisium consist predominantly of troctolitic/nortic/gabbroic anorthosites with smaller proportions of anorthositic norites/gabbros, and olivine norite/gabbros. Lemelin et al. [9] interpreted their data as indicating that noritic or gabbroic anorthosite (plagioclase 77.5–90 wt%) and anorthosite are the dominant lithologies in the innermost ring of the Crisium basin and are sub-equal in abundance (45% versus ~41%, respectively). Further, based on the work of [10], they estimated that the lithologies making up the inner ring consisted of near-equal proportions of upper mantle (73 km depth) and deep crustal components (28 km). The interpretation of gravity data is consistent with many of these models that suggest excavation of the lunar mantle by the Crisium event[11].

The initial results from studies of Luna 20 (L20) materials are summarized in a special issue of [12]. Here, we examine the crystalline lithologies returned by the L20 mission and integrate this sample data with orbital and empirical modeling to gain additional insights into role and distribution of the crust/mantle during the Crisium basin-forming event.

L20 samples: L20 sampled the highland material making up the noritic Hilly and Furrowed Terrain (nHFT) [7,13] adjacent to Crisium. Crisium ejecta contributed to the nHFT. Our focus for this initial examination is the crystalline rocks which appeared to be clast-free and products of crystallization from a melt (magmatic or impact). The fine- to medium-grained (<100 µm) lithologies include spinel troctolites, troctolites, norites, gabbronorites and gabbros (Fig. 1A-D). No ultramafic lithologies (e.g., dunites, pyroxenites) were observed. In addition to these fine-grained lithologies, there are coarse-grained plagioclase fragments (>250 µm) associated with much finer mafic grains, predominantly pyroxene (Fig 1E-F). Pyroxenes in all these assemblages do not exhibit exsolution lamellae greater than 2-3 µm in width. An example of pyroxene with fine exsolution lamellae is shown in Fig. 1E. Earlier X-ray examination of pyroxene from L20 indicated sub-micron lamellae of varying degrees of complexity [e.g., 14]. The spinel, *sensu stricto*, in these lithologies are high in Al_2O_3 (64-69%) with variable Mg'. In contrast to the pyroxene data, these spinel-assemblages have been interpreted as being derived from 26-60 km [e.g., 15,16].

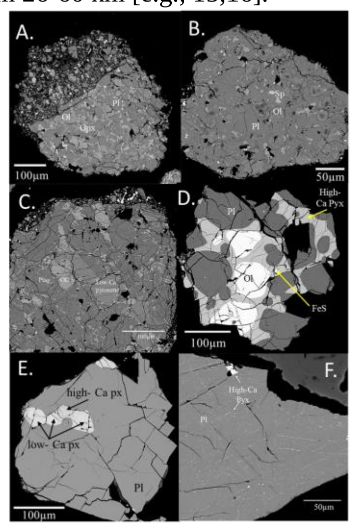

Figure 1. Backscattered electron (BSE) images of lithologies from L20. A. Troctolite. B. Spinel troctolite. C. Norite. D. Gabbro. E. Ferroan anorthosite (FAN). F. FAN.

Modal abundances of phases and their compositions in lithic fragments from the L20 sampling site are presented in Fig. 2A and compared to lithologies at the rim of the Crisium Basin (Fig. 2B from [8]). At the L20 site, the assemblages containing ferroan mafic phases are dominated by coarse-grained plagioclase (100 to 85%) and are anorthosites and noritic and gabbroic anorthosites. The mafic phases are predominantly low- and high-Ca pyroxene. Olivine is generally a minor phase. Those lithologies that have more Mg-rich mafic phases are finer-grained and have a wide range of plagioclase abundances (38 to 90%). They generally plot within the fields of anorthositic norite/gabbro, anorthositic troctolite, norite/gabbro, olivine norite/gabbro, and troctolite ± spinel (Fig. 2A). Our interpretation of the M^3 data is that there is not a dramatic change in pyroxene composition from the inner ring of Crisium to the L20 site. Unique "pink" spinel+plagioclase assemblages are adjacent to Crisium [2]. FeCr-spinels are distributed throughout the nHFT[17]

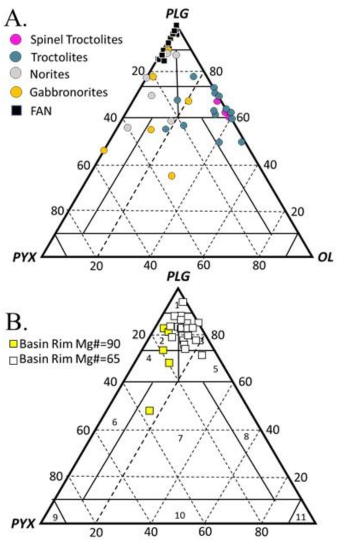

Figure 2. A. Modal mineralogy determined from L20 samples in this study from BSE images and X-ray maps. B. Modal mineralogy of olivine-bearing outcrops on the Crisium basin rim, estimated with radiative transfer modeling for M^3 olivine spectra [8]. Lithologies are differentiated based on olivine composition (Mg#=65, Mg#= 90). Fields identified in A and indexed in B are from [8].

On a traditional Mg# (mafic silicates) – An# (plagioclase) diagram for distinguishing highland crustal lithologies (Fig. 3), the compositions of coexisting mafics and plagioclase in L20 highland crystalline assemblages plot within the Mg-suite and FAN-suite fields. Unlike the range of FANs observed in the Apollo sample suite, the L-20 samples with FAN affinities only plot in the most Mg-rich portion of the FAN field. Those samples with a Mg-suite affinity show a somewhat limited relationship between lithology and distribution in the Mg-suite field, although in a very general sense the spinel troctolites tend to plot at higher Mg# and An#, while the norites, gabbronorites, gabbros plot at lower values of Mg# and An#. Troctolites are in intermediate positions in this plot. Ar/Ar ages of the highlands lithic fragments range from 4.42 to 3.84 Ga [e.g., 16,18].

Reconstruction of the chemistry of the L20 materials and integration with orbital data indicate that they do not represent products of impact melts [e.g., 7] and are not high in a urKREEP component. Our new M^3 analyses suggest a higher "mafic" (ol+pyx+spinel) abundance in the nHFT than in the Crisium inner rim, which seems to be volumetrically dominated by pure plagioclase.

Conclusions: (1) It has been proposed that lunar mantle material was excavated by the Crisium event. There is no evidence for this from the L20 samples. Ultramafic rocks such as dunites and orthopyroxenites are rare, and Mg-

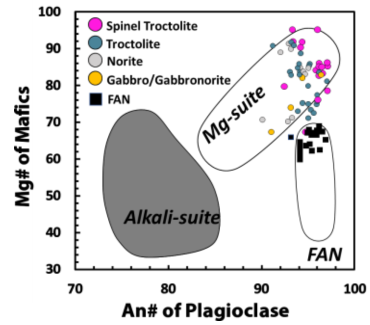

Figure 3. Plot of Mg# of mafic silicates vs An# in plagioclase in lithologies collected from the L20 landing site.

rich olivine- and orthopyroxene-bearing-assemblages appear to be derived from the shallow crust. (2) A companion abstract illustrates that the nHFT has more abundant FeCr-spinel lithologies than previously recognized [17]. Mg-spinel-bearing lithologies at Crisium have been interpreted as representing deep crustal lithologies (30-40 km) [15,16]. However, numerous studies [e.g., 19] and our observations suggest an alternative interpretation in which the spinel represents crystallization in a shallow crustal environment. (3) The lithic fragments emphasized in this study represent pre-Crisium episodes of shallowly emplaced Mg-suite magmas and FAN magmatism related to primordial differentiation. (4) Mg-suite magmas may be derived from either the melting of a hybrid mantle source [20] or through plagioclase assimilation by a mantle-derived, olivine- saturated basaltic magma [21,22]. However, the spinel-bearing troctolites may only be produced through assimilation of crustal plagioclase [21]. The Mg-suite lithologies associated with the Crisium basin indicate that this style of early lunar crust building is Moon wide. (5) Finally, one interpretation of our data is that from the Crisium inner ring to the L20 site materials are derived from increasingly shallower depths. Alternatively, although the inner ring is more plagioclase-rich than the L20 site it still has limited deep crustal assemblages. Where is the excavated mantle? The distribution of lithologies derived from various crust-mantle environments have profound implications for impact models.

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