THE EVOLUTION OF THE LUNAR CRUST. PLACING THE LUNA 20 SAMPLES WITHIN THE CONTEXT OF THE CRISIUM BASIN-FORMING EVENT.

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Introduction: Basin rims are well-known to reveal deep-seated lithologies at the lunar surface [1-5]. The initial remote sensing studies of the Crisium region relied on either Earth-based spectral data [1,6] or Clementine UV-VIS data [2]. As such they provided important constraints on the composition of the rings of Crisium and variability in the crust in that area. Analyses of Chandryaan-1 M^3 and Spectral Profiler data from Kaguya have revealed small exposures of olivine, suggesting the possible excavation of mantle materials [7,8]. However, we know that the Luna 20 samples contain a range of rock types [e.g., 9-12], some of which may represent deep-seated plutonic rocks from the deep crust or mantle [7,8], breccias, noritic impact melts produced during the Crisium forming event [13], and basalts from the adjacent mare basins. Other lithologies likely reflect a “non-local” component collected at the sample sites [e.g., 14, 15]. Here, we integrate the Luna 20 sample suite with remotely collected data, empirical modeling of the Crisium basin-forming event, and ejecta mixing models to address the following: Is the upper mantle or lower crust of the Moon exposed in the Crisium Basin and are these excavated materials in the Luna 20 sample suite? If so, what are the compositions of these lithologies, their distribution, and importance on reconstructing the composition and structure of the Moon? Are facies of Crisium impact melt sheet [13] sampled by the Luna 20 mission? If so, how do we recognize this component? Finally, what proportions of the Luna 20 samples represent “non-local” lithologies?

Luna 20 samples: Luna 20 sampled highland material making up the rim of the Crisium basin. The Luna 20 mission returned a partially filled core tube with 50 grams of sample. Through several exchanges, the United States, through the NASA Curatorial branch, was allocated approximately 2.69 grams. The soil sample contains crystalline lithic fragments (20-36% variation in the different size fractions) that consist of polymict breccias, impact melt rocks, basalts, and a variety of anorthosites, norites, and troctolite lithologies [e.g., 16-20]. Mineral compositions (e.g., TiO_2, Cr_2O_3, and Mg’) of the highland component making up the lithic fragments define two distinct suites of lithic fragments [17]. These two suites have mineral compositions analogous to the Mg-suite and FAN-suite. The samples are generally incompatible element-poor compared to similar lithologies at Apollo landing sites. This incompatible element signature may reflect a reduced abundance of a KREEP component. This reduction in a KREEP component may be attributed to the limited addition of Imbrium ejecta to the site and/or the limited contribution of KREEP to the magmatic lithologies making-up the crust. Pyroxene in many of the lithic fragments in the Luna 20 sample suite [16,20,21] exhibit complex and fine exsolution lamellae (from 10Å to 1-3μm) and partial inversion of pigeonite to orthopyroxene. Based on the approach of [22,23] many of these pyroxenes crystallized and reequilibrated at shallow crustal conditions (≤ 2 km). In contrast, spinel troctolite identified in the Luna 20 sample suite implies a deeper crustal origin for some of the highland component. The spinel, *sensu stricto*, in these lithologies are high in Al_2O_3 (64-69%) with variable Mg’. Estimates for the depth of origin for theses mineral assemblages range from 26-60 km [e.g., 22-25]. Previous studies of the Luna 20 samples [17, 26] had difficulty in identifying mare components. Only [16] found multiple fragments (8 of 157, ~5%) in the 250-500 μm and 125-250 μm size fractions, which is low when compared to the abundance of mare fragments in comparable Apollo 16 samples (6%; [27]) given that Luna 20 is much closer to nearby mare (39 km) than Apollo 16 (220 km). Potentially the low mare component may be partially an interpretive problem, as a larger a portion of the mare component may be represented by the more Fe-rich pyroxenes in the regolith. It is unclear if the Fe-rich pyroxenes represent a mare or ferroan highlands component. Ar/Ar ages of the highlands lithic fragments range from 4.42 to 3.84 Ga [e.g., 15, 28].

The mineralogy and geochemistry of the Luna 20 site from remotely collected data: To first order, spectral diversity across the Crisium region is dominated by variations in the abundance and composition of pyroxene (Fig. 1). The Crisium interior is dominated by Fe, Ca-rich mare basalts. However, several impact crater structures that excavate through or pre-date the mare (Peirce, Picard, Yerkes) exhibit abundant Mg-rich pyroxenes [e.g., 13]. It is likely that these craters expose Crisium impact melt. Since the depth of melting exceeds the depth of excavation for basin-scale impacts [*e.g.* 29], and lunar impacts excavate materials from depths of up to ~10% of their diameter [*e.g.*,30], Crisium’s impact melt pool should include abundant materials from beneath the ~40 km thick lunar crust. Numerical modeling of the Crisium-forming impact would greatly refine our understanding of the relevant depths of melting and excavation.

Crisium’s rim and adjacent highlands exhibit a wider range of mineralogical diversity (Fig. 1). Variations in pyroxene abundance may be related to mixing between Crisium ejecta (including upper crust and lower crust / upper mantle components), adjacent highlands material, and subsequent ejecta from later impact events. However, the mafic component in this zone is dominated by Mg-rich pyroxenes, similar to the Crisium impact melt exposed by Peirce, Picard, and Yerkes. This link between noritic Crisium ejecta and noritic Crisium impact melt suggests that some noritic lithologies observed in Luna 20 samples may be related to deep-seated materials excavated from the lower crust/upper mantle by the Crisium-forming impact. This link will be further explored through analysis of full-resolution M^3 images to constrain the regional diversity in non-mare pyroxene-bearing lithologies.

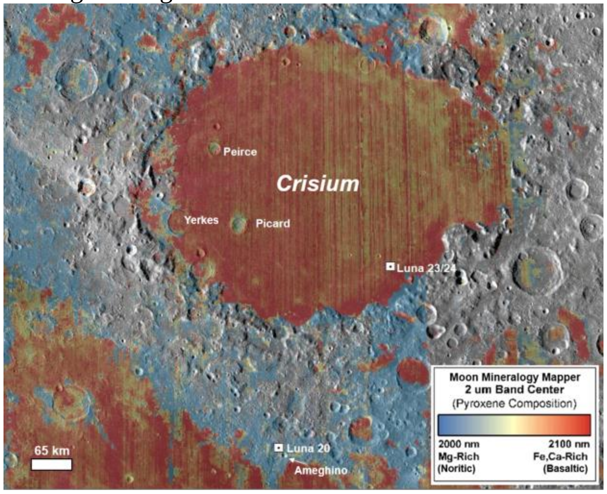

Fig. 1: A map of pyroxene compositions across the Crisium region, as revealed by 2-micron spectral absorption band centers derived from Moon Mineralogy Mapper data. Only pixels with band depths greater than 0.05 are mapped; colorless pixels indicate relatively feldspathic materials [31].

Elemental abundance maps from the Lunar Prospector gamma ray spectrometer provide further insight into the compositional context of Luna 20 samples. To first order, the rim / proximal ejecta of Crisium exhibit relatively low Fe, Th, Ti, and K abundance. Higher abundances of these elements are associated with mare basalts and/or materials ejected and redistributed from the PKT to the west. Surface materials across Crisium's rim exhibit patterns with intermediate elemental abundances consistent with impact-driven mixing between crustal materials, Crisium ejecta, mare basalts, and non-local ejecta. Specific evidence for this is observed at two young craters (Proclus and Condorcat A) that appear to excavate relatively pure highlands crustal materials (very low Fe, Th, Ti) from beneath mixed, intermediate surface materials. The Luna 20 site exhibits intermediate Fe, Th, Ti, and K abundances, indicating that the returned samples represent a well-mixed regolith incorporating multiple lithologies from the region.

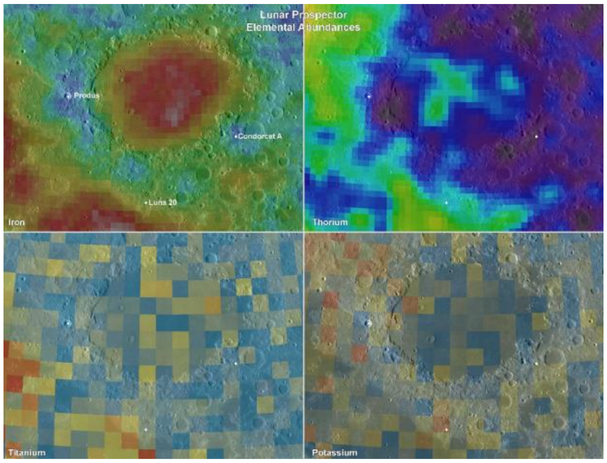

Fig. 2: Lunar Prospector elemental abundance maps [32,33] for the Crisium region. These maps are stretched to highlight regional variations.

Regolith Provenance for the Luna 20 Sample Site: Using the approach of [34] for the region surround the Luna 20 site we can estimate the contribution of post-Crisium craters to the sample site to better understand the provenance of regolith components. For example, one of the closest large craters is Ameghino, a 9 km diameter Imbrian aged crater. Based on the crater scaling [34] we estimate ~80 cm of ejecta could have been introduced to the Luna 20 sampling site. The Ameghino impact occurred in Crisium ejecta, which itself contains a non-negligible amount of Crisium impact melt. Modeling of the Crisium impact event, combined with an analysis of the redistribution of Crisium impact melt by subsequent cratering enables a prediction of how much Crisium melt was sampled by Luna 20.

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