Morphological and Spectrochemical Characterization of Pyroxene- and Spinel-bearing Lithologies and Impact Cratering Mechanics of the Moon: Implications for Lunar Endogenic and Exogenic Processes

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Abstract

The knowledge about endogenic and exogenic processes on the Moon is imperative to understanding the evolutionary history of our nearest neighbour. This Ph.D. work focuses on understanding these processes by studying the spectrochemical characteristics and geological context of pyroxene- and spinel-bearing lithologies and morphology of impact craters on the Moon. The research primarily utilized orbital remote sensing datasets from various lunar exploratory missions, particularly ISRO’s Chandrayaan-1 mission. The investigation of the Grimaldi and Humorum basins based on pyroxene chemistry and crater chronology provided new insights into the Main-phase and Late-phase volcanic history of the Moon. The estimated long span of volcanism in the Grimaldi and Humorum basins (3.5 Ga – 1.5 Ga) indicates the extended history of lunar thermal evolution. Multiple volcanic episodes have occurred in the Mare Humorum. The older mare basaltic units that erupted during the Imbrian period crystallized from a more fractionated magma, whereas the younger unit crystallized from Mg and Ca-rich magma. The younger basaltic unit's longward shift in Band I and Band II centres indicates a higher Ca^{2+}-rich parental magma composition. The older units' shortening of Band I and Band II centres indicates that the older basaltic magma formed more Fe^{2+}-rich pyroxenes or clinopyroxenes with lower Ca^{2+} concentrations during cooling. It has been concluded that magmas of diverse chemical nature originating from different source regions have erupted in the Humorum basin during the Imbrian to Eratosthenian periods. In addition to discoveries that fit prior identifications of older mare basalts in the Grimaldi basin, the current investigation has revealed younger basaltic units in the Mare Grimaldi and Mare Riccioli with greater FeO and TiO_2 concentrations. The chemical variations in these volcanic basalts were determined using their pyroxene compositions, hinting at the heterogeneous lunar mantle and multiple eruptions in the basins. The wide variations in FeO and TiO_2 contents of basalts and the presence of younger, olivine-bearing, high-Ti basalts point to the chemical evolution of the magma over time and their diverse source regions in the lunar mantle. The Late Imbrian low to intermediate-Ti basalts erupted in the Mare Grimaldi and Mare Riccioli at ~3.5 Ga are derived from, melting of early cumulate materials caused by radioactive heating, or from molten zones that remained in the mantle after initial global melting in the hybrid source region

of the post-overturn upper mantle, which erupted through dikes. The Eratosthenian high-Ti magma that erupted at ~2.5 Ga in the Mare Grimaldi is suggested to have been formed through partial melting caused by a hot plume rising from the deeper clinopyroxene-ilmenite-rich cumulates near the core-mantle boundary. The intermediate-Ti basalts (~1.5 Ga event) in the Mare Riccioli formed through a different process where the ilmenite-clinopyroxene cumulates remained in the upper mantle after the mantle overturn remelted to generate high-Ti magmas. The origin of these mare basalts at different depths in the mantle favour the idea of a possible lunar mantle overturn following the LMO (Lunar Magma Ocean) crystallization. In addition, the long span of volcanism in the Grimaldi and Humorum basins (3.5 Ga – 1.5 Ga) suggests the extended history of the thermal evolution of the Moon.

The investigation of compositional variations of spinels in diverse rock types on the Moon showed that lunar spinels are generally chromites, ulvospinels, pleonaste, and Mg-Al compositions. The comparison of lunar magmatic spinels with terrestrial spinel compositional fields showed an affinity to boninites and komatiites for lunar Cr-spinels, and hence suggested a mantle origin for Cr-spinels on the Moon. The comparison of lunar spinels with the terrestrial spinel from Sittampundi Anorthosite Complex (SAC) based on their spectrochemical characteristics has put significant constraints on the remote identification of lunar spinel chemistry. The Cr-spinels in SAC have a Fe- and Al-rich composition, with Cr_2O_3 concentrations and Cr# ranging from 32–37 wt percent and 0.44–0.53, respectively. The conspicuous Raman peak associated with Cr-spinels' A_{1g} mode ranges from 703 to 714 cm^{-1}, with a shoulder about 671 cm^{-1}. The coexistence of (Mg, Fe) in the tetrahedral site and (Al, Cr) in the octahedral site causes the A_{1g} peak position near 705 cm^{-1}. Because of the increased Al content (Al_2O_3 ~25 wt%) in the SAC Cr-spinels, the 2 μm band position is at shorter wavelengths than conventional Cr-spinels. The Cr# and Cr_2O_3 contents have a positive association with the 2 μm band location, but the Al_2O_3 concentration has a negative correlation. The replacement of Al and Cr for one another in the octahedral site explains the linear relationship. Based on their spectrochemical features, the observed linear connection between 2 μm band position and Cr/Al abundances can be used to distinguish Al-spinels from Cr-spinels. Through an integrated and comparative investigation of spectroscopic and chemical data, the study has unambiguously demonstrated the relationship between the spectral pattern and the chemistry of Cr-spinels. The interpretation of possible occurrences of Fe- and Cr-bearing spinels in the Sinus Aestuum on the Moon was made possible by comparing the spectral properties of SAC Cr-spinels with those of previously detected spinels from Sinus Aestuum. The established spectral-chemical relationships will serve as a reference for separating lunar Al spinels from Cr-spinels. If limited knowledge on their formation processes involving melt-wall rock interaction on both the planetary bodies is addressed, the SAC-hosted Cr-spinels could serve as a potential functional analogue for lunar Fe- and Cr-bearing spinels. Further, the spectrochemical data of terrestrial spinels derived in this study will greatly add to the lunar analogue database that could be utilized for instrument calibration in future exploration missions.

Impact cratering mechanics of the Moon have been understood by studying the cratering mechanics of Copernican craters (<1 Ga old). The Ohm and Das craters are Copernican craters on the farside of the Moon, which records the diverse processes of impact cratering events on the Moon. Starting with the sharp and scalloped rim, an alcove of wall terraces, the distinct scarp-tread system with steep slopes on the scarp, wall slumping, impact melt deposits, flat floor with hummocky texture, slump hillocks on the floor, melt platform, and central mounds with bedrock exposures, the morphological mapping interior to the crater cavity revealed the characteristic geological features of this complex impact crater. These diverse morphological elements show that the Das crater began as a simple bowl-shaped crater that evolved into a complex crater over time. In less than 4 seconds, the transient crater cavity for the Das crater was excavated. The greatest excavation depth is predicted to be 3 kilometers. The transient crater diameter is expected to be 30.4 kilometers, with a depth of 7.6-9.12 kilometers. The crater was excavated at the same time as shocked and melted debris was ejected outward as impact ejecta. Even before the central mounds developed from depths of maximally compressed materials at roughly 3.2 km, the crater was being modified. The consequent gravitational collapse of the rim resulted in terraced, steeper walls, resulting in a widening of the crater rim along W-E and enlargement of the final diameter to 38 km. On the western inner wall, the wall slumping was more severe, and the slumped materials fell to form heaps of hillocks, mostly in the western half of the floor. The eastern crater floor has sunk, most likely as a result of structural collapse and/or the cooling of the first melt column. The impact melts line the temporary crater cavity throughout its expansion, forming ponds in the wall terraces, vast melt sheets along the inner wall slopes, and melt-draped floor units, among other topographic features. Melt breccia, shattered impact melt deposits with boulders at their edges, and characteristic flow features like melt fronts or flow lobes centered on the inner wall of the crater are all diagnostic of impact-generated melts. Solid and melt phase ejecta are scattered around the crater rim outside the crater cavity, with highly shocked debris components occurring at radial distances beyond the rim and melted debris preferentially occupying topographic lows and slopes both inward and outward from the crater rim. The infilling of secondary crater chains and subsequent overprinting by the contiguous ejecta blanket resulted from the ground-hugging flow of heterogeneous materials. Within 7 km radial extents from the rim crest, melt-bearing ejecta is spread as rim veneer deposits, ponded melt, and lobate deposits, which entirely overlie the adjacent ejecta blanket. Ballistic ejecta facies have a non-uniform distribution across the crater, with the greatest radial extents in the northwestern and southeastern quadrants compared to the less extensive deposits in the southwest and NNE quadrants, exhibiting asymmetric ejecta with bilateral symmetry along the NNE-SSW line going across the crater's centre. The occurrence of a forbidden zone to the NNE that is free of distal ejecta rays and secondary crater chains shows that the impact was NNE-SSW. The crater's nearly circular shape, together with a well-defined forbidden zone in the uprange, imply that the impact happened at a 15°-25° inclination to the horizontal. The findings of this study show that studying Copernican craters is critical for furthering our understanding of the Moon's impact dynamics and cratering mechanics.

The discovery of the Late-Imbrian and Eratosthenian volcanic events on the lunar nearside, the compositional diversity of lunar spinels and possible mantle origin of Cr-spinels, and the interpretations on cratering processes and impact dynamics on the Moon during the Copernican epoch reveal that the geological history of the Moon is as vast as we have known yet, and our Moon could still be evolving.