Lunar regolith as an archive of Solar System history

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Lunar regolith as an archive of Solar System history

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Lunar glass beads are tiny particles which can be found in the lunar regolith (or "soil") covering almost the entire surface of the Moon. Glass beads can form due to volcanic eruption or be a result of impact flux, which defines two directions of the project. Volcanic glasses provide information about the lunar interior and the origin of mare basalts, mantle composition and its differentiation. Impact glasses aim to study compositional evolution of the lunar crust, regolith and impact processes. Investigation of glass beads will be help to decrease the ambiguity in the lunar chronology, providing precise U-Pb ages of the impact history.

Keywords: Moon, lunar regolith, lunar chronology

1. Introduction

Lunar science is a relatively young area of geologic investigation. Lunar return samples from known locations (and meteorites) allow us to directly investigate chemical and physical properties of our closest neighbour in detail. Less than a decade (1969-1976) of intense investigation, which started with six Apollo and three Luna sample-return missions, had changed a concept of the Moon as a simple planetary body to a highly differentiated one with a complex internal structure (e.g., Zubber et al., 1994) and unique crustal evolution (Hartmann and Davis, 1975).

2. Moon formation

It is generally thought that the Moon formed due to a collision of a Mars-sized body with the proto-Earth, which ejected hot material into the Earth's orbit, rapidly depleting in volatiles (e.g., Hartmann and Davis, 1975). Soon after planetesimal accretion, the Moon underwent extensive melting resulted in the lunar magma ocean (LMO), which was followed by the early differentiation and crystallization of the LMO completed by ~ 4.4 Ga (Nemchin et al., 2009). Fractional crystallization implies that the early lunar crust was produced by flotation of the plagioclase-rich crust formed by ferroan anorthosites and sinking of mafic cumulates (Shearer, 2006). Late stage precipitation of ilmenite led to formation of residual melt highly enriched in incompatible elements and referred to as KREEP (potassium, rare-earth elements and phosphorus rich), Figure 1A.

Based on textures and chemical composition, lunar rocks can be divided into 1. highland anorthosites and norites; 2. basaltic volcanic rocks or mare basalts; 3. polymict clastic breccias and impact melt rocks; and 4. lunar regolith or lunar "soil" (Figure 1B). The latter has been generated by impact "gardening" of the first three rock types and represents an unconsolidated fine-grained material with an average grain size of 60-80 µm, which covers almost the entire lunar surface. It is mainly composed of mineral and rock fragments, glass beads (volcanic and impact, Figure 1C) and agglutinates, which represent mineral and rock fragments welded by glass.

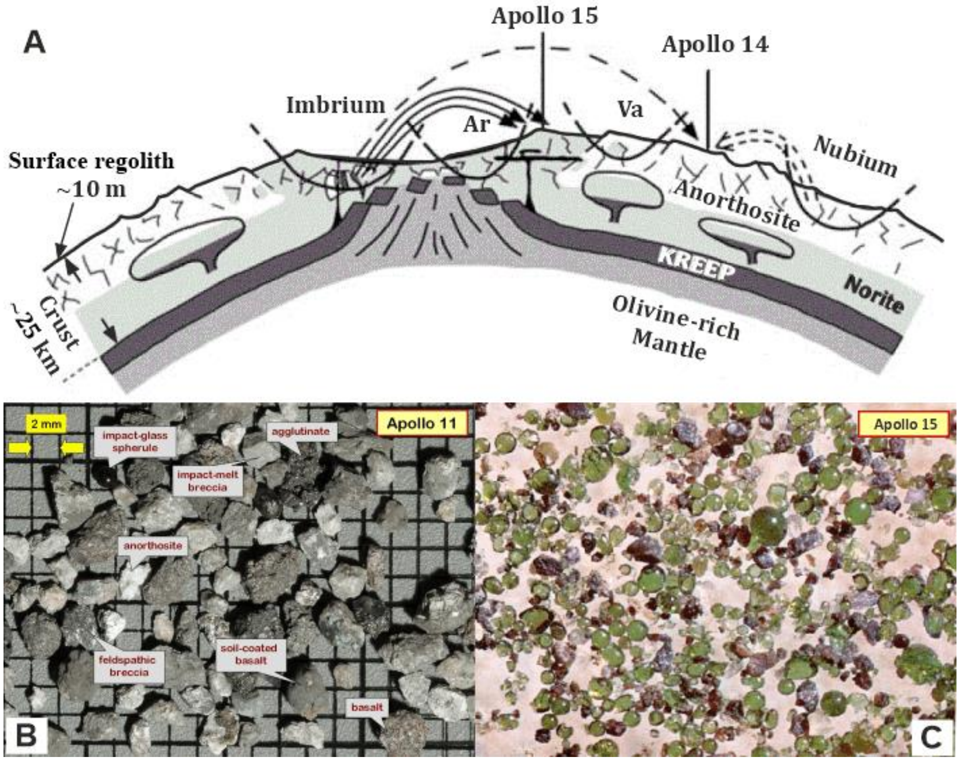

Figure 1. A. Simplified cross section of lunar crust and upper mantle at ~3.8 Ga after formation of Imbrium impact basin. Ar – Archimedes basin, Va – Vaporum basin. Modified after Stöffler (1990). B. Lunar regolith fragments from the Apollo 11. C. Green glass beads from Apollo 15 (40-250 µm-size fraction) from Carusi et al. (1972).

3. Lunar record

Compared to terrestrial planets, the Moon has a globally continuous lithosphere ("one-plate" planet), which has not been subject to plate tectonic processes. In turn, the most important process shaping the lunar surface after planetesimal accretion was projectile influx or "heavy bombardment", which was also responsible for impact-driven mixing and burial of the crust (Marchi et al., 2014). The existing model of the impact cratering history of the Moon suggests a rapid decline with a smaller or more prominent peaks between 3.5 and 4.2 Ga ago (Figure 2; Zellner, 2017; Hartmann et al., 2007). The hypothesis of a "terminal lunar cataclysm" at ~3.9 Ga leading to the formation of the most of the impact craters and thus the majority of lunar breccias and the impact melts (Tera et al., 1974; Stöffler and Ryder, 2001) is now largely abandoned due to possible sampling bias from Apollo 14 and 15 and thus a predominance of the Imbrium ejecta ages (Figures 1A and 2; Baldwin, 2006; Michael et al., 2018).

A later increase in the impact flux has been recorded within Apollo and Chang'e-5 landing sites with age peaks at ~2800 Ma (Zellner, 2017) and at < 1000 Ma and particularly predominant peaks at ~800 Ma and ~500-400 Ma (Culler et al., 2000; Long et al., 2022; Nemchin et al., 2022).

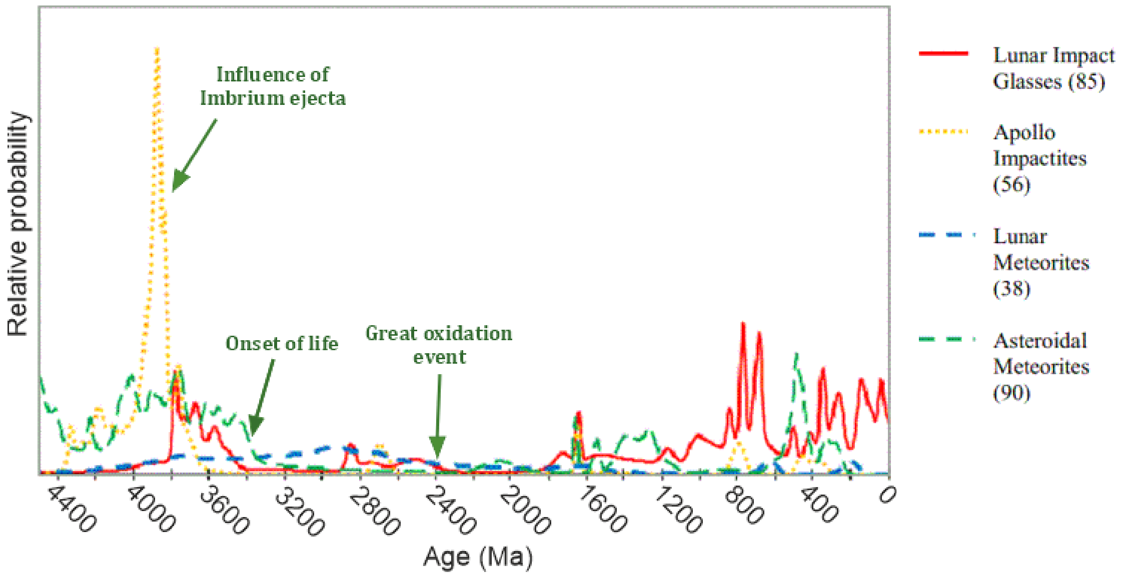

Figure 2. Relative probability of impact ages including important terrestrial biological events. Peak at ~3.9 Ga is probably due to influence of Imbrium ejecta. Modified after Zellner (2017).

4. Future work

In spite of more than fifty years of lunar exploration, the geochronological record of the early evolution of the Moon is still debated. Lunar chronology is dominated by ^{40}Ar/^{39}Ar ages, which often show around 300 m.y. younger ages compared to U-Th-Pb "chemical ages" (Zellner, 2019), this is not to mention the fact that the ^{40}Ar/^{39}Ar method is highly destructive. The purpose of the current project is to clarify the impact history of the Moon using *in situ* ion microprobe approach and providing absolute U/Pb ages of the impact and volcanic glass from the lunar regolith samples.

Furthermore, the project is aimed to study the Moon's interior through the volcanic eruptions (volcanic glass beads) and lunar crust through meteorite impacts (impact glass beads), which altogether will give a full image of the Moon's composition and processes involved into its formation.

Lack of plate tectonic recycling or exposure to any kind of weathering allowed lunar rocks to preserve a record of early (4.5-3.9 Ga) geological events and processes, for which we do not have evidence on the Earth. It is mostly agreed that the impact flux behaviour was the same throughout the inner Solar system, therefore clarifying the lunar record will not just define the early ages within the Moon, but also will shed the light on the impact regime under which life on the Earth became established and the rate at which volatiles and organic materials were delivered to the early Earth (Ryder, 2002; Zellner, 2017).

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