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Probing the volatile reservoirs in the Moon using lunar meteorites

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Abstract

1. North West Africa (NWA) 10989 is a lunar meteorite found in 2014. Petrology, bulk chemistry and mineralogy of NWA 10989 are consistent with it being an intermediate-iron meteorite, consisting of ~40% mafic nonmare material and 60% of very low Ti basalt material, with no obvious KREEP component. Analyses of chlorine and hydrogen isotopic composition and abundances of apatite grains support sampling of 2 distinct reservoirs, one being similar to those for known mare-basalts in Apollo collections, while the other could represent a yet unrecognized reservoir, which doesn't fit in existing H-Cl systematics of lunar samples. In situ Th-U-Pb dating reveals that phosphates represent two distinct ages with one ranging from 3.98 to 4.20 Ga, while the other are from 3.32 to 3.96 Ga, the latter being more similar to ages of basalts known from Apollo collections. This unique lunar breccia features mixing of material, which doesn't appear to have been recorded by Apollo samples. Consequently, we propose that NWA 10989 originated from a mare-highlands boundary, possibly on the lunar farside.

2. Introduction

The majority of lunar meteorites are thought to originate from different areas on the Moon to those which the Apollo and Luna missions visited, providing broader coverage across the Moon's surface of both the nearside and the farside. Therefore, lunar meteorites expand our knowledge of the surface composition of the Moon, and enhance our understanding of the bulk composition of the Moon and its evolution through history. Brecciated meteorites contain a variety of clast types and geochemical information providing a snapshot into the mixing processes which occur at a local scale, and the diversity of material which is present at a single location.

1.1 Lunar Meteorite NWA 10989

NWA 10989 is a lunar meteorite that was found near the Morocco/Algeria border in 2014. NWA 10989 is a single, roughly spherical stone with a diameter of ~2 cm and a mass of 14.41 g with a dark brown fusion crust. Based on an initial petrographic and geochemical investigation it was classified as an intermediate ('mingled') iron, lunar fragmental breccia. It is composed of mare- and highlands-derived materials in roughly equal proportions.

3. Methodology

This study presents a comprehensive mineralogical and geochemical data on mineral, lithic and impact melt clasts in this meteorite including its bulk-rock major- and trace-element composition, abundance and isotopic composition of chlorine and hydrogen and Pb-Pb dates in apatite. This new dataset is then utilized to perform comparisons with other lunar samples in order to gain insights into important lunar petrogenetic processes and evaluate potential source region(s) for NWA 10989.

4. Major Findings

There are several points to take into account for inferring the origin of NWA 10989 on the Moon:

1) NWA 10989 is an intermediate meteorite composed of materials from two distinct compositional sources – a magnesian highlands, not represented in Apollo or Luna collections, and a VLT-like basaltic material similar to Apollo 17 and Luna 24 mare basalts.

2) There is no lithological evidence for KREEP, despite the 'Apollo Model' mass balance suggesting up to 3 % KREEP, with 45 % mare material and 52 % feldspathic material. Indeed, all Apollo breccias consisting mainly of anorthosite and basalt also contain a little bit of KREEP, contrary to binary anorthosite-basaltic meteorites (i.e.YQEN group, MET 01210, Dhofar 1180 and NWA 3136). The 'Apollo model' does not distinguish between mare basalts and mafic lithologies which may occur within highlands rocks. As such, the incompatible elements may be supply by this mafic nonmare component, supported by the presence of ultramafic peridotite clasts; component which doesn't exist in the Apollo samples. Therefore, a significant proportion of the mafic material appears to be associated with felsdpathic material which is s. As a result, NWA 10989 derive from a region quite distant from the Procellarum KREEP rich Terrane.

3) δD and δ^{37}Cl analyses of NWA 10989 apatites show a strong resemblance with the KREEP rich breccia NW 4472. However, as just stated previously, NWA 10989 does not contain any significant KREEP-rich material. Combined analyses of δD-δ^{37}Cl with age dating of apatites highlight two groups of apatites: one group which sampled a typical mare basalt source (i.e. δD>400‰, δ^{37}Cl~15‰), while the other group sampled an unusual basaltic reservoir, with hydrogen isotopic composition as low δD as -433 ‰, similar to older Mg-suite rocks from Apollo collections but whose chlorine isotope signature is more akin to younger mare basalts. This evidence strongly argues for the presence of material in this breccia, which is either not yet identified in the Apollo collections or more likely represents an area of the Moon not sampled by the Apollo missions.

4) There is a variety of evidence suggesting that material from this rock did not come from the very surface layer of the moon, but slightly deeper in the crust. Indeed, the 1-2 µm thick exsolution lamellae in pyroxene, the presence of peridotite clasts that formed at high pressure-temperature, as well as the abundance of coarse-grained minerals, all suggesting a slow cooling regime. The various scenarios compatible with this slow-cooling could be a crustal intrusion, thick lava flow, hypabyssal setting or burial beneath a thick layer of hot ejecta from a basing scale crater like in a cryptomare region.

5) The effects of several impacts can be witnessed throughout this rock. The minerals and impact melt clasts show varying degrees of shock, with the maskelynitisation of certain plagioclase and shock crystallization textures in some other plagioclases. The range of impact melt clasts are likely to have formed closer to an impact crater than the reworked basalts, in order for higher temperatures and metamorphism to be reached.

6) As implied by its binary nature, NWA 10989 probably originated like other felsdpathic-mare intermediate-iron breccias from a region of the Moon where mare basalt has mixed with felsdpathic highland terrane. Mare-highland boundaries do exist on the lunar nearside, potentially close to the Luna 24 or Apollo 17 landing sites where VLT basalts have been found. However, some chemical features of NWA 10989 are incompatible with this possibility. First, the more mafic nature of the felsdpathic material in NWA 10989 compared to Apollo anorthositic highlands material argue for mafic nonmare component quite distinct from the FHT material sampled by Apollo missions. Secondly, the lack of KREEP component and high Ti mare material places this breccia far from the PKT, and again far from Apollo landing sites. As a result, the more probable source location for this breccia would be on a maria-highlands boundary on the farside.

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