CAN "GRANITE" CLAST FROM AN APOLLO 14 BRECCIA BE A FRAGMENT OF A TERRESTRIAL METEORITE?
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Introduction: Meyer and coauthors obtained U-Pb data for two zircon grains collected during the extraction of a felsic clast from lunar breccia sample 14321 and pointed out that these grains reside in the fragments that also contain grains of quartz and K-feldspar showing the same texture as that in the fused portions of the clast [1]. This led to the conclusion that two zircon grains originated from the partially melted "granite" clast described in section 14321,1027 by Warren and coauthors [2]. The clast has an estimated mass of 1.8 g and consists of 60% low-Ba alkali feldspar and 40% quartz with minor Fe-rich olivine and traces of ferrohedenbergite, ilmenite, and Fe-Ni-metal [2]. However, the clast is brecciated and also contains close to 30% of crystalline impact melt [2]. Unbrecciated areas are composed of quartz and alkali feldspar occurring as large (1.8 x 0.15 mm) inter-grown crystals [2]. Oxycalciobetafite is also found as intergrowths with some of the primary feldspar grains [3]. The crystalline impact melt consists of intergrowths of silica and feldspar less than a few micrometers in size with a significant proportion of pyroxene and small blebs of Fe-metal (Figure 1).

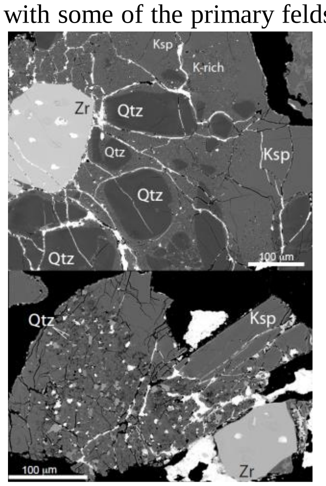

Figure 1: Fragments from saw cuts containing zircon grains, large K-feldspar and quartz crystals as well as quenched melt (K-rich matrix) with Fe-metal, pyroxene, K-feldspar and quartz.

Textural and chemical information available for this clast appears to be contradictory. Metallic Fe is indicative of low fO_2 conditions and is ubiquitous in lunar samples. Bulk clast concentrations of Zn, Ge, Ga, Au, Ba, Ta, and REE, a single pyroxene analysis indicating relatively low Mn/Fe [2], and the highly radiogenic Pb isotope compositions of K-feldspar analyzed in one of the thin sections [4] also support the lunar origin of the clast. However, the presence of oxycalciobetafite in the same felsite suggests this clast was formed under conditions that are not typically associated with the Moon [3]. It was found to contain significant amounts of Fe^{3+} and W^{6+}, interpreted as an indication of its formation under relatively oxidizing conditions [3]. Additionally, a more recent investigation of the sample indicated that the REE pattern of oxycalciobetafite shows a split to four consecutive curved segments that were referred to as tetrads and interpreted to reflect formation in the presence of water or F-rich fluid [5], which is also not fully consistent with a lunar environment that is considered to be relatively dry and reducing compared to terrestrial magmas.

These results in combination with the new trace elements data for zircon (REE and Ti) and quartz (Ti) from the "granite" clast, highlight controversy related to the interpretation of the origin of the clast.

Results: The REE analyses of two zircon grains in the thin section 14321,1613 show pronounced positive Ce/Ce* anomalies of 7.6 ± 2.3 and 17.5 ± 8.2 (2σ), (Figure 2A). Ti temperatures determined for two grains ranging from 763 ± 24 to 840 ± 28 ºC (2σ) are lowest ever recorded among nearly 100 analysed lunar zircon grains (Figure 2B). The Hf, U, and Th concentrations in these two grains, range between 1.29-1.85 wt%, 298-986 μg/g, and 153-542 μg/g, respectively, and are the highest of any analyzed lunar zircon reported so far. In contrast, the total REE content is among the lowest in the lunar zircon population (Figure 2A).

Titanium concentrations of 214 ± 5 μg/g were determined in quartz from the clast in thin sections 14321, 1047 and 1029. Combining this Ti in quartz estimates with values obtained for Ti concentrations in the zircon grains allows calculation of P as well as T of clast formation, assuming that both zircon and quartz crystallised from the same felsic melt. An average crystallization P of 7.4 ± 1.2 kbar (2σ) is determined from the obtained data, which on the Moon indicates a formation depth of 135 ± 22 km (2σ).

Discussion: "Granite" clast shows clear evidence of textural and chemical dichotomy. Assemblage consisting of quartz, K-feldspar, zircon and oxycalciobetafite appear to form as a result of magmatic crystallization, while presence of matrix in the samples indicates impact induced partial remelting of the clast. Additionally, the presence of Fe-metal and bulk concentrations of trace elements [2], in particular low concentrations of volatile metals in the clast, indicate an origin consistent with crystallization conditions typically ascribed to lunar melts. A lunar origin for the clast is further supported by the highly radiogenic Pb isotopic composition of K-feldspar [4]. However, the chemical characteristics shown by the zircon grains are more compatible with the crystallization of felsic melts on the Earth. Oxycalciobetafite appears to support the zircon data, indicating a relatively oxidized, low-T, incompatible element and possibly water or F- rich melt. Another profound contradiction is evident when comparing the impact modelling results made as a part of our investigation of "granite' clast, which limit the depth of excavation of the sample 14321 in the Imbrium ejecta to 30-70 km below the lunar surface, and P-T estimates obtained using Ti in quartz and zircon thermobarometry. The later suggests that formation depth of the felsite clast was 135 ± 22 km, significantly deeper than that indicated by the impact model.

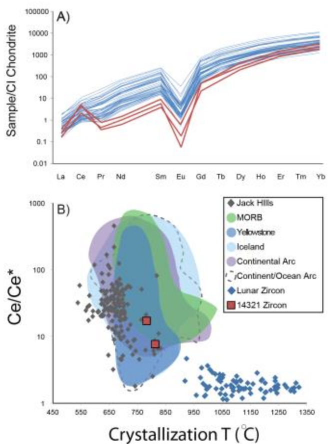

Figure 2: Trace elements in zircon from "granite" clast: A- REE (blue - zircon grains from [6 and 7]; red – zircon from saw cuts of the clast from breccia 14321); B- Ce/Ce* vs. crystallization *T* (lunar data from [6 and 7], terrestrial data from [8])

This dichotomy explicitly implies a multi-stage petrogenesis, where part of the mineral assemblage represents the primary magmatic characteristics of the rock while other was acquired during secondary modification. Zircon is highly stable with the ability to resist chemical, thermal, and mechanical modifications, hence the zircon is anticipated to best reflect primary magmatic conditions of the crystallizing felsic melt. Quartz is almost as chemically and mechanically resistant as zircon and could be expected to survive the changes that accompanied the secondary processes that have affected the rock. Texturally, these minerals appear to constitute the unbrecciated part of the clast, also supporting preservation of their primary characteristics. In contrast, the Fe-metal and pyroxene that has a lunar Mn/Fe ratio appear to be confined to the crystalline shock melt and likely formed by post-crystallization heating during incorporation of the felsite into the breccia. K-feldspar shows a highly radiogenic Pb isotope composition, which is likely to have been acquired as a secondary component resulting from relatively low-temperature diffusion of mobile, highly radiogenic Pb during the breccia formation.

Previous studies have proposed that the felsite clast in 14321 formed by extensive fractional crystallization, which concentrated highly charged cations in the residual liquid, also resulting in an increasingly oxidized melt, perhaps due to the presence of a fluid [3, 5]. While these conditions do not appear to be common on the Moon, the data obtained for the felsite clast suggest that they could have existed locally within the lunar crust, possibly resulting from slow cooling and fractionation of an initially basaltic melt within the lower crust or near the crust-mantle boundary. If that is the case, after crystallization at a depth of 30-70 km, the felsite was excavated during the Imbrium impact and the characteristics indicative of more reducing conditions were introduced to the clast during incorporation of the clast into the host breccia at ca. 3.9 Ga. The only observation that cannot be explained directly by lunar origin of the sample is Quartz/Zircon Ti-based pressure estimate for the felsite formation that places it at 135 ± 22 km. This depth estimate is difficult to accept from the perspective of both crystallisation of the felsite, as it places it significantly below mantle-crust boundary where felsite likely cannot crystalize, and the predicted depth of excavation even when large, basin forming impacts are considered. An alternative interpretation that can reconcile all observations including the high P of crystallization, is a terrestrial origin for the felsite clast. On Earth, the depth corresponding to 7.4 ± 1.2 kbar is 20 ± 3 km and places the sample comfortably within the middle crust where it could have formed under oxidizing, low-T, fluid rich conditions common for terrestrial magmas. In this scenario, zircon, oxycalciobetafite and quartz would have preserved the record of primary crystallization. The subsequent history of the felsite would include excavation by a large impact from the depth of 20 ± 3 km and its delivery to the Moon as a terrestrial meteorite. This would have been followed by its incorporation into Imbrium impact ejecta and ultimately the 14321 breccia, which would have also introduced all of the secondary 'lunar' features.

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