INTRUSIVE AND EXTRUSIVE LUNAR FELSITES.

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Introduction: Felsites are highly evolved lunar rocks, typically containing ~70 wt% SiO_2. Most have igneous textures that feature graphic intergrowths of K-feldspar and a silica polymorph. Sampled felsites occur as clasts in breccias, sometimes coexisting with Fe-rich, low-Si clasts (e.g., 77538, [1]). The pairing of high-Fe with high-Si compositions is strikingly like immiscible melt pairs observed experimentally [2,3], in the mesostasis of mare basalts [4,5], and in a quartz monzodiorite [6,7]. This has led many investigators to propose that felsites formed by silicate liquid immiscibility[3,8,9].

Silicic rocks also occur as volcanic constructs [10-15]. It is not clear that liquid immiscibility can produce the large volumes of silicic lava required to make features such as Hansteen Alpha or the Gruithuisen Domes, leading Hagerty et al. [14] to propose that these rhyolitic magmas formed when mare basaltic magmas intruded the crust, causing partial melting and production of large volumes of magma in a process analogous to basalt underplating on Earth (e.g., [16]). To elucidate the petrogenesis of felsite samples and silicic volcanic features, we have evaluated the bulk compositions of felsites and related lithologies, determined the silica polymorph present, and used Clementine data to evaluate the compositions of silicic features on the Moon.

Methods: Felsite samples on 20 thin sections were examined in a petrographic microscope. Silica polymorphs were identified by micro-Raman using a Wi-Tec confocal Raman microscope with 532 nm (green) laser. Silicic features on the Moon were selected based on Glotch et al.[15]. FeO concentrations were obtained from Clementine data [17].

Felsite Suite Compositions: Concentrations of K_2O and FeO (Fig. 1) in bulk felsites are particularly useful for identifying the roles of both silicate liquid immiscibility in fractionating magmas and partial melting of crustal rocks. End-member felsites have low FeO and high K_2O concentrations. Opposite to this are high-FeO, low-K_2O samples, a prominent example of which are clasts in rake sample 77538 [1]. Most published analyses fall into these two categories, but a significant number fall between with FeO between about 5 and 12 wt%. Some of these are breccias (e.g., [18]), and thus could be mixtures of two immiscible end members. Others may be unbrecciated and could represent samples of partial melts of crustal rocks. Compositions of partial melts (determined from MELTS) of KREEP basalt and the more evolved quartz monzodiorites (QMD) trend from those compositions towards higher K_2O (and higher SiO_2, not shown) and lower FeO. Partial melting of KREEP basalt or their derivatives could therefore produce silicic rocks with intermediate FeO concentrations.

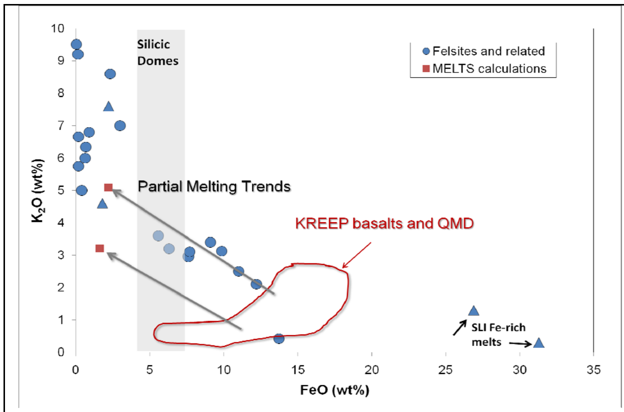

Figure 1. Compositions of felsites and associated high-Fe (low Si) melts formed by silicate liquid immiscibility (SLI). Low FeO felsites are composed mostly of intergrown quartz and K-feldspar. Points with intermediate FeO concentrations could be mixtures of high-Fe and high-Si melts, or partial melting products of KREEP basalts or their differentiates. Two examples of 20% partial melting products (calculated using MELTS) are shown; the lower-K sample uses KREEP basalt 15386 as starting composition and the higher one uses QMD 15405,152. Gray field indicates FeO in silicic domes [14,15].

Silica Polymorph: To first order, magmatic fractionation leading to silicate liquid immiscibility would take place in an intrusive environment, favoring formation of quartz. Extrusive rocks, such as rhyolite flows, are more likely to contain cristobalite or tridymite. To assess these possibilities we determined the silica phase present in 19 felsite clasts (Fig. 2). Quartz was the only silica phase present in the felsites studied. In the ferrobasalt paired with felsite in 77538, the silica phase appears to be glass. However, in the two clasts where the Si-rich portion has not completely separated from the Fe-rich portion, quartz is present in the Si-rich portion and silica is either amorphous or glassy in the Fe-rich portion. Felsite 12033,507 [20] is the only sample with intermediate FeO (7.6wt%) we have studied so far. It is a rapidly crystallized shock melt, but contains regions of apparently unmelted residues, which are graphic intergrowths of quartz and K-feldspar. The clast also contains fayalitic olivine and Fe-rich glass, suggesting that it could be a mixture of high-Si and high-Fe immiscible melts.

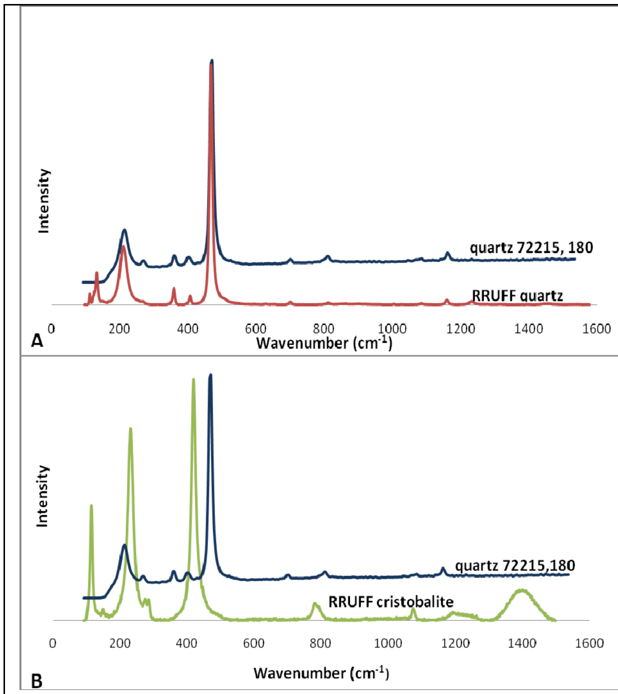

Figure 2. Raman spectra for quartz found in felsite 1 in 72215,180. Intensities have been normalized for clarity. A) Comparison of quartz found in 72215,180 with quartz from the RRUFF database. B) Comparison of quartz found in 72215,180 with cristobalite from the RRUFF database[19].

Remote Sensing: Lunar red spots (spectrally anomalous areas with strong adsorption in the ultraviolet) have been interpreted on the basis of morphology and chemistry to be silicic volcanic features [10-15]. Recent evaluations of Th concentrations [14] and interpretation of Diviner thermal infrared data [15] have strengthened the case that at least three of these features (the Gruithuisen domes, Hansteen Alpha, and the Lassell massif) are silicic. We assessed FeO concentrations of these three areas obtained from Clementine spectral data [17,21]. We selected the lowest FeO value in each area. Assuming some material in the silicic areas has been admixed from surrounding mare basalts, the areas with the lowest FeO concentrations are more likely to reflect the compositions of erupted lavas. These values fall narrowly in the range 5-6 wt% FeO. Using an uncertainty in the FeO determination of 1 wt% [21], a reasonable range for these silicic features is 4-7 wt% FeO. The compositions fall near the group of intermediate felsic compositions in Fig. 2.

Discussion: The presence of only quartz in felsite samples suggests that they are intrusive, formed by fractionation of a KREEP basalt magma via SLI. Kinetic data are lacking for quantifying cooling conditions for formation of quartz rather than higher temperature polymorphs, but we can make broad estimates. We have found using Raman spectroscopy that the silica phase in KREEP basalts is cristobalite. In contrast, quartz monzodiorite 14161,7373 contains quartz and relict cristobalite [7]. Our Raman data for KREEP and 14161,7373 also suggest a mixture of partly transformed quartz. This rock also contains inverted pigeonite from which Jolliff et al.[7] calculated an igneous cooling rate of 0.008ºC/y. The felsites in which the silica polymorph is entirely quartz may have cooled slower than this rate, indicating origin froma shallow intrusion or small magma body. This suggests that the clasts we studied are not samples of silicic domes, which ought to contain significant cristobalite or tridymite (e.g., [22]).

The felsites with intermediate FeO are intriguing. They could be mixtures of high-Si and high-Fe immiscible melts or they might be partial melts of crustal rocks. The only felsitic sample with intermediate FeO that we have studied, 12033,507, has an ambiguous petrologic history, though its overall texture suggests it has been modified by impact. The presence of Fe-rich glass suggests it is likely a mixture of two melts. However, the compositions of the silicic domes are also consistent with formation as rhyolitic lavas formed by partial melting of KREEP basalts and related rocks, as proposed by Hagerty et al. [14]. Continued search of lunar samples may lead to identification of volcanic, rather than intrusive, felsites.

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