THE PHYSICAL SETTING FOR FELSITE FORMATION. K. L. Robinson[1], E. Hellebrand[2], G. J. Taylor[1], [1]Hawaii Institute of Geophysics and Planetology, [2] Dept. of Geology and Geophysics, The University of Hawaii at Manoa, 1680 East-West Rd. POST 602, Honolulu, HI 96822. krobinson@higp.hawaii.edu

Introduction: The felsites are highly evolved lunar rocks, usually containing ~70 wt.% SiO_2. They are sometimes referred to in the literature as granites because of their high SiO_2 content [1]. They display igneous textures with distinctive graphic intergrowths of quartz and K-feldspar [2,3], and were likely formed through extreme differentiation of a KREEP basaltic magma [1,4,5]. Felsites returned by the Apollo missions occur exclusively as clasts in breccias, sometimes coexisting with Fe-rich, low-Si clasts (e.g., 77538, [4]). This corresponding ferrobasalt phase provides an important clue into felsite petrogenesis via silicate liquid immiscibility (SLI), which occurs when the final fraction of a crystalizing melt spontaneously separates into Si-rich and Fe-rich endmembers [4,5]. The felsites themselves are low in Fe, but have a high Fe/Mg ratio that is indicative of evolved rocks [5].

We previously evaluated the silica polymorph in the felsites [3] in an effort to determine if they are related to silicic domes observed from lunar orbit [e.g. 6-8]. Quartz was the only silica phase present in the felsites [3], leading us to conclude that the felsites likely formed in shallow intrusions rather than volcanic domes, which would be more likely to contain high T silica polymorphs such as tridymite or cristobalite. Based upon the presence of quartz, we can now expand upon that work more quantitatively by estimating the depth of the felsite parent intrusions, their cooling rates using Ti in quartz thermometry [9], and their sizes.

Depth of Formation: The pressure, and therefore depth, of formation of the felsites can be estimated by using the stability field of quartz on the silica phase diagram. The silicate liquid immiscibility temperature for KREEP basalts (14310, 15382, 15386) has been experimentally determined to be 1014-1050 ºC [10-12]. According to the silica phase diagram (Fig. 1, [13]), this temperature range is too high to crystallize quartz at low pressure. However, quartz becomes stable at higher pressure, between 0.85 and 1.05 kbar (Fig. 1). In order to crystallize quartz directly, the felsites' parental intrusions would have been at depths of 20-25 km (assuming a crustal density of 2550 kg/m^3) [14].

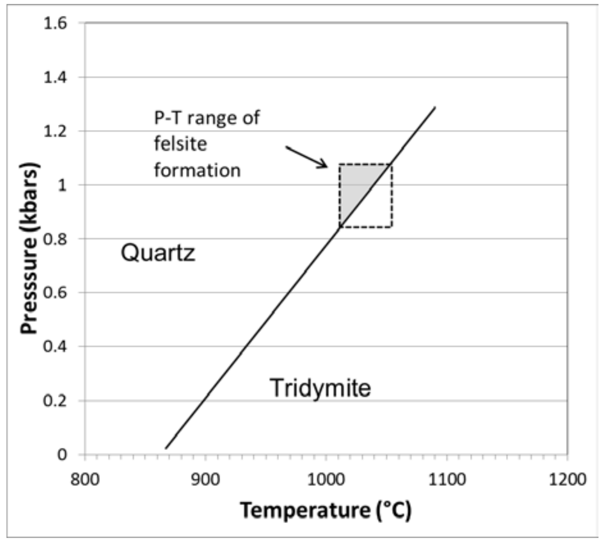

Fig. 1. The silica phase diagram [13], showing the P range of felsite formation based on SLI temperatures for KREEP basalts [10-12]

Cooling Rate: As shown by the presence of quartz, exsolved pyroxenes, and the depth of formation above, the felsites formed intrusively and therefore likely cooled slowly. We can estimate the cooling rates for the felsites from grain sizes in sampled felsite clasts and the closure temperature of those quartz grains, which is the temperature at which the crystal is closed to diffusion. To obtain the closure temperatures, we used the TitaniQ geothermometer [9], which requires the presence of quartz and any Ti-bearing phase (in this case, ilmenite). We measured Ti in quartz in representative felsite clasts on the University of Hawaii electron microprobe, using the same conditions as [9] (Table 1).

sample	average ppm Ti	2σ (ppm)	Temp (C)*
14321, 1047	213	7	930
73215, 43	264	7	960
14321, 1029	215	7	930
72215, 180	291	8	980
72215, 178	219	6	930

Table 1. Average Ti concentration in quartz for a representative group of felsites. The Ti detection limit was 14 ppm. *Equilibrium temperature calculated using TitaniQ [9].

Measured felsites have average Ti content < 300 ppm, which corresponds to closure temperatures of 930-980 C. This is below the SLI temperature (and thus quartz formation temperature) of the felsites, indicating that some sub-solidus equilibration of Ti took place. The closure temperature is related to the cooling rate of the magmatic body by Dodson's equation [15]. Figure 2 shows curves calculated using this equation that show quartz closure temperatures for a range of cooling rates and grain sizes. The felsite cooling rate can then be estimated for a specific grain size. The parent intrusions for felsites in 72215, 14321, and 73215 would have crystallized between 0.2-100 K/yr.

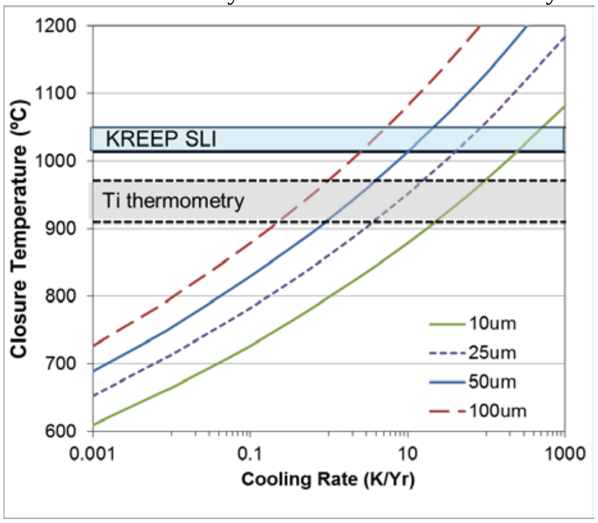

Fig. 2. Cooling rates based on quartz closure temperatures and grain sizes in 14321, 72215, and 73215 felsites. The cooling rate for a felsite with a given grain size will fall along the curve in the gray box.

Intrusion Size: Knowing the cooling rates allows us to estimate the size of the felsites' parental intrusion. The exact geometry of the intrusions are unknown, so we assume that they are approximated by a dike or sill shape. A magmatic dike cools from the outside to the center, and this solidification time is dependent on the width of the intrusion, the initial temperature of the intruding melt and the country rock, among other thermal parameters described by Turcotte and Schubert [16]. We can calculate the average cooling rate for the center of an intrusion by dividing the crystallization interval by the solidification time [16]. Taking a KREEP basalt liquidus temperature of 1175 ºC [11] and a crystallization interval of 150 ºC, we calculated cooling rates for a range of intrusion widths. By plotting the felsite cooling rates determined by Ti thermometry against the intrusion widths, we can estimate the size of the felsites' parental bodies (Fig. 3). Based on their cooling rates, the finer grained felsites in 72215, 73215, and 77538 likely formed in magmatic bodies between 15-150 m wide (Fig. 3). Coarser-grained felsite 14321 formed in a larger intrusion about 300 m wide.

Implications for Volatile Retention: The felsites studied here formed in relatively small intrusions ranging from 15-300 m wide, though it is possible that other felsites could have originated in larger or smaller intrusions. However, the felsites' formation at depth and therefore pressure, about ~1 kbar, has important implications for the retention of volatiles in the magma. Over 3 wt. % H_2O is soluble in a basaltic magma at 1 kbar pressure [17], which means that even these relatively small intrusive lithologies on the Moon were likely able to preserve a record of lunar interior volatiles and H isotopic composition.

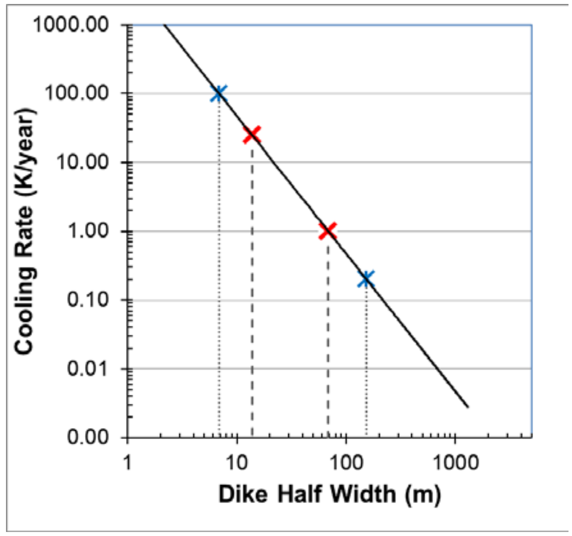

Fig. 3. Calculation of felsite magmatic body size by calculated cooling rates. The crosses represent cooling rates based on variable widths of felsite quartz, including granophyric 14321 and fine-grained felsites from 73215, 77538, and 72215. The dashed lines then indicate the half-width of the dike.

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