KREEP BASALT PETROGENESES.
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Introduction: KREEP basalts have an evolved trace element composition (i.e., possessing elevated concentrations of K, REE, and P, plus other incompatible trace elements - ITEs) [1]. However, paradoxically these same basalts have relatively primitive major element chemistry [1]. This paradox led to the development of two hypotheses for their formation, 1) KREEP basalts are endogenous melts of the lunar interior, and 2) they are the result of 2 or more lithologies mixing together via impact melting [2-3].

Different methods have been used to distinguish between the two hypotheses. Textural [2] and highly siderophile element (HSE) analysis [4]. The latter has typically been used in the past with varying degrees of success [5]. It has long been thought that the Apollo 14 KREEP basalts are impact derived, while those of Apollo 15 and 17 are considered endogenous melts of the lunar interior [2-3]. However, more recently the quantitative petrographic method of crystal size distributions (CSDs) has been used to distinguish between the two possible origins on samples that are too small for HSE analysis [e.g., 5] and has identified an endogenous Apollo 14 KREEP basalt and an inconsistent oddity, 15382, that has a texture suggesting an impact origin and HSE abundances that suggest this sample is pristine [6].

Continuing the work of [7] by utilizing in situ major and trace element analyses, qualitative and quantitative petrographic methods, element mapping, and the calculation of equilibrium liquids for plagioclase and pyroxene, we evaluate the petrogeneses of the endogenous and impact-derived KREEP basalts using samples 14073,16; 14155,11; 14160,214; 14310,25; 14431,2; 15205,110; 15243,6,.43,.60; 15382,6; 15386,3; 15434,181; and 72275,136

Methods: Electron Probe Micro Analysis (EPMA) on the samples were conducted using a JEOL JXA-8200 at Washington University St. Louis, a Cameca SX-50 Microprobe at Notre Dame’s Materials Characterization Facility. In total 836 pyroxene, and 390 plagioclase analyses were conducted.

Trace elements were analyzed using a Thermo Scientific Element 2 and a Nu Instruments Atom ICP-MS with a New Wave UP213 laser system at Notre Dame’s Midwest Isotope and Trace Element Research Analytical Facility (MITERAC). The internal standard was the NIST 612 glass [8] and Calcium (determined by EPMA) was used as the internal standards Background, Sample and washout times were all 60 seconds. Sixty-eight pyroxenes, and forty-four plagioclase analyses were carried out by LA-ICP-MS.

Equilibrium liquid compositions were calculated using the trace element data for pyroxene and plagioclase. Using the models of [9,10] for pyroxene, and those of [11,12] for plagioclase. Temperature information is necessary for these models to work, following previous work [13] we calculated pyroxene crystallization temperatures using the methods of [14].

Results: Pyroxene compositions within the KREEP basalts range are dominated by low-Ca compositions with augite and Fe-Pigeonite forming during the latter stages of crystallization. The Apollo 14 and 15 KREEP basalts have a higher starting Mg# (85 and 87, respectively) than that of Apollo 17 (74).

Figure 1: [Ce/Sm]N vs [Ce/Dy]N of pyroxenes and plagioclase.

As for plagioclase, Apollo 14 KREEP basalts range from An92,63, average around An92 with plagioclase in Apollo 15 KREEP basalts have a range An72,98 with an average of An73. The sample from Apollo 17 KREEP basalt 72275,136, contains a narrower range An94,88, with an average of An93.

Equilibrium liquids derived for plagioclase and pyroxene can be found in Fig. 1. There are three groups of equilibrium liquids 1) a LREE >> HREE liquid (greater than high-K KREEP [16]), which we call "über-KREEP"; 2) High-K KREEP-like liquid; 3) LREE-depleted liquid.

Discussion: The über-KREEPy liquid and LREE-depleted liquids are only found in pyroxene equilibrium liquids, whereas those of the high-K KREEP-like group are found in pyroxene and plagioclase. Importantly über-KREEPy equilibrium liquids are, with the exception of 15382 (see [6]) are found within the cores of low-Ca pyroxene crystals, implying that these liquids were present at the initial crystallization of these basalts. The LREE-depleted equilibrium liquids are only derived from rim/ground-mass analyses, suggesting these liquids were present during the latter stages of crystallization.

The slope of pyroxene equilibrium liquids REE content versus Wo% composition shows that endogenous melts tend to have low-Ca pyroxenes that formed from high-K KREEP-like liquids (Fig. 2). The pyroxene equilibrium liquids from the impact melts are more dispersed. Again, all of the über-KREEPy pyroxene equilibrium liquids are derived from low-Ca pyroxene (with the exception of one Pyx in 14160,214) reinforcing the idea that über-
KREEP compositions were the initial liquids at the beginning of KREEP basalt crystallization. The liquids appear to have then evolved from highly LREE enriched to LREE depleted at the conclusion of crystallization. The odd Pyx in 14160 may have inherited the über-KREEPy signature as an overgrowth [15].

Only two samples contain pyroxenes with LREE-depleted equilibrium liquids: endogenous melt 15386 and impact melt 14160,214. These samples also contain the über-KREEPy and high-K KREEP-like liquids. Both 15386 and 14160, were formed as a result of mixing of LREE-depleted and über-KREEPy materials. 14160,214 [15] was formed by an impact that mixed these two materials, whereas 15386 formed due to magma mixing [7].

![Figure 2: Wo% vs [Ce/Yb]N of pyroxenes and their corresponding equilibrium liquids. Vertical dashed line Wo=10% the cut off for low-Ca pyroxene. Horizontal dotted line über-KREEPy - High-K KREEPy boundary. Horizontal dashed line: High-K KREEPy - LREE-depleted boundary.](image)

Figure 3 plots the average residence time, as determined by plagioclase CSD (from [5]; using a growth rate of 1.304x10⁸ cm/y from [17]) vs. the [Ce/Yb]N ratio of each pyroxene analysis from. Three observations can be made: 1. the shortest plagioclase residence time (>0.45 years) belongs to a group of endogenous KREEP basalts that only possess high-K KREEP-like equilibrium liquids; 2. Endogenous KREEP basalt 15386,3 with über-KREEPy, high-K KREEPy and LREE-depleted equilibrium liquids possesses the highest average residence time (2.9 years); 3. all impact melts (14155,11 14160,214 and 14310,25) and endogenous KREEP basalt 15382,6 [6] have residence times between 0.6 and 1.0 years. The endogenous KREEP-basalts with only high-K KREEP-like equilibrium liquids may have lost their über-KREEPy and LREE-depleted signatures because they may be xenocrysts or antecrysts in other samples that are absent here.

![Figure 3: Pyx equilibrium liquid [Ce/Yb]N vs plagioclase residence time as calculated by CSD data form [5]](image)

Conclusions: Within KREEP basalts, both impact and endogenous, three equilibrium liquids are recorded, über-KREEP, High-K KREEP-like and LREE-depleted. Of the three, High-K KREEP is found in plagioclase and pyroxene, whereas the other two are only found within pyroxene. By mixing the über-KREEP and LREE-depleted compositions the third, a high-K KREEP-like liquid, is formed.

However, the method by which the impact and endogenous KREEP basalt samples formed are different, even though they require the same materials. For the endogenous KREEP basalts (e.g., 15386), über-KREEP, and the LREE-depleted liquid are the result of partial melting that then combine via magma mixing to produce high-K KREEP-like liquids. Whereas impact melts (e.g., 14160,214) are the result of mixing of two lithologies on the surface one bearing a über-KREEP signature and the other with a LREE-depleted signature, they are then mixed by impact.