

HOW DO KREEP BASALTS FORM? EVIDENCE FROM 14160,214. K Cronberger¹ and C. R. Neal¹, ¹Dept. Civil & Env. Eng. & Earth Sci., University of Notre Dame, Notre Dame, IN 46556, USA [kcronber@nd.edu; neal.1@nd.edu].

Introduction: KREEP basalts [1] are distinguished from the more common mare basalts by possessing higher incompatible trace element (ITE) concentrations and a higher Ca/Al ratio. The KREEP chemical signature has been detected at each sample return site on the Moon thus far, but it is never been found in its pure form urKREEP or “primordial KREEP”. UrKREEP is the last liquid fraction of the lunar magma ocean (LMO) [2-4]. KREEP basalts are the most ‘pure’ form of KREEP in the lunar sample collection, but how they formed is still not clear.

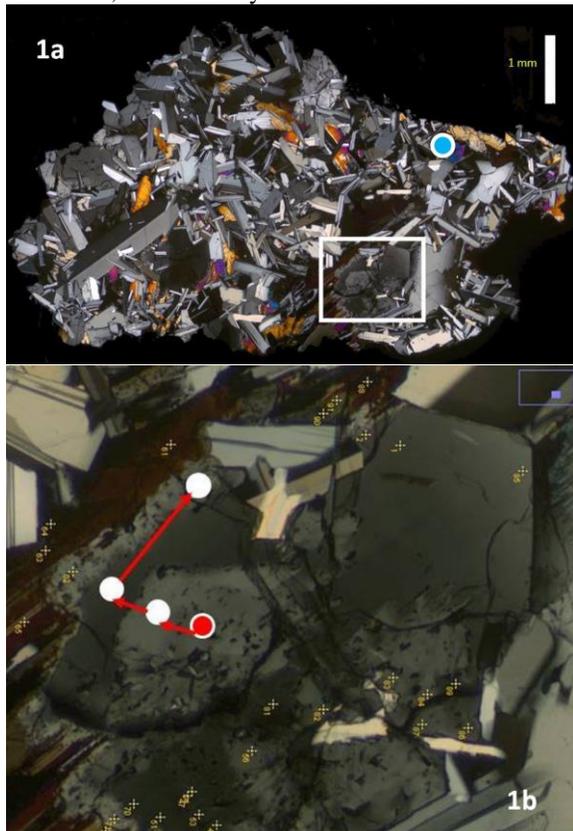


Fig. 1: a. XPL image of 14160,214. Scale bar = 1mm. White box = Fig. 1b location. b. Photomicro-graph showing growth-resorption of Opx and final overgrowth of pigeonite. White/red dots = EPMA locations, red arrows correspond to Figs. 3 & 4.

The majority of Apollo 14 KREEP basalts formed as impact melts [5,6] unlike the Apollo 15 KREEP basalts, which are products of volcanism [7,8]. New quantitative petrographic methods [9] have found that at least one Apollo 14 KREEP basalt, 14160,214, is an endogenous melt of the lunar interior [10].

Sample 14160 is comprised of 4 to 10 mm rocklets collected as a bulk soil sample from a small crater near the Apollo 14 lunar module. 14160,214 is

a 7 x 4 mm thin section; Opx, pigeonite (0.5-2.5 mm) and plagioclase (0.5-3.0 mm) are set in a groundmass of smaller plagioclase, K-feldspar, glass, augite, and pigeonite (Fig. 1a). Several larger pyroxenes show repeated growth and resorption. One such example exhibits at least 4 stages of growth and resorption (Fig. 1b). This repetition indicates cyclical changes in magma conditions.

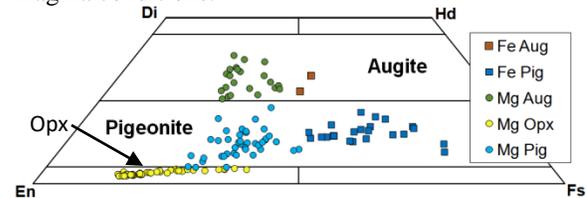


Fig. 2: 14160,214 Pyroxene quadrilateral

Hypothesis: KREEP basalts have relatively primitive major element chemistries and evolved (enriched) trace element contents (e.g., [11]). For impact-generated KREEP basalts this mixing would occur on the surface with the combination of basalt and KREEP components. For endogenous melts, was the KREEP signature inherited from the source or was it incorporated later? By utilizing in situ major and trace element mineral data the origin of the KREEP signature in this sample can be investigated.

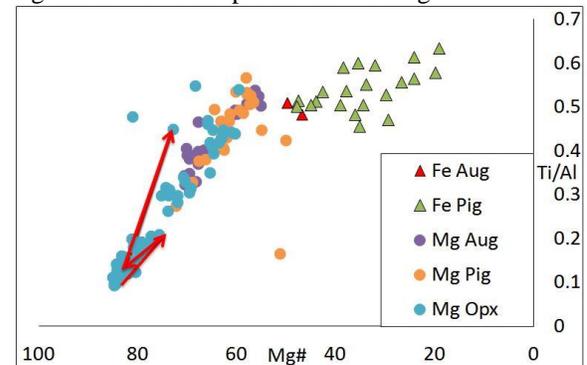


Fig. 3: Mg# vs Ti/Al (atomic abundance) of pyroxenes. Red arrows/lines are a core to rim transect of an Mg-rich Opx.

Methods: Previous Electron Probe Micro Analysis (EPMA) was carried out at Washington University in St. Louis (details in [10]). New EPMA data were collected at the University of Notre Dame's using a CAMECA SX-50 (settings: 15 kV at 25 nA; beam size = 1 μ m). LA-ICP-MS was conducted at the University of Notre Dame [10]. Partition coefficients for pyroxene were calculated using major element data [12,13] at 1200°C (temperature chosen to be consistent with 15386 [14]).

Results: Pyroxene major element compositions range from Opx through Mg-rich pigeonite to augite

and Fe-rich pigeonite (Fig. 2). The larger pyroxenes have Opx cores with increasing Fe and Ca towards the rim, becoming pigeonitic and occasionally augitic at the rim.

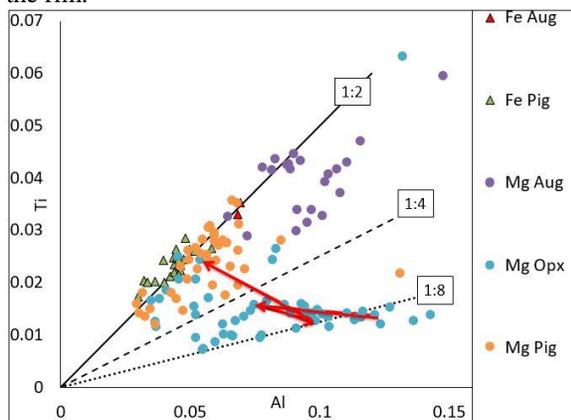


Fig. 4: Ti versus Al (atomic abundance) of pyroxene. Red arrows/lines are a core-rim transect of a pyroxene phenocryst. Lines = various Ti:Al ratios.

Variations of the minor components in pyroxene are shown in Figs. 3 & 4. As the Mg# decreases the Ti/Al ratio increases until approximately Mg# 50 where it remains constant. Analyzed Opx cores possess a Ti/Al ratio of 1:4 or less, while the rimward/small Opx analyses can be higher (up to ~1:2, Figs. 3 & 4). Mg-rich pigeonite and augite generally possess Ti/Al ratios of between 1:4 and 1:2 and a wide range of Ti and Al concentrations (Figs. 3 & 4). The Fe-rich pigeonite and augite possess Ti/Al ratios of ~1:2 and a slightly smaller range of Ti and Al concentrations (Figs. 3 & 4).

Calculated Opx equilibrium liquids (at 1200°C; Fig. 5) range from LREE depleted to LREE enriched. These equilibrium liquids are from the earliest forming Opx crystals and show a range above and below that of high-K KREEP [15] and the whole-rock composition of 14160,103 [16].

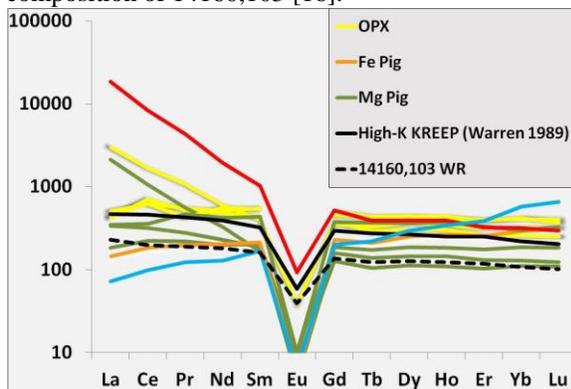


Fig. 5: Equilibrium liquids for Opx derived using calculated partition coefficients [12,13]. Red line: example Opx LREE enriched core composition (red dot Fig. 1b), blue line: example pigeonite HREE

depleted composition (blue dot Fig 1a). High-K KREEP [15] and 14160,103 [16] shown for comparison.

Discussion: The Opx core-to-rim transect (red arrows: Fig. 1, 3 and 4) shows variation in its Mg# and its Ti/Al (atomic) ratio. Mg# varies from 84 to 73 in an up down up fashion (84 – 76 – 82 – 73). The Ti/Al ratio varies from 0.11 to 0.45, following a similar pattern (approximately 0.11 – 0.20 – 0.13 – 0.45). This cycle of decreasing and increasing Mg# and Ti/Al ratio gives further evidence that this crystal formed within a magma chamber that was zoned and/or periodically recharged. It is possible that plagioclase coming on the liquidus is recorded by the ratio of Ti:Al changing from 0.125 to 0.5 (reflecting the diminishing availability of Al).

Pyroxene equilibrium liquids show that the cores of some Opx and pigeonite (Opx example: red dot Fig. 1b, red line Fig. 5) are enriched relative to high-K KREEP, while some of the smaller pyroxenes are LREE-depleted/HREE-enriched (e.g., Fe-pigeonite: blue dot Fig. 1a, blue line, Fig. 5) [10]. Our working hypothesis is that a superheated magma (REE profile similar to blue line, Fig. 5) assimilates a LREE enriched KREEPy material, either at the base of the lunar crust or within the lower crust, and slowly begins to crystallize. This “über-KREEPy” material (see the red line in Fig. 5) surrounding the magma chamber is slowly walled off via a chilled margin, while additional magma from the lunar mantle occasionally recharges the magma chamber.

It is evident that the recharge events that affected this sample introduced magma that did not have a KREEP signature. If the KREEP signature was in the source region, the subsequent recharge events would need to have been from a different source region to that of the parent. We plan to explore these possibilities in more detail at LPS 48.

References: [1] Meyer C. et al. (1971) *PLSC* 2, 393-411. [2] Warren P.H. & Wasson J.T. (1977) *PLSC* 8, 2215-2235. [3] Warren P.H. & Wasson J.T. (1979) *Rev Geophys* 17, 73-88. [4] Warren P.H. (1985) *AREPS* 13, 201-240. [5] McKay G. et al. (1978) *PLPSC* 9, 661-687. [6] McKay G. et al. (1979) *PLPSC* 10, 181-205. [7] Dowty E. et al. (1976) *PLSC* 7, 1833-1844. [8] Irving A.J. (1977) *PLSC* 8, 2433-2448. [9] Neal C.R. et al. (2015) *GCA* 148, 62-80. [10] Cronberger K. & Neal C.R. (2015) *LPSC* 46, #1295 [11] Taylor G. et al., (2012) *MaPS* 47, 861-879. [12] Yao L. et al., (2011) *CMP* 146, 261-280. [13] Sun C. & Liang Y. (2013) *GCA* 119, 340-358. [14] Rutherford M. J., Tonks B., and Holmberg B. (1996) *LPSC* 27, #1113 [15] Warren P.H. (1989) *LPI Tech Rpt.* 89-03, 149-153. [16] Ma M.S. et al. (1980) *LPSC* 11, 652-654.