CONTROLS AND CONSTRAINTS ON THOLEIITE-LIKE AND CALC-ALKALINE-LIKE IGNEOUS TRENDS ON THE MOON FROM NORTHWEST AFRICA 773 AND APOLLO 15405

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Introduction: Silica-rich rocks have been identified by remote sensing of the lunar surface and petrologic studies of lunar samples [1-3]. Many silica-rich rocks on Earth form by magmatic differentiation along the calc-alkaline trend, which leads to alkali-silica-rich compositions with moderate FeO-enrichment [4,5] (Fig. 1). In contrast, tholeiitic suites show FeO-enrichment with little increase in alkalis or silica. The tholeiitic trend is attributed to relatively low f(O_2), which results in high FeO/Fe_2O_3 and wide ranges of Fe-Mg solid solution in mafic silicates; higher f(O_2) can stabilize oxides or low-SiO_2 amphibole, driving residual liquids to higher silica contents with fractional crystallization [5-7].

We argue that clasts in the lunar breccia Northwest Africa 773 (NWA 773; Fig. 2A,B) comprise a suite comparable to the terrestrial tholeiitic trend. Quartz monzodiorite (QMD) clasts from Apollo sample 15405 are more akin to calc-alkaline rocks (Fig. 2C,D). Although these rocks show analogies to terrestrial igneous trends, the physico-chemical controls and magmatic processes are distinct from terrestrial cases.

Methods: Mineral textures and compositions were determined from one polished thin section (PTS) of NWA 773 (on loan from M. Killgore, Univ. Arizona) and three PTS of Apollo 15405 QMD (subsamples 56, 57 and 145; on loan from NASA/JSC). Back-scattered electron (BSE) images, X-ray elemental maps, and quantitative analyses were collected using a JEOL JXA-8900 electron microprobe at Waseda University. Wavelength dispersive analyses were collected using silicate and oxide standards at 15 kV, 20 nA and beam rastered at 100,000X (spot size ~ 1 µm).

Fractionation trends were modeled using MELTS [8,9]. Models were run at 1 bar pressure, f(O_2) buffered by Fe-FeO, fractionating solids at 5° intervals. Starting compositions included high Ti (70251 [10]; 10024 [11]), low Ti (NWA 032 [12]); very low Ti (NWA 773 olivine cumulate "parent" [13]) mare basalts, and KREEP basalt 15402,12 [2].

Results: Diverse clasts in the NWA 773 breccia show a wide range in Fe# (Fe/[Fe+Mg]) of olivine and pyroxene extending from the magnesian olivine cumulate to ferroan symplectite and FeO-alkali clasts (Figs. 2-4). Zoning trends and textural similarities indicate that these clasts can be plausibly linked as a magmatic differentiation sequence [3,13]. Only the FeO-alkali clasts (Fig. 3B) contain igneous silica (most symplectite silica formed by pyroxferroite breakdown). This trend is broadly similar to the tholeiitic trend. Apollo 15 QMD pyroxene also coexists with igneous silica, but has lower Fe# (Figs. 2,4), indicating silica enrichment prior to extreme FeO-enrichment, similar to terrestrial calc-alkaline rocks.

MELTS models of the mare basalts show tholeiite-like FeO-enrichment trends, consistent with experiments of [14] (Fig. 5). Modeling of the KREEP basalt shows less extreme FeO-enrichment; for high-T steps, this is consistent with experiments of [14], but the experiments show silicate liquid immiscibility at lower temperatures (Fig. 5). Whole-rock QMD compositions collected by us (modal recombination) and [15] fall along a mixing line between immiscible endmembers (Fig. 5), suggesting that silica-alkali-enrichment of the QMD may have been controlled by immiscibility.

References: [1] Glotch T. D. et al (2010) *Science, 329,* 1510–1513. [2] Ryder G. (1976) *Earth Planet. Sci. Lett., 29,* 255-268. [3] Fagan T. J. et al (2003) *MaPS, 38,* 529-554. [4] Irvine T. N. and Baragar W. R. A. (1971) *Canadian Jour. Earth Sci., 8,* 523-548. [5] Miyashiro A. (1974) *Amer. Jour. Sci., 274,* 321-355. [6] Sisson T. W. and Grove T. L. (1993) *Contrib. Mineral. Petrol., 113,* 143-166. [7] Zimmer M. M. et al (2010) *Jour. Petrol., 51,* 2411-2444. [8] Ghiorso M. S. and Sack R. O. (1995) *Conrib. Mineral. Petrol., 119,* 197-212. [9] Asimow P. D. and Ghiorso M. S. (1998) *Amer. Mineral.,* 83, 1127-1131. [10] Kesson S. E. (1975) *Proc. LSC, 6,* 921-944. [11] Beaty D. W. and Albee A. L. (1978) *Proc. LPSC, 9,* 359-463. [12] Fagan T. J. et al (2002) *MaPS, 37,* 371-394. [13] Jolliff B. L. et al (2003) *GCA, 67,* 4857-4879. [14] Rutherford M. J. (1976) *Proc. LSC, 7,* 1723-1740. [15] Taylor G. J. (1980) *Proc. Conf. Lunar Highlands Crust,* 339-352.

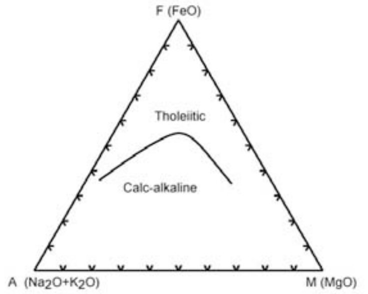

Fig. 1. Terrestrial tholeiitic and calc-alkaline trends [4].

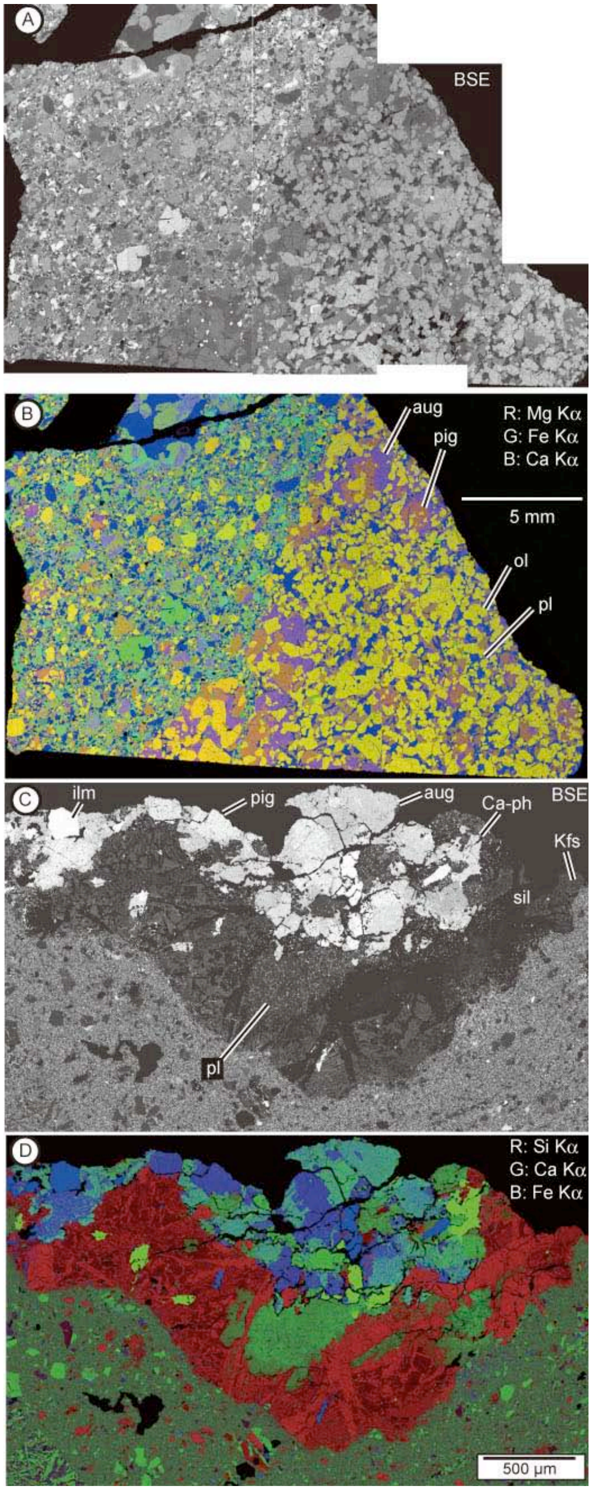

Fig. 2. Images of NWA 773 (A,B) and quartz monzodiorite from Apollo sample 15405,145 (C,D). Abbreviations: aug = augite; Ca-ph = Ca-phosphate; ilm = ilmenite; Kfs = K-feldspar; ol = olivine; pig = pigeonite; pl = plagioclase.

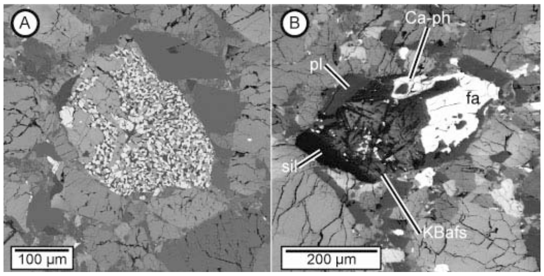

Fig. 3. BSE images of high FeO/(FeO+MgO) clasts from NWA 773 breccia. (A) symplectite. (B) FeO-alkali clast. Abbreviations as in Fig. 2 and: fa = fayalite; KBafs = K-Ba feldspar.

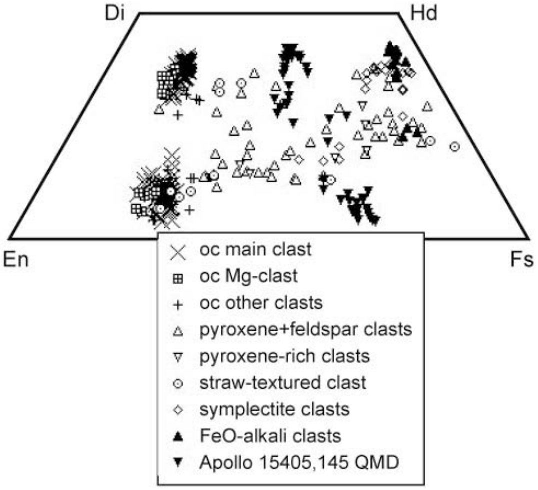

Fig. 4. Compositions of pyroxene from NWA 773 and Apollo 15405 QMD.

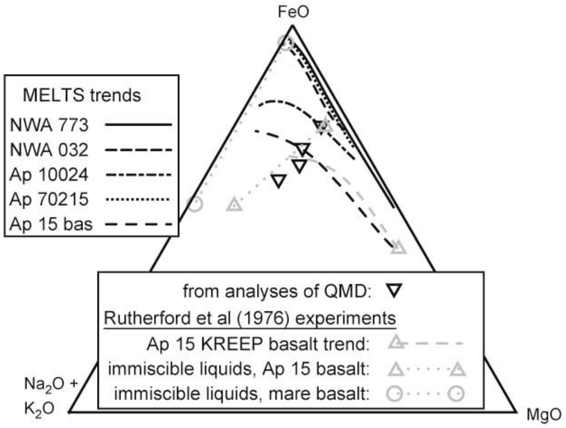

Fig. 5. AFM diagram showing trends from MELTS models (black lines), experiments reported by Rutherford et al (1976; gray lines), and whole-rock QMD compositions from this study and [15].