

**RE-EXAMINATION OF THE FELSITE CLAST WITHIN APOLLO SAMPLE 14321.** E.C. McIntosh<sup>1</sup>, J.M.D. Day<sup>1</sup> and F.M. McCubbin<sup>2</sup>, <sup>1</sup>Scripps Institution of Oceanography, La Jolla CA 92093-0244, USA E-mail: ecmcinto@ucsd.edu, <sup>2</sup>NASA Johnson Space Center, Houston, TX, 77058, USA.

**Introduction:** Felsite clasts have been identified in several Apollo samples and are typically characterized by intergrowths of potassium feldspar and a silica polymorph. Apollo 14321 was collected from the edge of Cone Crater and previous authors have interpreted the breccia to be a part of the Fra Mauro Formation [1-3]. Within 14321 is a highly unusual and relatively 'large' 1.8-gram felsite clast composed of ~60 vol% K-feldspar, ~40% quartz, <1% fayalite with trace amounts of ferrohedenbergite, ilmenite, Fe-Ni metal [4], and large zircon grains (>100  $\mu\text{m}$ ) [5,6]. Approximately 30% of the clast is brecciated and contains crystalline impact melt, and within the un-melted areas of the sample, K-feldspar and quartz occur as large intergrown crystals.

This clast is of importance for understanding processes that generated evolved magmas on the Moon and because it has been suggested to have a terrestrial origin based on Ce/Ce\* anomalies and low crystallization temperatures in zircon grains [7]. This latter terrestrial origin has been questioned based on low abundances of volatile trace elements such as Zn, Ga, and Ge and Lu/Sm ratios suggesting that the felsite clast within 14321 is of lunar origin [8].

If the 14321 felsite clast is of terrestrial origin, then it may reveal important information on the early Earth. However, if this clast is of lunar origin, further study is likely to yield new information on lunar magmatic evolution processes.

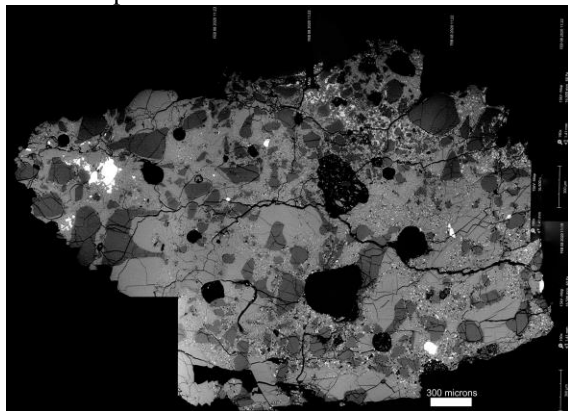


Figure 1: Backscatter electron image of nearly the complete section of 14321 (1891). Scale is 300  $\mu\text{m}$  across. Quartz (dark grey regions in BSE), K-spar (light grey continuous color regions), matrix (stippled regions between clasts), ilmenite and betafite (light regions) compose the polished section.

**Methods:** A bulk rock powder of 14321, 1030 was analyzed for major- and trace-element abundances, highly siderophile element (HSE) abundances, and osmium isotopic composition at the *Scripps Isotope Geochemistry Laboratory (SIGL)*. Six polished sections of felsite 14321 (993), (1027), (1029), (1494), (1613), and (1891) were analyzed for major element abundances using a *JEOL 8530F* electron probe microanalyzer (EPMA) at *NASA Johnson Space Center*, and for trace elements using a *New Wave UP-213nm* laser ablation system coupled to a *ThermoScientific iCAPq* inductively coupled plasma mass spectrometer (ICPMS) at the *SIGL*. Petrography of the polished sections was examined and noted using a reflected/transmitted light microscope and a bench-top *Phenom* scanning electron microscope at *SIGL*.

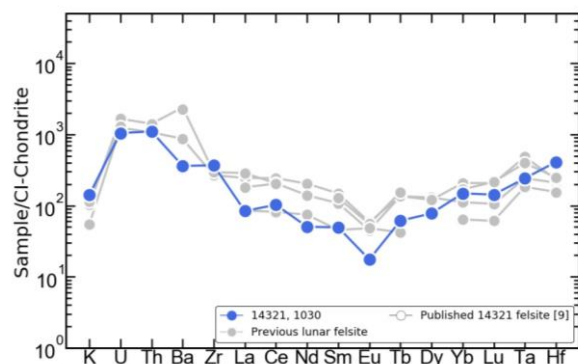


Figure 3: Bulk rock incompatible element abundance data for 14321 (1030) from this study versus previous study of the 14321 felsite and other lunar felsite rocks [9].

**Results:** *Bulk rock data.* Data from this study obtained using Paar bomb dissolution are similar to that of a previous study of the 14321 felsite using instrumental neutron activation analysis (INAA) [9]. Apollo 14321 (1030) exhibits suprachondritic incompatible trace elements at  $\sim 1.5$  to  $3.5 \times$  CI-chondrite (Figure 2). Potassium is relatively depleted compared to U and Th. Uranium, Th, and Ba abundances are relatively elevated compared to other trace elements within 14321 (1030). The felsite has a negative Eu anomaly of 0.12. Limited available data for other lunar felsite samples have a similar pattern to 14321 (1030) (Figure 2) [9]. On a total alkali versus silica plot, 14321 (1030) has a rhyolitic composition (Figure 3), entirely consistent with the quartz + potassium feldspar  $\pm$  accessory mineral composition of the felsite.

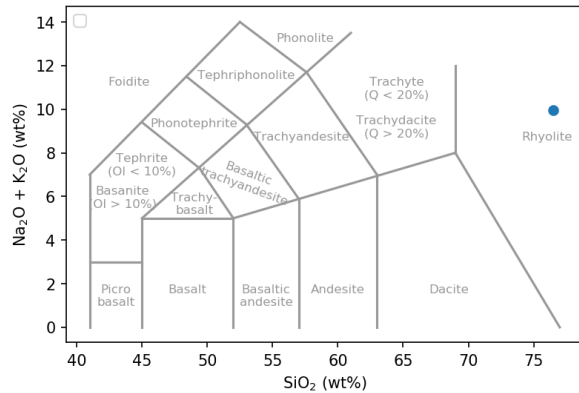


Figure 3: Total alkali vs. silica diagram showing that Apollo 14321 (1030) falls into the range for rhyolite.

**HSE abundances and  $^{187}\text{Os}/^{188}\text{Os}$  Systematics.** Highly siderophile elements (HSE: Os, Ir, Ru, Pt, Pd, Re) are tracers of planetary accretion, differentiation, and impactor contamination. The 14321 felsite has an HSE composition intermediate between the low HSE abundance pristine lunar crustal rocks [10] and HSE-rich impact melt coats and lunar regolith breccia meteorites (e.g., [11]). Abundances of the HSE in 14321 (1030) cluster around  $\sim 0.001 \times \text{CI-Chondrite}$  with a relatively flat pattern. Measured Re is slightly elevated compared to the other HSE. The ratio of  $^{187}\text{Os}/^{188}\text{Os}$  is  $0.1284 \pm 0.0003$ . Apollo 14321 has a Re/Os ratio of 0.23, Pd/Os ratio of 1.85, Ru/Os ratio of 1.1, and Pt/Ir ratio of 1.8.

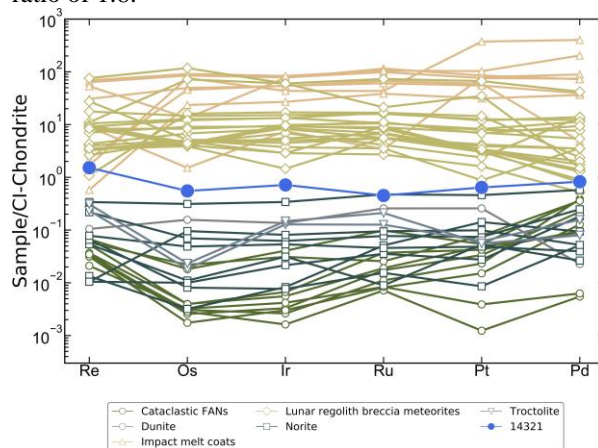


Figure 4: Plot of sample/CI-Chondrite for the HSE. Cataclastic FANs, Dunite, Norite, and Troctolite are from [10], and impact melt coats and lunar regolith breccia meteorites are from [11]. Carbonaceous Ivuna normalization values from [12].

**Discussion: Evidence for lunar or terrestrial origin.** Recently it has been argued that a lunar origin for the 14321 felsite is unlikely based on the high Ce/Ce\* ratios, and calculated crystallization temperatures for zircons, that are unusually low ( $771 \pm 88$  to  $810 \pm 37$  °C) [7]. Others have concluded it is a lunar rock based

on low Zn, Ga, and Ge abundances and Ba and Ta relationships [8].

From isotope dilution HSE abundance and Os isotope analyses of 14321, 1030, the felsite can be interpreted to have had very low initial HSE abundances that were subsequently contaminated by limited impact contamination from a broadly chondritic impactor composition (e.g., [12]), consistent with the presence of impact melt within the sample. The relatively flat CI-Chondrite relative HSE abundances and  $^{187}\text{Os}/^{188}\text{Os}$  are similar to that of CI-chondrites or ordinary chondrites and are most consistent with a lunar origin, as opposed to having the initially very high Re/Os ratios and high Re contents typical of terrestrial granitic crustal rocks. If the felsite clast were of terrestrial origin, the expectation would be for it to have strongly non-chondritic relative HSE abundances and non-chondritic  $^{187}\text{Os}/^{188}\text{Os}$ , especially given the minor chondritic-impact contamination experienced by the clast. This clast likely formed when an impactor struck the lunar surface, and the clast was incorporated into the brecciated 14321 sample.

**Petrology of the 14321 clast and whole-rock geochemistry.** Apollo sample 14321 contains traces of ferromagnetite, ilmenite, and Fe-Ni metal, which suggest low  $f\text{O}_2$  conditions (near the Quartz-Fe<sup>0</sup>-fayalite buffer) consistent with a lunar origin. Quartz and alkali feldspar are unusual within lunar rocks and betafite forms under more oxidizing conditions than typical lunar rocks [13]. These lines of evidence correspond to increasingly oxidized late-stage differentiated melts that can be relatively rich in K and other moderately volatile elements, as incompatible elements are concentrated during late-stage igneous differentiation processes.

**References:** [1] Wilshire H. G. and Jackson E. D. (1997) *U.S.G.S. Prof. Paper* 785. [2] Swann G. A. et al. (1972) *Apollo 14 Preliminary Science Rpt.* NASA SP-272, pages 39-85 [3] Swann G. A. (1977) *U.S.G.S. Prof. Paper* 800. [4] Warren P.H. (1983a) *Proc. 14<sup>th</sup> Lunar Planet. Sci. Conf.* in *J. Geophys. Res.* 88, B151-B164. [5] Meyer C. (1996) *Meteoritics & Planet. Sci.* 31, 370-387. [6] Grange M.L. et al. (2013) *Geochem. Cosmochim. Acta* 101, 112-132. [7] Bellucci J.J. et al. (2019) *Earth Planet. Sci.* 510, 173-185. [8] Warren P.H. et al. (2020) *Icarus*. 347, 113771. [9] Warren P.H. et al. (1983b) *Earth Planet. Sci.* 64, 175-185. [10] Day J.M.D. et al. (2010) *Earth Planet. Sci.* 289, 595-605. [11] McIntosh E.C. et al. (2020) *Geochim. Cosmochim. Acta*. 274, 192-210. [12] Horan M.F. et al. (2003) *Chem. Geol.* 196, 5-20. [13] Meyer C. et al. (1988) *Am. Mineral.* 73, 1420-1425.