

TRACE-ELEMENT AND TEXTURAL EVIDENCE FOR LUNAR, NOT TERRESTRIAL, ORIGIN OF THE MINIGRANITE IN APOLLO SAMPLE 14321. Paul H. Warren¹ and Alan E. Rubin¹, ¹Earth, Planetary, and Space Sciences, UCLA, Los Angeles, CA 90095, USA (pwarren@ucla.edu).

Introduction: The 14321 lunar granite (clast 14321g) has recently been reinterpreted [1] as a piece of the Hadean Earth, impact-transported to the Moon. In principle, samples of such derivation may afford important insight into the nature of Earth's Hadean crust [2]. Bellucci et al. [1] noted evidence for origin at a relatively high (by lunar standards) f_{O_2} : significant concentrations of W^{6+} and Fe^{3+} in oxycalcibetafite [3], a pattern of multiple curved “tetrads” within the oxycalcibetafite REE pattern [4], and elevated $Ce/(La+Pr)$ within zircon REE patterns. Bellucci et al. [1] also used Ti-in-quartz data, modeled after [5], to infer original crystallization at a surprising combination of low temperature, $\sim 790^\circ C$, and high pressure, 0.69 ± 0.12 GPa, which would correspond to an unlikely crystallization depth of ~ 150 km in the Moon.

We have tested the terrestrial-provenance hypothesis by comparing trace-element data from 14321g versus a large data base (many hundreds of analyses) for terrestrial granites and lunar “felsites”.

Petrology of 14321g: The clast was originally roughly 1.8 grams, and was classified [6] as “granite” in the strictly compositional-textural sense. No link to a Sierra-sized pluton of pure granite was implied. Apart from a portion ($\sim 30\%$) that is shock-melted glass, the clast contains ~ 60 vol% K-feldspar, 40 vol% quartz, $<1\%$ fayalite, and traces of ferrohedenbergite, ilmenite, Fe-Ni metal, plus [3] oxycalcibetafite and zircon. The clast is brecciated, but in much of its volume an undamaged igneous texture survives (Fig. 1). Compared to similar lunar samples that are generally termed “felsite” [7], 14321g is both larger and coarser-grained, and so distinguishing it as “granite” seems apt. No high-pressure polymorphs have been detected; [1] used Raman to confirm that the silica is quartz.

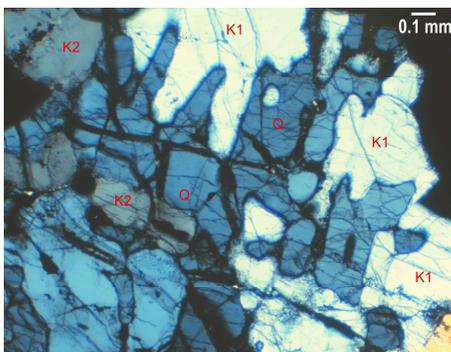


Fig. 1. In unbrecciated 14321g [6], K-feldspar (K) and quartz (Q) occur as large intergrown crystals.

Volatile trace metal depletions: As acknowledged (but only qualitatively) by [1], the transition volatile metals zinc, gallium and germanium are strongly depleted in 14321g. We find that the depletions are beyond the terrestrial granite ranges (Fig. 2). Relative to our terrestrial granite averages, the 14321g [6] depletion factors are 27 (Zn), 2.0 (Ga) and 18 (Ge).

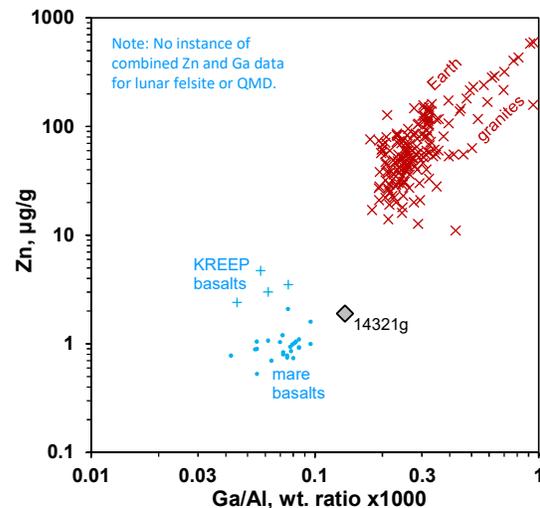


Fig. 2. Zinc and Ga/Al in 14321g show closer similarity to other lunar samples than to terrestrial granite.

Volatilization during intense shock metamorphism was invoked [1] to account, qualitatively, for these depletions. However, evidence from shocked chondrites, martian meteorites, and impact-shock studies in general, indicates that such major depletions are unlikely to develop without near-complete shock-melting, which clearly did not occur in 14321g. For example, data from highly shocked ordinary chondrites, mainly from Friedrich et al. [8], show no depletions in Zn or Ga even beyond shock stage 6. The one chondrite, Ramsdorf, that does show 14321g-like depletions suffered near-complete melting [9]. Martian meteorites have generally been shocked to similar, if not higher, intensity than 14321g [10], yet none shows 14321g-like depletions in Zn, Ga or Ge.

Barium, tantalum and Lu/Sm enrichments: Other aspects of compositional disparity between 14321g and terrestrial granites involve exclusively refractory trace elements. Compared to terrestrial granites of similarly high Ba content, 14321 is enriched in Ta by a factor of 10; and the few terrestrial granites that are as Ta-rich as 14321 have 10 times lower Ba (Fig. 3).

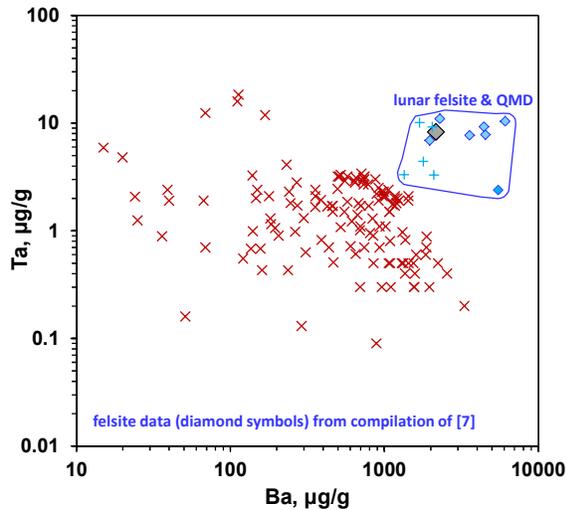


Fig. 3. Ba and Ta in 14321g show closer similarity to other evolved lunar samples than to terrestrial granite.

The Earth-Moon Ta-Ba disparity probably arose largely because Ta is more thoroughly incompatible in the Moon than it is in Earth's crust/mantle system. Relative to the arch-incompatible thorium and CI chondrites, Ta is depleted in KREEP, the dominant repository of the Moon's incompatible elements, by a factor of ~ 2.4 [11], but in Earth's continental crust the depletion factor is ~ 6.4 [12]. This well-known relative depletion of Ta (and Nb) in Earth's continental crust is suspected to derive mainly from rutile fractionation during high-pressure (eclogite facies) partial melting of subducted materials, although Kelemen et al. [13] also discuss six additional possible causative mechanisms (five of which would operate more effectively in the large, water-rich Earth than in the Moon).

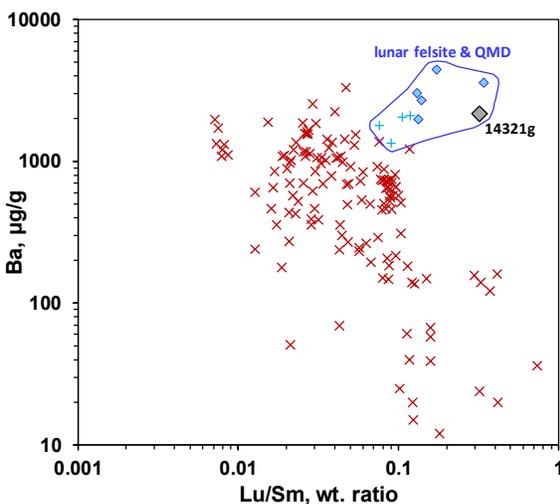


Fig. 4. Lu/Sm and Ba systematics; 14321g is again more similar to lunar felsites than to Earth granites.

The refractory-element ratio Lu/Sm is also close to 10 times higher in 14321g than in terrestrial granites of similarly high Ba content (Fig. 4). The more fractionated REE pattern among terrestrial crustal materials is probably engendered mainly, albeit indirectly, by fractionation of garnet, which as a host phase favors the heaviest REE, and the existence of which is favored by Earth's high interior pressures. At least some of the rare instances of terrestrial granite showing 14321g-like (superchondritic) Lu/Sm are linked to terrestrial complexities such as "post-magmatic alteration by a sodium- and fluorine-rich fluid phase" [14].

Discussion: Other highly evolved lunar rocks, most notably the felsites [7], strongly resemble 14321g in all these respects. We conclude that 14321g is very probably of wholly lunar derivation.

This finding admittedly stands in stark contradiction to the inference from Ti-in-quartz modeling [1] that 14321g crystallized at 0.69 GPa. The geodynamically limited Moon was presumably never capable of forming, or burying, such a highly granitic material ~ 100 km below the base of its crust, nor of excavating material from such a depth to the surface. However, the developers of the Ti-in-quartz method [5] acknowledge that it may yield erroneous results in systems that lack rutile (as in the present case).

If we accept the P and T inferences of [1] at face value, another issue arises. The geothermobarometer presumably records the conditions at completion of crystallization of the parental magma. At high P , water markedly lowers the solidus temperature of granitic materials, but at 0.69 GPa a system water content of ~ 5.1 wt% would be necessary to drive the solidus down to 790°C [15]. This implication is difficult to reconcile with the presence in 14321g of anhydrous hedenbergitic pyroxene and fayalitic olivine [6], and no hydrous mafic silicates such as amphibole or biotite.

References: [1] Bellucci J.J. et al. (2019) *EPSL* 510, 173-185. [2] Armstrong J.C. et al. (2002) *Icarus* 160, 183-196. [3] Meyer C. et al. (1996) *MAPS* 31, 370-387. [4] Monecke T. et al. (2011) In: *A Wet vs. Dry Moon*, LPI, Abstract #6066. [5] Thomas J.B. et al. (2015) *Contr. Min. Pet.* 169, 27. [6] Warren P.H. et al. (1983) *EPSL* 64, 175-185. [7] Seddio S.M. et al. (2013) *Am. Mineral.* 98, 1697-1713. [8] Friedrich J.M. et al. (2004) *GCA* 68, 2889-2904. [9] Yamaguchi A. et al. (1999) *MAPS* 34, 49-59. [10] Rubin A.E. (2015) *Icarus* 257, 221-229. [11] Warren P.H. and Taylor J.G. (2014) In: *Treatise on Geochemistry*. [12] Rudnick R.L. and Gao S. (2014) In: *Treatise on Geochemistry*. [13] Kelemen P.B. et al. (2014) In: *Treatise on Geochemistry*. [14] Wormald R.J. and Price R.C. (1988) *Austral. J. Earth Sci.* 35, 209-221. [15] Makhluף A.R. et al. (2017) *Contr. Min. Pet.* 172, 77.