Trace-element and textural evidence for lunar, not terrestrial, origin of the minigranite in Apollo sample 14321

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The great tragedy of science — the slaying of a beautiful hypothesis by an ugly fact.

Thomas Huxley

Or in this case, numerous facts.

Introduction

It has been suggested [1] that the 14321 granite clast [2] may be of terrestrial, impact-launch, origin; i.e., a sample of Earth's Hadean crust.

A. Texture inconsistent with ⊕ launch-off

The Apollo 14 14321 granite [2] is uniquely large (originally 1.8 g) and coarse-grained compared to the many otherwise similar lunar felsites [3]. Although "14321g" consists partly, about 30%, of shock-melted matter, it mostly preserves a graphic-intergrowth texture (**Fig. 1**), where the feldspar is crystalline, not diaplectic glass. In contrast, martian meteorites show that impact-launch off a large planetary body tends to induce extreme shock metamorphism. Based on gravity alone (ignoring potential atmospheric interference), Earth-escape requires higher energy/gram by a factor 5 over Mars-escape. Thus, even considered in isolation, the texture of 14321g is reason to doubt the terrestrial origin hypothesis.

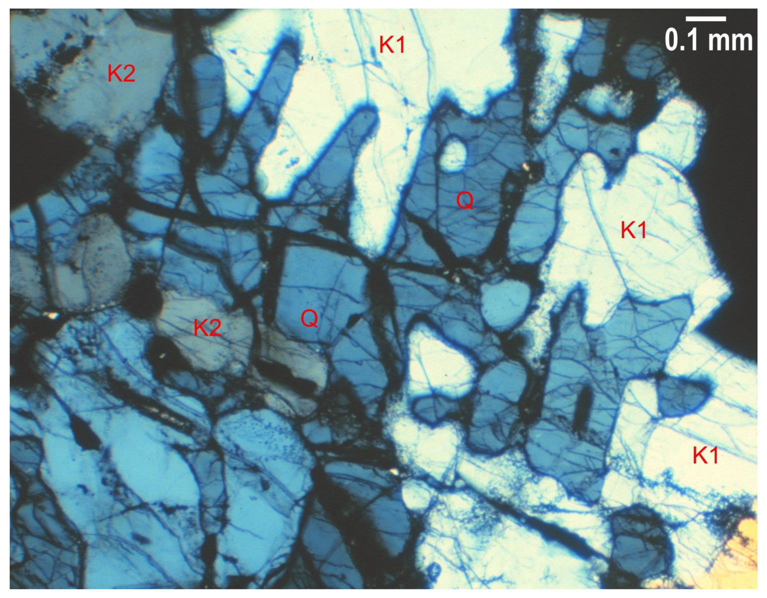

Fig. 1. In the unbrecciated portion of 14321g, K-feldspar (K) and quartz (Q) occur as large intergrown crystals.

The texture of 14321g also figures into interpretation of the next body of evidence against terrestrial provenance ...

B. Distinctively lunar volatile depletions

The transition volatile metals zinc, gallium and germanium are strongly depleted in 14321g. We find that the depletions are beyond the terrestrial granite ranges (**Figs. 2 and 3**). Relative to our terrestrial granite averages, the 14321g [2] depletion factors are 27 (Zn), 2.0 (Ga) and 18 (Ge).

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 texture and mineralogy show did not occur in 14321g. For example, data from highly shocked ordinary chondrites, mainly from Friedrich et al. [4], show no depletions in Zn or Ga even beyond shock stage 6. The one chondrite that does show 14321g-like depletions, Ramsdorf, suffered near-complete melting [5]. Martian meteorites have generally been shocked to similar, if not higher, intensity than 14321g, yet none shows 14321g-like depletions in Zn, Ga or Ge.

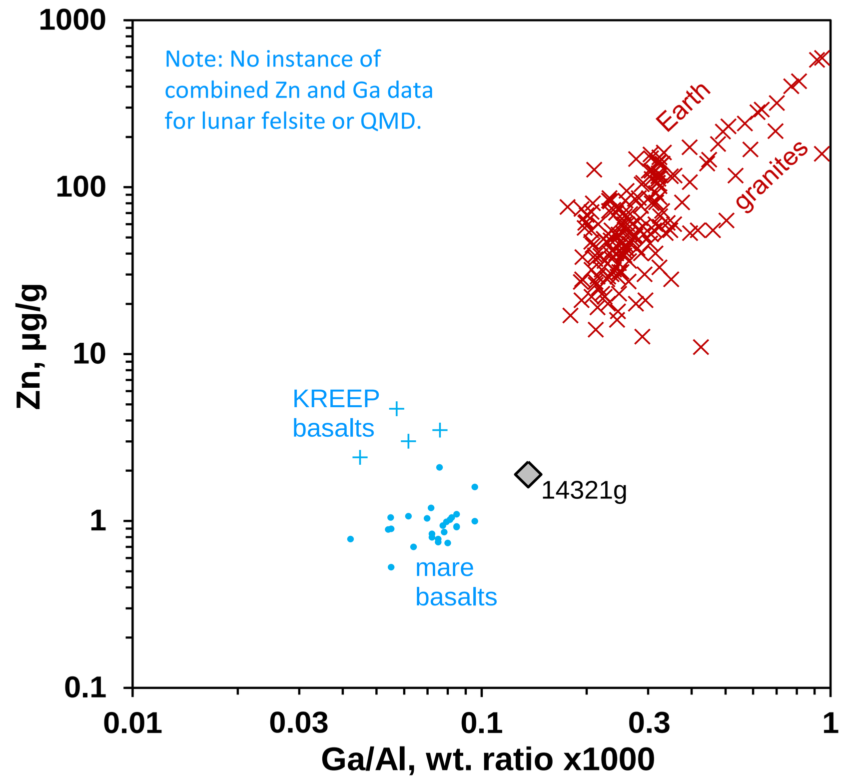

Fig. 2. Zinc and gallium in 14321g show closer similarity to other lunar samples than to terrestrial granite.

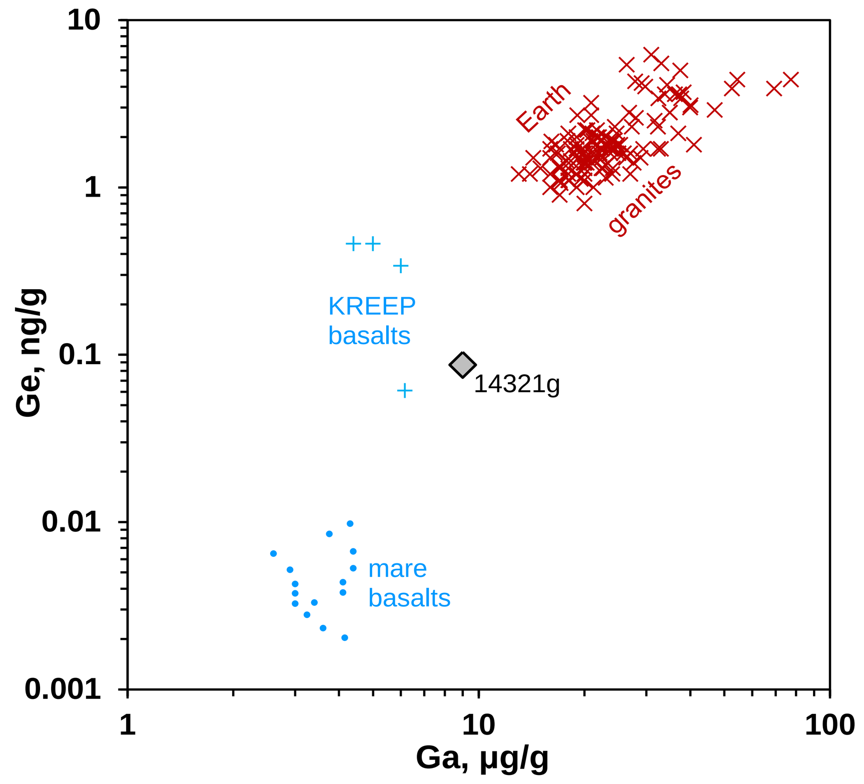

Fig. 3. Germanium and gallium in 14321g show closer similarity to other lunar samples than to terrestrial granite.

C. Distinctively lunar Ba, Ta and Lu/Sm

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. 4**).

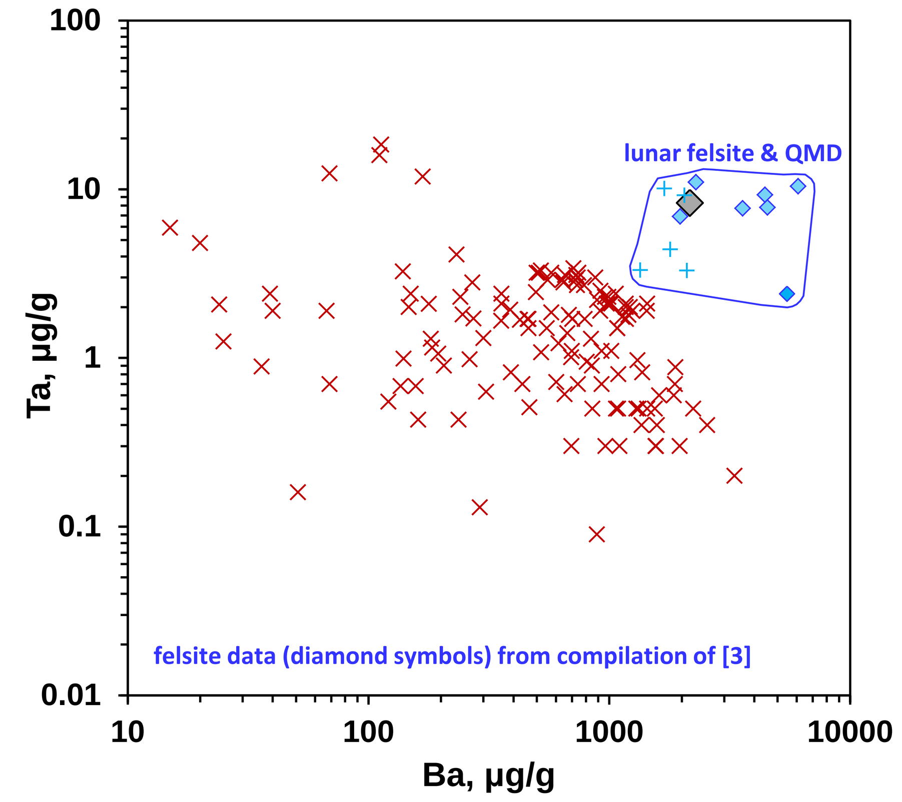

Fig. 4. Barium and tantalum in 14321g show closer similarity to other evolved lunar samples than to terrestrial granite.

The Earth-Moon Ta-Ba disparity probably arose because Ta is more 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 by a factor of ~2.4. But in Earth's continental crust the depletion factor is ~6.4 [6], likely due to rutile fractionation during high-*P* (eclogite facies) melting of subducted materials [7].

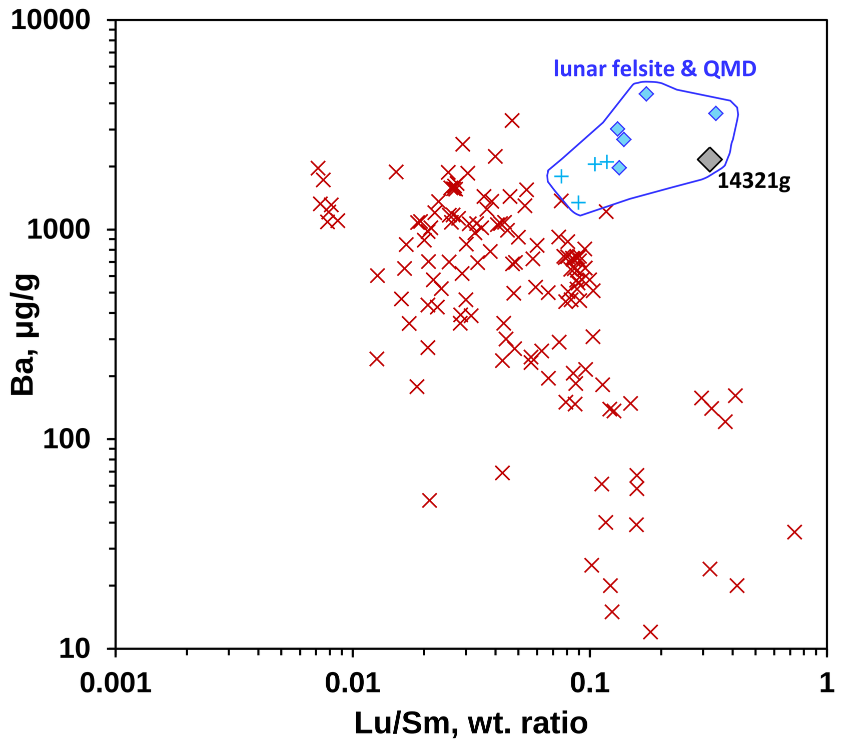

Fig. 5. Lu/Sm and Ba systematics; 14321g is again more similar to lunar felsites than to Earth granites.

The refractory-element ratio Lu/Sm is nearly 10 times higher in 14321g than in terrestrial granites of similarly high Ba content (**Fig. 5**). 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. Other highly evolved lunar rocks, most notably the felsites [3], strongly resemble 14321g in all these respects.

D. Distinctively lunar mineralogy

The terrestrial origin hypothesis [1] was motivated in part by a high pressure of crystallization, 0.69 GPa (clearly implausible for a lunar crustal lithology), inferred on the basis of the Ti-in-quartz method. However, the developers of this method [8] 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 igneous crystallization. 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 [9]. This implication is difficult to reconcile with the presence in 14321g of anhydrous hedenbergitic pyroxene and fayalitic olivine [2], with no hydrous mafic silicates such as amphibole or biotite.

Conclusion

We conclude that 14321g is very probably of wholly lunar derivation.

References: [1] Bellucci J. J. et al. (2019) *EPSL*. [2] Warren P. H. et al. (1983) *EPSL*. [3] Seddio S. M. et al. (2013) *Am. Mineral*. [4] Friedrich J. M. et al. (2004) *GCA*. [5] Yamaguchi A. et al. (1999) *MAPS*. [6] Rudnick R. L. and Gao S. (2014) In: *Treatise on Geochemistry*. [7] Kelemen P. B. et al. (2014) In: *Treatise on Geochemistry*. [8] Thomas J. B. et al. (2015) *Contr. Min. Pet.* [9] Makhluf A. R. et al. (2017) *Contr. Min. Pet.*