A TERRESTRIAL PERSPECTIVE ON THE RECORD OF LUNAR VOLATILES AS RECORDED BY APATITE.
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Introduction: Contrary to early studies of lunar rock samples, which concluded that the Moon was nominally anhydrous (see [1] for a summary), recent studies have established that there is measurable hydrogen (often loosely termed "water") in lunar rocks, especially found in the mineral apatite [2-4]. The origin, distribution, and significance of the water in those rocks, however, are still areas of substantial inquiry [5-7].

The hydrous mineral apatite has proven an invaluable tool in further study of volatiles in the Moon. Found in both intrusive and extrusive rocks from the Earth, Moon, and elsewhere in the solar system, apatite can help to constrain the amount of H in an evolving magma, as well as serve as the primary reservoir of H and Cl in rocks, making it an ideal target for isotopic analysis (D/H and $^{37}Cl/^{35}Cl$). A comparison of the H content of apatite from intrusive and extrusive lunar rocks suggests that a fundamental dichotomy exists within the lunar sample suite: Intrusive rocks contain apatite with low H, whereas extrusive rocks contain apatite with higher H abundances (Fig. 1 and [7]).

However, in comparing extrusive and intrusive rocks, it is reasonable to be concerned that their water contents might be affected by their petrologic and thermal histories, which are quite different. Consider, as an example, a terrestrial rhyolitic magma which might contain in excess of 5 wt. % H_2O, and thus H-rich apatites. If this magma is erupted, we can expect that the apatite and melt inclusions might retain the signature of the elevated, pre-eruptive, magmatic water content. It is not clear, however, that a slowly cooled granite forming from an identical water-rich magma would retain any signature of the originally elevated magmatic water. The first suggestion that loss of H from intrusive rocks is a concern is that granitic rocks in the GEOROC database have major element totals (sans H_2O) that average 99.3 wt. %, suggesting that they have much less H than their precursor rhyolitic magmas which average over 4 wt. % H_2O. Certainly the order of magnitude decrease in bulk water content between the rhyolitic magma and the granitic rock that would be predicted from the mineralogy of granites (10% biotite would yield a bulk rock H_2O content of less than 0.5 wt% H_2O) would suggest that H-loss is possible, at least for intrusive rocks on Earth. Thus we must admit that H-loss is possible in lunar intrusive rocks as well. We have used published data on terrestrial and lunar apatites from both intrusive and extrusive rocks to determine if any systematic behavior related to petrologic/cooling histories can be inferred. We are specifically testing two related hypotheses:

1) Apatite from intrusive rocks are always low in H, and would be different than apatite from extrusive rocks, even on a homogeneously hydrated planet.

2) Intrusive rocks are—in general—not immune to degassing despite crystallizing under pressure.

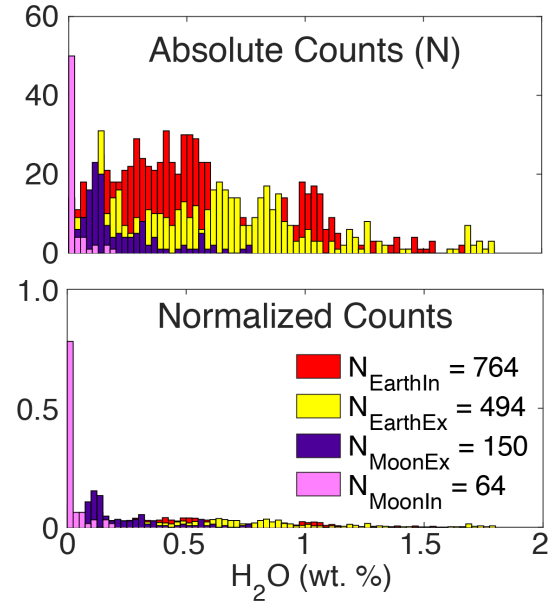

Fig. 1. Histograms (absolute counts and normalized counts) of hydrogen abundance in apatite from intrusive and extrusive rocks from both the Earth and Moon [7 and references therein, 8]. The distinctive difference observed between intrusive and extrusive rocks on the Moon is not observed on Earth. This is consistent with the idea that the intrusive and extrusive rocks on the Moon sampled reservoirs with different H abundances [7].

If there is any loss of volatiles from intrusive rocks, this would have implications not only for the H abundances observed in lunar rocks, but also for the extent to which the isotope ratios of H and Cl (and perhaps others) represent a primitive, unmodified reservoir.

Hydrogen in Lunar and Terrestrial Apatite: As has been observed previously [7] and is easily observed in the compilation of Fig. 1, the distribution of H abundances in apatite from lunar intrusive rocks is dominated by apatites that are poor in hydrogen, with approximately 75% of the published analyses under

250 ppm H_2O. The same cannot be said for extrusive lunar apatites, which define a distribution with a peak ~1200 ppm H_2O. This difference has been attributed to heterogeneity in the lunar source regions for the magmas that made these rocks [7].

In contrast to the lunar data, the terrestrial apatite data define much wider ranges of H_2O abundance, for both intrusive and extrusive rocks. Also in contrast to lunar data, the populations of intrusive and extrusive terrestrial apatites are indistinguishable from each other in their H abundances. A comparison of apatite from terrestrial and lunar rocks indicates that hypothesis #1 (apatite from lunar intrusive rocks are low in H relative to those from lunar extrusives because apatite from all intrusive rocks are lower in H than extrusive rocks from the same planet) is false. This means that the heterogeneously hydrated Moon model of [7] is plausible.

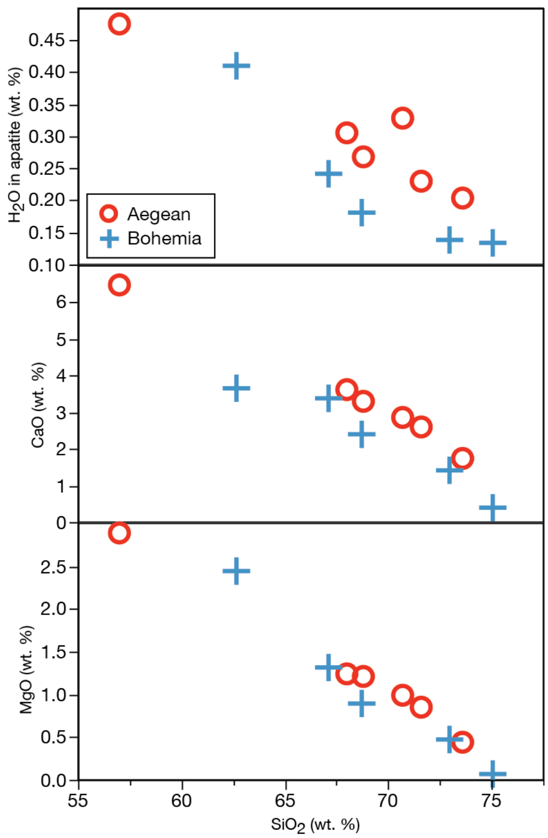

Fig. 2. Harker variation diagrams showing chemical evolution of intrusive rocks for two different suites of terrestrial samples, data compiled from [9,10,11,12,13]. In both cases, H abundances in apatite are seen to decrease with increasing fractional crystallization.

Preservation of Hydrogen abundances and D/H in Lunar Crustal Rocks: The comparison of apatite from intrusive and extrusive rocks does not prove that apatite in individual intrusive rocks nor the host rocks themselves are preserving their initial H abundances during cooling and crystallization. In order to test this hypothesis more rigorously, we have used the data of [9] for genetically related suites of samples from the Bohemian Massif and the central Aegean. Combined with the geochemical data of [10-13], we can trace the evolution of the magma via fractional crystallization, as well as the H content of apatite from the same rocks.

In both sample suites, we observe that H-abundances in apatite are decreasing during magma evolution. If the magmas were behaving as a closed system, we would expect the H abundance in apatite to increase with differentiation because most of the minerals growing are nominally anhydrous, and also because apatite fractionates F very strongly, and can increase the H/F ratio of any apatite crystallizing later (which might be a problem given that apatite is present in both suites of rocks even at low SiO_2). Data from both the Aegean and Bohemian suites indicate that hydrogen is being lost from the system during magma evolution and crystallization. This is in agreement with the global petrologic and bulk chemistry data described above. Hypothesis #2 is unfortunately true: Intrusive rocks are not immune from loss of H.

Conclusions: Published data for both terrestrial and lunar samples indicate that the difference between apatite from intrusive and extrusive lunar rocks is a feature that is not reproduced in terrestrial samples, and therefore the two rock types may be sampling variably hydrated portions of the lunar interior. However, the documented loss of H from terrestrial intrusive rocks means that it may be unwise to assume that intrusive rocks on any planet preserve their initial abundances of H or any other highly volatile element. Any loss can lead to fractionation, suggesting that caution is also warranted in interpreting D/H ratios from intrusive rocks, as they may have been modified during the cooling and crystallization of the magma.

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