EVIDENCE FOR HIGH VOLATILE ABUNDANCES IN LUNAR MELT INCLUSIONS.

E. H. Hauri[1], T. Weinreich[2], A. E. Saal[2], M. C. Rutherford[2], and J. A. Van Orman[2], [1]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington DC 20015 (ehauri@ciw.edu), [2]Department of Geological Sciences, Brown University, Providence, RI 02912, [3] Department of Geological Sciences, Case Western Reserve University, Cleveland, OH 44106

Introduction: Melt inclusions have been used for decades to determine pre-eruptive volatile contents of terrestrial magmas from subduction zones, hotspots and mid-ocean ridges [1], as well as volatile contents of Martian magmas [2]. Using standard petrographic methods, Edwin Roedder and Paul Weiblen were the first to identify silicate melt inclusions trapped within lunar minerals, ranging in size from 1µm up to 400µm, and they would go on to identify and melt inclusions in samples returned from all of the Apollo and Luna missions [3 and refs therein]. Many of these early-described melt inclusions were analyzed for major elements by microprobe, and though only a minority of the melt inclusions were trapped in early-crystallizing minerals such as olivine, it is clear from Roedder's data that most of the range in TiO_2 content observed in mare basalts and picritic pyroclastic glasses is reflected in the composition of silicate melt inclusions. This observation indicates that lunar melt inclusions preserve much of the range of magma compositions that are thought to have been erupted on the Moon's surface.

The Gas Phase in Lunar Melt Inclusions: For the purposes of studying the abundances of volatile elements in primitive lunar magmas, a key observation that can be gleaned from the early work on lunar melt inclusions is that they often contained a vapor bubble co-existing with glass ± daughter minerals within the inclusion cavity. The volume fraction of the inclusion cavity occupied by these vapor bubbles ranges from 1% up to 20%. These vapor bubbles could be syngenetic (trapped together with the inclusion), and/or they could be shrinkage bubbles that exsolved during differential shrinkage of melt within the inclusion during cooling of the host crystal; high volume fractions of vapor favor a syngenetic origin for some vapor bubbles. In either case, the presence of vapor bubbles in silicate melt inclusions from the Moon, including those trapped in olivine, is direct evidence that lunar magmas contained significant amounts of volatile elements that partition into a vapor phase at magmatic temperatures, and that lunar magmas likely reached vapor saturation at some point in their eruptive evolution. The importance of this observation was noted by Roedder & Weiblen in their very first study of lunar melt inclusions [4], but its significance has grown in light of new data indicating the presence of magmatic water in primitive lunar magmas, and extrapolation of low measured H_2O contents to provide estimates of pre-eruptive water concentrations [5].

Implications for Volatiles in Lunar Magmas: The amount of gas contained in a melt inclusion vapor bubble can be estimated from the ideal gas equation (PV=nRT), given measurements of the vapor saturation pressure within the inclusion cavity, the volume of the vapor bubble, and an assumption about the vapor trapping temperature (commonly assumed to be the glass transition temperature). If one assumes an origin as a shrinkage bubble, then this gas can be added back into the volume of melt to arrive at an estimate of the magma's volatile content at the time of trapping. This method is commonly used in studies of terrestrial melt inclusions, and is facilitated by measurement of volatiles whose pressure-dependence is well known, such as CO_2 and H_2O [6], to provide a measure of the vapor saturation pressure within the melt inclusion. Unfortunately, for lunar melt inclusions, low fO_2 does not favor the formation of CO_2 vapor, and so even if we knew the C and H_2O contents of glass within a lunar melt inclusion, the uncertainty about C speciation in the melt and its pressure-dependent solubility hinders any educated estimate at the vapor saturation pressure prevailing within lunar melt inclusion vapor bubbles.

Nevertheless, some simple calculations are instructive. If we assume a melt inclusion pressure of 100 bars, equivalent to a depth of only 300 meters below the lunar surface, and add the vapor phase back into the melt inclusion, vapor volume fractions of 1% to 20% result in ideal gas abundances in the melt that range from 685 to 13,200 ppm on a molar basis. This would translate into mass abundances of 60-1200 ppm C for a pure carbon vapor, or H_2O abundances of 90 to 1800 ppm H_2O for pure water vapor. These abundances are higher than directly measured in primitive lunar glasses, but overlap the range of pre-eruptive water contents extrapolated from picritic glass diffusion profiles [5].

References: [1] Hauri E. H. et al. (2002) *Chem Geol, 183,* 1–4. [2] Leshin-Watson L. et al. (1994) *Science, 265,* 86-89. [3] Roedder E. and Weiblen P. (1977) *LPS XVII,* 1767–1783. [4] Roedder E. and Weiblen P. (1970) *LPS I,* 801–837. [5] Saal A. E. et al. (2008) *Nature, 454*, 192-195. [6] Dixon J. E. et al. (1995) *J Petrol, 36,* 1607-1631.