DENSITY OF MOLTEN "APOLLO 17 ORANGE GLASS". M. van Kan Parker[1], C. B. Agee[2], W. van Westrenen[1], [1]Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085, 1081 HV Amsterdam, The Netherlands (e-mail: Mirjam.van.kan@falw.vu.nl), [2]Institute of Meteoritics, UNM, Albuquerque, USA.

Introduction: Modelling the dynamic evolution of the interior of the Moon is intrinsically linked to the density of lunar materials at high pressures and temperatures. Lunar magma density variations during crystallisation of the lunar magma ocean are particularly important, since the formation of plagioclase-rich highland rocks and mare basalts are related to density differences between lunar magma and co-existing minerals. So far the densities of high and low titanium end member primitive lunar glasses, containing 16.4 and 0.23 wt% TiO_2 respectively, have been determined at elevated pressure (P) and temperature (T) via quench methods [1,2]. However, so far it is unclear (1) if observed density differences are related to variations in titanium content only (2) or if density variations in lunar magma are linear as a function of titanium content. Here we study the density of a synthetic equivalent of the intermediate-high titanium, Apollo 17 (A17) orange glass, with 8.63 wt% TiO_2 [3].

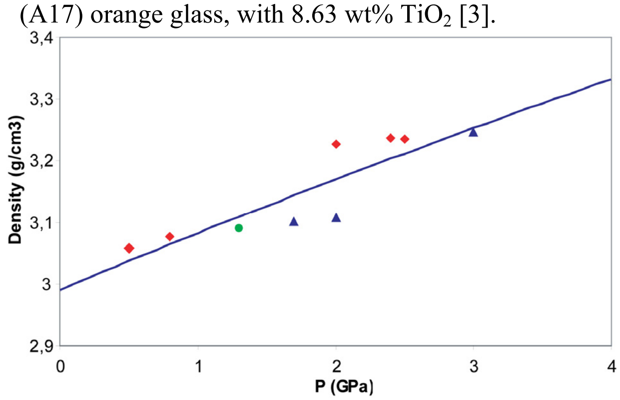

Figure 1. Summary of piston cylinder sink/float experiments on A17 orange glass. Red diamonds are floats, blue triangles are sinks, filled green circle corresponds to a neutral buoyancy.

Methods: Our experiments cover the P-T range of 0.5-3.0 GPa, using the Quick-press piston cylinder (PC) device at UNM, and 1723 -1853 K, directly relevant to the lunar mantle. A preliminary additional experiment at 8 GPa and 2223 K, using the Walker style multi anvil (MA) device at UNM, was performed to begin characterisation of the full compression curve of the liquid. To determine the magma density of the orange glass composition we use the sink-float technique [1,2,4]. Two density markers are packed in starting material, one at the bottom and one at the top of the capsule. The sample, enclosed in a Mo capsule, is then pressurised and heated. Charges are rapidly heated, 250 or 400 K per minute for the PC and MA respectively, and kept at P-T conditions for 30 s allowing the material to melt and for buoyancy forces to drive the spheres up or down the capsule. Floating spheres are interpreted as less dense than the liquid and sinking spheres as denser. When spheres do not move this is interpreted as neutral buoyancy implying that sphere density equals liquid density. Density markers in our PCexperiments are spherical olivine crystals: (Fo_{100} and Fo_{90}) with a diameter of 300-600 microns. For the 8 GPa experiment pyrope-rich garnet spheres were used.

Results: We present the results of nine PC experiments, in which sink, float and neutral buoyancy were observed (Figs. 1,2). Additionaly the preliminary run at 8 GPa and 2223 K resulted in a neutral buoyancy.

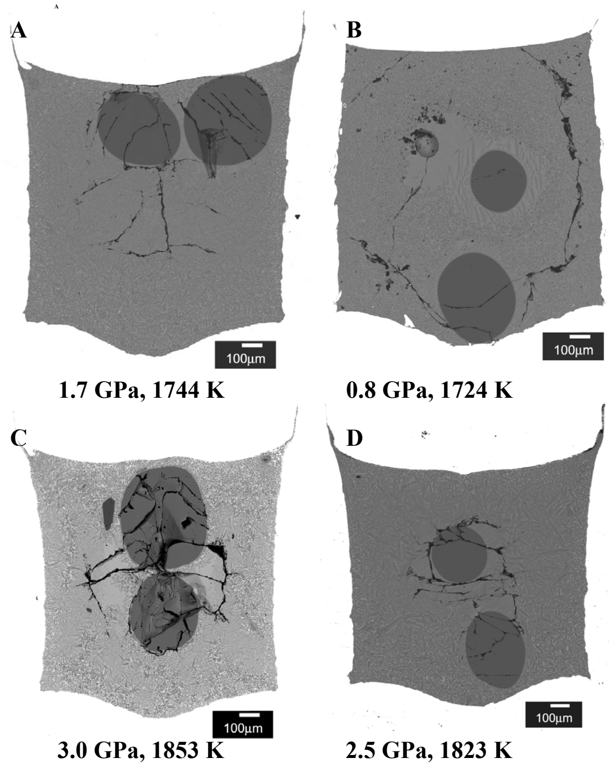

Figure 2. BSE images of selected piston cylinder experiments, dark spheres in A and B are Fo_{100}; C and D show Fo_{90} spheres. A and C are floats, B and D are sinks. Experimental P-T conditions are listed below corresponding images.

Discussion: Our experiments provide tight bounds on density of molten orange glass of 3.09 g cm^{-3} at 1.3 GPa, 1739 K and 3.24 $\pm$ 0.01 g cm^{-3}, bracketed by the sink and float at 2.5 GPa, 1823 K and 3 GPa, 1853 K.

It was previously noted that density cross-overs between magma and lunar minerals may have important implications for the origin of picritic glasses including the orange glass [6]. The conditions at which density cross-overs between the low and high Ti end-members and their equilibrium olivines and pyroxenes take place have therefore been previously studied [1,2,5]. Mineral densities depend mainly on their magnesium numbers, as quantified by the crystals (s) – liquid (l) distribution coefficient K_d:

$$K_d = \left(\frac{X_{Fe}}{X_{Mg}}\right)^s \left(\frac{X_{Mg}}{X_{Fe}}\right)^l \quad (1)$$

We use K_d olivine values from [6] and K_d orthopyroxene values, average from [1,2], to calculate when they are in equilibrium with the orange glass composition. The considered ranges of K_d values are 0.26-0.33 for olivine and 0.27-0.32 for orthopyroxene, resulting in equilibrium compositions of $Fo_{77.8\text{-}81.7}$ and $En_{78.4\text{-}81.1}$.

The resulting cross-over pressure for opx is between 2.3 and 2.7 GPa (Fig. 3). It has been shown [6] that the multiple saturation point (msp) of the orange glass is between 2.5 and 3.0 GPa depending on the oxygen fugacity. The msp is thus close to the calculated orthopyroxene cross-overs. The density cross-overs for the orange glass with olivine are outside the pressure range of the Moon, as was the case for the green glass composition [2]

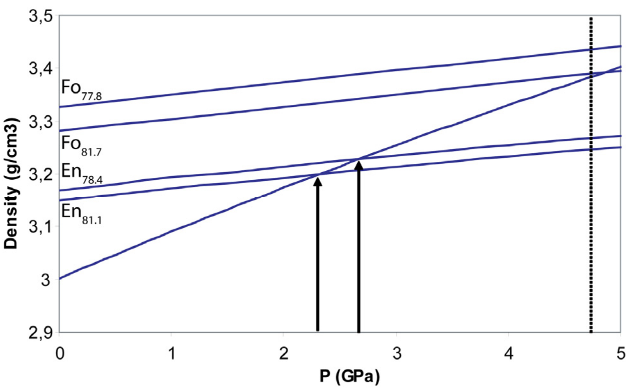

Figure 3. Density of molten orange glass, olivine ($Fo_{77.8\text{-}81.7}$) and orthopyroxene ($En_{78.4\text{-}81.1}$) as a function of pressure at liquidus temperatures, arrows indicate cross-overs. The pressure of the Moon's center (4.7 GPa) is indicated with the dotted line

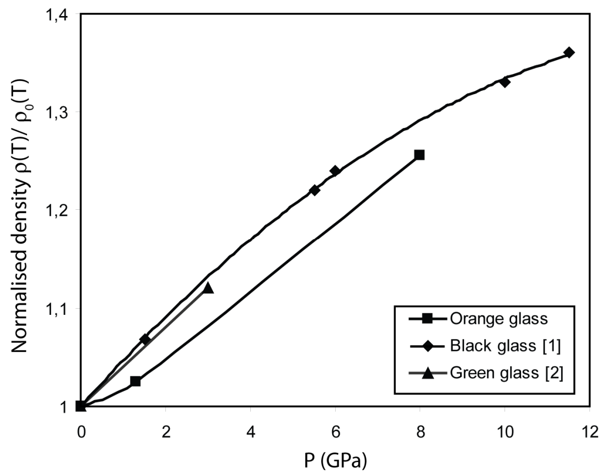

Figure 4. Compression curves of the orange, black [1] and green [2] glass. $\rho(T)$ is the liquid density at P-T of the sink/float bracket, and $\rho_0(T)$ is the calculated 1 bar liquid density [7] at T of the sink/float bracket.

In Figure 4 we compare the orange glass compressibility as constrained from our experiments with that of the other studied lunar glass compositions [1,2]. It appears that at low pressure (<3 GPa), the orange glass has a lower compressibility than black and green glass [1,2]. The black glass data set, which is by far the most comprehensive in terms of P-T coverage, shows an apparent decrease in compressibility with pressure whereas the orange glass shows an apparent increase with pressure. We note that the slope derived from our one high-pressure data point needs to be viewed with caution, since it was derived from a single neutral buoyancy experiment, which awaits conformation by sink/floats at lower and higher pressures. The next step in this work is to increase the overall P-T coverage to better constrain the compression curve. Complementary in situ liquid density measurements [8] are also planned.

References: [1] Circone and Agee (1996) *GCA 60,* 2709. [2] Smith and Agee (1997) *GCA, 61*, 2139. [3] Delano (1986) *Proc LPSC 16,* D201-212 [4] Agee and Walker (1988) *JGR*, 93, 3437-3449 [5] Delano (1990) *Proc LPSC 20*, 3-12 [6] Krawcynski and Grove (2008) *LPSC, abstract 1231.*[7] Lange (1997) *CMB 130*, 1-11 [8] van Kan (2008) *LPSC, abstract 1020.*

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