A REVISED MODEL FOR THE ASCENT AND ERUPTION OF GAS-SATURATED LUNAR PICRITIC MAGMA BASED ON EXPERIMENTS AND LUNAR SAMPLE DATA. M. J., Rutherford[1], J. W., Head[1], A. E. Saal[1], L. Wilson[2], and E. Hauri[3]. [1]Dept. of Geological Sciences, Brown University, Providence RI 02912 (malcolm_rutherford@brown.edu), [2]Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK, [3]DTM Carnegie Institute of Washington, DC 20015.

Introduction: Prior to the discovery of H_2O dissolved in the picritic lunar glass beads [1], models for the eruption of lunar picritic magmas involved both a column of melt extending deep into the lunar mantle, and a gas-assisted lift of the magma to achieve explosive eruption [2,3,4,5]. In a H-free moon, first gas phase formation would have involved the oxidation of reduced C (graphite) to produce a CO-rich gas (6). As little as 50 ppm C in a picritic magma was calculated as sufficient to cause fragmentation of the picritic orange glass magma as it erupted [5]. Additionally, as much as 400 ppm S and possibly other volatile species were partitioned into the gas phase associated with the orange glass magma during ascent [7]. However, recent experimental studies [8] indicate that gas formation is more complex than indicated in the above referenced studies, and needs to be significantly modified to incorporate CO solubility as Fe-carbonyl at lunar interior oxidation states. Further, the models of conduit flow do not adequately evaluate the dike formation stage of a fire–fountain eruption as is done in the model of [9]. The purpose of this paper is to integrate new data on C-O-H-S volatile speciation and solubility in picritic magmas into a revised eruption model based primarily on the dike formation process proposed by [3,4].

The Data: The melt inclusions trapped in olivine microphenocrysts of the A17 orange glass (74220) contain dissolved C and H ranging from 4 ppm C and 1400 ppm H_2O down to 0.4 ppm C and 800 ppm H_2O [10,11]. In the same inclusions, S decreases from 860 to 700 ppm as C and H decrease. The orange glass beads formed during the surface fire fountain eruption contain an average of 0.45 ppm C, 10-30 ppm H_2O, and 250 ppm S. Diffusion-loss profiles and diffusion data suggest post-bead formation loss was relatively minor for C and S but was significant for H [1].

Experimental data for C and H solubility in a graphite-saturated, orange glass melt at lunar oxidation states (Fig. 1) show how the C content varies with pressure in vapor-saturated magma with ~1000 ppm dissolved H_2O. Using this
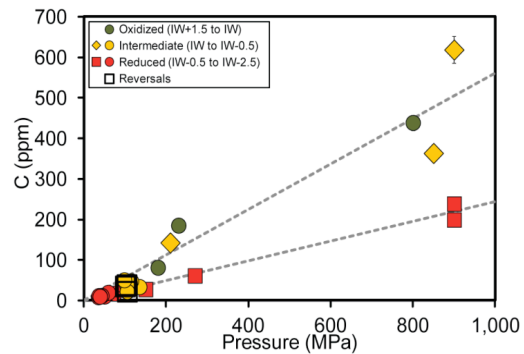

Fig. 1. C-solubility in lunar picritic green and orange glass melts as a function of fO_2 [8]. The C species present at IW and higher fO_2 values is carbonate (top curve); at IW-0.5 and below (bottom curve) the species are $Fe(CO)_5$ and minor CH_4; data for the A17 orange glass at IW-1 lie on the lower curve.

solubility curve, the C in the melt inclusion glasses indicate that the inclusions were trapped at pressures of 17 to 2 MPa, i.e., at depths of 4 to 0.45 km in the moon [11,12]. A CO-rich volcanic gas (X_{H2O}=0.1) would have been present and growing in volume during this ascent, and based on the presence and size of gas bubbles in the melt inclusions, possibly was present at depths approaching the magma formation depth of 500 km [13]. A conservative estimate of the C-O-H-S species volatiles dissolved in the orange glass magma at 4 km depth comes from the gas-rich melt inclusion analyses. From this depth to 0.5 km, where the last melt inclusion was closed off, the orange glass melt lost 3.5 ppm by wt C (8 ppm CO), 650 ppm H_2O (65 H_2), and 150 ppm S [12], probably speciated as H_2S and COS in the gas phase [14].

Gas-Volume: If no gas-melt separation occurred, the gas volume calculated above would yield a melt with ~2% vol. % gas at 500 m depth. Further partition of H, C and S into the gas to

reach the concentration found in the beads (Fig.1) yields a total gas phase volume of 90%. A conduit flow model [4] indicates that this would be a sufficiently large gas volume to cause fragmentation as the orange glass magma exited from the surface vent. However, the rise rate of the magma induced by 2 vol. % gas bubbles at 5 km is unlikely to be sufficient to keep gas bubbles (and crystals) from separating from the rising melt-rich A17 magma (4). Additionally, the conduit flow model dose not explain how the magma –filled conduit came to exist initially. A further problem is illustrated by the calculation of the energy released per unit of magma volume by release and expansion of volatiles [9]. This calculation used a similar near-surface volatile abundance and it indicated the maximum speed at which pyroclasts would be ejected on the moon from purely explosive activity is much less than that required to produce the 100 km range indicated by the A17 dark mantle deposit. Finally, the conduit steady state flow model does not explain how the conduit came to exist initially. To circumvent these problems we propose a new model that integrates the dike emplacement process envisioned by [4] and the constraints on magma degassing described above.

A Revised Model: The existing model for emplacement of a picritic dike into the lunar crust [3,4] involved a gas generated from graphite oxidation; the model appears even more viable now that we have determined that CO is soluble in such magmas as Fe-carbonyl. The key to the dike emplacement is a crack-tip propagation process where gas from the melt migrates to the crack tip. However, using graphite oxidation, the gas was difficult to generate at depths greater than 8 km in the lunar crust. The formation of a CO-rich gas in a rising magma with dissolved Fe-carbonyl has no such depth constraint; it would begin when the pressure on the rising melt reached that for Fe-carbonyl saturation, i.e., 35 ppm at 200 MPa or 50 km depth (Fig. 1). The transitory low-pressure crack propagation event at the crack/dike tip would allow bubble-bearing melt to rise into the newly formed tip [3], and the low viscosity of the melt would allow gas to rise in the melt and collect at the tip. With a growing gas volume in the melt, the propagation process would be increasingly rapid.

The rapid rise of the dike though the crust is fundamentally important in explaining the following basic aspects of the picritic glass deposits: (1) the general lack of phenocrysts in the high-liquidus temperature picritic magmas [15,16]. A slow rise though the crust would certainly result in some crystal growth due to heat loss through the dike walls; (2) the magma rise appears to have been accompanied by sample oxidation as indicated by Ni-rich rims on Fe-metal grains [17] and irregularly distributed Fe^{3+} in the glass beads [18]. This requires a process where the gas phase and melt were not maintaining chemical equilibrium; (3) while the process of emplacement had to be sufficiently rapid to prevent bubbles from escaping from the melt in the near-surface dike in order to achieve the observed fragmentation (small bead size means extremely thin bubble walls), it had to allow small-scale gas-melt separation at depth. The fact that picritic magmas have only been found as explosively erupted bead deposits (not as lavas) seems well explained by this model of magma rise from mantle depth in the moon. The picritic magma eruptions reached the lunar surface only in the explosive dike emplacement stage. Once the dike was completed to the surface, it appears that additional gas lift was not sufficient to help degassed picritic magma reach the lunar surface. This observation is a logical outcome given the high rate of magma rise during dike formation, and the low viscosity of the orange glass (and other lunar picritic) magmas.

References: [1] Saal A.E. et al. *Nature, 454*, p.192, 2008. **[**2] Housley, 1978; [3] Head et al., *JVGR*, 107, 5001, 2002. [4] Wilson and Head, *GRL*, 30, 1605, 2003. [5] Rutherford and Papale, *Geology*, 37, 219, 2009, [6] Sato, M., LSC 7, 1976. [7] Fogel and Rutherford, *GCA*, 59, 201, 1995. [8] Wetzel et al., PNAS, 110,. [9] Wilson et al., LPSC, 1223, 2014. [10] Hauri E.H. et al., *Science, 333*, 213. [11] Hauri, et al., EPSL, 409, 252-264, 2015. [12] Wetzel et al., LPSC 45, 2014. [13] Krawczinski, M. and Grove,T, *GCA*., 79, 1, 2012. [14] Zhang, C., and Duan, Z., GCA 73, 2089, 2009. {15] Heiken, G., et al., GCA, 38, 1703, 1974. [16} Weitz, C et al., MPS, 34, 527, 1999. [17] Weitz et al., *GCA*, 61, 2765, 1997. [18] McCanta et al., LPSC 46.