

EFFECTS OF C-O-H DEGASSING AND BUBBLE GROWTH ON EXPLOSIVE LUNAR VOLCANIC ERUPTIONS. P. Moitra¹, A. Mallik¹, J. J. Barnes² J. C. Andrews-Hanna². ¹Department of Geosciences, University of Arizona, Tucson, AZ; ²Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ; pmoitra@arizona.edu

Introduction: Explosive eruptions were common on the Moon as is evident from the widespread occurrence of pyroclastic deposits [1-4]. While estimates on the C-O-H volatile contents in lunar melts exist [5-6], the effects of joint C-O-H solubility on volatile degassing and bubble growth, and their subsequent effects on eruption explosivity remain largely unexplored in existing eruption models. Furthermore, an outstanding question is: which volatile species among H₂O, CO₂, H₂ and CO was the main propellant of explosive lunar volcanism [7-10]?

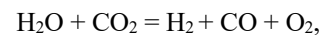
The solubility of dissolved volatiles decreases due to the decrease in pressure as magma ascends to the surface during volcanic eruptions [11]. For fast decompression during explosive eruptions, magma becomes supersaturated in dissolved volatiles causing exsolution of the dissolved volatiles into bubbles. Volatile supersaturation is reached in the melt due to diffusion limited volatile transfer which contributes to bubble growth as opposed to equilibrium exsolution of volatiles during magma ascent. The nucleated bubbles in magma continue to grow due to decompression and diffusion of remaining volatiles dissolved in the magma as it ascends to the surface. The dynamics of bubble growth in ascending magma is the key process that drives effusive versus explosive emplacement of magmas on planetary surfaces.

Using a joint H₂-H₂O-CO-CO₂ solubility model, we investigate the effects of volatile degassing and diffusive bubble growth on magma ascent dynamics and explosivity during fire-fountain style eruptions on the Moon.

Modeling bubbly magma ascent: The decompression- and diffusion-induced growth of bubbles are coupled with the ascent of bubble-bearing magma through a volcanic fissure during explosive fire-fountain style eruptions on the Moon. Unimodal bubbles are assumed to be homogeneously distributed in the ascending magma [13]. The number density of bubbles is based on the observed values from the terrestrial explosive eruptions, where each bubble is assumed to be surrounded by a melt shell. We further assume that lunar picritic melts ascended through volcanic fissures similar to typical terrestrial explosive eruptions of mafic magma [14]. The model also assumes a closed system condition along with an isothermal and steady-state ascent of magma during explosive eruptions [15].

The bubble growth model includes the diffusive flux of all four (H₂, H₂O, CO and CO₂) volatile species dissolved in the magma. Along with the dissolved H₂O and H₂, solubility of dissolved C species were included as CO [6] and CO₂ [16]. The diffusivities of C-O-H volatiles [18] were included in bubble growth calculations, where the diffusivity of CO is approximated as that of CO₂. Using the equation of state of [19], the pressure of gas inside bubbles was calculated from the mass and momentum balance of a growing bubble in the ascending magma.

The initial magma pressure was varied up to ~260 MPa in the model, based on the saturation pressure of the initially dissolved C content in the range of 4-64 ppm [6]. The initial dissolved bulk H content was varied in the range of ~100-1400 ppm [5], whereas the initial dissolved H₂ and H₂O content was calculated using the gas phase reaction:



along with the solubility formulations in [7-8] at a magma temperature of 1350°C. The models are run at oxygen fugacity (f_{O_2}) of Iron-Wüstite buffer (IW) to 2 log units below IW (IW-2), suitable for lunar magmatic conditions [12].

The fragmentation of low viscosity mafic magma during fire-fountain style eruptions might take place at or above the surface [10, 20]. Accordingly, the model was run until it reaches a pressure of ~10³ Pa [8] to evaluate the degree of magma vesiculation, which likely plays the key role in magma fragmentation and the generation of lunar pyroclasts [21].

Given small contents of dissolved H₂, CO and CO₂, the viscosity of magma depends on dissolved H₂O content along with the magma composition and temperature [22]. The competing effects of surface tension and silicate melt viscosity define the degree of deformation of bubbles in magma, which can significantly affect magma viscosity and is included in our model [23].

A set of ordinary differential equations that couple mass and momentum balance of bubble growth and bubbly magma ascent in a volcanic fissure with relevant friction factor [19] were modeled using implicit finite difference.

Results and discussion: The partial pressures of H₂, CO and CO₂ volatile species in bubbles decrease with decreasing depth due to a decrease in gas pressure, P_g , as a result of bubble growth (Fig. 1). However, the exsolution of dissolved H₂O into existing bubbles increases

at shallow depths that cause the relatively larger values of $p_{\text{H}_2\text{O}}$ as compared to p_{CO_2} , p_{CO} and p_{H_2} . This increased exsolution of H_2O drives the growth of bubbles, and thus the gas volume fraction of magma (Fig. 2), required for magma fragmentation. While dissolved volatile contents may vary with oxygen fugacity, the small contents of H_2 , CO_2 and CO do not significantly affect bubble growth, and thus, the development of high vesicularity in ascending magma.

The results from this study show that for a wide range of CO , CO_2 , H_2O and H_2 content, magma reaches a threshold vesicularity of $\sim 70\%$ (Fig. 2), required for magma fragmentation and formation of volcanic pyroclasts under lunar conditions. While CO_2 , CO and H_2 likely provide the initial buoyancy to magma, the vesicularity remains small ($<10\text{-}20\%$) until H_2O starts to exsolve at a shallow depth. These results are independent of the oxygen fugacity in lunar magmas in our model. The diffusive flux of H_2O causes an increase in melt viscosity, increasing gas pressure that in turn increases bubble radius and magma vesicularity.

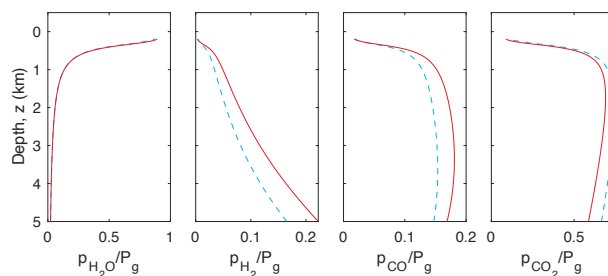


Fig. 1. Representative model results showing the mole fraction (shown as the ratio of partial pressures and the total gas pressure, P_g) of volatile species H_2O , H_2 , CO , and CO_2 as a function of depth (z). Initial gas pressure is ~ 50 MPa.

Given a fast decompression rate, any significant open system gas loss during such explosive eruptions is unlikely. Furthermore, any degree of crystallization due to H_2O degassing would increase magma viscosity, likely contributing to bubble growth. We find that the partial pressure of H_2O inside bubbles stays higher than other volatile species at shallow depths independent of oxygen fugacity of IW-2 to IW (Fig. 3). On the other hand, for a small initial H_2O content of ~ 100 ppm, all else being equal, magma reaches only $\sim 10\text{-}20\%$ vesicularity at the surface. Thus, H_2O plays a key role for increasing vesicularity during lunar volcanism, governing magma fragmentation.

Conclusions: Our coupled bubble growth and magma ascent model results for a suitable parameter space show that partial pressure of H_2O , as compared to the H_2 , CO and CO_2 volatile species, would be higher in

bubbles at shallow depths from the surface of the Moon. This exsolution of H_2O drives bubble growth and increases magma vesicularity from 20% to 70%. For lower values (~ 100 ppm) of dissolved H_2O content, our model results exhibit that gas volume fraction in magma would remain low, and the criterion ($\sim 70\%$ gas volume percent) for magma fragmentation would not be met. Thus, the findings from this study indicates that H_2O is likely the main driver for magma fragmentation, and therefore, a wet Moon (mantle sources) is a favorable condition for explosive volcanic eruptions on the Moon.

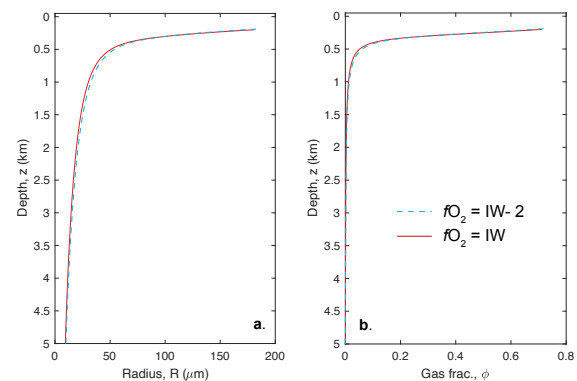


Fig. 2. Representative results of coupled bubble growth and magma ascent model show that the bubble radius, R , and gas volume fraction, ϕ , increases with decreasing depth, z . Results corresponding to calculations in Fig. 1.

References:[1]Heiken et al. (2009), *Geochim cosmochem Acta*, 38, 1703-1718.[2]Delano and Lindsay (1983), *JGR*, 88, B3.[3]Trang et al. (2017) 283, 232-253.[4]Wilson and Head (2017) *Icarus* 283, 146-175.[5]Hauri et al. (2011) *Science*, 333, 213-215.[6]Wetzel et al. (2013), *PNAS*, 8010-8013.[7]Hirschmann et al. (2012), *EPSL*, 345, 38-48 . [8]Newcombe et al. (2017), *Geochim Cosmochim Acta.*, 200, 330-352.[9]Wilson and Head (2018) *GRL.*, 45, 5852-5859. [10]Lo et al. (2021) *JGR*, 126, e2021JE006939.[11]Gonnermann and Manga (2007) *Ann-Rev FluidMech*, 39, 321-356. [12]Wadhwa (2008), *Rev Mineral Geochem*, 68, 493-510.[13] Moitra et al. (2018), *EPSL*, 500, 97-104.[14]Houghton and Gonnermann (2008), *Geochem*, 68, 117-140.[15]Mastin and Ghiorso (2001) *Contrib Mineral Petrol*, 141, 307-321.[16]Dixon et al. (1995), *J Petrol*, 36, 1607-1631.[17]Armstrong et al. (2015) *Geochim Cosmochim Acta.*, 171, 283-302.[18]Zhang and Ni (2010), *Rev Mineral Petrol*, 72, 171-225.[19]Zhang and Duan (2009) *Geochim Cosmochim Acta* 73, 2089-2102. [20]Parfitt (2004) *JVGR*, 134, 77-107.[21]Wilson and Head (1981) *JGR.*, 86, 2971-3001.[22]Hui and Zhang (2007), *Geochim Cosmochim Acta.*, 71, 403-416. [23]Pal (2003) *EPSL*, 207, 165-179.