VERIFYING LUNAR MAGMATIC VOLATILE CONTENT USING MODELS FOR MAGMA ASCENT AND ERUPTION.

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Introduction: Volatiles are valuable proxies for many planetary-scale geochemical processes. Therefore, quantifying the past and present volatile content of the Moon is a useful tool for understanding its formation, thermal evolution, and magmatic history [1, 2, 3]. Volatile species dissolved in magmas can be transported to the lunar surface via volcanic processes; understanding these processes gives useful insights into the lunar interior.

Lunar sample perspective: Geochemical analysis of returned samples and lunar meteorites has been crucial for measuring the abundances of different volatile species in bulk rock samples and within mineral phases [4]. These measurements are extremely valuable for calculating the volatile content and diversity of the lunar mantle, however, uncertainties exist for several reasons. First of all, partition coefficients for various volatile species may not be well constrained as they are dependent on certain conditions, such as pressure, temperature, and oxygen fugacity. The partition coefficients of all volatile species, so far, have not been quantified across the full parameter space present within different planetary bodies [5]. Secondly, volatile-bearing phases present in samples, such as apatite and melt inclusions, may have undergone post-crystallization diffusion of volatiles [6], meaning that measurements underestimate the total volatile content of the lunar interior. Finally, lunar samples may have a relatively low volatile content, meaning that terrestrial contamination is a significant source of error [7]. Overall, the initial volatile contents of the lunar mantle, parent melts, and magmas have yet to be constrained with certainty.

Theoretical model perspective: As volatile magmatic species, such as H_2O, CO_2, SO_2, and CO, play a fundamental role in planetary volcanic systems [8], we propose an alternative volcanological approach for inferring the volatile content of the lunar interior. Melt inclusions present within picritic pyroclastic glass beads, which were found in all returned soil samples, provide evidence for past explosive volcanic activity on the Moon [9]. These pyroclastic glasses provide a wealth of information on the Moon's composition, internal conditions, and volatile content. Based on their enrichment in compatible elements, Mg and Ni, we know that these glasses sample primitive mantle material that underwent very little fractional crystallization [10]. We also know that, using mineral phase relationships, the glass beads sample a distinct, much deeper source region to the mare basalts [11, 12].

The picritic glass beads are divided into five main compositional groups: green (very low-TiO_2), yellow (low- to intermediate-TiO_2), and orange, red, and black (high-TiO_2) [13, 14].

Our approach is to simulate the ascent of picritic magma within the lunar crust, with a numerical model for magma ascent. We will then model the eruption of these magmas onto the lunar surface with a pyroclast ejection model, and compare the results of our modelling with lab measurements of the volatile abundances of pyroclastic glass beads [4, 7].

Method: To investigate the effect of initial volatile content on magma ascent and eruption in a quantitative way, we utilize a terrestrial magma ascent model, which has recently been used adapted for lunar applications [15]. The 1-dimensional, Fortran 90-based model uses over 100 different input parameters to quantify magma ascent dynamics within a cylindrical volcanic conduit [16, 17]. The model is capable of simulating two dissolved volatile species within the magma at once. We model two main volatile combinations: (1) H_2O and CO, and (2) H_2 and CO. Based on thermochemical modelling, it has been calculated that CO and H_2 would be the most abundant volatiles present during lunar volcanic eruptions [18]. However, we also choose to model H_2O for several reasons: there is a greater amount of information on the solubility of H_2O at different pressure and temperature conditions compared with H_2 [19, 20]; it may be the most abundant H-species at the pressure and temperature conditions within the lunar mantle [5]; and to facilitate comparisons with terrestrial volcanism, where H_2O is the dominant H-species [21]. We modelled a wide range of values, up to 1-2 wt.%, for the initial magmatic H_2, H_2O, and CO content, based on measurements of lunar and terrestrial samples [4]. We used equivalent abundances of H_2 and H_2O, converting between each based on their relative molecular weights.

We modelled the ascent of an intermediate-Ti picrite. Previous modelling has shown that the composition of picrite modelled does not have a significant impact on the model outputs, therefore, we chose to model a single composition. From a very low-TiO_2 to a high-TiO_2, the main change in model outputs is that melt viscosity changes by 1 order of magnitude [15].

A sensitivity analysis was performed on the magma ascent model with two main aims: (1) to quantify the relationship between various input parameters (i.e., temperature and pressure at the base of the conduit, H_2

or H_2O content, CO content, and conduit radius) and model outputs for parameters within the conduit (i.e., gas volume fraction, exit pressure, exit velocity, and mass flow rate), and (2) to calculate a mean value and standard deviation for the exit velocity of pyroclasts at the vent. The sensitivity analysis was performed using the Dakota toolkit [22] an open-source software from Sandia National Laboratories. We adopted a Latin hypercube sampling technique, a technique where each input parameter is varied within a set range in a more efficient way than systematic or random sampling [23, 24]. We will complete 10,000 model simulations in order to create a robust mean value and standard deviation for the exit velocity of the pyroclasts.

Results: We have conducted a preliminary sensitivity analysis with 1000 model simulations, assuming a maximum initial H_2O and CO abundances of 2000 and 1000 ppm respectively (Fig. 1). Figures 1d and 1e show the relationship between initial H_2O and CO abundance and magma exit velocity where exit velocity increases with initial volatile content. Our results predict that a magma with an initial H_2O content between 50 and 2000 ppm would erupt with a mean exit velocity between 30 and 40 m s^{-1}. These results can be used to predict the mean exit velocity for specific initial volatile abundances, for example, a magma with an initial CO content of 500 ppm would erupt with a mean exit velocity of 33 m s^{-1}.

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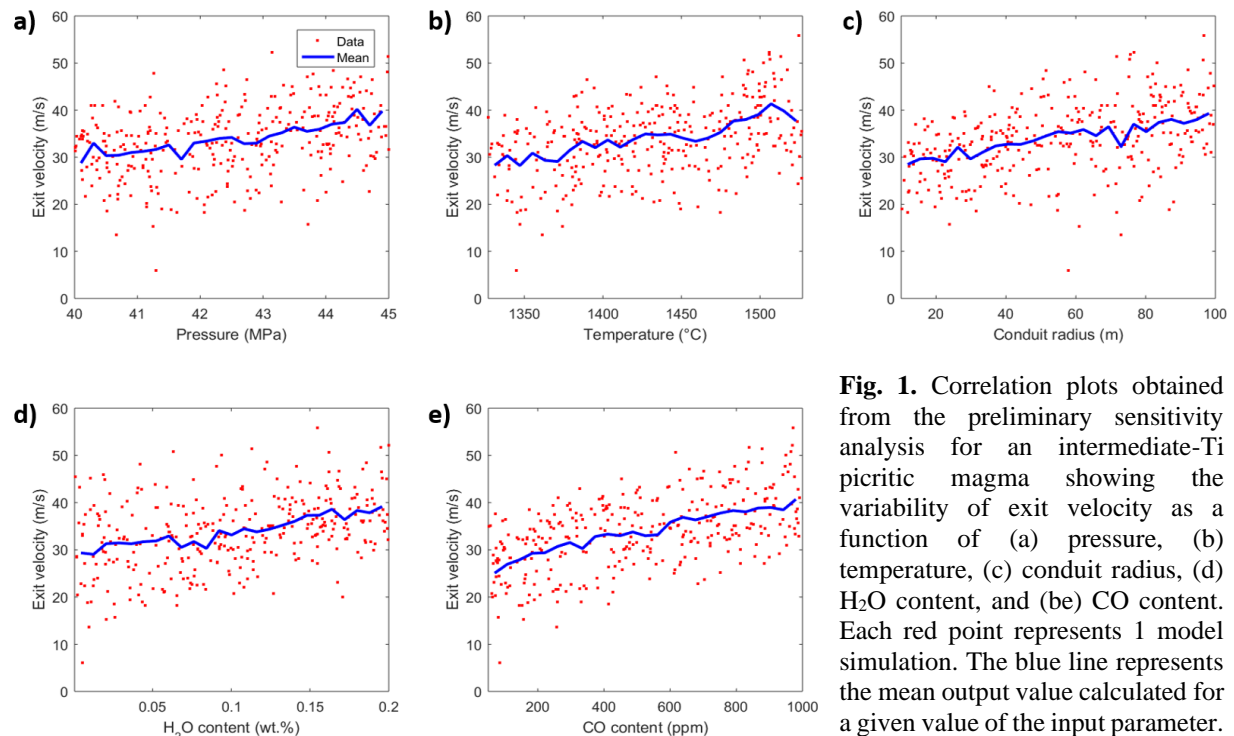

Fig. 1. Correlation plots obtained from the preliminary sensitivity analysis for an intermediate-Ti picritic magma showing the variability of exit velocity as a function of (a) pressure, (b) temperature, (c) conduit radius, (d) H_2O content, and (be) CO content. Each red point represents 1 model simulation. The blue line represents the mean output value calculated for a given value of the input parameter.