PHREATOMAGMATIC ACTIVITY ON THE MOON: POSSIBILITY OF PSEUDOCRATERS ON MARE FRIGORIS. José H. Garcia[1] and José M. Hurtado, Jr.[2], [1,2] UTEP Department of Geological Sciences and UTEP Center for Space Exploration Technology Research, 500 West University Avenue, El Paso, Texas, 79968, [1]jhgarcia3@miners.utep.edu,[2]jhurtado@utep.edu.

Introduction: New, high-resolution images from the Lunar Reconnaissance Orbiter (LRO) allow us to take a closer look at geologic features that were not visible in older photography from the Apollo and Clementine missions. Some of these features could be pseudocraters (rootless cones). Pseudocraters are volcanic landforms that are produced by steam explosions resulting from the interaction between lava flows and surface or near-surface water. On the Moon, such eruptions could have been triggered by interactions between mare lava flows and ice in the lunar regolith. The discovery of water and hydroxyl on the Moon by the Moon Mineralogy Mapper (M^3) [1] and the Lyman Alpha Mapping Project (LAMP) observations of the plume generated by the Lunar Crater Observation and Sensing Satellite (LCROSS) impact [2], raises the possibility that lava-water interactions occurred in the past on the Moon.

However, in order for this interaction to have occurred, a certain amount of water/ice must have been present in the lunar regolith. Was there enough ice at the lunar surface to trigger the formation of pseudocraters caused by phreatomagmatic interactions? Is it physically possible for pseudocraters to have developed, taking into consideration the unique planetary conditions on the Moon? This contribution addresses both questions, by presenting results of both modeling and remote sensing analysis.

Study Area: The region of interest is located in Mare Frigoris just north of Mare Imbrium, between the Fontenelle and Plato craters (56°30'2.86"N, 16°18'47.33"W) (Figure 1). In this area, several clusters of crater-like depressions can be seen on top of basaltic lava flows (Figure 1). Although they resemble simple impact craters, they have unusual characteristics. For example, they are very close together, in an area where it can be seen that the density of craters of that size is low (Figure 1). Narrow angle camera (NAC) and wide-angle camera (WAC) images from the Lunar Reconnaissance Orbiter Camera (LROC) show that the distance between the features is small and they appear to be on the edge of a lava flow, similar to how pseudocraters on Earth are clustered and where they form [3,4] (Figures 1, 2). In addition, there is an apparent absence of an ejecta blanket around the features, and they are irregular in shape, unlike the near-circular shape of an impact crater (Figure 1). The study area also lies in a region with inferred high hydrogen and hydroxyl content [5,6] (Figure 3). It is therefore possible that there was enough ice in the regolith in this area to produce phreatomagmatic eruptions coincident with mare volcanism.

Mechanisms of Pseudocrater Formation: A lava flow can heat subsurface ice to the point of vaporization. The confined water vapor will exert enough pressure on the overlaying lava flow to blast through the caprock. Lava can then fill the hole left over from the explosion, and the process can repeat. Each eruption produces a deposit of pyroclastic material around the crater that builds up into the conical landform. Pseudocraters in Myvatn, Iceland almost always have the crater floor above the median height of the surrounding plains, and have a crater/cone diameter ratio of 0.5 [4].

Fagents et al. [4] developed a model for the explosion dynamics of pseudocraters to test the possibility of lava-ground ice interactions on the surface of Mars. The Fagents et al. [4] model calculates the trajectories of ejected material and how far it lands from the explosion source. It makes predictions for the morphology of the resulting pseudocrater as well as the relative amounts of water and lava responsible for the eruption. Lava thickness, initial gas pressure, and atmospheric conditions are input parameters for the model. The results for Mars show that considerably less water/ice is needed for pseudocrater formation, compared to Earth [3].

Methods: The region of interest for this study was selected by analyzing WAC images of areas that show high hydrogen and hydroxyl content (Figure 3). After finding areas that also had unusual clusters of possible pseudocraters, NAC images were obtained for those sites to study them more closely. The Fagents et al. [4] model was modified and parameters chosen to account for the surface conditions on the Moon. For the model, the lava was assigned a density of 2,980 kg/m^3 [7], and thicknesses were varied between 1-10 m. The radius of the spherical gas region (zone of flash vaporization of water) was varied between 1-13 m. The temperature inside the gas region used was 573-800k [3,7], and an ejection angle of 70° was assumed. Each time the model was run we changed a different parameter.

Results and Conclusions: The results of our model runs are summarized in Table 1. The model determined that in order to produce a pseudocrater with a diameter of 450 m (similar in size to the circular features shown in Figure 2) only 245 kg of water vapor are needed. This amount of water corresponds to the simulation using a lava thickness of 10 m and a gas region of 9 m radius and is equivalent to 40 ppm of water in the lunar regolith. This amount of vapor is very low compared to the 15,000 kg of gas needed to form a pseudocrater of similar size in the Martian surface [3]. Previous studies suggest a range for water concentration in the lunar regolith of 800 ppm to 5.6% [2,5,6]. Our model yields values between 6 and 79 ppm. Therefore the amount of water needed to produce phreatomagmatic landforms such as those hypothesized at Mare Frigoris is far below what it is presumed available in the regolith. The implication of this result is that there is enough water in the lunar for phreatomagmatic eruptions to have occurred, and that it is physically possible for the pseudocraters to have developed. This water may be a useful resource for future human exploration of the Moon.

Table 1. Effects of changing model parameters in final crater diameter

Gas Region Radius * (m)	Lava Thickness (m)	Gas Mass H_2O ** (kg)	Water Concentration *** (ppm)	Diameter (m)
3	1	1	6	490
4	2	5	10	435
5	3	14	15	470
7	5	60	25	594
7	6	71	29	470
8	7	123	30	544
8	8	140	39	450
9	9	222	43	524
9	10	246	48	450
10	11	368	52	520
10	12	400	57	452
11	12	529	57	595
11	13	572	61	523
11	14	615	66	462
12	14	794	66	596
12	15	849	70	532
12	16	905	75	476
13	10	1213	79	545

Notes:
* Assuming an spherical gas region.
** Amount of water vapor needed.
*** Weight percentage of H_2O needed in the Lunar regolith to create a pseudocrater.

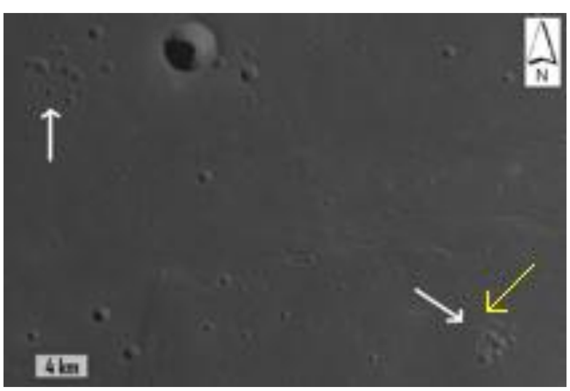

Figure 1. *LROC WAC image M119965687ME showing possible clusters of pseudocraters (white arrows) located in Mare Frigoris (56°30'2.86"N, 16°18'47.33"W). Yellow arrow points at inferred edge of lava flow. Illumination is from the southeast.*

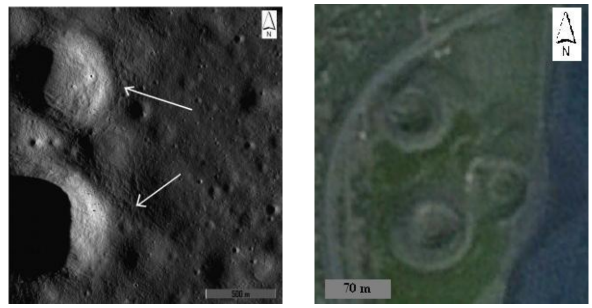

Figure 2. *(Left) LROC NAC image M11759731 showing the features in the lower right corner of Figure 1. White arrows are pointing at two of these possible pseudocraters. Illumination is from the east. (Right) Pseudocraters located in Myvatn, Iceland for comparison with the lunar candidates (image from* Google Earth*).*

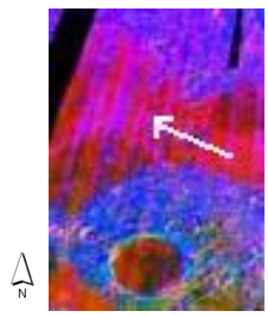

Figure 3. *Section of the map from Clark et al [1] showing the distribution of water and hydroxyl on Mare Frigoris. Blue, cyan, magenta and pink areas = hydrogen and/or hydroxyl. Arrow points to the region shown in Figure 1. Orange feature surrounded by blue in the lower portion of the image is Plato crater (95 km diameter).*

References: [1] Clark et al. (2010) Water and Hydroxyl on the Moon as seen by the Moon Mineralogy Mapper (M^3), *LPSC XLI*, abstract #2303. [2] Colaprete et al., Detection of Water in the LCROSS Ejecta Plume, *Science*, v. 330 p. 463-468. [3] Greeley, R. & Fagents, S.A. (2001) Icelandic pseudocraters as analogs to some volcanic cones on Mars, *JGR*, v. 106, p. 20527-20546. [4] Fagents et al. (2002) Rootless cones on Mars: A consequence of lava-ground ice interaction, *Geol. Soc. London Spec. Pub.*, v. 202, p. 295-317. [5] Gladstone et al. (2010) LRO-LAMP Observations of the LCROSS Impact, *Science*, v. 330, p. 472-476. [6] Pieters et al., Character and Spatial Distribution of OH/$H_2$0 on the Surface of the Moon Seen by M^3 on Chandrayaan-1, *Science*, v. 326, p. 568-572. [7] Rumpf et al., (2008), *LPSC XXXIX*, abs #2259.