EVALUATING BOILING CURVES AND THEIR IMPLICATIONS FOR IMPACT-GENERATED HYDROTHERMAL SYSTEMS ON MARS. M. R. Westenberg[1,2], E. G. Rivera-Valentín[1,3], K. L. Lynch[1], and D. A. Kring[1]; [1]Lunar and Planetary Institute (USRA), Houston, TX 77058, [2]School of Chemical and Biomolecular Engineering, Georgia Institute of Technology, GA 30318 (mwestenberg@gatech.edu), [3]Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723.

Introduction: Hydrothermal activity can be produced by an impact on a terrestrial body containing fluid or ice in the planetary crust (e.g., [1,2]). Impact cratering generates heat and a permeable subsurface structure for circulating fluids [2], which could support thermophilic organisms [3]. Such craters may thus be promising locations to discover biosignatures on Mars [3]. This is demonstrated by the ~180 km diameter Chicxulub impact crater on Earth, which contained a microbial population in a hydrothermal system that may have been habitable for over 2 million years [4]. Chicxulub is the only large, intact peak ring basin on Earth and is, therefore, often used as a model for hydrothermal systems on Earth and Mars (e.g., [2]).

Several factors may limit the habitability of impact-generated hydrothermal systems, such as temperature, pressure, water activity, and fluids in a boiling vs liquid state [5]. Thermophilic organisms require temperatures between 50°C and 120°C [4], and liquid water, whose stability is affected by its water activity, a measure of the amount of free water molecules in an aqueous system, where a value of 1 indicates pure water and a value of 0 indicates there is no water available [6]. Almost all microbial species require a water activity above 0.6, limiting the habitability of Martian brines [7,8]. The combination of such factors determines where habitable regions may have existed.

Methods: Boiling curves to determine the extent of liquid stability were calculated for three different locations within 30, 100, and 180 km-diameter craters. Boiling curves for pure water were generated as a function of temperature and pressure using a vapor pressure equation [9]. Depth was calibrated to pressure using a standard hydrostatic equation down to the crater floor [10]. Below the crater floor and in locations without a lake, a geostatic pressure equation was used [3]. Grain density and rock porosity data were taken from Martian meteorite Lewis Cliff 88516 [11]. That plutonic shergottite was selected because impact-generated hydrothermal systems can extend far beneath the surface [12]. We also investigated the stability zones for brines of water activity 0.6 to 1. We modeled the stability of a ferric sulfate brine following the methods in [13] to investigate their temporal evolution during evaporation. Water activity was also evaluated as a function of time using temperature data from thermal models of Martian craters [2].

Results and Discussion: In a 180 km crater, impact melt is initially bounded by a peak ring and crater rim (Fig. 1a; [2]). After 200,000 yrs, the impact melt rock and basalt units at the center reach thermophilic temperatures and contain entirely liquid solutions (Fig. 1b). In the peak ring and crater rim, boiling only occurs in the top ~10 m of basalt and temperatures drop below the boiling point after 4,000 yrs (Fig. 1c,d). When thermophilic temperatures are reached, the conditions are, therefore, viable for sustaining life. In a 100 km crater, the melt has a lower temperature than the 180 km crater and solidifies more quickly. When thermophilic temperatures are reached, hydrothermal fluids are entirely liquid within the crater center after 20,000 yrs and after 500 yrs at the rim. In the peak ring, 120 °C is reached after 500 yrs and solutions are liquid except in the top ~5 m of basalt where boiling persists. A 30 km crater with a lake does not contain a melt sheet. Thermophilic temperatures below the boiling point of water are reached quickly throughout the hydrothermal system, meaning the effects of boiling do not have to be considered in those regions.

The effect of water activity. While the boiling curves in Figure 1 assume pure water, fluids on Mars likely resemble salty brines [7, 12]. We note that there is a discrepancy between boiling curves calculated using [9] with a water activity of 0.97 and those for seawater [13]. The calculated curve displays higher pressures than seawater at the same temperatures. For example, at T = 300, 400, and 500 °C, boiling occurs using the calculated vs seawater curves at P = 97 vs 84, 370 vs 279, and 1116 vs 539 bars, respectively. The

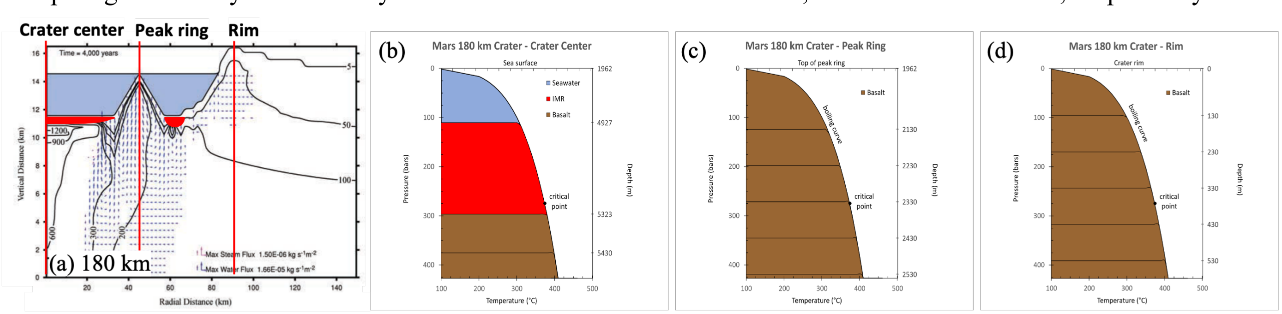

Figure 1: Boiling curves in Martian craters. **a.** Schematic diagram for a 180km diameter crater adapted from [1] and depicted under initial conditions (4,000 yrs after impact) with red lines indicating the locations that were evaluated with boiling curves. **b-d.** The boiling curves were generated for pure water under initial conditions with pressure and depth calibrated at the **b.** Crater center, **c.** Peak ring, and **d.** Rim of the 180 km crater as a representative example.

divergence is more pronounced at conditions exceeding 400 °C and 400 bars; we currently ignore the discrepancy because those conditions are beyond the potentially habitable zone being examined here. Using the calculated boiling curve as shown in Figure 2, the boiling period is shortened when the water activity decreases from 1 to 0.6, which increases the range of depths and temperatures where liquids can be found. In the modeled crater sizes, the change in water activity has a minimal effect on liquids at temperatures of 120°C or less. In locations with a crater lake, liquid water is stable throughout the entire depth of the rock regardless of the water activity. When a crater lake is not present, the depth at which boiling could occur decreases as the water activity is lowered. This indicates that lower water activities result in longer-lasting liquid availability. However, a lower water activity limits microbial growth; most organisms require >0.9 with 0.6 described as the minimum that can sustain life [7]. Therefore, at lower water activities, there is a tradeoff between a longer period of liquid stability within a crater and the amount of water available for growth. In the shallower areas where boiling is possible, the most habitable regions may have had a water activity between 1 and 0.6.

Water activity was also evaluated over time using existing thermal evolution models [2]. The deepest and most central areas tend to be hottest and evaporate faster, which causes rapid brine loss [1]. Regions near the surface and farther from the center tend to be cooler, evaporate slower, and have more stable brines. At a depth of 100 m, the temperature is low enough that the crater size and location within a crater has no effect on the brine lifetime. There is a rapid decrease in water activity within the peak ring at an earlier period than the central peak in the 100 and 180 km craters at a depth of 1000 m. This is the only exception to the pattern of shorter brine lifetimes in deeper and more central regions. This is due to excess generated heat in

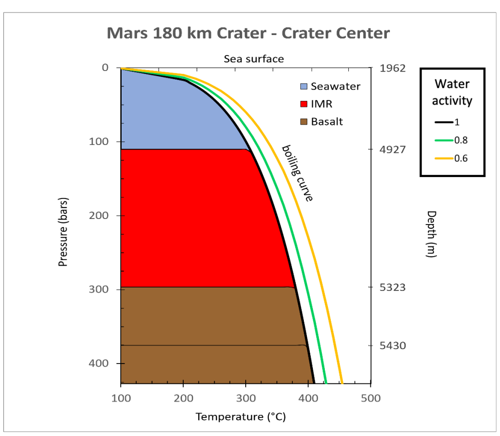

Figure 2: The effect of water activity on boiling curves in Martian craters. The boiling curves for water activities of 1, 0.8, and 0.6 are shown with solid colored lines. The center of the 180 km diameter crater was chosen as a representative example.

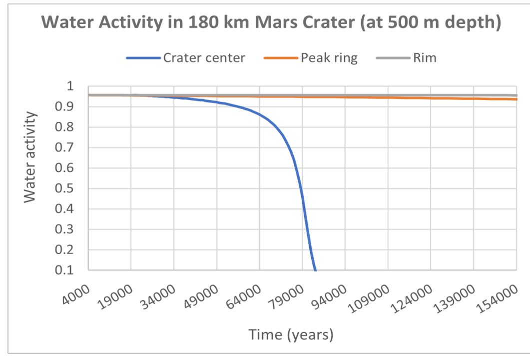

Figure 3: Change in water activity over time. The y-axis begins at the first point where temperature data is available [1]. The colored lines represent different locations within a crater. The change in water activity was analyzed in each crater size at three different depths; the 180 km crater at 500 m is shown as a representative example.

larger impacts which delays cooling in the central peak [2]. Most habitable locations contain a stable brine to allow the highest chance for a microbial population to develop [5]. This is likely to occur closer to the crater surface and farther away from the center (Fig. 3).

Conclusion: Impact-generated hydrothermal systems can create a habitable environment for microbes, as demonstrated by the Chicxulub crater [4]. Using boiling curves and thermal models, we find that liquids are available in each crater once thermophilic temperatures are reached. Lower water activity values increase the stability of liquids while limiting microbial growth, suggesting a biological tradeoff within boiling regions. Brines are also shown to be more stable near the surface and farther from the crater center. These findings provide a general understanding of where and for how long regions of habitability may have occurred within Martian craters. However, the findings also show that models are sensitive to several parameters, which will require further investigation.

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