MODELING HYDROTHERMAL ACTIVITY ASSOCIATED WITH MARTIAN IMPACT CRATERS: AN OVERVIEW.

O. Abramov, Department of Geological Sciences, University of Colorado, 2200 Colorado Ave., Boulder, CO 80309. (Oleg.Abramov@Colorado.edu)

Introduction: Impact events locally increase the temperature of a planetary crust, initiating hydrothermal activity if water or ice is present. Impact-induced hydrothermal activity is responsible for mineralogically and morphologically modifying many terrestrial craters [e.g., 1], and has been suggested for Martian craters [2, 3]. Present-day subsurface ice has been inferred at high latitudes (poleward of 60°) based on the detection of hydrogen by the Gamma Ray Spectrometer (GRS) onboard Mars Odyssey [4] (and confirmed by the Phoenix lander), and indirectly by the presence of fresh craters with fluidized ejecta blankets [e.g., 5] and rootless cones [6] at lower latitudes. Thus, a present-day impact may still generate hydrothermal activity.

Modeling history: The first modeling effort of impact-induced hydrothermal systems on Mars [2] focused on impact melt sheets and suggested that (i) hydrothermal circulation of steam in Martian melt sheets may have produced iron-rich alteration clays, ferric hydroxides, and near-surface accumulations of salts, (ii) the ability of vapor-dominated hydrothermal systems of concentrate sulfate relative to chloride is consistent with the high sulfate to chloride ratio found in the Martian soil by the Viking landers, and (iii) a major fraction of the Martian soil may consist of the erosion products of hydrothermally altered impact melt sheets. Further analytical modeling suggested that the formation of large impact craters on Mars (>65 km diameter) may have resulted in the creation of ice-covered impact crater lakes, which would not freeze for thousands of years, even under present climatic conditions [3].

The first numerical effort to model Martian impact-induced hydrothermal systems [7] used the finite-difference computer modeling code HYDROTHERM [8] to explore system mechanics, estimate lifetimes, and predict expected mineralogies. This work predicted cessation of any significant hydrothermal activity at a simple (~7 km) Martian crater in under 10,000 years. However, their simulations were limited to 50,000-100,000 years.

Abramov and Kring (2005) study: Building on the work by [7], hydrothermal activity was simulated for up to several million years, allowing estimates of system lifetimes for larger craters [9]. Crater lakes and the latent heat of fusion are were explicitly included in the model. The crater topography was improved based on observations of lunar craters, and was preserved throughout the simulation, rather than being removed shortly after crater formation. In addition, the post-impact temperature distributions that serve as starting conditions have been generated by hydrocode simulations either specifically for Mars [10] or were adapted for Mars with consideration of the different kinetic energy requirements for the formation of Martian craters.

While there are probably no active impact-induced hydrothermal systems today, they may have been prevalent at ~3.9 Ga, during an intense period of bombardment lasting 20 to 200 Ma [11, 12]. This cataclysm (also termed Late Heavy Bombardment) likely affected Mars, because meteorites from the asteroid belt, as well as the only sample of the ancient Martian crust (meteorite ALH 84001), show effects of impact-induced metamorphism at ~3.9 Ga [13, 14]. Thus, this study focused on an early Martian environment because it coincides with a sharply higher impact rate, and also because liquid water was likely stable in the subsurface and perhaps on the surface as well.

Hydrothermal activity in early Martian craters 30, 100, and 180 km in diameter was modeled using a modified version of a publicly available program HYDROTHERM [8], a three-dimensional finite difference code developed by the U.S. Geological Survey. Our modeling (e.g., Fig. 1) suggested the evolution of a post-impact hydrothermal system on early Mars proceeded as follows. The first step was the gravity-driven rapid draining of the rim and the flooding of the crater cavity by groundwater and any other available water source. The interaction between the incoming water and the hot interior of the crater may have produced large quantities of steam. Eventually, a crater lake should have formed in the basin of the crater, changing the flow of water from a gravity-driven to a hotspot-driven state. Our model simulations, plus observations at terrestrial impact sites [e.g., 1, 15], suggest that the most extensive hydrothermal alteration would have occurred in the central peak (for smaller craters) or the peak ring (for larger craters), and the modification zone where fluid flow is facilitated by faults. The region of active hydrothermal circulation extends laterally almost to the crater rim and to a depth of several kilometers. The habitable volume for thermophilic organisms (volume of rock that has water flow and a temperature between 50 and 100 °C) reaches a maximum of ~6000 km^3 in the 180 km crater.

The average lifetimes of impact-induced hydrothermal systems on early Mars are estimated at ~0.065 Ma for the 30-km crater, ~0.29 Ma for the 100-km crater, and ~0.38 Ma for the 180-km crater, and depend strongly on assumed ground permeability (Fig 2). The combination of relatively long lifetimes and long-lived upwellings suggest that impact-induced hydrothermal systems on early Mars would have resulted in a significant mineralogical alteration of the crust.

Follow-on studies: A study by Barnhart et al. [16] expanded the modeling of Martian impact-induced hydrothermal system to include freezing and an approximation of present-day atmospheric environment. This study found that convective systems subjected to surface temperatures below freezing force heat and fluid flow towards the center of the crater. This prolongs high temperatures, yields W/R ratios > 1000, and may explain mineral assemblages and fluvial features associated with central peaks of craters.

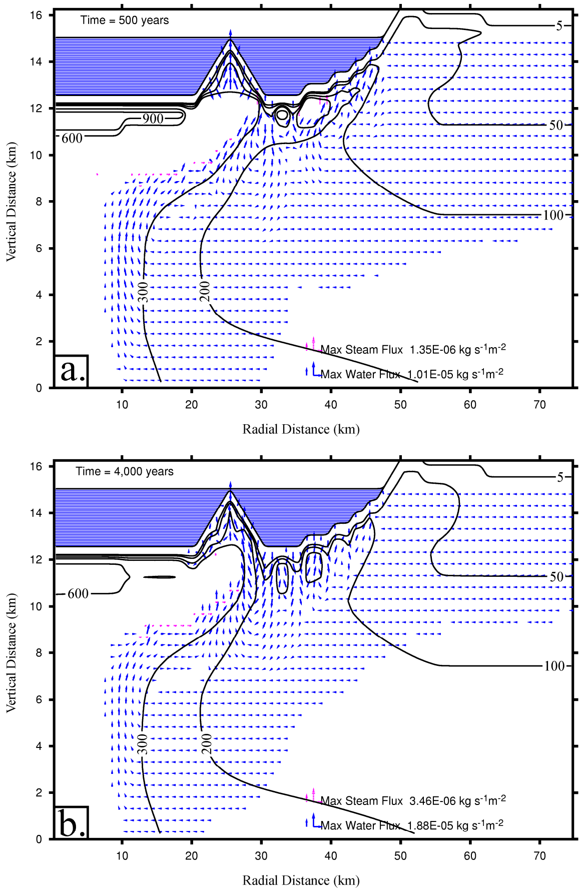
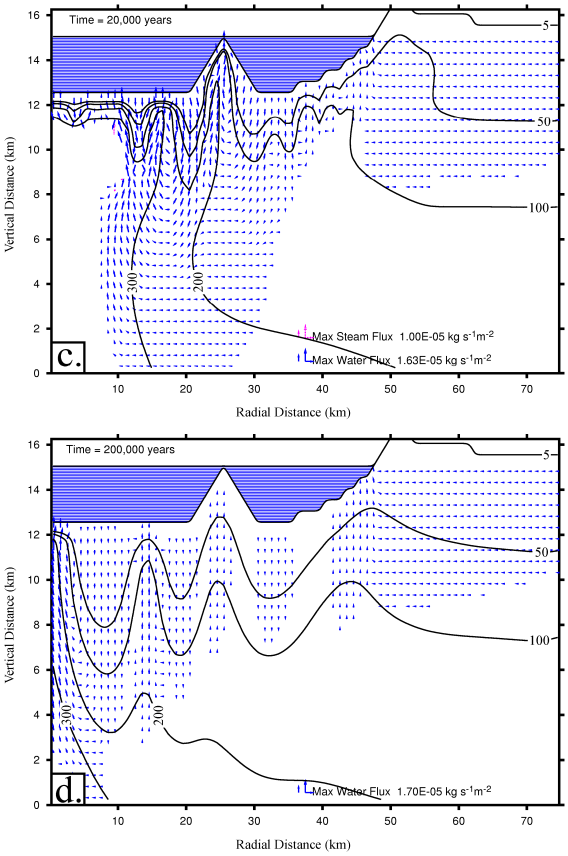


Figure 1. Results of a numerical simulation of the hydrothermal system at a 100-km impact crater on early Mars. Surface permeability is 10^{-2} darcies. Black lines are isotherms, labeled in degrees Celsius, and blue and red arrows represent water and steam flux vectors, respectively. The length of the arrows scales logarithmically with the flux magnitude, and the maximum value of the flux changes with each plot.



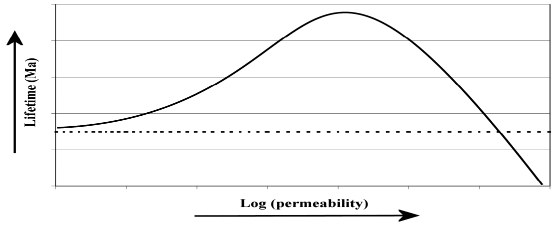


Figure 2. General dependence of system lifetime (defined by near-surface temperatures) on the average permeability of the subsurface. The dashed line indicates the lifetime in the absence of water.

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