NUMERICAL MODELING OF IMPACT-INDUCED HYDROTHERMAL ACTIVITY ON EARLY MARS.

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Introduction: Recent research suggests that impact generated hydrothermal systems may have played an important role on early Earth and potentially early Mars. Several lines of evidence point to a dramatic increase in the number of impact events at ~3.9 Ga [1-3], which coincides remarkably well with the earliest isotopic evidence of life at ~3.85 Ga [4]. This period, often referred to as the Lunar Cataclysm, lasted 20 to 200 million years [2,5], during which time hydrothermal heat generated by impact events may have exceeded that generated by volcanic activity [6]. These impacts would have resurfaced most of Earth and Mars, and may have vaporized any existing oceans for short periods of time, virtually eliminating surface habitats [7]. At the same time, an abundance of subsurface habitats in the form of large subsurface hydrothermal systems would have been created. These habitats could have provided sanctuary for existing life or perhaps the site of life's origin. Genetic evidence in the form of phylogenies that suggest that Archaea, Bacteria, and Eukarya have a common ancestor comparable to present day thermophilic or hyperthermophilic organisms [8], further underscores the potential importance of hydrothermal systems in general, and impact-induced hydrothermal systems in particular, at the dawn of life.

Several hydrothermal systems generated at terrestrial impact craters have been identified based on mineralogical evidence [e.g. 9-12] and have been suggested to occur on Mars as well [13,14]. The primary heat sources driving a hydrothermal system associated with a complex impact crater are the shock-emplaced heat , the central uplift and melt sheet.

Perhaps the most important question in assessing the importance of impact-induced hydrothermal systems is that of system lifetime. The lifetimes of hydrothermal systems in craters 20 to 200 km in diameter are 10^3 to 10^6 years if purely conductive cooling is assumed [15,16]. It has been suggested that convective cooling by circulating water would cool the crater faster than purely conductive cooling [14], but specific effects of circulating water on crater cooling are not thoroughly understood. In order to better constrain the expected lifetimes of these systems and further understand their mechanics, we use a finite-difference computer simulation to evaluate the additional effects of convective cooling.

Modeling technique: The numerical code used to model the post-impact water and heat flow is a modified version of the publicly available program HYDROTHERM (source code available from authors). HYDROTHERM is a three-dimensional finite-difference model developed by the U.S. Geological Survey to simulate water and heat transport in a porous medium [17]. Its operating range is 0 to 1200 C and 0.5 to 1000 bars; however, in this work the upper temperature limit has been extended to 1700 C to model the initial temperature of the impact melt sheets. The code solves the mass and energy balance equations at every mesh element and time step. HYDROTHERM has been successfully applied to hydrothermal systems of volcanic origin [18] and Martian impact craters [19].

HYDROTHERM requires input in the form of topography and temperature distribution, in addition to rock properties and planet-specific parameters such as gravity, atmospheric pressure, and the basal heat flux. The surface topography is reconstructed using laser-altimetry derived Martian crater dimensions [20] and morphometry of lunar craters [21]. The temperature distribution underneath Martian craters is obtained from hydrocode simulations [e.g. 22] or computed analytically using models for shock-emplaced heat, amount of uplift, and the volume of melt. Rock properties appropriate for the Martian basalts are used, with a density of 2600 kg/m^3, thermal conductivity of 2.5 W/(m K), and heat capacity of 800 J/(kg K). The surface porosity is conservatively estimated at 20% [23] and decreases exponentially with depth, while the permeability has a maximum surface value of 10^{-2} darcies and varies with both depth and temperature. The effect of other permeability values has also been evaluated. The geothermal gradient is taken to be 13 °C/km [24]. We assume an atmospheric pressure of 0.5 bars for early Mars and thus stable liquid water at the surface, and that the water table is within 150 m of the surface.

Results: We applied this numerical code to a range of craters from 30 km to 180 km in diameter. Our modeling suggests the evolution of a post-impact hydrothermal system at a crater on early Mars developed as follows. The first step was gravity-driven rapid draining of the rim and the flooding of the crater cavity by groundwater and possibly seawater. The interaction between the incoming water and the hot interior of the crater would have produced large quantities of steam. Because the boiling point of water increases rapidly with pressure, steam generation was limited to near-surface regions, except for production of supercritical fluid deep below the surface. Therefore, once the near-surface cooled there was probably little steam emission from the ground. 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. Newsom et al. [14] showed that the thermal energy of the impact melt and the central uplift can keep a lake from completely freezing for thousands of years under a thick sheet of ice, even under the current climatic conditions. Our model simulations and observations at terrestrial impact sites suggest that the most extensive hydrothermal alteration would have occurred in the central peak (for smaller craters) and in the peak ring and the modification zone where fluid flow is further facilitated by faults (for larger craters). The region of active hydrothermal circulation extends laterally almost to the crater rim and to a depth of several kilometers. The volume of target material that has water flow through it and a temperature between 50 and 100 °C reaches a maximum of ~20,000 km^3 for the 180 km crater.

The lifetimes of impact-induced hydrothermal system on early Mars range from 50,000 years for a 30 km crater to 1.1 Ma for a 180 km crater, and depend strongly on assumed ground permeability. These long lifetimes are partly explained by the most vigorous circulation taking place near the surface and the hotter parts of the models being impermeable due to the brittle/ductile transition at about 360 ºC. Thus, conduction remains the dominant form of heat transport in much of the model, especially for larger craters. Another important consideration is the vertical heat transport by flowing water, which can increase the temperature of near-surface regions and prolong the lifetime of the system. These systems produce suitable environments that could potentially have been habitats for thermophiles.

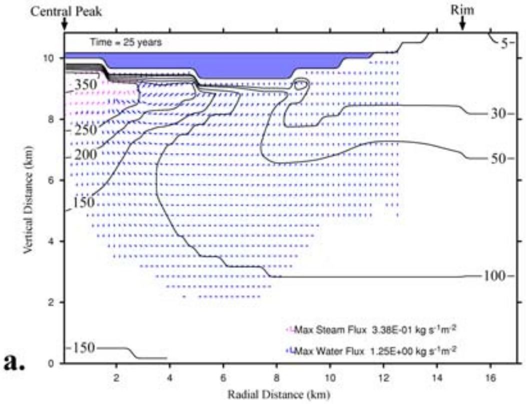
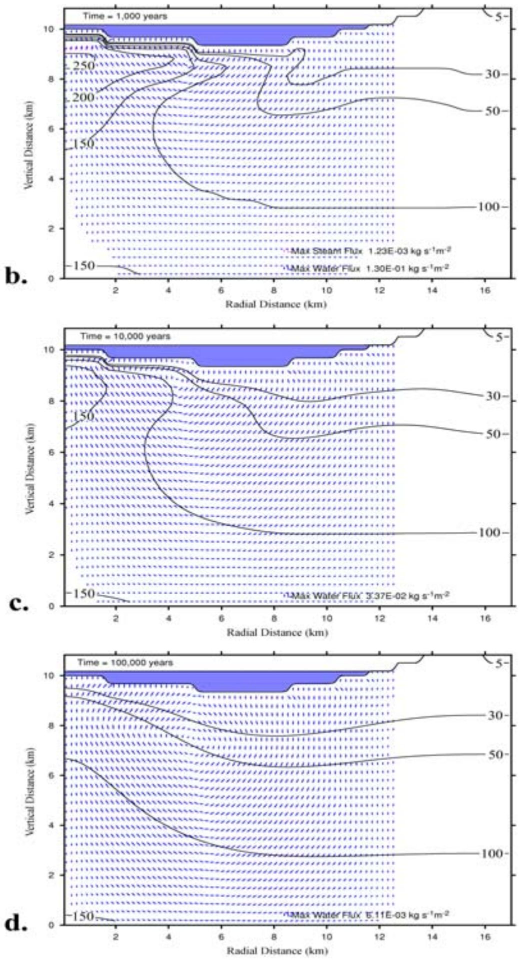


Figure 1. Results of a numerical simulation of the hydrothermal system at a 30-km impact crater on early Mars. Surface permeability is 10^{-2} darcies. Black lines are isotherms, labeled in degrees Celsius, and blue and red arrows represent water and steam flux vectors, respectively. The length of the arrows scales logarithmically with the flux magnitude, and the maximum value of the flux changes with each plot. Panels a to d show the state of the system at 25 years, 1000 years, 10,000 years, and 100,000 years, respectively.



References: [1] Turner, G. et al. (1973) *Proc. Lunar Sci. Conf.*, *4*, 1889–1914. [2] Tera, F. et al. (1974) *Earth Planet. Sci. Lett.*, *22*, 1–21. [3] Cohen, B. A. et al. (2000) *Science*, *290*, 1754-1756. [4] Mojzsis, S. J. and Harrison, T. M. (2000) *GSA Today*, *10*(4), 1-6. [5] Ryder, G. (1990) *Eos Trans. AGU*, *71*(10) 313, 322-323. [6] Kring, D. A. (2000) *GSA Today*, *10*(8), 1-7. [7] Zahnle, K. J., and Sleep, N. H. (1997) in *Comets and the Origin and Evolution of Life*, 175-208. [8] Pace, N. R. (1997) *Science*, *276*, 734-740. [9] Naumov M.V. (2002) In: Plado J. & Pesonen L.J. (eds.) *Impacts in Precambrian Shields,* 117-171, Springer. [10] Boer, R. H. et al. (1996) in *The Manson Impact Structure, Iowa: Anatomy of an Impact Crater,* 377-382. [11] Komor, S. C. et al. (1988) *Geology*, 16, 711-715 [12] Ames, D. E. et al. (1998) *Geology*, *26*(5), 447-450. [13] Newsom, H. E. (1980) *Icarus*, *44*, 207-216. [14] Newsom, H. E. et al. (1996) *JGR*, *101*, 14951-14956. [15] Daubar, I. J., and Kring, D. A. (2001) *LPSC XXXII*, Abstract #1727. [16] Turtle, E. P., et al. (2003) *Meteoritics Planet. Sci.*, *38*(2), 293-303. [17] Hayba, D. O. and Ingebritsen, S. E. (1994) *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *94-4045*, 85 pp. [18] Hayba D. O. and Ingebritsen S. E. (1997) *JGR,, 102*, 12,234-12,252. [19] Rathbun J. A. and Squires S. W. (2002) *Icarus 157*, 362-372. [20] Garvin, J. B. et al. (2002), *LPSC XXXIII*, Abstract #1255. [21] Melosh, H. J. (1989) *Impact Cratering: A geologic process*, Oxford University Press. [22] Pierazzo et al. (2004) *LPSC XXXV*, Abstract #1352. [23] Clifford, S. M. (1993) *JGR, 98,* 10,973-11,016. [24] Babeyko A. Yu. and Zharkov V. N. (2000) *Phys.Earth Planet. Inter.*, *117*, 421-435.