INTERACTION OF GROUNDWATER WITH IMPACTS ON MARS: POSSIBLE HYDROTHERMAL SYSTEMS.

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On the surface of Mars is found ample evidence for water, in liquid form in the past and in solid form currently or very recently [1, 2, 3]. Widespread heating of the planet has also occurred, both volcanoes and impact craters are evident in large quantities. Hydrothermal systems can form when water interacts with hot rock [4], and therefore can be expected to have developed at times on the martian surface. We have modeled the interaction of water with the heat generated by an impact and have followed the development of a hydrothermal system. We find that the system exists primarily on the floor of the crater and that in craters with a substantial melt sheet a lake will form, even under current martian conditions. By comparing these systems with those studied on earth, we make predictions as to the types of minerals that could be found, and the possible habitability of such systems for primitive life. We further identify problems with current modeling of such systems and suggest improvements.

The numerical code HYDROTHERM was developed to simulate multiphase groundwater flow and heat transport in the temperature range of 0 to 1,200 degrees Celsius [5], so it is particularly well suited to studying hydrothermal systems. Here, we use it to study these martian hydrothermal systems. It is optimized for conditions on Earth and cannot handle the lower temperatures and pressures and higher permeabilities that may exist on Mars. However, neither lower surface temperature and pressure nor higher permeability should affect the major results of this study, such as the location of the hydrothermal system. A further problem is that HYDROTHERM can handle only fully saturated ground. With no replenishing rainfall, the high areas in a martian crater (the peak and rim) should eventually completely drain of water. To approximate this, we calculated the velocity of water in the rim and the time it would take to completely drain. After this time, the calculation is stopped, the surface is reinitialized to the lowest point on the surface and the calculation is continued.

We investigate the groundwater interaction with two freshly formed impact craters. One is the largest possible simple crater on Mars, 7 km in diameter, while the other is a 180 km complex crater. The initial conditions for HYDROTHERM are pressure and temperature. We assume the pressure is hydrostatic in both craters. The temperature distribution in a simple crater can be approximated analytically using the Hugoniot equations. The temperature in a complex crater is a more difficult calculation and a hydrocode simulation must be used. We use the published hydrocode results of Ivanov and Deutsch, 1999 [6, 7] altered to account for martian geothermal temperatures as opposed to terrestrial.

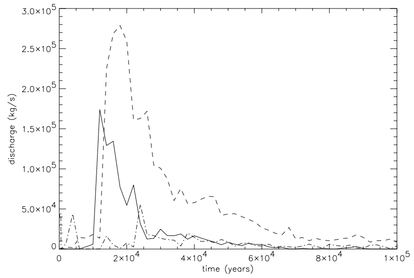

Figure 1: Discharge from the surface. Solid line is the mass of steam discharge, dash dot lines indicate water discharge and the dashed line shows water recharge. More water is discharged than recharged for approximately the first 12,000 years.

In the simple crater case the most obvious flow at early time steps is the water seeping from the rim. After the rim is drained, the majority of the flow takes place in the inner regions of the crater, where temperatures are warmest, beneath the crater floor. A toroidal water circulation cell develops which moves outward and downward with time. The amount of flux decreases with time and at the end of the simulation temperatures are almost geothermal and the fluxes are so low as to be negligible. The flux of water through the surface is relatively constant while the rim is draining, during the first 5,000 years. During this time, a modest amount of water (≈ 4 kg/s) is flowing from the rim of the crater into the floor. After the rim has completely drained, however, there is virtually no flow except for a small amount of water draining back into the subsurface, on order 10^{-2} kg s^{-1}. Therefore, any water that has pooled on the bottom of the crater will eventually drain back underground if environmental conditions are warm enough to allow it to remain liquid.

In the case of the complex crater, the initial flow is downward from the rim, as in the simple crater case. After the rim has drained, the majority of the flow occurs in the inner regions of the crater, where temperatures are close to the boiling point. Interaction of the hydrothermal system with the surface takes place primarily on the crater floor. Flow begins beneath the outer edge of the melt sheet, where temperatures are warmest while still being cool enough for the permeability to be low enough for flow to occur. The melt sheet cools primarily from the outer edge and also from the top. This is where a toroidal circulation cell eventually sets up and it moves inward and downward as the melt sheet cools. The flow begins above the melt sheet at its outer edge in the form of steam. As it moves downward, water must enter the circulation cell to keep it going.

The surface discharge into the crater as a function of time is shown in figure 1. Prior to 500 years, when the rim is drained instantaneously, the discharge is dominated by water flow from the peak. Since prior to 14,000 years more water is exiting the ground than seeping into it and it is flowing into a topographical depression (the crater floor), a lake will

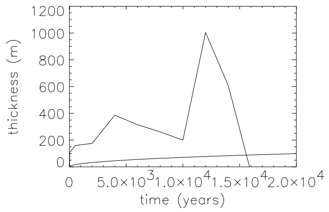

Figure 2: Depth of lake (top line) and the equilibrium thickness of an insulating ice layer (bottom line) as functions of time.

form. We calculate the cumulative volume of water that has discharged onto the crater floor as a function of time and, from the surface topography, calculate the depth of the lake (fig. 2).

The current martian surface pressure and temperature do not permit the existence of liquid water. However, water as deep as the depths calculated for this lake may exist beneath an insulating layer of ice. By balancing the conduction of energy out of the ice and the release of latent heat of fusion at the ice-water interface [8] thicknesses of about a kilometer have been calculated for current martian conditions [9]. Since this lake is lying on a cooling impact melt sheet an additional heat term must be included. This additional heating brings the thickness down to approximately one hundred meters (fig. 2). The lake formed in this crater is deeper, and therefore could persist for a significant period of time. The lake will disappear after about 15,000 years as the water begins to seep back into the ground.

On earth, hydrothermal systems can be categorized by the type of heat source and origin of the water in the system. In the hydrothermal systems that develop in craters the water source is meteoric, or groundwater, which places the systems described here in the category of volcano-plutonic magmatic-meteoric hydrothermal systems on earth [10]. The minerals that form in such systems are primarily silica and metal sulfides and sulfates. However, the exact chemistry of hydrothermal fluids and the precipitated minerals depend on the specific setting, rock mineralogy, and temperature [11, 12, 13]. There are several differences between these systems and those on earth. First, this one is covered by a lake which might make these systems more similar to sub-sea floor hydrothermal systems. The major difference between meteoric water and sea water on earth is its oxygen content, and the water in martian impact craters may be more similar to sea water in that it is likely to have little dissolved oxygen. Further differences include the surface pressure and temperature, rock and fluid composition, oxygen fugacity, and pH. Low pressures have not been well studied on earth and its effect is, therefore, not well known. The low martian surface temperatures should not cause consequential differences because of the heating from the impact and the presence of an insulating lake during much of the hydrothermal circulation. The martian atmosphere consists of only 0.13% molecular oxygen [14], significantly less than Earth. This may severely limit the formation of metal sulfates by hydrothermal alteration.

Of the multitude of life forms found at terrestrial hydrothermal systems, anaerobic hyperthermophillic chemolithoautotophic microbes could very likely survive in a hydrothermal system in a martian impact crater. These microbes use energy from chemical reactions and do not need oxygen to survive. They thrive at temperatures ($\sim$ 50 - 100C) that can be found at depth in a 180 km diameter complex crater over a course of more than 100,000 years without much movement of the temperature region over that time. These organisms are among those closest to the root of the tree of life [15]. Life has been hypothesized to have originated in hydrothermal systems on Earth [16]. Its origin in hydrothermal systems on other worlds remains purely speculative (see [17]).

There are several problems with the treatment performed here and more work is needed. First, a major limit of this work is that only two numerical simulations were performed. In order to study different sizes of craters, more hydrocode simulations need to be performed, preferably specifically designed for martian conditions. Also, a Mars-specific groundwater simulation would be particularly helpful, one that accounted for the lower pressure and temperature on Mars and the ice-water phase change as well as adapting the simulation so it can handle the higher permeabilities that may exist at the martian surface. Most important, and perhaps most difficult, it should be able to handle less than unity saturation. Once such a numerical code exists it can be used to simulate different possible martian surface regimes, including the presence of a lake. Work that can more accurately predict characteristics of the martian surface would also be extremely useful. Finally, a fully integrated geochemical simulation could model not only heat transport but solute transport as well. This would be particularly useful to predict the types and amounts of minerals that would precipitate and their location. Of course, a better understanding of the composition of martian rocks would be necessary for reliable results from such a simulation.

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