IMPACT-INDUCED HYDROTHERMAL SYSTEM AT THE SUDBURY CRATER: DURATION, TEMPERATURES, MECHANICS, AND BIOLOGICAL IMPLICATIONS.

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Introduction: Current research suggests that impact-generated hydrothermal systems may have played an important role on early Earth. 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 the Earth, and may have vaporized the Earth's oceans, virtually eliminating surface habitats. At the same time, an abundance of subsurface habitats [7] 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 [9-12] and have been suggested to occur on Mars as well [13,14].

Perhaps the most important question in assessing the role of impact-induced hydrothermal systems in these and earlier (~3.9 Ga) craters 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, a finite-difference computer simulation is used to evaluate the additional effects of convective cooling. We have applied this code to the Sudbury crater, where the results can be integrated with constraints from the rock record.

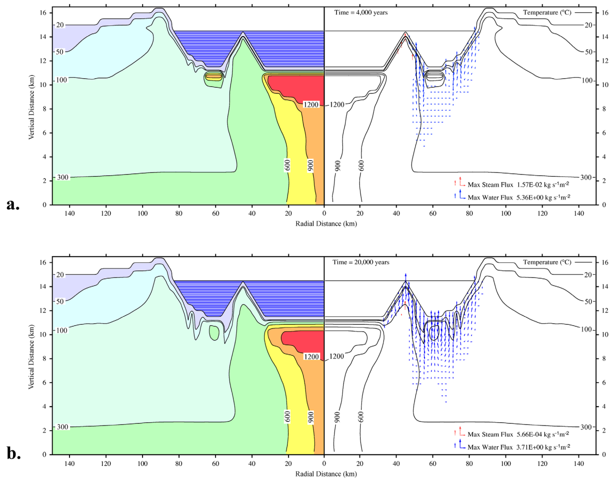
Sudbury Crater: While the origin of the 15,000 km^2 Sudbury Structure in Ontario, Canada, has been controversial for several decades [17], it is now largely accepted to be a remnant of a large impact crater. Post-impact tectonic activity has significantly deformed the central impact melt sheet, most of which is covered by an average of 3 km of impact breccias and post-impact sedimentary deposits [17]. Estimates of the original rim-to-rim diameter of Sudbury crater, based primarily on the radial position of shock metamorphic effects, range from 150 to 250 km. Uranium-lead dating by [18] places the formation of the Sudbury crater at 1.850 Ga. The Sudbury crater is the site of the most extensive hydrothermal alteration known in a terrestrial impact crater [19], although similarly large hydrothermal systems may have existed in other large terrestrial craters such as the Chicxulub crater in Mexico [20]. Specific examples of hydrothermal alteration at Sudbury include silicification, albitization, chloritization, calcitization, and complex feldspathization, indicating a wide range of fluid temperatures (~25-360°C). The alteration patterns are similar to those found at subseafloor hydrothermal systems [12], implying that the Sudbury crater was at least partly submerged shortly after its formation.

Modeling technique: The numerical code used to model the post-impact water and heat flow at Sudbury crater 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 [21]. 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 sheet as estimated by [22]. 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 [23] and Martian impact craters [24].

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 and temperature distribution of the Sudbury crater that are input into the simulation were previously calculated by a hydrocode simulation [22]. Rock properties appropriate for the Sudbury site are used, with a density of 2700 kg/m^3, thermal conductivity of 1.7 W/(m K), and heat capacity of 1050 J/(kg K). The porosity has a surface value of 20% 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.

Results: Numerical modeling results suggest the evolution of a post-impact hydrothermal system at the Sudbury crater proceeded as follows. The first step was the gravity-driven rapid draining of the rim and the flooding of the crater cavity by groundwater or seawater. The water fluxes seen at this stage were generally an order of magnitude greater than those encountered in the later stages of the hydrothermal system. Eventually, a crater lake should have formed in the bowl of the crater, changing the flow of water from a gravity-driven to a hotspot-driven state. Over time, long-lived upwellings would have developed, most notably in the annular trough between the peak ring and the outer wall and at the peak ring. The volume of rock between 50 and 100 °C (which represents a possible habitable zone for thermophilic organisms) that had significant water fluxes reached a maximum ~60,000 years after impact.

Our model predicts that a hydrothermal system at the Sudbury crater remained active from several hundred thousand up to ~2 × 10^6 years, depending on permeability. These long lifetimes are partly explained by the most vigorous circulation taking place only near the surface and the hotter parts of the model being impermeable to fluid flow due to the brittle/ductile transition at about 360 ºC. Thus, conduction remains the dominant form of heat transport in much of the model. Another important consideration is the vertical heat transport by circulating water, which can increase the temperature of near-surface regions and prolong the lifetime of the system. The results allow for long-lived near-surface ecosystems of thermophiles to be established when an impact event increases temperatures near the surface and provides heat sources to drive the circulation of water.



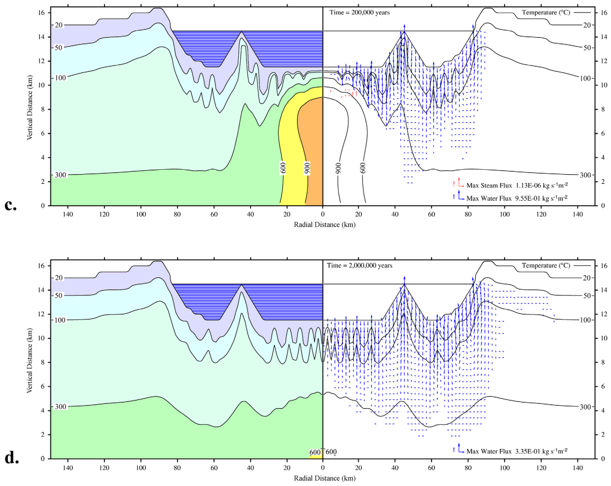


Figure 1. Results of a numerical simulation of the hydrothermal system at Sudbury crater. Surface permeability is 10^{-2} darcies. The left panel shows color-coded temperature fields, and the right panel displays fluid flux vectors. Black lines are isotherms, labeled in degrees Celsius, and blue and 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 4 × 10^3 years, 2 × 10^4 years, 2 × 10^5 years, and 2 × 10^6 years, respectively.

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