NUMERICAL MODELING OF IMPACT-INDUCED HYDROTHERMAL ACTIVITY AT THE CHICXULUB CRATER. O. Abramov and D. A. Kring, Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, Arizona 85721-0092. (abramovo@LPL.arizona.edu)

Introduction: A hypervelocity impact of a large bolide results in a significant but localized temperature increase in the planetary crust, initiating hydrothermal activity if water or ice are present. Evidence of this activity has been observed at several terrestrial craters in the form of alteration mineral assemblages, fractionated isotopic compositions, and fluid inclusion chemistry [e.g., 1-4].

While there are probably no active impact-induced hydrothermal systems today, they may have played an important role on early Earth and Mars, especially during a period of intense bombardment at ~3.9 Ga [5-7]. This cataclysm lasted 20 to 200 Ma [6,8], virtually coinciding with the earliest evidence for life dating to 3.85 Ga [9]. Also, phylogenies constructed from rRNA sequences suggest that all terrestrial life may have a thermophilic or a hyperthermophilic common ancestor [e.g., 10]. Possibly, life on Earth was exterminated by the impact cataclysm, except for organisms that were able to adapt to hydrothermal conditions. Alternatively, these systems may have provided a site for life's origin. In either case, evidence suggests that impact events, and the hydrothermal systems they initiated, may have influenced the evolution of life on early Earth and, perhaps, Mars [11].

For that reason, it is important to explore these systems with numerical modelling to determine their lifetimes, mechanics, and biological potential. It is also important to construct models that are consistent with observed hydrothermal alteration at extant craters. Consequently, we have developed a model of the Chicxulub impact crater, which has been extensively studied through the Yax-1 borehole (~60 km from the center of the crater) and other drillcores, as well as extensive seismic, magnetic, and gravity surveys.

Chicxulub Crater: Of the three largest terrestrial impact craters (Vredefort, Sudbury, and Chicxulub), the 65 Ma, ~180 km Chicxulub crater is by far the youngest and best preserved. The Chicxulub impact occurred into partially submerged Cretaceous sediments underlaid by a crystalline silicate basement, and has since been buried by up to 1 km of Tertiary carbonates. Seismic data [e.g., 12,13] indicates the presence of a very pronounced peak ring, a central uplift, and a central melt sheet, with a far smaller amount of melt in an annular trough between the peak ring and rim.

The melt and other impact-generated heat sources raised water temperature significantly, altering the primary melt and breccia mineral assemblages [14-17]. The alteration products in Yax-1 breccias suggest that, after an initial low-temperature phase, hydrothermal temperatures in that part of the crater exceeded 300 °C [15]. Lower-temperature (<300 °C) alteration then followed, in the form of abundant calcite veins and open-space fillings [15], and other alteration assemblages [16]. Isotopic and fluid inclusion data [18] indicate hydrothermal fluid temperatures in Yax-1 ranged from 100 °C (based on fluid inclusions in late calcite) to 270 °C (based on fluid inclusions in hydrothermal quartz veins).

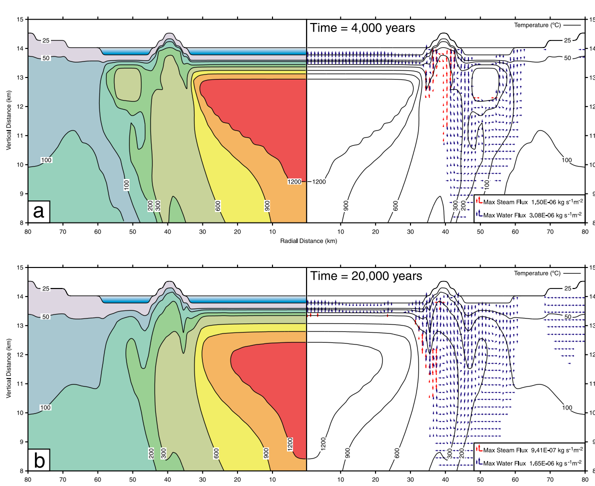
Modeling technique: Hydrothermal activity at the Chicxulub crater was modeled using a modified version of the publicly available program HYDROTHERM, a three-dimensional finite-difference model developed by the U.S. Geological Survey [19]. HYDROTHERM has been previously applied to hydrothermal systems of impact origin [e.g., 20-22].

HYDROTHERM requires input in the form of topography and temperature distribution, in addition to rock properties, gravity, atmospheric pressure, and the basal heat flux. The original topography of Chicxulub was reconstructed from seismic data [e.g., 12] and scaling laws [23]. The temperature distribution was generated by a hydrocode simulation [24], and the melt distribution was constrained by seismic, gravity, magnetic, and borehole data [e.g., 13,25,26]. Rock properties of Cretaceous sediments are based on borehole samples [e.g., 27], while typical continental crust values have been used for the crystalline basement. The surface porosity has been estimated at 25% [27] and decreases exponentially with depth, while the permeability has a maximum surface value of 10^{-3} darcies and is a function of both depth and temperature. The effect of other permeability values has also been evaluated. This work represents a number of improvements on the Sudbury crater model [21], such as increased resolution, layering, faults, and better geologic constraints.

Results: Our modeling (e.g., Fig. 1) and analyses of core samples suggest the evolution of a post-impact hydrothermal system at the Chicxulub crater proceeded as follows. The first step was the gravity-driven rapid draining of the rim and a partial flooding of the crater cavity by groundwater and/or seawater. This water would have quickly infiltrated the permeable breccias over the melt, resulting in short-lived period of intense steam emission followed by the circulation of water through these breccias. Over time, long-lived upwellings would have developed, most notably in the annular trough between the peak ring and the outer wall and below the peak ring. Multiple convection cells formed over the cooling central uplift in the later stages of the system, and eventually joined into a single central upwelling.

The temperatures observed in the location of the Yax-1 borehole breccias were, to first order, comparable to those described by [15]: there is an initial low-temperature phase, an increase in temperature due to the nearby melt, and a subsequent period of cooling.

Our model predicts that a hydrothermal system at the Chicxulub crater remained active for 1.5 to 2.3 Ma, depending on permeability. These lifetimes are a little longer than those of the hydrothermal system at the Sudbury crater for comparable permeabilities and breccia thicknesses (1.1 to 1.9 Ma) [21]. This is mainly due to the slightly higher initial temperatures in the center of the crater and system dynamics (influenced by melt volume, rock properties, etc.), which, while mostly similar, result in a single central upwelling at Chicxulub towards the end of the system versus multiple convection cells at Sudbury. The long lifetimes are partly explained by the most vigorous circulation taking place 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 crater. Long system lifetime is also promoted by vertical heat transport by circulating water, which can increase the temperature of near-surface regions. The combination of the long lifetime and a large habitable volume created by this system makes it possible that long-lived near-surface ecosystems of thermophiles were established, provided the chemistry of circulating fluids was suitable for life. Thus, future work should include a rigorous search for the signs of biological activity in the hydrothermal system induced by the Chicxulub impact.



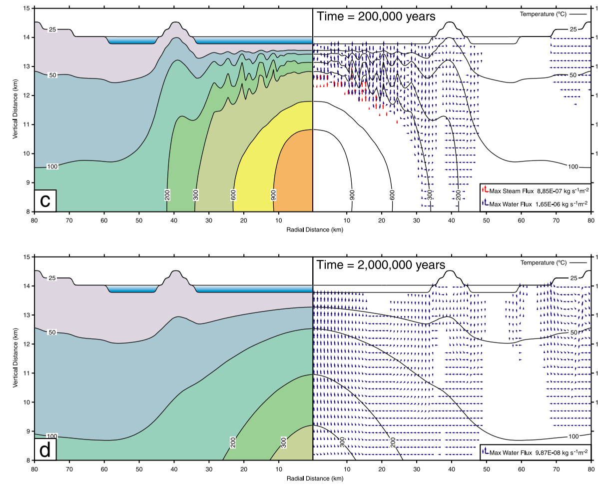


Figure 1. Results of a numerical simulation of the hydrothermal system at Chicxulub crater. Black lines are isotherms, labeled in degrees Celsius, and blue and red arrows represent water and steam flux vectors, respectively.

References: [1] Osinski, G. R., Spray, J. G., and Lee, P. (2001) *Meteoritics and Planet. Sci.*, *36*, 731-745. [2] Boer, R. H., Reimold, W. U., Koeberl, C., and Kesler, S. E. (1996) in *The Manson Impact Structure, Iowa: Anatomy of an Impact Crater,* 377-382. [3] Naumov M.V. (2002) In: Plado J. & Pesonen L.J. (eds.) *Impacts in Precambrian Shields,* 117-171, Springer. [4] Ames, D. E., Watkinson, D. H., and Parrish, R. R. (1998) *Geology*, *26*(5), 447-450. [5] Turner, G., Cadogan, P. H., and Yonge, C. J. (1973) *Proc. Lunar Sci. Conf.*, *4*, 1889–1914. [6] Tera, F., Papanastassiou, D. A., and Wasserburg, G. J. (1974) *Earth Planet. Sci. Lett.*, *22*, 1–21. [7] Cohen, B. A., Swindle, T. D., and Kring, D. A. (2000) *Science*, *290*, 1754-1756. [8] Ryder, G., (1990) *Eos Trans. AGU*, *71*(10) 313, 322-323. [9] Mojzsis, S. J. and Harrison, T. M. (2000) *GSA Today*, *10*(4), 1-6. [10] Pace, N. R. (1997) *Science*, *276*, 734-740. [11] Abramov, O., and Kring, D.A. (2005) *JGR*, *110*, doi:10.1029/2005JE002453. [12] Morgan, J., Warner, M., and the Chicxulub Working Group (1997) *Nature*, *390*, 472-476. [13] Morgan, J.V., Warner, M.R., Collins, G.S., Melosh, H.J., and Christeson, G.L. (2000) *Earth Planet. Sci. Lett.*, *183*, 347-354. [14] Kring, D.A., and Boynton, W.V. (1992) *Nature*, *358*, 141-144. [15] Zurcher, L., and Kring, D.A. (2004) *Meteor. Planet. Sci.*, *39*(7), 1199 – 1222. [16] Ames, D.E., Kjarsgaard, I.M., Pope, K.O., Dressler, B., Pilkington, M. (2004) *Meteor. Planet. Sci.*, *39*, 1145 – 1167. [17] Hecht, L., Wittmann, A., Schmitt, R.T., and Stöffler, D. (2004) *Meteor. Planet. Sci.*, *39*, 1169 – 1186. [18] Zurcher, L., Kring, D.A., Dettman, D., and Rollog, M. (2005) In: T. Kenkmann et al. (eds.) *Large Meteorite Impacts and Planetary Evolution III*, 323-338, GSA. [19] Hayba, D.O. and Ingebritsen, S.E. (1994) *U.S. Geol. Surv. Water Resour. Invest. Rep.*, *94-4045*, 85 pp. [20] Rathbun, J.A., and Squyres, S.W. (2002) *Icarus*, *157*, 362-372. [21] Abramov, O., and Kring, D.A. (2004) *JGR*, *109*, doi:10.1029/2003JE002213. [22] Sanford, W.E. (2005) *Geofluids*, *5*, 185-201. [23] Grieve, R.A.F., and Pesonen, L.J. (1992) *Tectonophysics*, *216*, 1-30. [24] Ivanov, B.A. (2004) *Solar System Res.*, *38*(4), 266–278. [25] Ebbing, J., Janle, P., Koulouris, J., and Milkereit, B. (2001) *Planet. Space Sci.*, *49*, 599-609. [26] Pilkington, M. Hildebrand, A.R., and Ortiz-Aleman, C. (1994) *JGR*, *99*, 13,147-13,162. [27] Mayr, S., Burkhardt, H., Popov, Yu., Romushkevich, R., and Bayuk, I. (2005) *IODP/ODP Joint Meeting*, March 14-16, Potsdam.