IMPACT-INDUCED HYDROTHERMAL ACTIVITY AND POTENTIAL HABITATS FOR THERMOPHILIC AND HYPERTHERMOPHILIC LIFE.

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Introduction: It has become increasingly clear that impact cratering processes can affect the biologic evolution of the Earth. The principal example of this relationship is the Chicxulub impact event and its likely role in the mass extinction that occurred at the Cretaceous-Tertiary boundary [*e.g.*, 1-4]. However, other impact events, both known [*e.g.*, 5,6] and hypothesized [*e.g.*, 7,8], have also been linked to a variety of local, regional, and global environmental consequences.

At the same time impact processes disrupt the habitats of some organisms, they also offer opportunities for other organisms. One straightforward way of doing this is to remove successful organisms from ecological niches, giving other organisms an opportunity to exploit them. Another way is to create new environments suitable for habitation. Common examples are impact crater lakes, both now (*e.g.*, Bosumtwi, Clearwater East and West, Lonar, New Quebec) and in the past (*e.g.*, Barringer, Haughton, Ries, Steinheim, Tswaing). These lakes can be long-lived (thousands to millions of years) and fossil evidence clearly indicates they can be utilized by a variety of flora and fauna [9-18]. Other environments that can be created by impact cratering events are hydrothermal systems. Similar systems generated by volcanic processes have been recognized as critical habitat for some of Earth's most deeply branching organisms [*e.g.*, 19,20] and may have been the type of habitat first populated by life on Earth [*e.g.*, 21-23]. The purpose of this paper is to explore the extent of impact-induced hydrothermal systems and their possible role in the evolution of life.

Evidence of Hydrothermal Systems: Most studies of impact processes have focused on the formation and modification of craters, not their subsequent evolution. Consequently, little is known about the post-impact hydrothermal processes that are produced and a complete evaluation of a hydrothermal system in a crater does not yet exist. Thus, the nature of these systems needs to be pieced together from evidence from several craters.

Chicxulub. This is an ~170 km diameter crater produced 64.98 ± 0.05 Ma [24]. Anhydrite and quartz veins attributed to hydrothermal processes were found in the Yucatán-6 borehole [25], ~50 km from the center of the crater, within the peak ring, and near the top of a section of impact melt at least 380 m thick [26]. However, little else is known about this system because there are so few samples from the buried structure. It is hoped that details will be forthcoming when a core is recovered by the Chicxulub Scientific Drilling Project in 2000.

Manson. This is a 35 km diameter crater produced 73.8 ± 0.3 Ma [24]. Evidence of hydrothermal activity is extensive. It includes quartz veins in impact melt breccias and fragmental breccias, altered granite, and altered granitic gneiss [27]. Fluid inclusions in these samples indicate the water was moderately saline (0.2 to 12.2 wt% $NaCl_{eq}$) and contained very little CO_2 (<0.2 mole%). Temperatures in the system ranged from 90 to 250 °C [27]. The fluids altered primary mineral assemblages in the central peak and in associated impact breccias, producing andradite garnet, ferroactinolite, epidote, prehnite, wollastonite, quartz, analcime, calcite, adularia, pyrite, molybdenite, and clay minerals [28]. Based on the paragenetic sequence, temperatures seem to have peaked between 275 and 360 °C and then cooled to ambient conditions [28]. Alteration occurs in both the central peak and in breccias in the surrounding annular trough.

Puchezh-Katunki. This is a 80 km diameter crater produced 175 ± 3 Ma [24]. The hydrothermal system extended to a depth of at least 5 km (the bottom of the Vorotilovskaya borehole) in the uplifted peak and overlying breccias in the center of the crater [29]. The source of the water in the system appears to be a lake that filled the annular trough [30]. Temperatures in the system were 100-200 °C in the suevites, allogenic breccia, and upper part of the authigenic breccia down to a depth of 2.5 km where zeolites, apophylite, calcite, anhydrite, and pyrite were deposited in vugs and fractures, veins of calcite-nontronite were produced locally, and iron saponite pervades the basement rocks [31,32]. Temperatures in the fluid system were hotter at depths between 2.5 and 4.2 km, reaching 200-300 °C. Chlorite with pyrite is common while albite, epidote, and calcite occur locally in this region [32]. Below 4.2 km, prehnite, anhydrite, calcite, and pyrite assemblages are tentatively inferred to reflect temperatures of 150-250 °C [32]. The extent of the hydrothermal system is not known, but a proposed model [30] suggests it was largely confined to the central peak region, which is ~12 km in diameter.

Saint Martin. This is an ~40 km diameter complex crater that was produced ~220 ± 32 Ma [24]. The impact melt sheet is 208 ft thick in the LSM-1 borehole ~11 km from the center of the crater [33]. The lower 30 ft of the melt sheet has a perturbed chemical composition which has been interpreted to be the result of hydrothermal circulation along the base of the melt sheet [33,34].

Siljan. This is a 52 km diameter crater produced

368.0 ± 1.1 Ma [24]. Hydrothermal activity has affected the target granite and left secondary fluid inclusions in quartz [35]. The inclusions contain water that is less saline (0.2 wt% $NaCl_{eq}$) than the fluids in the Manson crater. Maximum fluid temperatures are 327-342 °C in the central peak and minimum fluid temperatures are 135-225 °C near the surrounding annular trough. Drilling and surface sampling is extensive enough to indicate the impact-induced hydrothermal system affected the entire 52 km diameter region down to a depth of at least 1.2 km [35].

Sudbury. This is an ~250 km diameter crater produced 1850 ± 3 Ma [24]. Hydrothermal alteration of the impact melt sheet converted plagioclase to sericite and clinozoisite and pyroxene to uralite and chlorite [36]. The hydrothermal system is also the source of exhalative mineralization in sediments that cover the impact melt sheet and impact breccias [37].

In addition, tentative evidence of impact-induced hydrothermal systems has been reported for Roter Kamm [38] and Haughton [39].

Extent and Lifetimes of Hydrothermal Systems: These examples indicate that large hydrothermal systems can be created in and around the central uplifts of complex craters and possibly (*i.e.*, Siljan) outward as far as the rim of the craters. The systems can also affect entire melt sheets and the overlying breccias. The heat source driving these systems is the central uplift and/or the impact melt sheet. This implies that the lifetimes of these systems correspond to the time needed for the uplift or melt sheet to cool. In the case of a Chicxulub-size event, the melt sheet may have driven a hydrothermal system for 10^5 years [40]. Based on the temperatures inferred from fluid inclusions and alteration mineral assemblages, parts of these systems were clearly too hot for organisms, but other large regions would have had appropriate temperatures for thermophilic and hyperthermophilic organisms. In some cases the craters were subaerially exposed, in which case the hydrothermal systems may have vented in mud pots, hot springs, and geysers similar to those in volcanic terranes (*e.g.*, Yellowstone and Rotorua). However, in some cases the craters were filled with freshwater lakes or marine incursions (*e.g.*, Chicxulub and Puchezh-Katunki), in which case the hydrothermal systems may have vented subaqueously like those at Crater Lake [41].

Implications for Early Earth: Impact cratering occurred more frequently earlier in Earth's history and may have been a more important source of hydrothermal activity than volcanism. In particular, it has been inferred that the impact cratering rate in the Earth-Moon system was particularly high ~4 Ga based on analyses of impact melts in the Apollo collection [42-44]. Recent analyses of additional impact melt clasts in lunar meteorites, which sample a larger region of the Moon, support this assessment [45]. At ~4 Ga, or a few 100 Ma later when liquid water was clearly present on the surface of Earth, impact-induced hydrothermal systems should have been extensive and may have provided a significant habitat on Earth. Similarly, these types of hydrothermal systems, with or without life, may have been produced on Mars, supplementing the impact crater lakes that have already been hypothesized on that planet [46].

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