ENLARGING THE GEOGRAPHICAL DOMAIN OF THE IMPACT ORIGIN OF LIFE HYPOTHESIS.

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Introduction: As originally envisioned, the impact origin of life hypothesis [1] proposes pre-biotic chemistry and the early evolution of life occurred in subsurface hydrothermal systems within Hadean impact craters. Extensive hydrothermal activity in the ~180 km-diameter Chicxulub impact crater [2-10], our best proxy for large Hadean impact basins, supports that concept. Recent sulfur isotope evidence of a microbial ecosystem beneath the floor of the Chicxulub crater [11] further supports the concept. Research at several other impact sites confirm hydrothermal activity is a common post-impact feature (e.g., [12-14]), that it can be long-lived [15-17], that those craters can host life [18-20], and sugests the model is applicable to other planetary bodies such as Mars (e.g., [21-25]).

Alternative Proposal: Here I would like to broaden our examination of the impact processes that shaped the Hadean Earth and suggest a second geologic setting for the early evolution of life: fumaroles, hot springs, and related hydrothermal features in impact ejecta blankets.

Geographically Broad Hydrothermal Activity: Impact ejecta blankets cover areas an order of magnitude larger than source craters. Large impact ejecta blankets are deposited hot. Like volcanic ash flows, they can heat water on depositional surfaces and in the subsurface, generating degassing pipes (as in Ries Crater ejecta, 5 km beyond the crater rim [26]) and longer-lived fields of fumaroles and hot springs if ejecta blankets are sufficiently large.

Terrain. Although the magnitude of Hadean bombardment is still debated, one model [27] suggests ~200 craters 1000 to 5000 km in diameter, and thousands of craters 100 to 1000 km in diameter, were produced. Such basin-forming events generated ejecta blankets hundreds of meters thick (e.g., [28,29]). Ejecta would have been emplaced via ballistic sedimentation with tremendous kinetic energy, destroying any surficial meteoritic-derived biogenic components and/or diluting them when mixed upward into the impact unit. As with visible basin ejecta blankets on the Moon, the emplacement of impact debris may have produced deep radial chasms and fields of secondary craters. The Moon's Imbrium impact produced >2000 secondary craters with diameters of 4.5 to 29 km [30] and Orientale produced >2700 secondary craters with diameters of 2 to 27 km [31]. On Earth, a Hadean atmosphere may have consumed some of the ejected debris by ablation and fragmentation, an effect greater if there was a 10 bar CO_2 atmosphere rather than a 1 bar N_2 atmosphere [28]. Nonetheless, ejecta-covered surfaces would have new catchments that formed warm little ponds in a fashion different than that imagined by Darwin [32]. Subsequent weathering of ejecta blankets may have affected climate and water chemistry (e.g., [33,34]).

Biogenesis. Good analogues for hot impact ejecta blankets are volcanic ash flows, like that in the Valley of Ten Thousand Smokes where ash 60 to 80 m thick hosted fumaroles and thermal water for ~100 yrs (**Fig. 1**) [35]. Fumarolic activity fluctuated due to seasonal precipitation and hydrologic recharge. In such environments, cycles of hydration and dehydration can occur on hourly, daily, and seasonal time scales, producing wet-dry cycles that may be needed for the development of protocells [36]. The magnitude of any hydrologic recharge of impact ejecta blankets will depend on local climate and the scale of the last largest impact, because some impacts may have produced a post-impact deluge up to 1.85 oceans of water that had been lofted into a steamy atmosphere [37]. Such recharge and any hydrothermal activity would have affected cooling rates of ejecta blankets.

A model of hydrothermal cooling of a 350 m-thick ejecta blanket (**Fig. 2**) [29] indicate fumarolic and hot spring activity may have persisted for thousands of years. While time scales of 10^3 and 10^4 yrs are far shorter than the $>10^6$ yr time scale of hydrothermal systems within impact basins [9,15,16], such activity would have been far more widespread than that within impact basins. There are several other fascinating details to be explored. For example, like glaciers at Yellowstone National Park, the weight of ejecta would have affected the plumbing and boiling point of subsurface water in any existing hydrothermal system. Also, like glacial gravels at Yellowstone National Park, ejecta provides a wonderfully porous and permeable unit for hydrothermal activity and any biologic components. Some Hadean ejecta blankets may have buried volcanic fields. In such cases, additional heating, volatiles, and nutrients may have been provided by underlying magmatic systems. Important chemical constituents may have also fallen from the sky when impact-generated atmospheric haze precipitated to produce hydrocarbon sediments on top of ejecta blankets. Each vapor- and liquid-filled vent in those hot-water, hydrocarbon-rich systems would have been an experimental laboratory for organic chemistry.

Conclusions: The biochemical potential of Hadean impact ejecta blankets prompts modeling to evaluate the cooling rate of ejecta as a function of hydrologic

Figure 1. A fumarole exposed in a vertical cross-section of an ash-flow sequence in the Valley of Ten Thousand Smokes. The vent is about 2 m in diameter ([38]; used with permission of Wes Hildreth). Chemically-zoned encrustations around the tops of vents are up to ~20 m in diameter in the area.

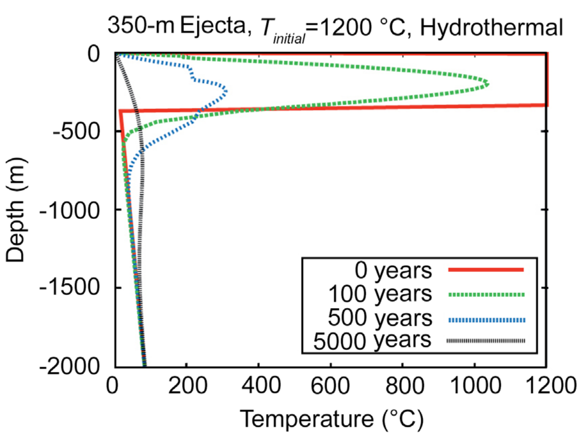

Figure 2. Cooling of a 350-m-thick Hadean impact ejecta blanket affected by hydrothermal activity [29].

recharge rate; to evaluate the chemistry of fluids within the ejecta, including fluid chemistry enhanced by buried magmatic systems; and to evaluate the chemistry of lakes that form in secondary craters at the surfaces of ejecta blankets.

A trade may exist in the impact origin of life hypothesis: Is the probability of the origin of life greater in long-lived hydrothermal systems within crater rims or is it greater in shorter-lived, but far more extensive hydrothermal systems within impact ejecta blankets? In either case, once life emerged, it may have inhabited both types of impact-generated niches.

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