HYDROTHERMAL DEPOSITS WITHIN MARTIAN IMPACT CRATERS: SIGNIFICANCE, LOCATION, AND SAMPLING STRATEGY.

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Introduction: Hydrothermal deposits offer one of the most promising locations to search for evidence of life on Mars. In this paper, we discuss the significance and characteristics of hydrothermal deposits associated with meteorite impact craters and the possibility of locating such lithologies on Mars.

Significance of impact-induced hydrothermal systems: On Earth, active hydrothermal systems are found only in volcanically active regions. However, over the past two decades it has become clear that hydrothermal activity is commonplace after the impact of an asteroid or comet on Earth and, by analogy, on any H_2O-rich solid planetary body. Some exceptions may occur with small so-called 'simple' craters (<2 and <5 km diameter on Earth and Mars, respectively) and in extreme arid environments.

Although impact-induced hydrothermal systems are transient in nature because they lack the usually longer-lasting heat sources that characterize volcanogenic hydrothermal systems, they might still have subsisted long enough to have experienced colonization by thermophilic (heat-loving) microbial communities [1]. Of the three domains of life currently recognized in the terrestrial 'tree of life' (Eukarya, Bacteria, and Archaea), it is the Archaea that are hyperthermophilic (optimum growth >80 ^{o}C) and which constitute the root of the other two domains. Impact-induced hydrothermal systems would have been common and widespread on Early Earth and may, therefore, have provided opportune sites for the growth and expansion of any available and suitable pre-existing Archaea [e.g., 1].

Whether impact-induced hydrothermal systems actually offered a suitable medium and might have lasted long enough to allow life to emerge from prebiotic chemical processes is more speculative [1]. However, it appears that the emergence of life on Earth coincided in time with, and even predated, the end of the Heavy Bombardment, the period of intense meteoritic bombardment experienced in the inner solar system ~3.8–4.5 Gyr ago [e.g., 2, 3]. As with the Earth, current models predict that Mars had a substantial initial endowment of H_2O. It follows that impact-induced hydrothermal systems on Mars were likely common and widespread [4], and thus, so would have been their associated habitats [1].

Location of hydrothermal deposits within martian impact craters: Where specifically might one find a record of past impact-induced hydrothermal activity on Mars? The terrestrial impact cratering record provides the only existing ground-truth data on the distribution of hydrothermal sites within and around impact structures. Based on our studies at the Haughton impact structure, Canadian High Arctic [5, 6] and a review of the existing literature we distinguish four main locations in an impact crater where post-impact hydrothermal deposits can form (Fig. 1):

(1) Vugs and veins within crater-fill impact melt rocks and/or breccias, with an increase in intensity of alteration towards the base.
(2) Vugs and veins within brecciated lithologies in the interior of central uplifts.
(3) Intense veining around the heavily faulted and fractured outer margin of central uplifts.
(4) Paleohydrothermal vents and mineralization along fault surfaces around faulted crater rims.

Thus, it is apparent that hydrothermal mineralization at Haughton and many other terrestrial examples is concentrated around the periphery of the crater (Fig. 1). Hydrothermal alteration also occurs at depth in the central uplifts of some larger terrestrial craters (e.g., Manson, USA, and Puchezh-Katunki, Russia).

Might impact-induced hydrothermal systems on Mars also be located predominantly in the peripheral zones of craters in the form of hydrothermal vents? An explanation of the close spatial association of many martian small valley networks and channels with the rims and walls of impact craters has indeed proposed by invoking the interaction of ground ice and hydrothermal systems [7]. It should be noted that the model of [7] does not take into account the complex faulting relationships present around the periphery of large (>5–10 km) martian impact craters.

More recently, based on a series of Mars analogue studies within and around the Haughton impact structure, the melting of transient surface ice deposits over a locally warm substrate was proposed as a possible alternative for the formation of the small valley networks on Mars [8]. In both scenarios, impact crater rim and wall areas represent locations where ice-rich materials may have once become exposed to a localized release of heat, possibly associated with impact-induced hydrothermal activity. The hydrothermal activity would have resulted in localized melting of ice, thus spawning networks of meltwater channels and eventually small valley systems. The concentration of post-impact hydrothermal activity in the peripheral zones of Haughton might thus help explain why the source regions of many small valley networks on Mars are concentrated around the rim and wall areas of martian craters.

Might impact-induced hydrothermal alteration on Mars also be located at the edge of impact melt sheets as at Haughton? The focusing of hydrothermal fluids at the edges of impact melt sheets has indeed been proposed for Mars [9, 10]. Our work, therefore, supports and strengthens previous theoretical and remote sensing investigations of martian craters which suggest that hydrothermal fluids are focused beneath, and at the edges, of impact melt sheets [9, 10].

Opportunities for sampling hydrothermal deposits within martian impact craters: We have recognized the presence of four distinct sites within an impact crater where hydrothermal deposits may form (Fig. 1). The question is now one of sampling. Would these various types of deposit be available for near-surface (<<10 m) sampling in future robotic missions? With respect to mineralization within impact melt rocks and breccias, and the interior and outer margins of central uplifts, the obvious answer would be "no". These hydrothermal deposits typically occur at depths of >200–1000 m, depending on the size of the crater. However, several processes can be invoked to expose previously 'inaccessible' materials in martian impact craters [11], so that sampling these lithologies may still be possible.

Compounding the already substantial difficulties in searching for hydrothermal deposits on Mars is the fact that mineralization with the central uplift and surrounding melt rocks is restricted in occurrence to vugs and veins, which by their very nature, are typically only centimetres to a few metres in size. However, we suggest that the possibility does exist for the sampling of hydrothermal deposits in martian craters, without the need to invoke other processes, in the form of fossil hydrothermal vents. At Haughton, these features are present at all stratigraphic/structural levels around the faulted crater rim, despite the differential erosion of the site (<20 to >200 m) [5, 6]. But would such sites be recognizable at the martian surface? At Haughton, the hydrothermal vents and their deposits are readily recognizable because of their characteristic hydrothermal mineral-induced orange colour which stands out in contrast to the generally brownish-grey appearance of most country rocks. However, aeolian and mass-wasting processes on Mars have resulted in substantial mantling of most surface features over time, while the mantling materials are often dominated by a ubiquitous bright orange dust. As a consequence, the search for impact-induced hydrothermal sites on Mars could represent a difficult challenge.

While the actual fossil hydrothermal vents at Haughton are typically ~1–5 m in diameter, the surface expression of these features can reach ~50–100 m^2 due to alteration of surrounding country rocks, leaching by groundwater's, and periglacial processes. Thus, it may be possible with high resolution hyperspectral imaging to discern such features on the martian surface. As we have shown, hydrothermal vents and other types of hydrothermal deposits will likely be located around the periphery of impact craters.

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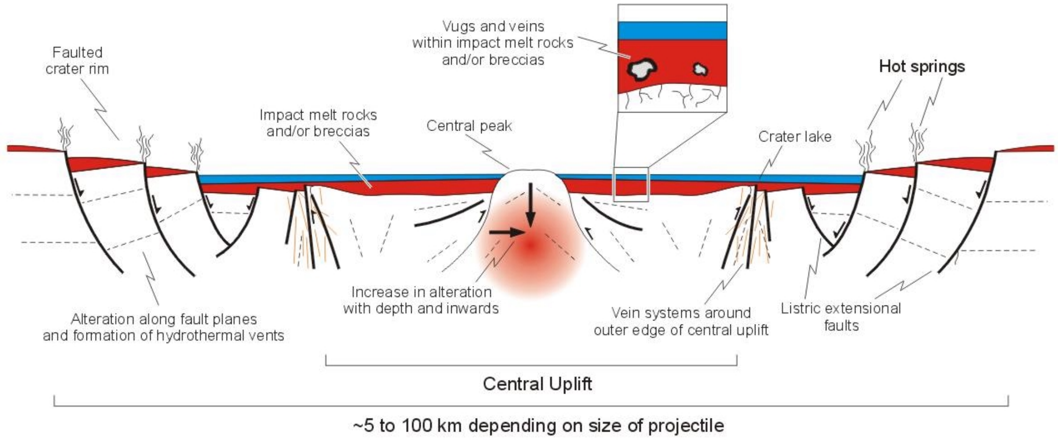

Figure 1. Schematic cross-section showing the distribution and style of hydrothermal alteration expected for complex impact structures on Mars.