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Post-impact heating of a crater lake

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Abstract

Lacustrine sediments from the 24 km diameter Boltysh impact structure record the rapid formation of an intra-crater lake. Stable isotope compositions and organic maturity parameters from the lake sediments deposited post-impact show that they were heated by underlying impactites. This heating is attributed to the establishment of an impact-generated hydrothermal system. Estimates of the duration of heating are ~30 – 40 k.y. consistent with the suggestion that crater lakes extend the longevity of impact-generated hydrothermal systems.

1. Introduction

Ancient hydrothermal systems on Earth and Mars have long been considered potential candidate habitats for the origin and evolution of life. As a result the recent exploration of Mars has focused on cratering environments where there is evidence for a long-term history of aqueous processes. Large impact events are capable of generating a hydrothermal system when the impact occurs on a water- or ice-rich target. However, the potential significance of impact-generated hydrothermal systems as habitats for life is dependent on their longevity as well as whether they provide hospitable environments for life in the form of post-impact lakes and lacustrine sediments [1]. In craters where the lake formed immediately post-impact, basal lacustrine sediments may have been altered by the impact-generated hydrothermal system enabling constraints to be placed on the extent and duration of heating. Such a lake existed in the Boltysh impact structure, a 24-km-diameter crater that formed on the Ukrainian shield 65.59 ± 0.64 Ma ago, that preserves a detailed post-impact lacustrine sedimentary record [2]. Here we show that stable isotope compositions and organic maturation parameters derived from basal intra-crater lacustrine sediments in the Boltysh impact structure record the post-impact heating of lake sediments and estimate the magnitude and duration of that heating.

2. Methodology

The oxygen and carbon stable isotope composition of authigenic carbonates in lake sediments can be used as proxies for hydrological change. In particular, the degree of evaporative concentration in the lake is dependent on water residence time so that changes in the lake's flushing rate caused by variable hydrothermal influx are potentially recorded in the stable isotope stratigraphy.

The extent and duration of any heating of post-impact sediments can be further investigated using organic geochemical biomarker data as a consequence of the differential thermal degradation of different molecules. The $17\beta,21\alpha$(H)-configuration ($\beta\alpha$) and the $17\beta,21\beta$(H)-configuration ($\beta\beta$) of hopanes, the latter characteristic of biological hopane precursors, are thermally less stable than the $17\alpha,21\beta$(H)-configuration ($\alpha\beta$) providing thermal maturity parameters, $\beta\beta/(\beta\beta+\alpha\beta+\beta\alpha)$ and $\beta\alpha/\alpha\beta+\beta\alpha$, which are sensitive to relatively low temperatures.

3. Results

Carbon and oxygen isotope compositions of authigenic carbonate and hopanoid hydrocarbon maturity parameters for the increasingly organic-rich sequence of mudstones between 580 m and 500 m are reported in Fig. 1. Hopanoid distributions contain abundant C_{31} extended hopanes with the $\beta\beta$ stereoisomers characteristic of biological hopane precursors predominant in the upper part of the section. Down-section towards the impactites the distribution changes with a slight decrease in the relative abundance of the $\beta\beta$ isomer. However, between 570 m and 577 m the degradation of hopanes is extensive and there is a marked decrease in the relative abundance of the $\beta\beta$ and, to a lesser extent, $\beta\alpha$ isomers. These changes are paralleled by a change in δ^{18}O and δ^{13}C values, which become progressively more ^{18}O-depleted down-section in the basal few meters of sediment.

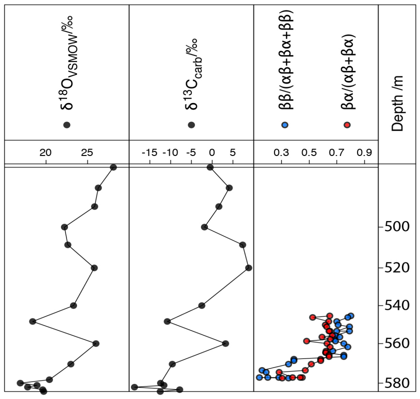

Figure 1: Stable isotope compositions of authigenic carbonate and organic biomarker maturity parameters for the basal 80 m of lacustrine crater-fill sediments, Boltysh impact structure, Ukraine.

4. Discussion

The variations in hopane maturity ratios observed over a few meters immediately above the contact with the underlying impactites cannot be attributed to differences in burial depth. However, they are remarkably similar to those observed in the maturation of hopanoid hydrocarbons by igneous intrusions [e.g. 3] and suggests a proximal heat source. Experimental simulations of the thermal degradation of hopanes found that temperatures of 75 – 250°C selectively removed ββ isomers in the presence of catalytic clays or sediments for short periods of time [4]. This suggests that the magnitude of heating experienced by the crater lake sediments was not high and the uniform maturation parameters observed above 560 m indicate that this heating was also time limited.

Organic maturation parameters are unable to distinguish whether this heating was largely conductive heating of wet lake sediments or entailed the interaction of hydrothermal fluids from the underlying impact rocks flowing through the overlying lake sediments via fissures. However, the stable isotope compositions of authigenic carbonate are consistent with changes in $\delta^{18}O$ values observed in volcanic crater lakes as a result of changing hydrothermal groundwater influx [5] suggesting that there was significant interaction between lake waters and the underlying impactites.

The preservation of ββ hopanes ~10 m above the contact with the underlying impactites implies that by the time those sediments were deposited, heatflows had diminished significantly. This enables constraints to be placed on the longevity of heating of post-impact sediments. Correlation with palynological and geochemical data [2] suggests a timescale of ~30 – 40 k.y. for the heating.

5. Conclusions

The astrobiological significance of hydrothermal environments generated by impacts is largely dependent on their spatial extent and the continued availability of liquid H_2O, energy and nutrients over extended periods of time. Estimates of the duration of impact-induced hydrothermal systems on Earth and their associated heat sources are related to crater size. For craters of similar size to Boltysh, there is variation in the estimated durations of hydrothermal activity from ~5 k.y. for the Haughton crater [8] to between ~600 k.y. and ~1.6 Ma for Lappajärvi [9]. Our study of the Boltysh core found no evidence for timescales of heating as long as 600 k.y., although the estimate of ~30 – 40 k.y. is longer than that determined for the Haughton crater. However, at Haughton, there is no evidence preserved for a crater lake forming post-impact supporting the suggestion that the presence an intra-crater lake may play a crucial role in determining the extent and duration of impact-induced hydrothermal systems [1].

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