SIX MILLION YEARS OF HYDROTHERMAL ACTIVITY AT CHICXULUB? A. E. Pickersgill[1,2], E. Christou[1], D. F. Mark[2,3], M. R. Lee[1], M. M. Tremblay[2,4], C. Rasmussen[5], J. V. Morgan[6], S. P. S. Gulick[5], M. Schmieder[7], W. Bach[8], G. R. Osinski[9], S. Simpson[9], D. A. Kring[7], C. Cockell[10], G. S. Collins[7], G. Christeson[6], S. Tikoo[11], D. Stockli[5], C. Ross[5], A. Wittmann[12], T. Swindle[13], and the Expedition 364 Scientists. [1]School of Geographical & Earth Sciences, University of Glasgow, Gregory Building, Lilybank Gardens, Glasgow G12 8QQ, U.K.; [2]NERC Argon Isotope Facility, Scottish Universities Environmental Research Centre (SUERC), Rankine Avenue, East Kilbride G75 0QF, UK, [3]Department of Earth & Environmental Science, University of St Andrews, St Andrews, KY16 9AJ, UK. [4]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette IN 47907. [5]Institute for Geophysics, Jackson School of Geosciences, University of Texas at Austin, 10100 Burnet Rd Bldg 196-ROC, Austin, Texas 78758 USA. Department of Earth Science and Engineering, Imperial College London, SW7 2BP, UK. [7]Center for Lunar Science and Exploration, Lunar and Planetary Institute, Universities Space Research Association, Houston TX 77058. [8]MARUM, Faculty of Geosciences, University of Bremen, Klagenfurter Straße 2-4, GEO Building, 28359, Bremen, Germany. [9]Institute for Earth and Space Exploration, Dept. of Earth Sciences, University of Western Ontario, 1151 Richmond Street, London, ON, Canada. [10]UK Centre for Astrobiology, School of Physics and Astronomy, University of Edinburgh, EH9 3FD, UK. [11]Department of Geophysics, Stanford University, Stanford, CA 94305 USA. [12]Eyring Materials Center, Arizona State University, 300 E University Drive, Tempe, AZ 85257-7205. [13]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ 85721-0092. (annemarie.pickersgill@glasgow.ac.uk).

Hydrothermal systems are considered to have played an essential role in the origin of life on Earth and, potentially, on other planets [1–4]. These systems are known to form within hypervelocity impact structures [1,5–7], making them a target for astrobiology research. Such environments provide heat sources on otherwise cold planetary surfaces, thereby creating habitable environments for thermophilic and hyperthermophilic microorganisms [3] and potentially acting as 'cradles' for prebiotic chemical reactions [4]. Constraining the duration of hydrothermal activity at impact structures is therefore crucial for understanding the origin of life. We present $^{40}Ar/^{39}Ar$ geochronology and numerical simulations of the hydrothermal system in and around the peak ring of the ~200 km diameter Chicxulub impact structure. Previous simulations of impact-induced hydrothermal activity found a maximum duration at Chicxulub of 2.3 million years, where the lifetime of the hydrothermal system is defined as the time taken to cool to 90 °C within 1 km of the surface [8,9].

Here we find that authigenic feldspar in the impact melt rocks at Chicxulub formed over ~6 Myr, from the time of impact ~66 Ma to ~60 Ma. We paired these empirical data with new, independently derived numerical simulations that show continued hydrothermal fluid flow up to 7 Myr post-impact. We therefore interpret hydrothermal activity at Chicxulub to have lasted at least 6 Myr.

We used samples and data obtained from the joint International Ocean Discovery Program (IODP) and International Continental Scientific Drilling Program (ICDP) Expedition 364 at Site M0077 (21.45° N, 89.95° W) [10,11]. Hole M0077A, drilled into the peak ring approximately 45 km from the crater center, revealed new stratigraphy and physical properties of the rocks [10,12] which suggested that the hydrothermal system might have endured longer than previously believed. Microscopic observations of impact melt rocks from Core M0077A additionally revealed the presence of hydrothermal feldspar [13], which we interpret to have formed as the water flux in the system declined.

We conducted $^{40}Ar/^{39}Ar$ step heating analyses on four samples of impact melt rock from three different depths: 706.4, 735.0, and 756.0 mbsf. Samples CHX 706.4, 735.0, and 756.0A are dominated by authigenic K-rich feldspar which nucleated around quench-crystallized plagioclase. Sample CHX 756.0B, from the same depth as 756.0A, is dominantly quench-crystallized plagioclase surrounded by pore space.

Samples CHX 735.0, 756.0A, and 756.0B all yielded plateau ages ranging from 58.3 ± 0.43 Ma (2σ) to 66.24 ± 0.74 Ma (2σ). Age probability of plateau ages yields a peak at ~60 Ma. The oldest ages measured in this study are indistinguishable from the K-Pg boundary (K-Pg = 66.052 ± 0.086 Ma, 2σ [14]). Sample CHX 706.4 did not yield any plateau ages. The spread of ages are interpreted to reflect protracted and heterogeneous formation of hydrothermal feldspar over at least ~4 to 6 Myr after the impact.

Independently of the $^{40}Ar/^{39}Ar$ results, numerical simulations were conducted to simulate water mass flux and heat distribution in the post-impact hydrothermal system at Chicxulub. These simulations followed a similar methodology to previous simulation studies [8,9,15], but are different in that they include constraints from the physical properties and stratigraphy of the M0077A core. For this study, we used a modified version of the U.S. Geological Survey

(USGS) HYDROTHERM - Version 3 software [16,17]. Simulations were conducted in two dimensions, creating a 160 km cross-section from the crater center, through the peak ring and up to its rim. Permeability is a key constraint in numerical simulations of hydrothermal systems, since permeability has yet to be measured on the M0077A samples, permeability values for these simulations come from analogous materials [18–22].

Results of the simulations suggest that hydrothermal fluid circulation at Chicxulub lasted for at least 6 to 7 million years after the impact (impact age = 66.038 ± 0.098 Ma [23]). After 6 million years the water mass flux in the system is 2 orders of magnitude smaller than at the start of the simulation, and after 7 million years the temperatures have returned close to the regional geothermal gradient.

The lifetimes of impact-induced hydrothermal systems in general are poorly constrained, with durations in only a few having been quantified by geochronological measurements [e.g., 19–21], and numerical simulations [e.g., 8,9]. The Sudbury impact structure, Canada, is the site of the most extensive hydrothermal alteration in a terrestrial impact structure [8]. Along with its large size (~250 km in diameter) it is therefore a useful analogue for the duration of a hydrothermal system in a large impact structure such as Chicxulub. A maximum duration of conductive cooling of the Sudbury igneous complex of 1 Myr was determined based on zircon U-Pb ages [27], and cooling of the hydrothermal system is considered to have been much faster, on the order of tens to thousands of years, due to the added effects of fluid convection. However, numerical modeling of the hydrothermal system at Sudbury by Abramov and Kring [8] suggests that the hydrothermal system could have remained active for hundreds of thousands to several million years depending on permeability of the host rock. Similar results (~1.5 to 2.3 Myr) were found for Chicxulub when conducting numerical modeling of hydrothermal activity, depending on permeability of the host rocks [9].

Based on the combined geochronological and numerical simulation results of the present study, the duration of the hydrothermal fluid flow at Chicxulub appears to have been at least 6 Myr, up to three times longer than the previously simulated ~2 Myr [9]. We attribute this difference primarily to the different physical properties of the rocks measured in the M0077A drill core relative to those in the Yaxcopoil-1 and Yucatan-6 cores. Specifically the lithologies from M0077A exhibit higher density of fractures and higher porosity than the cores used in previous simulations [12]. Additionally, the version of HYDROTHERM used in the present study is better able to account for complex stratigraphy than previous versions.

The duration of hydrothermal systems generated by large impact structures is clearly highly complex, and more thermochronometric data are necessary to unravel the intricate thermal history at Chicxulub [see also 28, 29]. If Chicxulub is found to be unique in terms of its cooling and/or fluid flow history, then the search for extraterrestrial life should be focussed on impact structures that were big enough to disrupt the mantle on their respective planets,; that formed when there was mantle convection, or that otherwise bear similarity to the formation environment of Chicxulub.

More work is needed to empirically measure the duration of hydrothermal activity at terrestrial impact structures of various sizes in order to constrain the ability of these systems to have provided habitable environments on early Earth or on other planets. This study has opened future research pathways to better understand the durations and temperatures involved in impact-generated hydrothermal systems.

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