THE RIES POST-IMPACT HYDROTHERMAL SYSTEM: SPATIAL AND TEMPORAL MINERALOGICAL VARIATION.
H. M. Sapers[1,2], G. R. Osinski[1,2,3], E. Buitenhuis[2], N. R. Banerjee[1,2], R. L. Flemming[1,2], J., Hainge[3], and S. Blain[1]. [1]Centre for Planetary Science and Exploration, University of Western Ontario, London, ON, Canada, 1151 Richmond St, N6A 5B7 (hsapers@uwo.ca). [2]Department of Earth Sciences, ibid. [3]Department of Physics and Astronomy, ibid.

Introduction: Large impacts into a water-rich solid planetary body will generate a hydrothermal system; recent work has shown that hydrothermal activity is commonplace in the immediate aftermath of an impact event[1],[2]. In an impact crater, the heat source is provided by impact-melted or -heated materials. The interaction of water with these hot materials forms a hot rock-water circulatory system that can dissolve, transport, and precipitate various mineral species[3] resulting in characteristic hydrothermal mineral alteration assemblages. Understanding the thermal, chemical, and temporal characteristics of post-impact hydrothermal systems has important astrobiological implications as such impact-induced environments may have played a role in the development of early life on Earth and possibly other rocky planets such as Mars[4].

The Ries impact structure is one of the first impact sites where a post-impact hydrothermal system has been proposed[5],[6]. The occurrence of secondary mineralization and hydrothermal alteration of the impact suites has been noted and described (e.g.[2],[7],[8],[11],[12]).

Despite the multiple studies identifying various alteration mineral assemblages and textures, the evolution and extent of the Ries post-impact hydrothermal system remains to be fully constrained. There are very few studies in the literature that systematically characterize post-impact hydrothermal systems. Such studies are important in understanding the impact cratering process on Earth, as well as to better characterize and identify potential astrobiology targets on other planetary bodies. The Ries post-impact hydrothermal system is of particular interest due to the extraordinary preservation of the impact ejecta units allowing for a thorough, systematic investigation into hydrothermal alteration. Furthermore, the recent identification of biogenic tubular features within the Ries impact glasses[9] highlights the importance of Ries in understanding the habitability potential of impact structures.

The Ries impact structure: The 24 km diameter ~14.5 Ma Ries impact structure located in southern Germany is arguably one of the best-characterized and best-preserved terrestrial impact structures (see [10] for review). There are four main proximal, well-preserved impactite ejecta lithologies: 1) polymict sedimentary breccia ("Bunte Breccia") and megablocks; 2) polymict crystalline breccias; 3) impact glass-bearing breccias located outside the crater rim ("surficial" or "outer" suevites"); and 4) coherent impact melt rocks. The crater-fill deposits consist of layered crater lake sediments overlying glass-bearing breccias ("crater suevite"). Previous studies of the Ries post-impact hydrothermal system have either individually focused on restricted outcrops of surficial suevite or the 1973 Nördlingen drill core sampling ~270 m of crater suevite beneath ~300 m of crater lake sediments[5].

Previous studies of the post-impact hydrothermal system: Two main styles of hydrothermal alteration have been proposed at the Ries: a high-temperature, long-lived and pervasive system beneath the crater lake as evidenced by the extensive hydrothermal alteration of the crater suevite; and isolated, low temperature, ephemeral systems outside the crater rim recorded by patchy, low-temperature alteration assemblages in the surficial suevites. The hydrothermal fluids of the Ries post-impact hydrothermal system were likely derived from a combination of meteoric water from the over lying crater lake and ground water influx from nearby country rocks. There is no evidence of a magmatic or metamorphic source[2].

Despite the identification of hydrous alteration phases and textures within the ejecta, work by [11] suggests that the Ries post-impact hydrothermal system was limited to the intensely altered glass-bearing breccias within the crater. Muttik et al.[11] argue that the alteration of the glass-bearing breccia outside the crater rim is largely due to weathering processes.

Samples: Here we correlate mineralogical data from suevite samples representing the entire spatial extent of exposed outcrops in addition to data from the Nördlingen drill core as well as the Wörnitzostheim core that samples ~81m of surficial suevite overlain by ~20 m of lake sediments. We are preforming a systematic mineralogical study based on bulk powder X-ray diffraction (XRD) of all impactite lithologies representing all known outcrops and all visibly identifiable variations in alteration. The mineralogical study of the ejecta units is being coordinated with detailed petrographic and XRD studies of the two drill cores. This study assesses all the various styles of alteration and the mineralogical assemblages both through the vertical extent of the crater-fill material as well as the radial extent of ejecta to understand the relative importance and timing of the various alteration processes. Four main transects representing the extent of the ejecta sequence at the Ries impact structure were chosen for detailed study: a vertical transect through 17 m of 'surficial suevite' from the erosional surface to the contact with the Bunte breccia; a detailed transect through the transition and alteration zone between the glass-bearing breccia and Bunte breccia; horizontal transects across breccia pipes within the glass-bearing breccia; and a suite of various alteration assemblages including vein fill material, variably altered matrix and glass clasts from the 'surficial suevite', variably altered melt rock, and scrapings from within breccia pipes.

Alteration of Crater Suevite Alteration phases of the crater suevite include: K-feldspar, albite, clays, chlorite, zeolites, calcite, and minor phases including pyrite, goethite, barite and siderite. The alteration assemblages as recorded in the Nördlingen core, are consistent with an early, high-temperature (200-300^{o}C) phase of K-metasomatism coinciding with albitization and chloritization followed by pervasive intermediate argillic alteration and zeolitization[2].

Alteration of Surficial Suevite: A number of hydrothermal alteration phases consistent with low-temperature (<100-200^{o}C) hydrothermal activity including clays, zeolites, quartz, calcite, hematite and goethite have been identified[12]. The main alteration phase is montmorillonite and Ba-phillipsite. It is significant to note that neither clasts of pre-impact target rocks nor impactite phases were enriched in Ba. Therefore the Ba was likely dissolved by the hydrothermal fluids, transported and precipitated during zeolitization of the surficial suevites[2].

Alteration of Surficial Suevite at depth: Study of the Wörnitzostheim core has shown alteration assemblages consistent with the surficial suevites described above defined by vesicle filling montmorillonite, Ba-rich phillipsite forming within vesicles, and groundmass montmorillonite. At depth (>78 m) montmorillonite and illite become major components and zeolitization occurs.

Evidence for hydrothermal activity outside the crater rim: Alteration textures are spatially restricted and include coliform/rhythmic banding, vesicle infilling, pervasive alteration to complete replacement of glass clasts by clay minerals and the occurrence of platy clays. If a limited extent of hydrothermal activity is assumed in these units, then alteration assemblages within the ejected glass-bearing breccia are predominantly formed by post-impact weathering processes. However, an extremely spatially limited hydrothermal system outside the crater rim does not offer an explanation for the Ba-phillipsite phase within the glass-bearing breccias. Furthermore, the similarity of the alteration assemblages between the surficial suevite and the suevite in the Wörnitzostheim core(s) suggests these phases are not due to weathering processes as the Wörnitzostheim core suevite was protected by ~20 m of overburden.

Studies of the alteration textures of glassy and formerly glassy clasts within both the ejected and crater-fill glass-bearing breccias has shown a consist progression from fresh glass through incipient, low temperature alteration (perlitic fracturing, devitrification and decomposition textures) to evidence of fluid circulation (alteration zones surrounding perlitic fractures and vesicles, banding and zonation) resulting in progressive alteration (globular replacement textures, platy clays) and finally pervasive alteration and total replacement including the formation of Ba-phillipsite (harmatone) and montmorillonite in both the crater-fill and ejected glass-bearing breccias. Consistent with a recent study[13] we suggest that alteration of the surficial suevite followed a progression from high- to low-temperature with textures consistent with hydrothermal alteration, *sensu stricto*, between the two temperature end members. Hydrothermal systems were likely spatially extensive in the surficial suevites with localized, higher intensity systems sporadically distributed. Hydrothermal alteration was likely preceded by high-temperature devitrification or autometamorphism and followed by low-temperature weathering.

Concluding remarks: This study provides comprehensive systematic mineralogical and petrographic analyses of the hydrothermal alteration assemblages present in glass-bearing breccias at the Ries impact structure. Taken together, the similar textural and mineralogical evidence of hydrothermal alteration in both the crater-fill and ejected glass-bearing breccias suggests a similar progression of alteration processes in both units consistent with hydrothermal alteration. We suggest that the post-impact hydrothermal system at the Ries impact structure was much more extensive and pervasive outside the crater rim area than previously reported.

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