A TALE OF TWO TEMPERATURES: HYDROTHERMAL OR AMBIENT AQUEOUS ALTERATION AT THE RIES IMPACT STRUCTURE.  H. M. Sapers1,2,3, G. R. Osinski4,5,6, C. Caudill5, F. J. Longstaffe3, L.L. Tornabene4,5, R. Flemming4,5, and S. Chauvin6,1 1 Div. of Geological and Planetary Sciences, California Institute of Technology, 2Dept. of Earth Sciences, University of Southern California, 3Planetary Chemistry & Astrobiology Group, Jet Propulsion Laboratory, 4Centre for Planetary Science and Exploration/ 5Dept. of Earth Sciences/ 6Dept. of Physics and Astronomy, The University of Western Ontario, London, Ontario (hsapers@caltech.edu)

Introduction: The ~15 Ma [10], ~26 km diameter, Ries impact structure is arguably the best-preserved complex impact structure on Earth [11]. Although there is wide-spread evidence of impact-associated hydrothermal activity at the Ries impact structure [12,13], the spatial extent of the system is debated [14]. It is accepted that there was a high-temperature hydrothermal system within the inner crystalline ring. The alteration assemblages within the crater suevite, as sampled by the Nördlingen 1973 core, are consistent with high-temperature (~200 – 300 °C) hydrothermal activity [13]. Glass-bearing breccias ejected beyond the inner-rim, surficial suevite, are variably altered. Phyllosilicate minerals dominate the fine-grained matrix and also occur as a larger-grained space-filling phase within fractures and vesicles. These clay minerals have been variably interpreted as products of weathering [15], high-temperature devitrification products [16, 17], and secondary hydrothermal precipitates [13, 18]. Here we present a comprehensive mineralogical and isotopic assessment of phyllosilicate assemblages suggesting a lateral extent to hydrothermal activity beyond the inner ring over-printed by ambient, surficial weathering. Suevite, or glass-bearing impact breccia was sampled from three distinct settings: crater suevite from within the central basin, and ejecta from 2 locations: surficial suevite exposed in the Aumühle quarry, and surficial suevite at depth samples by the Wörnitzstoffeim core.

Phyllosilicate minerals play an important role in understanding the paleoclimate and habitability. Impact craters provide a complex setting for phyllosilicates detected from orbit [1,2]. Pre-impact phases excavated by the impact process can be exposed in bedrock (e.g., walls, terraces or central uplift) and crater-related deposits [e.g. 2,3]. Syn-impact phases form via impact-induced alteration pathways [4,5]. It has been suggested that warm, wet conditions are restricted to the earliest period of Martian history implying that both habitable and phyllosilicate-forming environments are limited to the Noachian Period (~4.5 – 3.7 Ga) [e.g. 3, 6, 7]. However, syn-impact phyllosilicates can be formed during spatially and temporally extensive impact-generated hydrothermal systems and through the weathering of impact-derived materials [2]. While impact-generated hydrothermal activity may provide transient, warm, wet conditions associated with phyllosilicate formation and habitability [8,9], the weathering of impact-generated materials arguably continues long after the cessation of impact-generated hydrothermal activity, temporally extending the period of phyllosilicate formation beyond that of habitability. These two mechanisms of phyllosilicate generation: (1) aqueous associated, and (2) recrystallization/devitrification of metastable impact-products, have led to the two main models of the Ries post-impact hydrothermal system.

Hydrothermal deposits at the Ries impact structure: Despite intensive study, and long-standing recognition of secondary alteration phases, the extent of post-impact hydrothermal alteration within the surficial suevites beyond the inner crater ring is debated [14]. Mineralogical evidence of hydrothermal alteration varies considerably between the crater fill units and ejecta. Intense pervasive hydrothermal alteration is limited to the crater suevites indicating that early, high temperature (200 – 300°C) hydrothermal activity was restricted to the crater fill units [13]. In contrast, alteration textures in the surficial suevite are dominantly spatially restricted and include coliform/rhythmic banding, vesicle infilling, and local pervasive alteration. Phyllosilicate phases within both the groundmass and replacing glassy clasts in the surficial suevite have long been recognized. The groundmass, defined as fine-grained material enclosing fragments of shocked/ unshocked material c.f. [17], comprises 50–70 vol% of the surficial suevites and is ~50 vol% clayey material [17]. Detailed EDS analyses [17] indicate that the composition of the clayey fraction of the groundmass has a highly variable composition not always consistent with montmorillonite. Large, areas of platy clays that crosscut the fine-grained clay matrix, however, always have compositions consistent with montmorillonite [17] and have been interpreted to have originated both from hydrothermal processes [13] and ambient weathering [14] Montmorillonite comprises only

Previously we examined the surficial and crater suevite using a novel application of peak-intensity contour mapping of bulk powder X-ray diffraction data indicating a distinct mineralogical difference in the smectitic phyllosilicate fraction [19]. “Smectitic” phyllosilicates in the surficial suevite at Aumühle were found to be mineralogically distinct from the surficial
suevite in the Wörnitzostheim core that were more similar to the pervasively altered crater suevite sampled by the Nördlingen core [19]. Here we expand on this work by selecting 16 samples for detailed clay separation X-ray diffraction study and oxygen isotopic analysis.

XRD methods: Powdered sample were separated in two size fractions: < 2 µm and < 0.2 µm. Both < 2 µm and < 0.2 µm fractions were collected to differentiate the fine-grained phyllosilicates in the matrix from the larger, space-filling phases. Portions of each size fraction were Ca- and K-saturated. Ca-saturated samples were analyzed at 54 % relative humidity and then glycolated. K-saturated samples were analyzed at 0 % and 54 % relative humidity and then subsequently dehydrated by heating at 300 °C and 550 °C. 7 samples of suevite ejecta from exposed ejecta deposits at the Aumühle quarry were chosen, including a pervasively altered zone at the contact with the Bunte Breccia. 5 samples from the Wörnitzostheim 1965 drill core at depths between 20 – 93 mbs were selected. The Wörnitzostheim core is located outside of the inner ring of the crater, ~7.8 km SW of the crater center, and penetrates ~81 m of suevite ejecta overlain by ~20 m of lacustrine sediments. 4 samples from a suevite interval between 296 and 337 mbs were selected from the Nördlingen 1973 drill core. The Nördlingen core was extracted within the inner ring and penetrates ~270 m of crater-lake sediments and the ~400 m of crater-fill units, and extends into the crystalline basement.

XRD results: The results from the Ca saturated samples are consistent with a montmorillonite composition with basal (001) spacing at ~1.4 nm at 54 % relative humidity and ~1.7 nm when glycolated. However, when K-saturated and dried at 105 °C, the basal spacing does not collapse predictably with dehydration indicating the possible presence of chloritic or hydroxyl-interlayer material in the structure. Heating results in broad subtle peaks, in contrast to sharp 1.0 nm peaks as expected for pure montmorillonite. This is indicative of interstratification. The observed peak asymmetry is also suggestive of turbostratic stacking. Compared to the < 2 µm fraction, the < 0.2 µm fraction contains a higher proportion of amorphous material and exhibits a greater degree of collapse to 1.0 nm upon heating.

Oxygen isotopic results: A previous [15] found δ¹⁸O between +17.2 – +22.0 ‰ for surficial suevite samples and +8.6 – +15.2 ‰ for samples from the Nördlingen core corresponding to calculated temperatures between 17 – 13 °C and 111 – 60 °C, respectively. These results suggested that hydrothermal alteration was limited to the central basin and phyllosilicate phases in the surficial suevite were formed through ambient weathering processes. Our preliminary results show no systematic differences between the < 2 µm and < 0.2 µm clays isolated for analysis. We found δ¹⁸O between +15.3 – +21.3 ‰ for surficial suevite from Aumühle and +11.4 – +15.5 ‰ for crater suevite from the Nördlingen core, consistent with [15]. Samples of suevite ejecta from the Wörnitzostheim core were δ¹⁸O of +13.9 – +21.3 ‰, overlapping the range found in the Nördlingen core and the Aumühle samples. These results suggest that the surficial suevite units may have been subjected to higher temperatures in the past, and that surface-exposed clays in the Aumühle samples record a subsequent lower temperature, ambient weathering overprint.

Conclusions: These results suggest that there is a mineralogical diversity within the phyllosilicate component of the surficial suevite at the Ries that has not been previously reported. These data suggest a spatially extensive and heterogeneous post-impact hydrothermal system that was overprinted by extended weathering at ambient conditions. The XRD results indicate a complex, interstratified phyllosilicate mineralogy that varies at the outcrop scale, and which is suggestive of dynamic, heterogeneous alteration processes. Differentiating the phyllosilicate phases associated with a spatially extensive hydrothermal system from those formed by continuous ambient weathering at Ries has implications both for understanding: (1) planetary habitability following large impact events, and (2) paleoclimate implications of phyllosilicates associated with impact structures on Mars.