FORMATION OF SECONDARY CLAY MINERALS IN POST-IMPACT LACUSTRINE ROCKS AT THE RIES IMPACT STRUCTURE, GERMANY

M. J. O. Svensson[1], G. R. Osinski[1], F. J. Longstaffe[1], T. A. Goudge[2], [1]Centre for Planetary Science & Exploration / Dept. Earth Sciences, The University of Western Ontario, 1151 Richmond Street N. London, Ontario, Canada, N6A 5B7. (msvenss@uwo.ca) [2]Jackson School of Geosciences, The University of Texas at Austin, Austin, TX.

Introduction: Impact cratering is among the most commonly occurring geological processes on rocky and icy bodies in the solar system. On planets like Earth and Mars, impact craters are frequently capable of hosting lacustrine systems, which are valued for their climatic, geological and biological records [1]. Additionally, impact events forming complex craters are known to produce hydrothermal systems in the presence of sufficient amounts of H_2O [2]. The venting of hydrothermal systems into overlying lake environments could provide ideal habitats for life [1]. Many intra-crater-lakes on Earth or Mars could have been hydrothermally modified but deposits recording this interaction have, in many cases, likely been eroded or are otherwise inaccessible. Notably, Jezero Crater, the landing site of the Mars 2020 sample return mission, hosts rover-accessible deltaic deposits and possible lacustrine basin-margin carbonates [3, 4]. Whether any of these deposits were hydrothermally modified by the Jezero impact event remains to be determined.

The ~14.8 Ma Ries impact structure [5], Germany, provides a unique opportunity to study hydrothermally modified lacustrine deposits in detail. Access to lacustrine deposits preserved in scientific drill cores, such as the Nördlingen 1973 core and Wörnitzostheim 1965 core, have made the Ries an excellent subject for the study of post impact lacustrine environments. Several groups have studied the Ries' lacustrine deposits to ascertain the evolution of the host environment [6, 7, 8]. Here, we provide the most comprehensive study to date of the secondary clay phases present in the post-impact lacustrine deposits sampled by the Wörnitzostheim 1965 drill core.

Background: The Ries impact event penetrated through sedimentary Mesozoic rocks unconformably overlying a crystalline Hercynian basement. The event formed an ~24 km diameter complex crater with a ~16 km diameter central basin bounded by an inner ring (Fig. 1) [11]. A series of impact melt-bearing breccias (crater-fill suevites) occur within the inner ring, overlain by ~336 m of siliciclastic lacustrine rocks, hereafter called basin-center deposits. Similarly, a discontinuous series of impact melt-bearing breccias (surficial suevite) occur beyond the inner ring but rarely in contact with overlying lacustrine deposits [6, 12]. The localized concentration of hydrothermal alteration in the "suevite" suggests that it supplied the main source of heat during a period of post-impact hydrothermal activity [13]. The lacustrine, basin center deposits consist of fine-grained siliciclastic rocks. In contrast, the post-impact lacustrine rocks deposited beyond the inner ring (hereafter the basin margin deposits) predominantly comprise carbonates, with less frequent occurrences of fluvio-deltaic siliciclastic rocks [14].

Objectives and Methods: This study contributes a detailed characterization of secondary clay minerals and suggests potential fluid sources based on $\delta^{18}O$ and $\delta^{2}H$ measurements. The mineralogy was characterized by powder x-ray diffraction (*p*XRD) of bulk samples and preferentially oriented <2 μm and <0.2 μm clay separates. Additional characterization was conducted through electron microprobe analysis (EMPA). Values of $\delta^{18}O$ and $\delta^{2}H$ were measured for the <2 μm size fraction and possible temperature regimes were modelled using illite and smectite geothermometers from previous studies [9, 10]. Sample portions utilized for $\delta^{18}O$ measurements were treated with HCl at ~20 °C until effervescence no longer occurred to minimize contamination from carbonate minerals.

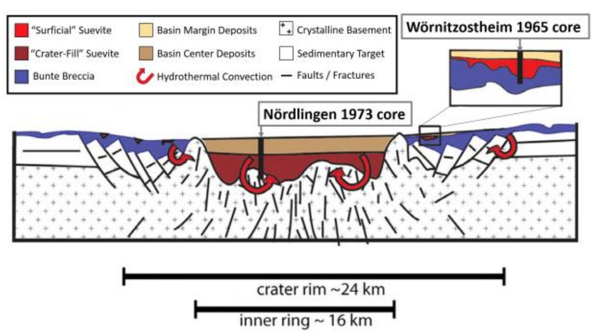

Figure 1: Cross section of the Ries impact structure showing the target material and the approximate distribution of major proximal impactites and post-impact lacustrine deposits [after 14].

Results and Discussion: The Wörnitzostheim 1965 core was drilled just outside the inner ring of Ries (Fig. 1) where it sampled siliciclastic basin margin deposits and underlying surficial suevite. The rock type gradually transitions from the surficial suevite to fine siliciclastic rocks. We identified fourteen different units in the stratigraphy of the Wörnitzostheim 1965 drill core. Six representative units, spread out across the transition from the upper to basal post-impact lacustrine rocks, were studied in detail.

EMPA analyses show a transition with depth in >100 μm sized non-clay mineral constituents from potassic feldspars and muscovite to a mixture of potassic and sodic feldspars. This change in relatively coarse material was accompanied by a change in clay mineralogy and grain-size. Fine-grained (<1 μm) illitic clays accompanied by lesser quantities of kaolinite and smectitic clays were more common at depths ≤11 m. In contrast, coarser (≥1 μm) smectitic clays accompanied by lesser amounts of illitic clays were more common at greater depths. This shift in mineralogy is reflected in the chemistry of the clay minerals as the shallower clay minerals have a higher K_2O content (~3 %) and the deeper clay minerals have a lower K_2O content (~1 %).

The EMPA data correlates well with results from the *p*XRD of the <2 μm size fraction, which suggests the presence of a larger amount of illitic clays at shallow depths and a larger amount of smectitic clays at greater depths. Additionally, these data indicated that interstratified illite-smectite could exist throughout the sampled section of drill core, and that kaolinite clays comprise a less abundant mineral constituent of samples dominated by illitic clays. *p*XRD of the <0.2 μm size fraction revealed that the clay minerals of this size are entirely dioctahedral, consistent with illitic and kaolinite clays.

The mixed clay mineralogy of the <2 μm size fraction is reflected in the $\delta^{18}O$ results, which are reported relative to VSMOW in per mil (‰). The most illitic samples have the highest $\delta^{18}O$ (+20.7 ‰), the most smectitic samples have the lowest $\delta^{18}O$ results (+16.4 ‰) and the samples containing both phases have intermediate results (e.g. +17.1 ‰). Plotted relative to the montmorillonite and illite weathering lines of Savin, (1967) [15] and the Global Meteoric Water Line (GMWL), the smectitic and illitic $\delta^{18}O$ and $\delta^{2}H$ results form two distinct groups (Fig 2). The illitic samples plot close to the illite weathering line, which suggests formation in equilibrium with meteoric waters at ~20–25 °C. The smectitic samples are offset from the montmorillonite weathering line in a fashion that suggests formation at higher temperatures. Based on previous temperature estimates for surficial suevite [13, 16], a potential temperature range for the fluids that precipitated the smectitic clays could be 75–130 °C. The elevated temperatures and depth of the smectitic samples suggests a fluid source comprising geothermally modified meteoric waters.

Conclusions: The estimated $\delta^{18}O$ and $\delta^{2}H$ values of the fluid that precipitated the illitic clays is in good agreement with the GMWL. Together with an estimated temperature in the range of 20–25 °C, these data suggest that the composition of this fluid was similar to meteoric water. Although illite is more commonly associated with higher temperature regimes, muscovite and potassic feldspars could have saturated the clay-forming fluid with potassium, resulting in the precipitation of illitic clay. The illitic clays could have also formed from weathering processes. Whether the illitic clays are neoformed or detrital remains unclear. In contrast, the fluids that precipitated the smectitic clays have isotopic compositions that fall far from the GMWL (Fig. 2) and are consistent with geothermally modified meteoric water. These conclusions suggest continued geothermal activity was a controlling factor of the temperature and fluid composition during post-impact lacustrine evolution. Possible geothermal influences are important considerations when assessing the clay mineralogy of Jezero's deltaic sedimentary units. Similarly detailed studies of clay material in analogous sites on Earth are needed to inform conclusions regarding the past habitability of Jezero crater.

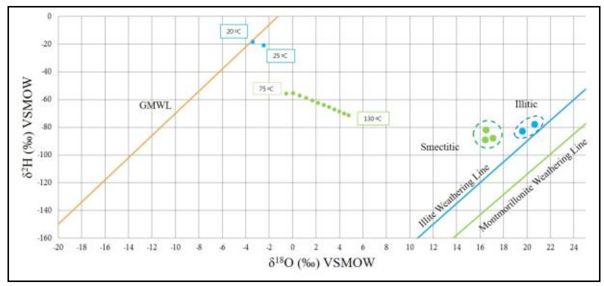

Figure 2: Sample $\delta^{18}O$ and $\delta^{2}H$ composition of smectitic (green) and illitic (blue) clays and estimates for their respective fluid sources and temperatures.

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