POST-IMPACT CRATER LAKE FORMATION ON EARTH & MARS: STAGES IN THE EVOLUTION FROM CLOSED-BASIN TO OPEN-BASIN LAKE IN THE RIES CRATER, GERMANY.

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Introduction: Late Noachian Mars was characterized by fluvial channels and open and closed-basin lakes, some with deltaic deposits, all evidence for the presence of running water (fluvial environments) and standing bodies of water (lacustrine environments) [1]. Debate is ongoing about whether these features were formed by pluvial (rainfall) activity [2] or nivial (snow) meltwater [3], and formed in a "warm and wet" [2] or cold and icy [3] Late Noachian Mars climate. Exploration of the floor of Gale Crater, a closed-basin lake, by the Mars Science Laboratory *Curiosity* rover has recently focused attention on these questions. *Curiosity* has found evidence for lake deposits on the floor of Gale Crater [4] and related fluvial channels and fan deposits [5], complementing the distinctive fluvial influx channel emanating from higher terrain outside and to the south of the crater [6]. In this contribution we examine the geology of the Ries impact crater [7] and its subsequent aqueous sedimentary history in order to document the evolving fluvial and lacustrine environments, and the evolution of the crater from 1) a fresh crater landform, to 2) a closed-basin lake, 3) an open-basin lake, and ultimately to 4) a post-lacustrine landform. Delineation of the characteristics of these stages and their associated deposits provides a basis on which to develop conceptual models of processes operating at different stages in the formation and evolution of Gale Crater. Here we outline the basic geologic setting of the Ries Crater lake [8-10] and assess the stages in its post-formation fluvial and lacustrine history. In a separate contribution [11] we describe fluvial sedimentary deposits preserved in the Ries Crater lake and their interpreted catchment basin, provenance, protolith, preprocessing, reworking, transport distances and implications for Gale Crater sedimentary deposits.

Ries Crater Geological Setting: The 15 Ma old Ries crater, a mid-sized complex impact structure (central crater, ring, megablock zone; in total 24 km diameter), shows potential similarities to martian impact craters, including impact in water-related landscape and production of a "double layer" ejecta deposit (Bunte Breccia, suevite) with a rampart structure [12]. In contrast to many Mars craters, the target rocks, were not basaltic, but layered sedimentary rocks (up to 580 m: carbonates and siliciclastics, Middle Triassic to Upper Jurassic in age), covering a crystalline basement (Hercynian Basement composed of gneiss, granite, and amphibolite).

Drilling of the Ries Crater Floor and Interpretation of Lake Deposits: Previous scientific drilling (drill core Nördlingen 1973) in the central Ries structure recovered an almost complete section of crater-lake sediments including i) coarse siliciclastics derived from suevite, followed by ii) bituminous shales successively turning into iii) marls and iv) organic-poor claystones with intercalated lignites [8]. This 314 m thick sequence has been considered to reflect a development from i) an alluvial and playa setting, succeeded by ii) an alkaline saline lake with permanent stratification, iii) a less saline unstratified lake, and iv) a freshwater lake with temporary coal swamps. The inferred decrease in salinity was attributed to a climate-controlled increase in freshwater influx plus a late formation of an outlet [8].

However, sedimentological, biogeochemical, isotopic and palynological, analyses of the new drill core Enkingen from the southern Ries, covering a partial section of the central basin sedimentary succession at reduced thickness, suggest that the change from bituminous shales to organic poor claystones with intercalated lignites is associated with a general increase in salinity [9]. The lignites are allochthonous and formed under hypersaline conditions. Therefore, the change from a hydrologically closed to an open basin is younger than the recovered basinal sediments, and climatic fluctuations evident for subordinate, small-scale fining-upwards cycles only. Furthermore, the unidirectional trend in carbonate $^{87}Sr/^{86}Sr$, declining from ratios of Variscan basement rocks towards marine ratios, indicates a change from (i) weathering of crystalline rocks and suevite to (ii) ejected Jurassic sediments (Bunte Breccia) in the catchment area as the major source of Sr^{2+} influx to the lake. Arp et al. [9] inferred from that trend a change in lake water composition and a general increase in ion concentrations.

Their new results [9] can be applied to a reassessment of the entire Ries crater lacustrine succession and a new model for the chemical and ecological evolution of the Ries crater lake: 1) After the establishment of a stratified brackish eutrophic soda lake due to silicate weathering and evaporation, the increasing influx of waters from the Bunte Breccia, carbonate and authigenic silicate precipitation lead to a mesotrophic halite lake with marine-like ion ratios and concentrations; 2) Further increase in ions, among them Mg^{2+} and Sr^{2+}, resulted in hypersaline conditions with gypsum precipitation, low primary production and phreatic Sr-rich dolomitization in marginal carbonates; 3) The final, sudden change to oligotrophic freshwater conditions is explained by the formation of an outlet late in the lake history. Thus, the chemical and ecological evolution of the Ries crater lake appears to be mainly controlled by the weathering history of the catchment area, with climate fluctuations causing superimposed cycles [9]. Similarly, changes in terrestrial palynomorph associations may at least partly reflect a change in soil types in the catchment area, from fertile, moist soils on suevite to dry karst soils and soils on Bunte Breccia.

Summary of Post-Impact Lake Formation and Evolution: In summary, subsequent to the impact, the Ries Crater underwent a long history of aqueous erosion and water filling to form a lake. The initial post-impact sedimentation in this hydrologically closed basin begins with alluvial clastics derived from suevite, followed by playa sediments and bituminous shales of a permanent, stratified soda lake. Subsequently, the change in ion supply from crystalline rocks and suevite to sediments of the primary ejecta layer (Bunte Breccia), and further evaporation caused a shift in water chemistry to marine-like ion ratios and concentrations. Laminated marls and clays were deposited during this interval. Late in the succession, allochthonous lignites intercalated between gypsum-cast-bearing sediments of a hypersaline halite lake indicate a re-establishment of fluvial systems in the Ries area. A sudden change to freshwater limestones and marls, preserved only as relics near the tectonic crater rim, indicates the formation of an outlet and change from a closed-basin lake, to a hydrologically open lake. By the end of the Miocene [8], the Ries basin was completely filled with sediments; later (Pliocene to Pleistocene) erosion removed up to 100 m of the initially 400-500 m thick crater fill.

Ries Crater Lake Fluvial Landforms and Sediments: A range of crater lake fluvial landforms (alluvial fans, deltas) and sediments attest to the initial erosion of the crater and its sedimentary infilling. There are several sites of unequivocal fluvial influx into the saline crater lake, most of them late in the sedimentary succession; these deltaic deposits include: 1) the NW sector ["delta of Trendel": [13]; 2) the SW sector [Ederheim]; 3) a small-sized occurrence at Benzen-zimmern, western Ries basin, and 4) NW sector [Ulrichsberg near Maihingen: former gravel pits [14] and road-cuts [15]]. These outcrops contain conglomerates.

There are several other conglomerate occurrences, all of them small in size: most of them appear to be shoreline deposits or alluvial fans [16]. The Ulrichberg conglomerates are of special interest, because 1) existing road-cuts as well as former outcrops (gravel pit: well documented [16], show 4-5 m thick poorly sorted pebbly sandstones and conglomerates with rounded (crystalline rock) clasts; 2) of the catchment area showing a well defined distribution pattern of crystalline and sedimentary ejecta: abundant crystalline rocks (granites, gneiss) in the immediate vicinity of the delta, while the former upstream area is almost exclusively composed of allochthonous blocks and breccias of Triassic-Jurassic sedimentary rocks; 3) sedimentary structures (unidirectional foreset beds of cross-bedding, lenticular gravel bodies) indicate an unequivocal fluvial origin; 4) the age of these deltaic deposits is well-constrained due to marginal-lacustrine carbonates interfingering with the conglomerates and reworked algal bioherm clasts within the conglomerates, marking the transition of the soda lake to a marine-like lake interval.

Conclusions: The Ries Crater lake shows four major stages in its evolution. The initial topography of the landform (deep depression, raised rim) meant that initial aqueous erosional activity was focused in the crater interior and that the provenance of sediments was determined by the stratigraphy of the rim and slumped wall ejecta (e.g., suevite overlying Bunte Breccia). Catchment basins were initially small and restricted to the topography of the crater wall, expanding with time through the outward erosion of the rim crest. Wall fluvial erosional water sources were pluvial, and relatively steep slopes led to rapid channel incision and sediment. Post-impact freshwater springs contributed to the rising lake level. Impact pre-processing [11] led to easily erodible and transported sediment, and its ready sorting and rounding. Lake geochemistry was heavily influenced by: 1) provenance stratigraphy and 2) transition from a closed to an open-basin lake. This setting provides important insight into the nature of the derived lake sediments and their pre-processing, reworking, transport distances, with implications for similar sedimentary deposits in Gale Crater [4, 5, 11].

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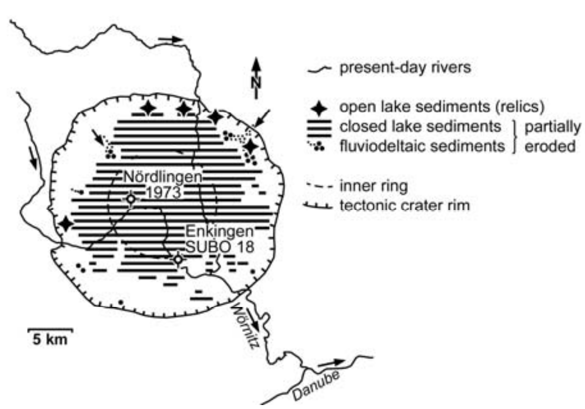

Figure 1. Overview of the Ries impact structure Miocene sedimentary fill and location of the Nördlingen 1973 and Enkingen drilling site.