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A water-saturated continental impact scenario for the Ries-Steinheim event (Germany)

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The ∼24 km Nördlinger Ries crater and the ∼3.8 km Steinheim Basin, Southern Germany, most likely struck by a binary asteroid ∼14.6 Ma ago in the Miocene, count among the best-preserved complex impact structures on Earth [1-4]. Both impact structures are hosted by a thick sequence of Mesozoic to Cenozoic sedimentary rocks that overlie the Paleozoic crystalline basement and build up the karstified limestone plateau of the Swabian-Franconian Alb (SFA) [5]. In addition to the proximal Ries ejecta, which comprise the lithic 'Bunte Breccia', impact melt rocks, and suevites, distal Ries ejecta define the Central European tektite strewn field ∼200-450 km to the NE [1] and the more proximal 'Brockhorizont' at a distance of ∼70-200 km from the crater [6]. The Ries and Steinheim impact structures, thus, provide unique insights into cratering mechanics, impactite petrogenesis, and ejecta emplacement under continental conditions. Lines of evidence are presented that suggest a strongly water-saturated continental Ries-Steinheim impact scenario [7].

Miocene shales and pisolithic-onkolithic limestones [8] that once covered larger parts of the SFA before and after the time of impact indicate limnic-palustrine conditions in a wide area surrounding the Ries and Steinheim impact sites. These sediments are to variable degrees incorporated into Bunte Breccia [9;10] but were also formed in post-impact time [3], which further suggests that the pre-, syn-, and post-impact landscape was water-saturated. Host to the coarse-grained lithic 'Brockhorizont' ejecta, fluvial to limnic siliciclastics alternating with paleosoils suggestive of waterlogging make up large parts of the Upper Freshwater Molasse in the North Alpine Foreland Basin [11].

Slight southeastward tilting of the South German terrane in response to the Alpine orogeny caused the Jurassic limestones and deeper parts of the SFA to progressively emerge [12]. Karstification of the SFA might have commenced in the Cretaceous but has been penetrative since the Paleogene, and the whole landscape is characterized by a number of deep multi-level caves [12;13]. In particular, this Paleogene to early Neogene time interval is marked by the occurrence of sedimentary pisolithic-nodular iron ores ('Bohnerz' formation) in karst fissures and caves, interpreted as the residues of subtropical chemical weathering of the SFA limestones [14]. A high karst groundwater level within the SFA is in accord with a high global sea level and a subtropical-humid regional paleoclimate in the Miocene [15;16]. The high supply of groundwater in the Ries-Steinheim area is substantiated by the spontaneous inflow of water and the formation of the Ries and Steinheim crater lakes [3;4], pronounced degassing of the Ries ejecta blanket [17], as well as pervasive hydrothermal activity at the Ries [18] and, to a minor degree, at Steinheim [19], accompanied by the post-impact precipitation of freshwater limestone deposits at both craters soon upon impact [4;20]. Furthermore, post-impact multiple fluvial reworking of Ries impact ejecta [21] was only possible under water-saturated surface conditions in the Ries area.

Ries and Steinheim impact ejecta petrology is compatible with elevated water contents in the target. Strong dispersion of impact melt [22;23], as well as the formation of accretionary lapilli in the Ries suevite [24], suggest water-saturated target rock conditions. Ries impact glasses are known to contain relatively high amounts of water [25], and surficial suevites are locally intensely altered to clay minerals [26]. Impact melt particles in the limestone-dominated Steinheim impact breccia have been largely transformed into hydrous phyllosilicates. A high amount of water in the target also goes well with a distinct shock buffering effect as proposed for the Steinheim impact [19].

As a nearby volcanic event 'analog', the roughly contemporaneous (∼13-17 Ma) volcanism at the Urach volcanic field, a ∼1,500 km^2 olivine melilititic volcanic province comprising ∼360 tuff breccia-bearing maar-diatremes set in the sedimentary succession of the central Swabian Alb and its northern foreland, demonstrates the strong impact of groundwater in contact to hot magmatic melts [27]. Explosive phreatomagmatism characterized by multiple eruptions at variable levels of the host rock, the generation of maar-diatremes filled with lapilli- and xenolith-bearing tuff breccias, and the subsequent formation of maar lakes [5;28] indicate deep groundwater saturation of the SFA in Miocene time.

In conclusion, the Ries-Steinheim impacts occurred in a water-saturated paleoenvironment, probably best described as a landscape of rivers, swamplands, and lakes. In addition to surficial waters that covered the region during the Miocene, the deeply karstified (i.e. highly 'porous') plateau of the SFA provided substantial amounts of subsurface water that notably influenced the formation and emplacement of Ries and Steinheim impact ejecta.

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