MODELING THE RIES-STEINHEIM IMPACT EVENT AND THE FORMATION OF THE MOLDAVITE STREWN FIELD.

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Introduction and approach: Since 1963 [1] it is generally agreed that the impact craters Ries (D=24 km) and Steinheim (D=3.8 km), S. Germany, and the moldavite strewn field (Bohemia, Moravia and Lusatia) were formed in a single impact event some 15 Ma ago [2,3,4,5]. Despite of almost 40 years of modern research, a comprehensive understanding of the process that formed the double crater and the tektites in one impact/ejection event is still lacking. We have started a numerical modeling project for the Ries-Steinheim-moldavite event [6,7] which is a unique terrestrial impact scenario. This case study will provide a better understanding of some fundamental aspects of impact cratering, such as (1) impact of a double projectile on a complex target, and (2) production and distribution of early and late melt ejecta in an oblique impact in the presence of an atmosphere.

Topographic and geologic database: Age data provide strong evidence for a cogenetic origin of all three impact features [2,8,9]. Topographically, they are arranged along a WSW-ENE running line with Steinheim at the western end, the Ries center some 42 km ENE of Steinheim, and the moldavites 200 to 400 km ENE from the Ries center forming a fan of ~56° (centered at the Ries). This fan is symmetrically arranged along the ENE Steinheim-Ries connection line with the highest concentration of moldavites in the E and in NE parts of the fan.

The pre-impact stratigraphy: The target rocks of both the Ries and Steinheim craters consisted of a ~620 m and ~1180 m thick layered sequence of Tertiary and Mesozoic sedimentary rocks (limestone, shale, sandstone), respectively, resting on Hercynian crystalline rocks (gneisses, granite, metabasites) [10]. Tertiary sand, clay, and freshwater limestone on top of Upper Malmian limestone formed a discontinuous layer at the pre-impact surface (0 – 50 m thick) [10].

Distribution of clastic ejecta and of shock- induced melts: In contrast to Steinheim large parts of the Ries continuous blanket are preserved (polymict clastic matrix breccia, or Bunte Breccia, <200 m thick) covered by "fallout" suevite patches (~5 to 90 m thick) [2] and extending radially to about 45 km and 23 km, respectively [10]. Moldavite tektites extending radially from ~200 to 400 km [2,4] represent distal melt ejecta from the Ries. The tektite melt originates from the top 50 m of mainly sandy Tertiary deposits of the Ries target [9] whereas the other type of Ries impact melt, confined to suevite of the crater itself, is derived from the melt zone in the crystalline basement. A layer of coherent melt rocks is missing in the Ries crater but two huge melt lumps ("red" crystallized melt rock, ~50 m in size) were deposited at the eastern crater rim [11]. They are inside the East part of the fan defined by moldavites. Such melt has not been found anywhere else in the Ries.

The Ries/Steinheim Impactor: We integrated the equation of motion of a body in the atmosphere (e.g., see [12]) to determine if two pieces of an asteroid that broke up in the atmosphere could be separated enough to create the Ries-Steinheim double crater. In this approach we do not include separation mechanisms like shock wave interaction, asteroid rotation, or lift forces (e.g., see [13]). These mechanisms become important only for rather small, m-size, fragments [13], and can be neglected in this study (smaller object is ~100 m in diameter). We assumed that breakup occurred at an altitude of around 50 km from the surface (the results do not change significantly by increasing the altitude). The entry velocity was varied between 11.2 km/s (Earth's escape) and 21 km/s above which there is no significant separation between the two bodies, and the entry angle (measured from the tangent to the surface) from 60° down to 10°. Since both Ries and Steinheim appear circular, the possibility of a highly oblique impact must be excluded. We find that the maximum separation of the bodies at the surface was around 3 orders of magnitude lower than the measured distance between the Ries and the Steinheim craters (~42 km). Therefore, the Ries/Steinheim craters could not have been formed as a result of the breakup of an asteroid upon entering the Earth's atmosphere or by the separation of a contact binary asteroid. The alternative is that they were formed by a binary object with a pre-impact separation at least similar to the distance between the two craters [14]. The discoveries of small objects orbiting larger asteroids, like the Ida/Dactyl system [15], confirm indeed the existence of well-separated binary asteroids in which one object is orders of magnitude larger than the other. The Ries-Steinheim craters indicate the extistence of well separated binary asteroids as small as ~1.5 and 0.15 km which currently cannot yet be observed for technical reasons (Ida/Dactyl being much bigger objects).

Hydrocode Modeling: Three-dimensional impact simulations were carried out with the hydrocode SOVA [16] coupled to equation of state tables constructed using the ANEOS equation of state package [17]. The simulations model spherical asteroids (granite with 5% porosity, for a bulk density of 2.5 g/cm^3) striking Earth's surface at angles of 45°, 30°, and 15° from the surface with velocities of 12, 20 and 40 km/s. To insure that all the simulations model the same transient cavity diameter (~12.2 km), the projectile sizes have been varied according to the Pi-scaling law [18], ($D_{pr,}$ Table 1). The spatial resolution has been optimized to best represent the target lithology, ranging from 10 m (to resolve the thin surface layers) to 60 m away from the impact site (we used bilateral symmetry, therefore we modeled the y>0 semispace only). The simulation starts with the projectile close to the surface.

The target layout consists of a 600 m thick sedimentary layer divided as follow [7]: 40 m of quartzite with 30% porosity to model the uppermost Tertiary sands; 140 m of calcite (no porosity) to model the Malmian limestone; 420 m of quartzite with 20% porosity to model the Jurassic/Triassic sands and shales. The crystalline basement below the sedimentary layer is modeled as non-porous granite.

Table 1. Amount of melt+vapor (in km^3) produced in the hydrocode simulations for the various target layers.

Impact Velocity	12 km/s		20 km/s			40 km/s
Angle	30°	45°	15°	30°	45°	45°
D_{pr} (km)	1.9	1.6	1.7	1.5	1.2	0.8
Sands (40m)	0.39	0.21	0.31	0.37	0.23	0.21
Limestone (140m)	0.98	0.57	1.43	1.14	0.58	0.49
Sandstone (420m)	5.39	3.73	4.33	6.27	3.77	3.38
Basement	6.7	7.2	3.41	13.44	9.72	8.22

Melt Production: For each simulation we estimated the amount of melting of the various layers modeled, including the crystalline basement. We used 55 GPa as the threshold for shock degassing of dense calcite (140 m layer). For 30% (upper 40 m) and 20% (420 m Jurassic/Triassic layer) porous quartzite the ANEOS-based shock pressure for complete melting is 20 and 32 GPa respectively, while it is 40 and 52 GPa for incipient vaporization. Finally, the ANEOS-based shock pressure for complete melting of granite (dense crystalline basement) is 56 GPa.

The simulations results (Table 1) show maximum melt production for a 20 km/s, 30° impact (Fig.1). The decrease in projectile size eventually counteracts the increase in impact velocity by focusing the impact energy on a smaller region (decreasing the projectile's footprint). Regardless of impact velocity, Table 1 indicates 30° as the most favorable angle for maximizing near surface melting.

Tektite Production: Finally, separate simulations are being carried out to investigate the formation and distribution of tektites formed in the Ries impact event. We find that the most favorable conditions for tektite production occur for impact angles between 30° and 45°, at least for an impact velocity of 20 km/s (Fig. 1). The modeling results account also for the asymmetric distribution of coherent melt lumps observed only at the eastern crater rim.

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Fig. 1. Snapshot at 0.5 seconds of a Ries-type impact at 30° (from surface) and 20 km/s (distances are in km). Granite is gray, quartzite is green and calcite is blue. Lagrangian tracers subjected to different shock compressions are shown in different colors (red>200 GPa to blue=10-20 GPa).