Impactite stratigraphy and depositional processes in the Chicxulub and Ries impact structures: Insights into crater floors

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Introduction: Orbital images of impact basin floors show heterogeneity in texture, relief of central structures, peak rings or terrace zones, and presence or absence of blocks. The rarity of subsurface data renders challenges in interpreting the thickness and stratigraphy of impactites that fill these craters. Whereas texture and age relationships in remotely sensed data give clues to emplacement process and timing, Earth craters uniquely (so-far) benefit from 2D and 3D subsurface seismic imaging and scientific drilling.

The Cretaceous-Paleogene (K-Pg, 66 Ma), 200 km Chicxulub impact crater, México, provides the unique opportunity to study crater formation processes related to a large impact [1]. Chicxulub is a multi-ring basin with an intact melt sheet, peak ring, and crater floor (Fig. 1) [1,2]. It is well preserved due to its youth and burial beneath 100s of meters of Cenozoic carbonates [1,2].

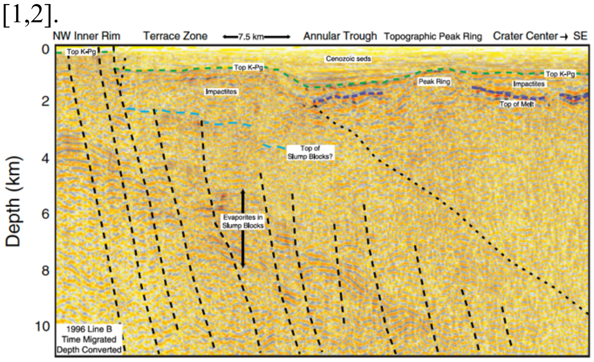

Figure 1. Northwest orientied, time migrated seismic line (Line B), which was depth converted using 3D seismic refraction velocity model, crosses from near the crater center to inner ring faults of Chicxulub impact structure showing features with 3x vertical exaggeration. Line shows that impactites represent substantial thicknesses of material burying slump blocks within annular trough, capping the peak ring, and overlying the central melt sheet. Top K-Pg represents top of suevite layer drilled in IODP-ICDP Expedition 364 (see Figure 2). Figure modified from [2].

The 14.9 Ma, 25 km Ries impact crater, Germany, appears to represent a transitional crater form between central peak and peak ring crater with a collapsed central uplift. It has a well-preserved crater floor within the central crater due to burial by lacustrine sediments, but no clear indication of a melt sheet [3].

Insights from Scientific Drilling and New Geophysical Analyses: The International Ocean Discovery Program with co-funding from the International Continental Scientific Drilling Project drilled into the Chicxulub peak ring in 2016 [4]. Hole M0077A (Fig. 2) recovered the uplifted crystalline rocks of the peak ring and the layered deposit that overlies it consisting of impact melt rock overlain by clast-rich impact melt rock and breccia, suevite, and finally sorted suevite with decreasing clast size upsection. These impactites all have a low velocity (~3000 m/s or less) and high porosity (20-40%). Interpretation of this low-velocity sequence is that the lower portion was rapidly deposited onto and perhaps intermixed with impact melt rocks during impactoclastic flows and melt-water interactions. The upper sorted suevite is a resurge deposit in this marine target setting [5].

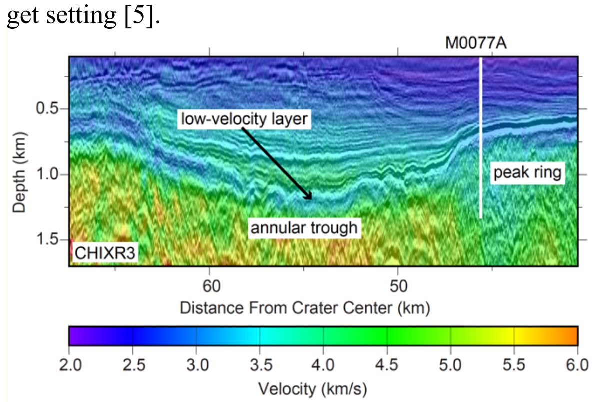

Figure 2. Seismic reflection Line ChicxR3 within the Chicxulub crater overlain by full waveform inversion generated velocity model. The Chicxulub impact crater peak ring is overlain by a low-velocity zone that can be mapped into the adjacent annular trough which maps to a sorted suevite within IODP-ICDP Exp. 364 Hole M0077A core. White line representing depth reach during drilling (1335 meters below seafloor) where this low velocity layer represented ~90 m thick and was underlain by additional 40 m of more melt rich impactites. Figure modified from [5].

2D, full-waveform tomographic velocity images from the grid of seismic data recorded on a 6-km streamer across the Chicxulub impact crater allow mapping of these units (Fig. 2). These images show both the lower and upper portions of the low-velocity layer present at Site M0077 thus allowing us to potentially map the thickness of both the resurge deposit,the lower more rapidly deposited layer, and any melt rock or material moved into the crater during the crater modification stage.

Along several profiles (e.g. Fig. 3), prominent high-velocity zones (>5500 m/s) correlate with low-frequency reflectors and are interpreted to represent intact melt rock [2]. Within the annular trough, a change in reflectivity and correlation with velocity structure also allow for a mapping of zones of melt rock < 750 m thick present outside of the peak ring (Fig. 3). Thin zones of melt rock are mappable farther outwards and observed to overlay the shallow slump blocks of the terrace zone in some profiles. Significant thicknesses <1.5 km of seismically diffuse material lies beneath the melt rock within the annual trough and above the intact slump blocks of the terrace zone (Fig. 1).

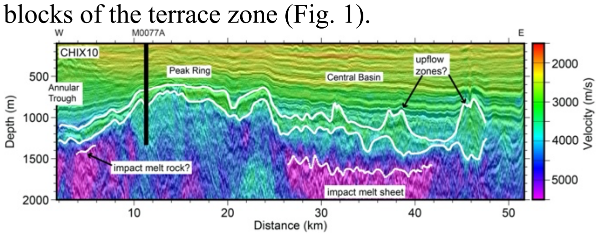

Figure 3. Seismic reflection Line Chicx10 within the Chicxulub crater overlain by full waveform inversion generated velocity model. Here the low velocity zone is bounded by thick white interpretations and a higher velocity impactite is visible away from the peak ring beneath this sequence. Beneath the central basin and the inner portion of the annual trough, a higher velocity (>5500 m/s) body is observed and interpreted to represent melt rock.

In the Ries Crater new high-resolution images (Fig. 4) highlight layered high-amplitude sequences within the central crater overlying a more discontinuous facies that lies disconformably on crystalline basement. One interpretation of the high-amplitude package is that it may represent so-called crater suevite penetrated by the Nördlingen 1973 drill core within the central portion of the crater. Based on the stratigraphic relationships, we suggest that the suevite was deposited in impactoclastic flows. In the Nördlingen drill core, the suevite is overlain by a thin section of sorted suevite perhaps similar to the upper low velocity zone at Chicxulub. Within the terrace zone, the suevite lays unconformably over bunte breccia, proximal ejecta which are transported inward during crater modification [3].

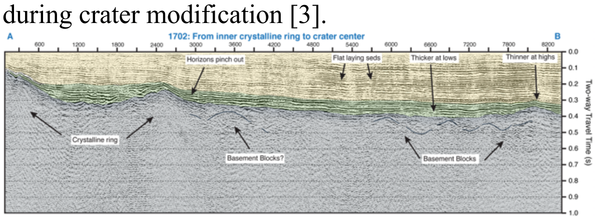

Figure 4. Seismic reflection Line 1702 within the Ries crater where A overlies a portion of the crystalline ring and B lies near the crater center. Image shows crystalline basement from the collapsed central uplift overlain by high amplitude semi-continuous reflectors (green) exhibiting pinch outs and onlap. This interval is interpreted to be the crater suevite encountered in Nördlingen 1973 drill core. Note the crystalline ring material that originated from collapse of the transient crater rim is emergent above the suevite and the maximum thicknss of impactites are ~0.2 s twt (<300 m).

Cross-crater Comparison of Impact Stratigraphy : The Chicxulub crater floor is largely made of the sorted suevite resurge deposit expressed as the upper low velocity zone, which only occasionally is penetrated by a cropping out of deeper impactites. The lower more rapidly deposited layer however varies with the greatest thicknesses in the central basin at Chicxulub which may provide insights for Ries. The layered crater suevite at Ries may be equivalent to this lower unit of melt rich impactites wherein impactoclastic flows incorporate the melt potentially providing an explanation for the lack of an intact melt sheet in this smaller crater.

In turn Ries may provide insights for Chicxulub in that the <1.5 km thick impactites, that lie below <750 m of impact melt rock in the annular trough at Chicxulub (Fig. 1), may represent ejecta curtain material similar to the bunte breccia at Ries that collapsed inward during crater modification.

Factors Controlling Crater Floor Geology and Morphology: These two large impacts provide some insights into factors that therefore affect the geology and morphology of crater floors- specifically the role of water and the volume of impactites deposited within the final crater. As with Chicxulub, marine impacts with a resurge that rapidly flood newly formed impact basins may yield relatively smooth crater floors due a blanketing by sorted impactites. However aiding in this infilling are the large volumes of impactites and proximal ejecta such that at Chicxulub kilometers of breccia, melt rock and suevite bury all features including the peak ring by >100 m. Non-marine impacts are likely to fill more slowly from seepage on crater rims, precipitation, or downcutting of fluvial systems yet at Ries a thinner layer of sorted suevite is present. Smaller impacts also likely produce less material for infilling, such that the Ries crater floor may have been more heterogeneous than Chicxulub with some areas exhibiting blocks of collapsed transient crater rim emergent through the suevite and the thinner sorted suevite perhaps not being present throughout the crater. These results highlight that final crater morphology is affected by infilling processes during crater modification with key factors being impact size and presence or absence of water. Such findings may yield insights into rarity of exposed peak rings on Mars and beneficial conditions on Earth for preservation of impact structures.

References: [1] Morgan et al. (1997) *Nature*, 390, 472-476 [2] Gulick et al. (2013) *Rev Geophysics*, 51, 31-52 [3] Stöffler et al. (2013) *Meteoritics & Planetary Science*, *48*, 515-589, [4] Morgan J. V. et al. (2016) *Science*, 354, 878–882 [5] Gulick et al. (2019) *Proc Nat Acad Sci.,*116, 19342-19351.