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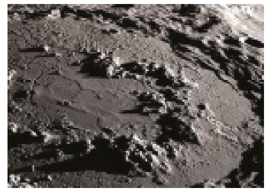

Peering inside the peak ring of the Chicxulub Impact Crater—its nature and formation mechanism

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The IODP-ICDP Expedition 364 drilled into the Chicxulub crater, peering inside its well-preserved peak ring. The borehole penetrated a sequence of post-impact carbonates and a unit of suevites and clast-poor impact melt rock at the top of the peak ring. Beneath this sequence, basement rocks cut by pre-impact and impact dykes, with breccias and melt, were encountered at shallow depths. The basement rocks are fractured, shocked and uplifted, consistent with dynamic collapse, uplift and long-distance transport of weakened material during collapse of the transient cavity and final crater formation.

The nature and formation mechanisms of peak rings, the semi-circular irregular mountain chains characteristic of large complex craters, have been a matter of intense scrutiny. A limitation in their study is the lack of information on their deep structure. The recent IODP-ICDP Expedition 364 Chicxulub drilling project provided critical data on the nature and structure of its peak ring. The project allowed a wide range of open questions on the formation of complex craters to be addressed, including the rheological behaviour and transport mechanisms involved during the collapse stage, with high energy release and over short-time scales. The marine drilling project builds on previous geophysical surveys and drilling programs on Chicxulub, adding a significant novel contribution towards its understanding.

Crater structure—geophysical surveys and drilling

Chicxulub was formed by an asteroid impacting the Yucatan carbonate platform ~66 Ma ago, with impact effects linked to the mass extinction at the Cretaceous–Palaeogene (K-Pg) boundary. The crater has a multi-ring morphology with a rim diameter of ~200 km (Fig. 1). It is covered by up to 600–1100 m of carbonate sediments, which have helped to protect the structure, but at the same time restricting direct access for sampling.

The crater's size, structure and stratigraphy have been surveyed using a range of geophysical methods, including gravity, magnetics, electromagnetics and seismic reflection, as well as drilling. The crater is characterized by a regional semi-circular gravity anomaly with a central high (Fig. 1b), marked by high-amplitude magnetic anomalies. Seismic images delineate the deep structure and crater asymmetries, with the terrace zone, slump blocks, exterior, outer and inner ring faults and the central uplift. The outer ring faults define a zone between around 95–105 km radial distance from the crater centre at Chicxulub Puerto in the Yucatan coastline, with asymmetries in the northern marine sector.

As part of the Petroleos Mexicanos (Pemex) oil exploration program, boreholes were drilled into the central gravity anomaly, with the Chicxulub-1, Sacapuc-1 and Yucatan-6 boreholes sampling post-impact carbonates and impactites. Drilling with continuous coring was carried out in the UNAM Chicxulub Project, which sampled the post-impact carbonates and impactites, showing an inverted stratigraphy, with suevites that contain fragments of impact melt rock and basement above the carbonate-rich breccias. The Chicxulub Scientific Drilling Project (CSDP) drilled the Yaxcopoil-1 borehole in the southern on-land crater sector, over the terrace zone positioned interior of the crater rim. This borehole sampled a ~800 m section of Palaeogene carbonate

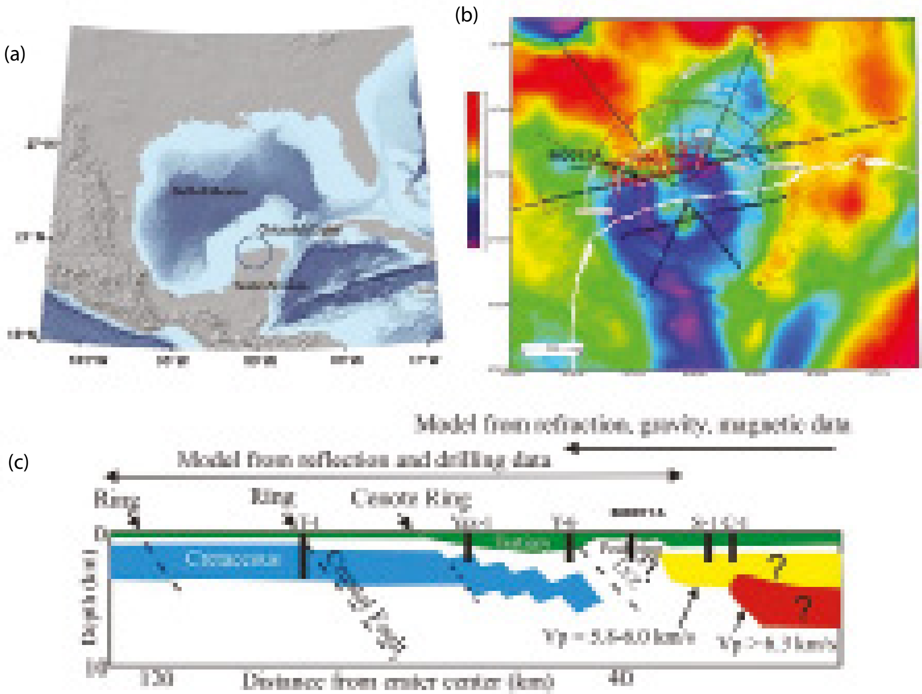

Fig. 1. a. Chicxulub impact crater in the Yucatan peninsula, southern Gulf of Mexico. b. Seismic reflection profiles, with location of M0077A drilling site over the peak ring in the marine crater sector. c. Schematic structural model of the Chicxulub crater, with major crater features (adapted from Urrutia-Fucugauchi *et al.*, 2011; Gulick *et al.*, 2013; Morgan *et al.*, 2017). Boreholes are indicated in black.

sediments, followed by ~100 m thick impact melt-rich breccias overlying Cretaceous carbonates down to 1511 m. The impactite section was formed of six subunits with distinct emplacement modes, with high-temperature ground surges, collapse breccias and reworked material affected by varying degrees of hydrothermal alteration. The Cretaceous rocks represented displaced blocks composed of limestones and dolomites, with 27 percent anhydrite, cut by melt and polymictic clastic dykes. The Pemex, UNAM and CSDP programmes have provided samples from the post-, pre- and impact lithologies, which can be used to analyse the composition, textures, hydrothermal alteration and nature of the sedimentary–crystalline target stratigraphy.

Complex craters and peak rings

The formation of large complex craters involves a large release of energy over short time scales, resulting in high temperatures and pressures. The impact produces a deep transient excavation cavity, with fragmentation and ejection of large amounts of crustal material. Simulations have been used to estimate excavation depths, lateral and vertical mass transport, basement uplift and scaling relationships for crater size, crustal deformation, crater structure and stratigraphy, ejecta material and impact dynamics. Studies of terrestrial structures, including drilling, provide input parameters for numerical modelling.

Peak rings are characteristic features of large impact basins and are key to an understanding of crater formation and deep structure, i.e. how deep bowl-shaped transient cavities form and then dramatically collapse to produce wide, flat final structures (Fig. 2). Peak ring formation has been linked to the outward collapse and faulting of centrally uplifted rocks and their interaction with the inward-collapsing transient cavity. Two end-member models, the ‘dynamic collapse’ and the ‘nested melt cavity’, are described and analysed by Baker and colleagues in 2016 (Icarus, v.273, pp.146–163).

An interesting question in the peak ring formation models is the original depth of the uplifted basement material. In Chicxulub, the peak ring roughly correlates with the location of a circular gravity low approximately 40 km in diameter, which surrounds high-amplitude magnetic anomalies and a central gravity high (Fig. 1). Geophysical models had suggested low densities and seismic velocities, interpreted as fractured and altered uplifted basement. Seismic surveys imaged the peak ring as a high-relief feature, showing the elevated topography above the annular

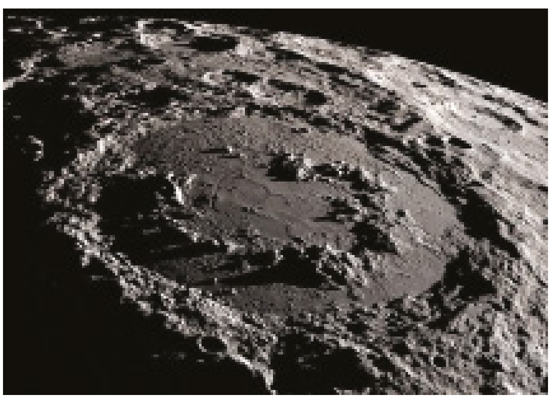

Fig. 2. Schrödinger peak ring crater. The crater on the lunar farside is ~320 km in rim diameter. Its peak ring is formed by anorthositic, noritic and troctolitic rocks uplifted from deep in the lower crust (credit NASA; Kring *et al.*, 2016).

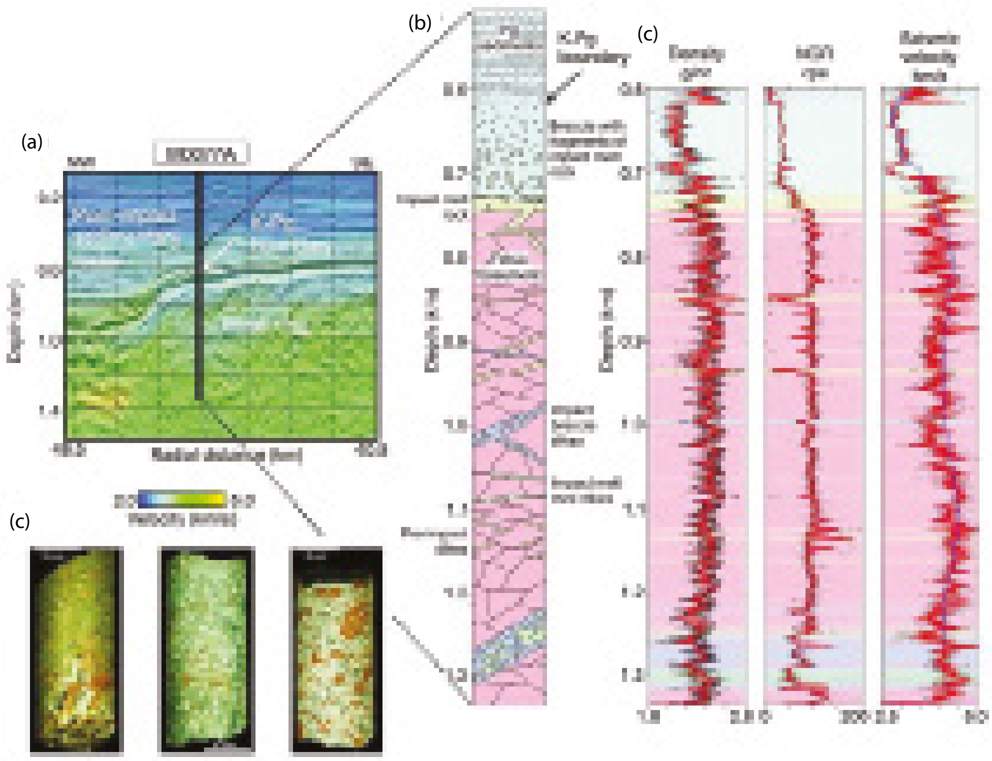

Fig. 3. a. Borehole M0077A plotted in the seismic line. b. Simplified column and geophysical logs. c. Core imagesofthebasementsection (adapted from Morgan *et al.*, 2016, 2017)

trough and central basin, with high elevations in the north-western and western sectors.

IODP-ICDP Expedition 364

The M0077A drill site is located at 21.45°N, 89.95°W, about 45.6 km radial distance from crater centre (Fig. 1b), with the jack-up platform deployed over shallow <20 m depths. The borehole was drilled through post-impact carbonates down to 617 m bsf (meters below seafloor), where it reached the ~130 m impactite section of suevites and basal clast-poor melt rocks. Below 748 m bsf, basement rocks were encountered, which are cut by pre-impact and impact dykes, with breccias and melt between 1250 and 1316 m bsf (Fig. 3). Core recovery started at 505.7 m bsf and was carried out continuously to a final depth of 1335.7 m bsf. Wireline logging was conducted from the sea floor to the final depth, and physical property measurements were also recorded uphole, directly on the cores.

Downhole logging and vertical seismic profiling (VSP) data acquired in three phases included the measurements of acoustic and optical images, borehole fluid parameters, caliper, electrical resistivity, induction conductivity, magnetic susceptibility, seismic velocities, spectral and total gamma rays and VSP seismic travel times as a function of depth. A challenging task for these offshore operations was the recovery of samples for the deep biosphere and habitability studies. Impact melt rocks, xenoliths and crystals from different depths were targeted for analysis of the past and present conditions and the biosignatures of microbial communities.

Pre-site geophysical studies included 3-D seismic reflection surveys along a grid in the central crater sector, providing high-resolution images of the structure, peak ring and potential drill sites. These surveys revealed crater asymmetries, related to pre-impact platform relief and features, and identified potential drill sites above the peak ring and on the annular trough. These studies have also proved useful for exploring the carbonate platform and Yucatan peninsula, including in particular the aquifers, groundwater flow and surface geology.

A geophysical–geotechnical survey was carried out with the UNAM R/V Justo Sierra. This provided a high-resolution multibeam bathymetric survey over the selected drilling sites. In addition to the site evaluation, this uncovered surficial karstic pans and sand bedforms, recording past and recent climatic and oceanographic conditions. The karstic semi-circular metre-scale dissolution pans indicated that subaerial arid conditions had developed during the last glacial period in the carbonate platform. The bathymetric images revealed unexpected characteristic surface sand kilometre-long linear forms oriented NE–SW with asymmetric transverse bedforms that recorded NE-directed currents. These current directions are oblique to the dominant westward current direction, and have been interpreted as platform sedimentary records of recent storms and hurricanes.

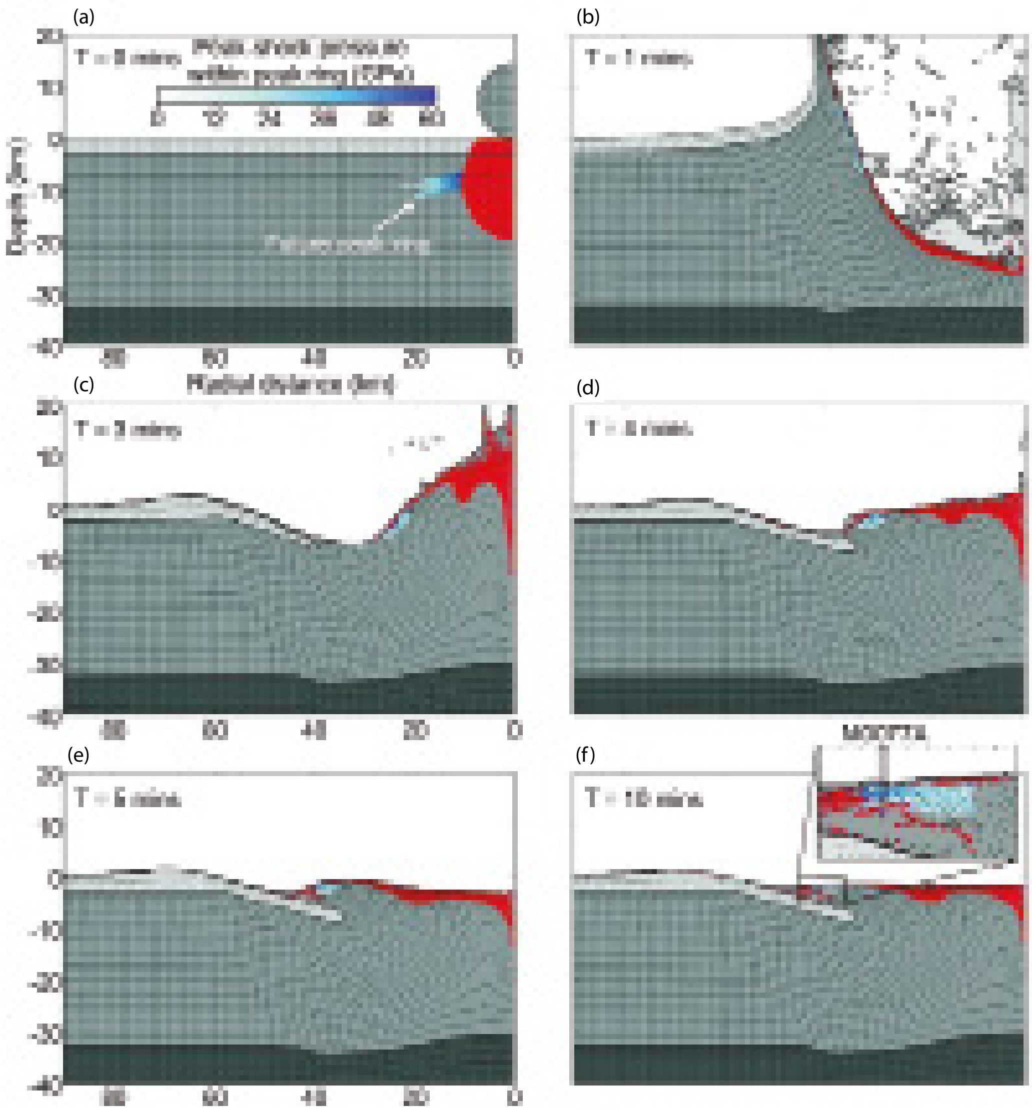

Fig. 4. a–f. Numerical simulation for formation of the peak ring (adapted from Morgan *et al.*, 2016). Note the modeled depth of material uplifted to form the peak ring (marked as future peak ring). The a to f sequence shows distinct times from contact to ten minutes.

Joint offshore/onshore analyses

Offshore core documentation and analytical measurements were complemented by dual-energy X-ray computed tomography (CT) at the Houston Weatherford Labs and processed in Austin by Enthought Inc., providing data on density and average atomic number, constraining textures, composition and fractures. At the University of Bremen IODP Core Repository, the cores were split in half and further described. The science party then worked on sub-sampling of the working half, core documentation and core analyses on physical properties, geochemistry, micropalaeontology, palaeomagnetism, mineralogy and petrology.

Offshore and onshore analyses have provided detailed documentation of the lithology, stratigraphy and physical and chemical properties of the samples. The carbonate-impactites contact is marked by high magnetic susceptibility and gamma ray values. The peak ring is characterized by low seismic velocities and densities, and higher porosity, with a narrow 0.1–0.2 km-thick low-velocity zone of suevites and melt. The basement rocks are characterized by increasing P-wave velocities and relatively constant gamma ray radiation, density, porosity and magnetic susceptibility (Fig. 3). Dykes are marked by high/low values in the logs and laboratory measurements. Foraminifer and nannoplankton biostratigraphical datums are identified in the carbonate section, constraining the K-Pg boundary and Paleocene and Eocene sequence. The analyses show low sedimentation rates in the Paleocene and higher rates for the Eocene.

Peak ring nature and formation mechanism

The basement rocks are intensely fractured and deformed, with foliated shear zones and cataclasites. The fact that uplifted basement, not carbonates, was reached at such a shallow depth, is consistent with dynamic collapse, uplift and long distance transport of weakened rocks during the collapse stage of crater formation (Fig. 4). The numerical simulation includes a 3-km thick sedimentary sequence above a ~30 km-thick crust, which is deformed and fractured. During the formation of a deep transient cavity, uplifted mid-crustal material is displaced outward and then inward to the central zone. During the interaction of the two collapse regimes, material is displaced outward and emplaced above the transient cavity material, which is mainly composed of platform carbonate sediments. The simulation in Fig. 4 shows stages at 0, 1, 3, 4, 5 and 10 minutes, which track the relative position of material in the target zone. Peak-shock pressures (blue colour scale) are modelled for the shock wave, which reached >60 GPa in the melted (red) zone. In the simulation, the peak ring basement rocks originate from the middle crust, about ~8–10 km depth, and are affected by >10 GPa shock pressures. Observations on cores and well logs are consistent with geophysical models that show the peak ring characterized by low densities and seismic velocities (Fig. 3), with the uplifted basement affected by shear fracturing, shock deformation and hydrothermal alteration.

Conclusions

The IODP-ICDP drilling reveals that the peak ring is formed by uplifted shocked and fractured basement rocks, reached at shallow depth beneath impactites and Palaeogene carbonate sediments. The well logs and detailed core analyses constrain the lithostratigraphical column of post-impact carbonates, breccias, melt and basement. Results support the hypothesis that the Chicxulub peak ring formed following a dynamic collapse of the central uplift and deep bowl-shaped transient cavity.

The drilling, logging and core analyses provide a detailed look into the nature of the peak ring, opening exciting opportunities on a wide range of questions on the impact, the K-Pg mass extinction, life recovery, hydrothermal system, deep biosphere and peak ring habitability.

Suggestions for further reading

Alvarez, L.W., Alvarez, W., Asaro, F. & Michel, H.V. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. Science, v.208, pp.1095–1108

Baker, D.M.H., Head, J.W., Collins, G.S. & Potter, R.W.K. 2016. The formation of peak-ring basins: Working hypotheses and path forward in using observations to constrain models of impact-basin formation. Icarus, v.273, pp.146–163.

Collins, G.S., Morgan, J., Barton, P., Christeson, G.L., Gulick, S., Urrutia-Fucugauchi, J., Warner, M. & Wünnemann K. 2008. Dynamic modeling suggests terrace zone asymmetry in the Chicxulub crater is caused by target heterogeneity. Earth and Planetary Science Letters, v.270, pp.221–230.

Goff, J.A., Gulick, S.P.S., Perez-Cruz, L., Stewart, H.A., Davis, M., Duncan, D., Saustrup, S., Sanford, J. & Urrutia-Fucugauchi, J. 2016. Solution pans and linear sand bedforms on the bare-rock limestone shelf of the Campeche Bank, Yucatan Peninsula, Mexico. Continental Shelf Research, v.117, pp.57–66.

Gulick, S.P.S., Barton, P.J., Christeson, G.L., Morgan, J.V., McDonald, M., Mendoza-Cervantes, K., Pearson, Z.F., Surendra, A., Urrutia-Fucugauchi, J., Vermeesch, P.M. & Warner M.R. 2008. Importance of pre-impact crustal structure for the asymmetry of the Chicxulub impact crater. Nature Geoscience, v.1, pp.131–135.

Gulick, S.P.S., Christeson, G.L., Barton, P., Grieve, R.A.F., Morgan, J.V. & Urrutia-Fucugauchi, J. 2013. Geophysical characterization of the Chicxulub impact crater. Reviews in Geophysics, v.51, pp.31–52.

Kring, D., Kramer, G.Y., Collins, G. Potter, R. & Chandnani, M. 2016. Peak-ring structure and kinematics from a multi-disciplinary study of the Schrödinger impact basin. Nature Communications, v.7, p.1316.

Milijkovic, K., Lemelin, M. & Lucey P.G. 2017. Depth of origin of the peak (inner) ring in lunar impact basins. Geophysical Research Letters, v.44, pp.140–146.

Morgan, J.V. & Gulick, S.P.S. et al. 2016. The formation of peak rings in large impact craters. Science, v.354, pp.878-882.

Morgan, J., Gulick, S., Mellet, C.L., Green, S.L. & Expedition 364 Scientists 2017. Chicxulub: drilling the K-Pg Impact Crater. Proceedings of the International Ocean Discovery Program, v.364, doi: 10.14379/iodp.proc.364,2017.

Schulte, P. et al. 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary, Science, v.327, pp.1214–1218.

Urrutia-Fucugauchi, J., Morgan, J., Stöffler, D. & Claeys P. 2004. The Chicxulub Scientific Drilling Project (CSDP). Meterorite and Planetary Science, v.39, pp.787–790.

Urrutia-Fucugauchi, J., Camargo-Zanoguera, A. Perez-Cruz, L. & Perez-Cruz G. 2011. The Chicxulub multi-ring impact crater, Yucatan carbonate platform, Gulf of Mexico. Geofisica International, v.50, pp.99–127.