International Ocean Discovery Program
Expedition 364 Scientific Prospectus

Chicxulub: drilling the K-Pg impact crater

In collaboration with the
International Continental Scientific Drilling Program

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Abstract

The Chicxulub impact crater in Mexico is unique. It is the only known terrestrial impact structure that has been directly linked to a mass extinction event and the only terrestrial impact with a global ejecta layer. Of the three largest impact structures on Earth, Chicxulub is the best preserved. Chicxulub is also the only known terrestrial impact structure with an intact, unequivocal topographic "peak ring." Chicxulub's role in the Cretaceous/Paleogene (K-Pg) mass extinction and its exceptional state of preservation make it an important natural laboratory for the study of both large impact crater formation on Earth and other planets and the effects of large impacts on Earth's environment and ecology. Our understanding of the impact process is far from complete, and despite more than 30 y of intense debate, we are still striving to answer the question as to why this impact was so catastrophic.

International Ocean Discovery Program (IODP) Expedition 364 proposes to core through the peak ring of the Chicxulub impact crater to investigate (1) the nature and formational mechanism of peak rings, (2) how rocks are weakened during large impacts, (3) the nature and extent of postimpact hydrothermal circulation, (4) the deep biosphere and habitability of the peak ring, and (5) the recovery of life in a sterile zone. Of additional interest is the transition through a rare midlatitude record of the Paleocene/Eocene Thermal Maximum (PETM); the composition and character of impact breccias, melt rocks, and peak-ring rocks; the sedimentology and stratigraphy of the Cenozoic sequence; and any observations from the core that would help us constrain the volume of dust and climatically active gases released into the stratosphere by this impact. Petrophysical property measurements on the core and wireline logs will be used to calibrate geophysical models, including seismic reflection data. Proposed drilling directly contributes to the IODP science plan initiatives (1) Deep Biosphere and the Subseafloor Ocean and (2) Environmental Change, Processes and Effects, in particular the environmental and biological perturbations caused by the Chicxulub impact.

Expedition 364 will be implemented as a mission-specific platform expedition to obtain subseabed samples and downhole logging measurements from the peak ring of the Chicxulub impact crater. The expedition aims to core a single borehole as deep as 1500 meters below seafloor (mbsf) to recover rock cores from above and into the Chicxulub impact crater preserved under the Yucatán continental shelf.

Schedule for Expedition 364

Expedition 364 is based on International Ocean Discovery Program (IODP) drilling Proposal 548-Full3 and Addendum 548-Add4. Following ranking by the IODP Science Advisory Structure, the expedition was scheduled by the European Consortium for Ocean Research Drilling (ECORD) Facility Board as a mission-specific platform (MSP) expedition to be implemented by the ECORD Science Operator (ESO). At the time of publication of this *Scientific Prospectus*, the expedition is scheduled for April–May 2016 with a total of 60 days available for the drilling, coring, and downhole measurements described in this prospectus and on the ESO Expedition 364 webpage. The Onshore Science Party (OSP) is provisionally scheduled to start September 2016 and last for approximately 3 weeks (dependent on core recovery).

The following links should be used in conjunction with this *Scientific Prospectus*:

- Proposal 548-Full3 can be found at **https://www.iodp.org/doc_download/2292-548-full3cover**, and Addendum 548-Add4 can be found at **http://www.eso.ecord.org/docs/364/548-Add4_Morgan.pdf**.
- The Expedition 364 webpage will be periodically updated with expedition-specific information on the platform, facilities, coring strategy, measurements plan, scheduling, and port call (**http://www.eso.ecord.org/expeditions/364/364.php**).
- General details about the offshore facilities provided by ESO are provided on the ESO-specific webpages on the MARUM website (**http://www.marum.de/en/Offshore_core_curation_and_measurements.html**).
- General details about the onshore facilities provided by ESO are provided on the ESO-specific webpages on the MARUM website (**http://www.marum.de/Onshore_Science_Party_OSP.html**).
- Supporting site survey data for Expedition 364 are archived in the IODP Site Survey Data Bank (**http://ssdb.iodp.org/SSDBquery/SSDBquery.php**; choose P584 in the Proposal number selection box). Please note that not all site survey data associated with this expedition are publicly available.

Introduction

Peak rings are rings of hills that protrude through the crater floor within large impact basins on terrestrial planets (Figure **F1**), and there is no consensual agreement on either their formational mechanism or the nature of the rocks that form them (Grieve et al., 2008). Geophysical data indicate that the peak ring at Chicxulub is formed from rocks that have low velocity and density, and one explanation for this is that they are highly fractured and porous (Morgan et al., 2000, 2011; Gulick et al., 2013). Immediately after impact, the peak ring was submerged under water and located adjacent to a thick pool of hot melt rocks. Hence, we expect intense hydrothermal activity within the peak ring (Ames et al., 2004; Zürcher and Kring, 2004). This activity might have provided a niche for exotic life forms, similar to the way hydrothermal vent systems do so in oceans. Drilling the peak ring will determine the origin, lithology, and physical state of the rocks that form it and allow us to distinguish between competing models of peak-ring formation and document the hydrothermal systems and microbiology.

Background

The peak ring

The term "peak ring" was first used to describe the often discontinuous mountainous ring that rises above the floor of large craters on the Moon. Peak rings are internal to the main topographic crater rim (Figure **F1**). Since they were first identified on the Moon, peak rings have been observed in large terrestrial craters on all large rocky planetary bodies. Notably, peak rings do not appear to occur on the icy satellites of Jupiter and Saturn, which indicates that crustal rheology plays a role in their formation. The peak ring is a topographic feature: it protrudes through the impact melt and breccia that line the floor of the crater and stands above the surrounding terrain. As a result, the unequivocal identification of a peak ring in Earth's largest craters is compromised by inevitable erosion and/or tectonism.

Two seismic experiments were conducted in 1996 and 2005 across the Chicxulub impact structure (Figure **F2**) (Morgan et al., 1997; Gulick et al., 2008). Reflection seismic data image impact lithologies and structures to the base of the crust 35 km deep (Christeson et al., 2009; Gulick et al., 2013). The impact basin is buried beneath a few hundred meters of Cenozoic sediments, and the present-day Cretaceous/Paleogene (K-Pg) surface deepens to ~1 s two-way traveltime (~1 km), revealing a ~145 km diameter postimpact basin (Morgan and Warner, 1999) with ring-shaped faults reaching diameters >200 km (Gulick et al., 2008). Within this postimpact basin, there is a ~80 km diameter topographic ring that appears analogous to peak rings observed on other planetary bodies (compare Figures **F1**, **F3**, **F4**). Reflective preimpact stratigraphy (Mesozoic sediments) were tracked around the crater, and large offsets in the stratigraphy define a 20–35 km wide terrace (or megablock) zone (Figure **F3**) (Gulick et al., 2008, 2013). Morgan and Warner (1999) argue that the head scarp of this terrace zone is analogous to the crater rim in peak-ring craters (Figure **F1**), and rings outside the head scarp (Figure **F3**) suggest that Chicxulub is a multiring basin (Morgan et al., 1997; Gulick et al., 2008). The acquired seismic data show that the water depth is deeper and the Mesozoic sediments thicker in the northeast quadrant of the crater (Bell et al., 2004; Gulick et al., 2008) and that lateral variation in the target at the impact site might explain the current crater asymmetry (Collins et al., 2008). Velocities and densities of the rocks that form the peak ring are low (Morgan et al., 2000; Vermeesch and Morgan, 2008; Barton et al., 2010), and a high-resolution velocity model obtained using full-waveform inversion (Figure **F4**) shows that the uppermost peak ring is formed from about 100–150 m of rocks with very low *P*-wave velocity (Morgan et al., 2011).

Given the lack of intact peak rings exposed at Earth's surface, there is no consensus as to either their geologic nature (what material they are composed of and from what stratigraphic location this material originates) or their mode of formation. Numerical simulations of large crater formation suggest that a peak ring is formed during the collapse of a deep bowl-shaped "transient cavity" formed during the initial stages of cratering (Figure **F5A**) (Morgan et al., 2000; Collins et al., 2002; Ivanov, 2005; Senft and Stewart, 2009). During this collapse, structural uplift of the crater floor produces a central uplift that is overheightened and unstable under gravity (Figure **F5B**). The subsequent outward collapse of the central uplift in some way leads to the formation of a ring of peaks between the crater center and the crater rim (Morgan et al., 2000, 2011). This model for peak-ring formation is consistent with seismic data that show downthrown Mesozoic rocks lie directly beneath the peak ring at Chicxulub at all azimuths (Morgan et al., 2000; Gulick et al., 2013). However, the precise kinematics and details of the mechanics of cavity modification remain unclear. Moreover, that such emphatic collapse of the transient crater occurs at all requires substantial weakening of target rocks relative to their static laboratory-measured strength (Melosh, 1979; O'Keefe and Ahrens, 1993). In numerical models, the precise kinematics of crater collapse and peak-ring formation is dependent on near-surface rheology, as well as the spatial extent, nature, and timing of the weakening of the target rocks (e.g., Wünnemann et al., 2005).

Previous drilling

Petróleos Mexicanos (Pemex) drilled several deep (~1.6 km) holes into or close to the Chicxulub crater (Figure **F2**), completing their drilling in the mid-1970s (Figure **F6A**). Unfortunately, the amount of coring was limited, and their interest in the area waned after they intercepted Paleozoic basement and impactites without any sign of hydrocarbons. Very few samples of the impact lithologies found in these wells are now available for examination. The Universidad Nacional Autónoma de México (UNAM) conducted a shallow drilling program in the 1990s, during which impact lithologies were penetrated at 3 sites: U5, U6, and U7 (Urrutia-Fucugauchi et al., 1996). International Continental Scientific Drilling Program (ICDP) borehole Yax-1 was drilled ~60 km south-southwest of the crater center (Stöffler et al., 2004; Urrutia-Fucugauchi et al., 2004) within the impact basin and inside a ring of cenotes (Figure **F6A**). The stratigraphy of the Chicxulub crater was constructed using the available core from these programs and the original Pemex logs (Figure **F6B, F6C**) (Ward et al., 1995; Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004).

The onshore wells indicate that postimpact sediments deepen from a few hundred meters at radii >90 km to ~1.1 km within the center of the postimpact basin (Figure **F6B**); this thickening of the Cenozoic sequence is in agreement with the offshore seismic data. Within the postimpact basin, Wells C1, S1, and Y6 penetrated a few hundred meters of melt-bearing impact breccia, Wells C1 and Y6 reached the true impact melt rock, whereas outside the basin, Wells T1, Y2, Y5A, Y1, and Y4 penetrated a few hundred meters of melt-poor impact breccia (Hildebrand et al., 1991; Sharpton et al., 1996; Urrutia-Fucugauchi et al., 2011). Several wells penetrated thick sequences of Cretaceous rocks. Close to the structure, these sequences are ~2 km thick and comprise dolomites and carbonates, with some thick beds of Lower Cretaceous anhydrite. Wells Y1 and Y2 penetrated Paleozoic basement at ~3.3 km. UNAM Well U5 shows Cenozoic rocks above melt-bearing impact breccia, and at Site U7, melt-bearing impact breccia overlies melt-poor breccia composed mainly of sedimentary clasts rich in evaporitic material (Urrutia-Fucugauchi et al., 2008). The upper breccias have high magnetic susceptibilities, low seismic velocities, low density, and high porosities and permeabilities; the lower breccias, in contrast, show low susceptibilities, variable seismic velocities, and lower porosities and permeabilities (Urrutia-Fucugauchi et al., 1996; Rebolledo-Vieyra and Urrutia-Fucugauchi, 2006). At Site U6, the Cenozoic rocks directly overlie this melt-poor breccia, with an erosional contact between them (Figure **F6C**). The melt-poor breccia in the two UNAM wells could be the same impact breccia observed in Y4, Y1, Y5A, Y2, and T1. No onshore wells have penetrated the peak ring, and no offshore wells have been drilled into the Chicxulub impact structure.

ICDP Hole Yax-1 is located ~60 km radial distance from the crater center and is positioned interior of the crater rim. Drilling recovered core from the ~800 m thick Cenozoic sequence, impact breccias, and underlying Cretaceous rocks to 1511 m (Urrutia-Fucugauchi et al., 2004). The earliest Cenozoic sediments indicate that gravity flows and resurge deposits formed part of the initial crater fill (Goto et al., 2004; Whalen et al., 2008) and contain geochemical evidence for long-lasting hydrothermal venting into the ocean (Rowe, et al., 2004; Zürcher and Kring, 2004). Unfortunately, its location on a steep slope means studies of the postimpact section were plagued by coarse-grained redeposited carbonates and lithification, and much of the Paleocene appears to be missing (Arz et al., 2004; Smit et al., 2004; Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004; Whalen et al., 2013). The 100 m thick impactite sequence is complex and comprises six distinct units (Claeys et al., 2003; Kring et al., 2004; Stöffler et al., 2004; Wittmann et al., 2004) that have been modified by postimpact hydrothermal circulation (Hecht et al., 2004; Zürcher and Kring, 2004). The Cretaceous rocks appear to be formed from a number of megablocks composed of dolomite, limestone, and about 27% anhydrite that have rotated relative to each other, probably during the crater modification stage (Kenkmann et al., 2004). The megablock lithologies are intruded by impact melt dikes and clastic, polymict dikes (Wittmann et al., 2004).

Proposed drilling

Expedition 364 will drill a 1500 m deep hole (Chicx-03B) into the peak ring approximately 45 km from the crater center, which, when projected onshore, lies between Pemex Wells S1 and Y6 (Figure **F6B**). Coring will start in the Cenozoic section at 500 meters below seafloor (mbsf) (Figure **F4**); the Paleocene/Eocene Thermal Maximum (PETM) is predicted to occur at ~600 mbsf, and the K-Pg boundary is predicted at ~650 mbsf. The uppermost peak ring rocks are formed from 100–150 m of low-velocity material that is most likely allochthonous impact breccia. A low-frequency reflector at the base of this interval is coincident with an increase in velocity and likely represents a transition to true peak-ring lithologies (Figure **F4**). The peak-ring rocks are predicted to comprise uplifted fractured basement intruded by dikes but might also contain pseudotachylytic breccia. Alternatively, they might be formed from a megabreccia with megablocks of Mesozoic and basement lithologies.

Scientific objectives

Expedition 364 will address the following objectives through the proposed drilling:

- The nature and formation of a topographic peak ring;
- The process of how rocks are weakened during large impacts to allow them to collapse and form relatively wide, flat craters;
- The nature and extent of postimpact hydrothermal circulation;
- The habitability of the peak ring and effect of this impact on the deep biosphere;
- The recovery of life in a sterile zone;
- The nature of the PETM transition;
- The nature and composition of the impact breccias, melt rocks, and peak-ring rocks;
- The climatic effects of this impact;
- The sedimentology and stratigraphy of the postimpact sequence; and
- The calibration of geophysical models of the crater using core and wireline logs.

1. *The nature and formation of peak rings*

Proposed Hole Chicx-03B will sample material that forms a topographic peak ring (Figure **F4**) to reveal the lithologic and physical state of these rocks, including porosity, fracturing, and extent of shock effects. The recovered core will be used to test the working hypotheses that peak rings are formed from (1) overturned and uplifted basement rocks, (2) megabreccias, or (3) some other material. If the peak ring is formed from uplifted rocks, as predicted by several independent numerical simulations of crater formation (Figure **F5**) (Collins et al. 2002; Ivanov 2005; Senft and Stewart, 2009), we can estimate their depth of origin (upper crust or deeper) using metamorphic grade, thermochronology, and possibly remanent magnetism. The orientation of impact-induced discontinuities, which might include breccia zones, brittle shear faults, and melt-filled fractures, will be used to infer the strain geometry (i.e., the orientation, and potentially also the magnitude, of the three principal strain axes during peak-ring formation) and thus constrain the kinematics of peak-ring formation. Collectively, these data will be used to discriminate between models of peak-ring formation and to groundtruth dynamic models of crater formation, which now include dilatancy, the increase in porosity induced during cratering, and the cause of the gravity low across impact craters (Collins, 2014). For example, shock levels within the peak ring are predicted to be relatively lower in the model by Baker and Head (2015), which is based on spectral analyses of lunar peak rings. Numerical simulations and observations from West Clearwater suggest higher shock pressures and a rapid decrease in shock pressure with depth (Rae et al., 2015).

2. *The weakening mechanism*

Numerical modeling of large impacts indicates that the rocks must behave in a fluid-like manner for a short period of time after impact to allow the dramatic collapse of a large bowl-shaped transient cavity to form a broad, flat final crater. In these models, the material that forms the peak ring has traveled the greatest distance during crater formation (e.g., Figure **F5**) and should thus have undergone the most mechanical weakening. Providing a physical explanation for the apparent transitory low strength of the target is an enduring and challenging problem in impact cratering mechanics. Proposed weakening mechanisms include acoustic fluidization (Melosh, 1979; Melosh and Ivanov, 1999), thermal softening (O'Keefe and Ahrens, 1993), and strain?rate weakening (Senft and Stewart, 2009). Geological investigations at complex craters have provided clues to the weakening mechanism, such as evidence for cataclastic flow (Kenkmann, 2003) and the identification of individual blocks surrounded by breccias in accordance with the block model of acoustic fluidization (Ivanov, 1994; Kenkmann et al., 2005; Riller and Lieger, 2008). Eroded complex craters often possess large zones of pseudotachylytic breccia that might act to reduce friction on fault planes (Spray 1992; Reimold and Gibson, 2005; Mohr-Westheide et al., 2009; Riller et al., 2010), although this appears to be in conflict with observational data that suggest melt was emplaced in a tensional stress regime (Lieger et al., 2009).

Quasistatic mechanical loading tests of intact and brecciated target material will be used to measure the strength difference between friction?controlled deformation of crushed rock and fracture-controlled deformation of intact rock. Such data, along with our analyses of samples of the peak-ring rocks, will be used to investigate what mechanism(s) allow the target rocks to behave temporarily as a fluid when hit by a hypervelocity impact.

3. *Hydrothermal circulation*

Both the postimpact sediments and peak-ring rocks will be examined for evidence of hydrothermal alteration and postimpact venting into the ocean to answer questions such as "How long did the circulation last?" and "How high was the peak temperature?" This line of inquiry will include petrological assessment, thermochronology, and X-ray diffraction (XRD), X-ray fluorescence (XRF), fluid inclusion, and stable isotope analyses to examine the alteration assemblage and characterize the hydrothermal fluid composition (Ames et al., 2004; Lüders and Rickers, 2004; Zürcher and Kring, 2004; Osinski et al., 2005, 2013). Hydrothermal circulation might have been focused in specific zones as it was in Hole Yax-1 (along faults and lithological contacts), or it might have been more pervasive. Wireline logs will be used to measure fracture density and, indirectly, porosity, which will help assess ancient permeability—an important parameter in modeling hydrothermal systems (Abramov and Kring, 2007).

4. *Deep biosphere and habitability*

Analyses at different depths of the borehole, focusing on samples of melt, crystal xenoliths embedded in the melt, and crystals from the peak ring itself, will be used to determine the duration of the crater cooling from 500°C to below 200°C and ultimately provide better quantification on how long a crater stays warm enough to be suitable for life evolution and deep subsurface microbial communities.

Both the postimpact sediments and peak-ring rocks will be examined for present-day microbiology and biosignatures of past life. Impacts can have an adverse effect on the deep biosphere because of hydrothermal sterilization but might also lead to an increase in microbial abundance due to impact-induced fracturing (Cockell et al., 2002, 2005; Cockell and Osinski, 2007). The diversity of microbial life will be quantified and compared with geological and geochemical data to answer questions such as "Was the microbiology shaped by the postimpact hydrothermal system?" and "Did organic matter get trapped within hydrothermal minerals?" The deep biosphere will be investigated using culturing, molecular biological analyses of DNA, and searching for biosignatures such as hopanoids and other lipids/biomolecules, as well as paired analyses of paleome and lipid biomarkers (Cockell et al., 2005, 2009; Coolen and Overmann, 2007; Coolen et al., 2013). Iron isotopes will also be used to detect biosignatures because they are particularly useful for studies of ancient, severely metamorphosed and/or altered rocks (Yamaguchi et al., 2005). The rehabitation of the deep biosphere following a large impact will shed light on whether peak rings and impact breccias are an ecological niche for exotic life and thus potentially important habitats for early life on Earth (Kring and Cohen, 2002; Bryce et al., 2015).

5. *Recovery of life*

Immediately after impact, the ocean is locally likely to have been sterile. We will core through the postimpact sediments to examine the recolonization of the ocean, including "What biota came back first (benthic vs. planktonics, dinoflagellates, and specialists vs. generalists)?" "How long did it take to return to normal conditions?" and "Did cold-water species return quickly?" Of interest will be the nannoplankton recovery at "ground zero" in comparison to the global response (e.g., Jiang et al., 2010). There might have been a significant lag in recovery due to a long-term, impact-initiated hydrothermal circulation system (Abramov and Kring, 2007). Diversity might have gradually recovered, with the hardiest taxa appearing first and other taxa taking longer to populate the impact basin, or the whole assemblage might have returned simultaneously once the environment stabilized. Reconstruction of the earliest Paleocene environment will be achieved using stable isotopes of planktonic and benthic foraminifers and fine-fraction carbonates. Many studies of plankton in the early Danian are from deep-water or shelf environments, and if the Danian is expanded in proposed Hole Chicx-03B, the recovery can be examined in more detail. Study of biomarkers at the molecular level (high-pressure liquid chromatography [HPLC], liquid chromatography–mass spectrometry [LC-MS]) and pigments (chlorophylls, bacteriochlorophylls, and its degradations products) from photosynthetic organisms (algae and photosynthetic bacteria) might indicate changes in and evolution of photosynthetic organism populations after the impact.

It is expected that both marine and terrestrial organic matter have accumulated in the postimpact sediments and that the paired stratigraphic analysis of the paleome and lipid biomarkers and their isotopic compositions using precisely dated core material will provide detailed insights into postimpact environmental conditions and the recovery and evolution of surface and deep subsurface life (Coolen et al., 2007, 2013). Of interest is the ocean chemistry and temperature immediately following the impact and any indicators of climatic recovery. Are there signs of local hydrothermal venting (Zürcher and Kring, 2004), short-term global cooling (Vellekoop et al., 2014), and/or indicators of ocean acidification? How long did it take to return to normal conditions? Oxygen isotope ratios, in particular, will help constrain surface and bottom water temperatures in the immediate postimpact interval. Intrinsic magnetic properties of sediments can be used as proxy of the relative abundance of biogenic versus detrital fraction in the sediments, and changes in magnetic mineralogy can be attributed to changes in the depositional environment (redox conditions, detrital source, etc.).

6. *PETM and hyperthermals*

Many PETM transitions suffer from poor preservation due to dissolution. The section we will recover at Chicxulub might be atypical, as it is in a midlatitude location and within a semi-isolated basin above the calcium compensation depth (CCD) and thus carbonate sediment accumulation should have been maintained throughout the PETM interval. The position of the coring site (on a topographic high some distance from the crater rim) will hopefully mean that the PETM succession is not plagued by coarse-grained redeposited carbonates, as was the case in Hole Yax-1. Thus, there is a possibility that the section might be able to address the relative timing of benthic extinction versus the spike in Carbon-13. Key to understanding this interval will be the documentation of changing paleoceanographic conditions (depth and redox state), sedimentary environments, and biological productivity. Biological productivity will be evaluated through analysis of total organic carbon, stable isotopes from organic matter (C and N) and carbonates (C and O), and XRF geochemical analyses to determine concentrations of micronutrients such as Cu, Ni, and Zn. Biomarkers might be able to distinguish between terrestrial and methane hydrates and thus help constrain the cause of warming. High-resolution biostratigraphy and magnetostratigraphy will be used to obtain a robust age model in the postimpact sediments and identify key events in the cored interval, including the hyperthermals (e.g., the Elmo event) and PETM.

7. *Impact breccias, melt rocks, and peak-ring rocks*

We expect to recover impact breccias that contain clasts of the target sedimentary sequence and basement rock. Chicxulub breccias appear to be quite variable, in particular with respect to the amount of anhydrite and the lithology and age of basement clasts (Kettrup et al., 2000; Kring, 2005). The mineralogical and geochemical characterization of the impactites and peak-ring rocks will provide key information on target rock composition (Koeberl et al., 2012). We will also search for an extraterrestrial signature using platinum group element (PGE) analyses and Os and Cr isotopes (Gelinas et al., 2004; Tagle and Hecht, 2006; Goderis et al., 2012; Sato et al., 2013, 2016) to determine whether a measurable fraction of the projectile remains at the impact site or whether most projectile material ends up within the global K-Pg layer. High-resolution ^{40}Ar/^{39}Ar analyses and electron microscopy on shocked and melted impactites and U-Pb dating of zircon will be used to study their thermochronologic and deformational history and for high-precision dating of the Chicxulub impact. Shock metamorphism of the feldspathic components will be used to investigate how impact processes affect argon (Ar) retention (Pickersgill et al., 2015). Shock metamorphism and pyrometamorphic indicators for the rock-forming minerals will help constrain peak shock pressure and temperature regimes (Grieve et al., 1996; Tomioka et al., 2007; Ferrière et al., 2008; Rae et al., 2015). Compositional and structural investigations of any intruded dikes will allow assessment of their origin, energy of emplacement, and timing and, for example, discover whether melt within dikes is more mafic than the impact melt in the central crater, as it is in Hole Yax-1 (Wittmann et al., 2004).

Magnetic susceptibility and paleomagnetic measurements will be used to investigate whether hydrothermal circulation led to the formation of ferromagnetic minerals and a chemical remanent magnetization (Quesnel et al., 2013). These measurements will also evaluate whether hydrothermal circulation is the source of the strong magnetic anomaly recorded at surface and whether a component of the natural remanent magnetization is shock induced (Tikoo et al., 2015), or detrital (detrital remanent magnetization [DRM]), as it is in the postimpact sediments in Hole Yax-1 (Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004).

8. *Dust and climatically active gases*

The study of the shock and thermal effects recorded in the carbonate and evaporite impactites will help to constrain more precisely the degassing process of carbonates and evaporates from the Yucatán target rock. Placing constraints on the impact energy with numerical simulations and the lithology, shock state, and porosity of the target rocks is important, as these are all critical input parameters for modeling the environmental effects of this impact (Pope et al., 1997; Pierazzo et al., 2003).

9. *Postimpact sequence, including resurge and/or tsunami deposits*

Was the peak ring (being a topographic high) protected from resurge deposits? Or is it covered by wash-back deposits such as multitiered, coarse-grained, cross-bedded sediments overlain by a K-Pg Ir-rich layer? There might also be evidence of repeated tsunami and seiche surges, as observed in the Brazos River, Texas (USA), in the form of several distinct graded layers (Vellekoop et al., 2014).

We will use drilling, a vertical seismic profile (VSP) experiment, and other logging data to identify the borehole depths and core-based lithologic contrasts that generate horizons in our reflection data (Figures **F2**, **F3**, **F4**). With this core-log-seismic mapping, we can identify the stratigraphic age of reflectors and map these across the impact basin using the extensive suite of seismic reflection data acquired in 1996 and 2005. Sedimentological and stratigraphic data are key to understanding the paleoceanographic and sea level history across this impact basin (Whalen et al., 2013). Detailed biostratigraphic and sedimentologic studies including analysis of grain size, mineralogy, sedimentary structures, and ichnofabric will be crucial in documenting the postimpact sedimentary history. Drill-core data will be used to groundtruth seismic reflectors that can be tracked into adjacent deep-water sections to help understand the nature of Lower Cenozoic sequences in the Gulf of Mexico, which are difficult to date because of the lack of publicly available scientific cores. This mapping into the broader Gulf of Mexico will enable testing of models for large-scale basin margin collapse caused by impact generated earthquakes and tsunami (Sanford et al., in press).

10. *Calibrate geophysical models*

Wireline logging and petrophysical measurements on the core will be used to groundtruth geophysical models of gravity, magnetic, refraction, and magnetotelluric (MT) data, which will be critical to improving our understanding of crater structure away from the drill hole, particularly onshore. The proposed drilling will allow us to address questions such as “What is the cause of the strong magnetic anomaly recorded at the surface?” “What is the cause of the low seismic velocities and densities within the peak ring (are these fractured deep-crustal basement rocks, megabreccia, or some other material)?” and “Is the thin (100–150 m thick) layer of very low velocity rocks forming the uppermost lithology of the peak ring composed of impact breccias?” We will also use borehole imaging to constrain dips within the peak-ring stratigraphy to test for overturning during emplacement and verify whether the dips are consistent with the observed inward-dipping reflectors and region of lowered velocities.

Proposed drill sites

Site location

The optimal location to target peak-ring rocks is at proposed Site Chicx-03B (Table **T1**; Figure **F7**). Two additional proposed sites, Chicx-02B and Chicx-04B, were selected as a contingency if any technical difficulties are encountered at the primary site.

Available survey data

In 1996, the British Institutions Reflection Profiling Syndicate (BIRPS) program acquired ~600 km of seismic reflection data along two radial lines (Chicx-B and Chicx-C) and along a line parallel to the Yucatán coast (Chicx-A and Chicx-A1). Refraction data were acquired at the same time with air gun shots recorded by ocean-bottom seismometers placed along the reflection lines and land seismometers across the Yucátan Peninsula. These reflection and refraction data were used to determine the size and morphology of the Chicxulub impact crater (Morgan et al., 1997; Morgan and Warner, 1999), propose a model for peak-ring formation (Morgan et al., 2000; Collins et al., 2002), and image deep crustal structure (Christeson et al., 2001).

In 2005, 1822 km of additional seismic reflection data were collected offshore, along with 3-D seismic refraction data that were recorded both offshore and onshore across the crater (Gulick et al., 2008, 2013). These data revealed asymmetries in crater structure (Gulick et al., 2008), a zone of structural uplift in the crater center (Vermeesch and Morgan, 2008), topography on the Moho (Christeson et al., 2009), and images of the melt sheet in the center of the crater (Barton et al., 2010).

Other geophysical data used to model crater structure include two additional seismic reflection profiles (Camargo-Zanoguera and Suarez-Reynoso, 1994), gravity and magnetic data (Hildebrand et al., 1991; Sharpton et al., 1996; Ortiz-Aleman et al., 2001; Rebolledo-Vieyra et al., 2010), MT data (Unsworth et al., 2002), and passive seismic data (Mackenzie et al., 2001).

A high-resolution geophysical survey was undertaken in 2013 onboard the R/V *Justo Sierra* with the specific objectives of mapping seabed morphology, shallow subsurface geology, and the presence of magnetic anomalies at proposed Expedition 364 drill sites (Stewart et al., 2013). Complete coverage of multibeam echo-sounder and side-scan sonar data was achieved across an area of 14.4 km^2. In total, 435 line km of side-scan sonar and compressed high-intensity radar pulse (CHIRP) data were acquired, along with 204 line km of magnetometer data and 194 line km of surface tow boomer data. Multibeam echo-sounder data were acquired concurrently with all other geophysics data. Geophysical data were groundtruthed using a cone penetrometer test (CPT) system and seabed sediment samples recovered using a Smith-McIntyre grab. Geophysical and geotechnical data were integrated and interpreted to determine the location of seabed or shallow subsurface features that might pose a hazard to drilling (e.g., amplitude anomalies suggesting trapped gas or any indicators of unstable ground conditions that might influence safe operation of a lift boat).

Operational strategy

Drilling platform

Expedition 364 will be implemented as an MSP, in which the platform and coring services are normally contracted from the industry market while the scientific services are provided by ESO. Because of a shallow water depth (17 m), a small jack-up type rig known as a lift boat has been selected for this expedition. The drilling platform, chosen by the contractor and inspected by ESO, will be the *LB Myrtle*, a 245 class liftboat that is three legged and self-propelled. The coring rig will be cantilevered off the bow of the liftboat between the two forward jacking legs.

The platform will have sufficient capacity by way of food and accommodation for 24 h operation but will require frequent resupply. This resupply will be carried out by a contractor-arranged supply boat.

Coring rig

The coring rig is an Atlas Copco T3WDH mining rig utilizing flush-jointed mining drill strings sized to allow the larger ones to act as casing if coring requires it. The rig has a mast capable of handling 6 m string lengths, and coring is done with a top-drive system installed in the mast. A wireline operation will be used to recover the core barrel from the base of the borehole.

Coring methodology

A single hole will be drilled to the target depth (TD) of 1500 mbsf or to the maximum possible depth. If difficulties are encountered at the start of the primary hole (Chicx-03B), two contingency sites have been selected (Chicx-02B and Chicx-04B; Table **T1**).

The drilling and coring strategy was designed to provide multiple backup options and to prepare for any technical difficulties that might be encountered during drilling. A multiple option drilling strategy provides the best chance to achieve the proposed TD of 1500 mbsf within the constraints of budget, platform size, and drill rig capability.

Using a rotary drill, a 12 inch open hole will be drilled from the seabed to 10 mbsf. This hole will be set and cemented with 9-5/8 inch conductor casing. From 10 to 500 mbsf, an 8 inch open hole will be drilled using a rotary drill, after which SWT casing will be set and cemented. At 500 mbsf, continuous coring will commence utilizing a PQ3 coring system with an oversized bit. The hole will be set and cemented with PWT casing to 700 mbsf. Below 700 mbsf, PQ3 coring will continue with a standard sized bit. If the PQ3 system becomes stuck at any point, PHD rods will be set as casing and coring will continue with an HQ3 coring system. If the HQ3 system becomes stuck, HQ coring rods will be set as casing and an NQ3 coring system will be used. NQ3 is not a desirable core size, but it can be used if the other strategies are not successful. The aim is to maintain a core diameter no less than HQ3.

The core-run length will be 3 m maximum. However, the length of a core run will be geared to maximize core recovery and maintain hole stability, even if this reduces overall penetration speed. In unconsolidated formations, core runs could be less than the 3 m maximum length.

A mud recycling system will be installed primarily to reduce mud usage during open-hole drilling to 500 m, and it is anticipated that this system will also be used during the coring stage. Cuttings will be collected and curated during open-hole drilling.

Drilling mud will be used to condition the borehole as dictated by circumstances and the driller's requirements.

The core liner will be clear polycarbonate, with the option to use splits.

The above is subject to change depending on the operations at the time of drilling.

Downhole logging

For all MSP expeditions, the downhole logging program, coordinated by the European Petrophysics Consortium (EPC), is an integral part of offshore operations and is designed to help meet the expedition-specific scientific objectives and maximize scientific output in general.

MSPs employ various coring technologies and pipe sizes, and they drill in a variety of water depths, each of which provides constraints on the anatomy of logging operations. This is different from the R/V *JOIDES Resolution* and the D/V *Chikyu*, where fixed pipe sizes allow more standard sets of logging tools to be deployed. Pipe diameter is typically the limiting factor on MSPs, and the type of logging tools, from slimline memory-mode tools to standard oilfield tool suites, varies from expedition to expedition.

For Expedition 364, slimline downhole logging services are contracted from the University of Montpellier (France) for wireline logging and the University of Alberta (Canada) for vertical seismic profiling and are managed by EPC. The logging equipment and staffing have been constructed to allow for seamless operation on the platform. Offshore, the Petrophysics Staff Scientist(s) will interface with the operational team, Expedition Project Manager, Co-Chief Scientists, and science party to ensure that the downhole logging program is successfully achieved.

Measurements available from standalone and stackable slimline tools during Expedition 364 include spectral and total gamma ray, *P*-wave sonic velocity, *S*-wave sonic velocity, acoustic and optical borehole imaging, electrical resistivity, magnetic susceptibility, hydrogeological measurements (fluid conductivity, pH, eH, temperature, and dissolved oxygen), caliper, flow meter, and VSP.

For Expedition 364, wireline logging data will be acquired in three logging phases at 0–500, 500–700, and 700–1500 mbsf. This plan will be adjusted as needed as drilling and coring operations progress. The VSP is planned in the 0–700 mbsf interval, with the objectives to acquire VSP data up to 100 m below a key seismic reflector observed on the seismic profiles.

The proposed downhole logging program is as follows:

- Through-pipe: spectral gamma ray.
- Open hole (by tool string): electrical resistivity, spectral gamma ray, total gamma ray + *P*-wave sonic velocity + magnetic susceptibility, total gamma ray + acoustic borehole imaging, and VSP (2.5 m spacing).

Other wireline logging measurements (to be acquired in open hole) will be included in the logging program, depending on hole conditions, operational progress, and preliminary scientific results. The final set of Quality Assurance/Quality Control (QA/QC) downhole data will be made available to the science party at the commencement of the OSP.

Marine mammal observation will be conducted by trained observers during VSP surveying if required as a condition of the research permit. A ramp-up (soft start) procedure will be followed when the air gun source begins operating after any 30 min period without operations during VSP surveying. The air gun will be fired at intervals, gradually increasing the pressure to the operational pressure over a ~30 min period. Ramp-up of the air guns will not be initiated if a sea turtle or marine mammal is observed within or near the applicable exclusion zones.

EPC's coordination of Expedition 364 logging will include data processing, QA/QC of data, and ongoing scientific support for data interpretation and research.

Core on deck

Once drilling operations commence and core begins to arrive on deck, the operations team will be responsible for delivering the cores to the curation container after they are initial labeled. The operation will proceed using a changeover of inner core barrels to ensure continuity of the coring operation in as timely a fashion as possible. The deck operators will deploy an empty core barrel immediately after the previous one has been retrieved and then address the core removal and subsequent readying of that core barrel for reuse. Because cores will be collected in a plastic liner, the usual IODP curation procedures will be followed and documented in an ESO Handbook.

Science operations

A Sampling and Measurements Plan (SMP) for Expedition 364 will be prepared by ESO and the Co-Chief Scientists to meet the scientific objectives of IODP Proposal 548-Full3 and Addendum 548-Add4.

Offshore science activities

It is the nature of MSP expeditions that there is limited laboratory space and accommodation on board platforms compared to the larger vessels *JOIDES Resolution* and *Chikyu*, and as such there is no splitting of the cores at sea and only selected scientific analysis carried out onboard by a subset of the science party. Science activities on the platform are confined to those essential for core curation, measurement of ephemeral properties, securing of proper samples for pore water chemistry and microbiology, downhole logging, and safety. Most scientific analysis is carried out during the OSP in Bremen, Germany, when the cores are split.

The current plan is that the cores will be split into 1.5 m lengths for curation.

The following is a summary of the offshore scientific activities (please refer to SMP link which will be available at **http://www.eso.ecord.org/expeditions/364/364.php** and the online tutorial at **http://www.marum.de/en/Offshore_core_curation_and_measurements.html**):

- Basic curation and labeling of cuttings and core.
- Running all cores on the multisensor core logger (MSCL) (gamma density, *P*-wave velocity where possible, electrical resistivity, and magnetic susceptibility).
- Core catcher (if available) description and sampling for initial structural and petrophysical or sedimentological and micropaleontological characterization, including taking a core catcher image.
- Taking and proper storage of samples for gas analyses, pore water, and microbiology.
- Interstitial water analysis and any other ephemeral properties agreed on in the SMP.
- Core storage.
- Downhole logging.
- Associated data management of all activities (see below).

In order to carry out the science requirements on the platform with a subset of the science party, a staffing plan will be devised. The plan will require flexibility of approach from all participants, with safety, core recovery, curation, and procedures for the measurement of ephemeral properties, including sampling for microbiology, as priorities.

Report preparation will take place on board as required; the reports to be compiled are as follows:

- Daily and weekly operations and science reports to the management and panels of ECORD and IODP, science party members, and any other relevant parties. Scientific reports are provided by the Co-Chief Scientists. Summarized daily reports will be publicly available on the ESO website for any interested parties.
- Completion of the offshore sections of the expedition reports (primarily the Methods chapter).
- Press releases in line with the ECORD outreach policy.
- Information for posting on the ESO expedition website.

Onshore science activities

The OSP will be held at the IODP Bremen Core Repository (BCR) of the MARUM, University of Bremen, Germany. The scientific work will follow the SMP to be developed in due course in conjunction with the Co-Chief Scientists.

Details of the facilities that will be available for the OSP at the BCR and MARUM laboratories can be found at the Expedition 364 SMP link, which will be available at **http://www.eso.ecord.org/expeditions/364/364.php**. Additional facilities can be made available through continuing close cooperation with additional laboratories at the MARUM-Center for Marine Environmental Sciences and the Department of Geosciences at Bremen University, as well as the Max Planck Institute for Marine Microbiology (MPI), all of which are situated nearby on campus.

The following briefly summarizes the OSP scientific activities:

- Natural gamma radiation (NGR): Prior to the OSP, total NGR measurements will be taken on all cores (as appropriate) using an MSCL-XYZ in the core repository. These measurements will be undertaken by ESO staff.
- Core splitting: an archive half will be set aside as per IODP procedure.
- Core description: ESO will provide a data-entry system that is IODP standard. For data entry, ESO will employ the Expedition Drilling Information System (DIS) that is entirely compatible with others being used in IODP. Please see **Data management**, below.
- Digital linescan imaging.
- Color reflectance (spectrophotometry).
- Core sampling for expedition ("shipboard") samples (to produce IODP measurements data for the expedition reports, e.g., physical properties).
- Smear slide preparation.
- Thin section preparation.
- Inorganic geochemistry: whole-rock and pore fluid chemistry.
- Bulk mineralogy: XRD analysis.
- Petrophysical measurements: *P*-wave and moisture and density analyses.
- Thermal conductivity.

- Core sampling for personal postexpedition research: a detailed sampling plan will be devised at the completion of the offshore phase and after the scientists have submitted their revised sample requests (please see **Research planning: sampling and data sharing strategy**, below).

A staffing plan will be developed with the Co-Chief Scientists to ensure that all required analyses and subsampling can be carried out efficiently. The measurement plan will take account of MSP specifications for QA/QC procedures.

In view of the existing geographical distribution of all DSDP/ODP/Integrated Ocean Drilling Program/IODP cores, the IODP Gulf Coast Repository (GCR) located at Texas A&M University (USA) will be the long-term location for the Expedition 364 cores, which will be shipped from the BCR after the moratorium period.

Report preparation will take place during the OSP as required by ECORD. The reports to be compiled include the following:

- Weekly progress reports to ECORD and relevant parties. Scientific reports are provided by the Co-Chief Scientists.
- Preliminary Report (submission to USIO Publication Services 1 week after OSP).
- Completion of the expedition reports (submission to USIO Publication Services as soon as practically possible after the OSP).

For more information please refer to SMP link which will be available at **http://www.eso.ecord.org/expeditions/364/364.php** and the tutorial at **http://www.marum.de/en/Offshore_core_curation_and_measurements.html**.

Staffing

Scientific staffing is decided on the basis of task requirements and nominations from the IODP Program Member Offices (**http://www.iodp.org/program-member-offices**). ESO staffing is based on the need to carry out drilling and scientific operations efficiently and safely (Table **T2**). Staff will be rotated on and off the liftboat in accordance with the requirements of drilling and scientific operations.

Data management

A data management plan for the expedition will be developed once the data requirements and operational logistics are finalized. The outline plan follows:

- The primary data capture and management system will be the Expedition DIS. This is a relational database. It will capture drilling, curation, and geoscience metadata and data during the offshore and onshore phases of the expedition.
- The Expedition DIS includes tools for data input, visualization, report generation, and data export.
- The database can be accessed directly by other interpretation or decision-making applications if required.
- A file server will be used for storing data not captured in the database (for example, documents and image files) and the inputs/outputs of any data processing, interpretation, and visualization applications used during the expedition.
- The EPC will manage the downhole logging data, MSCL data, and other physical properties data. Logging metadata and MSCL data will be stored in the Expedition DIS. Downhole logging data will be stored separately by the EPC for processing and compositing.
- On completion of the offshore phase of the expedition, the Expedition DIS database and the file system will be transferred to the BCR to continue data capture during the OSP.
- Between the end of the offshore phase and the start of the OSP, expedition scientists will have access to the data via a password-protected website.
- On completion of the OSP, Expedition Scientists will continue to have access to all data through a password-protected website throughout the moratorium period.
- During the moratorium, all metadata and data, apart from downhole-log data, will be transferred to PANGAEA for long-term data archiving.
- Downhole logging data will be transferred to the Lamont-Doherty Earth Observatory for long-term archiving.
- After the moratorium, cores and samples will be shipped from the BCR and archived at the GCR.
- After the moratorium, all expedition data will be made accessible to the public.

Research planning: sampling and data sharing strategy

All researchers requesting samples should refer to the IODP Sample, Data, and Obligations Policy and Implementation Guidelines posted at **http://www.iodp.org/doc_download/4038-iodp-sample-data-and-obligations-policy**. This document outlines the policy for distributing IODP samples and data to research scientists, curators, and educators. The document also defines the obligations that sample and data recipients incur. The Sample Allocation Committee (SAC; composed of Co-Chief Scientists, Expedition Project Manager, and IODP Curator for Europe [BCR and MSPs] or offshore curatorial representative) will work with the entire science party to formulate a formal expedition-specific sampling plan for shipboard (expedition = offshore and OSP) and postexpedition (postexpedition research) sampling.

Members of the science party are expected to carry out and publish scientific research for the expedition. Before the expedition, all shipboard scientists are required to submit research plans and associated sample/data requests via the IODP Sample and Data Request (SaDR) system at **http://web.iodp.tamu.edu/sdrm** before the deadline specified in their invitation letters. Based on sample requests (shore-based and shipboard) submitted by this deadline, the SAC will prepare a tentative sampling plan that will be revised on the ship as dictated by recovery and expedition objectives. All postexpedition research projects should provide scientific reasons for desired sample size, numbers, and frequency. The sampling plan will be subject to modification depending upon the actual material recovered and collaborations that may evolve between scientists during the expedition. This planning process is necessary to coordinate the research to be conducted and to ensure that the scientific objectives are achieved. Modifications to the sampling plan and access to samples and data during the expedition and the 1 y postexpedition moratorium period require the approval of the SAC.

Shipboard sampling will be restricted to those required for acquiring ephemeral data types that are critical to the overall objectives of the expedition and assist planning for higher resolution sampling postexpedition. Because of the time-sensitive nature of microbiological sampling, these samples will also be collected offshore, in accordance with the predefined sample plan.

The permanent archive halves are officially designated by the IODP curator for BCR and MSPs. All sample frequencies and sizes must be justified on a scientific basis and will depend on core recovery, the full spectrum of other requests, and the expedition objectives. Some redundancy of measurement is unavoidable, but minimizing the duplication of measurements among the shipboard party and identified shore-based collaborators will be a factor in evaluating sample requests.

If critical intervals are recovered, there may be considerable demand for samples from a limited amount of cored material. Sampling in and around these horizons will be avoided offshore. A sampling plan coordinated by the SAC will be required before critical intervals are sampled.

The SAC strongly encourages and may require collaboration and/or sharing among the shipboard and shore-based scientists so that the best use is made of the recovered core. Coordination of postexpedition analytical programs is anticipated to ensure that the full range of geochemical, isotopic, microbiological, and physical property studies are undertaken on a representative sample suite. The majority of sampling will take place at the OSP in Bremen, and the SAC encourages scientists to start developing collaborations before and during the expedition.

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Table T1. Location and elevation of proposed primary and contingency sites, Expedition 364.

Site name	Position	Water depth (m)	Penetration (m)	Preference
Chicx-03B	21°27.002′N, 89°56.967′W	17.6	1500	Primary site
Chicx-02B	21°27.364′N, 89°57.147′W	18.1	1500	Contingency site
Chicx-04B	21°28.632′N, 89°57.446′W	17.3	1500	Contingency site

Table T2. Summary of science party and operator (ESO) personnel, Expedition 364.

	Science party	
ESO (17)	Offshore science team (12)	Expedition scientists
ESO Operations Manager 1 ESO Expedition Project Managers 2 ESO Curators 2 ESO Geochemist 1 ESO Petrophysics Staff Scientist 1 ESO Petrophysicist 1 ESO Data Manager 1 ESO Drilling Coordinators 2 Logging Contractors 6	Co-Chiefs 2 Core describers 2 Paleontologists 2 Microbiologists 2 Petrophysicist 1 Geophysicist 1 Geochemists 2	Comprises the offshore science team, additional invited scientists, Expedition Project Manager, and Petrophysics Staff Scientist. The exact make-up of expertise of the science party will be chosen by ESO and the Co-Chief Scientists. A maximum of 33 invited scientists will join the science party.
Offshore team total 29		

Figure F1. Peak rings are roughly circular rings of rugged hills and massifs that stand above the otherwise flat crater floor. In peak-ring basins, the crater rim is the outer edge of a terrace zone. In multiring basins, two or more rings (inward-facing asymmetric scarps) lie outboard of the central basin. Image source: NASA.

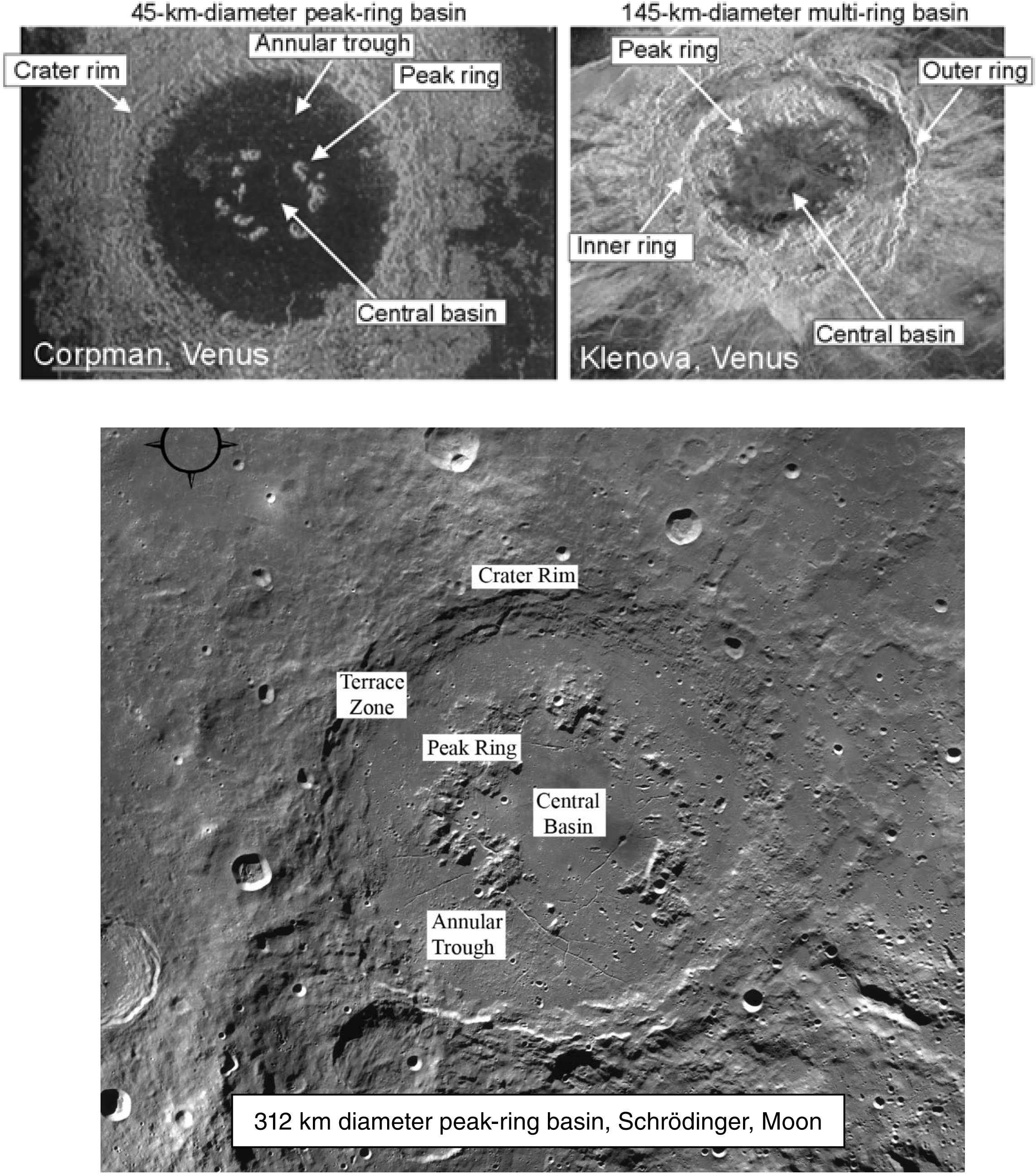

Figure F2. Location of site survey data overlain on the gravity field. Coastline is in white. Marine seismic profiles acquired in 1996 and 2005 are shown in black dashed and solid lines, respectively. Offshore and onshore seismometer locations in the 1996 and 2005 surveys are shown with large black and white circles, respectively. Modified from Gulick et al., 2013; copyright American Geophysical Union 2013.

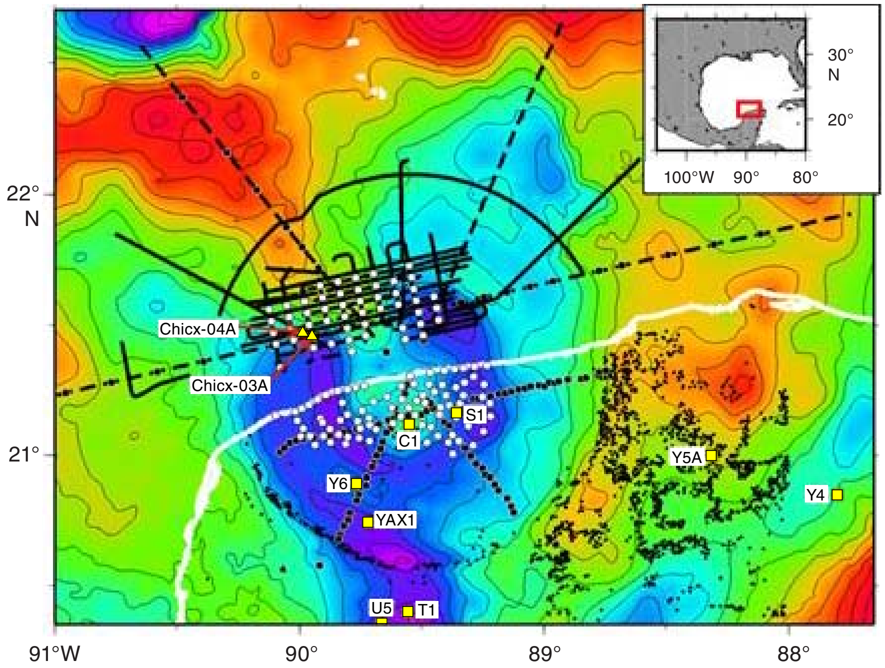

Figure F3. Seismic reflection data along Line Chicx-A. About 20–30 km outboard of the crater rim at Chicxulub, the relatively undisturbed, flat-lying, preimpact stratigraphy is abruptly offset vertically by 400–500 m (outer ring). Outer ring faults are observed to radial distances of 90–120 km, giving a crater diameter of ~195–210 km (Morgan et al., 1997; Gulick et al., 2008). Modified from Gulick et al., 2008; copyright Nature Geoscience 2008.

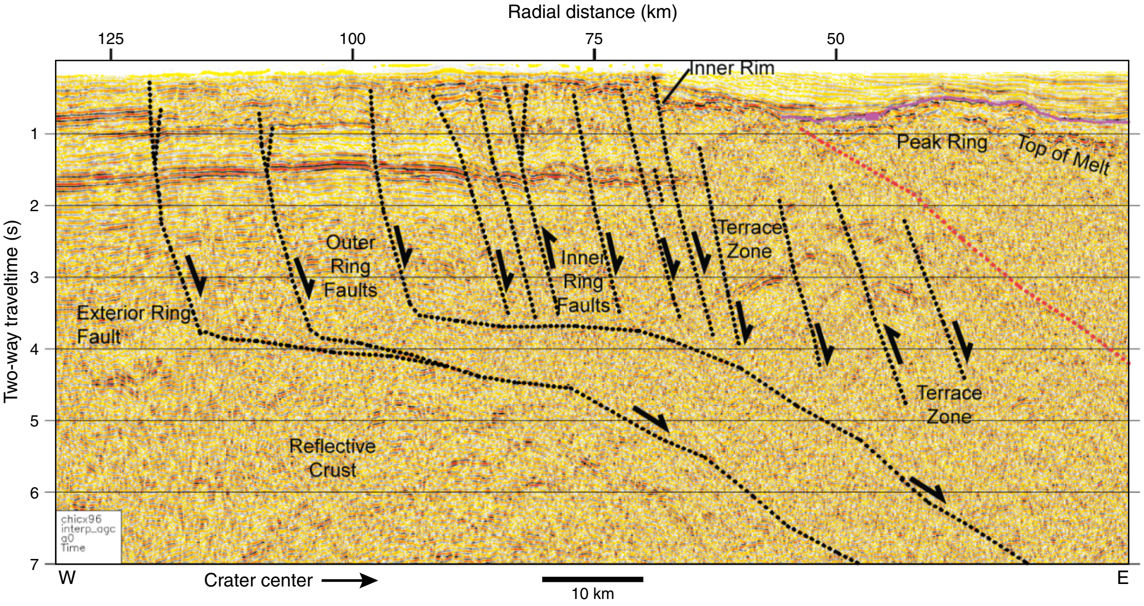

Figure F4. Proposed Hole Chicx-03B projected on to a seismic reflection profile and velocity model obtained from full-waveform inversion. Coring will start at 500 m; total proposed depth is 1500 m. The principal targets are the PETM at ~600 m, followed by the K-Pg boundary at ~650 m, and then we will penetrate ~850 m of rocks that form the peak ring. The uppermost peak-ring rocks are formed from 100–150 m of low-velocity material and are most likely to be allochthonous impact breccias. A low-frequency reflector is coincident with an increase in velocity and likely represents a transition to true peak-ring lithologies. Modified from Morgan et al., 2011; copyright American Geophysical Union 2011.

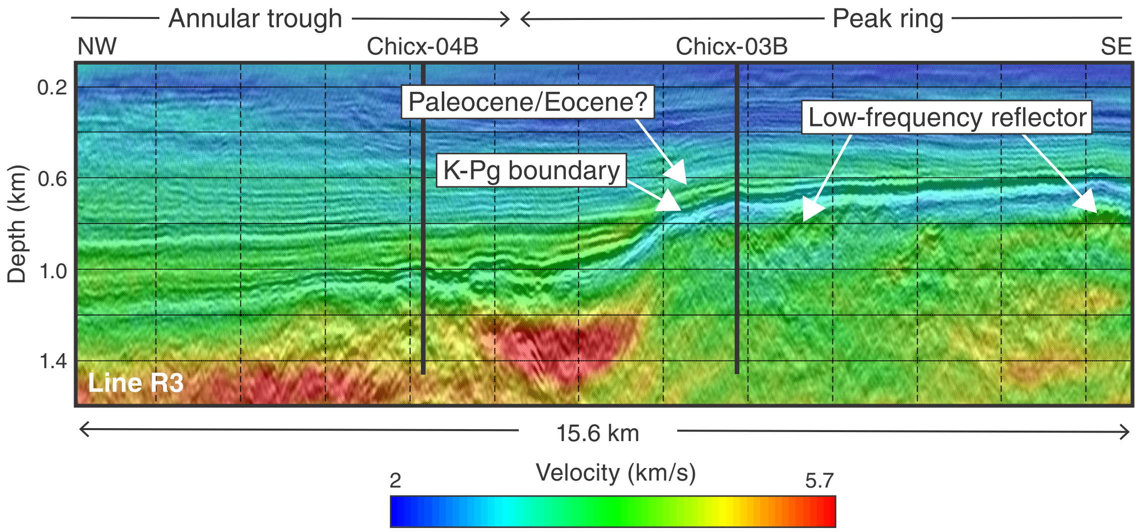

Figure F5. Hydrocode simulation of the formation of the Chicxulub crater (Collins et al., 2002; Morgan et al., 2011). Layering shows stratigraphy; impact point and center of crater are at a horizontal distance of 0 km. (A) Sediments that form the transient cavity rim collapsed inward and downward, whereas (B) material in the central crater collapsed upward. C. In this model, the stratigraphically uplifted material (central uplift) collapses outward across the downthrown rim material to form a peak ring. D. Cross section through the final crater. Colors = maximum shock pressures rocks were subjected to during crater formation. Dashed line = location of sediments that originally formed the transient cavity rim (see A). Modified from Morgan et al., 2011; copyright American Geophysical Union 2011.

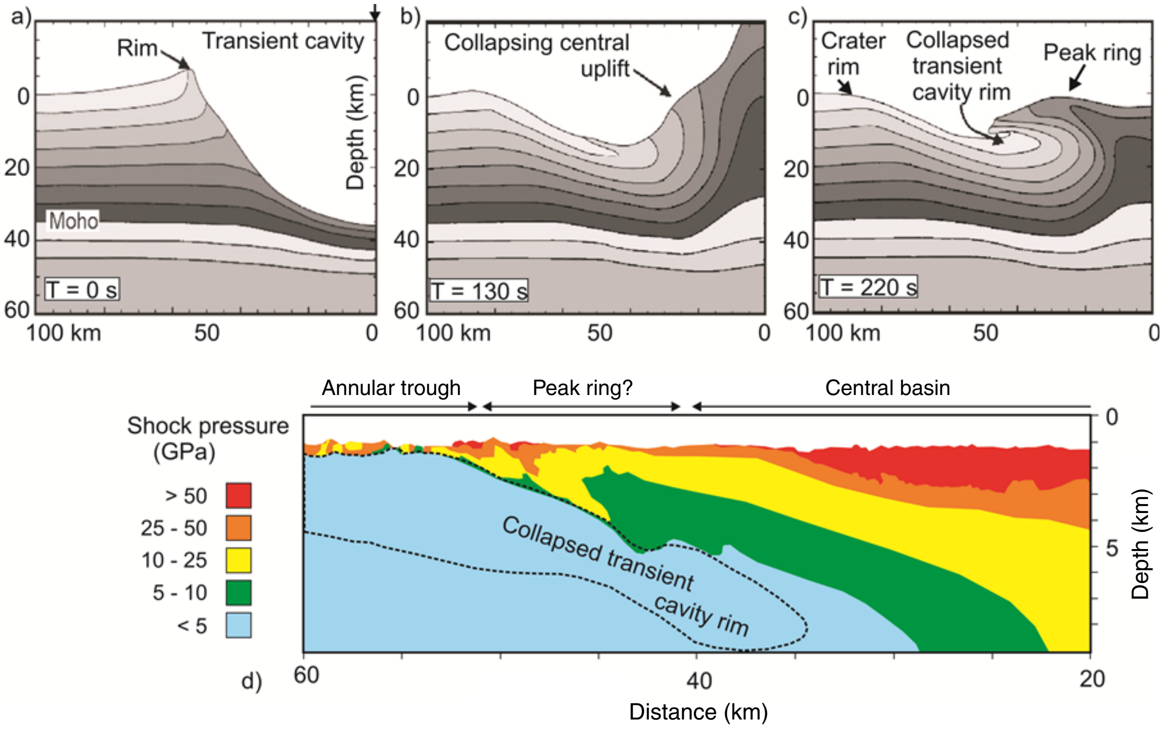

Figure F6. A. Location map showing onshore drill holes from the UNAM scientific drilling program (U1–U8), the ICDP borehole (Yax-1), and Pemex drilling. Modified from Rebolledo-Vieyra and Urrutia-Fucugauchi, 2004; copyright 2004 The Meteoritical Society. B. Lithologic columns and stratigraphy from Pemex boreholes and Hole Yax-1. Hole Chicx-03B is ~45 km from the crater center. Reproduced from Rebolledo -Vieyra and Urrutia-Fucugauchi (2004).

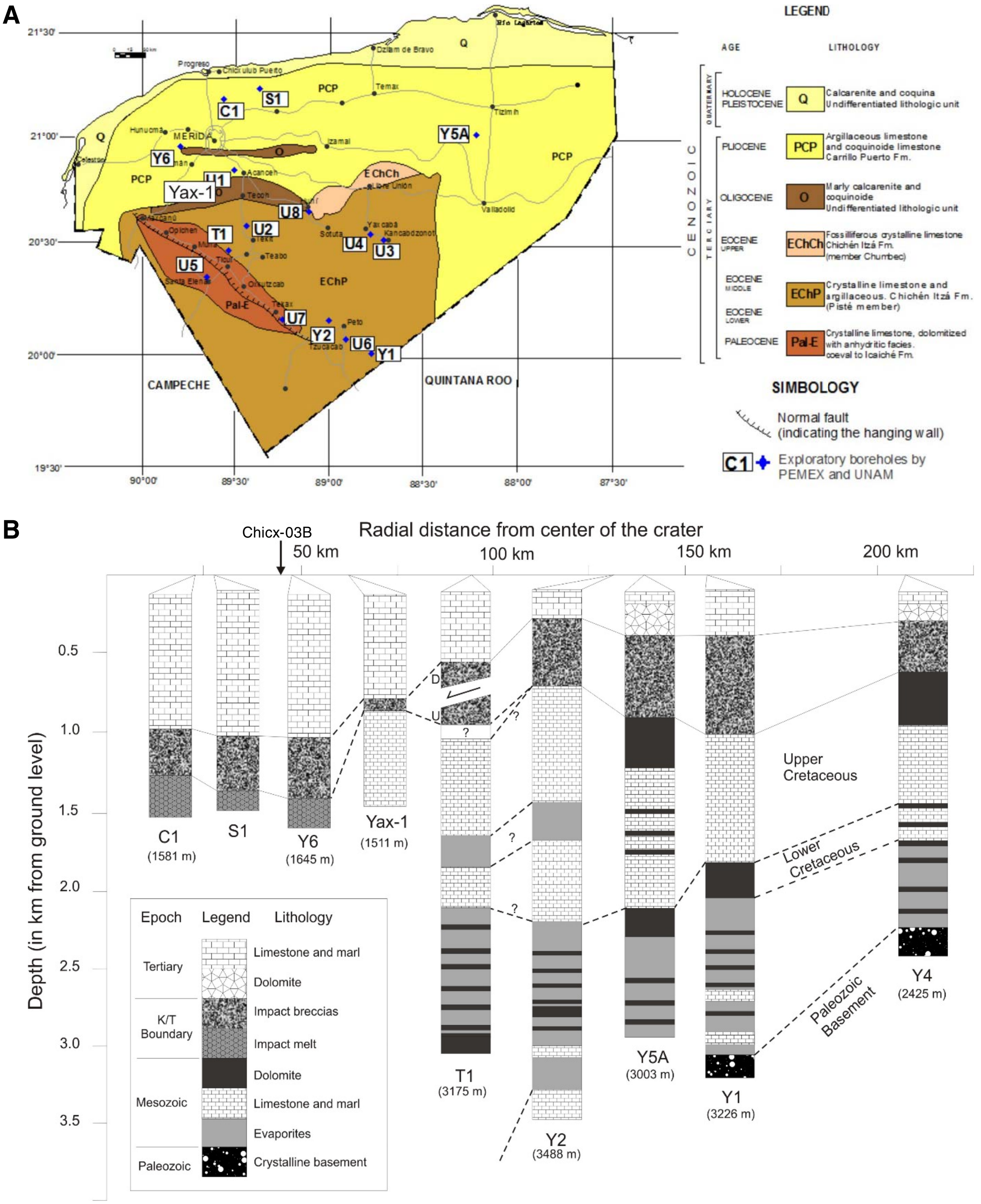

Figure F6 (continued). C. Lithologic columns and stratigraphy from UNAM boreholes and Hole Yax-1. Reproduced from Rebolledo -Vieyra and Urrutia-Fucugauchi (2004).

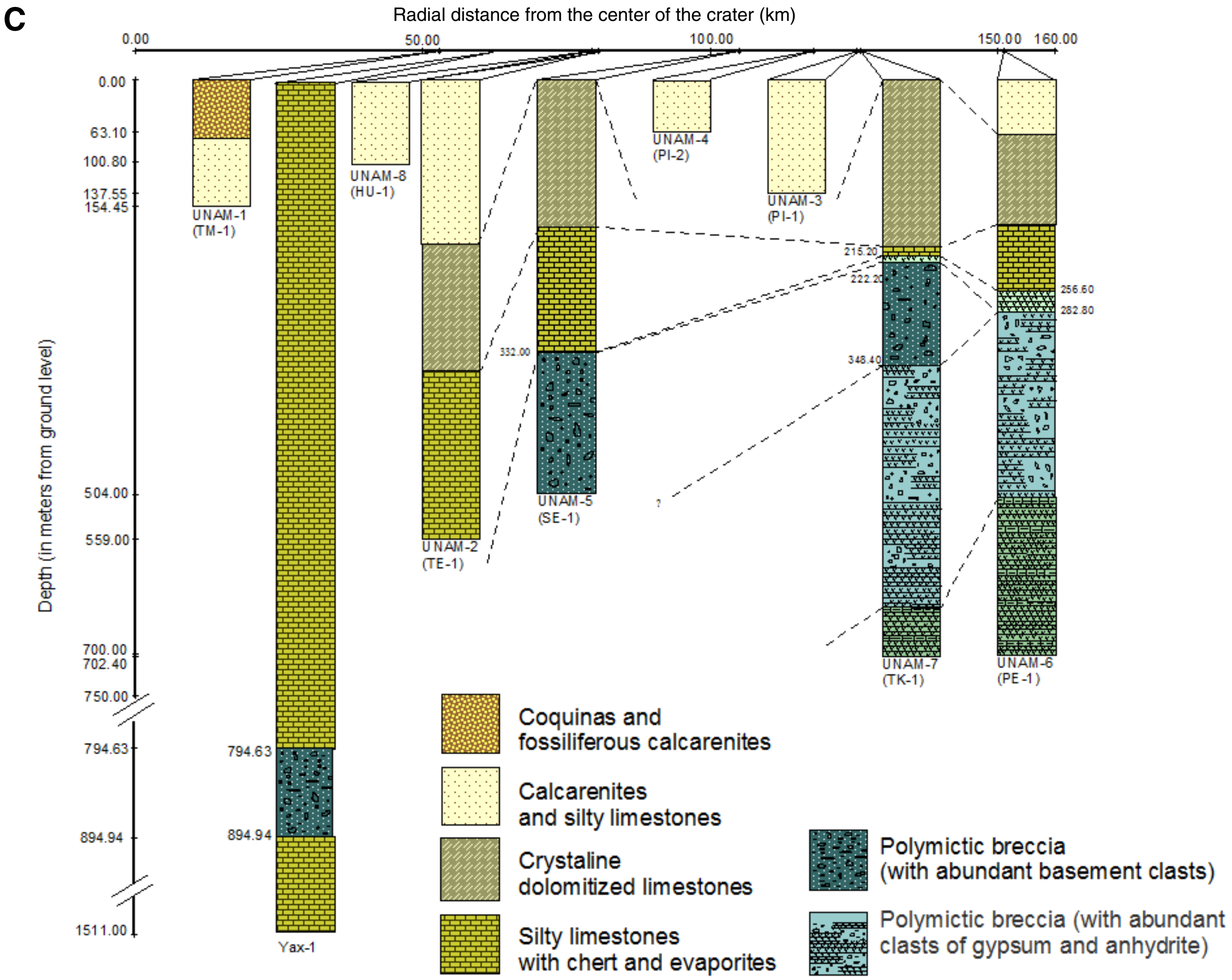

Figure F7. Site locations, Expedition 364. Bathymetry reproduced from Stewart et al., 2013; copyright NERC 2013.