Drilling Impacts

Discoveries from Chicxulub

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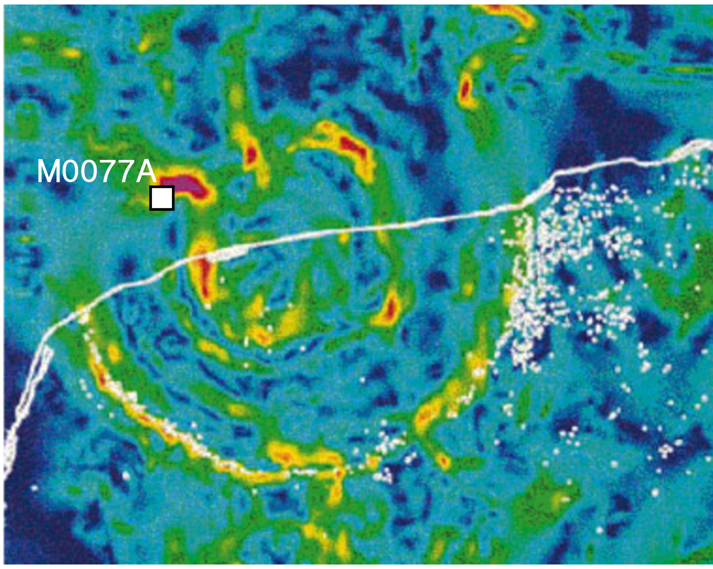
UK IODP scientists have made it into the prestigious **Science Magazine 2019 Breakthrough of the year Top 10** with findings from Expedition 364 Chicxulub Drilling in the Gulf of Mexico. The project was instigated and co-led by Professor Jo Morgan of Imperial College London, who described to me the journey from her initial idea to pioneering discoveries about the formation of large meteorite impact craters and the surprising response of the biosphere to the catastrophic Chicxulub event.

Professor Morgan first heard about the Chicxulub impact structure at a meeting in 1994, when she witnessed an argument about the size of the crater, with proponents arguing for a diameter of 170 km versus 300 km, based on gravity and magnetic data. At that time, the idea that the Chicxulub impact triggered the mass extinction 66 million years ago at the Cretaceous-Paleogene boundary was contentious. It occurred to Morgan, a Marine Geophysicist, that seismology could be used to answer the question of the Chicxulub crater size and, hence, provide information about the magnitude of impact energy released and the resulting effects on the environment. She and Michael Warner submitted a grant application to the NERC BIRPS (British Institutions Reflection Profiling Syndicate) program and were awarded funding to carry out a seismic experiment on and offshore in October 1996. The experiment was a success and Morgan and colleagues were able to show that the Chicxulub structure is a complex crater ~ 200 km in diameter, with an 80-90 km diameter peak ring. The discovery that Chicxulub is a multi-ring basin, similar to large impact structures elsewhere in our solar system, such as on Venus, was ground-breaking.



top: Chicxulub Bouguer anomaly map (Hildebrand et al., 1995) showing the location of the Expedition 364 borehole M0077A. bottom: The Expedition 364 Science Party at the Bremen Core Repository for the OSP.

A fundamental unknown at that time was the mechanism of complex crater formation, specifically: "How can the strength be removed from the rocks to allow them to rebound to form a wide, flat crater instead of just a big deep bowl? How can rocks temporarily become fluidised?" Morgan and her (then) PhD student, Gareth Collins, used numerical simulations to try to reproduce the Chicxulub crater structure that had been inferred from geophysical data. These simulations, in which the rocks are allowed to temporarily behave like a fluid, led to the so-called dynamic collapse model for peak ring formation. Alternative models were proposed and it became clear to Morgan that direct sampling of an intact peak ring via drilling was necessary to test these hypotheses. Opportunities for such sampling are extremely rare, however. Other than Chicxulub, only two impact structures with diameters ≥200 km are known on Earth: Vredefort (South Africa) and Sudbury (Canada), both of which are approximately two billion years old and have suffered either severe erosion (Vredefort) or tectonic deformation (Sudbury). Chicxulub therefore presents the best opportunity to study multi-ring impact craters on our planet.

Expedition 364 Principal Science Questions

1. What rocks comprise a topographic peak ring and how are peak rings formed?
2. How are rocks weakened during large impacts to allow the formation of relatively wide, flat craters?
3. What insights arise from biologic recovery in the Paleogene (post-impact sediments), within a potentially "toxic" ocean basin, that might be an Early Earth analogue?
4. What effect does a large impact have on the deep subsurface biosphere. Are impact craters (including peak rings) habitats for life?
5. Can we improve constraints on the environmental effects of this impact. What caused the extinctions?

Drilling in shallow waters (credit: D. Smith & ECORD)

Drilling the Chicxulub peak ring onshore would have been challenging because it was not feasible to acquire the necessary seismic data to image the drilling targets, due to the abundance of near-surface caverns in the platform carbonates. In 1998 Morgan and her co-proponents submitted a proposal to IODP to drill Chicxulub offshore. After a constructive review process, successful IODP proposals usually start drilling within three to five years from the original pre-proposal submission. Unfortunately, the shallow water depth of the proposed drill site in the Gulf of Mexico meant that the IODP Drilling Vessel (D/V) JOIDES Resolution could not perform the drilling, so a different platform would be required. In the meantime, the drilling proposal was expanded to include additional objectives with the help of astrobiologist Professor Charles Cockell (University of Edinburgh). Cockell studies terrestrial impact craters as analogues for Martian environments, to investigate which conditions are favourable for the potential emergence of life. Scientific drilling of the Chicxulub crater presented a unique opportunity to investigate the response of the deep biosphere to a newly created environment, and examine the subsequent recovery of life and the colonisation of the crater. It was hypothesised that the highly fractured rocks of the peak ring would be most likely to provide a favourable habitat for microbial life since they are the most porous parts of the crater. The addition of biological aspects to the redrafted proposal significantly strengthened the case for drilling, as it would now address major scientific questions from two different fields.

As the proposal was being developed further, Morgan and Dr Penny Barton (Cambridge University) successfully sought NERC funding for a site survey (a further seismic experiment) and received support also from NSF. The acquired seismic data were inverted to recover a high-resolution velocity model using a technique called full-waveform inversion; this fine-resolution image helped pinpoint the optimal location for drilling. With the introduction of IODP ECORD Mission Specific Platforms (MSPs) in the early 2000s, drilling the Chicxulub peak ring became feasible, and the proposal was approved and scheduled for drilling.

Expedition 364 was carried out as a collaborative operation between IODP and the International Continental Scientific Drilling Program (ICDP), using an MSP: the jack-up platform L/B Myrtle. Offshore operations ran from 5th April to 31st May 2016. Frequent and extreme changes in formation hardness presented a significant technical challenge for the drillers and resulted in numerous bit changes. The drilling mud had to be carefully selected for environmental as well as scientific reasons, and the microbiology team developed special protocols to limit and monitor potential biological contamination of the cores. Together, the drillers and science team overcame these difficulties, and achieved almost 100% core recovery. The 830 m of core from site M0077 includes samples of impact rocks (suevites, impact melt rocks, and shocked granitic basement) of the peak ring down to 1334.7 metres below seafloor, as well as post-impact rocks, including a record of the first few years after the impact event.

Morgan's experience offshore, actively leading drilling operations as Co-Chief Scientist (along with Professor Sean Gulick, University of Texas) on her first ever IODP expedition was "absolutely fabulous"; she recounted being in a state of constant excitement as she and the rest of the science team rushed out to gather around each new core as it arrived on deck, to see what had been drilled. The cores included a veritable geological treasure trove of stunning impact breccias, beautiful but crumbly granites, and the earliest Palaeogene sediments, deposited from seconds to weeks after the impactor struck. Shattercones (structures unique to impact craters, that show the orientation of shock waves produced by the meteorite strike) were found in the core - the first ever discovery of these in the

The L/B Myrtle at site M0077 (credit: L. Perez-Cruz & ECORD).

Chicxulub crater. The structural geologists were over the moon to find preserved cross-cutting relationships of various structures (which are usually lost in craters on land due to erosion, burial and tectonics) that for the first time ever, allowed them to determine the order of deformational events in the crater formation process. Morgan described the experience: “There was a lovely atmosphere; it was hard work but also a wonderful shared experience of scientific discovery - the best moment of my life scientifically”. The expedition generated much excitement onshore too, with streams of journalists arriving on the L/B Myrtle every few days and outreach activities organised for local school children. News of the Chicxulub drilling even travelled out of this world to British astronaut Tim Peake, who tweeted about it from the International Space Station.

The drilling was followed by an Onshore Science Party (OSP) at the Bremen Core Repository in Germany, from 21st September to 15th October 2016. The enthusiasm of the science team mounted further as the specialist groups were able to study the cores in more detail and test the hypotheses that the drilling had been designed to address. The location of site M0077 was selected to enable to the Expedition 364 science team to test two competing models for peak ring formation: the Dynamic collapse model (Morgan et al., 2000, 2011; Collins et al., 2002, 2008), which predicted that the Chicxulub peak ring is formed from mid-crustal rocks; and the Nested melt-cavity hypothesis (Head, Baker, 2011, 2015, 2016), which proposed that the peak ring formed from upper-crustal rocks that were uplifted and rotated, making them less shocked and of a shallower depth of origin than in the dynamic collapse model. Furthermore, drilling at “ground zero” would allow the team to investigate the effect of the meteorite impact and subsequent hydrothermal activity on the deep biosphere, and examine the recovery of life after the catastrophic event. In every team there was excitement as the cores began to reveal their secrets and new discoveries were made.

top: The Exp 364 Offshore Science Team on L/B Myrtle (credit: A. Wittmann & ECORD)
inset: The Expedition logo

When the Chicxulub impactor crashed into Earth, it triggered the mass extinction of 76% of species living on the surface of the planet. However, for the deep biosphere it provided a wealth of new subsurface habitats that persist to this day. The impact is estimated to have released energy equivalent to that of 10 billion WWII atomic bombs, geologically instantaneously bringing to the surface rocks from 10 km deep in the Earth’s crust. The geological disruption of the subsurface produced vast networks of fractures and juxtaposed lithologies to form new fluid flow pathways and mineralogical interfaces, respectively. These conditions constitute favourable habitats for microbial life, as evidenced by Cockell and colleagues’ discovery of increased microbial biomass within the suevite and elevated cell abundances at impact-generated interfaces in the suevite and underlying lithologies. Different geological units within the crater host taxonomically and metabolically distinct microbial communities, depending on the physical alteration of the rocks. These observations demonstrate that large impacts produce subsurface environments with enhanced fluid flow and supply of nutrients and energy, making them key targets in the search for life on Mars and other rocky planets.

Cores from hole M0077A: impact melt (left) and shocked granitoid (right) (credit: M. Mowat & ECORD)

While subsurface Chicxulub microbes flourished, it was widely believed that at "ground zero" the surface biosphere was wiped out, and that global cooling and the reduction in solar energy reaching Earth's surface afterwards slowed recovery. Before the impact event 66 million years ago, it is thought that the sea in the Chicxulub area was approximately 200 m deep. Immediately after the impact, ocean water flooded back into the crater carrying in debris from the surroundings. The Expedition 364 organic geochemists and microbiologists have identified biomarkers in the earliest post-impact sediments that suggest fragments of land plants, cyanobacteria and photosynthetic sulphur bacteria were washed from microbial mats on the adjacent carbonate platform into the crater basin by one or more tsunamis. Surprisingly, the data indicate that within days to months after the crater formed, single celled cyanobacteria were blooming, fuelled by nutrients washed from the coast. Further studies have shown that mammals and trees evolved very quickly to fill the ecological niches left by the mass extinction event.

It is this story of life rapidly re-emerging, phoenix-like, that has captured the attention of the media and public alike, leading to the accolade in Science. But for Morgan, the scientific highlight was finding evidence supporting the Dynamic collapse model, of which she had been an original proponent. The Chicxulub drilling has vastly improved our understanding of how large craters form, providing missing pieces of the puzzle: "The UK's involvement in IODP and ICDP has been absolutely critical to my work. All of my previous research on Chicxulub became so much more important when we drilled; it put everything into context and has been the highlight of my career". Morgan finally has the answers she has been searching for for nearly two decades, but she is quick to stress that hers has been an unusually long journey from pre-proposal to drilling, due to the technical issues associated with the drill site. She never gave up, because she knew that drilling the Chicxulub peak ring was the only way to address these important scientific questions. Her patience and perseverance finally paid off and the spectacular Chicxulub M0077A cores enabled the science team to address all of the objectives put forward in the drilling proposal. Her advice for anyone working on an IODP drilling proposal is to listen to the reviewers and be patient "The review process was very useful and improved the proposal. People are trying to assist you to do the best science you can. Embrace the reviews". While the journey from inception to realisation of the drilling has been long, the legacy of the Chicxulub drilling will last far longer; exciting findings have already been published but the totally unique cores will continue to support and generate scientific research for decades to come.