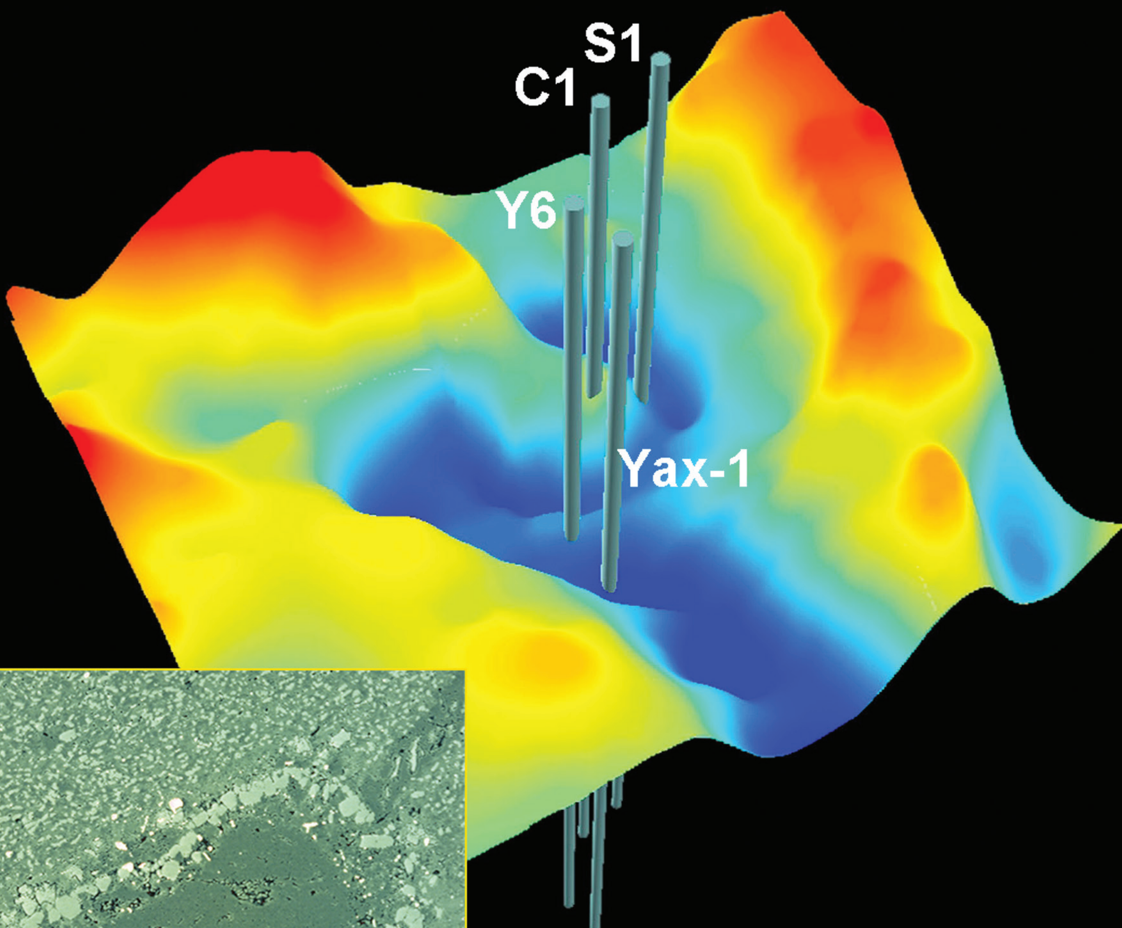
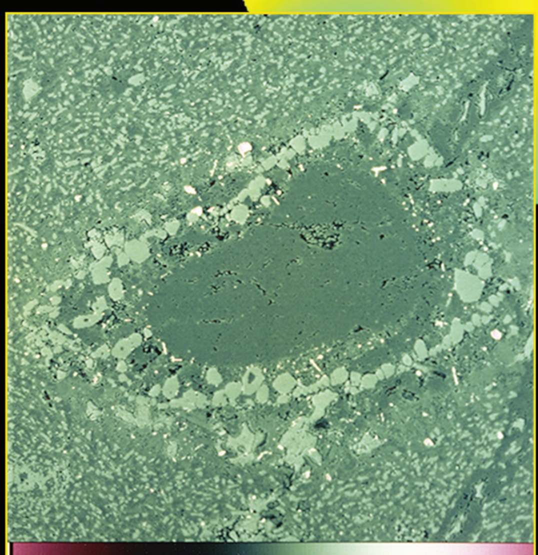
Chicxulub Crater, TWENTY-FIVE YEARS LATER





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— David A. Kring, Lunar and Planetary Institute

The Chicxulub impact event in eastern Mexico is infamous for the devastation it wrought to planet Earth. This 180-kilometer-diameter impact structure is contemporaneous with the largest mass extinction event during the past 100 million years, and is almost certainly responsible for the demise of dinosaurs and most life on Earth 66 million years ago, abruptly ending the 186-million-year-long Mesozoic Era.

Twenty-five years after evidence of its impact origin was presented at the 22nd Lunar and Planetary Science Conference (LPSC) in Houston, the link between the Chicxulub crater and the Cretaceous/Tertiary (K/T, or K/Pg) boundary events has been verified multiple times and, with the site of the impact identified, a better assessment of the profound global impact-generated environmental effects followed.

Interestingly, the subsurface Chicxulub structure, buried beneath ~1 kilometer of sediment, was identified decades earlier using geophysical techniques and exploration boreholes drilled in search of petroleum, the latter of which located what was interpreted to be intrusive and extrusive andesite with pyroclastic tuff. As divulged during an oral session at the 22nd LPSC in 1991, we learned that the melt rocks and breccias within the structure are not the product of magmatic intrusions and extrusions as previously interpreted, but rather the consequences of an impacting near-Earth asteroid (or possibly comet) with a kinetic energy equivalent to ~100 million megatons of TNT (Fig. 1). The breccias covering the upper Cretaceous elsewhere on the Yucatán Peninsula were neither volcanic materials nor debris eroded from tectonic uplifts as previously presumed, but rather products of >10,000 cubic kilometers of debris ejected from a crater. The confusion between volcanism and impacts that vexed the field of impact cratering a hundred years ago also confounded the discovery of the Chicxulub crater.

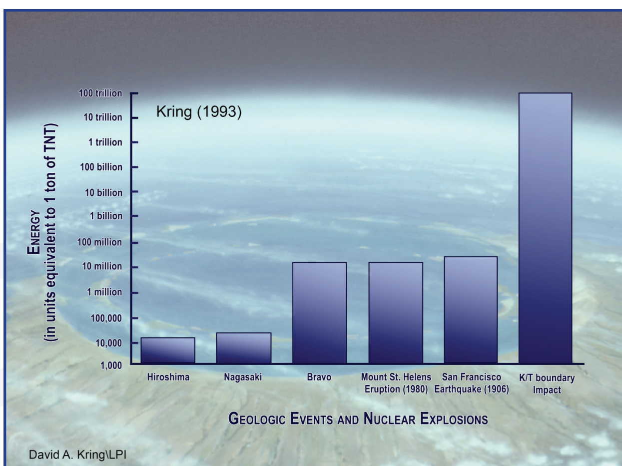

Fig. 1. The energy of the K/T boundary impact event compared to several other geologic events and nuclear explosions, including Bravo, the United States' largest nuclear test explosion. Credit: Adapted from Kring [(1993) The Chicxulub impact event and possible causes of K/T boundary extinctions, in Proceedings of the First Annual Symposium of Fossils of Arizona (D. Boaz and M. Dornan, eds.), pp. 63–79, Mesa Southwest Museum and the Southwest Paleontological Society, Mesa]. Background art by William K. Hartmann (©1991), used with permission.

Evidence linking the Chicxulub crater with impact ejecta in the K/T boundary layers include a crater-filling impact melt with a similar chemical composition and radiometric age as impact melt spherules deposited at the K/T boundary in Haiti; an ejecta thickness at the boundary that decreases radially away from the Chicxulub crater; shocked quartz grain sizes in boundary sediments that decrease with radial distance from the Chicxulub crater; shocked quartz, feldspar, and lithic fragments in boundary sediments similar to Chicxulub basement rocks; unshocked zircon in boundary sediments that are consistent with the age of Chicxulub basement rocks; and shocked zircon in boundary sediments with the same age as the Chicxulub crater. The projectile that produced the crater had affinities with carbonaceous chondritic meteorites and was the source of the iridium anomaly in K/T boundary sediments (Fig. 2) that initially prompted the impact-mass extinction hypothesis and the search for a crater.

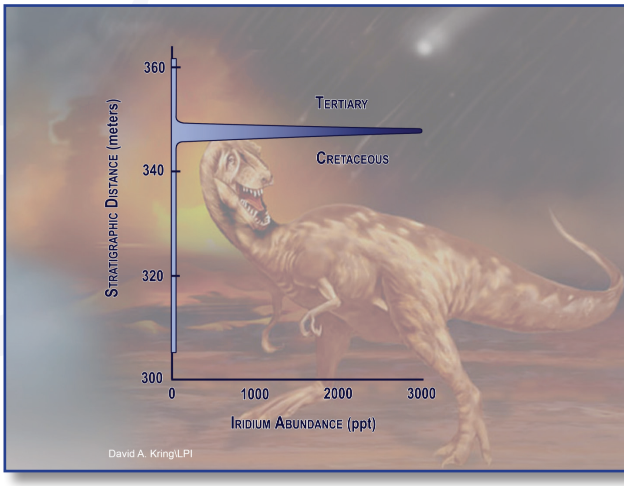

Fig. 2. A profile of iridium abundance in a stratigraphic column of sediments from Gubbio (Italy) that includes an anomalously high value at the K/T boundary. Credit: Data from W. Alvarez et al. [(1990) Iridium profile for 10 million years across the Cretaceous-Tertiary boundary at Gubbio (Italy), Science, 250, 1700–1702]; illustration adapted from Kring [(1993) The Chicxulub impact event and possible causes of K/T boundary extinctions, in Proceedings of the First Annual Symposium of Fossils of Arizona (D. Boaz and M. Dornan, eds.), pp. 63–79, Mesa Southwest Museum and the Southwest Paleontological Society, Mesa].

The impact occurred on a submerged portion of the Yucatán carbonate shelf surrounded by the Gulf of Mexico and the Caribbean Sea. The seas and near-shore deltaic systems were teeming with rudist and coral reefs, oysters, giant inoceramid clams, ammonites, bryozoans, gastropods, and crabs, many of which are found fossilized in K/T boundary sediments bounding the region. Those waters were haunted by ferocious mosasaurs, with different species ranging from 4 to 15 meters in length, hungrily feeding on ammonites, fish, and even smaller mosasaurs, before being extinguished forever by the impact event. Ubiquitous were foraminerfera, single-celled organisms with fascinating little shells, floating in the water column or inhabiting the sea floor, consuming diatoms, bacteria, algae, a type of crustacean called copepods, and other tiny detritus.

After a brilliant flash of light and heat that was quickly followed by shock waves and an air blast that roared over the surface, sea waves radiated across the Gulf of Mexico, cutting down into reefs, burying the seafloor with both impact ejecta and tsunami backwash deposits, including one that entrained a dismembered mosasaur. In some areas, seismically triggered landslides of submerged slope sediments roared down to cover deeper parts of the basin with vast breccia and turbidite deposits. The Chicxulub impact event was one of the largest geologic displacements of rock and sediment to occur across Earth's surface during the Phanerozoic, and that displacement occurred nearly instantaneously.

As devastating as those regional impact effects were, they were not responsible for the mass extinction that characterizes the K/T boundary. Rather, the global extinctions were driven by the distribution of ejecta, including climate-altering gases, that encircled the planet. The discovery of the Chicxulub impact site, which was covered with a sequence of carbonate and evaporite sediments, led to tremendous improvements in model calculations of its catastrophic effects.

The presence of anhydrite ($CaSO_4$) deposits in target rocks was not anticipated and immediately altered estimates of the environmental effects of the K/T impact, which had often been assumed to be in the deep ocean prior to the discovery of Chicxulub. Model calculations of a shock-heated atmosphere implied the production of nitric acid rain, but that model of precipitation was now compounded by the addition of sulfur chemistry. After discovering Chicxulub, it was clear that vaporized anhydrite was injected into the stratosphere, producing sulfate aerosols and eventually sulfuric acid rain, affecting shallow freshwater systems and estuaries and chemically leaching soils.

When ejecta carried into space by an expanding and accelerating vapor-rich impact plume reaccreted to the top of the atmosphere, it heated the atmosphere and, in some areas, heated the surface of Earth so severely that it ignited wildfires. The distribution of those fires is still debated and depends, in part, on the trajectory of the impactor, which is also still being debated. Those fires pumped greenhouse-warming carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4) into the atmosphere in proportions equal to or greater than that produced by vaporizing the carbonate target sediments at the Chicxulub site. They also released ozone-destroying chlorine, bromine, and fluorine, which, when combined with contributions from the projectile and target lithologies, greatly exceeded the threshold needed to destroy the ozone layer.

Initially surface temperatures across our planet rose when the atmosphere was heated by impact ejecta zipping through the atmosphere, then cooled by debris in the atmosphere that blocked sunlight and shut down photosynthetic organisms at the base of the food chain. It took 5 to 10 years for dust and aerosols to settle out of the atmosphere, after which surface temperatures rose due to the greenhouse gases ejected into the atmosphere. While many scientists in the community have been working to understand those processes in light of the discovery of Chicxulub, it is also important to note that several investigators are still pursuing potential volcanic crises for the mass extinction event, either spawned independently by the Deccan eruptions in India or catalyzed by a Chicxulub-enhanced extrusion rate in the Deccan province.

Although our attention is often riveted by the catastrophic environmental and biological consequences of the Chicxulub impact, the crater has also been a focus of study because it is a magnificent geologic structure. It is the best preserved peak-ring or multi-ring basin on Earth. That preservation is ensured, in part, by the tectonic stability of the Yucatán Peninsula and Tertiary sediments that blanket the structure. The challenge for geologists is to penetrate those sediments, which are up to ~1 kilometer thick, to reach the crater.

The first targeted effort to probe the crater was the Chicxulub Scientific Drilling Project of 2001–2002, which was sponsored by the International Continental Drilling Program (ICDP). That project bottomed at 1511 meters and recovered over 1100 meters of core from an impactite-filled trough between the peak ring of the basin and the modification zone of collapsed target rocks that expanded the crater to its final diameter. That project provided the first continuous core through an impactite sequence in the crater and provided samples of underlying target sedimentary rocks that had collapsed inward. It also provided a spectacular spatial and temporal measure of a post-impact hydrothermal system.

Beginning in April of this year, a second effort to probe the crater — this time into the peak ring — will be launched by the International Ocean Discovery Program (IODP) in collaboration with ICDP.

Expedition 364 Chicxulub Impact Crater project (Fig. 3) is a Mission Specific Platform Expedition, meaning it is being drilled from a platform specially selected for the project, rather than IODP's Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) Resolution or Chikyu scientific drilling ships. The selected drilling site is in an area with ecologically sensitive reefs and a shallow water depth of 17 to 18 meters, which calls for specialized equipment.

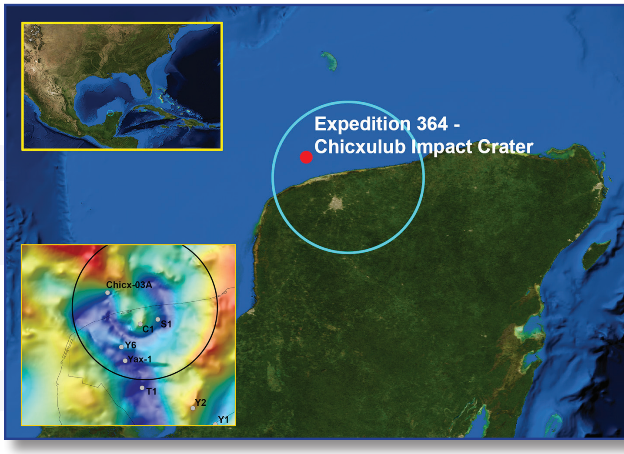

Fig. 3. A joint IODP-ICDP borehole will be drilled ~30 kilometers northwest of Progreso and the north shore of the Yucatán Peninsula of Mexico. That borehole, labeled Chicx-03A on a gravity map (inset), will target the peak ring in that quadrant of the crater. Credit: David A. Kring/LPI.

Sixty days are planned for drilling, coring, and downhole measurements in April and May. The drilling goal is to reach a depth of 1200 to 1500 meters and recover ~500 meters, possibly more, of peak ring rocks. Core logging by the science party is scheduled for September and October.

The scientific goals of the project include an assessment of peak-ring lithologies and how they may have been deformed and thus flowed during the cratering event. This information is critical in order to effectively test models of peak ring formation (Fig. 4). Those models are guided in part by observations of similar structures, such as the exquisitely exposed Schrödinger basin on the Moon (Fig. 5), but need to be evaluated with core samples from Chicxulub and, ideally, field geology on the lunar surface at some point in the near future.

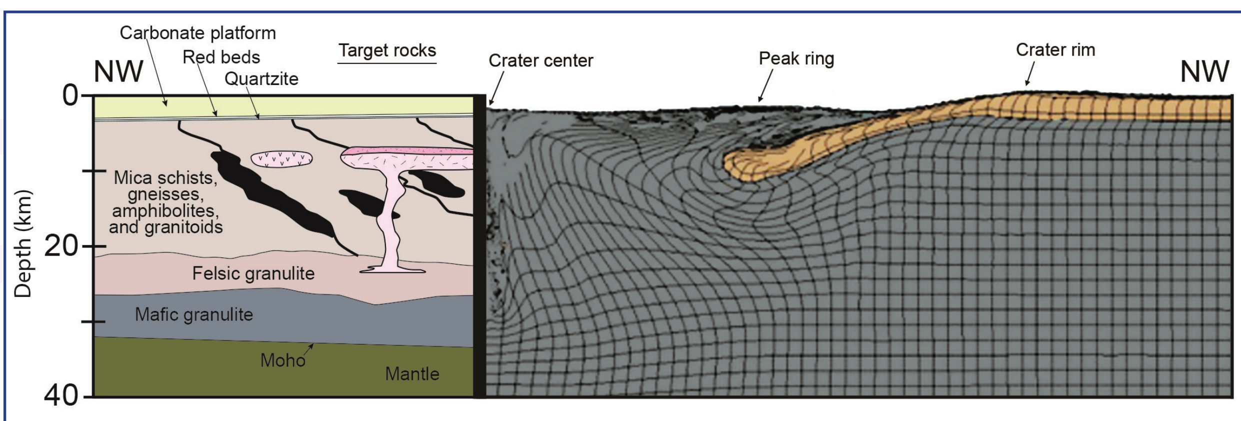

Fig. 4. A key objective of Expedition 364 is to test models of peak ring formation. On the left is a schematic diagram of the target [adapted from Kring (2005), Chemie der Erde, 65, 1–46] and on the right is a hydrocode simulation [Collins et al. (2008), Earth and Planetary Science Letters, 270, 221–230] where an uplifted central peak collapsed outward to form the peak ring. In an alternative model, the peak ring is uplifted directly from the walls of the transient crater cavity. Although horizontal lines appear on the right to track rock flow in the simulation, it is important to understand that the upper part of the crystalline basement in the target is not stratified, but rather composed of a tectonized assemblage of metamorphic rocks intruded by granitic magmas as shown on the left.

Fig. 5. The most dramatic impact event during the past half-billion years is the Chicxulub impact (inset, bottom center), which extinguished dinosaurs (inset, lower left) and most life on Earth at the K/T boundary 66 million years ago. The ~180-kilometer-diameter Chicxulub crater (left background) is the best-preserved example of a peak-ring basin on Earth, but it is buried beneath Tertiary sediments. To help understand the formation of that type of impact basin, geologists also study analog structures, such as the magnificently exposed Schrödinger basin on the lunar farside (right background) that formed ~3.8 billion years ago (inset, lower right). Credit: Background art, left, by William K. Hartmann (©1991), used with permission. Background illustration, right, produced by NASA GSFC's Scientific Visualization Studio. Insets (left to right) produced by LPI, William K. Hartmann (©1983), and Daniel D. Durda (©2011). This educational illustration is being released as part of the LPI's Never Stop Exploring series.

The drilling project will also measure the hydrothermal alteration in the peak ring and physical properties, such as permeability, needed to (1) further test models of impact-generated hydrothermal systems, (2) evaluate the habitability of the peak ring, and (3) investigate the recovery of life in a sterile zone. The nature and composition of any impact breccias and melt rocks, including any dikes in the peak ring, will be analyzed. An assessment of target lithologies will also be made to fine-tune estimates of the impact's climatic effects.

Finally, studies of the core and correlative downhole measurements will provide a calibration point for crater-wide geophysical imaging of the subsurface, greatly enhancing future three-dimensional application of those geophysical techniques to the entire impact basin. To fully understand the Chicxulub crater, however, it has been estimated that a total of six to eight boreholes will be needed to fully extract the geological details preserved in this fascinating structure. Thus, while the research done on this geologic structure over the past 25 years has yielded countless insightful results, it is clear that many secrets remain buried beneath the sediments of the Yucatán Peninsula, waiting to be revealed by the next generation of researchers.

Acknowledgements.

Hundreds of scientists have contributed to our understanding of Chicxulub and the K/T boundary events described above. Their work is gratefully acknowledged. For students wanting to access that literature and other information, the following publications are recommended:

- For marine K/T boundary sequences: J. Smit (1999) A*nnual Reviews of Earth and Planetary Science,* 27, 75–113.
- For crater lithologies: D. A. Kring (2005) *Chemie der Erde*, 65, 1–46.
- For links between Chicxulub and K/T boundary sediments: D. A. Kring (2007) *Palaeogeography, Palaeoclimatolology, and Palaeoecology*, 255, 4–21; P. Schulte et al. (2010) *Science*, 327, 1214–1218.
- For structural models integrating geophysical measurements and hydrocode simulations: J. V. Morgan et al. (2011) *Journal of Geophysical Research*, 116, B06303, 14 pp.
- For a popular science article: D. A. Kring and D. D. Durda (2003) The day the world burned, *Scientific American*, 289(6), 98–105.

LPI has posted additional online resources at *http://www.lpi.usra.edu/science/kring/epo_web/impact_cratering/Chicxulub*.

About the Author:

Dr. David Kring is a senior staff scientist at the Lunar and Planetary Institute in Houston, Texas. He has worked extensively with the Chicxulub impact crater and the Cretaceous-Tertiary mass extinction event. He has also studied, more broadly, the geologic processes associated with impact cratering and their environmental and biological consequences throughout Earth history, including an inner solar system bombardment that occurred more than 3.5 billion years ago. He is currently the Principal Investigator of the LPI-JSC Center for Lunar Science and Exploration, through which he is integrating his field experience in impact-cratered and volcanic terrains with his analytical experience of Apollo, Luna, and meteorite sample collections to assist training and mission simulations needed to advance the nation's human and robotic exploration programs.

About the Cover:

The locations of boreholes drilled into the Chicxulub crater are superimposed on a gravity map of the crater. Yucatán-6 (Y6) is the discovery hole in which shocked quartz, shocked feldspar, and impact melt were found. Two other petroleum exploration boreholes are Chicxulub-1 (C1) and Sacapuc-1 (S1). The first scientific borehole with continuous core was Yaxcopoil-1 (Yax-1). The inset is a backscattered-electron (BSE) image of relict quartz in the discovery borehole, surrounded by a corona of augite and feldspar, in the impact melt, which was subsequently cross-cut with a hydrothermal quartz vein. Credit: Gravity map by David A. Kring and Lukas Zurcher; BSE image by David A. Kring.

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