THE CHICXULUB IMPACT CRATER: Producing a Cradle of Life in the Midst of a Global Calamity

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THE CHICXULUB IMPACT CRATER: Producing a Cradle of Life in the Midst of a Global Calamity

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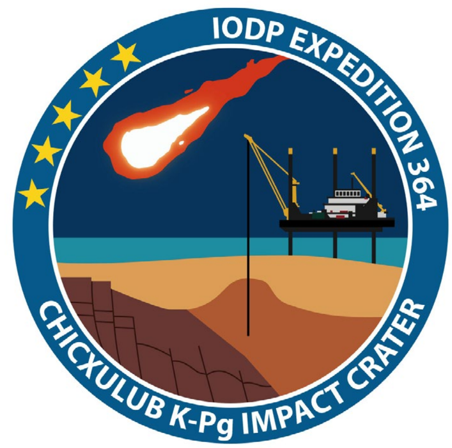


Expedition 364 mission patch

Introduction

Strategically located scientific drilling can be used to tap the Earth for evidence of evolutionary upheavals that transformed the planet. A good example is the Yucatán-6 borehole in Mexico that recovered rock samples from 1.2 and 1.3 kilometers beneath Earth's surface. I used those samples 30 years ago to show that a buried, geophysically anomalous structure on the Yucatán Peninsula contained a polymict breccia with shock metamorphism and an impact melt rock, indicating the buried structure was an immense impact crater that was excavated 66 million years ago. That structure, which we called Chicxulub, was produced by a ~100-million-megaton blast responsible for a global environmental calamity and mass extinction that defines the Cretaceous-Tertiary (K-T) boundary in Earth's evolution (see LPIB, March 2016, for additional details of that discovery). The impact provoked a biological crisis that extinguished indicator species throughout the world, including winged pterosaurs in the air, non-avian dinosaurs on land, and apex predator mosasaurs in the seas, along with 75% of the total breadth of species that existed on Earth at that time. Life was decimated.

Science has returned twice to probe the depths of Chicxulub, most recently in 2016 when the International Ocean Discovery Program (IODP) and International Continental Scientific Drilling Program (ICDP) initiated a new campaign with the call sign Expedition 364. Drilling from a marine platform a few meters above the sea surface, the new borehole reached a depth of 1335 meters beneath the sea floor (mbsf). The borehole penetrated seafloor sediments that bury the crater, finally reaching impactites at a depth of 617 mbsf. Continuous core was recovered from 506 mbsf, within Eocene sediments deposited 48 million years ago, to the bottom of the borehole within the crater's 66-million-year-old peak ring. The core is a scientific marvel, exceeding the expedition's highest hopes of success. Here, I briefly summarize the science party's analyses of that core and the insights they are gleaning about peak ring formation and the biological communities that reoccupied the site after most life on Earth had been extinguished.

Formation of the Crater's Peak Ring

Granite. Lots of spectacular-looking granite. That was a common observation when meter after meter of core was pulled from the sea, bringing to light one of the expedition's key questions: Why was granite so near Earth's surface in an area that had been a stable sediment catchment for over 100 million years? Clues began to emerge when the core was analyzed. Logging revealed chemical and petrological variations on the granitic theme, plus felsite and dolerite intrusions, in a granitoid rock sequence that represented continental crust that had been assembled through a series of tectonic events over more than a billion years. However, that crust in the core was crosscut by seams of impact melt rock and suevite. Moreover, quartz and other minerals in the granitoid rocks were deformed, corresponding to shock pressures of 16 to 18 gigapascals, indicating the tectonic construction of the crust had been superseded by an impact event.

Those observations indicated the granitoid rocks were uplifted from the geologic basement of the Yucatán, far beneath a carbonate platform sequence of sedimentary strata that covers the peninsula. Numerical simulations of the impact integrated with borehole observations suggest the crystalline rock was uplifted from a depth of 8 to 10 kilometers. During the crater-forming process, the uplifted rock formed a transient central peak that collapsed outward to form a peak ring, overturning the granitoid rocks. A dramatic cycle of compression, dilation, rotation, and shear all occurred within minutes as the crust of

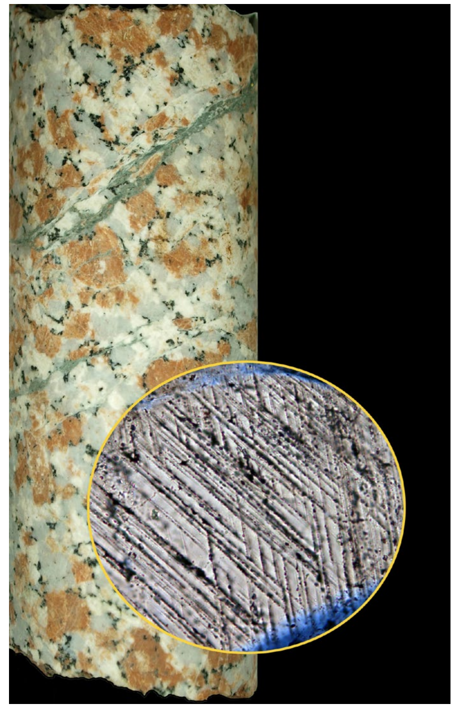
Earth flowed at speeds in excess of 100 kilometers per hour, producing zones of microcommunited rock (cataclasites), shear faults, and deformation bands that cross-cut shock metamorphic fabrics. Shearing is particularly intense in the basal 100 meters of the core, produced when overlying granitoid rocks were thrust over impact melt that had already covered underlying basement rocks. The resulting impact crater looked very much like the Schrödinger basin on the Moon, before being hidden from view beneath Tertiary sediments. Asymmetries in Chicxulub's peak ring and underlying mantle uplift were noted, however, and explored in numerical simulations of the crater-forming event. Those results suggest the impactor had a trajectory from the northeast to the southwest. The transient central uplift, potentially rising more than 10 kilometers into the atmosphere, was momentarily higher than Mt. Everest and would have been visible halfway across the Gulf of Mexico if not obscured by >25 trillion metric tons of ejecta lofted into the atmosphere.

Deposition of Impactites

Some of that ejecta fell back onto the granitoid peak ring, producing 130 meters of melt-bearing polymict breccia (suevite) and impact melt rock. The basal melt rock is a small portion of the 10^4 to 10^5 cubic kilometers of molten rock generated by wholesale melting of Earth's crust by the impact. Overlying breccia clast sizes grow smaller toward the top of the suevite, but do not form a single (normally graded) unit going from large to small clast sizes. Rather, there is at least one erosional contact in the lower portion of the breccias and several size-graded intervals toward the top of the sequence, indicating reworking by marine currents, including impact-generated seiches produced when tsunamis and other waves washed to and fro across the ocean basin.

Impact melt and suevite sampled in the borehole cover more than 100,000 square kilometers of the Gulf seafloor. The seismic properties of the suevite are being traced across the Chicxulub basin where the breccia blankets an ~3-kilometer-thick central melt sheet. Ejected debris was also launched beyond the crater rim, where some of it flew through the atmosphere faster than the speed of sound, producing sonic booms like billions of simultaneously falling meteorites. That curtain of debris hit the sea surface with such high speeds it caused the sea to boil with cavitation. The debris displaced seawater, too, while cascading to the seafloor and pummeling marine organisms caught in its path. The speed of that debris hitting Earth's surface grew larger with distance from the crater and increasingly ploughed into the surface it landed upon. Because the Chicxulub impact occurred at sea (albeit above continental crust rather than oceanic crust), the ballistic sedimentation process often mixed ejecta with water. In those cases, fluid target materials escaped the final deposit, leaving behind a blanket of wholly ejected rock and solidified impact melt. At greater distances, beyond the unit traditionally mapped as proximally emplaced continuous ejecta, impact melt spherules cascaded through the atmosphere and seas throughout the region, forming blankets of glass that are still preserved in Beloc (Haiti), Arroyo el Mimbral (Mexico), and Gorgonilla Island (Colombia).

The impact also generated a vapor-rich ejecta plume that expanded from the point of impact, accelerating through the atmosphere as it raced toward space. Superheated to temperatures on the order of 10,000°, that plume and other ejecta ignited vegetation on distant shores. Backwash from impact-generated tsunamis and/or strong atmospheric circulation carried charcoal from those fires back to the crater, where it is found buried in the core on top of the peak ring. That high-energy ejecta plume also carried vaporized components of the impacting object. When it and other debris reaccreted to Earth, they heated the atmosphere and generated a firestorm over a broader area. Scorched woodland fragments from those fires were incorporated into peak-ring sediments, too, with iridium rainout over a longer period of time, producing a second peak in charcoal abundance.

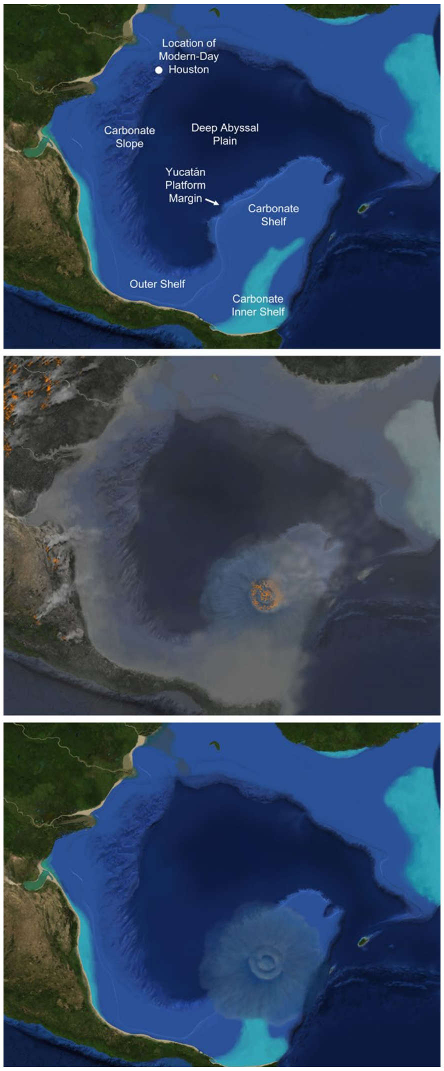


An 83-millimeter-diameter granitic core from the Chicxulub peak ring that is crosscut with cataclastic and hydrothermal veins, and which also has been shock-metamorphosed, as illustrated with planar deformation features with ~5-micrometer spacing in quartz (inset, with field of view 245 micrometers wide). Photomicrograph of quartz by expedition scientist Ludovic Ferrière. Previously published by D. A. Kring, Ph. Claeys, S. P. S. Gulick, J. V. Morgan, G. S. Collins, and the IODP-ICDP Expedition 364 Science Party (2017) Chicxulub and the exploration of large peak-ring impact craters through scientific drilling. GSA Today, 27, DOI: 10.1130/GSATG352A.1.

Decimating the Marine Environment

The concept of "ground zero" literally exploded into our lexicon with the 21-kiloton Trinity blast in the Jornada del Muerto desert valley of New Mexico in 1945. The devastating effects of high-energy explosions were immediately obvious and began coloring descriptions of impacting asteroids like the collision that produced Barringer Meteorite Crater (aka Meteor Crater) in Arizona. The Chicxulub impact blast was nearly five billion times more energetic than the Trinity test and seven million times more energetic than the Meteor Crater event. The Chicxulub blast occurred in a thriving marine ecosystem that was, with a flash of light, vaporized.

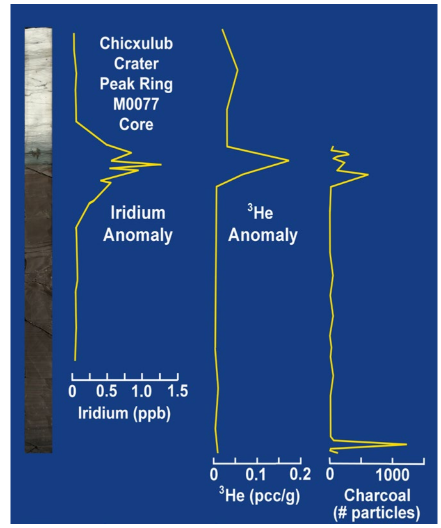
In the mid-1990s, I used the results of



Top panel: Pre-impact paleogeography of the Gulf of Mexico region. Middle panel: The Chicxulub impact crater superimposed on that late Cretaceous paleogeography. The impactor hit the sea, penetrating carbonate shelf sediments, underlying carbonate platform strata that included sulfate-rich anhydrite beds, and crystalline basement rocks. Impact melt fills the crater. The surrounding landmass was affected by an air blast and fire. Coastal seas were turbid with debris. Bottom panel: Post-impact view of the crater. In this view, early Tertiary vegetation covers the land, but the crater has not yet been buried by seafloor sediments. Credit: Pre-impact paleogeographic reconstruction provided by John Snedden, University of Texas-Austin. Other illustration details by the author. Credit: Art by Victor O. Leshyk for the LPI.

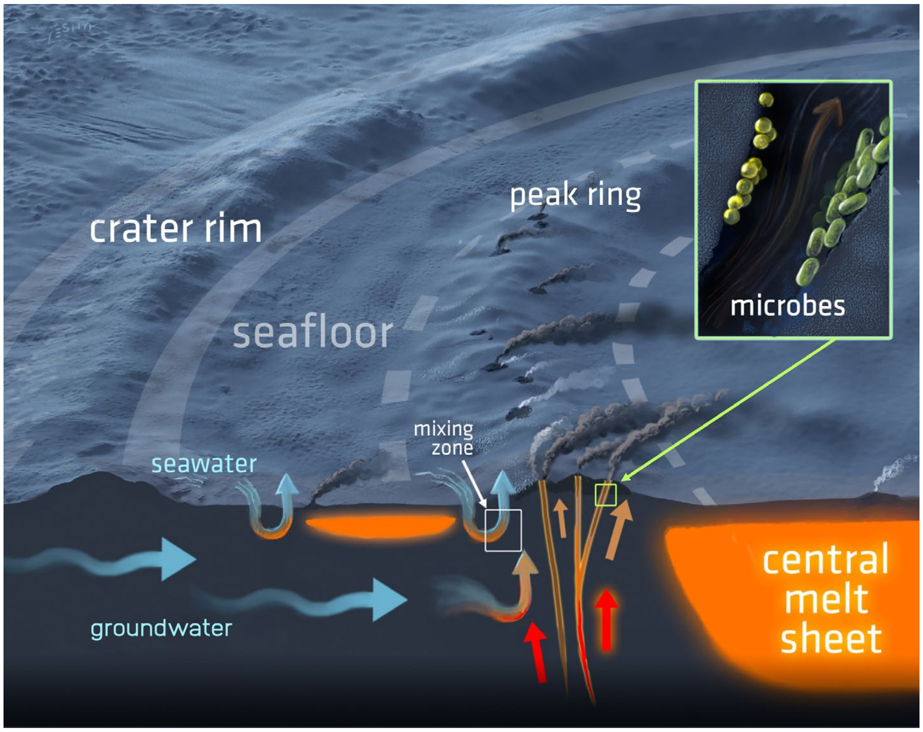
nuclear explosion tests to calculate shock pressure and air blast effects on fauna and flora that inhabited the land around Meteor Crater. Those same principles can be used to evaluate the blast effects in marine ecosystems that extended for hundreds of kilometers around the Chicxulub impact site. Near the coast, shock pressure radiating through the water may have been several thousand pounds per square inch (or a few to tens of megapascals) and likely lethal out to distances of about 2000 kilometers in the open sea. Underwater shock waves were also reflected, producing an amplifying (compression) wave from the seafloor and negative (rarefaction) wave from the sea-air interface. Both types of reflected waves modified peak pressure values and the shape of the pressure pulse that passed through seawater. Moreover, the shock wave that passed through the crust of Earth generated an additional wave at the seafloor interface. Collectively, those effects and the collapse of transient crater walls to produce the final crater rim generated a series of propagating disturbances. Shock waves reflected by the seafloor moved slower than the primary shock wave, approaching acoustic speeds of 1500 meters per second, reaching shore shortly before the Chicxulub crater was fully formed ~10 minutes after the impactor first made contact with the sea surface.

The pathology of internal damage produced by the blast in marine organisms is gruesome, so I limit a description of those effects to the most general terms. The pressure pulse generated extensive hemorrhaging and bone fractures in vertebrates, including mosasaurs and a variety of bony and cartilaginous fish. The outcome was worse for Cretaceous species with closed air bladders (like modern cod and rockfish) than those with air bladders that open to the mouth (like modern salmon) or those with no air bladders (like modern halibut and sole). Over a larger area, the pressure pulse and acoustic energy likely deafened mosasaurs (with ears similar to those of modern sea turtles), plesiosaurs (with ears similar to those of modern sea turtles or whales, depending on the species), and other animals with inner and middle ear structures. Because marine animals use hearing to navigate, avoid predators, and forage, the loss of hearing was crippling if not deadly (as it is in modern humpback whales with blast-damaged ears). Impact-generated tsunamis carried sea life onto shore, stranding fish, ammonites, and other organisms where they suffocated. A species of lagoonal crab that existed along the gulf coast would seemingly have been better fitted for survival from that marine assault, but it disappeared completely at the K-T boundary. Seafloor rudist and coral reefs, oysters, gastropods, and giant inoceramid clams were buried by rockfalls and landslides triggered by the impact's seismic impulses (equivalent to a magnitude 10 earthquake initially, followed by a series of lower-energy tectonic events) if not buried by impact ejecta and secondary debris carried by the backwash of impact-generated tsunamis. The sea surface was filled with faunal and floral flotsam from tsunami backwash that drained ravaged coastal mangroves and from marine animal kills. That post-impact scene was cloaked in darkness by a debris-filled sky, but the smell of smoke and stench of putrefying carcasses and vegetation filled the air. Although we scientists normally and necessarily write in colorless tones of objectivity, we also have to acknowledge the horror of the impact's aftermath.



Core section immediately above impact suevite, with an iridium anomaly produced when condensed components of the impactor settled through the atmosphere and blanketed Earth's surface. A helium-3 anomaly reflects changes in post-impact sedimentation rates. Also shown are charcoal anomalies, the first likely due to scorched vegetation along the coast, carried out to sea by tsunami backwash, while the second may be due to atmospheric rainout of debris lofted and scattered by a firestorm over a larger region. The core section is ~1 meter tall and 83 millimeters wide.

Those acute regional effects were significantly compounded by global environmental perturbations (e.g., atmospheric heating by reaccreting ejecta, cooling by atmospheric dust blocking sunlight, and then heating again by greenhouse warming gases; particulates in the atmosphere that shut down



A three-dimensional cross-section of the hydrothermal system in the Chicxulub impact crater and its seafloor vents. Credit: Art by Victor O. Leshyk for the LPI.

photosynthesis; acid rain) that drove many species to extinction. Low-frequency components of the impact's acoustic energy radiated through the sea to the farside of the world, where those anomalous vibrations may have forewarned life there of its impending doom.

Recovery of Life Within a Crater-Filling Sea

One might wonder how and when life returned to ground zero. The post-impact sediment portion of the core obtained by the new drilling effort reveals a fairly rapid recovery by the few species that survived the global mass extinction event. In the sea above the crater's peak ring, a cyanobacterial bloom may have occurred within months of the impact. A high-productivity ecosystem with diverse benthic and planktonic foraminifera (single-celled organisms with calcified shells) developed within 30,000 years, although nannoplankton were slower to recover. Over 60 species of foraminifera lived near the seafloor above the crater where sources of organic material had recovered for feeding. A food chain that included larger, higher trophic-level organisms is suggested by phosphatic fossils of fish and crustaceans deposited within that same interval and potentially as rapidly as a few years. Trace fossils indicate the seafloor substrate was colonized by burrowing survivors within a few years of impact and that a multi-tiered macrobenthic community existed within 700,000 years. Those data indicate the crater was a more favorable site for biologic recovery than other marine settings around the world. Interestingly, an impact-generated hydrothermal system (described in more detail below) may have had an important role in that recovery by providing nutrients and warm water to the seafloor environment. In addition to that post-impact recovery story, the new rock core is providing a measure of Eocene environmental changes, including those that occurred during the Paleocene-Eocene Thermal Maximum (PETM) about 56 million years ago when global temperatures rose dramatically. Expedition samples are producing a rich tapestry of life's evolution in an area where the biological slate was nearly wiped clean.

Submarine and Subterranean Biome

Two key objectives of Expedition 364 were to test models of impact-generated hydrothermal activity and determine the habitability of that hydrothermal system. I found the first hints of that hydrothermal system while studying the samples used to prove Chicxulub's impact origin in 1991. Hydrothermal overprinting of shock metamorphic features was pervasive. Hydrothermal alteration was also detected in core recovered by the International Continental Scientific Drilling Program at Yaxcopoil in 2001–2002, providing a foundation for a petrogenetic model that traced the cooling of the hydrothermal system, and a thermal evolution model that explored the subsurface extent and duration of the hydrothermal system.

The Expedition 364 team found evidence of subsurface streams of water that were heated and driven upwards toward the boundary between the crater floor and the bottom of the Yucatán sea, confirming the pre-expedition thermal evolution model. Groundwater flowing through the crust toward the peak ring may have been supplemented by smaller amounts of seawater drawn down into the system. The groundwater was saline, because it was derived from basinal brines similar to those along the gulf coast today. The salinity of water may have been further enhanced by subsurface boiling, particularly in the vicinity of the central melt sheet and a smaller volume of melt in the trough between the peak ring and crater rim.

Heated water streaming around the edges of the central melt sheet percolated through fractured rock in the peak ring and rose to the seafloor where it vented into the sea. The rock core recovered from that peak ring is cross-cut by fossil hydrothermal conduits that are lined with multi-colored minerals, some, appropriately enough, a fiery red-orange color. Nearly two dozen minerals precipitated from the fluids as they coursed through the porous and permeable rocks of the peak ring, replacing the rock's original minerals. Based on those observations, it is easy to imagine black and white "smoking" submarine vents throughout the uplifted range of seafloor mountains that form the ~90-kilometer-diameter peak ring around the crater center. The hydrothermal system was spatially extensive, chemically and mineralogically modifying ~1.4 × 10^5 km^3 of Earth's crust, a volume more than nine times that of the Yellowstone Caldera system.

Minerals identified in the new rock core indicate the hydrothermal system was initially very hot with temperatures of 300° to 400°C. Such high initial temperatures when plugged into a thermal evolution model suggest the hydrothermal system persisted for about 2 million years, which is supported by two additional observations in the core.

Magnetic minerals that precipitated in the hydrothermal system recorded changes in Earth's magnetic field, including a change from reverse polarity when the crater formed to a period of normal polarity at some later time. That paleomagnetic clock indicates hydrothermal activity remained at temperatures in excess of the magnetic recording temperature of 100° to 250°C temperature for at least 150,000 years, when the next magnetically normal period occurred, implying it took at least 1.5 million years for the system to cool completely to ~50°C.

Moreover, submarine venting of hydrothermal fluids on the seafloor deposited manganese in post-impact sediments. A biostratigraphically calibrated chronology of those core sediments indicates venting persisted for about 2.1 million years. As the hydrothermal system aged, peak hydrothermal activity migrated toward the center of the crater, where hydrothermal activity may have persisted for a longer period of time over the central melt sheet.

Close inspection of the core revealed another startling find: The submarine and subterranean hydrothermal system harbored life. From 15,000 kilograms of rock recovered from the borehole, tiny spheres of the mineral pyrite, only 10 millionths of a meter in diameter, were discovered nestled within lower-temperature hydrothermal mineral assemblages in the porous, permeable impact breccias that cover the peak ring. Isotopes of sulfur indicate the spheres of pyrite, called framboids, were formed by a microbial ecosystem adapted to the hot mineral-laden fluid of a hydrothermal system that coursed through the shattered rocks of the Chicxulub peak ring. Cavities within the overlying suevite had been transformed into microbial nurseries after the impact event.

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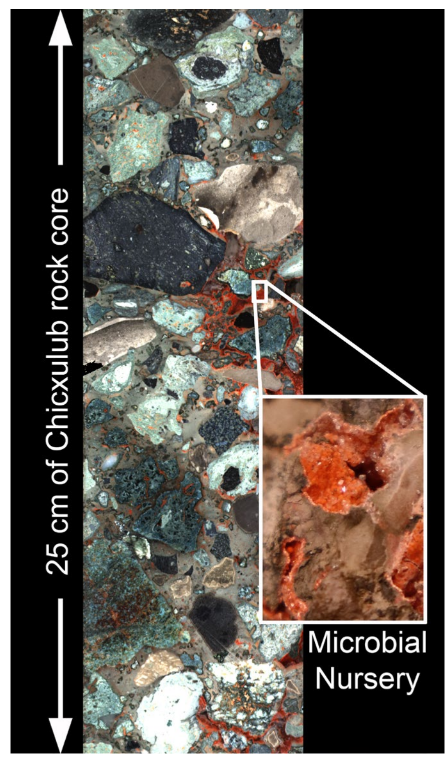
Life in the system extracted energy — or fed from — chemical reactions that occurred in the fluid-filled rock system. Microbes took advantage of sulfate in the fluid and its conversion to sulfide, preserved as pyrite, to provide the energy needed to thrive. The sulfate-reducing, hot-water (thermophilic) organisms were like some of the bacteria and archaea found at Yellowstone and other hydrothermal systems today. Similar sulfur isotope signatures in overlying sediments imply sulfate-reducing organisms persisted for at least 2.5 million years after impact, potentially in both the subsurface and in the water column above the crater floor. Those microbial communities may be the source of nutrients needed for larger organisms described above that populated the crater soon after impact.

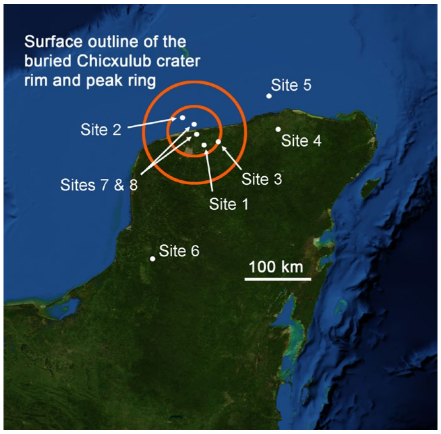
A search for other types of thermophilic organisms and metabolic pathways in the hydrothermal system is underway.

Implications for the Hadean Earth and Mars

Because the Chicxulub impact crater is our best proxy for impact basins that covered Hadean and early Archean Earth more than 3.8 billion years ago, Expedition 364 findings have important implications for origin of life models. Thousands of impact craters the size of Chicxulub and larger covered Earth's surface during that early epoch of planetary evolution. Some of the largest impact events vaporized surface waters, turning potential subaerial and marine ecosystems into uninhabitable wastelands. Studies of Chicxulub demonstrate, however, that those same impact events



Section of the Chicxulub core with the hydrothermal minerals dachiardite (bright orange), analcime (colorless and transparent), and pyrite framboids (not visible because of their small sizes). The minerals partially fill cavities in the rock that were niches for microbial ecosystems. This is a composite illustration of core section 0077-63R-2 and a closeup image of a portion of that core recovered from 685 meters below the sea floor.



Potential future scientific drilling sites designed to explore other attributes of the Chicxulub impact crater and its influence on the evolution of life on Earth. Site locations are for illustration purposes only and do not account for current land use, cultural issues, and local geologic limitations. Credit: Background image produced from NASA MODIS satellite observations in October 2004.

produced impact craters with porous, permeable subsurface environments; that such impact craters host vast subsurface hydrothermal systems; and that those systems can, in turn, host microbial ecosystems. In the Chicxulub proxy for such ecosystems, microbial sulfate reduction occurred, which is a metabolic pathway used as long ago as 3.52 billion years ago in the Paleoarchean. Sulfate may not have been available in the Hadean, but other metabolic reactions would have been available to provide the energy yields required by life. Thus, the results of Expedition 364 support the impact origin of life hypothesis and promotes the idea that life on Earth (and potentially elsewhere in the solar system, such as Mars) emerged from an impact crater.

Future Prospects

Expedition 364 core illustrates how perfectly geologic, geochemical, geobiological, and geophysical evidence is preserved in the buried Chicxulub impact crater and suggests the immense and complex structure can be used to study a broad range of geologic and biologic processes. For several years, the community has discussed the need for a borehole into the central melt sheet to assess chemical and mineralogical differentiation of that melt and its implications for early planetary crustal growth, thermal erosion and metamorphism of the underlying crater floor, the nature of a hydrothermal system within a melt sheet and underlying crater floor, and the return of life to a central crater basin. Such a borehole could be drilled along the margins of the central melt sheet on land (e.g., as in site 1 in the diagram of potential future drilling sites) or at sea (site 2).

The astrobiological implications of impact-generated hydrothermal systems in planetary crusts throughout the solar system prompted a borehole (site 3) in the peak ring on the farside of the Chicxulub crater from the Expedition 364 site. That core would make it possible to assess spatial variations in peak-ring hydrothermal activity. That location would also target a different portion of uplifted basement target rocks, which could reveal lithological effects on peak-ring formation and post-impact fluid flow, while also providing additional material to piece together the tectonic evolution of the Yucatán Peninsula.

A borehole that penetrates the ejecta blanket that covers the carbonate platform shelf could be used to evaluate the volume and composition of ejecta toward the suspected up-range side of the crater and the recovery of life on the carbonate shelf adjacent to the impact site. One wonders what the sea did with the chemical and biological potential of fresh rock surfaces generated by the ejecta blanket. Such a borehole could be drilled on land (site 4) or at sea (site 5).

To evaluate how water depth affected ejecta deposition and the recovery of life, it would be useful to have a borehole that penetrates the ejecta blanket and the inner carbonate platform toward the suspected downrange side of the crater, where there was a relatively shallow seaway between the crater and the coast. That borehole would have to be on land (e.g., site 6). Excavated lithologies in this borehole may differ from those in other boreholes and could be used to better reconstruct the complex target rock assemblage, including the amounts of limestone and anhydrite as sources of CO_2 and SO_x, respectively, that may have greatly influenced impact-generated modification of the world's climate.

Finally, a deep borehole that penetrates the thickest part of the melt sheet in the crater center would allow science teams to evaluate its thermal evolution, differentiation, and would provide insights about basin-size impact melt sheets that would complement observations at the Sudbury basin in Canada, which was similar in size to Chicxulub before being eroded. Importantly, the borehole would provide a measure of hydrothermal activity, seafloor venting, and how they affected biologic systems above a melt sheet. To penetrate the melt sheet will require a borehole at least 4 kilometers deep, which would make it among the deepest scientific boreholes drilled on Earth. The drilling location could be on land or at sea (sites 7 and 8).

Each of these borehole locations has the potential to be as scientifically productive as the Expedition 364 drilling site. Collectively, that suite of borehole locations would provide the first comprehensive assessment ever made of a large, well-preserved impact basin and would guide our assessment of such structures on planets throughout our solar system and among extrasolar planetary systems.

Conclusions

The Chicxulub impact crater is one of the most extraordinary scientific sites in the world: It is the smoking gun of the impact mass extinction hypothesis and at the center of an evolutionary radiation 66 million years ago that led to the origin of our own species, *Homo sapiens*; it is the world's best preserved peak-ring or multi-ring impact basin on Earth and, thus, a model for such

"The Chicxulub impact crater is one of the most extraordinary scientific sites in the world."

structures throughout the solar system; and the Chicxulub crater illustrates how such impact events can chemically and thermally modify large volumes of planetary crust and produce unique subterranean habitats for microbial ecosystems that may be a proxy for the earliest of life on our planet and potentially elsewhere where impact events modify hydrous planetary crust.

Acknowledgments. This report is a celebration of the 30th anniversary of the discovery of the Chicxulub crater. It is also designed to summarize recent studies of the crater that the lunar and planetary science community may find interesting. Those new results were produced by members of the IODP-ICDP Expedition 364 Science Party and their collaborators, all of whom are gratefully acknowledged: I. Arenillas, N. Artemieva, J. A. Arz, T. Bauersachs, P. A. Bland, M. E. Böttcher, T. J. Bralower, L. Brun, D. Burney, J. Carte, A. J. Cavosie, B. Célérier, S. A. Chen, E. Chenot, S. Chernonozhkin, G. Christeson, R. Christoffersen, P. Claeys, C. S. Cockell, G. S. Collins, M. J. L. Coolen, J. Cosmidis, M. A. Cox, X. Cui, T. M. Davison, S. J. deGraaff, T. Déhais, C. Delahunty, T. Demchuk, F. Demory, N. J. deWinter, M. Ebert, M. Elfman, T. M. Erickson, M. S. Fantle, K. Farley, J.-G. Feignon, L. Ferrière, K. H. Freeman, J. Garbar, J. Gattacceca, C. Gebhardt, S. Goderis, M. Gonzalez, K. Goto, S. L. Green, K. Grice, R. A. F. Grieve, S. P. S. Gulick, E. Hajek, B. Hall, P. J. Heaney, G. Henry, P. J. A. Hill, A. Ishikawa, D. M. Jarzen, H. L. Jones, S. Jung, P. Kaskes, C. Koeberl, D. A. Kring, P. Kristiansson, T. J. Lapen, E. LeBer, H. Leroux, L. Leung, J. Lofi, X. Long, F. J. Longstaffe, C. M. Lowery, S. L. Lyons, N. McCall, C. Mellett, H. J. Melosh, J. V. Morgan, C. R. Neal, C. Nixon, N. B. Nuñez Otaño, R. Ocampo-Torres, J. M. K. O'Keefe, K. O'Malley, J. Ormö, G. R. Osinski, J. D. Owens, J. Paris, B. H. Passey, N. Patel, M. A. Pearce, L. Pérez-Cruz, Ph. A. Pezard, A. E. Pickersgill, M. H. Poelchau, M. S. P. Pölchau, A. S. P. Rae, C. Rasmussen, M. Rebolledo-Vieyra, U. Riller, F. J. Rodríguez-Tovar, C. H. Ross, T. Salge, H. Sato, B. Schaefer, M. Schmieder, D. R. Schmitt, B. Schmitz, F. M. Schulte, T. Schulz, L. Schwark, B. J. Shaulis, E. Sibert, S. L. Simpson, M. Sinnesael, J. Smit, D. Smith, D. F. Stockli, R. E. Summons, S. M. Tikoo, N. E. Timms, N. Tomioka, F. J. Tovar, G. Turner-Walker, J. Urrutia-Fucugauchi, V. Vajda, F. Vanhaecke, S. J. M. Van Malderen, J. Vellekoop, C. M. Verhagen, S. Warny, M. T. Whalen, J. Wheeler, M. J. Whitehouse, A. Wittmann, L. Xiao, K. E. Yamaguchi, J. C. Zachos, J. Zhao, and W. Zylberman. I thank Martin Schmieder, Dan Durda, Julie Tygielski, Linda Chappell, Delia Enriquez, Renée Dotson, and Paul Schenk for their assistance during production.

LPI Online Resources

Chicxulub Impact Event website with educational materials (https://www.lpi.usra.edu/science/kring/Chicxulub/)
Video simulations of impact events, including a Chicxulub-sized impact event (https://www.lpi.usra.edu/exploration/training/resources/impact_cratering/)

Suggested Readings of Expedition Results

2016

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