EARTH'S SURFACE

Shock Therapy: How Earth Responds to Impacts From Outer Space

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Long after the dust has settled, scientists studying impact craters on Earth's surface are making some "shocking" discoveries.

by Randall T. Cygan, Geochemistry Department, Sandia National Laboratories, Albuquerque, N. M.

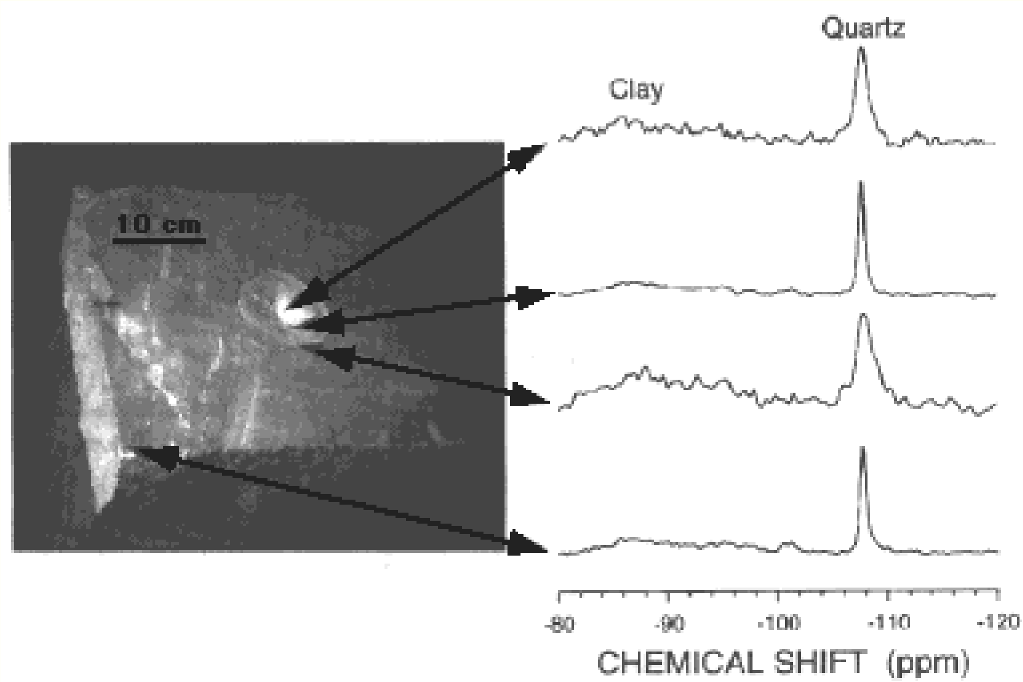
Imagine witnessing the impact of a 10 kilometer-sized comet or asteroid onto a broad expanse of sea just off the Yucatan peninsula of Mexico. The bolide, a brilliant fireball traveling at speeds of 15 to 20 kilometers per second, would melt about 20,000 cubic kilometers of rock and excavate a crater with a diameter of over 200 kilometers within a few seconds, all due to the release of energy equivalent to 100 mega-megatons of TNT. Now imagine, at a scale one trillion times smaller, a perfectly ordered crystalline quartz **lattice** and the sudden compression felt by the constituent atoms within microseconds. Sixty-five million years later, the dislocated layers of Earth, which are riddled with electronic defects, evidence of shock, **amorphization**, and a myriad of other features characteristic of shock metamorphism, are providing scientists with critical clues for unraveling the mysteries of the now famous Chicxulub impact structure.

Impact craters were not recognized as part of Earth's landscape until the early 1900s. Regardless of its immense size, the Chicxulub crater was not unequivocally identified as the result of an impact until just 5 years ago. Today, only 150 or so terrestrial impact structures have been identified; this amount probably underestimates the true number. They are difficult to find because many were buried or eroded, and researchers aren't sure of where to search. The increasing awareness and recognition of impact events such as Chicxulub, and their impact (pun intended) on the geological record of terrestrial and planetary processes, are leading to significant scientific findings. Last August scientists met to study impact craters in Cancun, Mexico, just down the coast from the small town of Chicxulub, where one of the largest terrestrial impact events ever was centered. The Chicxulub impact is thought by some to be responsible for the many global extinctions evident in the fossil record at the **Cretaceous/Tertiary** boundary. The conference brought together an international group of leading scientists with experience in terrestrial and planetary cratering, meteorites, hypervelocity impact, computational simulation of impact, shock microstructures, and remote sensing. This broad range of expertise underscores the multidisciplinary nature of the work required to unravel the chemistry and physics of how natural materials respond to shocks from impact events.

The Impact of Large Bolides on Jupiter and Earth

Results from hydrodynamic simulations of the July 1994 Shoemaker-Levy comet impact on Jupiter have been compared with data and images obtained from space-based and Earth-based observations. There is a possibility that such impacts may induce volcanism. Supercomputers are used by the researchers to model the coupling of physical processes and understand the physical motion of fluids involved with the impact. Hydrodynamic analysis provides a convenient tool for predicting and evaluating the ultra-high pressures and temperatures that occur during a planetary impact.

The Clearwater Lakes structure of Canada was formed by the impact of twin bolides. Petrographic observations, geochronology, and distribution of shock and structural elements can help in reconstructing the original size and shape of the crater. There is also strong evidence that the ore deposit complex in Sudbury (located in northern Ontario, Canada) is the result of a large-scale impact in crystalline rock. Reconstruction models based on the distribution of impact-related features at the site suggest that the crater's original diameter was approximately 250 km. Foremost in any diagnostic examination of material from a suspected impact site is the observation of shock effects among the mineral grains. They provide the most unequivocal evidence of a terrestrial impact. Although the microscope has been the traditional tool for observing shock effects, recent work using transmission electron microscopic analysis has improved our understanding of shock effects in minerals and provides new insights into how they form and the changes that occur after the initial shock. There are several new methods for examining shock effects and for recognizing planar deformation features (PDF) in minerals. PDFs are generally believed to be diagnostic of a shock event. Mössbauer and X ray fluorescence techniques help discriminate among iron meteorites. Nuclear magnetic resonance (NMR) spectroscopy is being developed to study irregular features in crystalline and **diaplectic** materials in quartz-bearing rocks as a result of shock from an impact, and for recognizing silica **polymorphs** and hydration associated with silica phases in naturally shocked Coconino Sandstone from Meteor Crater, Arizona. By smashing a copper sphere into a block of sandstone (see figure (1)), scientists can study what happens during a naturally occurring impact of a metallic meteorite. Nuclear magnetic resonance analysis of shocked quartz sampled from various locations about the crater help to interpret the peak stress field generated by the experimental impact. Significant contributions to our understanding of the structure of the Chicxulub basin are being provided by the Mexican drilling projects. Two 700-meter wells drilled within the impact crater in 1995 intercepted impact **breccias** below 220 meters of depth. Analysis of core materials from melted rock composed of andesite and suevite breccias suggests that sulfuric acid interactions significantly altered the material. Impact of the bolide with the anhydrite layers in the predominantly carbonate platform at Chicxulub generated SO_2 and S_2 gases that resulted in acid rain. Seismic reflection lines shot offshore of the Yucatan peninsula reveal that the Chicxulub basin is filled with Tertiary sediments that increase in thickness toward the center of the structure. A 1350-meter-thick sequence that lies above the Cretaceous carbonate rocks shows no stratigraphic coherence or lateral continuity. These results, and the diameter of the transient cavity interpreted from seismic reflection lines, suggest that the Chicxulub structure is about 310 km in diameter, making it the largest known terrestrial impact structure. In a separate study of gravity and magnetic **anomalies** associated with the Chicxulub basin, the data suggest that the impact melted approximately 20,000 cubic kilometers of the Earth. Recent studies of the Chicxulub ejecta deposits in Belize helped to determine what happened when the large bolide hit layers of carbonate and sulfate rock, releasing over a trillion tons of CO_2 and S_2. Mineralogical and isotopic analyses suggest that carbonate spherules, interspersed with altered glass shards and spherules, may have condensed directly from the impact vapor plume. These observations strongly suggest that complex high-energy processes were required to form the sedimentary deposits that are observed near the Yucatan peninsula.



(1) (Left) Oblique view of a 25-kg block of Coconino Sandstone that was struck by a 0.32-centimeter-diameter copper sphere accelerated at the surface at a velocity of 4.97 kilometers per second. The impact crater is approximately 9 centimeters in diameter. (Right) The ^{29}Si nuclear magnetic resonance spectra indicate the extent of shock damage experienced by the quartz grains of the sandstone. Sandstone was used for the experiment because it is the dominant sedimentary rock subjected to a natural impact at Meteor Crater, Arizona. The spectra exhibit a systematic change in peak width that corresponds to the shock pressure experienced by the rock. An increase in crystalline disorder and the formation of a diaplectic glass account for these spectral changes.

Cold Conditions Prevail Following Chicxulub Impact

Models suggest that solar transmission dropped 10–20% below normal for about 10 years after the Chicxulub impact. Compared to the long-term nature of greenhouse warming associated with the release of CO_2 (about 100 years), the sulfate effect is short-lived. Nevertheless, its effect on the atmosphere would be greater, leading to a decade of freezing and near-freezing conditions. The Chicxulub ejecta material also affected the climate. Experimental studies of the behavior of minerals such as anhydrite ($CaSO_4$) and dolomite ((Ca, Mg) CO_3) indicate that much smaller quantities of SO_3, SO_2, and CO_2 gases are produced by shock than expected assuming equilibrium processes. These small quantities of volatile gases could not alone account for the widespread K/T extinctions, which killed many species, including the dinosaurs. These results, in light of what was previously known about climatic effects, have led scientists to disagree about the true role of Chicxulub volatiles and global climate effects. Exciting opportunities for international scientific collaboration await the additional drilling of the Chicxulub structure and further study of the cores.

Source:*Eos*, May 21, 1996, p. 197.

GLOSSARY

- **amorphization**—the process of a crystalline material becoming amorphous, that is, transforming to a material with no regular arrangement of atoms;
- **anomalies**—unusual behavior in physical properties such as magnetic field or gravity that can occur in the Earth s crust;
- **breccia**—a rock comprised of large angular fragments that were mechanically transported;
- **Cretaceous/Tertiary**—the transition between time periods of the Earth at about 65 million years ago that is characterized by a large number of species extinctions;
- **diaplectic**—pertaining to a mineral glass formed at shock pressures that preserves the texture and morphology of the original mineral;
- **lattice**—the regularly ordered arrangement of atoms in a crystalline solid;
- **polymorph**—a chemical compound that may exist in two or more stable structures, for example, silica (SiO_2) as quartz, coesite, or stishovite

A Few Words From Author Randall T. Cygan ...

I am a senior scientist at Sandia National Laboratories in Albuquerque, New Mexico, where I have worked on various geochemical and materials science projects since 1983. I graduated from William Howard Taft Public High School in Chicago in 1973 and then went on to college at the University of Illinois at Chicago where I received a B.S. degree in chemistry in 1977. I then attended graduate school at The Pennsylvania State University in State College where I completed studies in geochemistry and mineralogy to obtain M.S. and Ph.D. degrees. My interest in science was sparked during my early years in grammar school with experiments and demonstrations in science class and with entries in the annual school science fairs. My fascination with geology and mineralogy originated with trips I took as a boy with my family around Illinois and Wisconsin searching for rocks, minerals, and fossils. The most important part of my education and career in the sciences was, and still is, the hands-on experience in the laboratory and the field, something that textbooks cannot directly provide.