Researchers Focus on Earth's Response to Hypervelocity Impacts

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Imagine witnessing the impact of a 10 km-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 km/s, would melt about 20,000 km^3 of rock and excavate a crater with a diameter of over 200 km within a few seconds, all due to the release of energy equivalent to 100 mega-megatons of TNT. Now imagine, at a twelve order-of-magnitude smaller spatial scale, a perfectly ordered crystalline quartz lattice and the sudden compression felt by the constituent atoms within a matter of microseconds. The creation of lattice dislocations, electronic defects, shock lamellae, amorphization, and a myriad of other features characteristic of shock metamorphism, 65 million years later, is providing scientists with critical clues for unraveling the mysteries of the now famous Chicxulub impact structure.

Impact craters were not recognized as part of the terrestrial 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 due to the biases associated with size recognition, erosion, burial, and search regions [*Grieve and Pesonen*, 1992]. 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 and results. Much of this new research was presented and discussed at a recent conference entitled "Planetary Impact Events: Materials Response to Dynamic High Pressure."

The meeting was held August 28 and 29, 1995, aptly 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 meeting was part of the IV International Conference on Advanced Materials that was sponsored by the Mexican Material Science Academy, the Materials Research Society, the Metals Society, and the International Union of Materials Research Societies. The Chicxulub impact is thought by some to be responsible for the many global extinctions that define the K/T boundary. The "Tail of the Devil," as the word Chicxulub has been translated from the Mayan language, proved to be of considerable interest to the symposium participants.

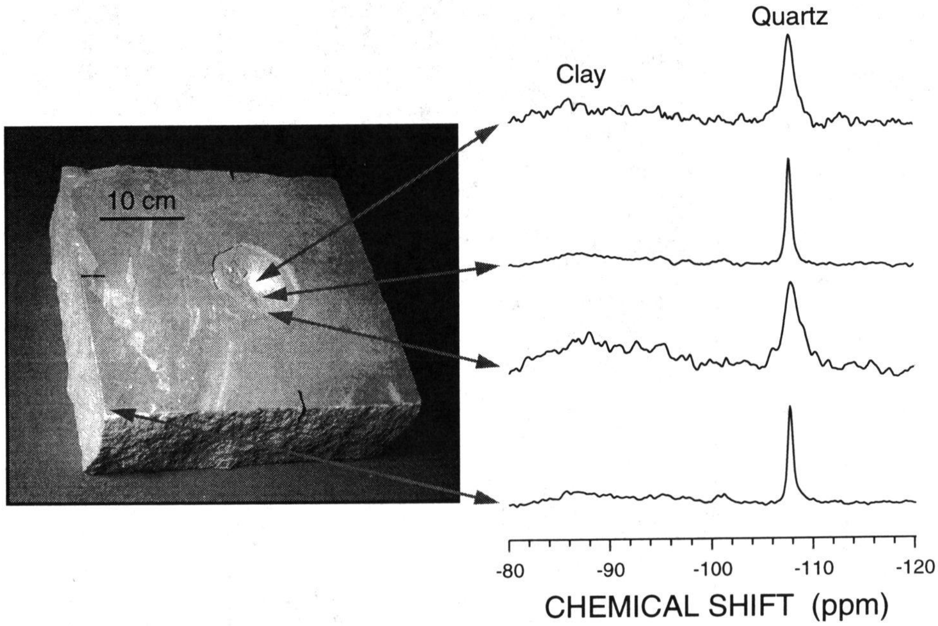

*Fig. 1. (Left) Oblique view of a 25-kg block of Coconino Sandstone that was impacted by a 0.32 cm-diameter copper sphere accelerated perpendicular to the surface at a velocity of 4.97 km/s. The resulting impact crater is approximately 9 cm in diameter. (Right) The ^{29}Si NMR spectra show the extent of shock loading 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 shock experiment was performed by D. A. Crawford (Sandia National Laboratories) using the Vertical Gun Facility at the NASA Ames Research Center. The quartz resonance for tetrahedrally coordinated silicon is significantly broadened for samples obtained from the crater relative to the unshocked material sampled from the extreme edge of the block. An increase in crystalline disorder and the formation of a diaplectic glass account for these spectral changes [*Boslough et al., *1996].*

The conference brought together an international group of leading Earth and materials scientists with experience in terrestrial and planetary cratering, meteorites, hypervelocity impact, computational simulation of impact, shock microstructures, remote sensing, hydrothermal alteration, and analytical characterization. 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 shock loading. The forum included over twenty contributed oral presentations punctuated by four longer invited talks, and an evening workshop and social gathering that featured the microscopic examination of an array of shocked materials. Extensive discussions and enlightening exchanges were generated throughout the symposium.

The large-scale aspect of impact processes was brought to light in the opening presentation on the impact of large bolides on Jupiter and Earth (M. Boslough). Boslough presented results from hydrodynamic simulations of the July 1994 Shoemaker-Levy comet impact on Jupiter and compared those with the data and images obtained from various space-based and Earth-based observations. The process of focusing the seismic energy from an impact source onto the Earth's axis of symmetry between the point of impact and its antipode was hydrodynamically and seismically simulated by Boslough and coworkers, and the possibility of impact-induced volcanism was assessed.

Several well-characterized terrestrial impact structures were discussed. The Clearwater Lakes structure of Canada provides an excellent example of one that resulted from the impact of twin bolides (A. Deutsch). Petrographic observations, geochronology, distribution of diagnostic shock elements, and structural elements provide a basis for reconstructing the original crater geometries. Deutsch also summarized the strong evidence that he and his coworkers have amassed on the origin of the Sudbury igneous complex as the result of a large-scale impact in a crystalline rock target. Reconstruction models based on the spatial distribution of impact-related features suggest an original crater diameter of 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 [*Stoffler and Langenhorst*, 1994]. Although optical (petrographic) microscopy has been the traditional tool in this effort, recent work using TEM analysis has improved our understanding of shock effects in minerals and provides new insights in their formation and postshock modification (F. Langenhorst). Shock classifications and the formation of planar microstructures, including planar deformation features (PDFs; see *Grieve et al.*, 1990) were presented by Langenhorst for the common rock-forming minerals quartz, olivine, and pyroxene.

Several new methods for examining shock effects and for recognizing PDFs in minerals were discussed. Mossbauer and X ray fluorescence techniques help discriminate among iron meteorites (R. Gomez). Nuclear magnetic resonance (NMR) spectroscopy is being developed to help identify the disorder state of crystalline and diaplectic materials in quartz-bearing rocks as a result of shock loading, and for recognizing silica polymorphs and the state of hydration associated with silica phases in naturally shocked Coconino Sandstone from Meteor Crater, Arizona (R. Cygan). The hypervelocity impact of a block of sandstone by a copper sphere (Figure 1) provides an experimental analog to the natural impact of a metallic meteorite. NMR analysis of shocked quartz sampled from various locations about the crater help to interpret the peak stress field generated by the experimental impact.

The conference participants turned to the "Tail of the Devil" on the second day; most of the presentations discussed some aspect of the Chicxulub K/T impact. Significant contributions to our understanding of the structure of the Chicxulub basin are being provided by the Mexican drilling projects.

Two 700-m wells with continuous core recovery drilled within the impact crater in 1995 intercepted impact breccias below 220 m of depth (L. Marin). Analysis of core materials from melt units of andesite composition and suevite breccias suggests significant alteration of material due to sulfuric acid interactions; bolide impact of the anhydrite layers in the predominantly carbonate platform generated SO2 and S2 gases that resulted in acid rain (F. Juarez-Sanchez). 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 (G. Suarez). A 1350-m-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, ranking it as the largest known terrestrial impact structure. In a separate study of gravity and magnetic anomalies associated with the Chicxulub basin, the data suggest an impact melt volume of approximately 20,000 km^3 (J. Royer).

Recent studies of the proximal Chicxulub ejecta blanket deposits in Belize provide details of the role of volatiles (over a trillion tons of CO_2 and S_2) that were released by the large bolide impact with the carbonate and sulfate layers (A. Ocampo). Mineralogical and isotopic analyses suggest that carbonate spherules, interspersed with altered glass shards and spherules, may have condensed directly from the impact vapor plume. The occurrence of these high-energy deposits also indicates a combination of ballistic sedimentation and debris flow processes. Radiative transfer models, coupled with SO_2 oxidation-diffusion and aerosol coagulation-sedimentation, suggest that solar transmission dropped 10–20% below normal for about 10 years (K. Pope). 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 effects of Chicxulub ejecta material on climate were addressed by presentations on the gravimetric constraints of volatiles released compared to total CO_2 and S budgets (J. Royer) and the experimental devolatization of calcium sulfate (T. Ahrens). The latter study showed that only about one hundredth of the equilibrium amount of SO_3 and SO_2 is produced by devolatization reactions for anhydrite at 42 GPa. Further support for the reduced budget of volatiles was provided in an experimental study of shocked dolomites at 60 GPa in which the net outgassing of CO_2 was limited due to a recombination of up to 70% of the gas with the metastable CaO (A. Deutsch). These small quantities of volatiles could not alone account for the widespread K/T extinctions. These results, in light of the previous talks on climatic effects, led to considerable discussion and some disagreement on the true role of Chicxulub volatiles and global climate effects. The "Tail of the Devil" intensified its grip on the symposium participants. Exciting opportunities for international scientific collaboration await the additional drilling of the Chicxulub structure and further study of the cores.

The workshop part of the meeting provided an informal environment to examine thin sections containing examples of shock metamorphism from Chicxulub and the Manson (Iowa) impact structures including unique shock features such as PDFs. Zeiss of Mexico kindly provided a state-of-the-art petrographic microscope and video camera/monitor equipment for use at the evening workshop. Additional support for the impact symposium was provided by the National Science Foundation.—*Randall T. Cygan, Geochemistry Department, Sandia National Laboratories, Albuquerque, N.M.; Laura J. Crossey, Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque; and Luis E. Marin, Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, Mexico City*

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REVIEW

Introduction to Geomagnetically Trapped Radiation

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Cambridge Atmospheric and Space Science Series, Martin Walt, Cambridge University Press, New York, xix +168 pp., 1994, $49.95.

The discovery of the Earth's radiation belts by the first U.S. satellites in the late 1950s was an astonishing surprise. Composed of magnetically trapped populations of charged particles with energies up to hundreds of MeV, these belts are intense enough to kill satellites and astronauts alike if appropriate measures are not taken. More recently, the exploration of the outer solar system by the Pioneer and Voyager spacecraft showed that rather than being a peculiar characteristic of the Earth's environment, intense and energetic radiation belts are common to the space environments of all magnetized planets. Jupiter, for example, a planet that could hardly be more different than Earth, has a radiation environment several orders of magnitude more severe than the Earth's. We can presume from this evidence that hyperacceleration, trapping, and redistribution of intense and energetic charged particles are omnipresent within magnetized astrophysical environments throughout the universe.

In *Introduction to Geomagnetically Trapped Radiation*, Martin Walt has written a fine new textbook that captures some of the lessons learned from the exploration of the Earth's radiation belts in a fashion that is accessible to students of various disciplines.