Drilling to Study Impact Processes and Their Effects on Life

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Abstract
Life on Earth evolved in the presence of impacts by asteroids and cometary nuclei, and the course of that evolution has been directly affected by changes to Earth's environment by the impact process. In most cases, impact-induced environmental changes are local, such as the hydrology of the Chesapeake Bay region having been permanently altered and controlled by the presence of an 85 km crater; however, in at least one case, when the impact of a ≥10 km asteroid formed the Chicxulub impact structure 65.5 Ma, the Earth's environment changed globally, resulting in the extinction of >65% of life. Impact is an ongoing process and, thus, must be considered a geohazard for society; there is a 1 in 10000 chance of a large diameter (>2 km) bolide impacting Earth in the next century. An asteroid only a few hundred meters in diameter impacting the ocean is estimated to result in tsunami damage in excess of $100 billion and directly affect up to several million people. Positive effects on life from impacts may include enhanced subsurface porosity combined with impact induced hydrothermal systems, such that impact craters are a chemically rich subsurface habitat. On early Earth, questions arise as to how life survived the late heavy bombardment phase (3.9 Ga), as well as the importance of impact crater habitat in the evolution of the deep biosphere. To examine impacts and their effect on life, drilling into large impact craters to directly examine the deep biosphere, the release of volatiles, and the local change to the geology and the environment is a vital step. Additionally, sampling across key mass extinction events, such as the Cretaceous-Paleogene boundary to examine potential impact ejecta, determine productivity and chemical changes, and biotic recovery after the event, should be carried out both within the sites of impact and at distal, well-preserved locations. Lastly, examining large craters that do not correlate with mass extinction events are instructive to compare scales of volatile and energy release as tests for proposed extinction mechanisms, and to study regional to continental effects.

Introduction

Comets and asteroids have regularly hit the Earth throughout its history, and have been invoked as mechanisms for bringing water and life to Earth, forming the Moon and causing extinction events, including the K-Pg (formerly K-T) mass extinction. Despite their importance, our understanding of impact processes and their effects remains relatively poorly known. Scientific ocean drilling has played a significant role in improving our understanding, for example of the K-Pg boundary impact and its global effect.

Future drilling can play a vital role in improving our understanding of impacts and their role in Earth's history. One key objective is to study the only example of an impact-caused mass extinction event known so far; specifically why the Chicxulub impact had such a catastrophic effect on life, whereas other large impacts, such as the 35 Ma Chesapeake Bay impact caused only a minor lasting record. Are the critical factors for global environmental devastation the energy of impact, the chemistry of the target rocks, multiple environmental stresses, or the vulnerability of life at the time of impact? Chicxulub is the largest known impact since the Cambrian explosion; the only other impacts of similar size are ~2 billion years old. The Chicxulub impact occurred on a continental shelf, and the release of gasses from the carbonate-evaporite sediments may have been particularly lethal. In addition, some biologists suggest that mass extinctions occur when life is particularly vulnerable to environmental/ecological change and unable to adapt. To further examine these issues, the new phase of scientific ocean drilling could target Chicxulub and other specific impact craters, and sample sites known to be expanded sections across key global events. Where impact is a potential cause of extinctions, increased use of osmium isotopes may help to determine or refute a large impact origin to an event.

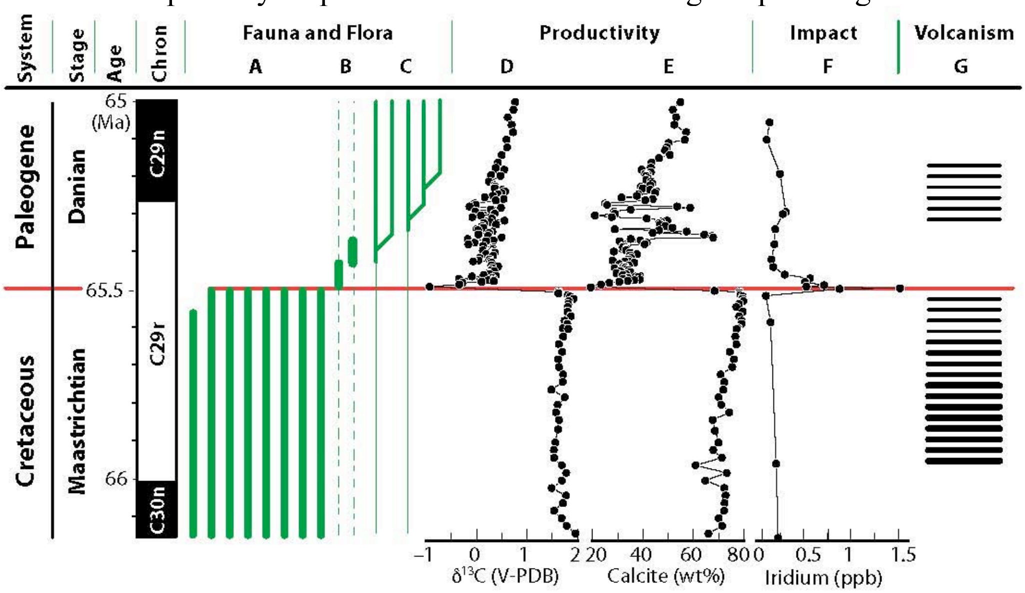

Figure 1: Cretaceous-Paleogene mass extinction event and its clear correlation to the Chicxulub impact. Note the poor correlation with volcanism.

Future drilling can also play a role in understanding how impacts affected microbial life on Earth. Insofar as microorganisms ultimately depend upon elements released from rocks in geochemical cycles in suitable habitats, then these energetic and perturbing events would be expected to play a significant role in the emergence of microbial life (Cockell et al. 2002). Most of the microbiota on Earth resides in the subsurface. Thus, a complete understanding the effects of impacts on life means that different impact craters must be drilled and the effects of impact on the microbiota examined.

Even the impact of relatively small asteroids or comets can have disastrous consequences for our civilization. There is a 1 in 10,000 chance that a large asteroid or comet 2 km in diameter (corresponding to a crater of about 25-50 km in diameter) may collide with the Earth during the next century, severely disrupting the ecosphere and annihilating a large percentage of the Earth's population. Understanding of impact structures, their formation processes, and their consequences should be of interest not only to earth and planetary scientists, but also to society in general.

Impacts as a geohazard

Impact hazardous effects are dependent on the energy of impact and the site of impact. A large-sized impact will have a global effect as material is ejected at high velocity around the world, and will temporarily block out sunlight and cause rapid cooling. The environmental effects will be more severe if the target rocks are volatile-rich, and large volumes of climatically-active gases are released on impact – as is postulated for the Chicxulub impact (Pierazzo et al., 2003). Impacts into the ocean will directly cause tsunamis, and impacts on the continents and continental shelf may cause landslides (which can cause tsunamis) during crater formation, and/or generate earthquakes that induce landslides and gravity flows, as occurred around the Gulf of Mexico and Atlantic margins following the Chicxulub impact. Even much smaller events are a severe local hazard – for example the Tunguska explosion ~100 years ago in Siberia caused high-speed winds, which would have been catastrophic if the impact site had been near a populous city. In general, the hazardous effects will be greatest close to the impact (Collins et al., 2005). Impacts arrive at velocities of > 11 km/s, which generate shock waves in the atmosphere – causing high-velocity winds. On impact, rapid compression and heating cause the target rocks to be vaporized and melted, and material is ejected at high velocity in a vapor plume, and hot ejecta can cause fires.

Almost 70% of the Earth is covered by ocean. Impacts into the water generate intensive surface waves, which transform into tsunamis in shallow water (Ward & Asphaug 2003, Wünnemann et al. 2007). The number of people affected by a tsunami depends upon how far the beaching wave rises in elevation (the run-up) and how far the waves surge inland (the run-in). Both values are defined by initial conditions (i.e. a projectile size and an oceanic depth), but also by the sea-bottom and coastline topography. On average, one near-Earth asteroid will survive atmospheric transit and strike somewhere into Earth's oceans every 5880 years. In the mean generic scenario, the tsunami from the impact affects 1.1 million people and destroys $110B of infrastructure. A generic impact of a 400 m diameter asteroid like 2004MN4 would destroy $400B of infrastructure. For comparison, the estimated infrastructure loss due to the December 2004 Sumatra tsunami was $10B (Chesley and Ward, 2006).

Impact craters and extinction events

The biological evolution of our planet's life is punctuated by mass extinction events, of which the one 65 million years ago, which marks the K-Pg boundary, is probably the best known. Abundant impact debris marks this boundary, providing a clear link with a major impact event (Alvarez et al., 1980; Smit et al., 1999; Schulte et al., submitted). The Chicxulub impact structure in Mexico, about 200 km in diameter, which resulted from the impact of a > 10-km-diameter asteroidal body, is widely agreed to be the principal cause. Following the discovery of the evidence for an impact event at the K-Pg boundary, and its associated environmental consequences, there were numerous suggestions that other extinction events might also be linked to impact events. The largest mass extinction event was at the Permian-Triassic (P-Tr) boundary, 251 million years ago. However, despite a number of claims to the contrary, there is no convincing evidence of an impact event at the P-Tr boundary. The Triassic-Jurassic (Tr-J) boundary is marked by yet another major mass extinction for which there is little or contradicting evidence for impact. The 100-km-diameter Manicouagan impact structure in Quebec has an age that is comparable to that of the Tr-J boundary, but currently available dates indicate that with an age of 214 Ma it predates the boundary. Probable impact ejecta from Manicouagan were identified in southwestern Great Britain, but there is no connection to the Tr-J boundary, whereas the presence of a minor Ir anomaly at the Tr-J boundary might not be related to impact because, as experience with the P-Tr boundary shows, minor PGE anomalies may or may not be indicative of impacts. Further geochemical studies should provide additional constrains on what happened at the Tr-J (and other) extinction events.

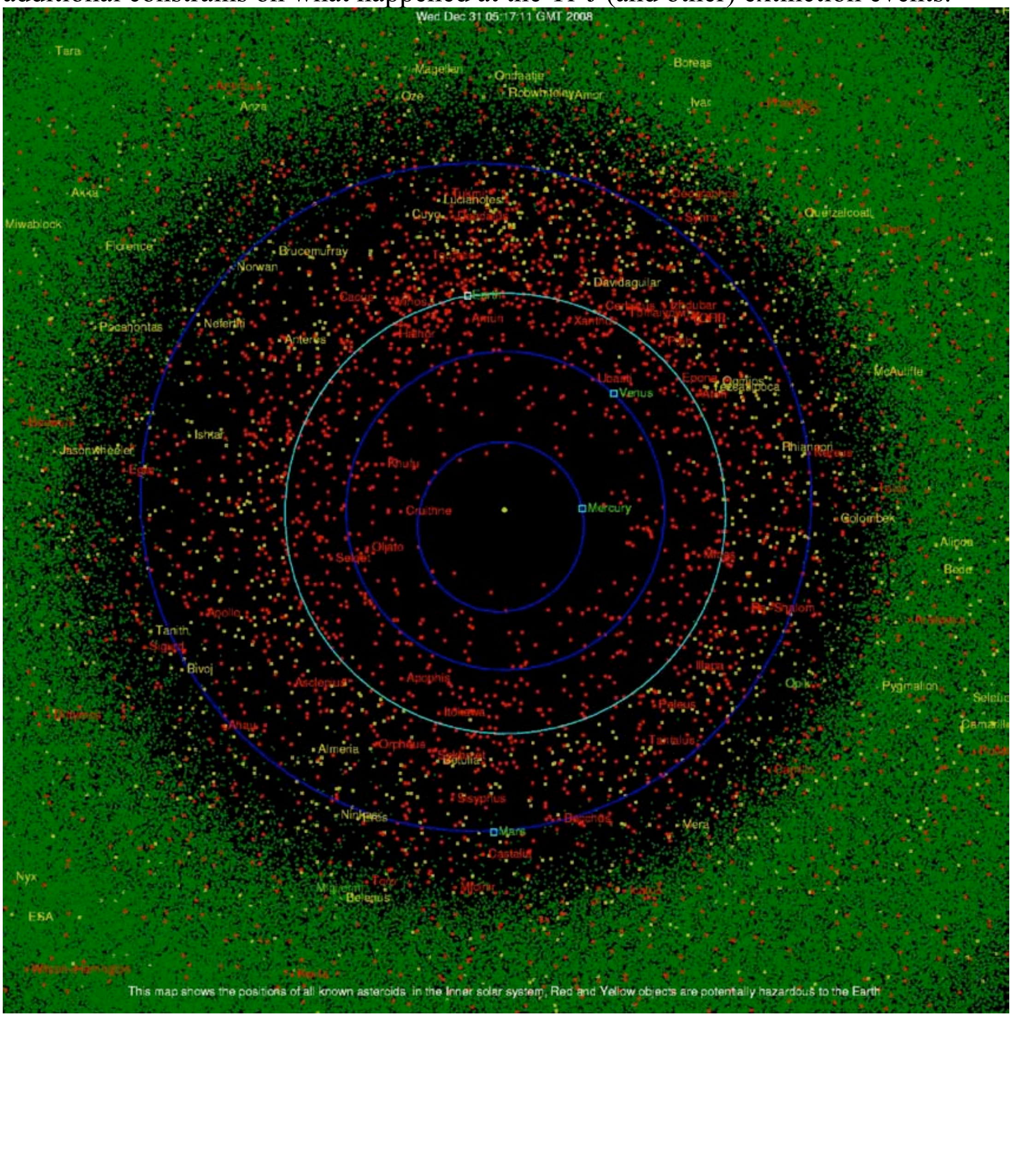

Figure 2: All known asteroids near Earth (2006); reds and yellows could potentially impact Earth whose orbit is shown in light blue.

Impact craters as a habitat

On early Earth, impact events were a common occurrence during the period of late heavy bombardment, during which microbial life may have emerged. Today, most impacts alter environmental conditions on a local scale (Toon et al. 1997; Kring 1997). In the early Archean, environmental perturbations caused by large impacts are thought to have been so great that the oceans may have boiled (Maher & Stevenson 1988; Zahnle and Sleep, 2006), periodically threatening conditions for microorganisms, although not necessarily on a planetary scale (Abramov and Mojzsis 2009). Drilling into impact craters will yield insights into how early deep subsurface life survived on a heavily bombarded Earth.

Although the consequences of impacts for a surface biota have been studied, the influence of impacts on the deep subsurface biosphere is not well understood. Impact events might be predicted to have both deleterious and beneficial effects on the deep subsurface biosphere. Deleterious effects could include sterilizing effects of a thermal excursion caused at the site of the impact by the kinetic energy of the impactor and the biologically disruptive effects of the shock waves produced (Kring, 1997). The beneficial effects of an impact could include: 1) an increase in the permeability and porosity of target materials (observed in the surface environment; Cockell et al., 2005) caused by impact-induced pressurization and heating; 2) an increase in the flow of nutrients and redox couples to biota through faults and fractures generated in the impact collision; 3) an improvement of water availability caused by cavity formation and the formation of a hydrologic depression (observed in the surface environment); 4) the mixing of lithologies, creating steep geochemical gradients and potentially more favorable redox environments for life; 5) the formation of a hydrothermal system, which, once cooled below the upper temperature limit for life, might offer a warm habitat (Osinski et al., 2005); and 6) the introduction of new nutrients into the crater cavity, such as, for example, from outside the impact zone in the case of a tsunami (Smelror and Dypvik, 2006).

The hypothesis that impact-induced fracturing would influence the conditions for microorganisms is supported by observations at the Chesapeake Bay impact, which was drilled by ICDP and United States Geological Survey (USGS) in 2005 (Gohn et al., 2008). This was the first impact structure to be drilled with microbiological contamination control. An increase in microbial abundance is associated within a region below a granite megablock in the region corresponding to suevite and fractured schist and pegmatite rock in the deep subsurface of the Chesapeake Bay impact structure. Other minerals such as quartz showed shock features including planar deformation features. The shock features and presence of melt in the upper part of the section show that the target rocks, or its constituent minerals, were subjected to sterilizing temperatures during impact. Although there is no evidence to support regional lateral advection, microorganisms could have gradually diffused in from nearby clasts that were not sterilized or may have been carried in by compaction-driven vertical advection from the permeable schist and pegmatite region below. Once ambient temperatures within the structure dropped below the upper temperature limit for microbial growth, colonization could occur. The presence of breccias dykes within the material suggests that dilatancy, or the opening of fractures, occurred during their emplacement before the introduction of a sedimentary cover, which would have contributed to increasing permeability for biological recolonization.

The Chesapeake Bay structure also exhibits a high salt concentration. Microbial isolation and enrichment data show that the indigenous microorganisms can grow at the high salt concentrations found in the impact structure and that many of them belong to phylotypes previously associated with saline environments such as Halobacterium and Exiguobacterium spp. These data show that the chemical conditions established by the impact event affect the physiology of the deep subsurface microbial communities up to today.

The study of the deep subsurface of craters has astrobiological implications. Insofar as no solar system-forming process is known that is completely free of remnant debris, then impact events are a universal phenomenon and would be expected to bring destructive energy to the deep subsurface surface of most terrestrial-type rocky planets. Thus, impact events are of biological importance in understanding the conditions for emergence and persistence of subsurface life elsewhere.

Outlook (Future Drilling Projects and Reasons)

Deep drilling of impact craters will provide new information about the Earth's deep biosphere, about the role of impacts in mass extinction events, and their potential for creating novel environments such as long lived hydrothermal systems to serve as new habitat. Bacteria are known to be present at depths as great as 4 km below the Earth's surface. The existence of a deep biosphere has profound implications for the origin and evolution of life. During the bombardment of the early Earth by bolides like those that produced the Vredefort and Sudbury structures, life may have survived only deep within the Earth. In future scientific drilling projects, fluids and gases need to be sampled within deep holes, and the recovered cores should be examined for traces of biological activity. Thus, deep drilling results of impact craters may provide a first glimpse of the deep limits of the biosphere. Additionally, craters of all sizes provide sediment catchments that should be exploited to better understand biologic evolution and changes in the regional climate both in response to an impact event and as passive recorders, sometime with expanded stratigraphic sections, of later non-impact climatic and environmental changes.

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