Impact as a Geologic Process: Motivations to Drill

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Abstract
Ocean drilling has a vital role to play in the study of impact as a geologic process. All rocky planets undergo impact by asteroids or comets as a process that changes the surface and subsurface of the planet over geologic time. In the case of large impacts these changes can be drastic with effects to the local hydrology, mineral content, basin formation and crustal structural being fundamentally and permanently modified. Earth is a challenge as the impact record can be destroyed or masked by tectonics; however, only on Earth can we directly sample rocks shocked by impact or use the basin forming process to examine the paleoclimate and paleoenvironment of key geologic intervals or boundaries. Direct sampling, such as through drilling, also remains the only way to confirm a structure is an impact. Continental drilling has been undertaken to study the physics of the impact process and the geology of terrestrial impact craters, with important results. Increasingly there is interest in the role of the target in impact processes both in the final crater produced and the potential for environmental effects. Future ocean drilling should perhaps be focused on large impacts to examine morphologic features created in such impacts not otherwise accessible, such as peak rings, to study energy and volatile release by impact, and to understand the thermal and hydrologic environment within craters subsequent to impact. Impact as a geologic process has fundamentally affected Earth's geologic and environmental evolution and opportunities exist to gain a major advance in our understanding of these events and their effects.

Introduction

Impact is the only ubiquitous geologic process on solar system bodies with solid surfaces. It differs from other geologic processes in the release of vast amounts of energy on time-scales that are virtually instantaneous. On impact, the bulk of the kinetic energy of the impacting body is transferred by a shock wave to a spatially limited, relatively near-surface volume of the planet (e.g., Melosh, 1989). Here, it is partitioned into kinetic energy, which produces a crater and ejecta, and internal energy, which leads to the irreversible changes (shock metamorphism) in the target rocks. In very large impact events, the effects of the resultant impact ejecta can be global in scale. Geologic effects of impact scale with both the size of the event and planetary gravity, and are influenced by target type (continental versus marine, dry rocks versus volatile-rich sediments).

The terrestrial record is currently the only source of ground truth data on the geological and geophysical consequences of natural impact events at scales from tens of meters to hundreds of kilometers. The terrestrial record is of particular utility in terms of the three-dimensional lithological and structural character of impact structures. These characteristics can be determined directly by drilling or cumulative observations at similar-sized structures exposed to different erosional levels and/or indirectly through the interpretation of geophysical data.

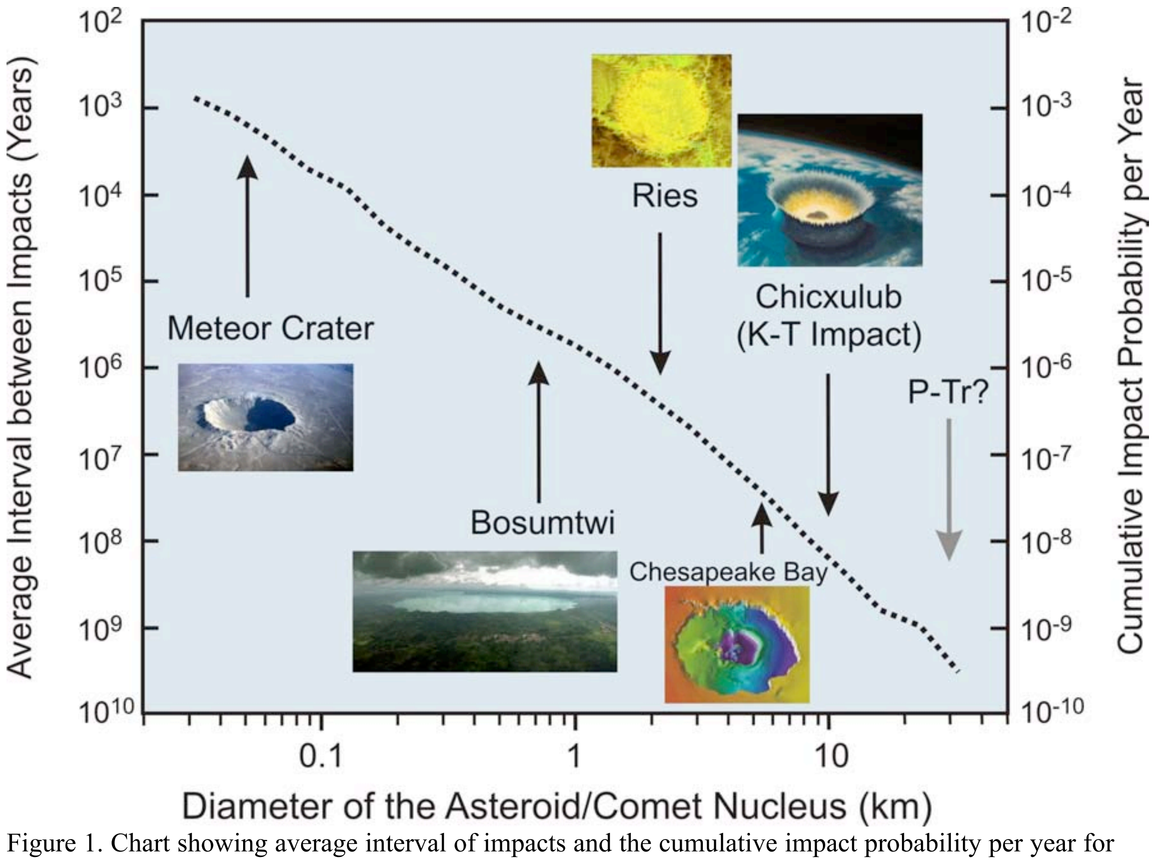

Figure 1. Chart showing average interval of impacts and the cumulative impact probability per year for Earth plotted against the diameter of the asteroid. Known example craters of varying sizes are displayed on this chart for reference. The inclusion of an impact at the Permian-Triassic boundary is hypothetical.

Although the surface of the moon is a constant reminder of the importance of impact in its evolution, at first glance the same cannot be said for the Earth. In fact, however, the larger physical and, more importantly, gravitational cross-section of the Earth has meant that the Earth has been subject to, at least, 25 times more impacts of a given size than the moon throughout geologic time (Grieve et al., 2006; Koeberl, 2006). If the results of these impacts were preserved, this would translate to a crater density on Earth that was approximately twice that of the moon. The Earth, however, is the most geologically active of the silicate planets and, given that impact structures are surficial features, it has the poorest record of preserved impacts of all the silicate planets. Currently, there are ~ 175 known terrestrial impact structures, with several new discoveries per year (http://www.unb.ca/passc/ImpactDatabase/). There are also ~ 20 impact events recorded in the stratigraphic column, not all of which are related to known impact structures. The calculated cratering rate in the Earth-Moon system indicates that 3 ± 2 impact events capable of producing impact structures with diameters ≥ 20 km, if they impacted dry land, occur every million years on Earth. Such events are capable of atmospheric blow-out above the impact site and, thus, potentially could distribute impact materials globally (e.g., Simonson and Glass, 2004). Such a cratering rate, however, is not reflected in areas with poorly known geology or in the current level of observations of the stratigraphic column. Thus, it is ironic that despite the fact that impact craters on Earth can be studied directly in the field, they may be much more difficult to recognize than on other planets. Therefore, diagnostic criteria for the identification and confirmation of impact structures on Earth were developed: a) crater morphology, b) geophysical anomalies, c) evidence for shock metamorphism, and d) the presence of meteorites or geochemical evidence for traces of the meteoritic projectile – of which only c and d can provide confirming evidence. Thus confirmation requires the study of actual rock samples. About one third of the currently known impact craters on Earth are not exposed on the surface and can only be studied by geophysics or drilling~~.~~

Motivation to Drill

Of the about 175 individual terrestrial impact structures and other small crater fields currently identified (ref Database), about half have been drilled in some way or another, although this does not mean that cores were obtained, that drill cores are preserved anywhere for study, or that that the drilling was documented and published. Of those that were drilled, 90% are not exposed on the surface. The initial motivation to drill these structures was either scientific or economic. Drilling was accomplished in order to: (1) confirm the presence of an impact structure and to learn about the physicochemical processes involved through the study of crater geology; and (2) satisfy economic geological interests, such as exploration for hydrocarbons in structural traps. The economic motivation has largely been potential recovery of commercial quantities of hydrocarbons or minerals. Successful drilling was performed at a number of craters in the form of local, regional, national, or otherwise collaborative projects. In many of those cases, cores were not documented to the degree that conforms to present-day standards, and/or cores are no longer preserved.

More recently the International Continental Scientific Drilling Program (ICDP) has supported projects to study four impact craters so far: Chicxulub, Bosumtwi, Chesapeake Bay, and El'gygytgyn craters. Results from these projects highlight the revolutionary science that can arise from impact drilling and the need for future studies (Koeberl and Milkereit, 2007).

Chicxulub

Chicxulub is the youngest of the three largest known terrestrial craters on Earth, and is widely believed to be responsible for the mass extinction at the K-Pg (formerly K-T) boundary. The ICDP borehole, Yaxcopoil-1, was drilled on the flank of the crater, between the crater rim and peak rim. The borehole recovered core from ~800 m of post-impact sediments, ~100 m of impact breccias and melt rocks, and ~600 m of pre-impact target rocks.

Drilling results together with geophysical and borehole data, including new offshore marine seismic data, led to a revised crustal model for the multi-ring Chicxulub structure and to new models for ejection and deposition of allogenic impact breccias within and close to the crater (Vermeesch and Morgan, 2008; Gulick et al., 2008). Particular opportunities for study that the Chicxulub crater provides include sampling an intact peak ring (a morphologic feature present in large craters but never sampled), obtaining a reliable estimate of energy and volatile release, testing extinction mechanisms and tsunami models, examining recolonization of the impact site by biota post-impact, determining the extent and biogeochemistry of the hydrothermal field formed in the wake of the impact, and testing the hypothesis that peak rings are a niche for microbial life (see white paper on Impacts and Life).

Bosumtwi (Ghana)

The Bosumtwi impact crater in Ghana is ~1 Ma and 11 km in diameter, and is one of only four known impact craters associated with a tektite-strewn field. It is well-preserved, displays a pronounced rim around a hydrologically closed basin, and possesses a buried 1.9-km-diameter central uplift. The scientific objectives of ICDP-led drilling were: to obtain a complete paleoenvironmental record from the time of crater formation about one million years ago, at a near-equatorial location in Africa, for which very few data are available so far, and to obtain a complete record of impactites at the central uplift. All central uplifts at exposed craters are eroded; hence drilling is the only method that pristine deposits can be recovered.

Two impactite cores, LB-07A and LB-08A were drilled into the deepest section of the annular moat (540 m) and the flank of the central uplift (450 m), respectively, and both penetrated melt rock/impact breccia layer into fractured bedrock. LB-07A comprises lithic (in the uppermost part) and suevitic impact breccias with appreciable amounts of impact melt fragments (Koeberl et al., 2007). The results have allowed us to further develop our understanding of crater formation, and show that different target rocks strongly affect the formation of central uplifts and the allogenic impact melts and breccias that cover them.

Chesapeake Bay (USA)

This impact structure, 35 Myr old and 85 km in diameter, is the source crater of the North American tektite strewn field. The Chesapeake Bay structure is unique among subaerial and submarine impact craters on Earth because: (1) it is a relatively young structure and therefore, in comparison to other known impact structures of such size, very well-preserved; (2) its location on a passive continental margin has prevented tectonic or orogenic disruption or distortion that is typical of many large terrestrial craters; (3) its original location on a relatively deep continental shelf allowed marine deposition to resume immediately following the impact, which buried it rapidly and completely, thereby preventing subsequent erosion; (4) the upper part of the breccia section inside the crater was derived from resurge currents and impact-generated tsunami waves; (5) the breccia body contains a large volume of impact-generated brine; (6) the crater underlies a densely populated urban corridor, whose two million citizens are still affected by crater-related phenomena, such as freshwater availability.

The International Continental Scientific Drilling Program (ICDP) and the U.S. Geological Survey (USGS) completed two deep coreholes and penetrated five major lithologic units: parautochthonous basement blocks, suevitic impact breccias, a thin interval of quartz sand (22 m), which contains an amphibolite block and other lithic clasts of centimeter to decimeter size that travelled many kilometers during the impact process, and a thick impactite unit of deformed sediment megablocks and overlying sedimentary clast breccia (Exmore beds). The Exmore beds contain clasts of target sediments and crystalline rock, as well as a small component of impact melt, and it is interpreted to represent late-stage collapse of the marine water column and its catastrophic flow back into the crater. Research is continuing to-date and has led to a better understanding of the formation of this large shallow marine impact structure and its far-reaching effects (Gohn et al., 2008).

El'gygytgyn (Russia)

In 2009, ICDP drilled the 18-km-diameter El'gygytgyn impact structure, which was formed ~3.6 Ma. The crater formed in acid volcanic rocks, hence drilling offers the unique possibility to study the impact and shock effects on such rocks, which has implications for comparative planetology. In addition, the crater is filled with ~300 meters of lake sediments and constitute a unique climate archive of the largely unknown Arctic climate history. Drilling recovered ~315 m of lake sediments and ~60 m of impact breccia, and ~140 m of broken and fractured volcanic basement rocks, which were shocked, brecciated, and uplifted during the impact event. Core will be provided to researchers at the end of the year, but expectation is that a significant increase in our understanding of effect of shock metamorphism on rocks commons to inner solar system surfaces will be forthcoming.

Summary

One of the focal points of future scientific drilling could be to drill very large impact craters (Chicxulub and others) that involve a vast volume of the continental crust and, thus, require deep drilling to recover representative samples through the structure. Scientific drilling of large craters will provide new petrological, structural, geochronological and geophysical data, allowing a quantum leap forward in our understanding of the evolution of large impact structures and the physical, chemical, and biological processes that have operated within these craters over time. Questions abound both about the impact process itself but also the long term effect on terrestrial processes in impact sites. For instance, both Chesapeake and Chicxulub permanently altered the hydrology of the region and the impact geology remains the dominant factor controlling groundwater in the Washington D.C. area and the Yucatan Peninsula. These large impact structures are examples of peak ring and multi-ring impact features on Earth and provide the only opportunity to study the internal stratigraphy, lithology distribution, and deformation patterns in these structures, which are otherwise only accessible on the Moon and other planets by remote sensing. In addition, these large impact craters will offer new insights into possible links to mass extinction events or can be utilized to determine the thresholds needed for extinctions to occur. Impact craters provide physically defined basins that can provide a record of post-extinction recovery (in the larger events) and a record of evolutionary and climatic change over thousands to several million years, as well as an assessment of the post-impact thermal evolution of large volumes of crustal melt, the associated hydrothermal activity and its effect on the redistribution of economically valuable mineral deposits. Submarine craters, such as Mjølnir in the Barents Sea, are important targets because of the formation mechanism and the wide effects of large marine impacts. It is important to note, however, that these studies will require multiple drill sites to fully map these complex processes.

Clearly it is not necessary to drill dozens of craters, but it is more important to obtain a good representation of the different forms, sizes, and target materials, and explore specific craters in more detail than with just one drill core. Drilling into impact structures will continue to be the main source of material for new and detailed studies of impact crater materials and, therefore, greatly enlarge our knowledge of the impact process into Earth and other rocky planets. Future impact cratering studies have much to gain from experience from past drilling projects into craters and through impact ejecta or impact horizons (e.g. K-Pg), and such projects (by IODP and ICDP) will provide crucial information to help us understand the formation of impact structures and their geological and biological importance and effects.

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