IMPACTS AND THE EARTH: A PERSPECTIVE

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"Why Study Impact Craters?" is the title of a fundamental contribution by one of the pioneers of impact crater research, Eugene M. Shoemaker, in a landmark book in this field: *Impact and Explosion Cratering* (Roddy et al. 1977). In his far-reaching vision, Shoemaker wrote:

> **"I submit that impact of solid bodies is the most fundamental of all processes that have taken place on the terrestrial planets. Without impacts, Earth, Mars, Venus, and Mercury wouldn't exist. Collisions of smaller objects are the process by which the terrestrial planets were born."**

As a result of planetary exploration missions, we now know that impacts are ubiquitous in the Solar System. The Earth is the most geologically active of the terrestrial planets and, therefore, most of its impact structures have been destroyed over geologic time. Nevertheless, the Earth's impact record is the only source of three-dimensional lithological and structural ground-truth data on natural impacts and their consequences. For obvious reasons, natural impact phenomena are not fully amenable to experimental duplication.

IMPACTS AND THE GEOLOGICAL EVOLUTION OF EARTH AND THE MOON

Until fairly recently, impact phenomena on Earth were of interest to a rather small community of geoscientists, who were focused on understanding impact processes and how Earth's impact record serves as an analogue for impact processes on the other terrestrial planets. Today, however, the concept of the importance of impact processes to terrestrial evolution has changed radically. Impact research, in its broadest sense, has led to a change of the fundamental paradigm of "gradualism" in geological science to a more pragmatic paradigm in which the processes of "catastrophism" interact with those of "gradualism." This is exemplified by the current knowledge of the origin and evolution of the Moon. Currently, the best working hypothesis for the origin of the Earth's moon is that a Mars-sized object impacted the primitive Earth, resulting in vaporized impactor and terrestrial mantle material being placed into orbit and later condensing to form the Moon (Canup 2004). The formation of the Moon resulted in important side effects, namely, stabilizing the Earth's obliquity and raising substantial tides in the oceans. Without these effects, the biological evolution on Earth would have been very different (Williams and Pollard 2000). Any primitive atmosphere existing at the time of the Moon-forming impact would have been removed by the event, and it has been suggested that later cometary impacts could have been a source of volatiles for the Earth. The first isotopic evidence for this hypothesis came recently when Hartogh et al. (2011) found that the deuterium/hydrogen ratio of water in some comets is the same as in the Earth's oceans. It is now recognized that the evolution of the Moon (and hence of the Earth) was dominated

Oblique aerial photograph of the canonical terrestrial simple impact crater, the 1.2 km diameter Barringer or Meteor Crater, Arizona, USA

in the first billion years by cataclysmic processes ("early heavy bombardment"), which became subordinate to more gradual endogenic processes but have still remained in effect over the past 3.5 billion years (Stöffler et al. 2006). In general, the existence and geological effectiveness of the "early heavy bombardment" phase is evident on all planetary bodies that have retained portions of their earliest crust. The role of impacts was likely also most influential in the early crustal evolution on Earth, but that role remains speculative (Grieve et al. 2006) as none of Earth's earliest crust has survived.

IMPACTS AND THE EVOLUTION OF LIFE

It has been argued that the early heavy bombardment had a major effect on the evolution and survival of life on the early Earth. Reasoned speculation suggests that surface sterilization would have been one of the consequences of impacts equivalent to those that formed the large multi-ring basins on the Moon, resulting in the late appearance of bacterial life on Earth (~3.9 billion years ago). More recently, increasing attention has been focused on the relationships between terrestrial impacts and bacterial life. They are complex, but some observational data indicate that impacts can both increase and decrease the abundance of bacterial life in crustal rocks, through the creation of fractures and impact-related hydrothermal systems (Cockell et al. 2003). Recent laboratory shock wave experiments indicate that bacterial life could survive the conditions of impact ejection and be transferred between planets, for example, between Mars and Earth (Meyer et al. 2011).

Whatever the effects of the creation of the Earth's moon and of the early heavy bombardment were on early biological evolution, there is physical and geochemical evidence that a major terrestrial impact event dramatically changed the Earth's biosphere in more recent geologic time. Since the initial working hypothesis was offered, evidence has continued to accumulate that a major impact was the driving force for the Cretaceous–Paleogene (K–Pg) mass extinction event ~66 million years ago. The extinction is related to the buried, 180 km diameter Chicxulub structure in Mexico. Chicxulub and its relation to the K–Pg extinction was a catalyst in the study of terrestrial impact structures and their local and global effects. This mass extinction event paved the way for the rise of mammals on land and, ultimately the human species.

Our species has derived other benefits from the effects of impact events. Impact craters are important sites of economically important resources. Some world-class natural resource deposits are linked to major impact structures; for example, the Sudbury impact structure contains an estimated total of 1.5 billion tonnes of Ni–Cu ore rich in Pd and Pt. In economic terms, however, hydrocarbon production dominates, with ~50% of known impact structures in hydrocarbon-bearing sedimentary basins hosting commercial production.

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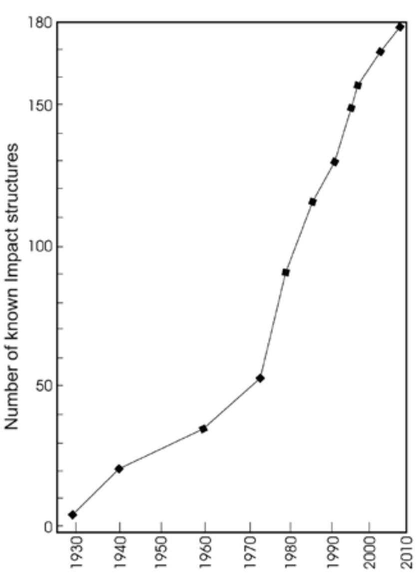
TERRESTRIAL IMPACT CRATERS: A LEARNING PROCESS?

As often happens in the evolution of science, impact research developed from a "dark or unenlightened" past into a "bright" future during the past century. In the early 1900s, it was suggested that two circular, crater-like features, Barringer Crater (Arizona, USA) and Ries Crater (Bavaria, Germany), were most likely formed by the impact of cosmic bodies. These proposals were largely ignored by geologists for over half a century, during which time even the craters on the Moon were believed, by some, to be of volcanic origin. Barringer and Ries were finally accepted as impact craters after the discovery of unequivocal shock effects in the target rocks (Chao et al. 1960; Shoemaker and Chao 1961). It was immediately recognized that the discovery of shock effects was the key evidence for an impact origin for any suspicious crater. Various types of shock effects were calibrated by shock experiments, leading to the development of a system of "progressive shock metamorphism" of minerals and rocks around 1965. These concepts were acknowledged in *Shock Metamorphism of Natural Materials* (French and Short 1968) and recently reaffirmed in an IUGS classification system (Stöffler and Grieve 2007).

About the same time as the fundamental importance of shock effects was recognized, it became clear that the change in the morphology of impact craters with increasing size—from simple bowl-shaped craters to shallow complex craters with central peaks, peak rings, and multiple rings—was related to the gravity-induced collapse of the so-called "transient cavity." This interpretation was a major challenge for the community and led to conflicting debates up to the late 1970s. It is now generally acknowledged that what changes in moving from simple to complex crater forms is not the relative size and shape of the transient cavity but the type of modification that the transient cavity undergoes in achieving the final crater form.



Cumulative number of known terrestrial impact structures as a function of time. The increase in discovery rate after the late 1960s can be attributed to the recognition of shock metamorphic effects as diagnostic indicators of impact.

As we move into the "bright" future of impact research, we are increasingly applying two important tools: numerical modeling and isotopic dating. These tools are driving forces for a better understanding of cratering processes *per se* and of the impact rate on Earth and the Moon, as a function of time and projectile size. Impact craters and their proximal and distal ejecta layers constitute unique stratigraphic markers providing an exact, absolute geochronology. Indeed, most of the lunar stratigraphy is based on dated major impact events. However, dating impact craters, which is mainly performed on impact melt lithologies, is not always straightforward. Either the dated samples cannot be unequivocally assigned to the source crater, as on the Moon, or older craters do not provide remnants of unequivocal datable lithologies, as on Earth.

Much insight is being gained through the latest generation of computer codes to model impact phenomena. Model calculations, however, have to be constrained and tested against observational data and, in some cases, are currently preceding the availability of such data. Computer modeling (Collins et al. 2002) provides explanations for the formation of so-called peak rings in large complex structures. The only terrestrial impact structure with a well-preserved peak ring, as interpreted from geophysics, is the buried Chicxulub structure. Until the peak ring is actually sampled through drilling, both the geophysical interpretation and the formational models will remain untested. Computational models of transient cavity modification at complex structures require a reduction in bulk rock strength during structural uplift. While a number of theoretical mechanisms to reduce strength have been suggested, for example, acoustic fluidization (Melosh and Ivanov 1999), there have been no substantive observational data forthcoming from studies of complex structures to support any one of the proposed mechanisms. There are also few observational constraints on ejection processes, as most terrestrial impact structures have lost any substantial ejecta deposits to erosion. This situation, however, may improve, as more and more impact debris are recognized in the terrestrial stratigraphic record. These, and other, fundamental remaining questions, combined with the increased general interest and influx of researchers with varied knowledge and skill sets, bode well for future studies of impact-related phenomena.

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