Impact cratering research and the diagnostic evidences of impact

Introduction :

One cannot better emphasize the importance of impact cratering research than what Eugene M. Shoemaker once said, "I submit that impacts 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 would not exist. Collisions of smaller objects are the process by which the terrestrial planets were born." The impact cratering process is of fundamental importance to the planetary and space sciences. Available evidences suggest its pivotal role in the formation of solar system including Moon and modification of planetary landscapes. On Earth, at least one major mass extinction event and a number of mineral (including hydrocarbon) deposits are associated with the bolide impacts. The importance of impact craters in planetary explorations is immense. India's historic first Moon mission (Chandrayaan-1) left its "foot prints" on Shackleton crater, Lunar south pole by landing the Moon Impact Probe (MIP) on November 14, 2008 and possibly gave the first indication pertaining to the presence of water ice on Moon! Similarly on August 6, 2012 the Mars Science Laboratory (MSL) mission targeted Gale impact crater, Mars in order to investigate the possible presence of life-supporting systems on the red planet. Hence, it is important to understand impact cratering process in general and its effects on terrestrial and extraterrestrial objects.

However, impact cratering research gained recognition, respectability and momentum in the last four decades. Petrographic study of meteorites was instrumental in the recognition of unequivocal shock metamorphic features and these features were later used to confirm terrestrial and lunar impact structures. The number of confirmed meteoritic impact structures on Earth is only 182 (http://www.passc.net/EarthImpactDatabase; 23:10:2012) compared to thousands of such structures on the Moon and Mars! It is estimated that several hundreds of impact structures on Earth are waiting to be discovered (French and Koeberl, 2010). The rarity of terrestrial impact structures is mainly attributed to the dynamic nature of planet Earth, the role of various geological agents in modifying the landscape; and the lack of knowledge about the diagnostic evidences for the confirmation of the bolide impact. Nowadays with the ease of availability of remote sensing data (digital and analogue), the identification of circular to near-circular structures have increased manifold and consequently many of them are wrongly identified as meteoritic impact structures. A detailed field study coupled with a careful petrographic examination of rock samples using a polarizing microscope is adequate to ascertain the tell-tale signatures of shock metamorphism *vis-à-vis* impact cratering. Shock metamorphism is defined as "all changes in rocks and minerals resulting from the passage of transient, high-pressure shock waves" (French, 1968) and the impactites are rocks comprising diagnostic shock metamorphic feature(s). In some rare cases, the impactor component is also found preserved within the impactites as meteorite fragments, otherwise it leaves an undeniable chemical trace depending upon the meteorite type.

Stages of cratering process

Bolide impacts involve an impactor (asteroid or comet) and a target (planetary surface). The size of the impactor (pea-sized to hundreds of kilometer), its shape, velocity (few km and up to about 70 km per second), composition, angle of impact (<10˚ to ~90º), and the target properties (crystalline or sedimentary and sub-aerial or sub-aqueous) are the factors that determine the final crater shape and size. The three stages of impact cratering (Melosh, 1989) include: 1. Contact and compression, 2. Excavation, and 3. Modification. The impact cratering process as a whole is completed in less than 15 minutes! However, this catastrophic hypervelocity (>11 km/s) impact event generates enormous shock pressure (up to 1000 GPa) and correspondingly the temperature can attain tens of thousands of degrees Celsius.

Types of structures

The impact structures are generally grouped into three types (Fig.1) and they include, 1. bowl-shaped simple structures having a central depression (e.g., Lonar crater, India, (Fig. 2); diameter: 1.88 km), 2. complex structure with a central peak/elevation (e.g., Dhala structure, India (Fig. 3); diameter: ~25 km) and 3. multiring structures (e.g., Mare Orientale, Moon; diameter: 930 km). The impactor often fails to reach the Earth's surface and explode in the atmosphere leaving a large area completely devastated (e.g., Tunguska, Russia). Despite the variation in types of impact structures, the depth to

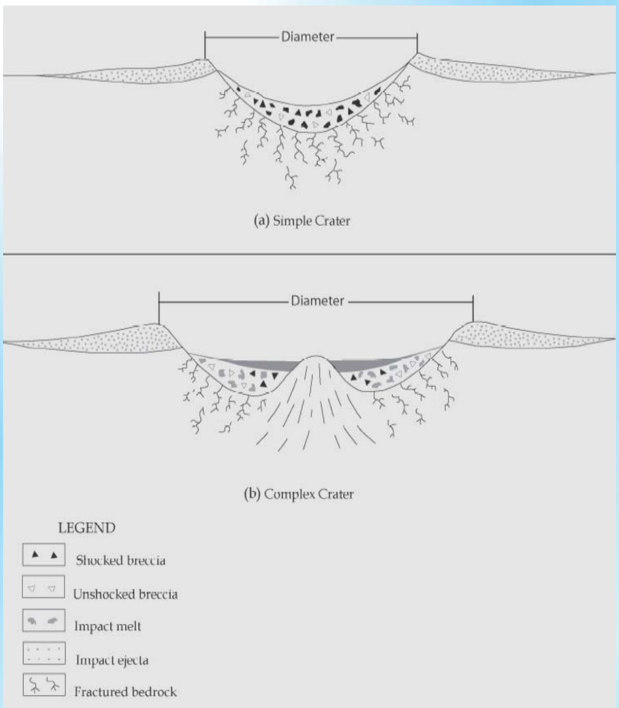

Figure 1: Types of terrestrial impact structures. The simple structures are bowl-shaped with a central depression and complex structures are marked a central elevation due to elastic rebound. The simple to complex structure transition takes place at about 4 km in terrestrial conditions. There are multi-ring structures also.

Figure 2: The Lonar structure, Maharashtra, India is a simple bowl-shaped structure in basaltic target rock.

Figure 3: the Dhala structure viewed from NE exhibiting the central elevated area, crater-fill sediments and the monomict breccia.

diameter ratios in case of simple structures generally varies between 1/5 and 1/3 (Melosh, 1989) and in case of complex structures, the stratigraphic uplift is about one-tenth of final crater diameter. Based on theoretical and field studies, the ratio between initial transient crater and final crater diameters varies between 0.5 and 0.7 (French, 1998).

Diagnostic evidences for the confirmation of impact structures

The meteoritic impact structures are often identified initially as circular to near-circular features in satellite images and/or geological maps. However, it is important to carry out field and detailed petrological investigation to confirm such probable or possible structures based on unequivocal impact diagnostic mesoscopic and microscopic shock features. French and Koeberl (2010 and the references there in) and a recent issue of Elements on impact cratering research (edited by Jourdan and Reimold, 2012) provide an excellent review with

Figure 4 Shattercones in quartzite from Vredefort impact structure, South Africa are the only mesoscopic shock metamorphic features.

recent developments. The physical presence of projectile component(s) or their chemical traces in the impactites are also considered as impact diagnostic evidences. The shatter cones are the only mesoscopic shock features (Fig.4) ranging in size from a few centimeters to meters and mostly observed close to the central uplift. However, this horse tailing like features can be confused with cone-in-cone structure, plumose markings and certain conical wind-blown structures (French and Koeberl, 2010). It is to be noted that the ridge and groove like structures in shatter cones radiate from a common centre, are penetrative and point towards the direction of impact. They occur in all types of target lithology but are best developed in fine-grained rocks.

The microscopic shock metamorphic features comprise planar fractures (PFs), feather features (Poelchau and Kenkmann, 2011 and the references there in) at low shock pressure, PDFs (planar deformation features; (Fig.5), ballen structures (Fig.6), high pressure mineral

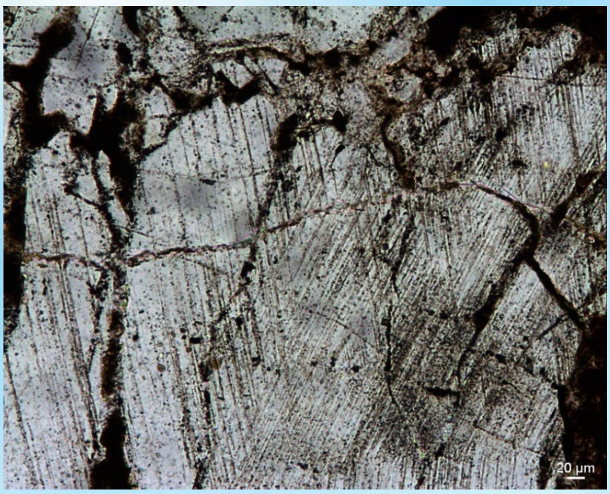

Figure 5. the planar deformation features (PDFs) are microscopic shock metamorphic features seen here in a quartz clast (Dhala impact melt breccia sample, India).

polymorphs (like coesite, stisovite, diamond, lonsdelite and reidite etc.), shock-induced diaplectic glasses (maskelynite and lechatelierite), granular zircons and checkerboard feldspar etc. These microscopic features can be easily identified with the help of a petrological

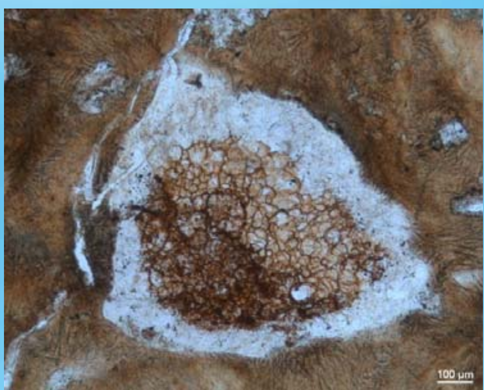

Figure 6. Ballen quartz with toasting in a fine-grained melt (annealed) matrix occurring Dhala impact melt breccia sample, India.

microscope but it is desirable to further analyze these features at higher optical resolution using a SEM (Scanning Electron Microscope) or TEM (Transmission Electron Microscope). The PDFs are reported from quartz and feldspars in terrestrial impactites and occur as single or multiple sets (up to 12 sets). Individual PDFs are perfectly planar, narrow (<2-3 µm) and the respective spacing between two consecutive PDFs may vary from 2 to 10 µm. The PDFs can be decorated type (bearing fluid inclusions) occurring in both toasted and non-toasted types. It is important to note that optical identification of PDFs needs to be supplemented by their optical orientation using a U-stage (Fig. 7) or spindle stage as the PDFs have tendency to form along specific crystallographic directions in minerals. TEM (transmission electron microscopy) technique is also employed to characterize shock diagnostic PDFs. The PDFs form in a pressure range of ~7 to 35GPa (French, 1998). The ballen texure is observed in quartz clasts from the impact melt breccia as nearly circular to elliptical forms in two dimensions with variable size and rim thickness. The individual ballen loops may show varied optical orientation. One can observe clear as well as toasted domains in ballen-bearing quartz grains (Pati et al., 2008; Pati et al., 2010). The ballen texture forms at pressures above 30-35 GPa and temperatures above 1200ºC. The checkerboard feldspar is another shock feature first reported from the Lappajärvi impact structure, Finland (Bischoff and Stöffler, 1984) and it develops due to total fusion of the plagioclase clasts followed by fractional crystallisation of the melt. The shock-metamorphosed zircons are known to retain the diagnostic evidences of impact even under granulite facies metamorphism (Kamo et al., 1996; Reimold et al., 2002) and in some cases contain planar microstructures (Kamo et al., 1996; Reimold et al., 2002; Wittmann et al., 2006). The shock melted mineral clasts, in general, include maskelynite

Figure 7. PLANEX facility developed in University of Allahabad for PDFs indexing using 4-axes Universal Stage (kindly donated by Professor Olaf Madenbach, Ruhr University, Germany).

(after feldspar) and lechatelierite (after quartz). The development of perlitic fractures in lithic clasts indicates complete melting under shock pressure in excess of 60 GPa. Laser Raman spectroscopy is instrumental in the characterization of shock-induced high pressure phases. Very rarely the impactor (meteorite) fragments are observed within the impact melt breccia (Maier et al., 2006). The extraterrestrial component can also be identified by measuring the concentration of PGEs (platinum group elements), especially Ir (iridium; >1 ppb) and using isotopic signatures (Os, Cr and Fe isotopic ratios). It is also necessary to analyze and differentiate non-diagnostic features frequently cited to report new impact structures. These so called evidences include: 1. an area with circular morphology, 2. geophysical anomaly showing a circular pattern, 3. brittle structures in macroscopic scale, 4. minerals having kink bands, 5. Mosaicism, 6. presence of pseudotachylitic breccia, 7. magmatic rocks and glasses, and 8. Spherules etc. (French and Koeberl, 2010). Sometimes errors may creep in owing to "the invocation of new and unverified features (e.g., fullerenes with trapped He) as evidence of impact" (French and Koeberl, 2010).

Shock features in Lonar and Dhala structures, india

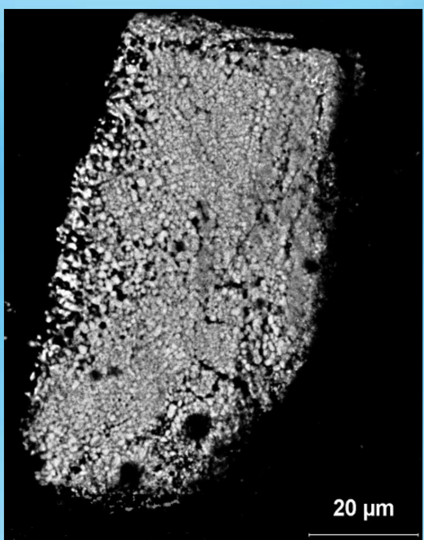

Figure 8: A BSE-SEM image of a granular zircon observed as a mineral clast in impact melt breccia from Dhala structure, India.

In India, there are only two confirmed impact structures known till date. The Lonar structure, Buldhana district, Maharastra state, India (Maloof et al., 2011 and the references there in) is a 1.88 km diameter simple structure with a central depression now occupied by a saline lake. The evidences put forth in favour of its impact origin include the presence of shatter cones (Fredriksson et al., 1973) and diaplectic glass (maskelynite; Nayak, 1993). Although, maskelynite has been reported in subsequent studies (Fudali et al. 1980; Osae et al. 2005; Maloof et al., 2011) but shatter cones have not been observed in later reports. Recently chemical signature of a chondritic impactor has been identified in the sub mm-sized impact spherules based on their high Ni, Cr, and Co contents compared to the target basalt (Mishra et al., 2009). The Dhala impact structure (25°17′59.7″N, 78°8′3.1″E), Shivpuri district, Madhya Pradesh state, India (Pati, 2005; Fig.3) is a complex impact structure with a central elevated area, monomict breccia ring and a thick impact melt breccia (Fig.4) sheet of Paleoproterozoic age (Pati et al., 2010). The geology of Dhala and adjoining areas is summarized in Pati and Reimold (2007), Pati et al. (2008) and Pati et al. (2010). The impact melt breccias, pseudotachylite breccias and suevite are the three types of impactites reported from Dhala structure so far. The shock features present in these impactites are PDFs (in quartz and feldspar), ballen quartz, high pressure silica polymorph, diaplectic glasses (maskelynite and lechatelierite), granular zircon (Fig. 8), checkerboard feldspar and chemical traces of the impactor.

Concluding remarks

Planetary and space sciences research in India have gained momentum in recent years. A large amount of data has been generated through Chandrayaan-1 and future missions to Moon (Chandrayaan-2) and Mars are in the pipeline. Hence, it is important to realize the significance of impact cratering research so that a better understanding of the planetary processes is made using now available high resolution data. At the same time a lot needs to be done, to investigate the terrestrial impact structures, increase crater count (including submarine structures), look for structures of Archean age, develop better techniques for the confirmation of impact structures (especially at low shock pressures and in soft rocks) and to understand cratering mechanism.

Acknowledgements

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Impacts on Solar System Objects

Introduction

Impact cratering processes invariably affected all planetary objects in our Solar System, but their preservation depends on the internal and/or external evolution of the host planetary object. Volcanism, tectonics and erosion have significantly removed most of the impact record on Earth and Venus; younger ones are exposed now. A thick atmosphere of Venus shattered most of the incoming projectiles, but some survived and produced craters/basins, and some caused multiple impacts. Denudation removed most of the impact structures on Earth, and to some extent on Mars. In the case of Io, no impact record could be preserved due to the on-going global volcanic activity. Interestingly, some planetary objects whose internal or external evolutions were frozen early in the past because of their distinct thermal evolution, could preserve most of the impact record, as in the case of the Moon, Mars and Mercury in the inner Solar System, and possibly some icy satellites of Jupiter and Saturn in the outer Solar System.

Because of our easy and frequent access to the Inner Solar System, our understanding about the impact structures in them have been improving, while we know little about the outer Solar System. In general, the impact structures on the planetary surfaces were recognized using images obtained by the orbiting satellites and interpreted by studying their morphology. However, the shock effects associated with the impacts were only documented for those on Earth and the Moon, because of our direct access to the rocks/minerals from the impact sites and the shock-imprints in the nature-returned meteorites. The impacts on planetary objects produced a wide variety of structures: simple craters (bowl-shaped ones), complex craters (circular structures with central peaks), peak-ring basins (a circular ring on the basin floor), multi-ring basins, and flat-floored large basins without rings. Some impact structures show a transitional form to some of these morphologies. All morphological variants of these structures are recognizable in almost all planetary objects but with some differences depending upon the size/mass of the planetary objects, projectile and target properties and the energy of the impacts. Impact structures in the inner Solar System bodies are mostly on

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