Terrestrial Impact Structures and their Confirmation: Example from Dhala Structure, central India

J. K. Pati\textsuperscript{1}, K. Prakash\textsuperscript{2} and R. Kundu\textsuperscript{1}

\textsuperscript{1}Department of Earth & Planetary Sciences, Nehru Science Centre, University of Allahabad, Allahabad, India
\textsuperscript{2}Department of Geology, Banaras Hindu University, Varanasi, India
Email: jkpati@yahoo.co.in; kuldeep_prakash@yahoo.com

Abstract

Although seventy percent of the Moon surface area is covered by meteoritic impact structures only 176 confirmed impact structures known on Earth hitherto. In India, the recently discovered Dhala impact structure, M.P. and the Lonar crater, Maharashtra are the only two confirmed impact structures. The simple, complex and multi-ring impact structures are confirmed on the basis of mesoscopic and microscopic shock metamorphic features besides the physical and/or chemical signature(s) of the impactor (meteorite). The role of bolide impacts in the formation of mineral deposits and playing a crucial role in some of the major mass extinction events is also well known. The impact cratering process is considered responsible for the planetary evolution, landscape modification, and the presence of water and life on Earth.

Introduction

Bolide impact structures broadly cover the surfaces of planetary bodies in the solar system (Taylor, 1992) but predominantly occur in the planets of the inner solar system, their moons and asteroids. Nearly 70% of the Lunar surface is covered by impact structures. However, these are rare features on the surface of the planet Earth and only 176 structures are currently known (http://www.unb.ca/passc/ImpactDatabase/Age; October 10, 2009) as confirmed impact structures. The discovery of meteoritic impact structures dates back to 1930 and a sharp rise in their numbers took place in 1960 with the increase in the awareness of various diagnostic petrographic and mesoscopic shock metamorphic features. Presently the rate of discovery is about 3 to 4 structures per year (Grieve and Shoemaker, 1994). Unfortunately, the newly reported structures are relatively young and only handful of older structures are known (Pati et al., 2008a). Most impact structures known on Earth are younger than 300 million years and smaller than \( \sim 20 \) km in diameter (Grieve et al., 1995; Reimold and Gibson, 1996). Only a few much larger and older structures have been recognized, which include the 2025 ± 4 Ma old, originally 280 km wide, Vredefort Structure in South Africa (Kamo and Krogh, 1995; Stöffler et al., 1994) the \( \sim 1850 \) Ma old and originally about 200 km wide Sudbury Structure in Canada (Deutsch et al., 1995; Pati, 2005), and the \( \sim 25 \) km diameter Paleoproterozoic Dhala impact structure, India (Pati et al., 2008b).

The recognition of relatively young and well-preserved impact structures and the process by which they were formed may be comparatively easy, provided diagnostic evidences, which include a variety of breccia types containing shock metamorphosed mineral and lithic clasts are preserved (Pilkington and Grieve, 1992). The identification of old deeply eroded impact structures are often difficult to recognize, but may still show geological and geophysical signatures (Grieve et al., 1996; Koeberl et al., 2004). In case of a perfectly circular regionally distinct structure, remote sensing and geophysical techniques have become increasingly important for the initial detection of possible impact structures. The use of remote-sensing techniques during the last decades has strongly supported the search for new possible impact structures (Buchner and Kenkmann, 2008; Koeberl and

Reimold, 2005; Koeberl et al., 2005) and research in impact cratering (Reimold et al., 2006; Donofrio, 1997; Grieve, 2005). However, only shock metamorphic features, presence of bolide component and/or geochemical evidences can provide final unequivocal evidence for the confirmation of an impact structure.

The bolide impacts generate enormous energy in terms of temperature (>20,000°C) and pressure (~500 GPa). They help in the generation and remobilization of the ore-bearing fluids and consequent mineralization. It is important to note that nearly sixty percent of the terrestrial impact structures are associated with some form of economic mineral deposits (Au, Ni-PGE, U, and diamond etc.) or natural resources which include some of the important hydrocarbon deposits. The large Chicxulub impact structure, Mexico (~190 km in diameter), for instance, produces ~2.1 million barrels of oil per day (Reimold et al., 2005a; Dietz, 1947; Dietz, 1959). However, even the small impact structure of View field, Saskatchewan, Canada (~2.5 km in diameter), produces significant amounts of oil and gas (~600 barrels of oil and ~250 million cubic feet of gas per day; Dietz, 1947). In addition, the process of impact cratering is known to have possibly contributed to the presence of life and water on Earth.

In India, the 1.83 km diameter Lonar structure, Buldhana district, Maharasstra is the first reported confirmed impact structure. It is a simple structure in basaltic target rock, discovered in 1823. The recently discovered Dhala structure, Shivpuri district, M.P., of more than 11 km diameter and possibly of Palaeoproterozoic age is the only other confirmed impact structure (Koeberl, Farley, Peucker-Ehrenbrink and Sephton, 2004; Buchner and Kenkmann, 2008) from India. The Ramgarh structure, Barana district, Rajasthan is yet to be confirmed as an impact structure since no diagnostic evidence of shock metamorphism has been reported till date.

**Meteoritic impact structures**

Impact structures are geological structures resulted due to the collision of a large meteoroid, asteroid or comet onto a planet or a satellite. All the inner bodies in our solar system are heavily cratered due to bolide impacts throughout the evolutionary history. The surfaces of the Moon, Mars and Mercury, where other geologic processes are believed to have stopped millions of years ago, record meteoritic impacts conspicuously. Although the Earth has been even more heavily impacted than the Moon but the imprints of impact are continuously erased by erosion and redeposition as well as by the resurfacing volcanic and tectonic activities.

**Types of impact structures**

The impact craters can be divided into two morphologically distinct types: Simple craters and Complex structures. Simple craters define a near circular "bowl"-shaped depression at the centre with a raised rim (Fig. 1a). Complex craters, on the other hand, possess central peaks, or an inner "peaked" ring, outer concentric faulted zones and terraced rim walls (Fig. 1b). Three distinct types of impact structures can be formed based on the extent of transient crater's modification. However, there are meteoritic impacts devoid of any characteristic structures, for example Tunguska, Russia. The common crater types include simple craters, complex structures and multiring basins.

**(a) Simple craters:**

Most of the impact craters with a bowl-shaped depression and diameter less than a few kilometers across are called simple craters. The depression helps to preserve the shape and dimensions of the original transient cavity. The transient crater is modified only by minor collapse of the steep walls into the crater cavity during its evolution to a simple crater, and by red deposition of a minor amount of ejected material in the crater (Grieve et al., 1995).
Fig.1: (a) Simple craters define a near circular "bowl"-shaped depression at the centre with a raised rim. (b) Complex structures, on the other hand, possess central peaks, or an inner "peaked" ring, outer concentric faulted zones and terraced rim walls.

(b) Complex structures:

The larger impact structures are generally characterized by a centrally uplifted region, a flat floor and extensive inward collapse around the rim and are called complex- craters (Reimold and Gibson, 1996). The nature of centrally uplifted area in case of large diameter impact structures becomes more complicated. It has been observed that with increasing diameter, the complex structures can also be distinguished into following three types: central peak structures, central-peak-basin structures and peak-ring basin structures.

(c) Multiring basins:

The multiple ring basins essentially comprise multiple concentric uplifted rings and intervening down-faulted valleys (ring grabens). These impact structures are invariably larger compared to other types of impact structures.

Confirmation of impact structures

Confirmation of impact structures are carried out by the evidences given below:

(i) Morphology of the crater (Non-diagnostic)
(ii) Geophysical anomalies (Non-diagnostic; especially magnetic and gravity anomalies)
(iii) Shock metamorphic evidences in macro and microscopic level (Diagnostic), and
(iv) Geochemical evidences (Diagnostic)
Morphological characteristics provide only preliminary information for the identification of a possible impact structure. Geological structures with a circular (near circular) outline (Fig.2), at least deserve additional attention, in an area where no other obvious mechanism for producing near-circular features exists. Morphological observations can be better understood by remote sensing studies especially in case of the deeply eroded impact structures, with better resolution and more spectral information data. Morphological and structural criteria can be applied to high-resolution images taken from space.

Geophysical methods are very useful for identifying the impact structures, especially in the case of subsurface features. In complex craters the central uplift usually consists of dense basement rocks and usually contains severely shocked material. This uplift is often more resistant to erosion than the rest of the crater, and, thus, in old eroded structures, the central uplift may be the only remnant of the crater that can be identified. Geophysical characteristics of impact craters include gravity, magnetic properties, reflection and refraction seismics, electrical resistivity, and others.

![Fig.2](image)

**Fig.2:** The satellite image of Dhala impact structure, India shows a near circular outline with a central elevated area. The red dotted line delimits the structure’s rim.

Shock metamorphic evidences can be expressed in megascopic form shatter cones (Fig.3) or in microscopic form (planar deformation features: PDFs, ballen quartz, checkerboard feldspar, high pressure glasses and various crystalline polymorphs). The shatter cones are the only megascopic (hand specimen to outcrop) feature which provide unequivocal evidences of shock metamorphism. Low shock pressures (2-10 GPa) produce distinguishing conical fracturing patterns in the target rocks, and the resulting shatter cones have proven to be a reliable field criterion for identifying and studying impact structures (Dietz, 1963; French and Short, 1968). Shatter cones occur as individuals or composite group cones and their length vary from millimeters to meters (Milton et al., 1996a; Stöffler and Langenhorst, 1994).
Some minerals of target rocks (e.g., quartz, graphite) may transform to their respective high-pressure polymorphs in shock pressures above 10 GPa. Graphite (C) converts to diamond (cubo-octahedral) or lonsdaleite (hexagonal diamond). Quartz is transformed to stishovite at shock pressures of >12–15 GPa and to coesite at >30 GPa (French and Short, 1968).

Shock waves create a variety of unusual microscopic features like, planer deformation features (PDFs), ballen textures and signatures of complete melting (lithic or mineral clasts) etc. Planar deformation features in quartz, feldspar and other minerals are the most subsequent identifications features of impact structures. These features characteristically occur as sets of parallel deformation planes within individual grains of the mineral. Distinctive planar features in quartz (SiO$_2$) have been one of the most widely applied criteria for recognizing impact structures (Koeberl and Martinez-Ruiz, 2003; Montanari and Koeberl 2000; French, 1998; Grieve et al., 1996).

Planar deformation features (Fig.4) is the shock produced microstructures that were formerly given a variety of names (e.g., "planar features," "shock lamellae"). In contrast to planar fractures, with which they may occur, PDFs are not open cracks. Instead, they occur as multiple sets of closed, extremely narrow, parallel planar regions. Individual PDFs are both narrow (typically <2–3 µm) and closely spaced (typically 2–10 µm).
In altered, geologically old, or metamorphosed samples, PDFs have an equally distinctive but discontinuous character. The original amorphous material in the PDF planes is recrystallized back to quartz, and in the process, arrays of small (typically 1–2 µm) fluid inclusions (“decorations”) develop along the original planes (Fig.5). The resulting features, called decorated PDFs (French and Short, 1968).

**Fig.5:** Photomicrograph showing decorated (notice the fluid inclusion trails) two sets of planar deformation features (PDF) in quartz grains of impact melt breccia, Dhala structure, India.

Ballen quartz (Pati et al., 2008; Reimold and Koeberl, 2008,) is an impact related microscopic features consisting of a series of closed or open loops that range in diameter from 12 to 142µm (Fig. 6) and considered as diagnostic of impact cratering process forming at pressures between 35 and 50 GPa with temperature in excess of 1200-1400°C.

**Fig.6.** Photomicrograph of a quartz grain occurring within impact melt breccia, Dhala structure, India showing open and closed loop-like structures (ballen texture).

Other less common, but equally definitive, megascopic indicators of impact include diaplectic glasses in which feldspar is transformed to maskelynite, high-pressure mineral phases like coesite, stishovite and lechatelierite (fused quartz) occur in impact melts.
In the absence of megascopic and microscopic evidences of shock metamorphism, geochemical analyses may provide definite evidence of impact by identifying a signature from the projectile, either excess iridium or distinctive osmium isotope ratios. Other geochemical signatures which provide strong support include: (1) a match in chemical and/or isotopic compositions between the breccias and melt rocks and the target rocks; and (2) isotopic signatures like Sm/Nd and Rb/Sr in the melt rocks that indicate derivation entirely from crustal rocks without any mantle-derived component.

**Economic importance**

Mineral deposits such as metals and hydrocarbons are associated with about twenty percent of all known impact craters and a recent study (Grieve and Shoemaker, 1994). The impact cratering events leads distinct structural as well as lithological changes in the target rock leading to remobilization followed by accumulation of various economic mineral deposits. The world’s largest PGE-bearing Ni-Cu deposit and world’s richest gold province, Witwatersrand Basin are associated with two most well known impact structures, the Sudbury impact structure, Canada and Vredefort Dome, South Africa, respectively. The Chicxulub, Mexico, Ternovka and Rotmistrovka, Ukraine and Avak, USA are some of the important impact structures hosting hydrocarbon reserves. The Carswell Lake Crater, Canada is associated with uranium deposit, while impact-produced diamonds are extracted from rocks at the Popigai structure, Siberia.

**Conclusion**

The study of impact structures is both essential and challenging to understand planetary evolution, decipher changes in planetary landscapes and to deal with very large-scale past- and future catastrophic natural hazards (including Tsunami). There are many geological unsolved problems (large magma oceans, mass extinctions, large mineral deposits, and formation of large sedimentary basins etc.) to which the endogenetic Earth processes have been unable to provide satisfactory answers. On the other hand, many perplexing questions regarding the origin of water and life on Earth can be answered on the basis of impact cratering research.

It is important to note that the remote sensing and geophysical methods may provide important initial data regarding the identification of an impact structure, but only petrographical and geochemical studies can provide unequivocal evidences.

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**References**


### About the Authors

**Dr. Jayanta K. Pati**, Associate Professor, Department of Earth & Planetary Science, University of Allahabad discovered the Dhala impact structure in 2005. He is currently working in impact cratering research and has visited five impact structures in different parts of the world.

**E-Mail:** jkpati@yahoo.co.in

**Dr. K. Prakash**, Lecturer, Department of Geology, Banaras Hindu University obtained his D.Phil. degree from Department of Earth & Planetary Science, University of Allahabad in 2008. He joined as a Lecturer in Department of Geology, Banaras Hindu University in 2007. His main interest lies in remote sensing study of impact structures.

**E-Mail:** kuldeep_prakash@yahoo.com

**Ms. R. Kundu** is a D.Phil. student pursuing her doctoral study in the Department of Earth & Planetary Science, University of Allahabad pertaining to Dhala impact structure. She is interested in remote sensing, GIS and impact crater research.