Definitive criteria for meteorite impact

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On Earth, because of the constant renewing of its surface by plate tectonics and erosion, and due to the deposition of sediments, or to the oceans and forest which cover craters, the identification of meteorite impact structures is much more difficult than on other planetary bodies (such as on the Moon or Mars) where impact craters are well preserved, and can commonly be recognized based on their morphological characteristics. Crater morphology alone is not a sufficient argument on Earth since a variety of circular features can be formed by completely different endogenic geological processes (e.g., volcanism, salt diapirism, and igneous activity). Because of these complications that essentially include weathering, obliteration, and/or burial of impact craters, it was necessary to develop definitive criteria (also called "diagnostic criteria") for the identification and confirmation of meteorite impact structures on Earth.

In the present contribution, the main definitive criteria for meteorite impact that need to be searched for are reviewed and discussed, so that they can be recognized and convincingly distinguished from non-impact-metamorphic features in the rocks of suspected impact structures.

These criteria are distinctive impact-metamorphic effects that are unique products of impact-produced shock waves. Note that the term “impact metamorphism” covers all types of shock-induced changes, such as the formation of planar microstructures and phase transformations (i.e., so called "shock effects"; including high-pressure phases) and it also encompasses the melting, decomposition and vaporization of target rocks. A great diversity of these irreversible changes in rocks and minerals are known and have been abundantly described, mostly for quartz and to some extent for feldspar, olivine, pyroxene, and zircon grains. Less is known about the shock effects in other minerals.

Shatter cones (distinctive multiple sets of striated conical fractures) are the only distinctive shock-deformation feature that can be seen with the naked eye (meso- to macro-scale features).

Upon shock compression, minerals develop irregular fractures (which are not diagnostic shock effects) and, if the involved pressure is strong enough, planar microstructures (generally crystallographically controlled) may form. Planar microstructures include: 1) planar fractures (PFs; by definition planar, parallel, thin open fissures), 2) feather features (thinly spaced, short, parallel to subparallel lamellae that branch off of PFs), and 3) planar deformation features (PDFs; narrow, individual planes of amorphous material that are less than 2 µm thick, comprising straight, parallel sets spaced 2–10 µm apart and generally occurring as multiple sets per grain). However, when occurring alone, PFs and feather features are not regarded as definitive criteria for meteorite impact.

At high-pressure regimes, diaplectic glass forms, generally from framework minerals, such as quartz or feldspar. Melting of individual minerals and of the whole rock starts at even higher pressures. However, the formation of glasses and/or melts does not necessarily require high shock pressures and can occur through non-impact processes, e.g., in the case of fulgurites or in the process of smelting ore, etc.

High-pressure phases, for example, coesite and stishovite (formed from quartz), diamond (from graphite), and reidite (from zircon) are diagnostic features of meteorite impact. However, the use of such high-pressure phases to confirm impact structures must be applied with some caution, as coesite and diamond are also products of endogenic processes (i.e., not exclusively formed during shock metamorphism).

In some rare cases, the identification of an impact crater can also be based on the occurrence of meteorites spatially associated with a structure. This is only possible for extremely young (as meteorites are rapidly altered) and small (as usually the impacting projectile is almost completely destroyed) craters. Finally, the last definitive criteria reliable as evidence for a meteorite impact event is a chemical and/or isotopic signature from the projectile itself, with for example the detection of siderophile elements (e.g., iridium) or isotopic (osmium, chromium) anomalies in specific geological settings.

It is important to note that because minerals subjected to impact metamorphism occur in different petrographic assemblages and in different rock types, the full spectrum of the diagnostic features described here may not necessarily be present in all impact structures and is strongly dependant on the lithology and other properties of the target rock(s), and is also a function of the magnitude of the hypervelocity impact and of the level of erosion of the considered crater.

As of 2012 about 182 impact structures have been unambiguously identified on Earth based on these criteria.

Fig. 1: Macro- (a, f) and micro-photographs (b-e) of impact metamorphic features. a) Shatter cone in limestone; b) PFs in quartz; c) PDFs in quartz; d) Diaplectic quartz glass and coesite in a shocked sandstone; e) Lechatelierite (quartz melt); f) Vesicular impact-melt glass with partially fused clasts (whitish) of the target material.