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How to Find Impact Structures

7.1. REASONS FOR THE SEARCH

Since the 1960s, the field of meteorite impact geology has evolved far beyond the early arguments about the impact origin of a few individual geological structures. Meteorite impacts on Earth are now widely accepted as an important geological process, and one whose effects are still not fully understood. At the same time, the identification of new impact structures through the discovery of shock-metamorphic effects has become a fairly simple and routine process.

The current search for new impact structures now emphasizes the recognition, among the new discoveries, of individual structures that can provide specific information about key problems: shock-wave transmission, cratering mechanics, physical conditions of the impact environment, impact-melt formation, environmental and biological effects, and the nature of the impact flux over geologic time. The last problem is especially uncertain and controversial, chiefly because relatively few impact structures have been accurately age-dated (*Bottomley et al.,* 1990; *Deutsch and Schärer,* 1994). The discovery and accurate dating of another 10–20 structures might make it possible to estimate more accurately the bombardment rate over time and to determine whether the bombardment process has been random or periodic.

For these reasons, the discovery and recognition of new terrestrial impact structures is still a critical component of future research in this field. To aid in this search, the remainder of this chapter summarizes the general properties of impact structures as they now appear on Earth, so that new candidates can be identified for detailed sampling and study (see also Appendix).

7.2. DETECTION OF CANDIDATE IMPACT SITES

The process of recognizing a new impact structure involves two steps: (1) *detection* of a *candidate* impact site through field studies, geophysical measurements, remote sensing, drilling programs, or (sometimes) pure accident; and (2) *verification* of the site as an impact structure by the discovery of shock-metamorphic effects in its rocks. (In some cases, verification can also be provided by the discovery of meteorites or a meteoritic signature — such as excess iridium — in the breccias or melt rocks associated with the structure.)

Many now-established impact structures first attracted attention because they appeared as anomalous circular features in topography or bedrock geology: lakes, rings of hills, or isolated circular areas of intense rock deformation in otherwise undeformed bedrock. A few impact structures developed in sedimentary rocks were noted because the upturned rocks of their central uplifts resembled salt domes, and the perceived economic potential promoted drilling and detailed geophysical studies. Other impact structures have been found by accident in the course of general field mapping or regional geophysical surveys. Some well-known structures [e.g., Ries Crater (Germany), Sudbury (Canada), and Vredefort (South Africa)] have been considered (often for many decades) as the sites of unusual volcanic activity or "cryptovolcanic" events. And a few structures, so deeply eroded that no circular form remains, have been recognized only by the presence of scattered patches of unusual breccias or strange "volcanic" rocks.

The increasing appreciation of extraterrestrial impacts as a mainstream geological process, and the increasing attention given to newly recognized impact structures, has promoted more searches for new structures as well as systematic mapping of recognized structures by the sophisticated methods of remote sensing and geophysical surveys. However, the discovery and verification stages still remain separate. A candidate impact structure may be detected in many ways (field geology, remote sensing, geophysics), but verification comes only from the identification of definite impact-produced features — shock-metamorphic effects, unique geochemical signatures, or both — in its rocks. At present, there are no other geological or geophysical criteria that unambiguously distinguish impact structures from other circular features such as volcanic calderas, plutonic intrusions, or salt domes. Definite proof of impact origin requires access to the rocks. The candidate structure must first be detected somehow, then it must be sampled.

7.2.1. Geological Features

The first indication of a possible meteorite impact structure is frequently a distinct circular (or nearly circular) feature in the topography or bedrock geology. This circular region commonly shows distinctive and often anomalous bedrock geology in comparison to the surroundings. The region may also be the site of intense and localized deformation (fracturing, faulting, and brecciation), or it may contain unusual (or even normal-looking) volcanic or intrusive igneous rocks.

The distinctive features of impact structures vary with age and erosional history (*Dence,* 1972; *Grieve,* 1991; *Grieve and Pilkington,* 1996). In the few impact structures young enough and fresh enough to still preserve their original crater rims, the circular form may be striking. Original ejecta and shocked rock fragments may still be preserved on the original ground surface outside the crater, and meteorite fragments may even be found to establish the origin of the structure beyond question. In more deeply eroded structures, where the original rim and outside ejecta have been removed, the circular outcrop pattern of breccias and melt rocks that filled the original crater may still attract attention. At deeper erosion levels, where these rocks have been removed, a circular pattern of intense deformation and brecciation, accompanied in larger structures by a preserved central uplift, may still be recognizable, especially in structures formed in sedimentary rocks. In very deeply eroded structures, the circular character may still be expressed by deformed or unusual rock types (e.g., pseudotachylite) in the bedrock, even when the structure has been strongly deformed by postimpact tectonic activity [e.g., Sudbury (Canada)].

A few impact structures have been so deeply eroded that no distinctive circular feature remains. Such structures exist only as patchy remnants of unusual "volcanic" breccias and other deformed rocks, and in many cases [e.g., Rochechouart (France), Gardnos (Norway)] the shock effects (e.g., shatter cones, PDFs in quartz) were only identified in the rocks decades after the rocks themselves had been first described. The accumulated geological literature, especially papers that describe strange breccias and unusual "volcanic" rocks, may be a rewarding ground in which to search for unrecognized impact structures of this kind.

7.2.2. Geophysical Features

The formation of impact structures involves shattering and brecciation of the rocks that already exist beneath the crater floor, followed by filling of the resulting crater by a variety of impact-produced breccias and frequently by postimpact sediments. These processes produce distinctive changes in the physical properties of the rocks in and around impact structures. These changes are expressed most notably as variations in the gravity and magnetic fields (*Pilkington and Grieve,* 1992; *Grieve and Pilkington,* 1996).

Gravity anomalies. Impact structures, even large ones, are relatively shallow, near-surface features in comparison to typical volcanic and tectonic structures. Even so, fracturing and brecciation of the target rocks beneath an impact structure extend to significant depths below the crater floor, and significant fracturing and brecciation may even be present at depths of several kilometers below large structures. Evidence from some studies, e.g., at Ries Crater (Germany), suggests that fracturing extends to depths of about one-third the diameter of the structure (e.g., 6–8 km at Ries Crater). The fractured rock is less dense than the unaltered target rock around the structure, and the resulting density contrast may be increased by the similarly underdense fragmental breccias and sediments that fill the crater. As a result, many impact structures, especially bowl-shaped simple craters, exhibit a *negative gravity anomaly* that is generally circular in shape and closely coincides with the structural boundaries of the circular feature.

Such a negative gravity anomaly is not a definite sign of impact, and such anomalies are absent from many established impact structures. In complex impact structures, where subcrater fracturing and brecciation are accompanied by uplift of denser deep-seated rocks into the central part of the structure, the normal negative gravity anomaly may be reduced or even converted to a positive anomaly, because the uplifted denser rocks overcome the effects of fracturing and brecciation (*Stepto,* 1990; *Pilkington and Grieve,* 1992; *Grieve and Pilkington,* 1996).

Magnetic anomalies. Magnetic field measurements around impact structures have not revealed any single specific signature that can be clearly related to the impact process (*Pilkington and Grieve,* 1992). Some impact structures show no significant magnetic signature because of the fragmentation and mixing of target rock during the cratering process, and they may appear only as an anomalous circular region of low or random magnetic signature among any regional magnetic patterns (e.g., linear anomalies) present in the surrounding preimpact bedrock (*Scott et al.,* 1997). At other impact structures, a strong local magnetic anomaly (positive or negative) may be produced by the remanent magnetization of units of impact melt within the structure or by the uplift of more magnetic units from depth into the central uplift (*Hart et al.,* 1995).

Seismic studies. Seismic profiling studies are increasingly being used to determine the structural deformation present beneath large impact structures [e.g., Gosses Bluff (Australia) (*Milton et al.,* 1972, 1996b); Montagnais (Canada) (*Jansa and Pe-Piper,* 1987); Chesapeake Bay (USA) (*Poag,* 1996, 1997); and Chicxulub (Mexico) (*Morgan et al.,* 1997)]. These studies have revealed a pattern of subsurface deformation features that appears distinctive for such impacts, especially in the larger basin-form structures: (1) modest downward and inward displacements of the rocks along the edges of the basin; (2) structural disruption, with no coherent seismic reflectors, in a central zone that corresponds approximately to the region immediately beneath the central uplift and the original transient cavity; and (3) beneath this central zone, evidence of preserved and continuous reflectors at depth, demonstrating that the structure is shallow and has no connecting roots to the lower crust or mantle. Seismic profiles have also played an important role in demonstrating the large size and complexity of the highly deformed Sudbury (Canada) structure (*Wu et al.,* 1994).

Despite the complexities of geophysical features and the lack of unique signatures for impact structures, geophysical measurements have been essential for the detection of impact structures that have been completely buried under layers of younger sediments. The appearance of circular anomalies in gravity or magnetic surveys has already led to the discovery of many verified subsurface impact structures, about one-third of the current known total (*Grieve,* 1991; *Grieve and Masaitis,* 1994; *Grieve et al.,* 1995). Surprisingly large and important impact structures have been discovered in this way: Puchezh-Katunki (Russia) (D = 80 km), Chicxulub (Mexico) (D ≥ 180 km), the Chesapeake Bay Crater (USA) (D = 90 km), and Morokweng (South Africa) (D ≥ 70 km?).

Geophysical studies will continue to play a critical role in the future discovery and study of impact structures. Even though a well-defined circular geophysical anomaly can only indicate a possible impact structure, the discovery of such anomalies has frequently been followed by verification through core drilling, sample recovery, and the identification of distinctive shock effects or chemical signatures in the rocks (e.g., *Corner et al.,* 1997; *Hart et al.,* 1997; *Koeberl et al.,* 1997a). The combination of geophysical field studies and subsequent core drilling is proving to be an important and effective approach for detecting and verifying new impact structures, and it is essential for detecting and exploring buried ones. Geophysical techniques also play an important and increasing role in exploring established impact structures to determine the details of their geology and formation.

7.3. VERIFICATION OF IMPACT STRUCTURES

The brief history of impact geology suggests that most of the new impact structures identified in the future will be noted first as some kind of anomalous circular or near-circular feature: (1) a circular or near-circular topographic or physiographic surface pattern that can be detected by some form of remote sensing such as air photography or (increasingly more common) space-based imagery; (2) a circular region of anomalous exposed bedrock, characterized by intense and localized deformation, uplift, breccia development, or by the occurrence of unusual "volcanic" rocks; or (3) a circular geophysical anomaly, most probably in the gravity or magnetic fields, associated with a surface or subsurface structural feature. Rarer candidate sites that may be deeply eroded impact structures may lack a circular signature and may appear only as scattered exposures of anomalous rocks on the ground or as descriptions in the geological literature.

Verification of an impact origin requires the discovery of unique impact-produced features. At present, the only generally accepted impact features are shatter cones, petrographic shock effects, or distinctive geochemical signatures in the rocks of the structure. Possible impact structures must therefore be sampled by means of field studies, core drilling, or examination of existing sample collections. In the field, well-developed and indisputable **shatter cones** are the best indicators of impact, because they are distinctive and widely distributed, especially in the basement rocks of deeply eroded structures. **Pseudotachylite breccias** in basement rocks may indicate an impact origin, especially where they occur over large areas or in thick veins (e.g., ≥10 m), but they are not yet accepted as a unique impact indicator because similar rocks can be produced by tectonic processes.

Rock samples can provide definite evidence of impact, often by applying only the straightforward and inexpensive methods of standard petrography. Many distinctive shock effects can be identified even in small samples, such as pieces of drill core. The presence of **PDFs in quartz** is the most widespread, distinctive, and generally accepted petrographic shock criterion. They may occur in samples from two discrete regions in the structure: (1) in shocked-metamorphosed rock fragments in crater-fill breccias and impact melts; and (2) (more rarely) in preserved regions of shocked parautochthonous rocks just below the original crater floor, or in the central uplift, where PDFs may occur in or with shatter cones. Less common, but equally definitive, indicators of impact include **diaplectic glasses** (e.g., feldspar transformed to **maskelynite**), high-pressure mineral phases (e.g., **coesite, stishovite**), and **lechatelierite** (fused quartz) in impact melts.

In breccias or melt rocks that display no shock features, geochemical analyses may provide definite evidence of impact by identifying a signature from the projectile, either **excess iridium** (or other platinum-group elements) or distinctive **osmium isotope ratios**. Other geochemical signatures that strongly support an impact origin, but do not provide definite proof, include: (1) a match in chemical and/or isotopic compositions between the breccias and melt rocks and the target rocks in which the structure is found; and (2) isotopic signatures (e.g., Sm/Nd, Rb/Sr) in the melt rocks that indicate derivation entirely from crustal rocks (especially from crustal rocks much older than the structure itself), without any mantle-derived component.