Earth-Science Reviews 98 (2010) 123–170

Contents lists available at ScienceDirect

Earth-Science Reviews

journal homepage: www.elsevier.com/locate/earscirev

The convincing identification of terrestrial meteorite impact structures: What works, what doesn't, and why

Bevan M. French [a], Christian Koeberl [b,*]

[a] Department of Paleobiology, Smithsonian Institution, PO Box 37012, NMNH, MRC 121, Washington, DC 20013-7012, USA
[b] Department of Lithospheric Research, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria

ARTICLE INFO

Article history:
Received 10 April 2009
Accepted 16 October 2009
Available online 25 October 2009

Keywords:
impact craters
shock metamorphism
shocked quartz
spherules
craters
crater identification

ABSTRACT

In the geological sciences it has only recently been recognized how important the process of impact cratering is on a planetary scale, where it is commonly the most important surface-modifying process. On the Moon and other planetary bodies that lack an appreciable atmosphere, meteorite impact craters are well preserved, and they can commonly be recognized from morphological characteristics, but on Earth complications arise as a consequence of the weathering, obliteration, deformation, or burial of impact craters and the projectiles that formed them. These problems made it necessary to develop diagnostic criteria for the identification and confirmation of impact structures on Earth. Diagnostic evidence for impact events is often present in the target rocks that were affected by the impact. The conditions of impact produce an unusual group of melted, shocked, and brecciated rocks, some of which fill the resulting crater, and others which are transported, in some cases to considerable distances from the source crater. Only the presence of diagnostic shock-metamorphic effects and, in some cases, the discovery of meteorites, or traces thereof, is generally accepted as unambiguous evidence for an impact origin. Shock deformation can be expressed in macroscopic form (shatter cones) or in microscopic forms (e.g., distinctive planar deformation features [PDFs] in quartz). In nature, shock-metamorphic effects are uniquely characteristic of shock levels associated with hypervelocity impact. The same two criteria (shock-metamorphic effects or traces of the impacting meteorite) apply to distal impact ejecta layers, and their presence confirms that materials found in such layers originated in an impact event at a possibly still unknown location. As of 2009 about 175 impact structures have been identified on Earth based on these criteria. A wide variety of shock-metamorphic effects has been identified, with the best diagnostic indicators for shock metamorphism being features that can be studied easily by using the polarizing microscope. These include specific planar microdeformation features (planar fractures [PFs], PDFs), isotropization (e.g., formation of diaplectic glasses), and phase changes (high pressure phases; melting). The present review provides a detailed discussion of shock effects and geochemical tracers that can be used for the unambiguous identification of impact structures, as well as an overview of doubtful criteria or ambiguous lines of evidence that have erroneously been applied in the past.

Contents

* Corresponding author.
E-mail addresses: frenchb@si.edu (B.M. French), christian.koeberl@univie.ac.at (C. Koeberl).

0012-8252/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.earscirev.2009.10.009

1. Introduction

The existence and importance of meteorite impact events in the terrestrial geological record — once ignored and even ridiculed — are now generally accepted (e.g., Marvin, 1986; Hoyt, 1987; Mark, 1987; French, 1990b; Marvin, 1990; Grieve, 1991; Grieve and Shoemaker, 1994; Grieve, 1998; Marvin, 1999; Reimold, 2003; French, 2004; Reimold and Koeberl, 2008). Meteorite impacts, especially large ones, are now recognized as the causes of large circular geological structures, major crustal deformation, large volumes of igneous rocks, important economic mineral and hydrocarbon deposits, extensive ejecta deposits and marine breccias, and at least one major biological extinction. These rare but catastrophic events are now being actively explored by an increasing number of investigators who are generating a rapidly growing literature in both scientific and popular publications. (For collections of relevant technical papers, see, e.g., French and Short, 1968; Hörz, 1971; Silver and Schultz, 1982; Nicolaysen and Reimold, 1990; Sharpton and Ward, 1990; Dressler et al., 1994; Ryder et al., 1996; Koeberl and Anderson, 1996; Johnson and Campbell, 1997; Papike, 1998; Grady et al., 1998; Dressler and Sharpton, 1999; Gilmour and Koeberl, 2000; Montanari and Koeberl, 2000; Peucker-Ehrenbrink and Schmitz, 2001; Buffetaut and Koeberl, 2002; Koeberl and MacLeod, 2002; Plado and Pesonen, 2002; Koeberl and Martinez-Ruiz, 2003; Pierazzo and Herrick, 2004; Dypvik et al., 2004; Poag et al., 2004; Horton et al., 2005a; Koeberl and Henkel, 2005; Glikson and Haines, 2005; Kenkmann et al., 2005b; Grieve, 2006; Cockell et al., 2006; Evans et al., 2008; Herrick et al., 2008). For more popular histories, see Raup (1986, 1991); Chapman and Morrison (1989); Verschuur (1996); Alvarez (1997); Powell (1998). For a general tutorial and literature guide, see French, 1998.

This revolution in geology has been based on a single critical factor: the ability of geologists to unambiguously identify meteorite impact structures and to distinguish them from similar structures formed by more conventional endogenic geological processes (cf. Grieve, 1987, 1991; Grieve and Shoemaker, 1994; Grieve, 1998, 2001). Because the impacting projectile is almost completely destroyed in an impact event (Melosh, 1989, Chs. 4–5; but see discussion below, Section 3.2.1), most diagnostic indicators of meteorite impact are found instead in the terrestrial target rocks, which have been subjected to the extreme pressure and temperature environment of intense shock waves generated by the impact (Melosh, 1989, Chs. 3–5).

Most of the geological features of meteorite impact structures are not unique; these include a generally circular form, a circular pattern of deformation, extensive fracturing and brecciation, circular gravity and magnetic anomalies, and the presence of large units of igneous rocks. Such features can be (and often are) the product of such conventional processes as tectonic deformation, salt-dome formation, volcanic eruption, or internal igneous activity. The unambiguous identification of impact structures has been based on a small set of distinctive shock-metamorphic effects (see French, 1968a; French and Short, 1968; French, 1998 and papers therein; Koeberl, 1997, 2002; Langenhorst, 2002) that are the unique products of impact-produced shock waves and have been used in establishing the impact origin of up to now approximately 175 terrestrial impact structures (e.g., French and Short, 1968 and papers therein; Grieve, 1991; Stöffler and Langenhorst, 1994; Grieve et al., 1996; Koeberl, 1997a; Grieve, 1998; Montanari and Koeberl, 2000, Ch. 1) (see Table 1). (For simplicity, in the remainder of this article, we will generally replace "shock-metamorphic" by "shock" or "shocked," as in "shock effects," "shock features," "shocked quartz," etc.).

Table 1
Shock-produced deformation effects: diagnostic and non-diagnostic.

A. Diagnostic indicators for shock metamorphism and meteorite impact
1. Preserved meteorite fragments (3.2.1)
2. Chemical and isotopic projectile signatures (3.2.2)
3. Shatter cones (3.3.1)
4. High-pressure (diaplectic) mineral glasses (3.3.2)
5. High-pressure mineral phases (3.3.3)
6. High-temperature glasses and melts (3.3.4)
7. Planar fractures (PFs) in quartz (4.2.1)*
8. Planar deformation features (PDFs) in quartz (4.2.2)
B. Non-diagnostic features produced by meteorite impact and by other geological processes.
1. Circular morphology (5.2.1)
2. Circular structural deformation (5.2.1)
3. Circular geophysical anomalies (5.2.2)
4. Fracturing and brecciation (5.3.1)
5. Kink banding in micas (5.3.2)
6. Mosaicism in crystals (5.3.3)
7. Pseudotachylite and pseudotachylitic breccias (5.3.4)
8. Igneous rocks and glasses (5.3.5)
9. Spherules and microspherules (5.4)
10. Other problematic criteria (5.5)

*When occurring in multiple sets oriented to specific low-index crystallographic planes. Numbers in parentheses indicate relevant sections in text.

Unfortunately, the rapidly spreading interest in impact structures among both scientists and media reporters has not been accompanied by an equally wide dissemination of the specific details about the exact nature and recognition of distinctive shock effects. As a result, there have been many recent reports of evidence for impact, both in ambiguous individual structures (e.g., Ernstson et al., 1985; Miura et al., 1995; Gorter and Bayford, 2000a,b; Gorter and Glikson, 2000; Miura, 2000; Ernstson et al., 2001; Miura et al., 2001; Paillou et al., 2003; Becker et al., 2004a; Paillou et al., 2004; Miura, 2005; Paillou et al., 2006; Sisodia et al., 2006; Chen, 2008) and at major extinction boundaries (Retallack et al., 1998; Kaiho et al., 2001; Becker et al., 2001; Ellwood et al., 2003; Shukla et al., 2003), which are problematic, controversial, and not generally accepted (see Reimold (2007), Pinter and Ishman (2008), and discussions below). In many cases, this confusion results from a lack of understanding about how to distinguish clearly between definite shock effects and the results of conventional geological deformation.

Continued investigations of shock features, and their use in identifying previously unrecognized impact structures, are critical to the future development of the exciting new field of impact geology. Most of the preserved impact structures on Earth, about several hundred, still remain to be discovered and identified (Trefil and Raup, 1990; Grieve, 1991). The continued identification of these impact structures will provide a better statistical data base for estimating the past impact rate on the Earth, and detailed studies of new structures will help understand better the mechanisms of crater formation and the geological and environmental effects of such events. In addition, expanded knowledge about the nature of shock effects will be critical in recognizing impact structures that form in a variety of target rocks (e.g., basalts, unconsolidated sediments) and in identifying regional or global ejecta layers from unknown craters that have not yet been found or may have been destroyed by conventional terrestrial processes (e.g., erosion, subduction) since their formation.

Several general principles constrain the search for and recognition of terrestrial impact structures: (1) Preserved terrestrial impact structures are relatively rare, probably <1000 features ≥ 10 km in diameter worldwide (Trefil and Raup, 1990; Grieve, 1991, 1998). (This is comparable to the number of currently active terrestrial volcanoes, about 1500 (Simkin and Siebert, 1994)). A corollary of this fact is that any given circular feature is more apt to be something other than an impact structure. (2) The largest volume of the rocks involved in an impact structure show only nondiagnostic, low-level deformation features, while the distinctive and diagnostic shock effects are restricted to relatively small specific areas of the structure (Dence, 1965; Grieve, 1991). (3) The positive identification of an impact structure can come only from petrographic or geochemical evidence contained in the rocks of the structure. (4) Remote-sensing observations and geophysical studies can be important in locating and studying impact structures, but they cannot by themselves provide an unquestioned identification for an impact feature (Grieve, 1991; Koeberl, 1997a; Grieve, 1998; French, 1998; Koeberl, 2004; French, 2005). Field work on the ground, including the collection and examination of rock samples, is essential.

The goal of this paper is, therefore, to describe the diagnostic shock-metamorphic deformation effects in detail, so that they can be recognized, documented, and convincingly distinguished from non-shock features in the rocks of suspected terrestrial impact craters. We emphasize the nature and characteristics of the shock features produced in quartz-bearing target rocks, which have been the major source of identifications (and alleged identifications) of terrestrial impact structures. We also discuss which unique geochemical effects are connected to impact events, and how they can be used for identification. The present paper does not address the related issues of tektite formation and distribution (see, e.g., O'Keefe, 1963, 1976; Koeberl, 1986, 1990, 1994; McCall, 2001) or the occurrence and significance of similar shock-metamorphic effects in meteorites (refer to, e.g., Stöffler et al., 1991; Rubin, 1992; Rubin et al., 1997; Schmitt, 2000; Rubin, 2003; Sharp and DeCarli, 2006; Xie et al., 2006).

This paper is an extensive expansion of an earlier informal report (French, 2005) and also builds on reviews by Montanari and Koeberl (2000) and Koeberl (2007). The following sections discuss: (1) the general conditions of impact and shock metamorphism; (2) the diagnostic physical and chemical effects that are unique indicators of shock metamorphism and meteorite impact; (3) non-diagnostic effects produced by both impact and endogenic geological processes; (4) other non-diagnostic effects that are produced primarily by endogenic processes; and (5) examples of problems involving the use of non-diagnostic effects in the identification of new impact structures and impact ejecta layers. Appendix A provides detailed instructions on the identification of diagnostic shock features and their distinction from non-impact deformation effects.

2. Conditions of shock metamorphism

Meteorite impact is, in principle, a simple process in which a large object strikes an even larger one at very high velocity, locally releasing a huge amount of energy. In contrast to many endogenic geological processes, this basic simplicity makes impacts and the resulting impact craters amenable to physical modeling, and studies in impact geology have been long supported by extensive theoretical and laboratory investigations (e.g., Shoemaker, 1963; papers in French and Short, 1968, and in Roddy et al., 1977; Melosh, 1989; Pierazzo and Herrick, 2004; Herrick et al., 2008; and references therein).

Simply summarized, a meteorite impact involves the transfer of the original kinetic energy of the incoming high-velocity projectile into a larger mass of target rock at a point on the surface of the Earth. Typical large stony impactors have diameters of 0.5–10 km, masses of 10^9–10^{16} kg, geocentric velocities of 20–40 km $\cdot$s^{-1}, and resulting kinetic energies of 10^{15}–10^{20} J. (For comparison, the total energy released by the 1815 eruption of the Tambora volcano, Indonesia, was about 10^{20} J, and the total annual heat flow from the Earth is about 10^{21} J; for further details and comparisons, see French, 1998, Table 2.1).

On impact, this kinetic energy is transformed, almost instantaneously, into intense high-pressure shock waves that originate at the contact point and radiate, approximately hemispherically, through the surrounding target (Melosh, 1989, Chs. 3–5). The pressure amplitudes of the shock waves decrease with distance (r) from the impact point, approximately as $1/r^{1.5}$ to $1/r^3$, depending on such parameters as the original impact velocity and target rock properties (Melosh, 1989, p. 62–63). At significant distances from the impact point (i.e., at about the location of the eventual crater rim, the shock waves decay to pressures sufficiently low (<1 GPa) that they transform into normal elastic (seismic) waves that can propagate for great distances (thousands of km) beyond the final rim of the crater.

Because the shock waves propagate outward approximately hemispherically (assuming homogeneous targets), the original impact point can be regarded as surrounded by a series of nested, approximately hemispherical, shells of outwardly decreasing shock pressure (Kieffer and Simonds, 1980; Melosh, 1989, p. 64, his Fig. 5.4). Near the impact point, initial shock pressures can exceed 100 GPa, resulting in the total melting and vaporization of a large volume of target rock together with virtually all of the impactor. Passing outward, the lower shock pressures produce a series of distinctive effects in the target: rock melting (≥60 GPa); selective mineral melting (40–60 GPa), diaplectic glass phases (30–45 GPa); high-pressure minerals (12–30 GPa), planar deformation features (PDFs) in quartz (10–25 GPa); multiple fracturing (cleavage) and basal Brazil twinning in quartz (5–10 GPa); shatter cones and rock fracturing (2–5 GPa). (Pressure values are approximate; for details see Stöffler, 1984, Table 3; Melosh, 1989, Table 3.2; and Stöffler and Langenhorst, 1994, Table 8).

As the shock waves move outward, interactions between them and the original ground surface (free surface), set the target material into outward and upward motion, thereby excavating a crater (the transient cavity) which is typically 10–20 times the diameter of the original impactor (Melosh, 1989, Chs. 5, 8). The subsequent crater excavation, which immediately follows the passage of the original shock waves, brecciates much of the shocked target rock within the transient cavity and ejects a large part of this fragmented material from the growing crater. Some of these distinctively shocked materials fall back into the crater, mixed with unshocked materials from the more distant collapsing crater rim, to form the allochthonous breccias (or crater-fill breccias). It is important to note that the bulk of the material ejected from the crater is not exposed to shock pressures in excess of a few GPa (Kieffer and Simonds, 1980; Grieve, 1991, 1998) and generally does not contain distinctive shock effects.

As a result of these combined shock and excavation processes, a family of diverse and unusual rock types is formed in and around the resulting crater: breccias, melts, ejecta deposits, and distinctively shocked bedrock (Dence, 1965, 1968; Dence et al., 1968; Stöffler and Grieve, 2007). However, rock types that contain certain diagnostic indicators of shock metamorphism tend to be found only in two specific regions of the final crater (e.g., Dence, 1965, 1968): (1) as discrete inclusions of shocked rock and melt in the crater-fill breccias; and (2) as a restricted near-surface zone beneath the center of the crater floor, in the shattered but (mostly) in place subcrater parautochthonous breccias (Fig. 1). Searches for shock effects in individual impact structures have therefore been most successful in deposits of crater-fill breccia in well-preserved structures and in the subcrater rocks and central uplifts in more deeply eroded ones. (Distinct shock-metamorphic effects, especially melting and PDF formation in quartz, are also found in a material that is ejected completely from the crater to form deposits of proximal ejecta [at distances of ≤$5R_c$, where R_c is the radius of the crater] or distal ejecta [at >$5R_c$, and even to global distances]).

During the processes of shock-wave passage and crater excavation, the target rocks are exposed to conditions that are totally unlike those of more normal geological deformation and metamorphism. Large volumes of target rock are exposed to transient shock pressures of 10–60 GPa, in comparison to the static pressures of 1–3 GPa present during metamorphism in the Earth's crust. Strain rates during passage of the shock waves are 10^4/s to 10^6/s, several orders of magnitude greater than those developed in normal tectonic processes (10^{-3}/s to 10^{-6}/s) (Carter, 1965, 1968a,b; Stöffler, 1971; Grieve, 1991). The passage of a shock wave through a rock also deposits waste heat in the rock, raising the post-shock temperature; for shock pressures >60 GPa, post-shock temperatures may exceed 2000 °C, several hundred degrees above the temperatures generated by igneous activity, producing distinctive melting and transformation reactions (Stöffler, 1984). In a meteorite impact event, these processes occur virtually instantaneously: only 10^{-6} s for the passage of shock wave through 1 cm of rock, ≤1 h for the complete production of an impact structure 100 km in diameter. These rapid processes, in turn, produce rapid cooling and result in the preservation of distinctive disequilibrium features, in sharp contrast to the more general approach to equilibrium observed in conventional igneous and metamorphic rocks (e.g., Philpotts, 1990; Vernon, 2004).

Deformation effects produced in impact events can be divided into two types: (1) features produced at higher shock pressures (≥10 GPa) that are unique to impact-produced conditions, and (2) features produced at lower shock pressures (<10 GPa) that cannot be distinguished from similar features produced by normal geological processes (see Table 1).

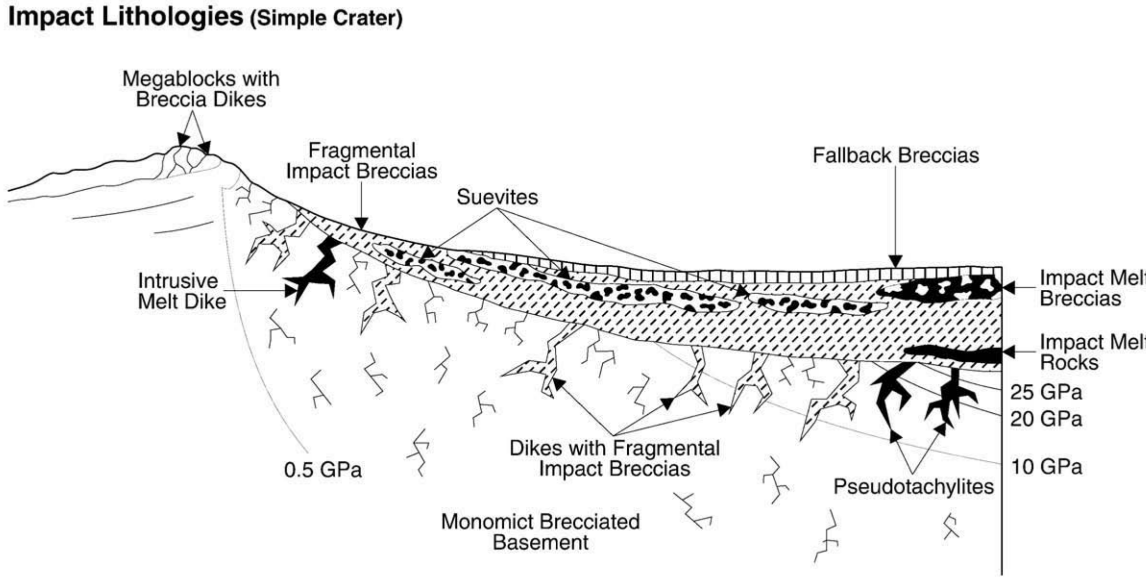

Fig. 1. Schematic radial cross-section through one-half of a simple impact structure, showing locations of different impact-produced lithologies. Curved lines show isobars of shock pressures (in GPa) produced in the basement rocks by the impact. Lithologies showing unique diagnostic shock effects, formed at pressures ≥10 GPa, tend to be restricted to two locations: (1) crater-fill materials (suevites, melt breccias, and fragmental impact breccias) deposited in the crater; and (2) brecciated basement rocks, often containing shatter cones, near the center of the structure (at right). The final impact structure is a relatively shallow geological feature, and both the impact structure and the distinctively shocked rocks can be removed by only modest amounts of erosion.

3. Shock-deformation features in impact structures

3.1. Shock metamorphism and the identification of impact structures

Shock metamorphism (French, 1968a; French and Short, 1968) is generally defined as "all changes in rocks and minerals resulting from the passage of transient, high-pressure shock waves" (French, 1968a, p. 2). Because hypervelocity meteorite impacts are the only known natural mechanism for generating such shock waves, the earlier term *impact metamorphism* (Chao, 1967) is equivalent when studying natural rocks, but the other, broader term also includes identical effects produced in the similar shock-wave environments of laboratory experiments and nuclear explosion events (see papers in French and Short, 1968). The unique formation conditions of shock-metamorphic features (also called "shock-deformation features" or simply "shock features"), and their significance in the rocks of terrestrial impact structures, have now been solidly established by a wide range of geological, experimental, and theoretical studies (e.g., French and Short, 1968; Hörz, 1968; Alexopoulos et al., 1988; Melosh, 1989; Stöffler and Langenhorst, 1994; Grieve et al., 1996).

Different shock-deformation features develop at different shock pressures. The most diagnostic shock features are produced at pressures ≥10 GPa; these include PDFs in quartz, diaplectic mineral glasses such as *maskelynite*, high-pressure mineral phases (e.g., coesite and stishovite), and ultrahigh-temperature melting effects. Some diagnostic shock features can develop at lower pressures (e.g., ≥2–10 GPa): shatter cones and certain unique planar microstructures in quartz (see discussion below). However, such low-pressure shock waves (≤5 GPa) can also produce both megascopic and microscopic deformation effects that are similar to, or even identical to, features produced by normal geological deformation: circular deformation patterns, fracturing, faulting, brecciation, and various microscopic planar microdeformation features in mineral grains. The determination as to whether such features are impact-produced or not is not straightforward, and many features actually produced by low-pressure shock waves are in fact not diagnostic of meteorite impact.

In past studies, several lines of evidence have been used successfully to identify both young and old meteorite impact structures: (1) surviving remnants of the crater-forming projectile, occurring either as discrete meteorite fragments or as distinctive chemical signatures in the impact-produced rocks; and (2) diagnostic shock-deformation features in the rocks, especially those produced at pressures ≥10 GPa (see Table 1). These two types of features are described in detail below. In addition, because PDFs in quartz have been one of the most widely-used indicators of impact structures (Stöffler and Langenhorst, 1994; Grieve et al., 1996), these features, the problems involved in identifying them, and the non-impact features that resemble them, are discussed in detail in a separate section below.

3.2. Traces of the impacting projectile

3.2.1. Preserved meteorite fragments

A spatial association between an anomalously large concentration of meteorite fragments and a geologically fresh crater can generally be accepted as evidence that the crater resulted from the impact of the meteorite (see, e.g., Herd et al., 2008). (However, it should be remembered that it took geologists several decades to accept this "obvious" connection in the case of the Barringer Meteor Crater, Arizona; see Hoyt, 1987.).

Unfortunately, this association, although powerful, is rarely found, and it is generally of little use in identifying geologically old or deeply eroded structures. The impacting projectile tends to be quickly destroyed, either in the impact or by post-impact weathering. During the impact event, the projectile is subjected to shock pressures >100 GPa, sufficient to produce complete melting and vaporization (Melosh, 1989, Ch. 4), and survival of unmelted meteorite fragments in the resulting impact structure is extremely rare (for exceptions, see Schnabel et al., 1999; Maier et al., 2006).

Any meteorite fragments that survive the impact process and are deposited in and around the newly-formed impact structure will be unlikely to survive for geologically long periods of time before being destroyed by post-impact weathering. Only in some young impact structures that formed by an iron meteorite projectile (e.g., Meteor Crater [Arizona], Henbury [Australia], Wolfe Creek [Australia]) can iron meteorite fragments be recovered for a few tens to hundreds of thousands of years after the impact — geologically short timescales. Terrestrial survival ages of meteorites, even in the less destructive environments of cold and hot deserts, do not exceed a few million years (Zolensky, 1998; Bland, 2001) and are often <50 ka (e.g., Jull et al., 1998; Jull, 2001). No preserved meteorites have been found associated with terrestrial impact craters more than 0.5 Ma old (Grieve, 1991).

Accordingly, the association between meteorites and impact structures will be useful only for very young structures, and the long-term survival of fresh meteorite fragments (e.g., over tens or hundreds of millions of years) should not be expected. Ancient meteorite fragments have been found at the K–T boundary (Gersonde et al., 1997; Kyte, 1998) and in Ordovician sediments (e.g., Schmitz and Tassinari, 2001), but the meteorites have been almost completely altered to diagenetic minerals and have been identified only from relict minerals (e.g., chromite; Alwmark and Schmitz, 2006) and by chemical signatures. The alleged occurrence of unaltered micrometeorite fragments at the Permian–Triassic boundary (Basu et al., 2003) is, therefore, difficult to understand because it is unlikely that these micrometeorites would have remained unaltered for periods that are orders of magnitude longer than observed elsewhere, and the occurrence remains in need of further study and independent confirmation.

The use of preserved meteorite fragments to identify impact structures is also limited by the existence of a continuing flux of meteorite bodies unrelated to large hypervelocity impact events. The presence of definite preserved meteorites does not per se indicate that a hypervelocity impact event occurred, and there is always the small possibility of a coincidental association of a small number of meteorite fragments with a suspect crater structure.

3.2.2. Chemical and isotopic signatures from the projectile

Although actual projectile fragments rarely survive an impact event, detectable amounts of melted and vaporized projectile are often incorporated into impact-produced breccias and melt rocks during formation of the resulting crater. This dispersed projectile (meteoritic) material can be conclusively identified, even after geological periods of time, by distinct chemical and isotopic signatures in the rocks containing it, thus providing reliable evidence for a meteorite impact event (for reviews, see Koeberl, 1998; Tagle and Hecht, 2006; Koeberl, 2007). Meteoritic material has now been identified at about 45 of the approximately 175 currently known impact structures (for a list, see Koeberl, 2007). Such meteoritic material can also be incorporated into debris ejected from the crater, and the same chemical and isotopic signatures have also been used to establish the impact origin of glassy bodies and other ejecta deposited at significant distances from the crater (e.g., Alvarez et al., 1980).

During the impact, the original projectile material is diluted by mixing with a volume of vaporized, melted, and fragmented target rock that is orders of magnitude larger than the projectile. As a result, the actual amount of projectile material incorporated into impact-crater rocks is generally small, typically <1 wt.%. Detection of such small amounts of extraterrestrial matter is based on the analysis of those elements that are highly enriched in meteorites relative to the target rocks (= typical terrestrial crustal rocks).

In practice, such analyses have been restricted chiefly to such siderophile elements as Ni, Co, Cr, Au, and the platinum group elements (PGEs; Ru, Rh, Pd, Os, Ir, and Pt). In particular, Ir analyses have been effectively used to establish impact origins, notably for the Cretaceous–Tertiary (K–T) boundary layer (Alvarez et al., 1980) and for a number of impact structures (Palme et al., 1981; Palme, 1982; Koeberl, 1998). Other elements that have on occasion been proposed as impact indicators (e.g., As, Sb, Ni, V) are considered unreliable because of their common enrichment in target rocks and their tendency to be mobilized and concentrated by post-impact hydrothermal activity (Koeberl, 1998). In addition to elemental abundances, the isotopic ratios of Os (Koeberl and Shirey, 1993; Koeberl et al., 1996b, 1997; Lee et al., 2006) and Cr (Shukolyukov and Lugmair, 1998; Shukolyukov et al., 1999; Koeberl et al., 2007) can also be used as impact indicators because the isotopic ratios in meteorites are distinctively different from those in terrestrial rocks.

These methods can be both effective and convincing. Chemical analyses can conclusively establish the presence of <1 wt.% of an extraterrestrial projectile component. In typical samples, contents of Ir ≥ 1–2 ppb strongly suggest the presence of an extraterrestrial signature, and such results can be strengthened by demonstrating that the abundances of other siderophile elements follow a meteoritic (e.g., chondritic) distribution pattern, rather than a terrestrial one (Koeberl, 1998, 2007). A siderophile element plot for several different impact-related rocks is shown in Fig. 2.

In addition to establishing the presence of meteorite impact events, siderophile-element analyses have been used to indicate the type of projectile, because different meteorite classes have different elemental ratios (e.g., Palme et al., 1981; Palme, 1982; see reviews by Koeberl, 1998, 2007). These attempts have not been entirely successful, chiefly because of variations in siderophile element contents within similar classes of meteorites, and the nature of the projectiles is still debated for many structures (for details, see Koeberl, 1998; McDonald, 2002; Koeberl, 2007).

Even so, these critical elements occur in very small quantities (ppm to ppb amounts) ($1\ \text{ppm} = 10^{-6}$ g/g; $1\ \text{ppb} = 10^{-9}$ g/g) in typical rock samples, and sophisticated analytical methods, combined with careful planning and sample selection, are essential to produce reliable results. Elemental abundances are usually determined by Instrumental Neutron Activation Analysis (INAA) methods (Palme et al., 1981; Palme, 1982; Koeberl, 1998; Koeberl and Huber, 2000; Huber et al., 2000). In some cases, methods with more selectivity and sensitivity are necessary — namely measurements of the isotopic compositions of the elements Os and/or Cr. These require more complex chemical separation techniques and mass-spectrometric measurements (Koeberl and Shirey, 1993; Koeberl et al., 1996b; Koeberl, 1998; Shukolyukov and Lugmair, 1998; Shukolyukov et al., 1999; Lee et al., 2006). These methods have a much greater potential to allow the identification of even small amounts of a meteoritical component (in the case of the Os isotopic method; Fig. 3) or constrain the type of meteorite involved (in the case of the Cr isotopic method; Fig. 4).

Despite the potential of siderophile element analyses to establish the origin of suspected impact structures and to identify distal impact

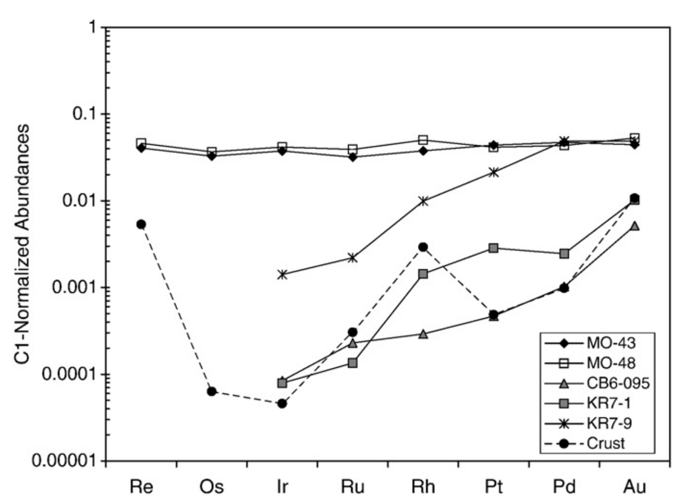

Fig. 2. Plot of platinum-group element and related metal abundances, normalized to carbonaceous-chondritic compositions (Orgueil meteorite), in two impact melt rocks from the Morokweng impact structure, South Africa (MO-43 and MO-48), a suevite from the Chesapeake Bay impact structure, USA (CB6-095), a lithic breccia and a suevite from the Bosumtwi impact structure, Ghana (KR7-1 and KR7-9, respectively), and the average upper continental crust. A clear meteoritic component is visible only in the Morokweng data, representing a relatively high (several percent) amount of meteorite admixture. (See Koeberl, 2007, for references.)

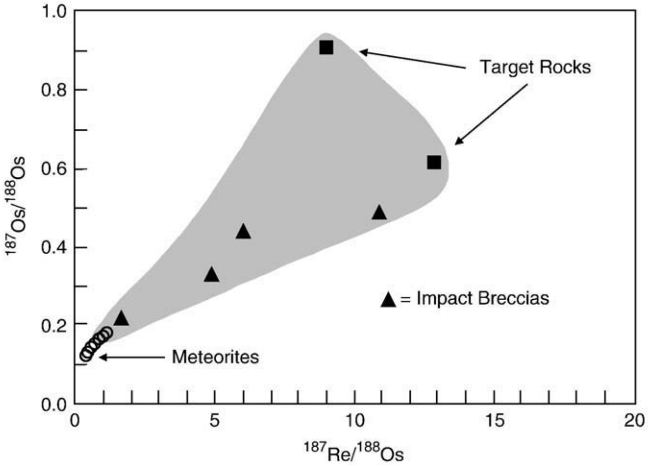

Fig. 3. Re–Os isotopic diagram used as a mixing diagram between meteoritic and target rock compositions, showing the admixture of a meteoritic component in rocks from the Kalkkop impact crater, South Africa (modified after Koeberl, 2007). Suevitic breccia samples plot between the meteorite and the target rock data points, indicating a variable admixture of a meteorite component. The amount of meteoritic material detectable with this method is about an order of magnitude lower than for elemental abundance measurements.

ejecta, the actual analyses and their interpretation involve complexities that are often not appreciated:

3.2.2.1. Reliance on Ir analyses alone. Because of its good detection limits and relatively easy analysis, Ir abundances alone have been commonly used as proxies for the complete range of the PGEs, and small apparent Ir anomalies have been cited as evidence for impact (e.g., Xu et al., 1985; Firestone et al., 2007). However, slight Ir enrichments (up to a few hundred ppt) (1 ppt $=10^{-12}$ g/g) can be produced by purely terrestrial processes such as hydrothermal

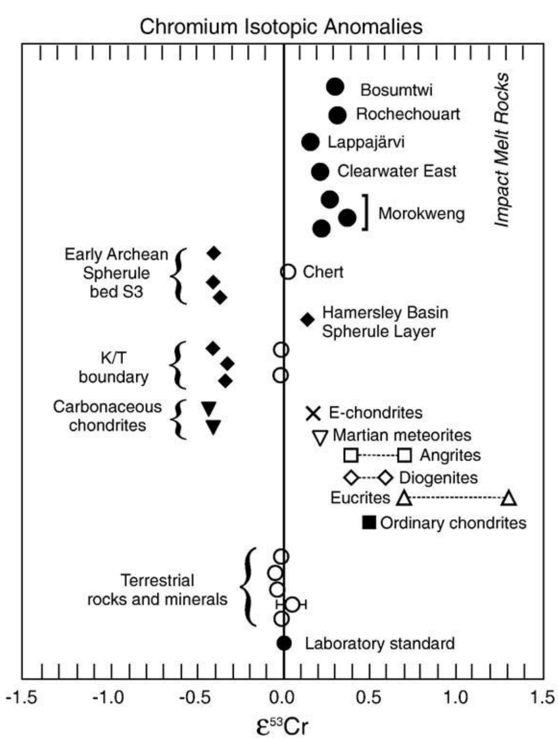

Fig. 4. Plot of chromium isotopic anomalies in meteorites, terrestrial rocks, and a variety of impact-related materials (modified after Koeberl, 2007; Koeberl et al., 2007). Values different from zero indicate the presence of a meteorite-derived component. This method also allows constraining the type of meteorite involved — in particular a distinction between ordinary and carbonaceous chondrites.

activity or the incorporation of ultramafic rocks, and the use of such small enrichments as impact indicators is highly questionable (see Koeberl et al., 2004). More reliable results can be obtained by measuring the abundances and ratios of a larger suite of siderophile elements (e.g., Fig. 2) and demonstrating that these results are consistent with a meteoritic component.

3.2.2.2. Analysis of associated target rocks. To establish firmly that any observed siderophile-element anomalies are due to extraterrestrial material in a sample, it is essential to analyze a representative suite of associated (non-impact) target rocks to determine and compensate for the amounts of terrestrially-derived siderophile elements. Even impact-produced rocks that are highly enriched in extraterrestrial projectile material will still be composed of >95 wt.% of terrestrial materials. Many terrestrial rocks contain significant amounts of siderophile elements, i.e., ≤10 ppb for ultramafic rocks (e.g., Palme et al., 1981; Palme, 1982; Koeberl, 1998), and such rocks, if present at an impact site and involved in the impact, could introduce significant Ir into the resulting melts and breccias. The ideal way to estimate the terrestrial siderophile contribution is to collect and analyze a suite of target bedrocks, exposed in the region of the crater, but not involved in the cratering event. In cases where a sufficient number of target rock analyses is difficult to obtain, a statistical regression approach (see discussion by McDonald et al., 2001; Tagle and Hecht, 2006) may be applicable. In either case, the background (indigenous) contribution needs to be subtracted.

3.2.2.3. Interpretation of null results. The apparent absence of extraterrestrial siderophile enrichments in samples from suspected impact structures does not establish that a meteorite event did not occur. Some meteorites (e.g., achondrites) are not enriched in siderophile elements, and such projectiles would not produce a siderophile anomaly in an impact event. (Achondritic contributions can only be detected by using the Cr isotopic method; cf. Koeberl, 2007, for a review). Furthermore, the presence of vaporized and melted projectile material in an impact event is generally restricted to those materials that were originally close enough to the impact point to have been penetrated by dispersed projectile melt and vapor: crater-filling allochthonous breccias, impact melt bodies, and glasses and other materials distributed in proximal and distal ejecta deposits. Anomalies are unlikely to be present in other materials, such as parautochthonous breccias and shattered rocks below the crater floor, which have been mostly fractured and brecciated in place, with little or no movement, mixing, or penetration of projectile melt and vapor.

Anomalous concentrations of siderophile elements, when carefully measured and interpreted, provide a powerful technique for recognizing the impact origin of suspect geological structures, impact breccias, melt units, impact-produced glasses, and distal impact ejecta layers in sequences of sedimentary rocks. However, the successful application of these methods requires much more than quick and casual analyses for Ir alone. Careful sample collection, characterization, and preparation, reliable analyses of multiple elements, and critical interpretation of the results, are essential to make a convincing case for meteorite impact.

3.3. Unique target-rock deformation features formed by shock-wave conditions

3.3.1. Shatter cones

Shatter cones are distinctive multiple sets of striated conical fractures that develop at relatively low shock pressures in the rocks of terrestrial impact structures (Dietz, 1959, 1963a,b, 1968; Milton, 1977). They were the first feature to be proposed as a diagnostic impact criterion (Dietz, 1947, 1959), and they remain the only diagnostic shock effect that is visible at megascopic (outcrop and hand-specimen) scales. Shatter cones are a valuable impact criterion because they can form in large volumes of target rock, especially in deeply eroded impact structures, and they have played a significant role in the identification of impact structures by being the first (and sometimes the only) diagnostic shock effect observed (e.g., Howard and Offield, 1968; Hargraves et al., 1990; Fackelman et al., 2008).

When ideally developed, shatter cones form complete or partial cones that penetrate the target rocks in which they form (Fig. 5). Cones vary greatly in size, from ≤1 cm long, small enough to be recognized in drill core samples (e.g., Sawatsky, 1977) to large structures as much as several meters long (Dietz, 1968; Sharpton et al., 1996; Fackelman et al., 2008). Over small (outcrop-sized) areas, shatter cone apices are often oriented in one direction, and the cone axes are generally parallel. The general parallelism of shatter cones and their axes in most occurrences has been used to support the argument that the cone apices point in the direction from which the shock wave came. This argument is also supported by a few studies of shatter-cone orientations (Guy-Bray et al., 1966; Milton et al., 1972; Milton, 1977), in which the shatter cones have been shown to point inward and upward in cases where the target rocks (e.g., originally horizontal sediments) can be graphically restored to their pre-impact positions (Dietz, 1959, 1968; Milton, 1977). However, cones with widely divergent orientations have also been observed in both outcrops and hand specimens (e.g., Dressler et al., 1999; Wieland et al., 2006).

Shatter cones have several distinctive characteristics that distinguish them from non-impact features: (1) they can form in all the rock types present in an impact structure: carbonates, shales, clastic sediments, granites, gabbros, and other crystalline rocks; (2) they consist of penetrating fracture surfaces, along which the rock can be broken to reveal new cones or partial cones; (3) the surfaces have positive and negative relief, and concave negative surfaces ("casts") of the convex cone surfaces can commonly be found; and (4) the striations on cone surfaces are distinctive and directional; they consist of alternating positive and negative grooves that radiate downward and outward from the apex of the cone. Secondary radiating striations commonly develop along the primary ones, forming a distinctive structure called "horsetailing".

Despite their abundance in many impact structures and the long history of shatter-cone studies, the physical details of shatter-cone formation have not been extensively studied and are still unclear (Johnson and Talbot, 1964; Gash, 1971; Baratoux and Melosh, 2003). Experimental and geological studies suggest that shatter cones can form over a wide range of shock pressures, from as low as ≥2 GPa to possibly as high as 30 GPa (Dietz, 1968; Milton, 1977; Roddy and Davis, 1977). In-place shatter cones tend to be restricted to the central areas of impact structures where such pressures are developed, and they are commonly observed in the uplifted parautochthonous rocks of the central uplift. Shatter cones are also rarely observed in individual rock fragments in the allochthonous breccias above the crater floor or in breccia dikes in the parautochthonous subcrater rocks. These observations suggest that the shatter cones formed as immediate products of shock-wave passage, before the subsequent brecciation and excavation of the rocks of the transient cavity. In most cases, shatter cones do not contain petrographic shock effects, which require shock pressures of ≥10 GPa. However, depending on shock pressure and rock type, shatter cones may contain petrographic shock effects such as quartz PDFs and even diaplectic glass (Dressler, 1990, p. 242; and pers. comm.).

The quality of shatter cones varies greatly with the rock type in which they form: fine-grained rocks (such as limestone and dolomite) produce excellent, finely-detailed cones (Fig. 5), while coarser rocks (sandstone, quartzite, and other crystalline rocks) produce cruder cones that may be more difficult to recognize (Fig. 6). Even in suitable rocks, shatter cones are not always well-formed, and the typical conical shape may degenerate into nearly flat and poorly-striated surfaces (Fig. 7) that may be hard to distinguish from non-impact features such as fault slickenslides, wind-abrasion surfaces (Fig. 8), cone-in-cone structures in sedimentary rocks, or even artificial blast cones in quarries and road cuts (Dietz, 1963a,b, 1968).

With careful observation, shatter cones can be distinguished from such features. For example: (1) the striations in shatter cones are divergent; striations in slickenslides tend to be parallel; (2) shatter cones form in all rock types and at all angles to preexisting rock structures such as bedding; cone-in-cone structures (Pettijohn, 1957, pp. 209–210, Plates 8, 30) typically form only in shaly rocks, with the cone axes normal to bedding and the cone apices pointing downward

Fig. 5. Unusually fine group of shatter cones in very fine-grained carbonate rock from the Steinheim structure, Germany. The specimen shows in great detail the typical features of shatter cones: nesting of multiple cones, generally parallel orientation of cone axes, radial divergence of striations downward and outward from the cone apices (at upper left), and the distinctive subsidiary striations ("horsetailing") along the cone surface.

Fig. 6. Large crude shatter cones, in fine- to medium-grained crystalline rocks at the recently discovered Santa Fe (New Mexico) structure (see Fackelman et al., 2008, Figs. 3). Although these cones lack the fine details of cones developed in finer-grained rocks, they show the distinctive conical shape, parallelism of cone axes, and development of subsidiary cones along the surfaces of the larger cones. White card at lower center gives scale in cm (left side) and inches (right side).

Fig. 7. Flat to slightly curved striated surfaces in a shatter-coned outcrop of Serpent Quartzite at the Sudbury (Canada) structure. Although conical shapes are not well developed, the effects of shatter-coning are still recognizable in the slight convexities of surfaces bearing the striations, in the definite divergence of striations from right to left, and in the presence of occasional crude subsidiary cones (upper right, just above pen). Cone axes are nearly horizontal. Pen is 12 cm long.

(Lugli et al., 2005); and (3) shatter cones are penetrative features; striated wind-abrasion structures do not extend into the underlying rock (Elston and Lambert, 1965; Elston et al., 1968).

At present, no quantitative criteria have been developed to clearly distinguish shatter cones from similar non-impact features, and the identification of shatter cones (especially poorly-developed ones) depends considerably on the experience and the eye of the beholder (e.g., Reimold and Minnitt, 1996). In many occurrences, shatter-coned rocks in impact structures are accompanied by other impact-produced lithologies that exhibit distinctive shock effects (e.g., quartz PDFs) and provide complementary and convincing evidence of impact. (In many cases, the initial discovery of shatter cones has spurred successful searches for other shock effects.) However, in some cases, exposures of well-developed shatter cones have been generally accepted as evidence of an impact origin (e.g., Manton, 1965; Hargraves et al., 1990; Salameh et al., 2006, 2008; Fackelman et al., 2008). For new structures, especially when distinctive shock effects are not present, identification of shatter cones must be firmly based on careful descriptions which establish that the features show the unique characteristics of shatter cones and are clearly distinct from similar non-impact features (e.g., Wieland et al., 2006; Fackelman et al., 2008).

Fig. 8. Conical wind-abrasion features developed on the surfaces of outcrops of sedimentary rocks exposed in a desert environment at the Tsenker structure, Mongolia. Crude conical forms, produced by sandblasting, point downward and to left, in the direction of the prevailing wind. Although these features resemble shatter cones, they are restricted to the surface of the exposed rock and do not form a fracture network below the surface. White card (at right) gives scale in cm (left edge) and inches (right edge).
Photograph courtesy of Jens Ormö.

To be convincing, identifications of shatter cones in suspected impact structures should demonstrate the following, using quantitative measurements as far as possible: (1) that the conical features are present in a variety of rock types; (2) that the cones are oriented at variable angles to pre-impact rock structures such as bedding or schistosity; (3) that complete cones are present, or (4) that the alleged shatter cone surfaces are definitely curved, with the exposed perimeters of the curved surfaces corresponding to at least 90° of the full (360°) perimeter of the theoretical cone; (5) that the surfaces are directionally striated with striae that radiate outward from the cone apex; (6) that subsidiary striations ("horsetailing") are present; and (7) that the conical surfaces are actually fractures that penetrate the underlying rock and have reciprocal positive and negative surfaces.

3.3.2. High-pressure (diaplectic) mineral glasses

At higher shock pressures (>30–50 GPa), the same tectosilicate minerals (chiefly quartz and feldspar) that develop PDFs (see below, Section 4.2.2) are converted into distinctive amorphous or "glassy" phases without actual melting. These phases are called *diaplectic glasses* (Engelhardt and Stöffler, 1968; the equivalent term *thetomorphic glasses* (Chao, 1967) has also been used), and they constitute another set of unique and distinctive criteria for the recognition of shock-metamorphosed rocks in impact structures. Diaplectic feldspar glass (*maskelynite*) has long been known from shocked meteorites (e.g., Tschermak, 1872; Stöffler et al., 1991) and it has now been recognized in many terrestrial impact structures (e.g., Bunch et al., 1967, 1968; Dvorak, 1969; Arndt et al., 1982), commonly associated with diaplectic quartz glass as well (Chao, 1967; Engelhardt and Stöffler, 1968; Stöffler and Langenhorst, 1994; Grieve et al., 1996). Diaplectic glasses formed from other minerals are occasionally observed (e.g., cordierite; Stähle, 1973).

A critical (but often overlooked) characteristic of diaplectic glasses is that they are produced directly by the action of high-pressure shock waves and do not go through a normal melting process at high temperatures (Bunch et al., 1967, 1968; Stöffler, 1984). Typical diaplectic glasses closely pseudomorph the form of the original mineral grain, and they show no disruption or flow. Structurally, diaplectic glasses do not resemble thermally-produced melts. Instead, they retain considerable short-range structural order, and they show significant differences from both the original unshocked mineral and normally-melted glasses when studied by refractive index measurements (Stöffler, 1972, 1974, 1984; Stöffler and Langenhorst, 1994), X-ray diffraction (Hörz and Quaide, 1973), infrared spectroscopy (Bunch et al., 1968; Johnson and Hörz, 2003), or Raman spectroscopy (Heymann and Hörz, 1990; Treiman and Treado, 1998).

In general, diaplectic glasses are less abundant in impact structures than are shatter cones or PDFs in quartz. Because diaplectic glasses form at higher pressures than these features, they will be produced in a correspondingly smaller volume of target rock around the impact point. Nevertheless, diaplectic quartz and feldspar are found in a large number of impact structures, either in shocked inclusions in crater-fill breccias (Stöffler, 1966; Engelhardt and Stöffler, 1968) or in the central uplifts of large structures where adequate pressures were developed in the crater-floor rocks (Dence, 1965, 1968; Dvorak, 1969; Dressler, 1990).

Diaplectic quartz and feldspar glasses, when found, are just as diagnostic for shock and impact as are shatter cones and PDFs, but their unquestioned identification is more complicated. The mere isotropic appearance of a grain in thin section on a flat-stage microscope is not enough to verify the presence of diaplectic glass. Similar isotropism can also be produced by normal thermally-melted glasses, by isotropic or low-birefringent minerals, or even by a fortuitous orientation of the optic axis of the grain normal to the microscope stage. Rigorous identification of diaplectic glasses requires several steps: (1) recognition of an isotropic grain that pseudomorphs the shape of an original mineral; (2) demonstration that the grain is in fact monomineralic (quartz or feldspar), most conveniently with the electron microprobe; and (3) verification of the special character of the grain (fully isotropic and "glassy" but unmelted) by any of several techniques: refractive indices, U-stage measurements, X-ray diffraction (XRD), transmission electron microscopy (TEM), or spectral methods (infrared absorption or Raman).

The recent controversy about the presence of shock-produced maskelynite in a possible Australian impact structure (Becker et al., 2004a,b,c; Renne et al., 2004; Glikson, 2004; Wignall et al., 2004; Müller et al., 2005), indicates the problems involved in such identifications. Typical maskelynite does not produce a simple "glassy" Raman spectrum (Heymann and Hörz, 1990; Treiman and Treado, 1998; Chen and El Goresy, 2000). There are complexities in the Raman spectra of even fully isotropic maskelynite, and careful analysis of well-documented reference samples is an essential step in basing the identification of a new impact structure on maskelynite or other diaplectic glasses alone. There are also debates about the formation of maskelynite itself: Chen and El Goresy (2000) interpreted maskelynite to be not "true" diaplectic glass, but a glass quenched from shock-produced dense melt at high pressures.

3.3.3. High-pressure mineral phases

In addition to deforming crystal structures, high-pressure shock waves can also convert target rock minerals into new phases that are normally stable only at high static pressures that correspond to the lower crust or mantle of the Earth. The presence of such high-pressure phases in circular structures developed in near-surface rocks is definite evidence of shock-wave action and therefore of meteorite impact. Two high-pressure forms of SiO_2, coesite (Fig. 9A) and stishovite, have served as early indicators of shock metamorphism in impact structures (Chao et al., 1960; Shoemaker and Chao, 1961; Chao et al., 1962; Martini, 1978, 1991; Stähle et al., 2008).

Shock-produced diamonds (sub-mm to mm-sized and clearly produced from graphite in the target rocks) have been identified at a large number of established impact structures, where they provide definite evidence of impact (Hough et al., 1995; Gilmour, 1998; Masaitis, 1998; Gilmour et al., 2003). The interpretation of the so-called nanodiamonds found at some impact sites is less clear. These diamonds, which occur as crystals typically 3–5 nm in size, occur in some meteorites and can also be synthesized at low pressures by a variety of nonequilibrium chemical-vapor-deposition (CVD) techniques (see, e.g., Hazen, 1999, Chs. 11 and 12). The use of nanodiamonds as definite impact criteria is still debated (e.g., Gilmour, 1998), and their formation and relation to terrestrial impact events is still not clear (see also discussion below, Section 7.2).

Recent studies have identified other impact-produced high-pressure polymorphs, formed by the action of shock waves on accessory minerals that are common in a wide variety of potential target rock types. Reidite, a high-pressure polymorph of zircon, has been found associated with microtektite deposits (Glass et al., 2002; Wittmann et al., 2006), and a TiO_2 polymorph possibly derived from rutile or anatase has been identified from the Chesapeake Bay structure (Jackson et al., 2006).

The use of such high-pressure polymorphs to identify impact structures must be applied with some caution. Unlike the identification of PDFs, high-pressure minerals cannot generally be identified by microscopic observations alone. While a possible high-pressure polymorph may be located in thin section, other measurements are necessary to verify its identity. Such verification is not difficult and usually involves X-ray diffraction, TEM, Raman spectroscopy (Fig. 9B) or other methods such as nuclear magnetic resonance (Chao et al., 1960; Shoemaker and Chao, 1961; Chao et al., 1962; Yang et al., 1986; McHone et al., 1989; Cygan et al., 1990; Martinez et al., 1993; Fiske et al., 1998; Myers et al., 1998).

The use of coesite and diamond as impact criteria requires caution; both minerals can also be found in non-impact environments in deep-seated terrestrial rocks, where they have formed in equilibrium at high static pressures (e.g., Smith, 1984; Chopin, 1984; O'Brien et al., 2001). In using these two minerals as impact criteria, it is therefore necessary to consider the geological context as well. Coesite and diamond found in structures formed in relatively shallow sediments and crustal rocks are definite indicators of impact. In addition, impact-produced coesite and diamond are generally associated with other phases in disequilibrium relationships not present in ordinary crustal rocks (e.g., multiple silica phases in the same sample; Kieffer, 1971; Kieffer et al., 1976a). The higher-pressure mineral stishovite, however, has until very recently been identified only in impact environments (Chao et al., 1962; Martini, 1978; McHone et al., 1989; Martini, 1991). However, minute amounts of stishovite have recently been found within diamonds (Wirth et al., 2007) and post-stishovite phases have been reported from ultra-high-pressure rocks (Liu et al.,

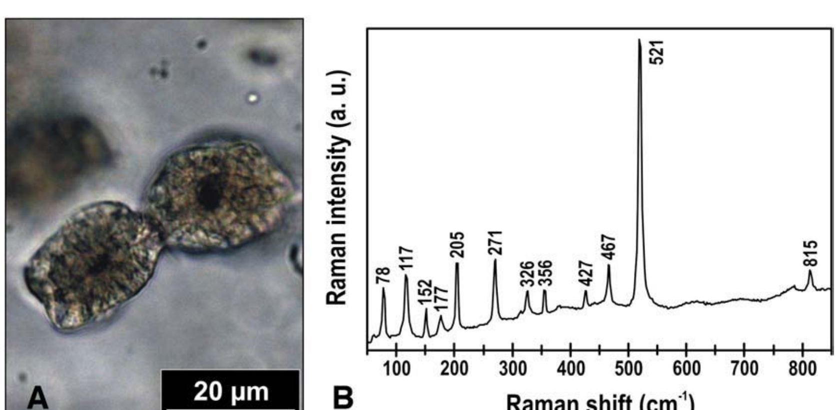

Fig. 9. (A) Microphotograph (in plane-polarized light) of two coesite aggregates within diaplectic quartz glass from suevite (Bosumtwi [Ghana] crater; sample LB-44B, from outside the crater rim) and (B) its associated microRaman spectrum.
Photograph and spectrum courtesy of L. Ferrière.

2007). Nevertheless, these associations occur in very deep-seated mantle rocks, so that stishovite remains an excellent impact indicator when found in sediments or upper crustal rocks.

3.3.4. High-temperature glasses and melts

Distinctive shock effects are not limited to the deformation or transformation of target rock minerals at pressures <40 GPa. Higher shock pressures, especially >50 GPa, produce increasingly high residual temperatures in the target rocks through which they pass (e.g., Dence, 1971; Stöffler, 1984; Melosh, 1989, Ch. 5). In any impact, large or small, a significant volume of the target rock close to the impact point will be raised to post-shock temperatures >1500 °C, sufficient to melt and decompose minerals that are unaffected by the lower temperatures produced in non-impact geological environments. Such melting and decomposition reactions, observed in the rocks and glasses of impact structures, can serve as independent evidence of meteorite impact events (El Goresy, 1968; Stöffler, 1984). The high temperatures involved also serve to homogenize the chemical composition of the resulting melts and to reset isotopic systems used in radiometric age measurement, so that such impact melts are extremely valuable in determining the age of the impact event and the resulting crater (for reviews, see Bottomley et al., 1990; Deutsch and Schärer, 1994; Schärer, 1998).

The most common indicator of such impact-produced high temperatures is the occurrence of *lechatelierite*, or silica glass, which is found in melted rocks or as bands and stringers (*schlieren*) in completely glassy bodies from young and well-preserved impact structures (Hörz, 1965; Engelhardt and Stöffler, 1968; Stöffler, 1984). The presence of lechatelierite indicates temperatures ≥1750 °C, far above the range of normal near-surface geological processes (Stöffler, 1984; Stöffler and Langenhorst, 1994). Other indicators of impact-produced high temperatures include the decomposition of zircon ($ZrSiO_4$) to baddeleyite (ZrO_2) (T = 1850 °C) (El Goresy, 1968; Wittmann et al., 2006), and the melting of titanite (sphene) (T = 1450 °C) (French, 1968b). The melting of sulfide minerals may also provide evidence of unusually high impact-produced temperatures. Spheres of quenched immiscible sulfide melt within silicate glass fragments in suevite from the Chesapeake Bay impact structure indicate temperatures on the order of 1500 °C or above (Belkin and Horton, 2009).

The use of lechatelierite formation and similar high-temperature reactions as evidence for meteorite impact events also requires some caution. In thin section, lechatelierite may be confused with low-temperature opal or opaline chert, which may also appear isotropic under crossed polarizers. A careful distinction can be made on the basis of associated textural and mineralogical associations or the appearance in the phases (e.g., well-developed flow structures in lechatelierite glass).

In addition, one rare non-impact geological process, lightning strikes, can locally create similar high-temperature environments in near-surface rocks. Such strikes generally form thin, narrow, tubular bodies or branching networks of melted soil beneath the surface (Rogers, 1946; Williams and Johnson, 1980; Frenzel et al., 1989; Appel et al., 2006), and such bodies (*fulgurites*) may contain lechatelierite or other high-temperature reaction products (Switzer and Melson, 1972; Essene and Fisher, 1986). In outcrop, it will generally be simple to distinguish the thin, tubular fulgurites from glassy inclusions in impact deposits. However, the problem can become more complicated when only loose fragments of lechatelierite-bearing glass are present on the surface (Haines et al., 2001). A clear distinction can be made between fulgurites and impact-produced glass if petrographic shock features (e.g., PDFs in quartz grains) or chemical signatures from the projectile (see discussion above) can be found in the glass. Marini and Rauka (2004) report the presence of lechatelierite in up to 200-μm-sized microspherules that were produced from burning oil shales, although most of them are hollow or contain abundant vesicles and are thus distinguishable from most impact products.

An unusual texture called "ballen quartz" (or "ballen cristobalite"), observed in some silica grains in high-temperature impactites (Fig. 10), may be related to the impact-produced formation of lechatelierite or diaplectic quartz glass. In "ballen quartz", the original silica grain displays a distinctive fine-grained granular or internal texture composed of small spherical or rounded bodies which may be isotropic or partly to completely microcrystalline (e.g., French et al., 1970; Carstens, 1975). Ferrière et al. (2009) have recently suggested that these features may have formed in two processes: (a) an impact-triggered solid–solid transition from α-quartz to diaplectic quartz glass, followed by the formation at high temperature of ballen of β-cristobalite and/or β-quartz, and finally back-transformation to α-cristobalite and/or α-quartz; and (b) a solid–liquid transition from quartz to lechatelierite followed by nucleation and crystal growth at high temperature.

Because of the evident high-temperature formation conditions, and because ballen silica has been so far only observed in impactites, Ferrière et al. (2009a) suggested adding this feature to the list of impact-diagnostic criteria. However, because of the limited number of studies on this subject, it is probably premature at present to call the presence of ballen alone to be impact-diagnostic, although in virtually all the occurrences so far noted, ballen quartz is accompanied by definite shock-metamorphic features, e.g., PDFs in quartz.

4. Planar microdeformation features in quartz: impact-produced and endogenic features

4.1. Background

Quartz (SiO_2) has been the most commonly-used mineral in identifying suspected meteorite impact structures and in studying the mechanics of shock-wave production and crater development in established structures. The value of quartz as a geological shock-wave indicator arises from a combination of its abundance, its durability, and its tendency to develop striking and unique deformation features over a range of shock-wave pressures. Most striking, and most diagnostic of shock-wave pressures and impact conditions, are the

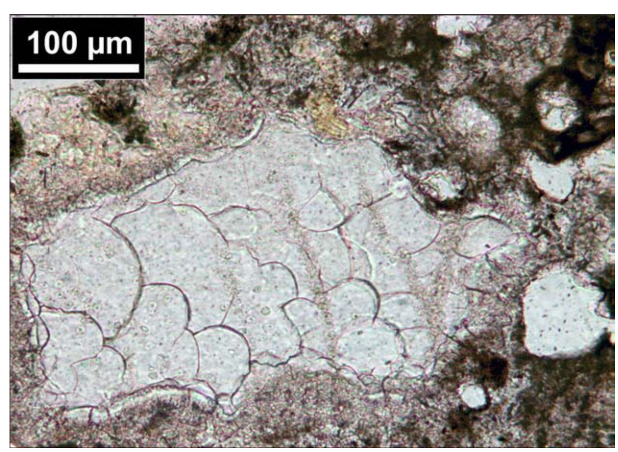

Fig. 10. Typical texture of "ballen quartz" (here "ballen cristobalite") in a shock-metamorphosed quartz grain from a suevite unit outside the Bosumtwi (Ghana) impact structure (cf. Ferrière et al., 2009). In such "ballen quartz" grains, the material may be isotropic or recrystallized (in this case, to α-cristobalite). The "ballen quartz" grain also contains small grains of coesite (lower center: high-relief, greenish). The origin of the "ballen" texture is uncertain; it may develop during the cooling and/or recrystallization or either (or both) shock-produced lechatelierite (fused silica glass) or diaplectic quartz glass. Regardless of its origin, "ballen" texture may be a diagnostic feature for shock metamorphism and meteorite impact events. Sample BH1-0790b; plane-polarized light.
Photograph courtesy of L. Ferrière.

unusual planar deformation features (PDFs) that have served reliably as an impact indicator for several decades (e.g., Engelhardt and Stöffler, 1965; Chao, 1967, 1968; Robertson et al., 1968; Engelhardt and Stöffler, 1968; Engelhardt and Bertsch, 1969; Stöffler and Langenhorst, 1994; Grieve et al., 1996).

Unfortunately, the use of quartz as a shock and impact indicator is complicated by the fact that natural quartz also exhibits a variety of planar and quasi-planar growth and deformation features that develop under normal endogenic geological conditions. These features can be — and often have been — misinterpreted as the results of shock deformation. In studying possibly shocked rocks, it is necessary to appreciate the characteristics of endogenically deformed quartz and to demonstrate conclusively that any planar microstructures observed are the results of shock rather than of normal endogenic deformation.

In the following discussions, we use the nongenetic term *planar microstructure (PM)* to designate a planar or quasi-planar structure within a quartz grain. Shock-produced PMs are divided into *planar fractures (PFs)* and *planar deformation features (PDFs)*, following Stöffler and Langenhorst (1994). (We consider that PFs are identical with *cleavage*.) For simplicity, we also designate by MDL the endogenic features called metamorphic deformation lamellae or Böhm lamellae (see discussion below, Section 4.3.4).

4.2. Shock-produced planar microdeformation features

4.2.1. Planar fractures (PFs)

Low-level shock waves (<10 GPa) can produce multiple sets of parallel open *planar fractures (PFs)* in quartz (Robertson et al., 1968; Engelhardt and Bertsch, 1969; Kieffer, 1971; Stöffler and Langenhorst, 1994; French et al., 1997, 2004). These PFs, which appear identical to cleavage, occur typically in multiple sets, usually 2–3 sets per grain (Stöffler and Langenhorst, 1994; French et al., 1997, 2004). Individual fractures are virtually planar, and adjacent planes are closely parallel. The fracture sets may be from 0.5–5 mm long, depending on the size of the host grain. They do not cross grain boundaries, and they are oriented at specific angles to the *c*-axis of the host quartz (Bunch, 1968; French et al., 2004). The planes consist of open fractures, often filled with secondary minerals. The fractures are relatively thin (typically 3–10 μm), but thicker than PDFs (see below). The planes are also more widely spaced than PDFs, from >20 μm (Stöffler and Langenhorst, 1994) to 100–500 μm (French et al., 2004). Examples are shown in Figs. 11 and 12.

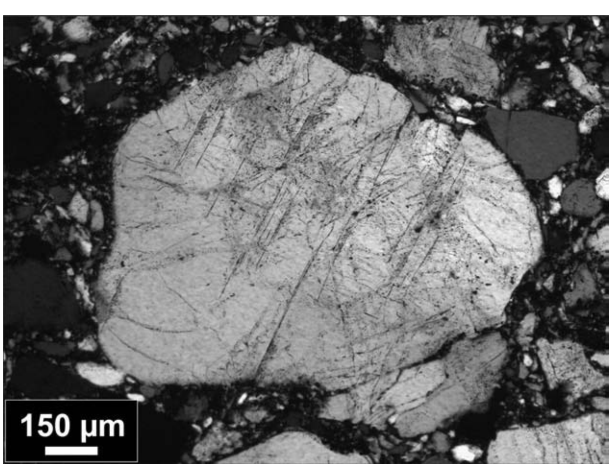

Fig. 11. Planar fractures (PFs) developed in a brecciated quartzite from the central uplift of the Aorunga (Chad) impact structure. A well-developed parallel set of narrow open fractures, filled with dark material, trends NE–SW, and a possible second, less definite, set appears oriented ENE–WSW. Sample OR-10; crossed polarizers. Directions (e.g., "NE–SW") are in relation to an arbitrary "North" at the top of the image. Photograph courtesy of L. Ferrière.

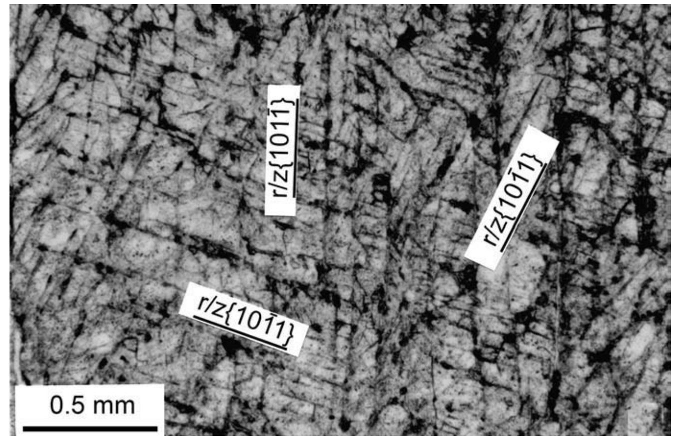

Fig. 12. Three sets of closely-spaced planar fractures (PFs) in a large single quartz grain from a pebble in sandstone from the Rock Elm (Wisconsin) structure (see French et al., 2004, Fig. 3). The open fractures are filled with dark material, probably a mixture of iron oxides, clays, and other alteration products. The sets, oriented N–S, NE–SW, and WNW–ESE, are all parallel to the r/z{1011} direction. Sample WRF-98-15B, crossed polarizers. Directions (e.g., "N–S") are in relation to an arbitrary "North" at the top of the image. Photograph used courtesy of the Geological Society of America.

Multiple PF sets are definitely the product of impact-generated shock waves; they are developed in the rocks of established impact structures while being absent in the surrounding undeformed country rock (Kieffer, 1971; Stöffler and Langenhorst, 1994; French et al., 1997, 2004). They may also be intimately associated in the same quartz grain with definite PDFs developed at higher shock pressures (Engelhardt and Bertsch, 1969; Stöffler and Langenhorst, 1994). The PFs apparently reflect very low shock pressures, possibly <5 GPa (Kieffer, 1971), certainly <10 GPa (Stöffler and Langenhorst, 1994). However, there is still debate over whether such multiple PF sets can be considered as unique impact criteria (Carter, 1968a,b; Hörz, 1968; Kieffer, 1971), since cleavage in quartz has been rarely reported from non-impact environments (Frondel, 1962, p. 104–111; Flörke et al., 1981) and in low-pressure laboratory experiments (Bloss, 1957; Bloss and Gibbs, 1963). For a detailed discussion of this issue, see French et al. (2004), who conclude that multiple PF sets in quartz can be used as an impact criterion, especially if they are accompanied by larger-scale structural indications of impact such as a circular geological pattern, anomalous circular deformation, or significant stratigraphic uplift (e.g., Kenkmann and Poelchau, 2009).

In several established impact structures, sets of parallel PFs in quartz grains form a more complex structure in which smaller, subparallel closed planes of fluid inclusions diverge from the PF planes to form unusual and distinctive "feather" structures (see French et al., 2004, Fig. 3b, pp. 205–207 and references therein; Ferrière and Osinski, 2009; Poelchau and Kenkmann, 2009). Although the smaller planes forming the "feathers" are not identical to well-developed planar deformation features in quartz, it has been suggested (French et al., 2004, pp. 206–207) that they may represent the development of incipient PDFs at relatively low shock pressures <10 GPa. The nature and origin of these "feather" structures needs to be examined in much more detail; it is possible that, even if they do not contain definite PDFs, they may still be a unique signature of significant shock pressures and may come to be used in the future as a definite criterion for meteorite impact events (Poelchau and Kenkmann, 2009).

4.2.2. Planar deformation features (PDFs)

The shock effect most used in recognizing new impact structures is the presence of unique, multiple, parallel, thin, closely-spaced planes of deformation in quartz that are recognizably distinct from endogenic planar microdeformation features (Engelhardt and Stöffler, 1965, 1968; Robertson et al., 1968; Engelhardt and Bertsch, 1969;

Alexopoulos et al., 1988; Stöffler and Langenhorst, 1994; Grieve et al., 1996). Early descriptions of these features designated them as "planar features" or "shock lamellae" (see papers in French and Short, 1968); they are now generally referred to as planar deformation features (PDFs) in quartz (Alexopoulos et al., 1988), and they are generally accepted as unique indicators of high shock pressures and therefore of meteorite impact.

PDFs in quartz consist of multiple sets of thin, parallel, closely-spaced planes that traverse a significant fraction of the width of the individual quartz grains that contain them (e.g., Alexopoulos et al., 1988). Good examples are shown in Figs. 13 and 14. PDF sets remain within a single quartz grain without crossing grain boundaries. The individual planes are straight, although bending of PDFs is observed in deformed quartz grains, where the trend of the PDFs follows the undulose extinction in the quartz (Trepmann and Spray, 2005). Individual PDF planes are typically ≤1 µm thick and only a few micrometers apart. They show no birefringence separate from that of the host quartz, and at higher magnification (with the scanning electron microscope [SEM] or transmission electron microscope [TEM]), optically single planes can be resolved into even finer sets of parallel planes (Gratz et al., 1996); see Fig. 15.

The most distinctive characteristic of PDFs (Fig. 16) is that they are oriented parallel to specific crystallographic planes within the quartz lattice, most commonly to planes with low Miller-Bravais indices such as c(0001), ω{10$\bar{1}$3}, and π{10$\bar{1}$2} (see papers in French and Short, 1968; also Engelhardt and Stöffler, 1965, 1968; Robertson et al., 1968; Engelhardt and Bertsch, 1969; Alexopoulos et al., 1988; Stöffler and Langenhorst, 1994; Grieve et al., 1996). These orientations of PDFs can be easily established by routine universal-stage or spindle-stage techniques to determine the angles between the quartz c-axes and the poles to the PDF planes and then plotting the resulting angles as a histogram or other statistical plot (Fig. 17) for details, see Robertson et al., 1968; Engelhardt and Bertsch, 1969; Bloss, 1981; Stöffler and Langenhorst, 1994; Grieve et al., 1996; Montanari and Koeberl, 2000, Ch. 6; Ferrière et al., 2009b; Kile, 2009). In carrying out these procedures, it is important to measure the orientations of a statistically significant number of PDFs in each sample (e.g., >20–50 grains from each thin section), to concentrate on those grains that contain two or more PDF orientations, to use a well defined data reduction and plotting routine, and to describe the used methods in detail (Figs. 18 and 19; e.g., Morrow, 2007; Ferrière et al., 2007, 2008). Ferrière et al. (2009b) give a thorough discussion of current methods, with a new plotting template. Such statistical measurements have been the most effective method for distinguishing between shock-produced PDFs and other, non-impact, deformation features in quartz (see discussions below, Section 4.3).

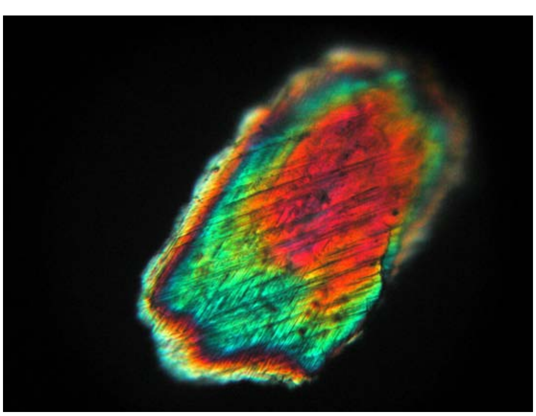

Fig. 13. Two intersecting sets of fresh (undecorated) planar deformation features (PDFs) in a single quartz grain (long dimension: 120 µm) from the Crow Creek member of the Pierre Shale in South Dakota, a unit interpreted to contain ejecta from the Manson impact structure in Iowa (USA). The PDFs are continuous, closely-spaced planes, composed of amorphous material (glass?) with a different refractive index from the host quartz. Crossed polarizers.

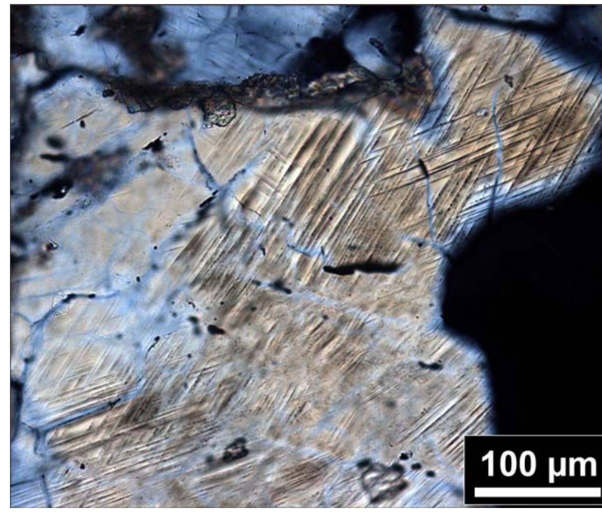

Fig. 14. Quartz grain displaying two intersecting sets of relatively fresh, continuous PDFs. Sample is from a quartzite clast in suevite breccia from a recent drill core into the Bosumtwi (Ghana) impact structure. PDF sets trend NE–SW and ENE–WSW. Sample KRB-006, depth 240.36 m; crossed polarizers. Directions (e.g., "NE–SW") are in relation to an arbitrary "North" at the top of the image.
Photograph courtesy of L. Ferrière.

The actual details of PDF formation are still not clear, although their formation seems to involve interactions between the passing shock wave and specific directions in the quartz crystal lattice (Brannon et al., 1983; Stöffler and Langenhorst, 1994; Trepmann, 2008). Fresh PDFs, produced in laboratory experiments and preserved in some young impact structures, consist of thin continuous lamellae of shock-produced glass (Hörz, 1968; Müller, 1969; Stöffler, 1984) More commonly, natural PDFs occur in an altered form, in which the original glass has been recrystallized to quartz and the original planes are marked by planar arrays of small fluid inclusions. These arrays of "decorated PDFs" (Figs. 20–22) preserve the original orientation of the

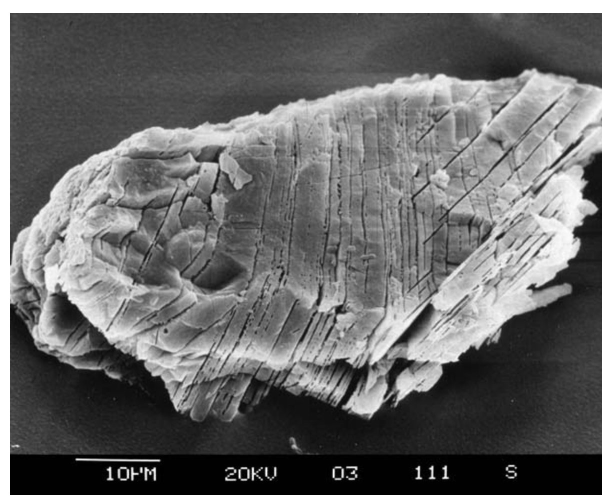

Fig. 15. Scanning electron micro-photograph of an acid-etched shocked quartz grain, showing two parallel sets of narrow planar voids (trending approximately N–S and NE–SW) produced by the preferential dissolution of the amorphous material composing the original fresh PDFs. The presence of such former PDFs is indicated by the planar character of the voids, their arrangement in closely parallel sets, and their penetration into the interior of the quartz grain. This combination of selective acid dissolution and SEM examination can provide definite identification of the presence of fresh PDFs in quartz grains and can help distinguish them from non-impact deformation features. Sample is from the K–T boundary layer from DSDP drilling site 596 in the South Pacific. Directions (e.g., "N–S") are in relation to an arbitrary "North" at the top of the image.
Photograph courtesy of B.F. Bohor.

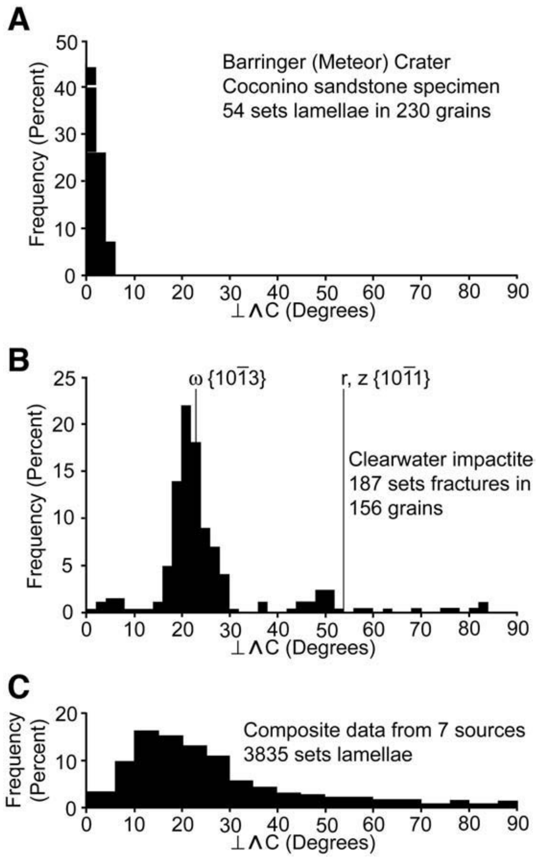

Fig. 16. Histograms of orientations of impact and non-impact planar microdeformation features in quartz grains, showing the frequency distribution of the polar angle (⊥ ∧ c) between the quartz *c*-axis and the pole to the planes (modified from Carter, 1965, Fig. 1). The shock-produced fabrics ([A], top and [B], center) show strong concentrations at specific planes in the host quartz crystal: the base c(0001) (Meteor Crater [Arizona]) and ω{10$\bar{1}$3} Clearwater [Canada]). In contrast, non-impact metamorphic deformation lamellae (MDLs) show a broad, bell-shaped distribution with a wide peak between about 5° and 30° ([C], bottom).

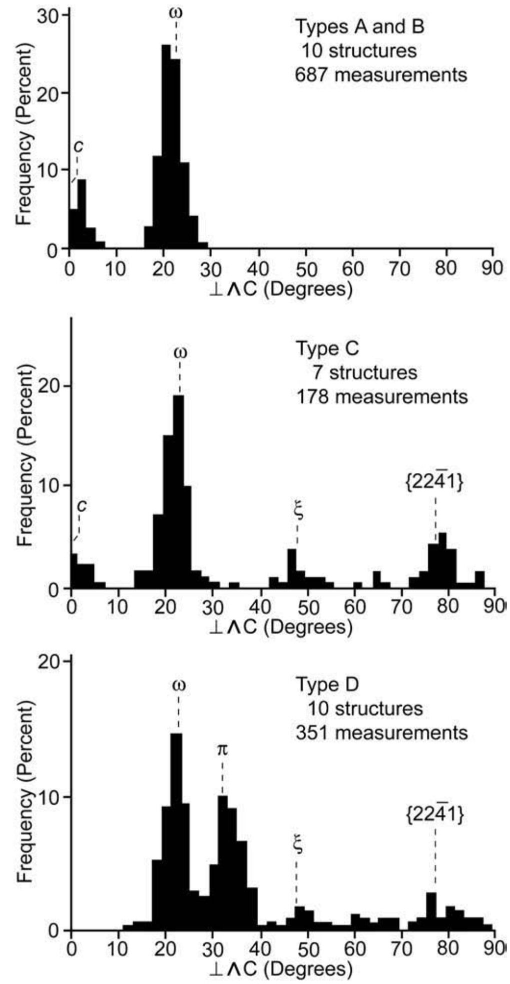

Fig. 17. Histograms of orientations of shock-produced PDFs in quartz from various Canadian impact structures, showing the frequency distribution of the polar angle (⊥ ∧ c) between the quartz *c*-axis and the pole to the planes (modified from Robertson et al., 1968, Figs. 11–13). The shock-produced fabrics are characterized by strong concentrations at specific planes in the host quartz grain, notably c(0001), ω{10$\bar{1}$3} and π{10$\bar{1}$2}. The different fabrics (Types A–D) reflect different shock pressures, and the observed fabrics have been used for shock barometry in several impact structures.

PDFs, allowing the critical petrofabric measurements to be made even in old or highly altered rocks (French, 1968b; Robertson et al., 1968; Schreyer, 1983; Grieve et al., 1990).

Extensive geological and experimental studies (e.g., Hörz, 1968; Müller and Defourneaux, 1968; Stöffler and Langenhorst, 1994; Huffman and Reimold, 1996) have established that these features develop at pressures of approximately 10–30 GPa, far higher than pressures produced by non-impact processes in crustal rocks. Despite considerable controversy and misidentifications (Officer and Carter, 1991; Lyons et al., 1993), it is now generally recognized that true PDFs have never been found in natural quartz from non-impact settings.

PDFs apparently form in several other minerals in addition to quartz (papers in French and Short, 1968; Wolfe and Hörz, 1970; Stöffler, 1972, 1974). These include other tectosilicate (network) silicates (feldspars, scapolite; Dvorak, 1969; Stöffler, 1972, 1974; Dressler, 1990), sillimanite, cordierite, garnet, apatite, and, possibly, zircon (Fig. 23) (Bohor et al., 1993; Krogh et al., 1993; Wittmann et al., 2006). Possibly similar planar features, distinct from typical cleavage, have also been observed in mafic minerals such as pyroxenes and amphiboles (e.g., Stöffler, 1972, 1974). However, the identification of impact structures has emphasized PDFs in quartz for several reasons (Grieve et al., 1996): (1) quartz is abundant in a wide range of common target rock types; (2) quartz develops PDFs over a range of (relatively) low shock pressures (approximately 10–30 GPa), and the resulting shocked quartz is distributed through a large volume of the target rocks within this range of shock pressures; (3) the characteristics of PDFs in quartz (number of sets, orientation) vary with pressure, allowing quartz to be used as a shock barometer (Robertson, 1975; Grieve and Robertson, 1976; Robertson and Grieve, 1977; Dressler et al., 1998, 1999); (4) the stability of quartz can preserve PDFs through subsequent episodes of metamorphism, erosion, and sedimentation; and (5) quartz is optically simple (uniaxial), and the petrofabric measurements needed to characterize PDFs are correspondingly rapid and simple.

4.2.3. Basal microdeformation features

Several types of planar microdeformation features have been observed oriented parallel to the basal plane (0001) in quartz crystals from established impact structures. These include both shock-produced PFs (Bunch, 1968; French et al., 2004) and (rarely) PDFs (Therriault and Lindström, 1995; Grieve et al., 1996). In addition, two normally endogenic features, MDLs and Brazil twins, which normally form in other crystallographic orientations, also occur in basal orientations and, when found in this orientation, have also been regarded as indicators of shock. Basal MDLs have been reported from both Meteor Crater (Arizona) and the Vredefort (South Africa) structure (Carter, 1965, 1968b), using petrographic methods, while basal Brazil twins (whose normal orientation is parallel to π{10$\bar{1}$2}) have been detected by TEM in samples from several impact structures: Vredefort (South

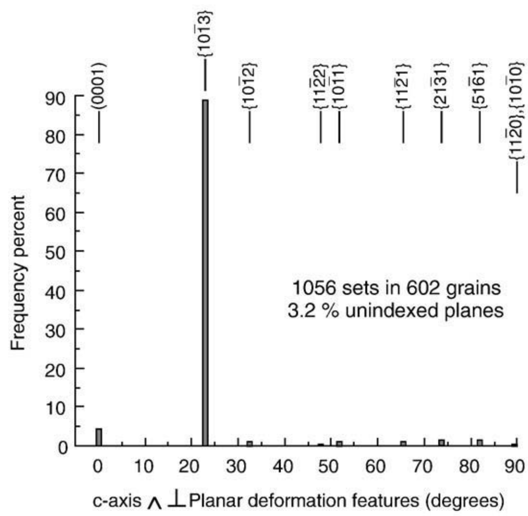

Fig. 18. Histogram of the absolute frequency percent of indexed PDFs (recalculated to 100% without unindexed PDF orientations) in 602 quartz grains from 17 shocked basement meta-graywacke samples from drill core LB-08A in the central uplift of the Bosumtwi crater (Ghana). Binning at 5°. Unlike the simple histogram plots (Figs. 16 and 17), this diagram results from a combination of three distinct operations: (1) measurement of the polar angles; (2) rotation of the stereographic diagram so that the quartz *c*-axis is vertical; and (3) use of a template to make definite assignment of the PDFs to specific planes. This set of samples shows a virtually complete concentration of all planes parallel to the ω{1013} direction, with only a small amount parallel to the base c(0001).
Diagram courtesy of L. Ferrière.

Africa) (Goltrant et al., 1991, 1992; Leroux et al., 1994) and Sudbury (Canada) (Joreau et al., 1996).

These reports have argued that MDLs and Brazil twins, when oriented parallel to the base (0001) in quartz, are the result of impact-produced shock pressures and may therefore be used as criteria for impact events. Because neither basal MDLs nor Brazil twins have been produced in shock-wave experiments, the conditions of formation are not clear. If these features are unique shock products, they probably reflect relatively low shock pressures of <10 GPa (Goltrant et al., 1991, 1992). In any case, the discovery of such PMs (fresh or decorated) parallel to (0001) in a quartz grain may suggest a shock history and should spur further study.

4.3. Endogenic planar microdeformation features

Because of the importance of quartz in mineralogy, metamorphic petrology, and rock deformation, an extensive literature exists on the nature and origin of the growth and deformation features that develop in quartz under endogenic conditions (for general sources, see, e.g., Fairbairn, 1949; Frondel, 1962; Spry, 1969; Weiss, 1972; Vernon, 1975; Barker, 1990; Snoke et al., 1998; Blenkinsop, 2000; Vernon, 2004; Passchier and Trouw, 2005). Many of these features, produced by both crystal growth and deformation, are planar or quasi-planar. Their basic characteristics, and their distinction from definite shock features such as PDFs, are discussed briefly below (for more detailed comparative discussions, see also Carter 1965; Heard and Carter, 1966; Carter 1968a,b; Bunch, 1968; Robertson et al., 1968; Engelhardt and Bertsch, 1969; Alexopoulos et al., 1988; Grieve et al., 1996, pp. 28–30; Vernooij and Langenhorst, 2005).

4.3.1. Growth features

4.3.1.1. Twinning. Several types of twinning develop in growing or deformed quartz grains (for details, see Frondel, 1962). Brazil twinning, normally parallel to a{11$\bar{2}$0}, has been found oriented to the base c(0001) in shocked quartz (Goltrant et al., 1991, 1992). Dauphiné twinning, in which the twin plane is parallel to the *c*-axis,

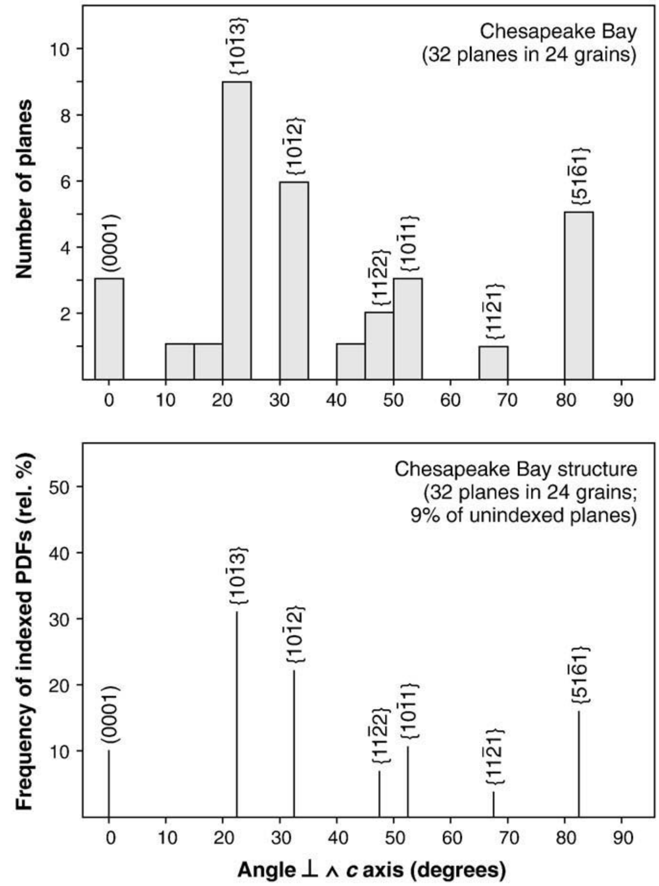

Fig. 19. Comparison of two separate plots for PDFs in shocked quartz grains from the Chesapeake Bay impact structure (modified from Koeberl et al., 1996c, Fig. 5). The upper plot is a simple histogram showing the frequency distribution of the polar angle (⊥ ∧ c) between the quartz *c*-axis and the pole to the planes. The lower plot shows the same data after further processing, involving (1) rotation of the stereographic diagram so that the quartz *c*-axis is vertical; and (2) use of a template to make definite assignments of the PDFs to specific planes. Both plots show the definite shock-produced orientation of the PDFs to specific planes in the quartz grain.

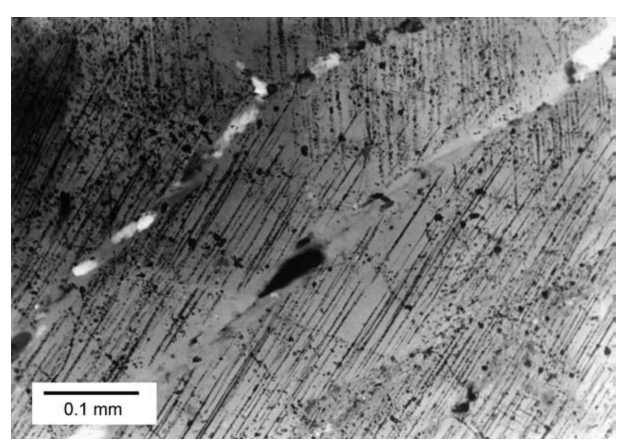

Fig. 20. Two sets of partially decorated planar deformation features (PDFs) in a large quartz grain from a sample of Precambrian basement gneiss in the central uplift of the Carswell structure (Canada). The planar sets, which trend NE–SW and N–S (upper left), are largely continuous, but display a slightly beaded texture produced by the development of secondary fluid inclusions ("decorations") along the individual planes. Sample DCR-11-63B; width of image 0.65 mm, crossed polarizers. Directions (e.g., "NE–SW") are in relation to an arbitrary "North" at the top of the image.
Photograph courtesy of M.R. Dence.

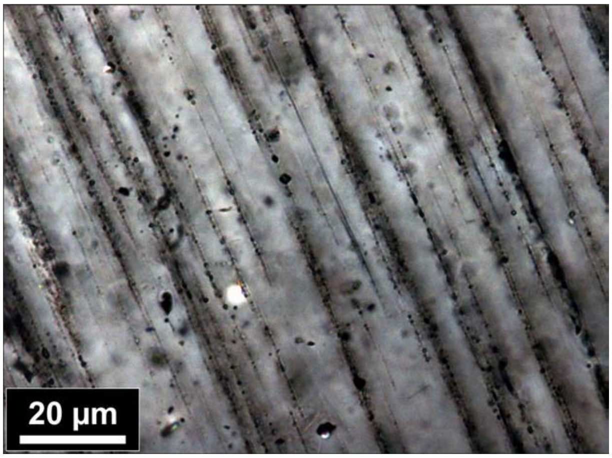

Fig. 21. High-magnification view of decorated planar deformation features (PDFs) in a quartz grain from a medium-grained graywacke (shocked basement in the central uplift) in drill core from LB-08A in the Bosumtwi (Ghana) impact structure. The PDFs, which trend NNW–SSE, are largely converted to arrays of small fluid inclusions which preserve the shape and orientation of the original planes. Sample KR8-056, depth 384.54 m; crossed polarizers. Directions (e.g., “NNW–SSE”) are in relation to an arbitrary “North” at the top of the image.
Photograph courtesy of L. Ferrière.

along the plane m{10$\bar{1}$0}, has been observed in shocked quartz from the Charlevoix structure (Canada) (Trepmann and Spray, 2005), where it seems to have developed during post-shock cooling after the formation of PDFs (Trepmann and Spray, 2006), and at Vredefort (South Africa), where it may indicate the development of impact-produced preferred orientation in quartzite (Wenk et al., 2005). The basal Brazil twins have been proposed as a unique shock criterion (Goltrant et al., 1991, 1992; Leroux et al., 1994), but their potential usefulness is limited by the fact that they are not visible in plane-polarized light and require TEM examination for their detection.

4.3.1.2. Growth lines. Quartz crystals growing into open spaces such as vugs or veins often develop successive growth lines parallel to specific crystal faces as the crystallization front advances. The resulting sets of parallel lines may resemble PDFs, especially if the growth lines have developed parallel to more than one crystal face (Fig. 24). In general, such growth lines may be identified by the fact that they occur in typical open-space quartz structures composed of parallel or radiating crystals, e.g., comb structure in veins (Hibbard, 1995, p. 399). However, in doubtful cases, growth lines can be rigorously distinguished from PDFs by their orientation: growth lines will tend to be parallel to the pyramidal (r/z{10$\bar{1}$1}) or prismatic (m{10$\bar{1}$0}) planes of crystal growth and will not be oriented to such typical PDF orientation directions as the base c(0001), ω{10$\bar{1}$3}, or π{10$\bar{1}$2}.

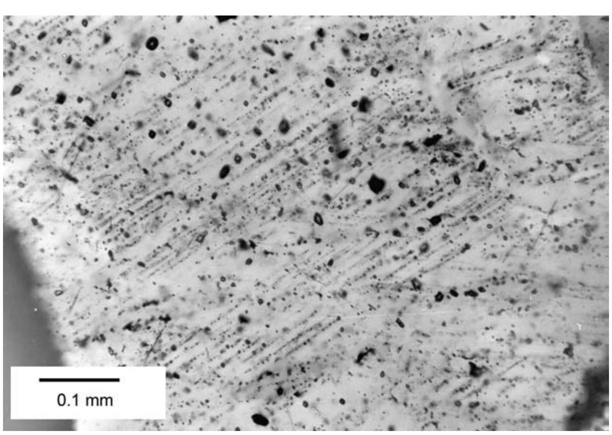

Fig. 22. Faint but definite decorated planar deformation features (PDFs), trending NE–SW and E–W, in a quartz grain from a granite inclusion in a metamorphosed suevite deposit (Onaping Formation) from the Sudbury (Canada) impact structure. Despite post-impact metamorphism, the original PDFs can still be recognized, and their orientations measured, from the arrays of small fluid inclusions that decorate the original planes. The grain also contains larger, randomly located, fluid inclusions. Sample CSF-66-39; crossed polarizers. Directions (e.g., “NE–SW” are in relation to an arbitrary “North” at the top of the image.
Photograph courtesy of N.M. Short.

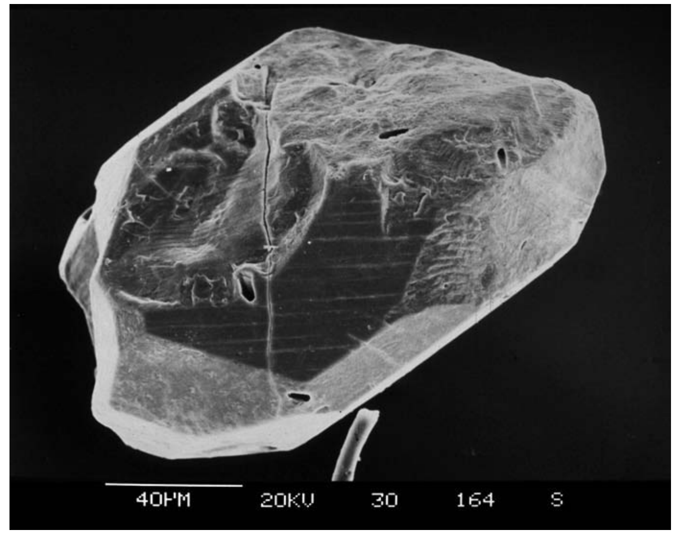

Fig. 23. Scanning electron microphotograph of a shocked zircon grain from the Berwind Canyon (Colorado, USA) Cretaceous–Tertiary boundary site. These zircons have been traced back to the Chicxulub impact structure by isotope geochemical studies (Krogh et al., 1993). The planar features in zircon are not exact equivalents of the PDFs in shocked quartz or feldspar because they do not appear to be filled with amorphous material. At higher shock pressures, a distinctive granular texture develops in shocked zircon.
Photograph courtesy of B.F. Bohor.

4.3.2. Internal strain features

4.3.2.1. Extinction bands. Under crossed polarizers, areas of differently oriented extinction (extinction bands or undulose extinction) are typically present in quartz grains from a wide range of igneous and metamorphic environments (Vernon, 1975, Ch. 7). In such grains, extinction directions may change gradually with rotation of the microscope stage, or the quartz grain may consist of discrete individual areas whose extinction directions may be oriented as much as 5–10° from one another. Individual areas tend to be large (typically >20 µm across) and widely spaced; boundaries between areas are curved, irregular, and nonparallel, and individual areas and their boundaries do not extend into adjacent grains. Extinction bands are generally wide and have nonplanar boundaries; they are difficult to confuse with PDFs.

4.3.2.2. Deformation bands (kink bands). These features are similar in character to extinction bands, but they tend to be smaller (<20 µm across) and thinner, forming bands within a host quartz grain. The bands are curved and relatively wide; they do not cross grain boundaries. Extinction directions in the bands are different from those of the host, resulting in observable birefringence differences between the band and the host. Because of their relatively large size, slightly nonplanar character, and discrete birefringence, they are also difficult to confuse with shock-produced PFs or PDFs.

4.3.3. Fracturing

Fracturing can be produced in quartz by both low-level tectonic deformation and low-pressure shock waves. In many cases, where the fractures are nonplanar and randomly oriented, the resulting fracture patterns are virtually identical, and their origin cannot be clearly

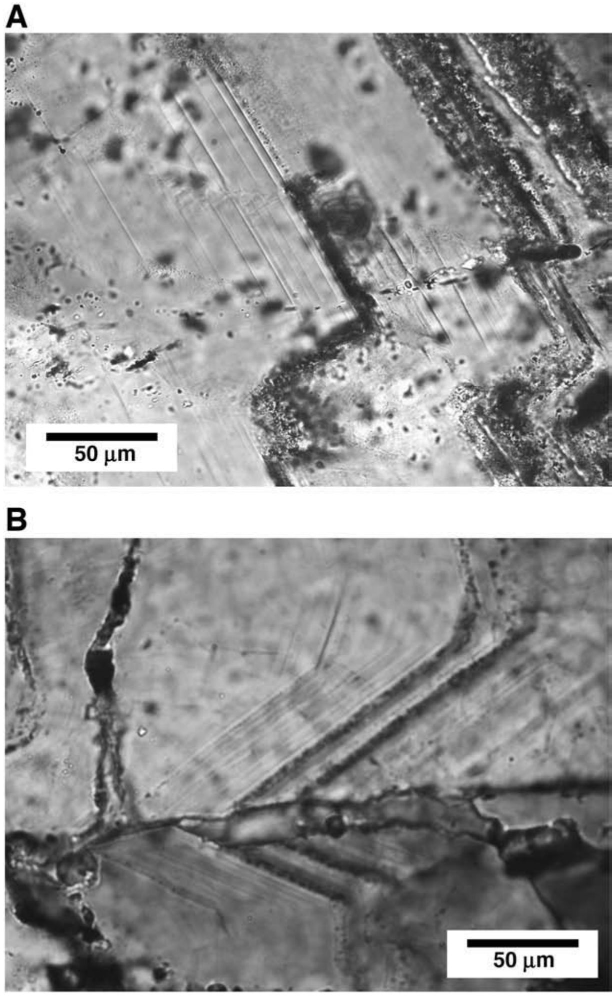

Fig. 24. Single set of parallel, closely-spaced non-impact growth lines in vein quartz from the Crooked Creek (Missouri) structure. (A) In this image the lines trend dominantly NW–SE. Sample MOF-05-8-1, crossed polarizers. (B) A grain boundary runs approximately E–W, and growth lines are diversely oriented in the separate grains: NE–SW (top) and NW–SE (bottom). Sample MOF-05-8-2; crossed polarizers. These lines resemble PDFs in their parallelism, close spacing, and refractive index differences, but they differ in: (1) the presence of only single sets; (2) irregular spacing of the planes (see especially Fig. 24[b]); (3) the presence of kinks and zig-zags in the trend of the sets; (4) the absence of crosscutting planes; and (5) the occurrence of occasional wider bands (dark) that are extremely rich in fluid inclusions. Directions (e.g., "NW–SE") are in relation to an arbitrary "North" at the top of the image.

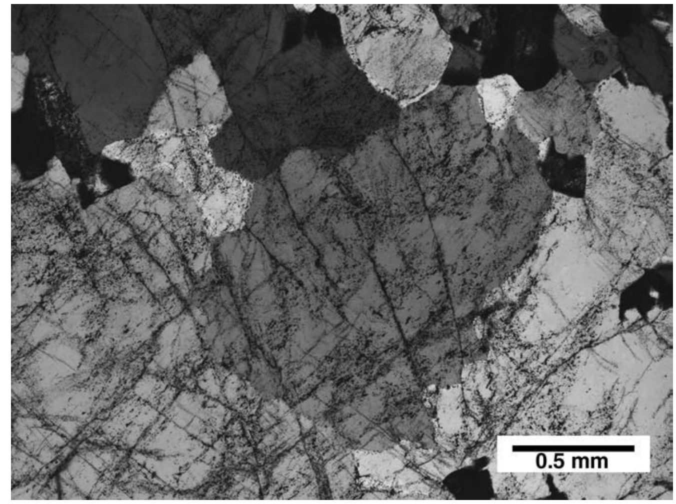

Fig. 25. Crudely subparallel non-impact fractures in quartz grains from a quartzite unit in the Phepane Dome, Bushveld Complex, South Africa. The fractures, which appear partly decorated with small fluid inclusions, occur as subparallel sets that trend approximately NNW–SSE and NE–SW, but they are distinct from shock-produced PFs and PDFs in: (1) their slightly irregular and nonplanar character; (2) their lack of rigorous parallelism; and (3) the tendency of individual fractures to continue into adjacent grains which have different optical orientations. Sample PO6-16; crossed polarizers. Directions (e.g., "NNW–SSE") are in relation to an arbitrary "North" at the top of the image.
From the University of Maryland, Department of Geology, courtesy of R. Potter and S. Penniston-Dorland.

established (e.g., Robertson et al., 1968). More organized fractures, characterized by a planar character, parallelism, and distinct orientations (designated as PFs or cleavage; see above) may be a shock product. In most cases, the morphology of fractures, together with their open character, are sufficient to distinguish them from PDFs.

4.3.3.1. Irregular (random) fractures. Quartz and quartz-bearing rocks from many non-impact geological environments often show irregular, straight to curved, subparallel to randomly oriented open fractures (e.g., Higgins, 1971; Snoke et al., 1998; Blenkinsop, 2000; Vernon, 2004; Passchier and Trouw, 2005). The development of these fractures is a natural consequence of the brittle character of quartz during deformation at relatively low pressures (Griggs et al., 1960; Christie et al., 1964; Hirth and Tullis, 1994). These fractures typically occur as irregular planes, often crudely subparallel, or as curved and nested arcs, and they may cut through single quartz grains and extend into adjacent grains as well (Fig. 25). Individual fractures often show minor faulting and small displacements along them. In some cases, a network of irregular, subplanar, or curved fractures may divide an individual quartz grain into an irregular mosaic of still-coherent fragments.

Virtually identical fracturing is often observed in quartz from impact structures (e.g., Robertson et al., 1968; Engelhardt and Bertsch, 1969; Kieffer, 1971; Stöffler and Langenhorst, 1994) and in samples from laboratory shock-wave experiments (Short, 1966, 1968a,b; Hörz, 1969; Lambert, 1979). In impact structures, such quartz fracturing may be distributed widely in rocks of the crater floor and rim, as well as in fragments in the crater-fill breccias (e.g., Robertson et al., 1968; French et al., 1997). Such fractures are generally nonplanar, randomly oriented, and at best only subparallel (Robertson et al., 1968); they are too irregular and randomly oriented to be considered as PFs or cleavage (see discussion above, Section 4.2.1).

Despite their similarity to non-impact fractures, these irregular fractures in impact structures are regarded as shock-wave effects. They have been reproduced in shock-wave experiments (Short, 1966, 1968a,b; Hörz, 1969; Lambert, 1979), and studies at several impact structures have shown that comparable fracturing is often reduced or absent in target rocks distant from the impact point (Engelhardt and Bertsch, 1969; Kieffer, 1971). The density of fracturing shows a positive correlation with estimated shock pressure (Short, 1966, 1968a; Hörz, 1969; Lambert, 1979), although this relation is too uncertain to use as a shock barometer.

A special type of fracturing, concussion fracturing, has been observed in specimens of shocked Coconino Sandstone from Meteor Crater, Arizona (Kieffer, 1971, p. 5456–5458), as a pattern of radiating tension fractures that spread out into adjacent quartz grains from their mutual points of contact. Concussion fractures may form when adjoining quartz grains are suddenly brought into violent contact by the passage of the early, low-pressure phase of impact-produced shock waves (Kieffer, 1971, p. 5457). Similar concussion fractures in other structures have been used to support an impact origin (Milstein, 1988; Stone, 1999; Milstein, 2001).

Both irregular fracturing and concussion fracturing in quartz may be produced by low-pressure shock waves associated with an impact event (or by the later-stage elastic waves derived from them), but neither type of fracturing can be used independently as evidence of impact. In static experiments, quartz develops similar tensile fractures at low stresses, generally <5 GPa and often <1 GPa (Griggs et al., 1960; Christie et al., 1964; Hirth and Tullis, 1994). Such stresses, and the resulting fractures, can therefore develop in non-impact environments, particularly during low-level tectonic deformation, and shock pressures in this range are too low to produce more diagnostic features such as cleavage (PFs) and PDFs. In addition, it is possible that concussion fractures could develop statically from stresses produced on adjoining quartz grains by overburden or by slow deformation.

Although the presence of irregular or concussion fractures in single specimens cannot be used as evidence of impact, more detailed areal studies of fracture densities have some potential for future investigations in identifying anomalous (possibly impact) sites and for establishing crude gradients of shock pressure (Short, 1966; Lambert, 1979).

4.3.3.2. Healed fractures. Healing of originally open fractures by recrystallization of the host quartz (e.g., during subsequent metamorphism or hydrothermal activity) produces closed irregular to subplanar surfaces that are decorated with small secondary fluid inclusions (e.g., Tuttle, 1949; Robertson et al., 1968; Roedder, 1984, pp. 19–26, 343–346; Barker, 1990; p. 189–192). Depending on the nature and orientation of the original open fractures, the resulting decorated surfaces may be single or multiple, curved to nearly planar, parallel or diversely oriented (Fig. 26). Healing and decorating of originally subplanar and subparallel fractures can produce textures suggestive of decorated PDFs (French, 1990a, p. 295, his Fig. 4) (Fig. 27). However, such textures can be distinguished from PDFs by: (1) the generally nonplanar character of individual surfaces; (2) the absence of rigorously parallel orientations of multiple surfaces; (3) their wider spacing, usually >10 µm; (4) their tendency to cross grain boundaries into adjacent grains with different optical orientation without changing direction; and (5) their different orientation with respect to the *c*-axis of the host quartz (Fig. 28).

4.3.4. Metamorphic deformation lamellae (MDLs)

Metamorphic deformation lamellae (MDLs), also known as Böhm lamellae, are a common, well-known, and long-recognized feature of deformed quartz in igneous and metamorphic rocks and in the sedimentary rocks derived from them (Fairbairn, 1941; Ingerson and Tuttle, 1945; Fairbairn, 1949; Tuttle, 1949). (Detailed descriptions of MDLs, their origin, and their distinction from shock-produced PDFs, are given by Christie and Raleigh, 1959; Carter, 1965; Carter and Friedman, 1965; Scott et al., 1965; Carter, 1968b; Tullis et al., 1973; Vernon, 1975, Ch. 7; Alexopoulos et al., 1988; Grieve et al., 1996, p. 28–30). MDLs

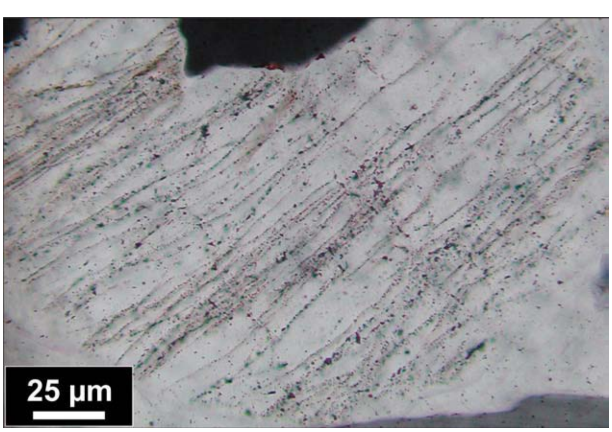

Fig. 26. Irregular to subparallel inclusion trails, representing healed and decorated subparallel non-impact fracture planes, in a quartz grain from a quartzite unit in Egypt. Although these features superficially resemble (and may be confused with) shock-produced decorated PDFs, they differ in: (1) their clearly irregular and nonplanar character; (2) their lack of exact parallelism. Sample LDG-2006-12; crossed polarizers. (Photograph courtesy of L. Ferrière).

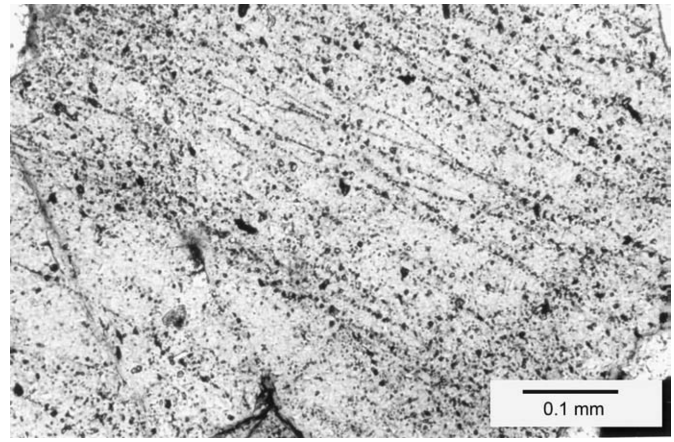

Fig. 27. Irregular to subparallel inclusion trails, representing healed and decorated subparallel non-impact fracture planes, in a quartz grain from a quartzite inclusion in the Rooiberg Felsite, Bushveld Complex, South Africa (modified from French, 1990a, his Fig. 4). Although these features superficially resemble (and may be confused with) shock-produced decorated PDFs, they differ in: (1) their clearly irregular and nonplanar character; (2) their lack of exact parallelism; (3) their tendency to continue uninterrupted into adjacent grains with different optical orientations; and (4) their different orientations within the quartz grain (see Fig. 28). Sample ABF-81-228, crossed polarizers.

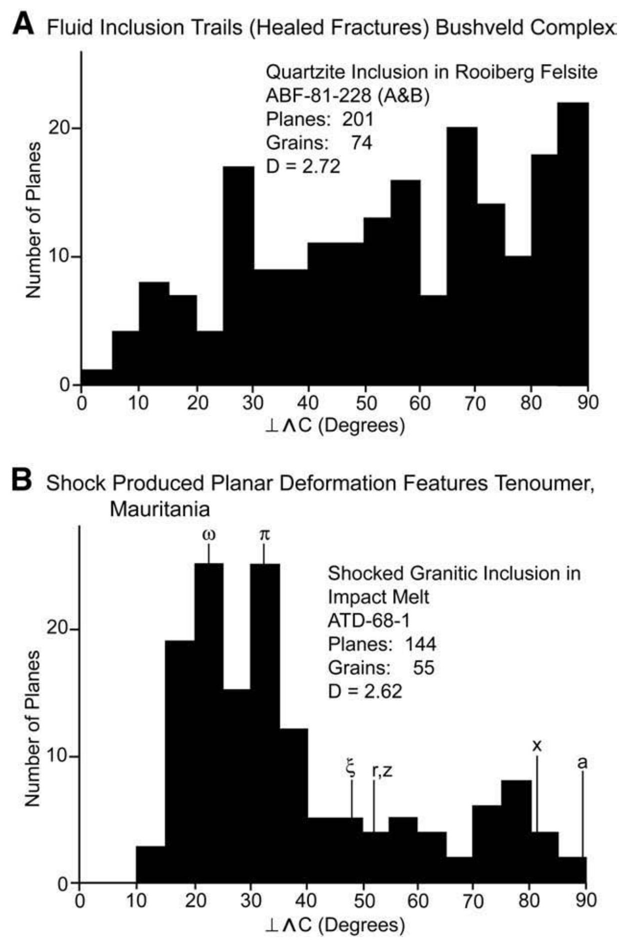

Fig. 28. Histogram plot (modified from French, 1990a, Fig. 5) comparing orientations of non-impact healed fractures from a quartzite inclusion in the Rooiberg Felsite, Bushveld Complex, South Africa ([A], top) and shock-produced PDFs from the Tenoumer (Mauritania) impact structure ([B], bottom; French et al., 1970, their Fig. 3). The plots show frequency distribution of the polar angle (⊥ ∧ c) between the quartz c-axes and the poles to the planes. The orientations of the non-impact healed fractures are distinctly different from those of the PDFs and display: (1) a broader and more scattered angular distribution; and (2) a general concentration towards higher polar angles, rather than sharp peaks corresponding to the shock-produced lower-angle ω$\{10\bar{1}3\}$ and π$\{10\bar{1}2\}$ orientations. Bushveld sample ABF-81-228, Tenoumer sample ATD-68-1.

generally form sets of narrow planar to subplanar lamellae in quartz grains. The individual lamellae, typically ≥2 μm thick, are often slightly bent or lenticular, and contacts with the surrounding host quartz are usually vague and indistinct (Figs. 29 and 30). Individual lamellae show discrete birefringence under crossed polarizers, and the extinction directions are slightly different (typically 2–5°) from the host quartz. Individual lamellae may be decorated with small fluid inclusions. MDLs do not cross the boundaries of the host grains and may fade out and become virtually invisible close to the boundary. MDLs characteristically form parallel sets, with individual MDLs spaced ≥5 μm apart. Generally only one set of MDLs is present in a single quartz grain, although two distinct sets are rarely observed (Lyons et al., 1993).

Because of their near-planar and near-parallel characteristics, MDLs are especially liable to be confused with (and misinterpreted as) shock-produced PDFs, especially by workers unfamiliar with the characteristics of endogenically deformed quartz (Lyons et al., 1993; Buchanan and Reimold, 1998; Retallack et al., 1998). MDLs clearly differ from PDFs in many characteristics (e.g., Carter, 1965, 1968b; Alexopoulos et al., 1988; Grieve et al., 1996). Optically, MDLs are often lenticular or curved; they are thicker and more widely-spaced than PDFs, and they are individually birefringent. TEM studies of MDLs show the presence of high dislocation densities (McLaren et al., 1967; Goltrant et al., 1991), while PDFs are either amorphous or composed of quartz with low dislocation densities. In particular, MDLs are never observed to form more than 1–2 sets per grain, whereas PDFs are frequently present in ≥3 sets in highly-shocked rocks (Robertson et al., 1968; Stöffler and Langenhorst, 1994; Grieve et al., 1996).

However, the most rigorous means of distinguishing between MDLs and PDFs is their orientation as measured with universal-stage methods. Unlike the concentration of PDF orientations parallel to specific planes in the quartz crystal, MDL planes are oriented over a broad range of low angles to the base c(0001) As a result, plots of polar angles of MDLs vs. frequency are totally different from those of PDFs (Figs. 16, 17, and 28b). Plots of MDL poles form a bell-shaped curve with a broad maximum at about 20–30° to the *c*-axis (Fairbairn, 1941; Ingerson and Tuttle, 1945; Carter, 1968b). In sharp contrast, plots of PDF poles are concentrated into sharp "spikes" at the polar angles associated with specific lattice planes (Carter and Friedman, 1965; Carter, 1965, 1968b; Alexopoulos et al., 1988; Grieve et al., 1996; Ferrière et al., 2009b).

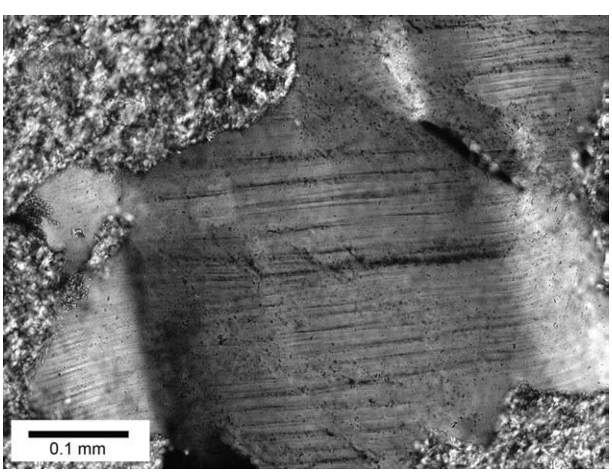

Fig. 29. Typical close-spaced tectonic metamorphic deformation lamellae (MDLs) in a quartz grain from deformed granite, Big Jim Pond, Maine. The MDLs occur as a single set of slightly curved, generally parallel planes, which trend E–W. Some of the planes (darker) are highly decorated with small fluid inclusions. In comparison to shock-produced PDFs, the MDLs tend to be: (1) thicker; (2) more widely spaced; (3) slightly curved and sinuous; (4) present as single sets; and (5) more diversely oriented within quartz grains. Crossed polarizers. Directions (e.g., "E–W") are in relation to an arbitrary "North" at the top of the image.
Photograph courtesy of R. H. Vernon.

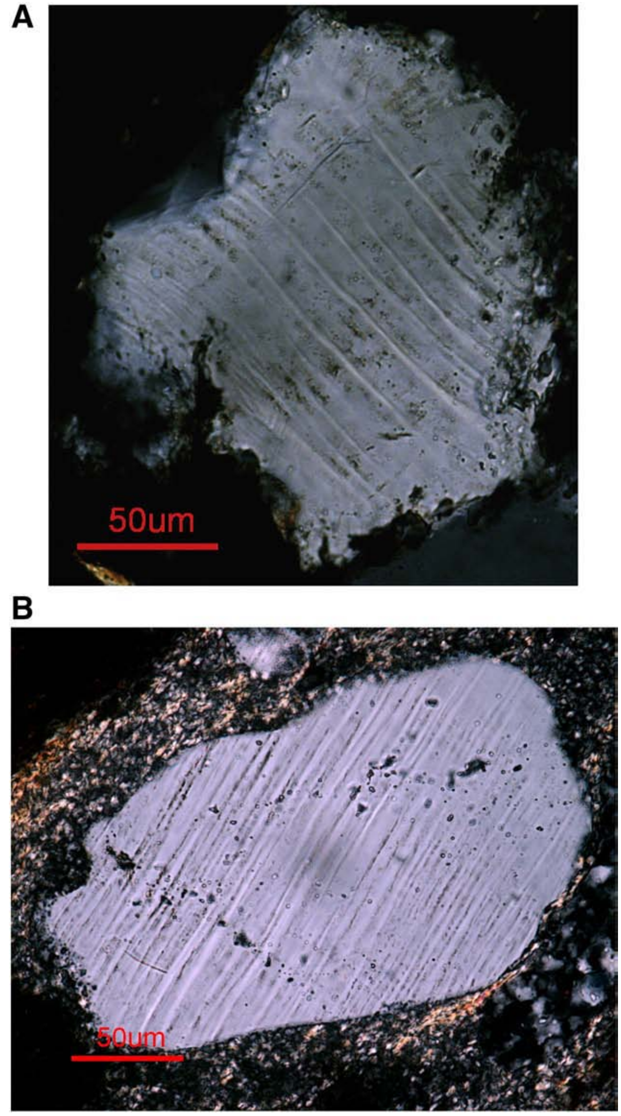

Fig. 30. (A, B). Thicker, more widely-spaced tectonic metamorphic deformation lamellae (MDLs) in quartz grains from a sedimentary quartzite in the Precambrian Michigamme Formation, McClure, Michigan. In each case, the MDLs, trending NW-SE (a) and NE-SW (b), occur as a single set of discrete, slightly curved, generally subparallel planes. The significant thickness (several μm) and relatively wide spacing (typically 10–20 μm) make it difficult to confuse this type of MDLs with the narrower and more closely-spaced shock-produced PDFs. Crossed polarizers. Directions (e.g., "NW–SE") are in relation to an arbitrary "North" at the top of the image.
(Photographs courtesy of W.F. Cannon).

Although several previous studies have confused MDLs with PDFs (see discussion below, Section 6.3.3), especially when the studies have been limited to flat-stage microscopy, the distinction between the two features should be straightforward. Careful study of the optical appearance of the different features, especially if supplemented by U-stage measurements, can produce a clear distinction. (U-stage measurements can also establish whether observed MDLs have a basal orientation, which may be used as a criterion for shock; see discussion above). Future identifications of possible PDFs should include sufficient documentation to make clear that the features are not MDLs instead.

5. Non-diagnostic impact deformation effects

5.1. Background

Despite the unique characteristics of some shock-metamorphic effects (e.g., PDFs in quartz), the greatest difficulty in identifying suspected impact structures arises from the fact that most of the impact-produced deformation effects observed in the final structure are not sufficiently different from effects produced by normal endogenic geological processes, for two reasons:

(1) The generally circular symmetry of the impact process (even for moderately oblique impacts) (Melosh, 1989; Grieve, 1991, 1998;) produces structures that show circular patterns of topography, morphology, geological deformation, and geophysical anomalies (especially gravity and magnetics), but such circular patterns may be duplicated by many other geological processes.
(2) The extreme pressure and temperature conditions of shock metamorphism, and the resulting diagnostic shock-deformation effects, are produced only within a relatively small volume of target rock near the impact point (Dence, 1965, 1968; Kieffer and Simonds, 1980; Melosh, 1989, Ch. 5; Grieve, 1991, 1998). Most of the subsequent deformation and development of the much larger final structure therefore takes place at pressures and temperatures corresponding closely to lithostatic conditions (Melosh, 1989; Chs. 5, 8; Grieve, 1991, 1998), and the products of such deformation and melting may be indistinguishable from the results of normal geological activity.

As a result, many geological, geophysical, and petrological characteristics of suspected impact structures, often determined only by remote sensing or geophysical studies, have been incorrectly invoked as evidence of impact, when in fact they are not unique impact signatures. It has now become clear that the only convincing and reliable evidence for an impact origin is the discovery of unique and diagnostic shock-metamorphic features, or the identification of traces of projectile materials, in the rocks of the structure. Field studies and sample collection are therefore essential; remote sensing studies alone cannot provide any confirming evidence regarding an impact origin (Koeberl, 2004; Reimold, 2007), although such studies can help to identify possible impact structures for further investigation or provide important information on confirmed impact structures.

The characteristics listed below may be useful in focusing a search for definite impact-produced shock effects or in expanding the study of an established impact structure, but they cannot be used *per se* as evidence for the impact.

5.2. General geological and geophysical features

5.2.1. Circular morphology and circular structural deformation

Several problematical or highly speculative publications have claimed to identify impact structures on the basis of circular morphology or structural patterns alone (e.g., Abbott et al., 2003a; Paillou et al., 2004, 2006; El-Baz and Ghoneim, 2007). Such identifications are not convincing. Circular shapes, or circular patterns of geological deformation (e.g., faulting, folding, brecciation), are consistent with an impact origin, and such circular features, once recognized, have often been established as impact structures by subsequent field work and petrological studies (e.g., Dence, 1965, 1968; French et al., 1997**).** However, virtually identical circular features can be produced by numerous endogenic geological processes**:** volcanic craters, diatremes, large igneous intrusions, salt domes, tectonic fold patterns, and erosional processes. Several striking circular features, originally identified as impact structures solely on the basis of morphology and structure, have been shown by subsequent geological studies to be of endogenic origin (Dietz et al., 1969; Matton et al., 2005).

5.2.2. Circular geophysical anomalies

Many established impact structures show well-developed circular geophysical anomalies, most notably in the gravity and magnetic fields associated with the structures (e.g., Pilkington and Grieve, 1992; Grieve and Pilkington, 1996). Small impact structures less than about 10 km in diameter often show negative gravity anomalies reflecting the presence of brecciated target rocks below the crater floor or of low-density sediments filling the crater. Large structures may show more complicated circular gravity anomalies consisting of a small positive anomaly in the center (reflecting the uplift of higher-density deep-seated rocks), surrounded by a negative anomaly. Magnetic anomalies at impact structures are more variable and more unpredictable; they may arise from various factors such as the uplift of deeper rocks, the presence of melt layers, or the alteration of original magnetic patterns by impact-produced temperatures above the Curie point (Pilkington and Grieve, 1992; Grieve and Pilkington, 1996).

Even though not diagnostic, geophysical studies are an important component in the identification and study of impact structures. In many cases, they have served to locate areas where clearly shock-metamorphosed rocks are present, thus proving an impact origin for a previously problematical subsurface structure (e.g., Poag et al., 1994; Therriault and Gratz, 1995; Koeberl et al., 1996a,c, 1997a). In other cases, targeted geophysical studies have provided essential two- and three-dimensional information to explore established impact structures and their mechanisms of formation.

In some instances, geophysical studies, especially including active seismic profiling, have established strong and compelling arguments for an impact origin, e.g., in recent studies of the Silverpit structure (offshore the United Kingdom) (Stewart and Allen, 2002; Collins et al., 2003a,b, Smith, 2004; Stewart and Allen, 2005; Thomson, 2006) and the Upheaval Dome (Utah) structure (Kenkmann, 2003; Kenkmann et al., 2005a; Scherler et al., 2006). (Upheaval Dome has recently been confirmed as an impact structure by the identification of shocked quartz; see below and Buchner and Kenkmann, 2008). However, until the presence of definitely shock-metamorphosed rocks can be established in such structures, their identification as impact structures remains controversial to some extent (e.g., Smith, 2004; Thomson, 2006).

5.3. Deformational effects in the target rock

5.3.1. Brecciation

Breccias of several types are probably the most abundant (and often the most noticeable) impact-produced rock type in established impact structures (Dence, 1965, 1968; Grieve, 1991; French et al., 1997; Dressler and Sharpton, 1997; Grieve, 1998; Dressler and Reimold, 2004). Impact-produced breccias may form in the target rocks beneath the crater floor (parautochthonous breccias), or they may be deposited within the crater during subsequent development of the structure (allochthonous breccias). Unfortunately, most such breccias are produced at relatively low shock pressures (<1 GPa) late in the impact process (Kieffer and Simonds, 1980; Melosh, 1989, Chs. 5, 8) or at significant distances from the impact point, and they do not reflect pressures high enough to produce distinctive PDFs or other unique shock features. As a result, most impact-produced breccias lack distinctive shock effects, and they are difficult (if not impossible) to distinguish from endogenically produced breccias, unless distinctively shocked materials are incorporated into them (e.g., Leroux et al., 1995).

There are literally dozens of processes (sedimentary, igneous, and metamorphic) that can produce endogenic brecciated rocks**,** and the occurrence of brecciated rocks, in the absence of definite shock-metamorphic effects, cannot be used as evidence for impact. As with geophysical signatures, occurrences of breccias may indicate the existence of a possible impact structure and may guide further searches for distinctive and convincing shock-metamorphic effects.

5.3.2. Kink banding in micas

Kink bands transverse to the prominent basal cleavage in muscovite and biotite micas are commonly observed in shock-metamorphosed rocks (Chao, 1968, p. 152; Cummings, 1968;

Engelhardt and Stöffler, 1968, p. 162; Short, 1968a, p. 202; Stöffler, 1972, p. 85; Dressler, 1990, p. 236). Such kink bands apparently develop at relatively low shock pressures. They may occur in single or multiple sets, and they may be accompanied by distinctive PDFs in the associated quartz. Unfortunately, similar kink-banding is also common in ordinary metamorphic rocks (e.g., Spry, 1969; pp. 64–66; Vernon, 2004, pp. 302–307), and it is not now possible to distinguish between shock-produced kink bands and those resulting from normal tectonic deformation. Some distinction may be possible on the basis of the kink-band orientation within the host mica grain (Cummings, 1968), but the orientation of the mica grain itself to the shock wave represents a major complicating variable (Cummings, 1968; Dressler, 1990). At present, kink-banding in micas can only be considered as a possible result of shock metamorphism and not as a diagnostic indicator of impact.

5.3.3. Mosaicism in quartz and other minerals

Mosaicism (also called "mosaic structure") is a condition in which a uniform single crystal is actually composed of a large number of smaller crystalline domains (also called "subgrains") whose crystal lattices are slightly to significantly misoriented to each other. Mosaicism is visible optically as a dispersion of optic axis orientations (Dachille et al., 1968; Stöffler and Langenhorst, 1994, p. 168), producing a patchy or "mottled" extinction under crossed polarizers (Stöffler and Langenhorst, 1994, p. 168). In X-ray diffraction studies, mosaicism appears (in diffractometer patterns) as a broadening of the normally sharp diffraction peaks of lattice planes (Hanss et al., 1978) or (in photographs) as a broadening of the normally sharp spots of lattice planes into curved and elongate spots ("asterism") or even into continuous arcs closely similar to powder diffraction patterns (Dachille et al., 1968; Hörz and Quaide, 1973).

Mosaicism is frequently observed in shocked samples of quartz and other minerals, and it is often highly developed in quartz grains that also exhibit PDFs (Stöffler and Langenhorst, 1994, p. 168). Mosaicism produced by relatively high shock pressures (typically $\geq$10 GPa) is generally much more extreme than that produced by endogenic processes such as tectonic deformation (Dachille et al., 1968), and individual shocked quartz grains may produce X-ray diffraction patterns virtually identical to those generated by randomly oriented powders (Hörz and Quaide, 1973). Although such extreme mosaicism is definitely a shock effect, the use of mosaicism as a unique diagnostic indicator of shock and impact is not justified at present. Similar mosaicism and fine-grained mosaic structures can also be produced by a variety of endogenic processes: crystallization, growth, deformation, recrystallization, and replacement (e.g., Spry, 1969, pp. 34, 157–158, Plate I). Past studies of mosaicism have not been carried far enough to establish reliable parameters for quantitatively estimating the intensity of mosaicism or for distinguishing rigorously between endogenic and shock-produced mosaicism (e.g., Dachille et al., 1968). In addition, there is little information about the relationship between the characteristics of mosaicism and such factors as mineral composition, grain size, and lithologic fabric in the affected rocks. A further problem in using mosaicism as a shock criterion is the common existence of mosaicism in unshocked rocks and the resulting need to establish the "baseline" level of mosaicism in target rocks not affected by the possible impact event, so that the more extreme shock-produced mosaicism can be convincingly determined.

5.3.4. Pseudotachylite and pseudotachylitic breccia

The subcrater target rocks of established impact structures often contain distinctive, even striking, bodies of melt-bearing rocks that range from small veinlets to large, inclusion-bearing bodies hundreds of meters in size (Shand, 1916; Fairbairn and Robson, 1941; Bischoff and Oskierski, 1987; Spray and Thompson, 1995; Dressler and Reimold, 2004). From their first recognition (Shand, 1916), there has been continuous debate and controversy over these pseudotachylites or pseudotachylitic breccias (Reimold, 1995, 1998): their character, nomenclature, origin, and use as unique impact criteria (for reviews and discussions, see, e.g., Reimold, 1991, 1995; Thompson and Spray, 1996; Gibson et al., 1997; Reimold, 1998; Dressler and Reimold, 2004; Reimold and Gibson, 2005).

Despite a controversy over these rocks, most workers have distinguished two fundamental varieties of pseudotachylites in the field. One type occurs as small, typically cm-length veinlets, composed of glassy material and often containing high-pressure phases (coesite, stishovite) or PDFs in quartz-bearing clasts (Martini, 1978; Lambert, 1981; Martini, 1991; Spray, 1998). These pseudotachylites probably form during the initial passage of the impact-generated shock waves, and the presence of ultrahigh-temperature glasses and high-pressure minerals can provide convincing evidence of impact, even in old or metamorphosed structures (Martini, 1978, 1991). These bodies have various designations: "Type A" (Lambert, 1981), "A-Type" (Martini, 1991), and "S- (shock) Type" (Spray, 1998). Small glassy veins, generated at lithologic contacts during shock-wave experiments, are similar to this type of pseudotachylite (Kenkmann et al., 2000a), indicating that both shock and friction play a role in their formation.

The second type is the more familiar, more striking, and longer-known material, originally designated as pseudotachylite (Shand, 1916), which forms large veins and irregular areas consisting of target rock fragments in a dark matrix composed partly to completely of melted material (Reimold and Colliston, 1994; Thompson and Spray, 1994; Reimold, 1995; Thompson and Spray, 1996; Spray, 1998). This type of pseudotachylite has been variously called "Type B" (Lambert, 1981), "B-Type" (Martini, 1991), and "E- (endogenic) Type" (Spray, 1998). Individual pseudotachylite bodies, observed at some structures e.g., Vredefort (South Africa) and Sudbury (Canada), may extend over hundreds of meters to kilometers (Dressler and Reimold, 2004). Shock effects are generally not found with this type of pseudotachylite; high-pressure minerals have so far not been observed, and target rock inclusions with PDFs have only rarely been noted.

The origin of this type of pseudotachylite, and its relation to the process of crater development, has been a complicated and controversial problem (Thompson and Spray, 1994; Reimold, 1995; Spray, 1995; Thompson and Spray, 1996; Reimold, 1998; Spray, 1998; Melosh, 2005). Recent proposals have suggested that there is no fundamental difference between this type of impact-produced pseudotachylite and similar materials produced by tectonic processes, i.e., that both kinds are the result of frictional melting between rapidly moving blocks of crustal rocks (Spray, 1995, 1997, 1998). In this view, these impact pseudotachylites are generated by the friction between large, fast-moving crustal blocks during collapse and modification of the original transient cavity (Spray, 1995, 1998). However, Reimold and co-workers do not fully agree with this view (see, e.g., Reimold, 1995, 1998), because no significant movement between the pseudotachylite walls is evident. Similar relations are observed in fault zones unrelated to impacts, in which pseudotachylites generated along shear planes have been injected as veins into nearby dilational fractures that show no lateral movement (e.g., Snoke et al., 1998).

Because the second type of pseudotachylite also lacks shock features and may be identical to the products of tectonic fault movements, its presence cannot be used as a unique indicator of shock metamorphism and meteorite impact. However, the presence of unusually large pseudotachylite bodies may indicate an impact origin (Spray, 1998). Most tectonic pseudotachylite bodies tend to be quasi-planar and thin, generally <1 m across (Philpotts, 1964; Higgins, 1971; Sibson, 1975; Magloughlin and Spray, 1992; Snoke et al., 1998). Larger bodies (i.e., $\geq$100 m in extent) may reflect the more extensive melting produced by impact conditions, in which the movement of individual crustal blocks is much more rapid than in the tectonic case (Spray, 1997, 1998). In any case, the discovery of large pseudotachylite bodies should spur a more detailed search for definite shock-metamorphic features in the surrounding environment.

5.3.5. Igneous rocks and glasses

The formation of large and small bodies of melted target rocks (from mm-size to thousands of km^3 in volume) is a common characteristic of meteorite impact events. During the initial stages of impact, the more intense shock waves (≥40 GPa) generated near the impact point produce near-instantaneous heating to extreme temperatures (≥2000 °C) throughout a large volume of the surrounding target rock (Grieve et al., 1977; Melosh, 1989, Chs. 4, 5, 8; Grieve and Cintala, 1992). The resulting impact melts may form small glassy bodies that are ejected from the developing crater or may produce larger dike-like and sill-like bodies of igneous rock that remain within the resulting structure (e.g., Dence, 1971; Grieve, 1978; Grieve et al., 1987; Grieve and Cintala, 1992; Pierazzo et al., 1997; See et al., 1998; Dressler and Reimold, 2001; Hörz et al., 2002; Whitehead et al., 2002).

For many of these impact-produced igneous rocks, their origin by shock and impact is not immediately obvious. Once formed, despite their extreme high-temperature origin, both large and small impact melt bodies cool, crystallize, and migrate in the same manner as do endogenic melts (magmas and lavas), following the same thermodynamic and mechanical laws. When solidified, most impact melts closely resemble, in textures, chemical composition, and mineralogy, the products of normal terrestrial igneous activity (Schüller and Ottemann, 1963).

The simple presence of glassy or crystalline igneous material, either within a suspect structure or as distant ejecta, cannot therefore be used as evidence either for or against an impact origin. The normal mineralogical and petrological characteristics of impact melts are not diagnostic for impact, and critical evidence of impact must be obtained from more detailed studies of the rocks themselves. Several characteristics of impact melts have been used to establish their origin by impact: (1) preserved xenoliths and xenocrysts from the target rocks, which may in turn contain definite shock-metamorphic features such as PDFs in quartz or lechatelierite (French et al., 1970; Carstens, 1975); (2) anomalous bulk-chemical compositions that can establish an origin by the bulk melting of atypical target rock assemblages (French and Nielsen, 1990); (3) the presence of chemical anomalies, e.g., excess Ir abundances, chondritic ratios of other PGEs, or distinctive Os isotope ratios, that indicate the presence of material from the projectile (Koeberl et al., 1996b; Koeberl, 1998, 2007); and (4) isotopic characteristics (e.g., in the Rb/Sr and Sm/Nd systems) that indicate derivation of the melts from crustal rocks that are much older than the age of the suspect structure itself (Hurley, 1963; French et al., 1970; Faggart et al., 1985; Howard, 2008).

Large bodies of impact melt, m to km in size and generally partly to wholly crystalline, are typically found as sills or dikes in individual structures, where they may be closely associated with other impact-produced rock types (e.g., breccias, shocked basement) containing definite shock effects. Such associated rocks can provide a strong indication of an impact origin for the melt bodies, even in the absence of more definite evidence from within the melts themselves. In addition, discovery of impact melt bodies in suspect structures may focus a search for more diagnostic shock effects.

Smaller impact melt bodies, mm to cm in size and generally glassy, may be ejected from the impact crater, often to regional or global distances, as individual "splash-form" objects, e.g., spherules and microspherules, dumbbells, droplets, and other aerodynamically shaped forms. On deposition, these objects often accumulate in distinct layers or as widely-distributed strewnfields. Tektites and microtektites are the best-known and most-studied of these ejecta deposits (see e.g., Koeberl, 1994; McCall, 2001), but a variety of other glass-rich ejecta deposits, of both Precambrian and Phanerozoic ages, have also been identified (Montanari and Koeberl, 2000, Chs. 2,3) (See "Spherules and Microspherules," Section 5.4 below.). Because their existence as melt particles is not diagnostic for impact, their identification as impact products has depended chiefly on association with other, definitely impact-produced features, e.g., coesite, quartz with PDFs.

Intermediate-sized (cm to dm) bodies of impact-produced glass in some cases occur as individual objects composed either of dense glass or of scoriaceous and vesicular melt. Many of these glassy bodies are clearly associated with a definite or possible impact structure, e.g., Meteor Crater (Arizona) (Hörz et al., 2002; Mittlefehldt et al., 2005), Lonar Crater (India) (Osae et al., 2005), Aouelloul (Mauritania) (Koeberl et al., 1998); Henbury (Australia) (Spencer, 1933; Ding and Veblen, 2004); Rio Cuarto (Argentina) (Schultz and Lianza, 1992; Aldahan et al., 1997); and Darwin (Australia) (Howard and Haines, 2007; Howard, 2008). However, there are numerous occurrences of scattered glass fragments for which no impact crater has yet been identified: Libyan Desert Glass (Montanari and Koeberl, 2000, p. 95–99); scoriaceous glasses from the Argentine pampas (Schultz et al., 1998, 2004, 2006); and isolated glass fragments from Russia (Deutsch et al., 1997), Africa (Osinski et al., 2007), and Australia (Haines et al., 2001).

The identification of such glasses as impact or non-impact products is difficult and commonly controversial (e.g., Milton, 1964). In many cases, the fragments are rare, there is no associated possible impact structure, and the glasses may closely resemble such non-impact products as fulgurites, volcanic glasses, non-impact frictional melts, or artificial (archeological) glasses. In the case of the Libyan Desert Glass, an impact origin has been supported by association of the glasses with shock-metamorphosed rocks (Kleinmann et al., 2001; Koeberl, unpublished data), the presence of high-temperature effects in the glasses (Kleinmann, 1969), the detection of chemical signatures from the projectile (Koeberl, 1997b), and abnormally low water contents (Beran and Koeberl, 1997). However, the impact origin for many glasses still remains controversial and unconfirmed (e.g., Haines et al., 2001; Osinski et al., 2007). These problems also affect attempts to establish the impact origin of distal ejecta deposits if no source crater has been (or can be) identified, as in the case of some tektites or early Archean deposits (see below, Section 5.3.3).

5.4. Spherules and microspherules in distal ejecta layers

During major cratering events, impact melting can also produce large numbers of individual mm- to cm-size droplets of inclusion-free impact melt (later usually recrystallized), which can be ejected to regional or even global distances from the crater (Grieve, 1997; Symes et al., 1998; Montanari and Koeberl, 2000, Chs. 2, 3; Simonson and Glass, 2004). Deposits of such spheroidal objects (spherules of >1 mm and microspherules of <1 mm diameter) in sedimentary layers can provide evidence for impact events, even in cases where the impact structure cannot be identified (Simonson, 2003; Simonson and Glass, 2004).

These individual droplets of melted target rock are generally produced during the early stages of cratering (Kieffer, 1975; Melosh, 1989, Chs. 4, 5; Melosh and Vickery, 1991) and are immediately ejected at high velocities from the developing crater, often to regional or even global distances. Such bodies are therefore rare in the proximal ejecta deposits associated with the crater itself (Graup, 1981; French, 1987, 1998, pp. 87–90); they are found instead in the distal ejecta deposited at significant distances (>5 crater radii) from the crater (Kyte, 1988; Grieve, 1997; Symes et al., 1998; Smit, 1999).

Tektites and microtektites are the best-known and longest-studied types of impact glass and spherules (for reviews, see O'Keefe, 1963, 1976; Glass, 1984; Koeberl, 1986, 1990; Glass, 1990; Koeberl, 1994; Glass, 2002; Montanari and Koeberl, pp. 64–93; McCall, 2001). These objects actually form a distinct subgroup of impact-produced glasses, and they have several distinctive characteristics that separate them from other impact and non-impact glasses (e.g., Montanari and Koeberl, 2000, p. 71): (1) they are completely glassy (amorphous);

(2) they lack crystals and crystallites; (3) they are homogeneous melts whose compositions represent silicic rocks, not minerals; (4) they commonly contain lechatelierite; (5) they are water-poor (<0.1 wt.%); and (6) they can, in three of the four known cases, be linked to a single source impact crater by geographical and geochemical studies. However, tektites do not occur close to their source crater; instead, they are widely distributed to form extensive strewnfields that extend over distances of hundreds to thousands of km. Three of the four known strewnfields have been convincingly linked to established impact structures ranging from about 1 Ma to 35 Ma in age.

The size-based division into tektites (>1 mm) and microtektites (<1 mm) (Glass, 1990) has not yet been applied to other types of impact melt droplets because many such objects show significant mineralogical and chemical differences from tektites (for details, see, e.g., Montanari and Koeberl, 2000, Ch. 2). Here we use the term "spherule" for convenience to designate such droplets regardless of size or compositional characteristics (Simonson, 2003; Simonson and Glass, 2004). Fig. 31 shows some examples of microtektites and impact-related microspherules — indicating that it is impossible to derive the mode of origin from the morphology of a spherule alone.

In addition to the four known tektite/microtektite strewn fields, other layers of spherule-bearing distal impact ejecta have been identified and connected to known impact structures. Identification of these layers as impact ejecta (Montanari and Koeberl, 2000, Ch. 3; Glass et al., 2004) has been based, not on the spherules themselves, but on the presence of definite impact products (shocked quartz grains or extraterrestrial siderophile-element enrichments) associated with them. Examples include spherule deposits associated with the Chicxulub (Mexico) crater at the Cretaceous–Tertiary (K–T) boundary (Fig. 32) (e.g., Bohor, 1990; Izett, 1990, 1991; MacLeod et al., 2007), as well as the recently recognized thick layer of ejecta from the 1.85-Ga Sudbury structure (Canada) preserved at several sites in the north-central United States and adjacent areas of Canada (Addison et al., 2005; Pufahl et al., 2007; Cannon et al., 2010), in which spherules are associated with other impact-produced components (shocked quartz grains, vesicular glass fragments, and accretionary lapilli). In addition, several Archean and Proterozoic impact events, for which the craters have not yet been identified, have been established by studies of similar spherule-rich layers (Lowe and Byerly, 1986; Lowe et al., 1989a,b; Simonson, 1992; Koeberl and Reimold, 1995b; Simonson et al., 1997, 1998; Montanari and Koeberl, 2000, pp. 142–148; Simonson, 2003; Reimold et al., 2000; Byerly et al., 2002; Simonson and Glass, 2004; Simonson et al., 2004; Jones-Zimberlin et al., 2006), with examples shown in Figs. 33–35.

Recent studies, in which such spherule layers have been carefully examined by geological, petrographic, and geochemical techniques, have provided strong evidence that they have been formed by meteorite impact events (Margolis et al., 1991; Montanari and Koeberl, 2000, Chs. 2,3; Simonson, 2003; Simonson and Glass, 2004). However, in most cases the confirmation of the impact origin did not come from the spherules themselves, but from associated minerals or geochemical anomalies. Unfortunately, there has also been an increasing tendency in recent publications to invoke the presence of any kind of spherules as definite proof of impact events, both in the geological record in general (e.g., Jones, 2005) and in specific deposits associated with major biological extinctions (e.g., Claeys et al., 1992; Kaiho et al., 2001; Hagstrum and Abbott, 2002; Ellwood et al., 2003). In many of these studies, as described below, the characterization of the "spherules" is sketchy and incomplete, and their use to support the existence of impact events is uncertain, speculative, and premature. (See Detre and Toth (1998) for a large collection of studies, of varying quality, on natural and artificial spherules.).

There are several major problems in attempting to use spherules as independent evidence for meteorite impact events:

1. Spherules alone do not provide diagnostic evidence of origin by impact. Like other impact melts, droplet spherules generally preserve no evidence of shock processes or of their original ultra-high-temperature origin. There are rare exceptions: inclusions of lechatelierite, coesite, and shocked zircon, which establish an

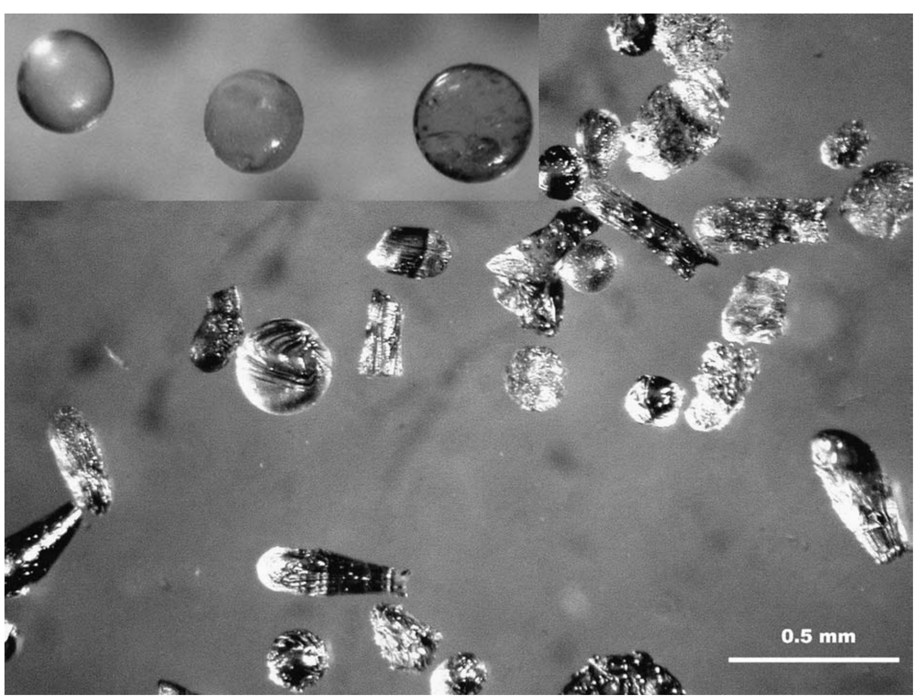

Fig. 31. Microtektites from the Ivory Coast tektite strewn field, showing both spherical and elongate droplet-shaped forms. Inset (upper left, same scale) shows fallback impact spherules found in drill core LB-05A from the Bosumtwi impact structure (Ghana). Both spherule types are glassy (not yet recrystallized) and originated from the Bosumtwi (Ghana) crater.
Photograph courtesy of B.P. Glass.

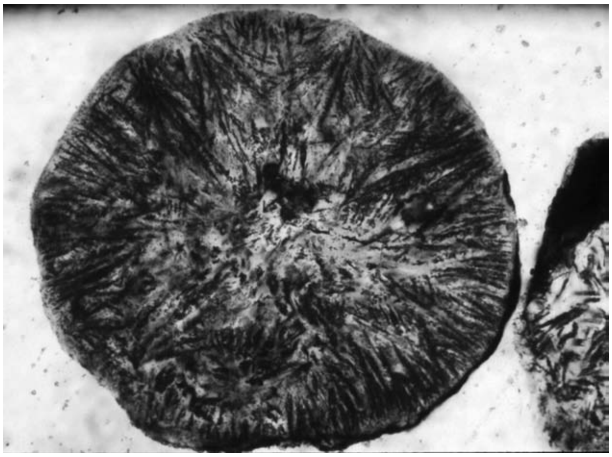

Fig. 32. Partly recrystallized individual impact-melt spherule from the K–T boundary layer at Caravaca, Spain (for details, see Simonson and Glass, 2004, Fig. 6). The spherule now consists of authigenic K-feldspar microlites that form a distinctive texture in which sheaves of microlites radiate inward from points on the rim of the granule. Plane polarized light; spherule is approximately 0.5 mm in diameter.
Photograph courtesy of B.M. Simonson; reprinted with permission from the Annual Reviews of Earth and Planetary Sciences [journal title in italics], Volume 32, (c) [Copyright symbol] 2004 by Annual Reviews, www.annualreviews.org.

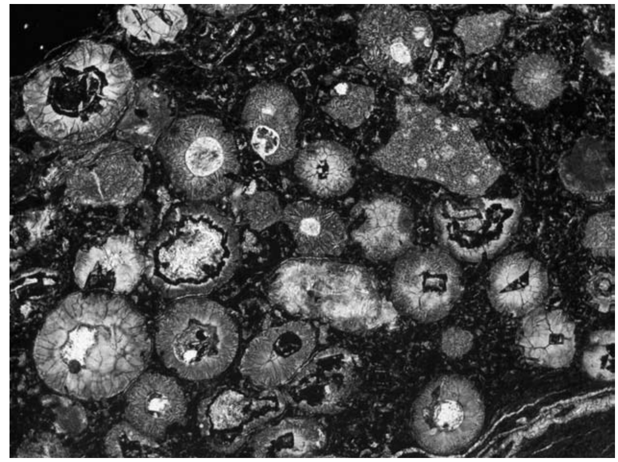

Fig. 34. Microscopic view of impact-melt spherule layer in the Neoarchean Bee Gorge Member of the Wittenoom Formation, Australia. At this site, the layer consists of lenses of well-sorted spherules, redeposited by impact-induced tsunami waves and/or currents. Most of the spherules display coarsely-crystalline cores of K-feldspar, quartz, and/or carbonate that represent filled-in vesicles and/or replaced glass, surrounded by typical rim textures composed of inward-radiating K-feldspar microlites. Sparry ferroan carbonate crystals, which replaced some spherules and filled the interstitial pores, have oxidized during weathering to form most of the dark material. The high abundance of spherules (>10 vol.%) strongly suggests that the layer originated as impact ejecta rather than as volcanic tephra. Plane polarized light; field of view is 4.7 mm wide; typical spherules are 0.5–0.9 mm in diameter.
Photograph courtesy of B.M. Simonson.

impact origin directly, have been reported from both individual tektites and microtektites (Glass and Barlow, 1979; Glass et al., 2002). (However, lechatelierite has also been reported from spherules produced in natural oil-shale fires; see Marini and Rauka, 2004). This lack of direct impact evidence is more general in older spherule deposits (e.g., those of Precambrian age), in which the original characteristics of the spherules have been obscured by subsequent mineralogical and chemical alteration (Lowe and Byerly, 1986; Simonson, 1992; Koeberl and Reimold, 1995b; Simonson, 2003; Simonson and Glass, 2004).

2. In many distal ejecta layers, spherules are not accompanied by other materials that show distinctive and unambiguous shock-metamorphic effects. Exceptions include the occurrence of coesite and shocked quartz grains with microtektites in material from the Australian and North American strewnfields (Glass and Wu, 1993), the presence of shocked quartz with spherules in the K–T boundary layer (Bohor et al., 1984, 1987; Izett, 1990, 1991; Alvarez et al., 1995), and the occurrence of a single grain of apparently shocked quartz contained in an Archean spherule (Rasmussen and Koeberl, 2004). Likewise, siderophile-element anomalies may be absent in spherule layers, although distinctive signatures of Ir abundances and of Os isotopic ratios have been detected in the K–T boundary layer (Alvarez et al., 1980; Koeberl and Shirey, 1997) and in several of the older Precambrian layers (Simonson and Davies, 1996; Simonson et al., 1998, 2000; Shukolyukov et al., 2000; McDonald and Simonson, 2002; Simonson, 2003; Simonson and Glass, 2004; Rasmussen and Koeberl, 2004). In such cases, the impact origin of the associated spherules can be considered to be well established, even though the spherules themselves do not contain diagnostic impact features.

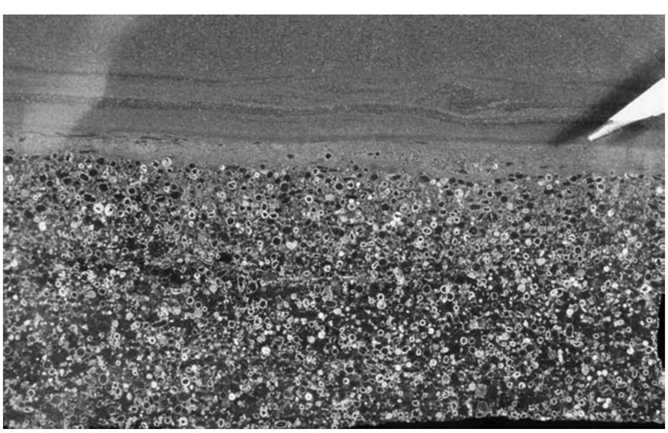

Fig. 33. Macroscopic view of polished slab of spherule-rich layer, showing contact between lower spherule-rich subunit and fine-grained upper backwash(?) subunit; from the Paleoproterozoic Dales Gorge Member of the Brockman Iron Formation, Western Australia. Field of view is about 10 cm wide, and spherules average about 1.4 mm in diameter. The anomalous occurrence of this coarse, spherule-rich layer, which is only 30 cm thick on average yet contains meter-scale rip-up clasts, emplaced in a series of quiet-water sediments, strongly suggests a sudden, violent event involving rapid and turbulent deposition of the spherules. In addition, the high percentage of spherules present suggests an origin as impact-melt particles rather than as volcanic ejecta.
Photograph courtesy of B.M. Simonson.

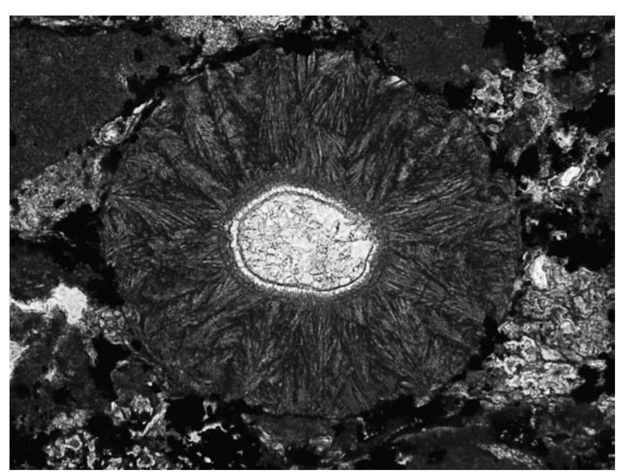

Fig. 35. Highly recrystallized individual impact-melt spherule from the Neoarchean Jeerinah Formation, Western Australia. (For details, see Simonson, 2003, his Fig. 3) The spherule now consists of a core of coarsely crystalline authigenic K-feldspar, a thin band of sericite lining a former vesicle, and a thick rim of authigenic K-feldspar microlites that form a distinctive texture in which sheaves of microlites radiate inward from the outer edge of the spherule. Plane polarized light; longest axis of spherule is 850 µm long.
Photograph courtesy of B.M. Simonson; published with permission of Astrobiology.

3. An especially severe problem in using spherules as a unique impact criterion is that the spheroidal shape by itself is not a unique indicator of impact or even of melting. A wide variety of non-impact spherical, spheroidal, or droplet-shaped bodies, both natural and artificial, are abundant in the geological environment. Such features can easily be (and frequently have been) interpreted as impact-produced objects.
4. Natural glassy spheroidal objects in the same size range as impact-produced spherules include volcanic droplets and lapilli (Fisher and Schmincke, 1984, p. 96–106; Heiken and Lofgren, 1971; von der Borsch, 1971; Heiken and Wohletz, 1985, pp. 22–25; Iyer et al., 1997) and meteorite ablation debris (Blanchard et al., 1980; Brownlee, 1985; Taylor et al., 1998; Brownlee, 2001; Peucker-Ehrenbrink and Schmitz, 2001; Koeberl, 2001; Taylor and Lever, 2001). In addition, natural nonmelting processes can produce a wide variety of similar spheroidal objects. Low-temperature sedimentary and diagenetic processes can produce spheroidal oolites, fecal pellets, spherulites, fossils, algal structures, and other organic and inorganic constructions (Pettijohn, 1957, pp. 95–97, 197, 201–202, 220; Carozzi, 1960, pp. 236–260, 344–370, 373–381; Johnson, 1951, Pl. 98; Horowitz and Potter, 1971). Other spheroidal objects in sediments can include organic pollen and plant spores (Felix, 1961; Taylor, 1981; Montanari, 1986), siliceous plant phytoliths (Piperno, 2006), and objects produced by the alteration of hydrocarbon deposits (Stevenson et al., 1990).

In addition, a dismayingly large variety of artificial spherules, produced intentionally or accidentally by various melting and manufacturing processes, are being increasingly recognized as contaminants in geological samples and laboratories. These materials include: fly ash from coal-fired power plants (Fisher et al., 1976; Hulett et al., 1980; Day and Glasser, 1990; Jones and Olson, 1990; Rose, 1996; Olson and Jones, 2001; Sulovsky, 2002; Sokol et al., 2002; Matsunaga et al., 2002; Hower and Robertson, 2004; Jordanova et al., 2004; Veneva et al., 2004), spheroidal products from a variety of metallurgical processes (e.g., Vuorelainen and Tornroos, 1986a,b), and small droplets produced during the artificial high-temperature fusion of geological materials to produce road-metal and other materials (e.g., Finkelman et al., 1976; Byerly et al., 1990). (A wider range of potential sources of contaminant spherules, based on anecdotal reports, includes welding spatter, droplets from ferrosilicon alloy production, fusion products from automobile brake linings and catalytic converters, lead pellets from shotgun shells, and glass beads manufactured for reflecting highway signs and for other laboratory or industrial uses.) These artificial contaminants are being increasingly recognized in geological samples, and distinguishing these objects from natural spherules is a serious problem that has rarely been given adequate attention (e.g., Glass, 1969; Finkelman et al., 1976; Byerly et al., 1990; Jones and Olson, 1990; Storzer, 1992; Wang, 1992; Wang and Chatterton, 1993; Rose, 1996; Olson and Jones, 2001; Jordanova et al., 2004; Vuorelainen and Tornroos, 1968a,b; Marini, 2003; Marini and Rauka, 2004). In some areas, studies have demonstrated that industrial fly ash is such a widely distributed pollutant that it can be used as a geological and historical tracer (Jones and Olson, 1990; Rose, 1996; Olson and Jones, 2001; Jordanova et al., 2004).

Impact-produced spherules, when convincingly identified, can provide important evidence for impact events. They can also provide clues to the mechanics of the impact process and to the former existence of now-destroyed impact structures. But the use of microspherules alone as impact indicators requires careful and meticulous work to demonstrate conclusively that they are: (1) natural and (2) impact-produced. For example, it is not possible to distinguish between, e.g., microtektites (Fig. 31) and fly ash spherules based solely on optical or electron microscopy.

The character and geological setting of spherule-bearing layers can provide strong (if not conclusive) indications of a meteorite impact origin (Simonson, 2003). For example, the presence of an anomalous, coarse, spherule-bearing layer in an otherwise fine-grained, quiet-water, and slowly-deposited sedimentary sequence suggests a sudden and catastrophic event consistent with a meteorite impact (Hassler and Simonson, 2001; Simonson, 2003; Simonson and Glass, 2004). In addition, high abundances of spherules (>10 vol.%) to the exclusion of other objects are suggestive of an impact origin and are inconsistent with volcanic tephra deposits (Simonson, 2003; Simonson and Glass, 2004).

Petrographic characteristics of impact-produced spherules include (Simonson, 2003, pp. 52–62): (1) a restricted size range (typically 60–2000 μm); (2) the presence of abundant splash-form shapes (spheroids, dumbbells, teardrops, etc.) indicative of melting; (3) crystallization textures that develop inward from the rims rather than outward from a central core; (4) an absence of associated typical nonspheroidal fine volcanic materials (e.g., glassy shards, glassy filaments ["Pele's Hair"], corroded phenocrysts, or volcanic rock fragments); and (5) the presence of associated definite shock effects, such as particles containing lechatelierite or grains of shocked quartz with PDFs (but see also Marini and Rauka, 2004). Geochemical indicators of impact-produced spherules include (Montanari and Koeberl, 2000, pp. 71–77, 118–123; Simonson, 2003; Simonson and Glass, 2004): (1) original compositions corresponding to natural crustal target rocks or to mixtures of such rocks; (2) compositions unlike typical volcanic rocks; (3) an absence of exotic compositions, e.g., rare-metal alloys, hydrocarbons or enrichments in non-meteoritic elements such as Ba, Ti, Mn, Pb, etc., which, if present, suggest a natural or artificial terrestrial origin; and (4) the presence of anomalous concentrations of projectile-related chemical elements (e.g., Ir and the other PGEs) or isotopic signatures (e.g., Os, Cr).

The initial steps in studying a spherule layer for a possible impact origin should be a careful description of the geological setting and characteristics, followed by detailed mineralogical and geochemical analyses to eliminate the most common non-impact origins (e.g., volcanism, contamination) and to search for associated definite shock effects. In some cases (e.g., altered spherule layers that lack definite shock indicators), the origin may remain ambiguous, but careful studies can often provide at least a strong case for an impact origin, together with information about the cratering event in which the spherules were produced. However, the mere presence of a small number of spheroidal objects in a sample cannot be regarded as evidence for an impact event.

5.5. Other problematic criteria

5.5.1. Fullerenes

Fullerenes (especially C_{60} and C_{70}; Aldersley-Williams, 1995) have been reported from several impact environments, including both the Cretaceous–Tertiary boundary layer (Heymann et al., 1994), crater-fill breccias from the well-established Sudbury (Canada) impact structure (Becker et al., 1994, 1996; Mossman et al., 2003; Elsila et al., 2005), and samples from other impact structures (Elsila et al., 2005). The fullerenes at Sudbury have been variously explained as chemical products of the impact event (Heymann et al., 1994) or as components introduced from the impacting body itself (Becker et al., 1994, 1996). However, the origin and significance of fullerenes, in both impact and non-impact geological settings, remain controversial (Taylor and Abdul-Sada, 2000; Buseck, 2002), and significant concerns still exist about their formation, analytical detection, geological survival, and significance as impact products or impact indicators.

Fullerenes, by themselves, cannot be used as an independent indicator of impact or of shock-metamorphic conditions. Fullerenes can be formed artificially at ambient pressures, by applying high temperatures (e.g., flames, electric currents) to carbon or to gases of appropriate composition (Aldersley-Williams, 1995, Ch. 8), and fullerenes neither require nor indicate the presence of high pressures or shock waves. In using fullerenes as impact evidence, Becker and others have therefore argued that the evidence for impact is provided instead by the presence of isotopically unusual He "caged" in the fullerenes (Becker et al., 1996, 2001), and not by the presence of the fullerenes themselves. However, these observations of unusual He have not been confirmed by other workers (Farley and Mukhopadhyay, 2001; Koeberl et al. 2004; Farley et al. 2005), and they remain uncertain.

Furthermore, reports of natural fullerenes do not show a consistent connection to impact structures. Many of the best-established natural occurrences of fullerenes are from clearly non-impact geological environments (Parthasarathy et al., 1998; Jehlička et al., 2003; Mossman et al., 2003), while several searches for fullerenes in the rocks of impact structures have produced contradictory results (Frank et al., 2005; Elsila et al., 2005). The presence and formation of fullerenes in impact events is a complex and potentially important issue that needs to be explored further. At present, however, neither the presence of fullerenes, nor their contents, can be used as independent and diagnostic indicators of meteorite impact events.

5.5.2. Iron-rich nanophase particles

Wdowiak et al. (2001) report the detection, by Mössbauer spectroscopy, of small Fe-rich particles a few tens of nm in size (nanophase particles) in the upper layer of the impact deposit at the Cretaceous–Tertiary boundary, a thin layer that also contains both the Ir enrichment and shocked quartz. The authors raise the intriguing possibility that these particles, now composed chiefly of the mineral goethite (α-FeOOH), may represent condensed material that was originally vaporized from the impactor and deposited with other ejecta components. If such nanophase particles are in fact a unique product of impact events, they might be used as a unique criterion for impact events and might provide details about the mechanics of the impact (Wdowiak et al., 2001). However, goethite is an abundant mineral in non-impact, near-surface geological environments, and more detailed comparative studies will be needed to demonstrate that the nanophase particles are in fact a unique indicator of impact conditions.

5.5.3. Impact-produced damage in microfossils

Unusual mechanical and thermal deformation effects have been observed in calcareous and organic-containing microfossils recovered from the crater-fill breccia unit ("Exmore breccia") at the Chesapeake Bay Crater (USA). These effects include unusual fracturing of calcareous fossils (Self-Trail, 2003) and the welding, melting, and deformation of organic ones (Edwards and Powars, 2003). Because these deformed microfossils are associated with definite evidence of impact (PDFs in quartz and an Ir anomaly), it has been suggested that the deformation features are impact-produced and may be used as criteria for similar impact events (Self-Trail, 2003; Edwards and Powars, 2003; Horton et al., 2005b).

These reports indicate a potentially important and exciting area for future research. Future studies could lead to the establishment of new impact criteria that would be valuable in recognizing impact events in unconsolidated marine sediments, a rock type for which few impact criteria now exist. At present, more studies are needed to establish whether such deformation features are unique to impact and to determine the conditions under which they form. Additional field studies should examine whether similar deformation features are observed in fossils found at other established impact craters formed in marine sediments (e.g., Silverpit [United Kingdom]; see Section 6.2.4). Experimental studies should be undertaken on such fossils and their sediments to determine the pressure and temperature conditions under which the observed deformation structures form and to establish with certainty that they are distinct from those produced by normal sedimentary and diagenetic processes.

6. Problematic reports of impact events, structures, and shock-deformation effects

6.1. Background

In the last several years, numerous "identifications" of new impact structures, and alleged evidence for major impact events, have appeared in the scientific literature. Many of these reports are problematical, uncertain, and speculative, and the evidence on which their conclusions are based is incomplete, ambiguous, or incorrect (see, e.g., Reimold, 2007; Pinter and Ishman, 2008).

Such reports are harmful for several reasons: (1) the unproved claims insert incorrect and speculative information into the scientific literature; (2) they create false impressions about the abundance of terrestrial impact structures and the role of meteorite impact in past and present earth history; (3) they promote false perceptions about exactly what criteria are convincing and diagnostic for recognizing impact events. Because of the widespread interest in meteorite impact among both scientists and the public, and because of the perception of a "controversy" between the "establishment" and the creators of the controversial reports, these incorrect data and perceptions are often eagerly transmitted by the media to wide segments of the scientific and public communities.

These problematical reports (discussed individually in more detail in the Sections below) can be divided into three general types: (1) those based on morphological, structural, or geophysical characteristics, or (occasionally) on historical reports (e.g., Abbott et al., 2003b, 2005), with no supporting evidence from ground studies or analyzed rock samples; (2) those involving geological studies and rock samples, which describe alleged shock-deformation features which are often not adequately described and are not demonstrably shock-produced. Such reports typically involve either normal endogenic features unrelated to impact or features that are in fact impact-produced but are not diagnostic (e.g., fracturing, breccias, and melts); and (3) those that invoke new but generally unaccepted or not yet sufficiently documented features as evidence of impact, e.g., the presence of microspherules or fullerenes (C_{60}) (see above). In many of these cases, an impact origin may be possible or probable, but such reports do not provide conclusive evidence.

6.2. Morphological, structural, and geophysical studies

6.2.1. Introduction

Numerous structures have been claimed to be of impact origin solely on the basis of morphological patterns, geological structures, and geophysical anomalies. Such reports are useful in identifying candidate sites for further study, but none of those features provide conclusive evidence for origin by impact. These reports range from highly speculative assertions based only on perceived geological patterns to more solid descriptions (and cautious interpretations) that include field work, structural mapping, or geophysical studies. The structures described often show features consistent with an impact origin: localized deformation (often in a circular pattern), a central uplift, and circular magnetic and gravity anomalies. (Details about such individual possible impact features, which have widely varying degrees of evidence for impact, are given on several Web pages, e.g., SEIS, 2006; Rajmon, 2006, 2009; PASSC, 2009; IFSG, 2009).

For many of these reported structures, meteorite impact is a plausible means of formation. Nevertheless, such features as the circular crater form, structural deformation, central uplift, and geophysical anomalies are all produced late in the cratering process, during the modification stage (see above, Sections 2, 5.2.1, and 5.2.2), under physical conditions that are much less extreme than the original shock-wave conditions that generate distinctive shock features in the target rocks. Therefore, in the absence of definite shock features (i.e., features indicating shock pressures ≥ 10 GPa), endogenic methods of formation cannot be entirely eliminated.

The current absence of shock effects in many structures may reflect only the limited amount of geological study so far done on them or the difficulty of finding such evidence, e.g., in old or deeply eroded structures. In many such possible structures, more detailed searches can be expected to turn up more definite evidence of impact. A more serious problem in verifying the impact origin of such structures is that many of the diagnostic shock effects (e.g., PDFs in quartz) are restricted to quartz-bearing crystalline rocks or coarse sandstones (Grieve et al., 1996), while many suspect structures have formed in rock types unsuitable for the development of such distinctive shock-metamorphic features in quartz: carbonates, fine shales, unconsolidated sediments, and mafic gabbros and basalts.

Three groups of possible impact structures can be distinguished on the basis of the type and amount of geological information presented in the various reports; (1) circular or linear morphological patterns; (2) structural studies that demonstrate the presence of circular deformation and uplift; and (3) geophysical studies (especially gravity, magnetic, and seismic observations) that provide detailed three-dimensional information. The plausibility of an impact origin, and the evidence for it, increases with the amount of information available, but endogenic origins cannot be entirely eliminated unless definite shock-deformation features can be identified.

6.2.2. Circular features and patterns

Many reports of possible impact structures are based only on the observation of circular morphological patterns, often observed only in remote-sensing observations, and often without any discussion of, or reference to, the bedrock geology. A notable (and certainly the most visible) feature is the Nastipoka (or Hudson Bay) Arc, a nearly perfect segment of a circle 450 km in diameter, located in the southeast corner of Hudson Bay, Canada (Beals et al., 1968). A large number of smaller circular features with a range of sizes have also been reported (e.g., Flinn, 1970; El-Baz, 1981; Barakat, 1994; Isachsen et al., 1994; Gonzalez and Alonson, 2006; El-Baz and Ghoneim, 2007), on the basis of remote-sensing data alone. (Linear patterns, composed of multiple structures, have also been invoked as evidence of impact; Rampino and Volk, 1996.) The proposal by Paillou et al. (2004) regarding the existence of an impact-crater field containing more than 1300 separate structures was also supported by images of alleged "shatter cones", which, however, are most certainly ventifacts (wind abrasion features), and more recent studies (Orti et al., 2008) found no evidence for any impact origin of these structures.

Although many of these reports are appropriately cautious and only suggest the possibility of impact origin for the circular features they describe, some authors have apparently assumed, without further justification, that circular morphology by itself establishes an impact origin (e.g., Windolph, 1993; Leung and Abbott, 2003; Abbott and Manzer, 2003; Manzer and Abbott, 2003; Abbott et al., 2003a; Paillou et al., 2004; Abbott et al., 2006; Martos et al., 2006; Bryant et al., 2007). Such sweeping, unproven, and speculative reports (mostly only published as unreviewed abstracts) do lend themselves readily to transient media attention (Abbott et al., 2003b; Petit, 2003), but their value to further research is questionable.

6.2.3. Structural and geological studies

Strong, if not conclusive, arguments have been made for the impact origin of several suspect structures on the basis of field mapping and other geological studies. Such methods can establish that a suspect structure displays characteristics that are consistent with impact, e.g., anomalous and localized deformation, circular deformation patterns, and central uplifts. This category includes the so-called traditional "cryptovolcanic" or "cryptoexplosion" structures (Bucher, 1936, 1963; Dietz, 1963a,b; Snyder and Gerdemann, 1965; Luczaj, 1998), many of which have since yielded definite shock-metamorphic features to establish a definite impact origin. Other examples, such as Jeptha Knob (Kentucky) (Seeger, 1968), Versailles (Kentucky) (Seeger, 1972), Kilmichael (Mississippi) (Robertson and Butler, 1982), Hico (Texas) (Milton, 1987), and Calvin (Michigan) (Milstein, 1988, 2001) have still not yielded shock effects; their impact origin still remains unproved, but they remain interesting candidates for further examination.

6.2.4. Geophysical studies

Geophysical studies (seismic, gravity, magnetics) cannot by themselves provide independent evidence of shock metamorphism and impact (Pilkington and Grieve, 1992; Grieve and Pilkington, 1996). However, such studies are important in identifying anomalous structures for future examination (e.g., Waddington and Dence, 1979; Forsyth et al., 1990; Poag et al., 1994; Talwani et al., 2003), and for studying confirmed impact structures in more detail. Geophysical studies can establish that the characteristics of a suspect structure (especially of a subsurface one) are consistent with impact structures, i.e., that circular deformation, breccia zones, and central uplifts are present. Seismic profiling techniques can establish that the near-surface structural deformation decreases and disappears with depth, an important characteristic of an exogenic meteorite impact. Gravity measurements can also eliminate the presence of anomalous high- or low-density rock at depth beneath the structure, providing evidence against alternative theories of origin by (respectively) igneous intrusion or salt-dome uplift.

Geophysical studies of suspect structures, and the discovery of gravity and magnetic anomalies associated with them, have also led directly to their confirmation as impact structures through the subsequent discovery of shock-metamorphic effects associated with them. In many cases, especially involving subsurface structures, the process of establishing suspect features as definite impact structures has been initiated by geophysical studies of the region or of the structure itself, and definitive shock effects have been found by studies initiated on the basis of geophysical information (e.g., Hildebrand et al., 1991; Kirschner et al., 1992; Koeberl and Reimold, 1995a; Koeberl et al., 1996a,c; Carleton et al., 1998; Stone, 1999; Comstock et al., 2004).

In a few intensely-studied structures, geophysical studies, especially including seismic profiling, have provided very strong evidence for meteorite impact by documenting the presence of intense, localized, anomalous, and apparently rapid structural deformation, even though definite shock-metamorphic features have not yet been discovered in them. The Silverpit structure in the North Sea (United Kingdom) (e.g., Stewart and Allen, 2002; Smith, 2004; Stewart and Allen, 2005; Thomson, 2006) has become widely accepted as an impact structure on the basis of its isolated circular character, development of multi-ring deformation in soft sediments, and the consistency of its form and structure with sophisticated computer models (Collins et al., 2003a,b). However, in the absence of shock-metamorphic evidence (Koeberl and Reimold, 2004) (which may be difficult to find in a deep marine structure formed in soft sediments) the origin is still debated, and endogenic mechanisms have not been ruled out (Smith, 2004; Thomson, 2006).

The recent establishment of the Upheaval Dome (Utah) structure as an impact feature by the recent discovery of shock-metamorphosed quartz grains in its rocks (Buchner and Kenkmann, 2008) is a good demonstration of the process by which field and geophysical studies can provide support for an impact origin and can promote the discovery of actual shocked materials to confirm it. The Upheaval Dome structure shows intense localized deformation and a central uplift, and it has been plausibly regarded for some time as a deeply eroded impact structure formed in the horizontal lithified sediments of the Colorado Plateau (Kriens et al., 1999; Kenkmann, 2003; Kenkmann et al., 2005a; Scherler et al., 2006). However, in the continued absence of shock-metamorphic effects, despite considerable searching (Koeberl et al., 1999), alternative endogenic theories such as salt dome uplift and volcanic activity had continued to be held.

A stronger case for impact had recently been made, based on detailed geophysical analyses of the deformation, which had apparently been intense, rapid, and characterized by horizontal components of movement unlike those produced by the alternative endogenic mechanisms (Kenkmann and Stöffler, 2002; Scherler et al., 2006). The scarcity of shock-metamorphosed material at Upheaval Dome may reflect deep erosion of the structure after formation, but the recent discovery of shocked materials has now established its impact origin with certainty.

In the absence of any studies on the actual rocks (e.g., findings of shock-metamorphic features), geophysical signatures alone are mostly meaningless and non-unique, and such reports must be regarded with caution (e.g., Talwani et al., 2003; von Frese et al., 2009). In at least one case, the Fohn-1 structure (Australia) (Gorter and Glikson, 2000), an initial identification as an impact structure was based on geophysical signatures, supplemented by petrological and geochemical characteristics of breccia in a core sample. This identification, initially controversial, had to be discarded because of misinterpretation of the geochemical data, as was pointed out by Reimold et al. (2001), and an endogenic origin was subsequently accepted by Gorter and Glikson (2001). The "Puffin Structure" in Australia, a "semicircular" feature whose evidence for impact is so far based only on geophysical interpretations (Gorter and Bayford, 2000a,b; Hough, 2000), is the subject of a similar debate. The report of a potential impact structure in California (Spevack et al., 2007), based only on seismic studies so far, has attracted media attention, but no scientific confirmation has been produced. A similar but larger argument is centered on the even more controversial Bedout structure (Australia), which is allegedly connected with the Permian–Triassic extinction boundary (Becker et al., 2004a,b; Müller et al., 2005) (see discussion below, Section 7.1.6). Finally the recent report of a 500-km-diameter impact structure of possible Permian–Triassic age in the Antarctic (von Frese et al., 2009), is based entirely on satellite gravity measurements, provides no geological context, and completely ignores the absence of any predictable regional and global geological effects from such a large impact event, e.g., the absence of any thick ejecta layer at nearby Antarctic Permian–Triassic boundary sections (Collinson et al., 2006).

6.3. Field and petrographic studies

6.3.1. Megascopic features

6.3.1.1. Questionable shatter cones. Well-developed shatter cones are now generally regarded as convincing indicators of meteorite impact, even when they are not accompanied by other shock effects (e.g., Manton, 1965; Read, 1983; Hargraves et al., 1990) However, the recognition of shatter cones in the field remains to a large degree a matter of individual perception, experience, and judgment. Similar conical or striated surfaces can be produced by non-impact processes, including sedimentary cone-in-cone structures (Lugli et al., 2005) or wind-abrasion features on outcrop surfaces (Elston and Lambert, 1965; Elston et al., 1968).

The conical features reported as "shatter cones" from the Arkenu structures (Libya) (Paillou et al., 2003) strongly resemble shatter cones, but they appear to have developed only on outcrop surfaces (their Fig. 6) as wind-abrasion features (cf. our Fig. 8). The authors have not established that the features are actually fracture patterns that cut through the rocks, a typical characteristic of impact-produced shatter cones. Deformation features in the associated quartz (their Fig. 8) do not resemble typical PDFs; for example only one set of apparent (sub)planar fractures ("PFs") is present (cf. our Fig. 26). Recently, Di Martino et al. (2008) presented evidence against an impact origin of Arkenu. The establishment of the impact origin of the structures requires better documentation of the characteristics and orientation of these conical features, or the discovery of definite shock effects (e.g., definite PDFs in quartz) within the cones themselves or elsewhere in the structures.

6.3.1.2. Quartz fracturing. Ernstson et al. (2001) proposed that cm- to mm-scale fracturing of quartzite cobbles and individual quartz grains, together with the development of small crater-like features on the cobble surfaces, may be diagnostic impact-produced effects associated with two possible impact structures in Spain: Azuara and Rubielos de la Cerida (Ernstson et al., 1985, 2002). Although fracturing in quartz, both across grains and within grains, does occur in impact structures (Kieffer, 1971; French et al., 2004), there is no evidence that the fractures described in this paper are either shock-produced or are diagnostic impact features, and no other, more convincing, evidence of impact has yet been provided for those two Spanish structures.

Problems with the impact interpretation for these structures include: (1) the fractured rocks described are located 60–100 km from the presumed source impact structures (diameters about 30 km), and no comparisons have been made of similar materials at greater distances, where any effects associated with impact would be virtually negligible; (2) the "PDFs in quartz" (Ernstson et al., 2001, their Fig. 3A) are not described in detail; only one set appears present, and no critical orientation data are presented; and (3) the larger fractures apparently result from tensional stresses, as demonstrated by the authors' production of similar fractures in low-pressure dynamic experiments (Ernstson et al., 2001, pp. 13–14); however, quartz is weak in tension, and the fracture patterns were produced at pressures <1.5 GPa (see also Hirth and Tullis, 1994, for similar results in static experiments), pressures which might be generated in non-shock tectonic processes (see also Fig. 25). The occurrences deserve further study (in particular, more comparison of the fractured rocks with more distant materials affected only by regional tectonic pressures), or with tectonically deformed rock from known non-impact environments. However, whether or not the fractures may in fact be associated with impact events, they do not provide independent evidence of impact because of the low pressures involved in their formation.

6.3.2. Misidentification of coesite

The high-pressure phases coesite and stishovite are still reliable and diagnostic criteria for impact, at least in geologic settings unlikely to contain pre-impact endogenetic occurrences of these minerals, However, they have not generally been sought in recent studies of possible impact structures. Most recent identifications of impact structures have instead emphasized PDFs in quartz because of their wider distribution, greater geological durability, and greater ease of detection and measurement. In addition, the separation of coesite and stishovite for identification (e.g., by X-ray diffraction) requires a complex dissolution procedure, using HF and HCl, that requires laboratory safeguards (see Fahey, 1964), and failure to follow this procedure can lead to an incorrect identification of coesite. An example of such misidentification involves the "coesite" originally reported from the Richat structure, Mauritania (Cailleux et al., 1964) that was subsequently identified as barite (Fudali, 1969), which has an X-ray diffraction pattern unusually similar to that of coesite, but which was not removed by the heavy-liquid separation procedure used by the original authors. Confirmation of individual coesite grains and their petrographic relations in thin section is best obtained by Raman spectroscopy (cf. Fig. 9).

6.3.3. Incorrect and questionable identifications of PDFs in quartz

Numerous recent claims of an impact origin for suspect structures and possible ejecta layers have been based on the misidentification of other features as shock-produced PDFs in quartz from their rocks. In many cases, described in detail below, these identifications have not been convincingly established, and descriptions of the alleged "PDFs" are often too poor to permit definite identification of any kind. In particular, detailed information is generally lacking on such critical data as the width and spacing of the planar microstructures, the number of planar sets in individual grains, and the percentage of grains in the sample containing such "PDFs". Photomicrographs are often poor in quality and published in sizes too small for critical evaluation (which may in some cases result from attempts by journals to save space), and, in most cases, no petrofabric measurements have been made to establish the orientation of the features.

The publication of these reports is unfortunate. Although they may indicate structures and geological units that deserve further study and may in fact be of impact origin, these unjustified identifications of problematic deformation features create a false impression of certainty in the study of individual structures and meteorite impact geology in general.

The authors of these publications seem unaware of (or at least do not mention) the unique and distinctive characteristics of true PDFs (see above, Section 4.2.2): multiplicity, straightness, lack of individual birefringence, occurrence either as solid glassy lamellae (when fresh) or as planar arrays of small inclusions (when decorated), and specific orientations relative to the quartz crystal lattice, Many of these reports describe as "PDFs" what are apparently normal deformation features in quartz, features that were probably not impact-generated: metamorphic deformation lamellae (MDLs; see Fig. 30A,B), irregular fractures, and subparallel inclusion planes that probably represent healed fractures (see Figs. 26–28). Other features identified as "PDFs" may have been impact-generated, such as irregular and subparallel fractures, but such features form at low shock pressures and are therefore not diagnostic. In several cases, subsequent detailed studies of these "PDFs" (e.g., by TEM) has established that they are not true PDFs.

Carter et al. (1986) identified planar microstructures interpreted as PDFs in volcanic ash from the Toba caldera, arguing that the presence of such features in a volcanic environment indicated that the K–T extinction could have been produced by volcanic activity rather than by meteorite impact. Both the identification and the conclusion are questionable (Izett and Bohor, 1987; Carter and Officer, 1987; Sharpton and Schuraytz, 1989). The "PDFs" are extremely rare (in $\ll$1% of all quartz grains), they occur typically in single sets (in contrast to the multiple sets found in quartz grains from the K–T boundary layer), and (based on photographs) they appear more similar to typical normal MDLs, showing only moderate to poor definition, a lack of sharpness, and a broad spectrum of orientations within the host quartz grains (Alexopoulos et al., 1988, pp. 797–798).

Questionable "PDFs" have also been reported from several structures for which an impact origin was proposed. In some cases (e.g., Sisodia et al., 2006; Chen, 2008), the identifications of "PDFs" are based on flat-stage photomicrographs that show small numbers of vaguely planar features (similar to, e.g., our Figs. 29, 30B). These features are not well developed, lack petrofabric measurements, and resemble typical endogenic quartz deformation features (e.g., open or healed random fractures) rather than PDFs (e.g., Reimold et al., 2006).

The questionable "PDFs" in quartz from the pumiceous rocks in a landslide deposit at Köfels (Austria) (Surenian, 1988) show microstructures that are curved and locally faulted; only surfaces of broken grains are shown in SEM images, which is totally inadequate. The paper does not distinguish between open fractures (possible PFs) and closed features, and the paper contains no detailed data on the planes themselves, e.g., width, spacing, number per grain, or orientation. A subsequent TEM study (Leroux and Doukhan, 1993) concluded that no shock-metamorphic features were present.

The Ševětín structure, Czech Republic, was proposed as an impact structure on the basis of various planar microstructures in quartz (Vrana, 1987): "concussion fractures" and "planar elements and cleavages". Details on these features are lacking, but the photographs (Vrana, 1987, his Figs. 8, 14, and 16) seem to show a combination of typical MDLs with irregular healed fractures that are only subparallel. A later TEM study (Cordier et al., 1994) established that these features are only subparallel, that they are too widely spaced (>20 μm) to be PDFs, and that the rocks show no other shock features.

In describing a possible double impact structure (Arkenu, Libya) (Paillou et al., 2003) and a possible large field of small impact craters (Gilf Kebir, Egypt) (Paillou et al., 2004), the authors present only photographs of ambiguous deformation features in quartz and do not include details on number, width, spacing, or orientation of these features. Based on the photographs (Paillou et al., 2003, their Fig 8; Paillou et al., 2004, their Fig. 5), the features resemble a combination of MDLs (our Fig. 30) and random fractures rather than true PDFs. In addition, geological evidence (Di Martino et al., 2008) does not support an impact origin for the Arkenu structures, while the impact origin of the Gilf Kebir crater field has also been challenged (Orti et al., 2008).

A problematic but intriguing occurrence of possible quartz PDFs has been described from fragments of vesicular, slaggy silicate glass at Edowie, Australia (Haines et al., 2001), although debate continues about whether the glasses have been produced by impact or are the result of lightning strikes (fulgurites). The appearance of the possible PDFs in photographs (Haines et al., 2001, their Figs. 2, 3) is ambiguous. They occur in up to 3 sets/grain, but many of the planes are wavy and curved like typical MDLs, while fractures also appear present. Orientation measurements, however, strongly suggest shock-produced orientations, particularly ω and π. Further studies of this material are needed, both to confirm whether the deformation features in the included quartz grains are shock-produced and to explore the range of possibly similar deformation and melting phenomena that can be produced in non-impact fulgurites.

Questionable "PDFs" in quartz have also been identified from several putative impact ejecta layers. The notable identification of such features from the Permian–Triassic boundary layer in Antarctica (Retallack et al., 1998) was originally an important component in the continuing debate over the presence of a large impact event at this major extinction boundary (see discussion below, Section 7.1.2), and this study included orientation measurements of the features. However, in the photographs, the features strongly resemble typical MDLs, and a later re-examination using TEM (Langenhorst et al., 2005) demonstrated conclusively that the features are not shock-produced PDFs.

Possible "PDFs" in quartz grains are also reported with microspherules in a mid-Devonian layer in Morocco (Ellwood et al., 2003). Descriptive details on the "PDFs" are lacking, but they occur in about one set per grain, which is consistent with MDLs. Orientation measurements (Ellwood et al., 2003, their Fig. 2; but without information on the percentage of indexed orientations) produce a scattered histogram which appears more consistent with the typical "bell-curve" of MDLs (our Fig. 16C) than with true PDFs. This misidentification of PDFs was pointed out by Racki and Koeberl (2004). A subsequent paper (Schmitz et al., 2006), which included some of the original authors of the Ellwood et al. (2003) study, acknowledged that geochemical data rule out an impact origin of the Moroccan layer.

A claim for "shocked quartz" occurs in a study (Jones, 2005) that argues that the large British Tertiary igneous province was generated by impact-produced melting (see discussion below). The "shocked quartz" from a "Tertiary breccia" in Antrim, Ireland, is shown only in a photograph (Jones, 2005, Fig. 2) with no details or orientations reported. The features shown are two sets of subparallel planes, which most resemble healed fractures. There is not even a superficial resemblance of these features to true PDFs, and the use of these features to support such a major and wide-ranging theory is totally unjustified.

6.4. Microspherules

Microspherules have acquired increasing importance as possible indicators of distal ejecta from both known and unknown impact structures. However, microspherules are not, by themselves, diagnostic indicators of impact events, because similar objects can be produced by a wide range of geological and artificial processes (see discussion above, Section 5.4). Identification of microspherule-bearing layers as impact ejecta needs additional evidence: geological context, association with genuine quartz PDFs, high-pressure minerals, or definitely extraterrestrial siderophile-element anomalies.

Many descriptions of microspherule-bearing layers are brief and do not provide solid arguments for an impact origin. Material reported as a possible impact layer at the base of the Middle Ordovician in Illinois (Read, 1986) contains some spherical features with concentric structures, together with extensive replacement by secondary quartz. An origin as a silicified oolite layer seems more probable based on the limited data available.

Other microspherule occurrences provide more solid, if not yet conclusive, evidence for an impact origin. An impact origin has been proposed for a 1-m-thick spherule-bearing layer in Greenland, approximately 1800–2100 Ma (Chadwick et al., 2001), based on its characteristics and geological context and on the arguments against biological or volcanic origins; the authors speculate about a possible Vredefort connection, but this has not been substantiated. Several microspherule beds also occur in rocks of the British Tertiary igneous province at Disko, Greenland (about 62 Ma old) (Jones et al., 2005). Unlike the highly speculative report of alleged quartz PDFs in rocks of similar age (Jones, 2005; see discussion above, Section 6.3.3), an impact origin for the Disko microspherule beds is more solidly supported by their textures, mineralogy, and chemistry and by apparent differences between them and similar volcanic products.

More definite evidence for an impact origin, in the form of quartz grains showing apparent PDFs, occurs in an older microspherule layer in the Late Triassic of southwest Great Britain (Walkden et al., 2002; Kirkham, 2003). In this layer, typically 25–150 mm thick, the original spherules have been converted to glauconite, but associated quartz grains retain structures whose appearance and orientation strongly resemble those of genuine PDFs. An impact origin for this unit appears probable (Glass et al., 2003), and the age measured for this layer (214 Ma) is close to that established for five other impact structures, including both Rochechouart (France) (which is too small an impact structure to have produced such a spherule layer at the observed distance) and Manicouagan (Canada).

7. Questionable “impact” effects at major extinction boundaries

7.1. The Permian–Triassic boundary

7.1.1. Background

The end of the Permian period, about 250 Ma ago, is marked by the largest known mass extinction in geological history. At this time, in two closely-separated events, more than the 90% of known marine species disappeared, accompanied by a major portion of terrestrial species as well (Erwin, 1993, 2006). Since the establishment of a firm connection between the later K–T extinction and a major impact event (Alvarez et al., 1980), numerous workers have searched for evidence of a similar connection between another large impact event and the Permian extinctions. Most efforts have concentrated on the younger and larger of the two extinction events, which marks the actual Permian–Triassic (P–Tr) boundary at 251 Ma.

The numerous attempts to find convincing evidence of impact at the P–Tr boundary have provided a highly visible demonstration of the difficulties involved in establishing the existence of past impact events and of the widespread ignorance and misunderstanding concerning the use of specific features as definitive evidence of impact. The studies to date have generated a large amount of ambiguity, controversy, and publicity (see discussion below), but they have not yet produced any convincing evidence for a large meteorite impact at the P–Tr boundary.

The studies fall into two types: (1) ambiguous, unconfirmed, and discredited reports of features generally regarded as diagnostic for meteorite impact, e.g., quartz PDFs and Ir anomalies; and (2) reports of other features that may be consistent with a large meteorite impact but are not definite evidence for one: micrometeorite fragments, microspherules, fullerenes, and exotic ratios of noble gases.

7.1.2. Quartz PDFs and siderophile elements

The presence of definite PDFs in quartz grains from the P–Tr boundary has yet to be convincingly established. The features described as PDFs in an early report (Retallack et al., 1998) are more suggestive of MDLs (see discussion above, Sections 4.3.4 and 6.3.3), and have since been shown by TEM studies (Langenhorst et al., 2005) not to be shock-produced PDFs. Later reports of shocked quartz at the P–Tr boundary in Australia (Becker et al., 2004a) provide only photographs, and the features shown are not convincing. Similarly, early reports of enhanced Ir and siderophiles at the boundary at several locations in China (Xu et al., 1985; Xu and Yan, 1993) have not been confirmed (Yin et al., 1989), and several subsequent detailed investigations have found no excess extraterrestrially-derived siderophiles at well-documented and carefully sampled sections across the boundary (Clark et al., 1986; Holser et al., 1989; Koeberl et al., 2004).

A particularly careful study of a P–Tr boundary in Austria (Koeberl et al., 2004) demonstrates why critical, detailed, and extensive analyses are needed to establish the presence of meteorite impact signatures. At this location, the boundary sediments do display a small excess in the abundances of siderophile elements such as Ir and other PGEs, but the anomalies are much smaller than at the K–T boundary. Furthermore, the elements occur in completely non-meteoritic proportions, and neither the associated chemical data nor measured Os and He isotopic ratios provide any evidence for meteorite impact.

7.1.3. Micrometeorites and Cr isotope anomalies

The reported presence of micrometeorites among the magnetic particles separated from a layer at the P–Tr boundary at Graphite Peak, Antarctica (Basu et al., 2003; Petaev et al., 2006) is intriguing, but the presence of small meteorite fragments (<500 μm) does not provide evidence for a large meteorite impact event at that time. Even if these objects are not from the normal micrometeorite flux, they could reflect the infall of a larger object, large enough to produce abundant microparticles but too small to produce a significant crater.

In addition, the apparent preservation of 250-Myr-old micrometeorites and their component minerals also raises questions, because other meteorite fragments recovered from marine environments are heavily altered. Fragments of the K–T bolide have been extensively altered after 65 Ma in a marine environment (Kyte, 1998), while preserved Ordovician (>400 Ma) meteorites in Scandinavia are completely replaced by other minerals and are recognizable only by texture and by the presence of rare relict chromite grains (Nyström et al., 1988; Schmitz and Tassinari, 2001).

Other samples of magnetic materials separated from these P–Tr boundary samples display anomalous $^{53}Cr/^{52}Cr$ ratios that also indicate the presence of an extraterrestrial component in those specific samples analyzed by Shukolyukov et al. (2004) and Becker et al. (2006), but independent analyses of the original samples from the same location (obtained from G. Retallack) in the laboratories of the Free University of Brussels, the University of Vienna, and the University of the Witwatersrand did not show the presence of any micrometeorites or meteoritic signatures (P. Claeys, C. Koeberl, W.U. Reimold, unpublished data). Given how unlikely it is that micrometeorites remain unaltered for 250 Ma, the source of the Cr anomaly observed by Shukolyukov et al. (2004) and Becker et al. (2006) remains a mystery.

7.1.4. Spherules

Large concentrations of spherules (“microspherules”), typically 5 μm to 600 μm in size and varying widely in composition, have been reported from P–Tr boundary sediments at several locations in China (Gao et al., 1987; Xu et al., 1989; Yin et al., 1989, 1992; Xu and Yan, 1993; Jin et al., 2000). Many of these spherules show textures consistent with formation from droplets of melt, but their exact character and origin are still uncertain. Several different types of spherules have been identified chemically, including both Fe-rich and Si-rich compositions. Other spherules have phosphatic (apatitic) compositions that are consistent with organic or diagenetic formation mechanisms, while some have been identified as actual fossils (prasinophyte algae) (Yin et al., 1989, 1992). The origins of these spherules have not been definitely established, and various workers have interpreted them to be the products of either volcanic activity or a large meteorite impact. However, none of the data so far determined have provided any unique or convincing evidence for a meteorite impact origin (see Section 5.4). (An additional problem in interpretation is that many of the Chinese P–Tr sections are closely associated with active coal mines and coal-fired power plants [D.H. Erwin, personal communication], so that contamination of surface samples by fly ash or similar materials is a concern.)

7.1.5. Fullerenes and noble gases

More controversial features reported from the P–Tr boundary are fullerenes, allegedly containing caged noble gases with exotic and allegedly planetary isotopic ratios (Becker et al., 2001; Poreda and Becker, 2003), which are proposed to have survived from the impacting body. As mentioned above, fullerenes can form under non-shock conditions, and their occurrence and preservation under geological conditions for long periods of time are still controversial (Becker et al., 1994, 1996; Taylor and Abdul-Sada, 2000; Buseck, 2002). The occurrence of caged He in fullerenes from the P–Tr boundary also remains controversial, and the original determinations (Becker et al., 2001) have not yet been reproduced (Farley and Mukhopadhyay, 2001). More importantly, analyses of P–Tr boundary sediments at two other locations (Gartnerkofel, Austria and Opal Creek, Canada) (Koeberl et al., 2004; Farley et al., 2005) have detected no anomalous He and have indicated the possibility of contamination from natural terrestrially derived He (Farley et al., 2005).

7.1.6. The Bedout Permian(?) impact(?) structure

The related suggestion (Becker et al., 2004a) that the Bedout structure, Australia could be "the" P–Tr impact structure has also produced an extensive controversy over the nature, age, and origin of the structure and about the allegedly shock-produced features in its rocks (Renne et al., 2004; Wignall et al., 2004; Glikson, 2004; Becker et al., 2004b,c,d;). Bedout is a submarine structure, and much of the evidence for its form and features derives from geophysical studies, which are not diagnostic for impact. The problem of identification is further complicated by the fact that the target rocks are basaltic volcanic rocks that lack quartz grains. Petrographic evidence for impact (Becker et al., 2004a) includes alleged "silica glass", "fractured and melted plagioclase", and "spherulitic glasses". These features are ambiguous and could as easily represent normal features in altered and silicified volcanic rocks (Glikson, 2004).

The report of alleged maskelynite in the Bedout samples by Becker et al. (2004a) would be more suggestive of impact, because maskelynite and other diaplectic mineral glasses are diagnostic criteria for shock and impact. However, the descriptions and photographs of the "maskelynite" presented are not conclusive. Later claims for the identification of maskelynite in the Bedout samples by micro-Raman spectra (Basu et al., 2004, 2006) provide ambiguous and generally featureless spectra that show virtually no differences between "maskelynite" samples and unshocked comparison samples. These results seem inconsistent with earlier demonstrations that experimentally shocked plagioclase can develop a variety of complex and variable Raman spectra, depending both on plagioclase composition and shock pressure (Heymann and Hörz, 1990; Treiman and Treado, 1998).

The petrographic evidence for an impact origin of the Bedout structure is, therefore, controversial at best. In addition, criticisms have been raised that the proposed Permian–Triassic age for the structure is not established (Renne et al., 2004) and that the complete range of available geophysical evidence is not consistent with an impact structure (Glikson, 2004; Müller et al., 2005).

At present, it seems clear that no convincing or generally accepted evidence for impact has yet been found at the Permian–Triassic boundary, nor have any large impact structures of the appropriate age been identified. Although an end-Permian impact remains a possible and plausible cause for the catastrophic extinction (e.g., Erwin, 2006, Ch. 8), the search for conclusive evidence needs to be carried on with more sophistication, more care, less controversy, and a wider geographic scope.

7.2. The Younger Dryas (Pleistocene) Event

A new controversy about the terrestrial consequences of meteorite impacts has recently been generated by the suggestion (Firestone et al., 2007; Kennett et al., 2009a,b) that the extinctions and environmental changes associated with the so-called Younger Dryas Event about 12,900 years ago were triggered by one or more extraterrestrial impacts. These reports provide a good example of: (1) the enthusiasm for meteorite impacts as a causative agent for sudden and otherwise unexplained environmental and biological changes; (2) the uncritical use of nondiagnostic criteria as evidence for meteorite impact events; (3) the way in which even problematic reports can focus new attention on long-debated questions and (hopefully) generate new, detailed, and critical investigations.

The Younger Dryas has long been recognized as a time of significant and sudden climate cooling, accompanied by significant faunal extinctions (especially of large vertebrates) and by the apparent disappearance of the Clovis human culture from North America. The nature, characteristics, and causes of these changes have been widely studied and are still being debated (for background and discussions, see, e.g., G. Haynes, 2002; C.V. Haynes, 2005; Bonnichsen et al., 2005). Firestone et al. (2007) suggested that these changes resulted from the entry of one or more extraterrestrial objects into the Earth's atmosphere over North America. These objects were either destroyed in Tunguska-like atmospheric explosions ("airbursts") or survived to impact the then-extensive Laurentide Ice Sheet, releasing large amounts of energy and producing wildfires, global cooling, and destabilization of the ice sheet. None of the objects penetrated the ice cap to excavate bedrock or produce permanent impact craters.

Support for this interpretation is provided by analysis of particulate materials separated from globally-collected samples of unconsolidated sediments from the Younger Dryas boundary (Firestone et al., 2007). These sediments typically consist of two layers, each a few cm thick: (1) a carbon-rich "Black Layer"; (2) an underlying "Younger Dryas Layer", from which much of their particulate materials were separated. Firestone et al. report (2007, pp. 16017–16019), as evidence of impact, the following materials: (1) magnetic microspherules; (2) magnetic grains; (3) magnetic grains containing Ir, Ti, and Ni; (4) charcoal; (5) soot and polycyclic aromatic hydrocarbons (PAHs); (6) carbon spherules with possible nanodiamonds; (7) fullerenes containing extraterrestrial He; (8) glass-like carbon with nanodiamonds (see also Kennett et al., 2009a,b).

These reports, and the discussions about them, have generated an extensive and continuing controversy (e.g., Kerr, 2007, 2008; Pinter and Ishman, 2008; Kerr, 2009), and the continuing detailed discussion of the evidence is beyond the scope of this paper. However, it should be noted that none of the materials so far identified in the Younger Dryas sediments by Firestone et al. (2007) and Kennett et al. (2009a,b) can be regarded as diagnostic and unarguable evidence of meteorite impact.

1. The magnetic microspherules (Item 1) are not well-enough characterized to distinguish them from such contaminants as fly ash or normal micrometeorites (see above, Section 5.4).

2. The magnetic grains (Item 2) are also not well-characterized and could be trace minerals (such as Ti-magnetite) eroded from glaciated crystalline rocks.
3. The carbonaceous materials (Items 4–6 and 8) suggest the presence of combustion, possibly at high temperatures, but do not directly establish that the fires were caused by impact. Recently, Marlon et al. (2009) demonstrated that there were no widespread and coincident wildfires at the time, invalidating this argument in favor of an impact event.
4. Fullerenes and their He contents (Item 7) have never been confirmed as definite impact criteria, as they do not occur in all materials, and because of the lack of reproducibility of the original determinations (see above, Section 5.5.1).
5. The only items suggestive of impact are the reported Ir anomalies (Item 3) and the presence of nanodiamonds (Items 6 and 8; see also Kennett et al., 2009a,b). The Ir analysis are not well described, and, as noted above (Section 3.2.2), isolated Ir analyses are not strong evidence for impact unless they can be supported by analyses of other related elements. Paquay et al. (2009) have searched for an extraterrestrial signature using PGE abundances and Os isotopes at several Younger Dryas sections, but have found a purely terrestrial signature instead, in clear contradiction to the much more limited analyses by Firestone et al. (2007). Although nanodiamonds have been found associated with some impact events, they can also be produced in low-pressure non-impact environments (for reviews, see Hazen, 1999, Chs. 11, 12), and their relationship to impact events is still undetermined (e.g., Gilmour, 1998; also see above, Section 3.3.3).

More recently, Kennett et al. (2009a,b) have reported the discovery of nanodiamonds in the Younger Dryas layers at several locations, and they have claimed that such nanodiamonds are characteristic for impact. The latter claim is demonstrably not correct. Kennett et al. (2009b) list abundances of nanodiamonds of up to about 3.7 ppm. Two types of nanodiamonds are mentioned, and it is not exactly clear which types are included in these estimates: the "n-diamonds" that supposedly "crystallize under lower temperature–pressure conditions" and the "cubic diamonds" that are supposedly shock-produced. The images in the published article are not of sufficient quality, magnification, and resolution to allow an easy comparison to meteoritic nanodiamonds, and the X-ray d-spacings cited are not uniquely characteristic of diamonds.

If nanodiamonds are present, there are two options: a) they could come from an extraterrestrial source (i.e., the impacting projectiles), or b) they could come from the target. An origin from target materials (graphite or coal in the target rocks) implies an actual impact, with high pressures, suitable carbon-bearing target rocks, and a resulting world-wide distribution of an ejecta layer. In that case, it is difficult to explain why this ejecta layer would contain only nanodiamonds but no shocked rock or mineral fragments. In contrast, an explosion in the atmosphere (assuming numerous incoming small bodies) will not produce shocked diamonds because the resulting pressures are much too low. The possibility remains that nanodiamonds are extraterrestrial components in the impacting bodies, However, the abundances claimed by Kennett et al. (2009a) are almost as high as those present in the rare meteorites that do contain presolar nanodiamonds. The proposed "ejecta layers" would therefore have to consist almost entirely of pure meteoritic matter, which raises the question why no other (and far more abundant) physical or chemical components from the meteorite have been identified in the layers (e.g., Paquay et al., 2009).

In addition, there are a number of logical contradictions in the Younger Dryas impact hypothesis. If, as was claimed in one model, the impacting body was a 5-km-diameter comet nucleus (or asteroid), a body of this size would hit the Earth at very high speed. (Comets, which tend to move in highly elliptical orbits, would have particularly high impact velocities, possibly as high as 40 km/s relative velocity.) A body this size and entry velocity cannot be slowed down in the atmosphere because the body diameter is almost the scale height of the atmosphere; it would thus transit the atmosphere in less than a second, striking the ground and creating a crater 50–100 km in diameter. Even hitting an ice cap 2 km thick, the impacting body will excavate a transient crater cavity about 10 km deep, resulting in the excavation of several km^3 of crustal target rocks and the ejection of shocked and unshocked rock and mineral fragments to global distances. Finally, a 50–100-km- diameter crater would be still be highly visible — and probably hot as well — after less than 13,000 years. Only about half a dozen impact craters of this size have formed during the past 50 million years; such a recent impact of this size would be an extremely unlikely event.

A second version of the hypothesis involves a large number of small, Tunguska-like comets, which would all explode in the atmosphere and heat up the ice underneath, but would form no bedrock craters or leave any remnants of shocked minerals. In this case, all the impacting objects would have to be in the same restricted size range (30–50 m diameter), because any larger bodies would penetrate the atmosphere and create surface craters, while any smaller objects would explode without effect in the upper atmosphere. In addition, such clusters of objects are so far unknown in the solar system.

Understanding the nature and causes of the events in the Younger Dryas is an important scientific goal, and these reports (Firestone et al., 2007; Kennett et al., 2009a,b) may be valuable in stimulating interest in the problem and in generating further work that is both critical and detailed. However, the case for meteorite impact cannot be accepted on the basis of the results so far presented. The alleged impact criteria are neither reliable nor diagnostic, and there are many unresolved geological problems associated with the proposed "airburst" impact mechanism (e.g., see discussions in Kerr, 2007, 2008, 2009). More methodical and detailed studies of the Younger Dryas sediments are needed to establish their chemical, mineralogical, and organic character (e.g., C.V. Haynes, 2008) and to search for reliable evidence of impact events at that time. No such evidence has been confirmed so far (Paquay et al., 2009). An independent study has been unable to confirm the presence of peaks in the contents of magnetic grains and magnetic spherules at the Younger Dryas boundary (Surovell et al., 2009).

8. Discussion

8.1. Constraints on the Detection of Shock Effects

Impact events produce a wide range of structural, microdeformational, and thermal effects in the target rocks, but only a few of these effects are uniquely diagnostic for high shock pressures and impact (see Table 1 and Appendix). The recognition of such effects, and their use to establish the impact origin of a suspected structure or a layer of possible ejecta, is further constrained by the conditions of formation, distribution, and preservation associated with an impact event.

The initial formation of diagnostic shock effects is strongly dependent on location within the structure. During crater formation, peak shock pressures decrease outward from the impact point, and shock pressures high enough to form shatter comes (>2 GPa) and PDFs in quartz (>10 GPa) are restricted to relatively small volumes of target rock in the central part of the structure. Further out, shock pressures quickly decrease below the levels needed to form diagnostic shock effects, and typical pressures near the rim of the final excavated crater are <1 GPa, possibly as low as 0.1–0.2 GPa (Kieffer and Simonds, 1980, p. 177–178). The volume in which diagnostic shock effects develop is therefore a small fraction of the total volume of target rock involved in crater formation, possibly 10–20 vol.% for shatter cones and 2–5 vol.% for PDFs in quartz.

The distribution of diagnostic shock effects is further modified by movement and redistribution during crater formation. In the final structure, distinctive shock effects will be located only in specific areas: shocked parauthochthonous rocks below the crater floor; layers of melt and breccia within the crater; and material ejected from the crater as proximal and distal ejecta. The final crater is a geologically shallow structure, and most of the units containing distinctive shock effects are deposited near the existing ground surface, so that the detection of shock effects also depends on the preservation of the rocks that contain them. Subsequent burial, erosion, or metamorphism can make the critical rock types inaccessible or remove them entirely.

Diagnostic shock effects are small in comparison to the size of the crater, ranging from cm-m scales (shatter cones) to mm-μm scales (deformed mineral grains), and even to the atomic scales represented by chemical and isotopic analyses. There are as yet no established shock features that appear at the scales of hundreds of meters to km, and remote-sensing observations at these scales are not sufficient to identify impact structures conclusively (Koeberl, 2004). Field studies and ground observations, combined with sample collection and laboratory study, are essential to discover, characterize, and establish the presence of shock effects.

The identification of shock effects can best be carried out in a series of steps involving increasing complexity, sophistication, and expense: (1) field studies and sample collection, including the examination of outcrops or core samples for shatter cones; (2) petrographic and petrofabric studies to identify and verify such key features as diaplectic glasses or PDFs in quartz; (3) mineralogical searches for high-pressure phases, using XRD, Raman, and related methods; (4) chemical and isotopic analyses to identify the basic characteristics of the rocks and to search for signatures of extraterrestrial projectiles. Some of the latter methods are intricate and expensive, but the required equipment is widely available; no major facilities or specific instrumentation are required.

The constraints on the use of shock effects to identify impact events can be summarized as follows: (1) remote sensing observations are not adequate; (2) ground-based field observations and sample collection are essential; (3) most of the rocks (probably >90 vol.%) in an impact structure show no shock effects; collection of a diverse suite of samples, accompanied by a little luck, may be necessary to find ones that do; (4) most shocked material is deposited in geologically vulnerable near-surface deposits: breccias and melt inside the crater and ejecta deposits around it; these units (if they are preserved) represent the best locations to search for shocked material.

8.2. Shock Effects and Target Rock Characteristics

A major limitation on the use of shock effects is that their development and expression depend significantly on the individual characteristics of the target rocks in which they form. The formation, appearance, and discovery of many diagnostic shock features are closely related to such rock properties as mineralogy, grain size, porosity, fracturing, foliation, and mineral distribution (e.g., papers in French and Short, 1968; Kieffer, 1971; Kieffer et al., 1976a; Grieve et al., 1996).

Even though shatter cones are observed in a wide range of rock types, from fine-grained limestones to coarse crystalline rocks, they develop more impressively, and are more detectable, in fine-grained rocks such as carbonates (Fig. 5) and shales, and their development may also be triggered and localized by discontinuities in the rock (see discussion above, Section 3.3.1; also Dietz, 1963a, 1968). The development of diagnostic petrographic shock effects (e.g., PDFs, diaplectic glasses, and high-pressure polymorphs) is even more controlled by mineralogy and other rock properties (Kieffer, 1971; Walzebuck and Engelhardt, 1979; Grieve et al., 1996).

Virtually all the petrographic shock effects so far used in impact crater identification have been based on a limited suite of rock types, chiefly quartz-bearing crystalline rocks and compact quartzose sediments (Grieve and Therriault, 1995; Grieve et al., 1996). These shock criteria can be effectively applied if such rock types are present in a suspected impact structure, but significant problems arise in studying structures developed in other rock types such as mafic crystalline rocks, basalts, carbonates, and fine-grained or unconsolidated sediments.

8.2.1. Mafic crystalline rocks and basalt lavas

Shock effects produced in mafic crystalline rocks and basalts are significantly different from those observed in quartz-bearing crystalline rocks and sediments. Shock effects in mafic rocks are more characterized by such nondiagnostic features as twinning and brittle fracturing in mafic minerals and by melting of both feldspar and mafics at higher shock pressures (Kieffer et al., 1976b; Schaal and Hörz, 1977). Although the absence of quartz in such rocks makes it difficult to recognize the presence of low shock pressures (<20 GPa), shocked basaltic rocks can be recognized, and impact structures identified, by the presence of maskelynite or heterogeneous high-temperature melting (Fredriksson et al., 1973; Kieffer et al., 1976b).

8.2.2. Carbonate Rocks

Except for the development of macroscopic shatter cones, carbonate rocks (including limestone and dolomite) show no distinctive shock effects at low shock pressures. Multiple twinning does occur in carbonates from impact structures (Roddy, 1968, p. 299–300; Burt et al., 2005), but it has not yet been possible to distinguish shock-produced twinning from that produced by normal tectonic deformation (Carter and Friedman, 1965; Spry, 1969). At high shock pressures (>40 GPa), shocked carbonate apparently melts instead of deforming or decomposing to release CO_2 (Tyburczy and Ahrens, 1986; Lange and Ahrens, 1986; Agrinier et al., 2001), and carbonate melts are now recognized as a significant component of impact breccias in several structures (Graup, 1999; Osinski and Spray, 2001; Osinski, 2003, 2004; Osinski et al., 2004, 2008). (Similar shock-produced melting, without major decomposition, has also been observed in anhydrite [sulfate]-rich sedimentary rocks associated with carbonate sediments (Osinski and Spray, 2003)).

It is, therefore, difficult to identify impact structures developed in carbonate targets unless shatter cones or definite carbonate melts can be identified. Identification of old and deeply-eroded impact structures in carbonate rocks has depended on the presence of shatter cones or on the discovery of PDFs in quartz from minor associated quartz-bearing units (Wilshire et al., 1971, 1972; Offield and Pohn, 1979; Carleton et al., 1998). However, many suspect structures of plausible impact origin lack such features, and their origin remains uncertain. Future field and experimental studies need to explore whether carbonate minerals develop distinctive shock effects below their melting points, by using XRD and similar techniques (Skála and Jakeš, 1999; Burt et al., 2005). Furthermore, deformation features such as twinning, even if not diagnostic for shock, can nevertheless provide information about the origin and development of impact structures (e.g., Schedl, 2006).

8.2.3. Fine-grained sediments

Finer-grained rock types, especially sediments such as fine sandstones and shales, display a general lack of petrographic shock features, even when closely associated with coarser-grained rocks in which petrographic shock effects are well-developed. Fine-grained quartz is relatively more resistant to forming PDFs than is coarser quartz (Grieve and Robertson, 1976; Walzebuck and Engelhardt, 1979; Grieve et al., 1996), whereas associated carbonates and sheet silicates (e.g., micas, chlorite) do not form diagnostic shock features even in larger grains. Shock-metamorphic effects in fine-grained sediments appear restricted to the partial or complete melting produced at relatively high shock pressures, e.g., >10–15 GPa in fine-grained or porous rocks (Kieffer, 1971, 1975; Stöffler, 1984). The effects of such melting can provide evidence for shock and impact, but only if the effects can be distinguished from the results of normal igneous melting.

8.2.4. Unconsolidated sediments

There is virtually no field or experimental information available about the response of unconsolidated or poorly consolidated target sediments to shock waves, and possible impact structures developed in such targets present major problems regarding identification (Robertson and Butler, 1982; Kyte et al., 1988; King et al., 2002; Stewart and Allen, 2002, 2005). In such non-brittle targets, impact-generated shock waves may produce neither shatter cones nor petrographic shock features, and evidence of impact may be limited to melts formed from the projectile and/or target (Kyte and Brownlee, 1985; Kyte et al., 1988; Gersonde et al., 1997) or to geological and geophysical signatures (Robertson and Butler, 1982; Stewart and Allen, 2002, 2005) that are only suggestive, but not diagnostic. Because the number of suspect impact structures in such unconsolidated targets will probably increase in the future, the problems of identifying them are an important topic for current research. Such research should include shock experiments on unconsolidated materials, the recognition of impact melts produced from such materials, and the refinement of geophysical criteria to uniquely identify impact structures in such targets.

8.3. Identification and Documentation of Quartz PDFs

The widespread use (and misuse) of planar microstructures in quartz to identify impact structures deserves particular comment. PDFs in quartz are probably the most-used criterion for the identification of impact structures, and they have certainly been one of the most misidentified and mis-applied. This situation is unfortunate, because the identification of shock-produced PDFs and PFs in quartz, and their distinction from other deformation features that develop in quartz in non-impact environments, are basically straightforward and require only a reasonable amount of background information, routine operations, care, and time. Precise and convincing identification of quartz PDFs can be done with a standard petrographic microscope and U-stage (cf. Grieve et al., 1996; Morrow, 2007; Ferrière et al., 2007, 2008, 2009b), although more sophisticated studies by SEM or TEM can be a valuable supplement.

In summary, the most common characteristics of quartz PDFs are: (1) restriction of PDFs to individual grains, i.e., the PDFs do not cross grain boundaries; (2) multiplicity (often >3 sets/grain); (3) a strictly planar character; (4) narrowness (typically $\leq 3\,\mu m$ in width); (5) close spacing (typically $\leq 10\,\mu m$); (6) presence of solid glassy lamellae (when fresh) or arrays of small fluid inclusions (when decorated); (7) unique orientations within the host quartz crystal, which can be conveniently and convincingly established by standard petrofabric methods. In particular, items (2) – (7) are generally unique to PDFs and can serve to distinguish them from other planar microstructures in quartz (Figs. 13–19).

In contrast, planar microstructures in quartz that show any of the following characteristics are almost certainly not PDFs (Figs. 24–30) (also see Grieve et al., 1996, p. 29): (1) presence of only single sets of parallel or subparallel lamellae; (2) slightly wavy, curved, and indistinct boundaries to individual lamellae; (3) lamella width ≥ 10–$20\,\mu m$; (4) slight (2–3°) misorientations of the lamella optic axis relative to the host quartz grain, producing separate birefringence in the lamella; (5) slightly nonplanar shapes, e.g., sinuous, wavy, or curved trends; (6) continuation of the feature, without deviation, from the host grain into adjacent grains which have different optical orientations. These characteristics are typical for metamorphic deformation lamellae (MDLs) (1–5) (Figs. 29 and 30) (see above, Section 4.3.4) and fluid inclusion trails (6) (Figs. 26 and 27) (see above, Section 4.3.3.2), respectively, two structures that have been commonly misinterpreted as PDFs. In uncertain cases, a reliable distinction between these features and true PDFs can be made on the basis of petrofabric measurements (Fig. 28).

Claims for the presence of quartz PDFs should document that the required criteria are fulfilled. In particular, information presented to support such a claim should include: (1) the percentage of grains in the sample showing the features; (2) number of planar sets/grain; (3) width of individual lamellae; (4) spacing of lamellae; (5) character of lamellae: solid and glassy or decorated; (6) high-quality photographs with scale bars or other size indicators; (7) orientation diagrams, using either the simple histogram plot or the more detailed template plot (Stöffler and Langenhorst, 1994; Grieve et al., 1996; Ferrière et al., 2009b). By documenting these details, and by comparing them with the characteristics of non-impact deformation features in quartz, the presence of actual shock-produced PDFs can be convincingly established.

8.4. Documentation of Extraterrestrial PGE (including Ir) and Siderophile Anomalies

The detection of anomalous excesses of Ir (e.g., ≥ 1 ppb) and other siderophile elements in the rocks of suspect structures can also provide convincing evidence of meteorite impact, but only if some additional criteria are met (see below). Such geochemical methods have a special advantage over petrographic shock effects: they can be applied to breccias and impact melts produced from a complete range of target rocks, including fine-grained or non-siliceous ones in which distinctive petrographic shock effects may not be present.

Despite these advantages, siderophile-element measurements must be performed with care, and their results should be regarded with caution. Isolated reports of high siderophile-element contents, without details or supporting data, should not be considered as reliable evidence of impact. To be credible, reports of extraterrestrial siderophile enrichments need to demonstrate that the high siderophile abundances: (1) are real; (2) are not caused by the presence of terrestrial sources (see Koeberl, 1998; Montanari and Koeberl, 2000; Koeberl, 2007, pp. 42–51). Details required to support these conclusions include, at a minimum: (1) the precision, accuracy, and reproducibility of the analytical techniques, and their verification by analyses of standard samples; (2) the background levels of terrestrial iridium in a comprehensive suite of target rocks (for an impact structure) or in adjacent sedimentary units (for a possible ejecta layer); (3) the abundance levels of other siderophile and related elements, and the determination whether they do or do not occur in ratios appropriate for meteorites; (4) data for elements not typical for meteoritic components (e.g., As, Sb, V, Ti) should not be used in searching for a meteorite component. Within this background, the detection of an extraterrestrial signature can also be independently pursued by isotopic analyses, especially for Os and Cr, which may establish the presence of an extraterrestrial component at levels as low as >0.1 rel.%. A recent report, which fails by all of these rules, is the claim of Jørgensen et al. (2009) to have found evidence of cometary material in early Archean rocks from Greenland, a claim that is solely based on iridium analyses without any other supporting petrographic or geochemical information. Without any other chemical, mineralogical, and petrographic information on analyzed rocks, Ir data by themselves are absolutely meaningless.

8.5. Structural and Geophysical Criteria for Impact

Structural and geophysical methods will play an increasingly critical role in the future detection, identification, and study of impact structures. The contribution of such methods to impact geology has already been substantial. Nearly one-third of presently known impact structures are subsurface features that have been originally detected during geophysical surveys and petroleum exploration (Grieve, 1991; Grieve and Masaitis, 1994; Grieve, 1998); this proportion will probably increase in the future. In addition, numerous structures, both surface and subsurface, are either inaccessible to sampling, are developed in lithologies unlikely to show diagnostic petrographic and chemical indicators of impact, or are so old or deeply eroded that rocks containing distinctive petrographic or geochemical indicators of shock have been removed or metamorphosed beyond recognition. Geophysical and structural techniques, accompanied by deep drilling (Koeberl and Milkereit, 2007; Gohn et al., 2008), are essential methods of study for such structures.

At present, geophysical and structural methods have made major contributions to detecting and characterizing candidates for possible impact structures, but such methods do not provide, by themselves, definitive evidence of impact (see discussion above, Section 5.2; also Pilkington and Grieve, 1992; Grieve and Pilkington, 1996, etc.). However, current field and modeling studies suggest that such methods have the potential to develop criteria for the unambiguous identification of impact structures in the future, chiefly by recognizing and documenting large-scale deformation features that can be shown to be unique results of the impact process (see., e.g., papers in Pierazzo and Herrick (2004) and Herrick et al. (2008) and discussion below).

Current trends in geophysical and structural studies of impact structures include: (1) major geophysical surveys of large established impact structures such as Chicxulub (Mexico) (e.g., Vermeesch and Morgan, 2004; Stöffler et al., 2004) and the Chesapeake Bay structure (USA) (Poag et al., 2004; Horton et al., 2005a; Catchings et al., 2008); (2) increasingly realistic comparative modeling of impact structures, made possible by the combination of detailed field studies with increasing computer power (Turtle et al., 2003; Collins et al., 2003a,b; Pierazzo and Herrick, 2004; Grieve and Therriault, 2004; Herrick et al., 2008); (3) documentation of unusual impact-generated mass movements in impact structures, e.g., intense and rapid horizontal motions in otherwise circular features (Kenkmann and von Dalwigk, 2000; Kenkmann et al., 2000b; Kenkmann and Stöffler, 2002; Kenkmann, 2002, 2003; Kenkmann et al., 2005a; Kenkmann and Poelchau, 2009); (4) the recognition and comparative modelling of unusual multi-ring structures (e.g., Silverpit, [United Kingdom] [Stewart and Allen, 2002; Collins et al., 2003a,b; Stewart and Allen, 2005]) whose anomalous character may reflect the unusual properties of the unconsolidated target rocks. In addition, strong supporting evidence for impact can be provided by the demonstration, using geophysical methods, that a deformed circular structure is a relatively shallow, near-surface feature that has no extension at depth and is underlain by an undisturbed sequence of pre-impact target rocks (Pilkington and Grieve, 1992; Grieve and Pilkington, 1996; Milton et al., 1996).

Structural and geophysical studies form a critical and growing area for impact geology. Such studies are essential for understanding the details of crater formation and development, especially the details of crater modification and central uplift formation in recognized impact structures (e.g., Grieve and Therriault, 2004). These methods also provide the only approach for identifying impact structures that lack definite shock-metamorphic effects because of the presence of inappropriate target rocks, deep erosion, or metamorphism, and they represent an essential approach to the identification of large and ancient impact structures which may not be comparable to younger, smaller, and better-studied examples (Kenkmann et al., 2000b). Finally, such studies can provide an important scientific bridge between the analysis of impact-produced petrological, mineralogical, and geochemical effects and numerical models of the cratering process (Pierazzo and Herrick, 2004; Herrick et al., 2008).

9. Conclusions

The geologically unique conditions created by a meteorite impact on the Earth's surface (high transient pressures, high strain rates, and high temperatures) produce in the target rocks a wide variety of deformation features that form on scales ranging from micrometers to tens of kilometers. A small number of these effects (e.g., shatter cones, PDFs in quartz) are unique enough to be used as diagnostic criteria for meteorite impact (Table 1). Other effects (e.g., circular deformation patterns, fracturing, brecciation, melting) are so similar to the results of non-impact geological processes that they cannot be used to identify impact events, although they may be important in discovering new impact structures and understanding their formation.

A small number of specific features in rocks and minerals are now generally accepted as conclusive evidence for impact events (Table 1): (1) chemical and isotopic traces of the impacting projectile; (2) shatter cones; (3) high-pressure (diaplectic) mineral glasses; (4) high-pressure mineral phases; (5) high-temperature glasses and melts; (6) planar fractures (PFs) (cleavage) in quartz; and (7) planar deformation features (PDFs) in quartz.

Of these criteria, the use of PFs (item 6) to identify impact structures is relatively recent and still somewhat problematical because of reported occurrences of cleavage in quartz from at least a few non-impact environments (Frondel, 1962, p. 104–111; Flörke et al., 1981). The use of PFs alone to establish impact structures should therefore be done with caution. Observed PFs should be described in detail (e.g., width, spacing, planar character, multiplicity, and orientation). PF orientations should be measured and should correspond to the low-index planes observed in quartz from established impact structures, and the PFs should ideally occur with other features of plausible impact origin. (For a detailed discussion of these issues, see French et al., 2004.)

A wider range of deformation features are suggestive of impact but do not provide conclusive evidence for it (Table 1): (1) circular morphology; (2) circular patterns of structural deformation; (3) circular geophysical anomalies; (4) fracturing and brecciation; (5) kink banding in micas; (6) pseudotachylite and pseudotachylitic breccias; (7) igneous rocks and glasses; and (8) spherules and microspherules.

Some features proposed as impact effects remain problematical and require more study and verification before they can be accepted, e.g.,: (1) fullerenes with trapped He; (2) iron-rich nanophase particles; (3) thermal and mechanical damage to microfossils.

The recognition and effective use of diagnostic criteria to identify impact events has led directly to a major increase in the perceived importance of meteorite impact as a geological process. The number of recognized terrestrial impact structures has grown from about <20 in 1960 to more than 175 today. At the same time, impact events have been associated with at least one major biological extinction and with the formation of numerous widespread layers of ejecta preserved in the sedimentary record.

The recent enthusiasm for meteorite impacts among scientists, the public, and the media, has unfortunately led to the proliferation of incorrect and questionable reports of impact events, involving both individual structures and extinction boundaries. These reports involve several types of errors: (1) misidentification of normal petrographic and mineralogical effects (e.g., random or non-parallel fracturing in quartz) as diagnostic impact criteria; (2) the use of non-diagnostic impact effects (e.g., circularity, brecciation) to justify impact interpretations; and (3) the invocation of new and unverified features (e.g., fullerenes with trapped He) as evidence of impact. As a result of these reports, both scientists and the general public are receiving a distorted picture about the nature of the evidence required to establish impact, the actual number of established terrestrial impact structures, the importance of impact events in geology, and the association of large impact events with major biological extinctions.

A major problem in identifying impact events is that virtually all the diagnostic indicators of impact can be (and often are) confused with non-impact features, and careful detailed work is often necessary to resolve the differences. Typical slickenslides or random rock fractures have been identified as shatter cones. Non-impact deformation features in quartz (fractures, metamorphic deformation lamellae) have been reported as PDFs without making the detailed microscopic examinations and orientation measurements that are critical to the distinction. Fused glasses or isotropic minerals may superficially resemble diaplectic glasses, and detailed studies by X-ray diffraction or other methods are needed to demonstrate that the unique structural and chemical characteristics of impact-produced diaplectic glass are in fact present. Reports of extraterrestrial chemical signatures (such as excess Ir or other siderophiles) have been presented without providing analytical details or comparative analyses of target rocks. Microspherules are an established impact product, but their use as evidence of impact often neglects the careful work that is needed to distinguish between impact-produced microspherules and the products of non-impact geological or artificial processes.

This paper provides information, guidelines, and specific details for the reliable identification of diagnostic impact-produced deformation effects. These identifications are simple in principle, but they require good planning, careful study, detailed descriptions, and well-documented analytical methods.

At present, the discovery, identification, and application of diagnostic impact effects are constrained by several factors: formation only at specific locations within an impact structure; movement and redistribution during crater formation; and post-impact preservation over geological periods of time. A particular constraint is the virtually complete reliance on quartz-bearing target rocks as recorders of impact events, together with a corresponding lack of knowledge about the nature of impact effects in other lithologies. Furthermore, diagnostic impact effects span a limited range of scales: meters to centimeters (shatter cones), millimeters to micrometers (quartz PDFs), and the atomic scales associated with chemical analyses. There is an unfortunate lack of reliable impact criteria for larger scales (tens of meters to kilometers).

Active research is needed in several areas to expand the range and variety of diagnostic impact effects: (1) field and experimental studies of impact effects formed in different lithologies, such as basalts, carbonates, fine-grained sediments, and unconsolidated or volatile-rich target rocks; and (2) detailed studies of distinctive shock-produced changes in a wider assortment of rock-forming minerals, e.g., feldspars, zircon (Wittmann et al., 2006) and TiO_2 polymorphs (Jackson et al., 2006); (3) physical and chemical studies of impact glasses, and their distinction from non-impact natural or artificial ones; (4) structural and geophysical studies to develop larger-scale diagnostic impact criteria; (5) the processes of formation, emplacement, and cooling of large bodies of impact melt.

More information about the formation and reliable identification of diagnostic impact effects is essential to improve our understanding of the importance of meteorite impact in terrestrial geology, especially for such problems as: (1) determining the numbers, ages, and formation rates of terrestrial impact structures; (2) identifying impact structures now present in non-silicate or metamorphosed target rocks; (3) recognizing major structural effects associated with large impacts; (4) establishing more firmly the nature of the association between large impact events and major biological extinctions; and (5) recognizing the significance of impact structures for hosting mineral deposits, forming traps for hydrocarbon resources, and controlling the location and movement of water supplies. If present and future investigators can follow the rules and procedures described here, their work will produce improved understanding of the nature, formation, and identification of diagnostic shock features, more reliable and convincing identifications of genuine impact structures, and a better appreciation of the role of meteorite impact events in the history of the Earth.

Acknowledgments

We are grateful to a large number of colleagues who have provided comments, input, encouragement, material, photographs, discussions, etc. These include: B. Bohor, M. Boslough, W. Cannon, P. Claeys, G. Collins, M. Dence, A. Deutsch, B. Dressler, L. Ferrière, B. Glass, R. Grieve, G. Izett, S. Jaret, F. Langenhorst, H.J. Melosh, A. Montanari, J. Morrow, J. Ormö, G. Osinski, E. Pierazzo, W.U. Reimold, N.M. Short, B. Simonson, J. Spray, D. Stöffler, R.H. Vernon, and many others. We also thank the Department of Geology, University of Maryland, and S. Penniston–Dorland for the assistance with samples and photography of non-impact deformation structures in quartz, and JoAnn Sanner, Department of Paleobiology, Smithsonian Institution, for help with preparation of some graphics. We are especially grateful to Jared R. Morrow and J. Wright Horton, Jr. for thorough, detailed, and extremely helpful reviews of the manuscript. CK has been supported by the Austrian Science Foundation, most recently by grant P18862-N10. BMF thanks the Smithsonian Institution for support of this work as an Adjunct Scientist, and Mary-Hill French for continuing support, commentary, and patience.

Appendix A. Critical characteristics and measurements to determine the presence of diagnostic shock effects

This section summarizes the critical characteristics of shock effects regarded as uniquely diagnostic for meteorite impact and describes the essential observations and measurements required to verify their presence. To be credible, published reports should include specific details about as many of these observations and measurements as possible. More general information is provided in specific sections of the text (in parentheses).

Shock effects considered diagnostic for meteorite impact are: (1) preserved meteorite fragments (Section 3.2.1); (2) chemical and isotopic projectile signatures (Section 3.2.2), (3) shatter cones (Section 3.3.1), (4) high-pressure (diaplectic) mineral glasses (Section 3.3.2), (5) high-pressure minerals (Section 3.3.3), (6) high-temperature glasses and melts (Section 3.3.4), (7) planar fractures (PFs) in quartz (Section 4.2.1), and (8) planar deformation features (PDFs) in quartz (Section 4.2.2). Although spherules and microspherules are not technically diagnostic for meteorite impact (see above, Section 5.4), a similar summary is included here because their occurrence and characteristics can often provide strong evidence for impact. Similar tables and summaries have been compiled for impact features in general (e.g., Dence, 1972, p. 78–79; French, 1998, pp. 107–110) and for quartz PFs and PDFs in particular (Alexopoulos et al., 1988, p. 799; Stöffler and Langenhorst, 1994, p. 165; Grieve et al., 1996, p. 29).

Applicable study and analysis techniques include optical petrography, refractive-index (RI) determinations, U-stage measurements, bulk chemical analyses, electron microprobe analyses (EMP), scanning electron microscope (SEM), transmission electron microscopy (TEM), X-ray diffraction (XRD), infrared (IR) spectroscopy, and Raman spectroscopy.

1. Preserved meteorite fragments (very rare)
   Detection in breccias, impact melts, ejecta.
   Anomalous appearance, characteristics; distinct from target rocks.
   Determine as meteorites:
      petrographic study in thin sections
      detection of unique meteorite minerals
      chemical analyses: unique meteorite chemistry
2. Chemical and isotopic projectile signatures
   Determine petrology, mineralogy, chemistry of samples.
   Analyze standard samples: determine precision, accuracy
   Determine Ir abundance: >1 ppb

Determine PGEs and other siderophiles (Cr, Co, Ni): cosmic (meteoritic) abundance ratios.
Determine Ir, PGE background in related target rocks or associated sedimentary layers (above, below)
Measure Os, Cr isotopic ratios: confirm presence of extraterrestrial material.

3. Shatter cones
   Document field occurrence:
      present in all available rock types (better developed in fine-grained rock types)
   Determine form and shape characteristics
      multiple cones or partial cones
      penetrative fractures; cones break along surfaces
   Determine cone orientations:
      not related to pre-impact rock fabric
      cone axes typically subparallel (occasionally diversely oriented over short distances)
      cones usually point upward (when rocks restored to pre-impact orientation)
   Note surface characteristics:
      curved, not flat; striated
      individual surfaces may constitute 10°–360° of full cone
      both positive/negative surfaces present
   Note striation characteristics:
      not parallel; radiating from apex of cone
      secondary striations ("horsetailing") developed
   Search for petrographic shock effects within cones
      e.g., quartz PDFs may be present in quartz-bearing rocks
   Make quantitative measurements of orientations of striations and cone axes to demonstrate:
      divergent (radiating) orientation of striations
      orientation of cone axes
      apical angle of cones
4. High-pressure (diaplectic) mineral glasses
   Describe optical appearance in thin section (flat-stage):
      preserves shape, texture of original mineral
      (e.g., outlines, twinning, inclusions)
      isotropic character throughout individual grains
      or gradual transition between isotropic and non-isotropic areas
   Determine abundance of diaplectic grains in thin section
      generally abundant in crystalline rock samples
   Describe pervasiveness of isotropism in individual grains: complete, partial, selective
      (e.g., only one set in feldspar twin lamellae)
   Verify isotropic character: multi-axis rotation on U-stage
   Verify mineral composition by chemical analyses
      electron probe, SEM, Raman spectroscopy
      monomineralic composition; typically quartz or feldspar
   Obtain comparative spectra of appropriate standard samples
   Determine crystal structure (XRD, IR or Raman spectrometry)
      generally intermediate between crystalline mineral and normal melted mineral glass
5. High-pressure mineral phases
   Establish geological setting of samples
      lithology: sediments or upper-crustal rocks (pre-impact depth <100 km)
   Locate phases in rock (petrography; electron probe; SEM)
   Describe associated materials:
      other minerals (deformed?)
      diaplectic glasses, melt glasses, quartz PDFs
   Separate minerals from rock (acid dissolution techniques)
      or examine in place in thin sections
   Obtain comparative spectra of appropriate samples.
   Identify minerals:
      XRD (powders or single crystals)
      SEM or Raman spectroscopy (in-place)
6. High-temperature glasses and melts (with lechatelierite)
   Establish geological setting of samples
      e.g., specific structure, sedimentary layer
      eliminate fulgurites (cylindrical, tubular)
   Determine petrographic characteristics:
      structures: flow banding
      heterogeneity (if present), mineral inclusions
   Determine chemical composition: bulk analyses or microprobe
   Eliminate artificial origins (slags, archeological glasses)
      exotic or anomalous chemical compositions
      modern ages
   Identify lechatelierite if present
      irregular patches or flow regions (schlieren)
      determine characteristics
         composition: >95% SiO_2 (microprobe)
         glassy character: XRD, Raman
         optical properties; RI determinations
   Identify significant associated materials
      mineral grains, rock fragments with quartz PDFs
      melted or decomposed mineral grains
      e.g., zircon, sphene
7. Planar fractures (PFs or cleavage) in quartz
   Verify occurrence: multiple sets of parallel planes within individual grains
   Describe appearance: straight, planar, open fractures
      occasionally filled with secondary minerals
   Note intersections:
      individual sets cross each other
      offsets at intersections small or none
   Record multiplicity: multiple sets
      typically >2/grain, up to 6/grain
   Measure and describe characteristics:
      width: 3–10 μm
      spacing: >20 μm – 500 μm
      length: across most of grain, typically 0.1 – 5 mm
   Determine distribution:
      abundant in grains, often in all grains in rock
      planar sets do not cross grain boundaries
   Measure orientations in host quartz grain (U-stage)
      "spike" pattern of polar angles;
      orientations parallel to specific planes
      most common planes:
      c(0001) (0°), r/z$\{10\bar{1}1\}$ (52°), ξ$\{11\bar{2}2\}$ (48°)
8. Planar deformation features (PDFs) in quartz
   Verify occurrence: multiple sets of close-spaced parallel planes within individual grains
   Describe appearance:
      fresh: continuous, optically distinct lamellae
      decorated: discontinuous planar arrays of small fluid inclusions, typically <1–2 μm in size
   Note intersections:
      individual sets cross each other
      offsets at intersections small or none
   Record multiplicity: multiple sets
      typically >2/grain, rarely up to 6–12/grain

Measure and describe characteristics:
width: <1 μm
spacing: typically <5 μm
length: across most of grain, typically 0.1 – 0.5 mm
Determine distribution:
abundant in grains, often in all grains in rock
may form preferentially in larger grains
Measure orientations in host quartz grain (U-stage)
"spike" pattern of polar angles;
orientations parallel to specific planes
most common planes:
c(0001) (0°), ω{10$\bar{1}$3} (23°), π{10$\bar{1}$2} (32°)

9. Spherules and microspherules

(Not diagnostic, but often good evidence of impact.)
Establish geological context:
nonvolcanic setting
typically quiet-water, nondetrital sediments
Describe character:
fresh glasses (isotropic)
altered (mineral composition, crystallization textures)
Establish abundance:
typically >10 % for undiluted impact ejecta layers
Determine particle shapes, varieties, and percentages:
spherical, spheroidal, ellipsoidal, droplet-shaped, dumbbell-shaped
Determine associated materials:
volcanic or nonvolcanic materials
quartz (with PDFs), high-pressure minerals (coesite)
excess siderophile element signatures
Determine chemical compositions for fresh material
(e.g., by EMP)
compare with meteorite materials or terrestrial crustal rocks (siliceous, carbonate)
Eliminate origin as natural, artificial contaminants
exotic chemical composition (metallic, siliceous)
similarity to known contaminants (fly ash, glass beads, plant material)

References

Abbott, D., Manzer, D., 2003. Effects and implications of a proposed Gulf of Maine K/T impact (abstract). Geological Society of America, Northeastern Section — 38th Annual Meeting. Annual Meeting, Paper, vol.7–16.

Abbott, D.H., Nunes, A.A., Leung, I.S., Burckle, L., Hagstrum, J.T., 2003a. The Ewing impact structure: a progress report (abstract). EOS, Transactions of the American Geophysical Union 84 (46) Fall Meeting, Supplement, Abstract P52A-0472.

Abbott, D.H., Matzen, A., Bryant, E.A., Pekar, S.F., 2003b. Did a bolide impact cause catastrophic tsunamis in Australia and New Zealand? (abstract). Abstracts with Programs - Geological Society of America 35 (6), 168.

Abbott, D., Biscaye, P., Cole-Dai, J., Breger, D., 2005. Evidence from an ice core of a large impact circa 1443 A.D. (abstract). EOS, Transactions of the American Geophysical Union 86 (52) Fall Meeting, Supplement, Abstract PP31C-05.

Abbott, D.H., Martos, S., Elkinton, H., Bryant, E.F., Gusiakov, V., Breger, D., 2006. Impact craters as sources of megatsunami-generated chevron dunes (abstract). Abstracts with Programs - Geological Society of America 38 (7), 299–300.

Addison, W.D., Brumpton, G.R., Vallini, D.A., McNaughton, N.J., Davis, D.W., Kissin, S.A., Fralick, P.W., Hammond, A.L., 2005. Discovery of a distal ejecta layer from the 1850 Ma Sudbury impact event. Geology 33, 193–196.

Agrinier, P., Deutsch, A., Schärer, U., Martinez, I., 2001. Fast back-reactions of shock-released CO_2 from carbonates: an experimental approach. Geochimica et Cosmochimica Acta 65, 2615–2632.

Aldahan, A.A., Koeberl, C., Possnert, G., Schultz, P., 1997. ^{10}Be and chemistry of impactites and target materials from the Rio Cuarto crater field, Argentina: evidence for surficial cratering and melting. Geologiska Föreningens Förhandlingar (GFF) 119, 67–72.

Aldersley-Williams, H., 1995. The Most Beautiful Molecule: the Discovery of the Buckyball. New York, John Wiley and Sons. 340 pp.

Alexopoulos, J.S., Grieve, R.A.F., Robertson, P.B., 1988. Microscopic lamellar deformation features in quartz: discriminative characteristics of shock-generated varieties. Geology 16, 796–799.

Alvarez, W., 1997. T. Rex and the Crater of Doom. Princeton University Press, Princeton, N.J. 185 pp.

Alvarez, L.W., Alvarez, W., Asaro, F., Michel, H.V., 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. Science 208, 1095–1108.

Alvarez, W., Claeys, P., Kieffer, S.W., 1995. Emplacement of Cretaceous–Tertiary boundary shocked quartz from Chicxulub crater. Science 269, 930–935.

Alwmark, C., Schmitz, B., 2006. Extraterrestrial chromite in the resurge deposits of the early Late Ordovician Lockne crater, central Sweden. Earth and Planetary Science Letters 253, 291–303.

Appel, P.W.U., Abrahamsen, N., Rasmussen, T.M., 2006. Unusual features caused by lightning impact in West Greenland. Geological Magazine 143, 737–741.

Arndt, J., Hummel, W., Gonzales-Cabeza, I., 1982. Diaplectic labradorite glass from the Manicouagan impact crater. I. Physical properties, crystallization, structural and genetic implications. Physics and Chemistry of Minerals 8, 230–239.

Barakat, A., 1994. El-Baz crater: basaltic intrusion versus meteorite impact crater. Annals of the Geological Survey of Egypt 24, 167–177.

Baratoux, D., Melosh, H.J., 2003. The formation of shatter cones by shock wave interference during impacting. Earth and Planetary Science Letters 216, 43–54.

Barker, A.J., 1990. Introduction to Metamorphic Textures and Microstructures. Stanley Thames Publishers, Ltd., Cheltenham, UK. 264 pp.

Basu, A.R., Petaev, M.I., Poreda, R.J., Jacobsen, S.B., Becker, L., 2003. Chondritic meteorite fragments associated with the Permian–Triassic boundary in Antarctica. Science 302, 1388–1392.

Basu, A.R., Chakrabarti, R., Peterson, J., Poreda, R., Becker, L., 2004. Laser Raman spectroscopic confirmation of maskelynite in the Bedout impact breccia, offshore, NW Australia (Abstract). EOS, Transactions American Geophysical Union 85 (47) Fall Meeting, Supplement, Abstract B31E-06.

Basu, A.R., Chakrabarti, R., Peterson, J., Poreda, R., Becker, L., 2006. Laser Raman spectra of Bedout "maskelynite": comparisons with shocked plagioclases from Martian meteorite (SaU 005) and the Lonar impact crater, and synthetic albite (CIT# 1424) and anorthite (CIT# 1301) (Abstract). Lunar and Planetary Science 37 abs. #2307 (CD-ROM).

Beals, C.S., Halliday, I., Wilson, J.T., 1968. On the possibility of a catastrophic origin for the great arc of eastern Hudson Bay. In: Beals, C.S. (Ed.), Science, History, and Hudson Bay, vol. 2. Department of Energy, Mines, and Resources, Ottawa, Canada, pp. 985–1033.

Becker, L., Bada, J.L., Winans, R.E., Hunt, J.E., Bunch, T.E., French, B.M., 1994. Fullerenes in the 1.85-billion-year-old Sudbury impact structure. Science 265, 842–845.

Becker, L., Poreda, R., Bada, J.L., 1996. Extraterrestrial helium trapped in fullerenes in the Sudbury impact structure. Science 272, 249–252.

Becker, L., Poreda, R.J., Hunt, A.G., Bunch, T.E., Rampino, M., 2001. Impact event at the Permian–Triassic boundary: evidence from extraterrestrial noble gases in fullerenes. Science 291, 1530–1533.

Becker, L., Poreda, R.J., Basu, A.R., Pope, K.O., Harrison, T.M., Nicholson, C., Iasky, R., 2004a. Bedout: a possible end-Permian impact crater offshore of northwestern Australia. Science 304, 1469–1476.

Becker, L., Poreda, R.J., Basu, A.R., Pope, K.O., Harrison, T.M., Nicholson, C., Iasky, R., 2004b. Is Bedout an impact crater? Take 2 (Response). Science 306, 611–612.

Becker, L., Poreda, R.J., Pope, K., 2004c. Is Bedout an impact crater? Take 1 (Response). Science 306, 609–610.

Becker, L., Poreda, R.J., Basu, A.R., Pope, K.O., Harrison, T.M., Nicholson, C., Iasky, R., 2004d. Response to comment on "Bedout: a possible end-Permian impact crater offshore of northwestern Australia". Science 306, 613c.

Becker, L., Shukolyukov, A., Macassic, C., Lugmair, G., Poreda, R., 2006. Extraterrestrial chromium at the Graphite Peak P/Tr boundary and in the Bedout Impact Melt Breccia (abstract). Lunar and Planetary Science 37 abs. #2321 (CD-ROM).

Belkin, H.E., Horton, J.W., Jr., 2009. Silicate glasses and sulfide melts in the ICDP-USGS Eyreville B core, Chesapeake Bay impact structure, Virginia, USA. In: Gohn, G.S., Koeberl, C., Miller, K.G., Reimold, W.U. (Editors), The ICDP-USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes. Geological Society of America, Boulder, CO, Special Paper 458, 447–468.

Beran, A., Koeberl, C., 1997. Water in tektites and impact glasses by fourier-transformed infrared spectrometry. Meteoritics and Planetary Science 32, 211–216.

Bischoff, L., Oskierski, W., 1987. Fractures, pseudotachylite veins, and breccia dikes in the crater floor of the Rochechouart impact structure, SW-France, as indicators of crater-forming processes. In: Pohl, J. (Ed.), Research in Terrestrial Impact Structures. Friedrich Vieweg und Söhne, Wiesbaden, Germany, pp. 5–29.

Blanchard, M.B., Brownlee, D.E., Bunch, T.E., Hodge, P.W., Kyte, F.T., 1980. Meteoroid ablation spherules from deep-sea sediments. Earth and Planetary Science Letters 46, 178–190.

Bland, P.A., 2001. Quantification of meteorite infall rates from accumulations in deserts, and meteorite accumulations on Mars. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, pp. 267–303.

Blenkinsop, T.G., 2000. Deformation Microstructures and Mechanisms in Minerals and Rocks. Elsevier, New York. 164 pp.

Bloss, F.D., 1957. Anisotropy of fracture in quartz. American Journal of Science 255, 214–225.

Bloss, F.D., 1981. The Spindle Stage — Principles and Practice. Cambridge University Press, New York. 340 pp.

Bloss, F.D., Gibbs, G.V., 1963. Cleavage in quartz. American Mineralogist 48, 821–838.

Bohor, B.F., 1990. Shocked quartz and more; impact signatures in Cretaceous/Tertiary boundary clays. In: Sharpton, V.L., Ward, P.D. (Eds.), Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality. Geological Society of America, Boulder CO, Special Paper, vol. 247, pp. 335–342.

Bohor, B.F., Foord, E.E., Modreski, P.J., Triplehorn, D.M., 1984. Mineralogical evidence for an impact event at the Cretaceous–Tertiary boundary. Science 224, 867–869.
Bohor, B.F., Modreski, P.J., Foord, E.E., 1987. Shocked quartz in the Cretaceous/Tertiary boundary clays: evidence for global distribution. Science 236, 705–708.
Bohor, B.F., Betterton, W.J., Krogh, T.E., 1993. Impact-shocked zircons: discovery of shock-induced textures reflecting increasing degrees of shock metamorphism. Earth and Planetary Science Letters 119, 419–424.
Bonnichsen, R., Lepper, M.B., Stanford, D., Waters, M. (Eds.), 2005. Paleo-American Origins: Beyond Clovis. Texas A & M Press, College Station, TX. 374 pp.
Bottomley, R.J., York, D., Grieve, R.A.F., 1990. ^{40}Argon-^{39}Argon dating of impact craters. Proceedings of the 20th Lunar and Planetary Science Conference. Pergamon Press, New York, pp. 421–431.
Brannon, P.J., Konrad, C., Morris, R.W., Jones, E.D., Asay, J.R., 1983. Studies of the spectral and spatial characteristics of shock-induced luminescence from X-cut quartz. Journal of Applied Physics 54, 6374–6381.
Brownlee, D.E., 1985. Cosmic dust: collections and research. Annual Review of Earth and Planetary Sciences 13, 147–173.
Brownlee, D.E., 2001. The origin and properties of dust impacting the Earth. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter Throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, NY, pp. 1–12.
Bryant, E., Walsh, G., Abbott, D., 2007. Cosmogenic mega-tsunami in the Australia region: are they supported by Aboriginal and Maori legends? In: Piccardi, L., Masse, W.B. (Eds.), Myth and Geology. Geological Society, London, Special Publication, vol. 273, pp. 203–214.
Buchanan, P.C., Reimold, W.U., 1998. Studies of the Rooiberg Group, Bushveld Complex, South Africa: no evidence for an impact origin. Earth and Planetary Science Letters 155, 149–165.
Bucher, W.H., 1936. Cryptovolcanic structures in the United States. International Geological Congress, 16th, United States, 1933, Reports, vol. 2, pp. 1055–1084.
Bucher, W.H., 1963. Cryptoexplosion structures caused from without or from within the Earth? ("Astroblemes" or "Geoblemes?"). American Journal of Science 261, 597–649.
Buchner, E., Kenkmann, T., 2008. Upheaval dome: impact origin confirmed. Geology 36, 227–230.
Buffetaut, E., Koeberl, C. (Eds.), 2002. Geological and Biological Effects of Impact Events. Springer-Verlag, New York. 295 pp.
Bunch, T.E., 1968. Some characteristics of selected minerals from craters. In: French, B.M., Short, N.M. (Eds.), Shock metamorphism of natural materials. Mono Book Corp, Baltimore, MD, pp. 413–422.
Bunch, T.E., Cohen, A.J., Dence, M.R., 1967. Natural terrestrial maskelynite. American Mineralogist 52, 244–253.
Bunch, T.E., Cohen, A.J., Dence, M.R., 1968. Shock-induced structural disorder in plagioclase and quartz. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 509–518.
Burt, J.B., Pope, M.C., Watkinson, A.J., 2005. Petrographic, X-ray diffraction, and electron spin resonance analysis of deformed calcite: meteor crater, Arizona. Meteoritics and Planetary Science 40, 297–306.
Buseck, P., 2002. Geological fullerenes: review and analysis. Earth and Planetary Science Letters 203, 781–792.
Byerly, G.R., Hazel, J.E., McCabe, C., 1990. Discrediting the late Eocene microspherule layer at Cynthia, Mississippi. Meteoritics 25, 89–92.
Byerly, G.R., Lowe, D.R., Wooden, J.L., Xie, X., 2002. An Archean impact layer from the Pilbara and Kaapvaal Cratons. Science 297, 1325–1327.
Cailleux, A., Guillemaut, A., Pomerol, C., 1964. The presence of coesite, an indicator of high pressures, in the circular Richat structure (Mauretanian Adrar). Comptes Rendus Academy of Sciences, Paris 258, 5488–5490.
Cannon, W.F., Schultz, K.J., Horton, J.W., Jr., Kring, D.A., 2010. The Sudbury impact layer in the Paleoproterozoic iron ranges of northern Michigan, USA. Bulletin of the Geological Society of America 122, 50–75.
Carleton, R.W., Koeberl, C., Baranoski, M.T., Schumacher, G.A., 1998. Discovery of microscopic evidence for shock metamorphism at the Serpent Mound structure, south-central Ohio: confirmation of an origin by impact. Earth and Planetary Science Letters 162, 177–185.
Carozzi, A.V., 1960. Microscopic Sedimentary Petrography. John Wiley and Sons, New York, NY. 485 pp.
Carstens, H., 1975. Thermal history of impact melt rocks in the Fennoscandian Shield. Contributions to Mineralogy and Petrology 50, 145–155.
Carter, N.J., 1965. Basal quartz deformation lamellae — a criterion for recognition of impactites. American Journal of Science 263, 786–806.
Carter, N.L., 1968a. Meteoritic impact and deformation of quartz. Science 160, 526–528.
Carter, N.L., 1968b. Dynamic deformation of quartz. In: French, B.M., Short, N.M. (Eds.), Shock metamorphism of natural materials. Mono Book Corp, Baltimore, MD, pp. 453–474.
Carter, N.J., Friedman, M., 1965. Dynamic analysis of deformed quartz and calcite from the Dry Creek Ridge Anticline, Montana. American Journal of Science 263, 747–785.
Carter, N.L., Officer, C.B., 1987. Comment and reply on "Dynamic deformation of volcanic ejecta from the Toba caldera: Possible relevance to Cretaceous/Tertiary boundary phenomena". Geology 15, 91–92.
Carter, N.L., Officer, C.B., Chesner, C.A., Rose, W.I., 1986. Dynamic deformation of volcanic ejecta from the Toba caldera: possible relevance to Cretaceous/Tertiary boundary phenomena. Geology 14, 380–383.
Catchings, R.D., Powars, D.S., Gohn, G.S., Horton Jr., J.W., Goldman, M.R., Hole, J.A., 2008. Anatomy of the Chesapeake Bay impact structure revealed by seismic imaging, Delmarva Peninsula, Virginia, USA. Journal of Geophysical Research 113, B0843 23 pp.
Chadwick, B., Claeys, P., Simonson, A.B., 2001. New evidence for a large Paleoproterozoic impact: spherules in a dolomite layer in the Ketilidian orogen, South Greenland. Journal of the Geological Society of London 158, 331–340.
Chao, E.C.T., 1967. Impact metamorphism. In: Abelson, P.H. (Ed.), Researches in Geochemistry, vol. 2. John Wiley and Sons, New York, pp. 204–233.
Chao, E.C.T., 1968. Pressure and temperature histories of impact metamorphosed rocks — based on petrographic observations. In: French, B.M., Short, N.M. (Eds.), Shock metamorphism of natural materials. Mono Book Corp, Baltimore, MD, pp. 135–158.
Chao, E.C.T., Shoemaker, E.M., Madsen, B.M., 1960. First natural occurrence of coesite. Science 132, 220–222.
Chao, E.C.T., Fahey, J.J., Littler, J., Milton, D.J., 1962. Stishovite, SiO_2, a very high pressure new mineral from Meteor Crater, Arizona. Journal of Geophysical Research 67, 419–421.
Chapman, C.R., Morrison, D., 1989. Cosmic Catastrophes. Plenum Press, New York. 302 pp.
Chen, M., 2008. Impact-derived features of the Xiuyan meteorite crater. Chinese Science Bulletin 53, 392–395.
Chen, M., El Goresy, A., 2000. The nature of maskelynite in shocked meteorites: not diaplectic glass but a glass quenched from shock-induced dense melt at high pressures. Earth and Planetary Science Letters 179, 489–502.
Chopin, C., 1984. Coesite and pure pyrope in high-grade blueschists of the Western Alps: a first record and some consequences. Contributions to Mineralogy and Petrology 86, 107–118.
Christie, J.M., Raleigh, C.B., 1959. Origin of deformation lamellae in quartz. American Journal of Science 257, 385–407.
Christie, J.M., Heard, H.C., LaMori, P.N., 1964. Experimental deformation of quartz single crystals at 27 to 30 kilobars and 24 °C. American Journal of Science 262, 26–55.
Claeys, P., Casier, J.G., Margolis, S.V., 1992. Microtektites and mass extinctions: evidence for a late Devonian asteroid impact. Science 257, 1102–1104.
Clark, D.L., Wang, C.-Y., Orth, C.J., Gilmore, J.S., 1986. Conodont survival and low iridium abundances across the Permian–Triassic boundary in south China. Science 233, 984–986.
Cockell, C., Koeberl, C., Gilmour, I. (Eds.), 2006. Biological Processes Associated with Impact Events. Springer, New York. 376 pp.
Collins, G.S., Ivanov, B.A., Turtle, E.P., Melosh, H.J., 2003a. Numerical simulations of Silverpit crater collapse (abstract). Lunar and Planetary Science 34 abs. #2115 (CD-ROM).
Collins, G.S., Turtle, E.P., Melosh, H.J., 2003b. Numerical simulations of Silverpit crater collapse: a comparison of Tekton and Sales 2 (abstract). Impact Cratering: Bridging the Gap Between Modeling and Observations, February 7–9, 2003. LPI Contribution, vol.1155. Lunar and Planetary Institute, Houston, TX, p. 18.
Collinson, J.W., Hammer, W.R., Askin, R.A., Elliot, D.H., 2006. Permian–Triassic boundary in the central Transantarctic Mountains, Antarctica. Bulletin of the Geological Society of America 118, 747–763.
Comstock, J.M., Dietz, R.D., Morrow, J.R., 2004. The Peerless structure, Daniels County, northeastern Montana: a probably Late Ordovician impact structure. Meteoritics and Planetary Science 39, 683–692.
Cordier, P., Vrana, S., Doukhan, J.-C., 1994. Shock compression in quartz at Sevetin and Susice (Bohemia)? A TEM investigation. Meteoritics 29, 98–99.
Cummings, D., 1968. Shock deformation of biotite around a nuclear explosion. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 211–217.
Cygan, R.T., Boslough, M.B., Kirkpatrick, R.J., 1990. NMR spectroscopy of experimentally shocked quartz: shock wave barometry. In: Ryder, G., Sharpton, V.L. (Eds.), Proceedings of the 20th Lunar and Planetary Science Conference. Lunar and Planetary Institute, Houston, TX, pp. 451–457.
Dachille, F., Gigl, P., Simons, P.Y., 1968. Experimental and analytical studies of crystalline damage useful for the recognition of impact structures. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 555–569.
Day, R.L., Glasser, F.P. (Eds.), 1990. Fly ash and coal conversion by-products: characterization, utilization, and disposal VI. Materials Research Society Symposia Proceedings, vol. 178. Materials Research Society, Pittsburgh, PA, 292 pp.
Dence, M.R., 1965. The extraterrestrial origin of Canadian craters. Annals of the New York Academy of Sciences 123, 941–969.
Dence, M.R., 1968. Shock zoning at Canadian craters: petrography and structural implications. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 69–184.
Dence, M.R., 1971. Impact melts. Journal of Geophysical Research 76, 5552–5565.
Dence, M.R., 1972. The nature and significance of terrestrial impact structures. 24th International Geological Congress, Montreal, Canada, Proceedings, Section 15, pp. 77–89.
Dence, M.R., Innes, M.J.S., Robertson, P.B., 1968. Recent geological and geophysical studies of Canadian craters. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 339–362.
Detre, C.H., Toth, I. (Eds.), 1998. Impact and extraterrestrial spherules: new tools for global correlation. Abstracts of papers presented to the 1998 Annual Meeting of I.G.C.P. Geological Institute of Hungary, Budapest, Hungary, p. 384. 101+4 pp.
Deutsch, A., Schärer, U., 1994. Dating terrestrial impact events. Meteoritics 29, 301–322.
Deutsch, A., Ostermann, M., Masaitis, V., 1997. Geochemistry and neodymium-strontium isotopic signature of tektite-like objects from Siberia (urengoites; South Ural glass). Meteoritics and Planetary Science 32, 679–686.
Di Martino, M., Cigolini, C., Orti, L., 2008. Non-impact origin of the Arkenu craters (Libya) (abstract). Meeting on Large Meteorite Impacts and Planetary Evolution IV, Parys, South Africa. Abstracts volume, Lunar and Planetary Institute. abs. #3012 (CD-ROM).
Dietz, R.S., 1947. Meteorite impact suggested by the orientation of shatter-cones at the Kentland, Indiana disturbance. Science 105, 42–43.
Dietz, R.S., 1959. Shatter cones in cryptoexplosion structures (meteorite impact?). Journal of Geology 67, 496–505.

Dietz, R.S., 1963a. Cryptoexplosion structures: a discussion. American Journal of Science 261, 650–664.
Dietz, R.S., 1963b. Astroblemes: ancient meteorite-impact structures on the Earth. In: Middlehurst, B.M., Kuiper, G.P. (Eds.), The Moon, meteorites, and comets. University of Chicago Press, Chicago IL, pp. 285–300.
Dietz, R.S., 1968. Shatter cones in cryptoexplosion structures. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 267–285.
Dietz, R.S., Fudali, R., Cassidy, W., 1969. Richat and Semsiyat Domes (Mauritania): not astroblemes. Geological Society of America Bulletin 80, 1367–1372.
Ding, Y., Veblen, D.R., 2004. Impactite from Henbury, Australia. American Mineralogist 89, 961–968.
Dressler, B., 1990. Shock metamorphic features and their zoning and orientation in the Precambrian rocks of the Manicouagan Structure, Quebec, Canada. Tectonophysics 171, 229–245.
Dressler, B., Reimold, W.U., 2001. Terrestrial impact melt rocks and glasses. Earth Science Reviews 56, 205–284.
Dressler, B., Reimold, W.U., 2004. Order or chaos? Origin and mode of emplacement of breccias in floors of large impact structures. Earth Science Reviews 67, 1–54.
Dressler, B.O., Sharpton, V.L., 1997. Breccia formation at a complex impact crater: Slate Islands, Lake Superior, Ontario, Canada. Tectonophysics 275, 285–311.
Dressler, B.O., Sharpton, V.L. (Eds.), 1999. Large Meteorite Impacts and Planetary Evolution II. Special Paper, vol. 339. Geological Society of America, Boulder, CO. 464 pp.
Dressler, B.O., Grieve, R.A.F., Sharpton, V.L. (Eds.), 1994. Large Meteorite Impacts and Planetary Evolution. Special Paper, vol. 293. Geological Society of America, Boulder, CO. 348 pp.
Dressler, B.O., Sharpton, V.L., Schuraytz, B.C., 1998. Shock metamorphism and shock barometry at a complex impact structure: Slate Islands, Canada. Contributions to Mineralogy and Petrology 130, 275–287.
Dressler, B.O., Sharpton, V.L., Copeland, P., 1999. Slate Islands, Lake Superior, Canada: a mid-size, complex impact structure. In: Dressler, B.O., Sharpton, V.L. (Eds.), Large Meteorite Impacts and Planetary Evolution II. Geological Society of America, Boulder, CO, pp. 109–124.
Dvorak, U., 1969. Stosswellenmetamorphose des Anorthosits vom Manicouagan Krater, Quebec, Canada. Contributions to Mineralogy and Petrology 24, 306–347.
Dypvik, H., Burchell, M., Claeys, P. (Eds.), 2004. Cratering in Marine Environments and on Ice. Springer, New York. 340 pp.
Edwards, L.E., Powars, D.S., 2003. Impact damage to dinocysts from the late Eocene Chesapeake Bay event. Palaios 18, 275–285.
El Goresy, A., 1968. The opaque minerals in impactite glasses. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 531–553.
El-Baz, F., 1981. Circular feature among sand dunes of the Great Sand Sea, Egypt. Science 213, 439–440.
El-Baz, F., Ghoneim, E., 2007. Largest crater shape in the Great Sahara revealed by multi-spectral images and radar data. International Journal of Remote Sensing 28, 451–458.
Ellwood, B.B., Benoist, S.L., El Hassani, A., Wheeler, C., Crick, R.E., 2003. Impact ejecta layer from the mid-Devonian: possible connection to global mass extinctions. Science 300, 1734–1737.
Elsila, J.E., de Leon, N.P., Plows, F.L., Buseck, P.R., Zare, R.N., 2005. Extracts of impact breccia samples from Sudbury, Gardnos, and Ries impact craters and the effects of aggregation on C_{60} detection. Geochimica et Cosmochimica Acta 69, 2891–2899.
Elston, W.E., Lambert, P.W., 1965. Possible shatter cones in a volcanic vent new Albuquerque, New Mexico. Annals of the New York Academy of Sciences 123, 1003–1010.
Elston, W.E., Lambert, P.W., Smith, E.L., 1968. Striated cones: wind-abrasion features, not shatter cones. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 287–290.
Engelhardt, W.V., Bertsch, W., 1969. Shock induced planar deformation features in quartz from the Ries Crater, Germany. Contributions to Mineralogy and Petrology 20, 203–234.
Engelhardt, W.V., Stöffler, D., 1965. Spaltflächen im Quarz als Anzeichen für Einschläge grosser Meteoriten. Naturwissenschaften 17, 489–490.
Engelhardt, W.V., Stöffler, D., 1968. Stages of shock metamorphism in crystalline rocks of the Ries Basin, Germany. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 159–168.
Ernstson, K., Hamman, W., Fiebag, J., Graup, G., 1985. Evidence for an impact origin for the Azuara structure (Spain). Earth and Planetary Science Letters 74, 361–370.
Ernstson, K., Rampino, M.R., Hill, M., 2001. Cratered cobbles in Triassic Buntsandstein conglomerates in northwestern Spain: an indicator of shock deformation in the vicinity of large impacts. Geology 29, 11–14.
Ernstson, K., Claudin, F., Schüssler, U., Hradil, K., 2002. The mid-Tertiary Azuara and Rubielos de la Cerida paired impact structures (Spain). Treballs del Museu de Geologia de Barcelona 11, 5–65.
Erwin, D.H., 1993. The Great Paleozoic Crisis. Columbia University Press, New York. 327 pp.
Erwin, D.H., 2006. Extinction: How Life on Earth Nearly Ended 250 Million Years Ago. Princeton University Press, Princeton, NJ. 296 pp.
Essene, E.J., Fisher, D.C., 1986. Lightning strike fusion: extreme reduction and metal-silicate liquid immiscibility. Science 234, 189–193.
Evans, K.R., HortonJr. Jr., J.W., KingJr. Jr., D.T., Morrow, J.R. (Eds.), 2008. The sedimentary record of meteorite impacts. Special Paper, vol. 437. Geological Society of America, Boulder, CO. 213 pp.
Fackelman, S.P., Morrow, J.R., Koeberl, C., McElvain, T.H., 2008. Shatter cone and microscopic shock-alteration evidence for a post-Paleoproterozoic terrestrial impact structure near Santa Fe, New Mexico, USA. Earth and Planetary Science Letters 270, 290–299.
Faggart Jr., B.E., Basu, A.R., Tatsumoto, M., 1985. Origin of the Sudbury Complex by meteorite impact: neodymium isotopic evidence. Science 230, 436–439.
Fahey, J.J., 1964. Recovery of coesite and stishovite from Coconino Sandstone of Meteor Crater, Arizona. American Mineralogist 49, 1643–1647.
Fairbairn, H.W., 1941. Deformation lamellae in quartz from the Ajibik Formation, Michigan. Geological Society of America Bulletin 52, 1265–1278.
Fairbairn, H.W., 1949. Structural Petrology of Deformed Rocks. Addison-Wesley Publishing Co., Inc., Cambridge, MA. 344 pp.
Fairbairn, H.W., Robson, G.M., 1941. Breccia at Sudbury. Report of the Ontario Department of Mines, vol. 50, Part 6, pp. 18–33.
Farley, K.A., Mukhopadhyay, S., 2001. An extraterrestrial impact at the Permian–Triassic boundary? (Technical Comments and Replies). Science 293, 2343a.
Farley, K.A., Ward, P., Garrison, G., Mukhopadhyay, S., 2005. Absence of extraterrestrial ^{3}He in Permian–Triassic age sedimentary rocks. Earth and Planetary Science Letters 240, 265–275.
Felix, C.J., 1961. An introduction to palynology. In: Andrews, H.N. (Ed.), Studies in Paleobotany. John Wiley and Sons, New York, NY, pp. 436–451. Ch. 17.
Ferrière, L., Osinski, G., 2009. Characterization of shock-metamorphic effects in quartz from sandstones at the Houghton impact structure, Canada (abstract). Meteoritics and Planetary Science 44, A68.
Ferrière, L., Koeberl, C., Reimold, W.U., 2007. Drill core LB-08A, Bosumtwi impact structure, Ghana: petrographic and shock metamorphic studies of material from the central uplift. Meteoritics and Planetary Science 42, 611–633.
Ferrière, L., Koeberl, C., Ivanov, B.A., Reimold, W.U., 2008. Shock metamorphism of Bosumtwi impact crater rocks, shock attenuation, and uplift formation. Science 322, 1678–1681.
Ferrière, L., Koeberl, C., Reimold, W.U., 2009a. Characterization of ballen quartz and cristobalite in impact breccias: new observations and constraints on ballen formation. European Journal of Mineralogy. doi:10.1127/0935-1221/2009/0021-1898.
Ferrière, L., Morrow, J.R., Amgaa, T., Koeberl, C., 2009b. Systematic study of universal-stage measurements of planar deformation features in shocked quartz: implications for statistical significance and representation of results. Meteoritics and Planetary Science 44, 925–940.
Finkelman, R.B., Milton, C., Larson, R.R., 1976. Industrial glass beads in beach sand from Chesapeake Bay, Maryland. Chesapeake Science 17, 310.
Firestone, R.B., West, A., Kennett, J.P., Becker, L., Bunch, T.E., Revay, Z.S., Schultz, P.H., Belgya, T., Kennett, D.J., Erlandson, J.M., Dickenson, O.J., Goodyear, A.C., Harris, R.S., Howard, G.A., Kloosterman, J.B., Lechler, P., Mayewski, P.A., Montgomery, J., Poreda, R., Darrah, T., Que Hee, S.S., Smith, A.R., Stich, A., Topping, W., Wittke, J.H., Wolbach, W.S., 2007. Evidence for an extraterrestrial impact 12,900 years ago that contributed to the megafaunal extinctions and the Younger Dryas cooling. Proceedings of the National Academy of Sciences 104, 16016–16021.
Fisher, R.V., Schmincke, H.U., 1984. Pyroclastic Rocks. Springer-Verlag, New York. 472 pp.
Fisher, G.L., Chang, D.P.Y., Brummer, M., 1976. Fly ash collected from electrostatic precipitators: microcrystalline structures and the music of the spheres. Science 192, 553–555.
Fiske, P.S., Neills, W.J., Xu, Z., Stebbins, J.F., 1998. Shocked quartz: a ^{29}Si magic angle-spinning nuclear magnetic resonance study. American Mineralogist 83, 1285–1292.
Flinn, D., 1970. Two possible submarine craters in Shetland. Proceedings of the Geological Society of London 1663, 131–135.
Flörke, O.W., Mielke, H.G., Weichert, J., 1981. Quartz with rhombohedral cleavage from Madagascar. American Mineralogist 66, 596–600.
Forsyth, D.A., Pilkington, M., Grieve, R.A.F., Abbinett, D., 1990. Major circular structure beneath southern Lake Huron defined from potential field data. Geology 18, 773–777.
Frank, O., Jehlika, J., Hamplová, V., Svatoš, A., 2005. The search for fullerenes in rocks from the Ries impact crater. Meteoritics and Planetary Science 40, 307–314.
Fredriksson, K., Dube, A., Milton, D.J., Balasundaram, M.S., 1973. Lonar Lake, India: an impact crater in basalt. Science 180, 862–864.
French, B.M., 1968a. Shock metamorphism as a geological process. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 1–17.
French, B.M., 1968b. Sudbury structure, Ontario: some petrographic evidence for an origin by meteorite impact. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 383–412.
French, B.M., 1987. Comment on "Early Archean silicate spherules of probable impact origin, South Africa and Western Australia". Geology 15, 178–179.
French, B.M., 1990a. Absence of shock-metamorphic effects in the Bushveld Complex, South Africa: results of an intensive search. Tectonophysics 171, 287–301.
French, B.M., 1990b. 25 years of the impact-volcanic controversy: is there anything new under the sun? Or inside the Earth? EOS, Transactions of the American Geophysical Union 71, 411–414.
French, B.M., 1998. Traces of catastrophe: a handbook of shock-metamorphic effects in terrestrial meteorite impact craters. Lunar and Planetary Institute, Houston, TX, Contribution CB-954. 120 pp. (available online at: http://www.lpi.usra.edu/publications/books/).
French, B.M., 2004. The importance of being cratered: the new role of meteorite impact as a normal geological process. Meteoritics and Planetary Science 39, 169–197.
French, B.M., 2005. Stalking the wily shatter cone: a critical guide for impact-crater hunters. Impacts in the Field, Vol. 2 (Winter, 2005), pp. 3–10. (Published by the Impact Field Studies Group, available at: http://web.eps.utk.edu/~faculty.ifsg.htm.).
French, B.M., Nielsen, R.L., 1990. Vredefort Bronzite Granophyre: chemical evidence for origin as a meteorite impact melt. Tectonophysics 171, 119–138.
French, B.M., Short, N.M., 1968. Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD. 644 pp.
French, B.M., Hartung, J.B., Short, N.M., Dietz, R.S., 1970. Tenoumer crater, Mauritania: age and petrologic evidence for origin by meteorite impact. Journal of Geophysical Research 75, 4396–4406.

French, B.M., Koeberl, C., Gilmour, I., Shirey, S.B., Dons, J.A., Naterstad, J., 1997. The Gardnos impact structure, Norway: petrology and geochemistry of target rocks and impactites. Geochimica et Cosmochimica Acta 61, 873–904.
French, B.M., Cordua, W.S., Plescia, J.B., 2004. The Rock Elm meteorite impact structure, Wisconsin: geology and shock-metamorphic effects in quartz. Bulletin of the Geological Society of America 116, 200–218.
Frenzel, G., Irouschker-Zumthor, A., Stähle, V., 1989. Stosswellenmetamorphose, Aufschmelzung und Verdampfung bei Fulguritbildung an exponierten Berggipfeln. Chemie der Erde 49, 265–286.
Frondel, C., 1962. The System of Mineralogy, 7th edition. Silica Minerals, vol. 3. John Wiley and Sons, New York. 334 pp.
Fudali, R.F., 1969. Coesite from the Richat Dome, Mauritania: a misidentification. Science 166, 228–230.
Gao, Z., Xu, D., Zhang, Q., Sun, Y., 1987. Discovery and study of microspherules at the Permian–Triassic boundary of the Shangsi section, Guangyuan, China (in Chinese with English abstract). Geological Review 33, 203–211.
Gash, P.J.S., 1971. Dynamic mechanism of the formation of shatter cones. Nature Physical Sciences 230, 32–35.
Gersonde, R., Kyte, F.T., Bleil, U., Dickmann, B., Flores, J.A., Gohl, K., Grahl, G., Hagen, R., Kuhn, G., Sierro, F.J., Völker, D., Abelmann, A., Bostwick, J.A., 1997. Geological record and reconstruction of the late Pliocene impact of the Eltanin asteroid in the Southern Ocean. Nature 390, 357–363.
Gibson, R.L., Reimold, W.U., Wallmach, T., 1997. Origin of pseudotachylite in the lower Witwatersrand Supergroup, Vredefort Dome (South Africa): constraints from metamorphic studies. Tectonophysics 283, 241–262.
Gilmour, I., 1998. Geochemistry of carbon in terrestrial impact processes. In: Grady, M.M., Hutchison, R., McCall, G.J.H. (Eds.), Meteorites: Flux with Time and Impact Effects. Geological Society Special Publication, vol. 140. Geological Society, London, pp. 205–216.
Gilmour, I., Koeberl, C. (Eds.), 2000. Impacts and the Early Earth. Lecture Notes in Earth Science, vol. 91. Springer Verlag, New York. 445 pp.
Gilmour, I., French, B.M., Franchi, I.A., Abbott, J.I., Hough, R.M., Newton, J., Koeberl, C., 2003. Geochemistry of carbonaceous impactites from the Gardnos impact structure, Norway. Geochimica et Cosmochimica Acta 67, 3889–3903.
Glass, B.P., 1969. Silicate spherules from Tunguska impact area: electron microprobe analysis. Science 164, 547.
Glass, B.P., 1984. Tektites. Journal of Non-Crystalline Solids 67, 333–344.
Glass, B.P., 1990. Tektites and microtektites: key facts and inferences. Tectonophysics 171, 393–404.
Glass, B.P., 2002. Upper Eocene impact ejecta/spherule layers in marine sediments. Chemie der Erde 62, 173–196.
Glass, B.P., Barlow, 1979. Mineral inclusions in Muong-Nong-type indochinites: implications concerning parent material and process of formation. Meteoritics 14, 55–67.
Glass, B.P., Wu, J., 1993. Coesite and shocked quartz discovered in the Australasian and North American microtektite layers. Geology 21, 435–438.
Glass, B.P., Lu, S., Leavens, P.B., 2002. Reidite: an impact-produced high-pressure polymorph of zircon found in marine sediments. American Mineralogist 87, 562–565.
Glass, B.P., Koeberl, C., Kirkham, A., 2003. Glauconitic spherules from the Triassic of the Bristol area, SW England: probably microtektite pseudomorphs: discussion and reply. Proceedings of the Geologists' Association 114, 175–179.
Glass, B.P., Huber, H., Koeberl, C., 2004. Geochemistry of Cenozoic microtektites and clinopyroxene-bearing spherules. Geochimica et Cosmochimica Acta 68, 3971–4006.
Glikson, A., 2004. Comment on "Bedout: a possible end-Permian impact crater offshore of northwestern Australia". Science 613b.
Glikson, A., Haines, P.W. (Eds.), 2005. Shoemaker memorial issue on the Australian impact record, 1997-2005 update. Australian Journal of Earth Sciences, 52, pp. 475–798.
Gohn, G.S., Koeberl, C., Miller, K.G., Reimold, W.U., Browning, J.V., Cockell, C.S., Horton Jr., J.W., Kenkmann, T., Kulpecz, A.A., Powars, D.S., Sanford, W.E., Voytek, M.A., 2008. Deep drilling into the Chesapeake Bay impact structure. Science 320, 1740–1745.
Goltrant, O., Cordier, P., Doukhan, J.-C., 1991. Planar deformation features in shocked quartz: a transmission electron microscopy investigation. Earth and Planetary Science Letters 106, 103–115.
Goltrant, O., Leroux, H., Doukhan, J.-C., Cordier, P., 1992. Formation mechanisms of planar deformation features in naturally shocked quartz. Physics of the Earth and Planetary Interiors 74, 219–240.
Gonzalez, E., Alonson, S., 2006. Evidence of two possible impact structures in Chad: separate impacts, binary asteroids or Aorunga crater chain? (abstract). Proceedings, Workshop — Impact Craters as Indicators for Planetary Environmental Evolution and Astrobiology, Sweden. CD-ROM.
Gorter, J.D., Bayford, S.W., 2000a. Possible impact origin for the Middle Miocene (Serravallian) Puffin Structure, Ashmore Platform, northwest Australia. Australian Journal of Earth Sciences 47, 707–714.
Gorter, J.D., Bayford, S.W., 2000b. Discussion and reply: possible impact origin for the Middle Miocene (Serravallian) Puffin Structure, Ashmore Platform, northwest Australia. Australian Journal of Earth Sciences 47, 1128–1129.
Gorter, J.D., Glikson, A.Y., 2000. Origin of a Late Eocene to pre-Miocene buried crater and breccia lens at Fohn-1, North Bonaparte Basin, Timor Sea: a probable extraterrestrial connection. Meteoritics and Planetary Science 35, 381–392.
Gorter, J.D., Glikson, A.Y., 2001. Comment on "Origin of a late Eocene to pre-Miocene buried crater and breccia lens at Fohn-1, North Bonaparte Basin, Timor Sea: a probable extraterrestrial connection" by J.D. Gorter and A.Y. Glikson (Authors' Reply). Meteoritics and Planetary Science 36, 749–751.
Grady, M.M., Hutchison, R., McCall, G.J.H., Rothery, D.A., 1998. Meteorites: Flux with Time and Impact Effects. Geological Society Special Publication, vol. 140. Geological Society, London. 278 pp.
Gratz, A., Fisler, D.K., Bohor, B.F., 1996. Distinguishing shocked from tectonically deformed quartz by the use of SEM and chemical etching. Earth and Planetary Science Letters 142, 513–521.
Graup, G., 1981. Terrestrial chondrules, glass spherules and accretionary lapilli from the suevite, Ries Crater, Germany. Earth and Planetary Science Letters 55, 407–418.
Graup, G., 1999. Carbonate-silicate liquid immiscibility upon impact melting: Ries Crater, Germany. Meteoritics and Planetary Science 34, 425–438.
Grieve, R.A.F., 1978. The melt rocks at Brent Crater, Ontario, Canada. Proceedings of the 9th Lunar and Planetary Science Conference. Pergamon Press, New York, pp. 2579–2608.
Grieve, R.A.F., 1987. Terrestrial impact structures. Annual Review of Earth and Planetary Science 15, 245–270.
Grieve, R.A.F., 1991. Terrestrial impact: the record in the rocks. Meteoritics 26, 175–194.
Grieve, R.A.F., 1997. Extraterrestrial impact events: the record in the rocks and the stratigraphic column. Palaeogeography, Palaeoclimatology, Palaeoecology 132, 5–23.
Grieve, R.A.F., 1998. Extraterrestrial impacts on earth: the evidence and the consequences. In: Grady, M.M., Hutchison, R., McCall, G.J.H., Rothery, D. (Eds.), Meteorites: Flux with Time and Impact Effects. Geological Society, London, Special Publication, vol. 140, pp. 105–131.
Grieve, R.A.F., 2001. The terrestrial cratering record. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, NY, pp. 379–402.
Grieve, R.A.F., 2006. Impact structures in Canada. GEOtext, vol. 1208–2260; no. 5. Geological Association of Canada. 210 pp.
Grieve, R.A.F., Cintala, M.J., 1992. An analysis of differential impact melt-crater scaling and implications for the terrestrial meteorite record. Meteoritics 27, 526–538.
Grieve, R.A.F., Masaitis, V.L., 1994. The economic potential of terrestrial impact craters. International Geology Review 36, 105–151.
Grieve, R.A.F., Pilkington, P.B., 1996. The signature of terrestrial impacts. AGSO Journal of Australian Geology and Geophysics 16, 399–420.
Grieve, R.A.F., Robertson, P.B., 1976. Variations in shock deformation at the Slate Islands impact structure, Lake Superior, Canada. Contributions to Mineralogy and Petrology 58, 37–49.
Grieve, R.A.F., Shoemaker, E.M., 1994. The record of past impacts on Earth. In: Gehrels, T. (Ed.), Hazards Due to Comets and Asteroids. University of Arizona Press, Tucson, AZ, pp. 417–462.
Grieve, R.A.F., Therriault, A., 1995. Planar deformation features in quartz: target effects (abstract). Lunar and Planetary Science 26, 515–516.
Grieve, R.A.F., Therriault, A., 2004. Observations at terrestrial impact structures: their utility in constraining crater formation. Meteoritics and Planetary Science 39, 199–216.
Grieve, R.A.F., Dence, M.R., Robertson, P.B., 1977. Cratering process: as interpreted from the occurrence of impact melts. In: Roddy, D.J., Pepin, R.O., Merrill, R.B. (Eds.), Impact and Explosion Cratering: Planetary and Terrestrial Implications. Pergamon Press, New York, NY, pp. 791–814.
Grieve, R.A.F., Reny, G., Gurov, E.P., Ryabenko, V.A., 1987. The melt rocks of the Boltysh impact crater, Ukraine, USSR. Contributions to Mineralogy and Petrology 96, 56–62.
Grieve, R.A.F., Coderre, J.M., Robertson, P.B., Alexopoulos, J., 1990. Microscopic planar deformation features in quartz of the Vredefort structure: anomalous but still suggestive of an impact origin. Tectonophysics 171, 185–200.
Grieve, R.A.F., Langenhorst, F., Stöffler, D., 1996. Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience. Meteoritics and Planetary Science 31, 6–35.
Griggs, D.T., Turner, F.J., Heard, H.C., 1960. Deformation of rocks at 50° to 800 °C. In: Griggs, D., Handin, J. (Eds.), Rock Deformation. Geological Society of America Memoir, vol. 79, pp. 39–104.
Guy-Bray, J., Geological Staff, 1966. Shatter cones at Sudbury. Journal of Geology 74, 243–245.
Hagstrum, J.T., Abbott, D., 2002. Evidence for a large bolide impact in the Proto-Pacific ocean preceding the Chicxulub impact by about 2 million years (abstract). EOS, Transactions of the American Geophysical Union 83 (47), F797 Fall Meeting, Supplement, Abstract OS22C-0297.
Haines, P.W., Jenkins, R.J.F., Kelley, S.P., 2001. Pleistocene glass in the Australian desert: the case for an impact origin. Geology 29, 899–902.
Hanss, R.E., Montague, B.R., Davis, M.K., Galindo, C., Hörz, F., 1978. X-ray diffractometer studies of shocked minerals. Proceedings of the 9th Lunar and Planetary Conference. Pergamon Press, New York, pp. 2773–2787.
Hargraves, R.B., Cullicott, C.E., Deffeyes, K.S., Hougen, S., Christiansen, P.P., Fiske, P.P., 1990. Shatter cones and shocked rocks in southwestern Montana: the Beaverhead impact structure. Geology 18, 832–834.
Hassler, S.W., Simonson, B.M., 2001. The sedimentary record of extraterrestrial impacts in deep shelf environments — evidence from the early Precambrian. Journal of Geology 109, 1–22.
Haynes, G., 2002. The Early Settlement of North America: the Clovis Era. Cambridge University Press, New York, NY. 360 pp.
Haynes Jr., C.V., 2005. Clovis, pre-Clovis, climate change and extinction. In: Bonnichsen, R., Lepper, B.T., Stanford, D., Waters, M.R. (Eds.), Paleoamerican Origins: Beyond Clovis. Texas A & M University Press, College Station, TX, pp. 113–132.
Haynes Jr., C.V., 2008. Younger Dryas "black mats" and the Rancholabrean termination in North America. Proceedings of the National Academy of Sciences 105, 6520–6525.
Hazen, R.M., 1999. The Diamond Makers. Cambridge University Press, New York. 244 pp.
Heard, H.C., Carter, N.L., 1966. Experimentally induced "natural" intragranular flow in quartz and quartzite. American Journal of Science 266, 1–42.
Heiken, G., Lofgren, G., 1971. Terrestrial glass spheres. Bulletin of the Geological Society of America 82, 1045–1050.
Heiken, G., Wohletz, K., 1985. Volcanic Ash. University of California Press, Berkeley, CA. 246 pp.

Herd, C.D.K., Froese, D.G., Walton, E.L., Kofman, R.S., Herd, E.P.K., Duke, M.J.M., 2008. Anatomy of a young impact event in central Alberta, Canada: prospects for the missing Holocene impact record. Geology 36, 955–958.

Herrick, R., Osinski, G., Pierazzo, E. (Eds.), 2008. Bridging the Gap II: effect of target properties on the impact cratering process. Meteoritics and Planetary Science, vol. 43, pp. 1915–2107.

Heymann, D., Hörz, F., 1990. Raman-spectroscopy and X-ray diffractometer studies of experimentally produced diaplectic feldspar glass. Physics and Chemistry of Minerals 17, 38–44.

Heymann, D., Chibante, L.P.F., Brooks, R.F.R., Wolbach, W.S., Smalley, R.E., 1994. Fullerenes in the Cretaceous–Tertiary boundary layer. Science 265, 645–647.

Hibbard, M.J., 1995. Petrography to Petrogenesis. Prentice-Hall, Englewood Cliffs, NJ. 587 pp.

Higgins, M., 1971. Cataclastic Rocks. U.S. Geological Survey Professional Paper, vol. 687. 97 pp.

Hildebrand, A.R., Penfield, G.T., Kring, D.A., Pilkington, M., Camargo, Z.A., Jacobsen, S.B., Boynton, W.V., 1991. Chicxulub crater: a possible Cretaceous–Tertiary boundary impact crater on the Yucatan Peninsula, Mexico. Geology 19, 867–871.

Hirth, G., Tullis, J., 1994. The brittle-plastic transition in experimentally deformed quartz aggregates. Journal of Geophysical Research 99, 11,731–11,747.

Holser, W.T., Schönlaub, H.P., Attrep, M., Boeckelman, K., Klein, P., Margaritz, M., Orth, C.J., Fenninger, H., Jenny, C., Kralik, M., Mauritsch, H., Pak, E., Schramm, J.M., Statteger, K., Schmöller, R., 1989. A unique geochemical record at the Permian-Triassic boundary. Nature 337, 39–44.

Horowitz, A.S., Potter, P.E., 1971. Introductory Petrography of Fossils. Springer-Verlag, New York, NY. 302 pp.

Horton Jr. J.W., Powars, D.S., Gohn, G.S., (Eds.), 2005a. Studies of the Chesapeake Bay impact structure — the USGS-NASA Langley corehole, Hampton, Virginia, and related coreholes and geophysical surveys. U.S. Geological Survey Professional Paper, vol. 1688. chapters A-K, separately paginated.

Horton Jr., J.W., Aleinikoff, J.N., Kunk, M.J., Gohn, G.S., Edwards, L.E., Self-Trail, J.M., Powars, D.S., Izett, G.A., 2005b. Recent research on the Chesapeake Bay impact structure, USA — impact debris and reworked ejecta. In: Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), Large Meteorite Impacts III. Special Paper, vol. 384. Geological Society of America, Boulder, CO., pp. 147–170.

Hörz, F., 1965. Untersuchungen an Riesgläsern. Beiträge zur Mineralogie und Petrographie 11, 621–661.

Hörz, F., 1968. Statistical measurements of deformation structures and refractive indices in experimentally shock loaded quartz. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 243–253.

Hörz, F., 1969. Structural and mineralogical evaluation of an experimentally produced impact crater in granite. Contributions to Mineralogy and Petrology 21, 365–377.

Hörz, F., 1971. Meteorite impact and volcanism. Journal of Geophysical Research, vol. 76, pp. 5381–5798.

Hörz, F., Quaide, W.L., 1973. Debye–Scherrer investigations of experimentally shocked silicates. Moon 6, 45–82.

Hörz, F., Mittlefehldt, D.W., See, T.H., Galindo, C., 2002. Petrographic studies of the impact melts from Meteor Crater, Arizona, USA. Meteoritics and Planetary Science 37, 501–531.

Hough, R.M., 2000. Discussion and reply: possible impact origin for the Middle Miocene (Serravallian) Puffin Structure, Ashmore Platform, northwest Australia. Australian Journal of Earth Sciences 47, 1127–1128.

Hough, R.M., Gilmour, I., Pillinger, C.T., Arden, J.W., Gilkes, K.W.R., Yuan, J., Milledge, H. L., 1995. Diamond and silicon carbide in impact melt rock from the Ries impact crater. Nature 378, 41–44.

Howard, K.T., 2008. Geochemistry of Darwin glass and target rocks from Darwin crater, Tasmania, Australia. Meteoritics and Planetary Science 43, 479–496.

Howard, K.T., Haines, P.W., 2007. The geology of Darwin crater, western Tasmania, Australia. Earth and Planetary Science Letters 260, 328–339.

Howard, K.A., Offield, T.W., 1968. Shatter cones at Sierra Madera, Texas. Science 162, 261–265.

Hower, J.C., Robertson, J.D., 2004. Chemistry and petrology of fly ash derived from co-combustion of United States coal and tire-derived fuel. Fuel Processing Technology 85, 359–377.

Hoyt, W.G., 1987. Coon Mountain Controversies: Meteor Crater and the Development of the Impact Theory. University of Arizona Press, Tucson, AZ. 442 pp.

Huber, H., Koeberl, C., McDonald, I., Reimold, W.U., 2000. Use of γ–γ coincidence spectrometry in the geochemical study of diamictites from South Africa. Journal of Radiochemical and Nuclear Chemistry 244, 603–607.

Huffman, A.R., Reimold, W.U., 1996. Experimental constraints on shock-induced microstructures in naturally deformed silicates. Tectonophysics 236, 165–217.

Hulett Jr., L.D., Weiberger, A.J., Northcutt, K.J., Ferguson, M., 1980. Chemical species in fly ash from coal-burning power plants. Science 210, 1356–1358.

Hurley, P.M., 1963. Rb–Sr isotopic investigation of crater rocks of possible impact origin. In Variations in Isotropic Abundances of Strontium, Calcium, and Argon and Related Topics, Massachusetts Institute of Technology Document M.I.T.-1381-17, Seventeenth Annual Progress Report for 1969, U.S. Atomic Energy Commission Contract At(30-1)-1381, p. 27, December 1, 1969.

IFSG, 2009. Impact Field Studies Group, University of Tennessee, Knoxville, TN. WWW Page, http//web.eps.utk.edu/~faculty.ifsg.htm.

Ingerson, E., Tuttle, O.F., 1945. Relations of lamellae and crystallography of quartz and fabric directions in some deformed rocks. EOS, Transactions of the American Geophysical Union 26, 95–105.

Isachsen, Y.W., Wright, S.F., Revetta, F.A., 1994. The Panther Mountain circular feature possibly hides a buried impact crater. Northeastern Geology 16, 123–136.

Iyer, S.D., Prasad, M.S., Gupta, S.M., Charan, S.N., Mukherjee, A.D., 1997. Hydrovolcanic activity in the central Indian Ocean basin. Does nature mimic laboratory experiments? Journal of Volcanology and Geothermal Research 78, 209–220.

Izett, G.A., 1990. The Cretaceous–Tertiary boundary interval, Raton Basin, Colorado and New Mexico, and its content of shock-metamorphosed minerals: evidence relevant to the K/T boundary impact-extinction hypothesis. Special Paper, vol. 249. Geological Society of America, Boulder, CO. 100 pp.

Izett, G.A., 1991. Tektites in Cretaceous–Tertiary boundary rocks on Haiti and their bearing on the Alvarez impact extinction hypothesis. Journal of Geophysical Research 96, 20879–20905.

Izett, G.A., Bohor, B.M., 1987. Comment and reply on "Dynamic deformation of volcanic ejecta from the Toba caldera: possible relevance to Cretaceous/Tertiary boundary phenomena". Geology 15, 90.

Jackson, J.C., Horton Jr., J.W., Chou, I.-M., Belkin, H.E., 2006. A shock-induced polymorph of anatase and rutile from the Chesapeake Bay impact structure, Virginia, U.S.A. American Mineralogist 91, 604–608.

Jehlička, J., Svatoš, A., Frank, O., Uhlik, P., 2003. Evidence for fullerenes in solid bitumen from pillow lavas of Proterozoic age from Mitov (Bohemian Massif, Czech Republic). Geochimica et Cosmochimica Acta 67, 1495–1506.

Jin, Y.G., Wang, Y., Wang, W., Shang, Q.H., Cao, C.Q., Erwin, D.H., 2000. Pattern of marine mass extinction near the Permian–Triassic boundary in south China. Science 289, 432–436.

Johnson, J.H., 1951. Introduction to the study of organic limestones. Quarterly of the Colorado School of Mines, 62. 185 pp.

Johnson, K.S., Campbell, J.A. (Eds.), 1997. Ames Structure in Northwest Oklahoma and similar features: origin and petroleum production (1995 symposium). Oklahoma Geological Survey Circular, vol. 100. University of Oklahoma, Norman, Oklahoma. 396 pp.

Johnson, J.R., Hörz, F., 2003. Visible/infrared spectra of experimentally shocked plagioclase feldspars. Journal of Geophysical Research 108 (E11), 5120. doi:10.1029/2003JE002127 6 pp.

Johnson, G.P., Talbot, R.J., 1964. A theoretical study of the shock-wave origin of shatter cones. M.S. Thesis, Air Force Institute of Technology, Wright–Patterson Air Force Base, Ohio, 92 p.

Jones, A.P., 2005. Meteorite impacts as triggers to large igneous provinces. Elements 1, 277–281.

Jones, R.L., Olson, K.R., 1990. Fly ash as a time marker in sedimentation studies. Soil Science Society of America Journal 54, 855–859.

Jones, A.P., Kearsley, A.T., Friend, C.R.L., Robin, E., Beard, A., Tamara, A., Trickett, S., Claeys, P., 2005. Are there signs of a large Paleocene impact preserved around Disko Bay, West Greenland? Nuussuaq spherule beds origin by impact instead of volcanic eruption? In: Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), Large Meteorite Impacts III. Special Paper, vol. 384. Geological Society of America, Boulder, CO, pp. 281–298.

Jones-Zimberlin, S., Simonson, B.M., Kress-Tomkins, D., Garson, D., 2006. Using impact spherule layers to correlate sedimentary successions: a case study of the Neoarchean Jeerinah layer (Western Australia). South African Journal of Geology 109, 245–261.

Jordanova, D., Hoffmann, V., Fehr, K.T., 2004. Mineral magnetic characterization of anthropogenic magnetic phases in the Danube River sediments (Bulgarian part). Earth and Planetary Science Letters 221, 71–89.

Joreau, P., French, B.M., Doukhan, J.-C., 1996. A TEM investigation of shock metamorphism in quartz from the Sudbury structure (Canada). Earth and Planetary Science Letters 138, 137–143.

Jørgensen, U.G., Appel, P.W.U., Hatsukawa, Y., Frei, R., Oshima, M., Toh, Y., Kimura, A., 2009, The Earth–Moon system during the Late Heavy Bombardment period. Icarus 204, 368–380.

Jull, A.J.T., 2001. Terrestrial ages of meteorites. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, NY, pp. 241–266.

Jull, A.J.T., Cloudt, S., Cielaszyk, C., 1998. ^{14}C terrestrial ages of meteorites from Victoria Land, Antarctica, and the infall rates of meteorites. In: Grady, M.M., Hutchison, R., McCall, G.J.H., Rothery, D.A. (Eds.), Meteorites: flux with time and impact effects. London, The Geological Society, Special Publication, vol. 140, pp. 75–91.

Kaiho, K., Kajiwara, Y., Nakano, T., Miura, Y., Kawahata, H., Tazaki, K., Ueishima, M., Chen, Z., Shi, G.R., 2001. End-Permian catastrophe by a bolide impact: evidence of a gigantic release of sulfur from the mantle. Geology 29, 815–818.

Kenkmann, T., 2002. Folding within seconds. Geology 30, 231–234.

Kenkmann, T., 2003. Dike formation, cataclastic flow, and rock fluidization during impact cratering: an example from the Upheaval Dome structure, Utah. Earth and Planetary Science Letters 214, 43–58.

Kenkmann, T., Poelchau, M.H., 2009. Low-angle collision with Earth: the elliptical impact crater Matt Wilson, Northern Territory, Australia. Geology 37, 459–462.

Kenkmann, T., Stöffler, D., 2002. New structural constraints on the Upheaval Dome impact crater (abstract). Lunar and Planetary Science 32 abs. #1037 (CD-ROM.

Kenkmann, T., von Dalwigk, I., 2000. Radial transpression ridges: a new structural feature of complex impact craters. Meteoritics and Planetary Science 35, 1189–1202.

Kenkmann, T., Hornemann, U., Stöffler, D., 2000a. Experimental generation of shock-induced pseudotachylites along lithological interfaces. Meteoritics and Planetary Science 35, 1275–1290.

Kenkmann, T., Ivanov, B.A., Stöffler, D., 2000b. Identification of ancient impact structures: low-angle faults and related geological features of crater basements. In: Gilmour, I., Koeberl, C. (Eds.), Impacts and the Early Earth. Springer, New York, pp. 279–307.

Kenkmann, T., Jahn, A., Scherler, D., Ivanov, B.A., 2005a. Structure and formation of a central uplift: a case study at the Upheaval Dome crater, Utah. In: Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), Large Meteorite Impacts III. Special Paper, vol. 384. Geological Society of America, Boulder, CO, pp. 85–115.

Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), 2005b. Large Meteorite Impacts III. Geological Society of America, Special Paper, vol. 394. 476 pp.

Kennett, D.J., Kennett, J.P., West, A., Mercer, C., Que Hee, S.S., Bement, L., Bunch, T.E., Sellers, M., Wolbach, W.S., 2009a. Nanodiamonds in the Younger Dryas boundary sediment layer. Science 323, 94. doi:10.1126/science.1162819.

Kennett, D.J., Kennett, J.P., West, A., West, G.J., Bunch, T.E., Culleton, B.J., Erlandson, J.M., Que Heeg, S.S., Johnson, J.R., Mercer, C., Shen, F., Sellers, M., Stafford Jr., T.W., Stich, A., Weaver, J.C., Wittke, J.H., Wolbach, W.S., 2009b. Shock-synthesized hexagonal diamonds in Younger Dryas boundary sediments. PNAS 106, 12623–12628.

Kerr, R., 2007. Mammoth-killer impact gets mixed reception from earth scientists (News). Science 316, 1264–1265.

Kerr, R.A., 2008. Experts find no evidence for a mammoth-killer impact. Science 319, 1331–1332.

Kerr, R.A., 2009. Did the Mammoth Slayer leave a diamond calling card? (News of the Week). Science 323, 26.

Kieffer, S.W., 1971. Shock metamorphism of the Coconino Sandstone at Meteor Crater, Arizona. Journal of Geophysical Research 76, 5449–5473.

Kieffer, S.W., 1975. Droplet chondrules. Science 189, 333–340.

Kieffer, S.W., Simonds, C.H., 1980. The role of volatiles and lithology in the impact cratering process. Reviews of Geophysics and Space Physics 18, 143–181.

Kieffer, S.S., Phakey, P.P., Christie, J.M., 1976a. Shock processes in porous quartzite: transmission electron microscope observations and theory. Contributions to Mineralogy and Petrology 59, 41–93.

Kieffer, S.W., Schaal, R.B., Gibbons, R., Hörz, F., Milton, D.J., Dube, A., 1976b. Shocked basalt from Lonar impact crater, India, and experimental analogues. Proceedings of the 7th Lunar Science Conference. Pergamon Press, New York, pp. 1391–1412.

Kile, D.E., 2009. The universal stage: the past, present, and future of a mineralogical research instrument. Geochemical News 140 (July 2009), 8 pp. (online at: http://www.geochemsoc.org/publications/geochemicalnews/gn140jul09/theuniversalstage.htm).

King Jr., D.T., Neathery, T.L., Petruny, L.W., Koeberl, C., Hames, W.E., 2002. Shallow-marine impact origin of the Wetumpka structure (Alabama, USA). Earth and Planetary Science Letters 202, 541–549.

Kirkham, A., 2003. Glauconitic spherules from the Triassic of the Bristol area, S.W. England: probable microtektite pseudomorphs. Proceedings of the Geologists' Association 114, 11–21.

Kirschner, C.E., Grantz, A., Mullen, M.W., 1992. Impact origin of the Avak structure, Arctic Alaska, and genesis of the Barrow gas fields. American Association of Petroleum Geologists Bulletin 76, 651–679.

Kleinmann, B., 1969. The breakdown of zircon observed in the Libyan Desert Glass as evidence of its impact origin. Earth and Planetary Science Letters 5, 497–501.

Kleinmann, B., Horn, P., Langenhorst, F., 2001. Evidence for shock metamorphism in sandstones from the Libyan Desert Glass strewn field. Meteoritics and Planetary Science 36, 1277–1282.

Koeberl, C., 1986. Geochemistry of tektites and impact glasses. Annual Review of Earth and Planetary Science 14, 323–350.

Koeberl, C., 1990. The geochemistry of tektites: an overview. Tectonophysics 171, 405–422.

Koeberl, C., 1994. Tektite origins by hypervelocity asteroidal or cometary impact: target rocks, source craters, and mechanisms. In: Dressler, B.O., Grieve, R.A.F., Sharpton, V.L. (Eds.), Large Impact Structures and Planetary Evolution. Special Paper, vol. 293. Geological Society of America, Boulder, CO, pp. 133–152.

Koeberl, C., 1997a. Impact cratering: The mineralogical and geochemical evidence. In: Johnson, K.S., Campbell, J.A. (Eds.), Ames Structure in Northwest Oklahoma and Similar Features: Origin and Petroleum Production (1995 Symposium). Oklahoma Geological Survey Circular, vol. 100, pp. 30–54.

Koeberl, C., 1997b. Libyan Desert Glass: geochemical composition and origin. In: Proceedings, Silica 96, Meeting on Libyan Desert Glass and related desert events, Bologna, Italy. Pyramids, Milano, Italy, pp. 121–131.

Koeberl, C., 1998. Identification of meteoritic component in impactites. In: Grady, M.M., Hutchison, R., McCall, G.J.H., Rothery, D. (Eds.), Meteorites: Flux with Time and Impact Effects. Geological Society, London, Special Publications, vol. 140, pp. 133–153.

Koeberl, C., 2001. The sedimentary record of impact events. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter Throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, NY, pp. 333–378.

Koeberl, C., 2002. Mineralogical and geochemical aspects of impact craters. Mineralogical Magazine 66, 745–768.

Koeberl, C., 2004. Remote sensing of impact craters: how to be sure? Comptes Rendus Geosciences 336, 959–961.

Koeberl, C., 2007. The geochemistry and cosmochemistry of impacts. In: Davis, A. (Ed.), Treatise of Geochemistry, vol. 1. Elsevier, New York, NY, pp. 1.28.1–1.28.52. doi:10.1016/B978-008043751-4/00228-5. online edition.

Koeberl, C., Anderson, R.R. (Eds.), 1996. The Manson Impact Structure, Iowa: Anatomy of an Impact Crater. Special Paper, vol. 302. Geological Society of America, Boulder, CO. 468 pp.

Koeberl, C., Henkel, H., 2005. Impact Tectonics. Springer-Verlag, New York. 552 pp.

Koeberl, C., Huber, H., 2000. Optimization of the multiparameter γ–γ coincidence spectrometry for the determination of iridium in geological materials. Journal of Radioanalytical and Nuclear Chemistry 244, 655–660.

Koeberl, C., MacLeod, K.G. (Eds.), 2002. Catastrophic Events and Mass Extinctions: Impacts and Beyond. Special Paper, vol. 356. Geological Society of America, Boulder, CO. 746 pp.

Koeberl, C., Martinez-Ruiz, F. (Eds.), 2003. Impact Markers in the Stratigraphic Record. Springer Verlag, New York. 363 pp.

Koeberl, C., Milkereit, B., 2007. Continental drilling and the study of impact craters and processes — an ICDP perspective. In: Harms, U., Koeberl, C., Zoback, M.S. (Eds.), Continental Scientific Drilling. Springer, Heidelberg, pp. 95–161.

Koeberl, C., Reimold, W.U., 1995a. The Newporte impact structure, North Dakota. Geochimica et Cosmochimica Acta 59, 4747–4767.

Koeberl, C., Reimold, W.U., 1995b. Early Archean spherule beds in the Barberton Mountains Land, South Africa: no evidence for impact origin. Precambrian Research 74, 1–33.

Koeberl, C., Reimold, W.U., 2004. Silverpit structure, North Sea: search for petrographic and geochemical evidence for an impact origin (abstract). Meteoritics and Planetary Science 39, A53.

Koeberl, C., Shirey, S.B., 1993. Detection of a meteorite component in Ivory Coast tektites with rhenium–osmium isotopes. Science 261, 595–598.

Koeberl, C., Shirey, S.B., 1997. Re–Os isotope systematics as a diagnostic tool for the study of impact craters and ejecta. Palaeogeography, Palaeoclimatology, Palaeoecology 132, 25–46.

Koeberl, C., Reimold, W.U., Brandt, D., 1996a. Red Wing Creek structure, North Dakota: petrographical and geochemical studies, and confirmation of impact origin. Meteoritics and Planetary Science 31, 335–342.

Koeberl, C., Reimold, W.U., Shirey, S.B., 1996b. A Re–Os isotope and geochemical study of the Vredefort Granophyre: clues to the origin of the Vredefort structure, South Africa. Geology 24, 913–916.

Koeberl, C., Poag, W., Reimold, W.U., Brandt, D., 1996c. Impact origin of the Chesapeake Bay structure and the source of the North American tektites. Science 271, 1263–1266.

Koeberl, C., Reimold, W.U., Brandt, D., Dallmeyer, R.D., Powell, R.A., 1997. Target rocks and breccias from the Ames impact structure, Oklahoma: petrology, mineralogy, geochemistry, and age. In: Johnson, K.S., Campbell, J.A. (Eds.), Ames Structure in Northwest Oklahoma and Similar Features: Origin and Petroleum Production (1995 symposium). Oklahoma Geological Survey Circular, vol. 100. University of Oklahoma, Norman, Oklahoma, pp. 169–198.

Koeberl, C., Reimold, W.U., Shirey, S.B., 1998. The Aouelloul crater, Mauritania: on the problem of confirming the impact origin of a small crater. Meteoritics and Planetary Science 33, 513–517.

Koeberl, C., Plescia, J.B., Hayward, C.L., Reimold, W.E., 1999. A petrographic and geochemical study of quartzose nodules, country rocks, and dike rocks from the Upheaval Dome structure, Utah. Meteoritics and Planetary Science 34, 861–868.

Koeberl, C., Farley, K.A., Peucker-Ehrenbrink, B., Sephton, M.A., 2004. Geochemistry of the end-Permian extinction event in Austria and Italy: no evidence for an extraterrestrial component. Geology 32, 1053–1056.

Koeberl, C., Shukolyukov, A., Lugmair, G.W., 2007. Chromium isotopic studies of terrestrial impact craters: Identification of meteoritic components at Bosumtwi, Clearwater East, Lappajärvi, and Rochechouart. Earth and Planetary Science Letters 256, 534–546.

Kriens, B.J., Shoemaker, E.M., Herkenhoff, K.E., 1999. Geology of the Upheaval Dome impact structure, southeast Utah. Journal of Geophysical Research 104, 18,867–18,887.

Krogh, T.E., Kamo, S.L., Bohor, B.F., 1993. Fingerprinting the K/T impact site and determining the time of impact by U–Pb dating of single shocked zircons from distal ejecta. Earth and Planetary Science Letters 119, 425–429.

Kyte, F.T., 1988. The extraterrestrial component in marine sediments: description and interpretation. Paleooceanography 2, 235–247.

Kyte, F.T., 1998. A meteorite from the Cretaceous/Tertiary boundary. Nature 396, 237–239.

Kyte, F.T., Brownlee, D.E., 1985. Unmelted meteoritic debris in the Late Pliocene iridium anomaly: evidence for the ocean impact of a nonchondritic asteroid. Geochimica et Cosmochimica Acta 49, 1095–1108.

Kyte, F.T., Zhou, L., Wasson, J.T., 1988. New evidence on the size and possible effects of a Late Pliocene oceanic asteroid impact. Science 241, 634–665.

Lambert, P., 1979. Fractures induced by shock in quartz and feldspar. Mineralogical Magazine 43, 527–533.

Lambert, P., 1981. Breccia dikes: geological constraints on the formation of complex craters. In: Schultz, P.B., Merrill, R.B. (Eds.), Multi-Ring Basins: Formation and Evolution. Pergamon Press, New York, pp. 59–78.

Lange, M.A., Ahrens, T.J., 1986. Shock-induced CO_2 loss from $CaCO_3$: implications for early planetary atmospheres. Earth and Planetary Science Letters 77, 419–428.

Langenhorst, F., 2002. Shock metamorphism of some minerals: basic introduction and microstructural observations. Bulletin of the Czech Geological Survey 77, 265–282.

Langenhorst, F., Kyte, F.T., Retallack, G.J., 2005. Reexamination of quartz grains from the Permian–Triassic boundary section at Graphite Peak, Antarctica (abstract). Lunar and Planetary Science 36 abs. #2358 (CD-ROM).

Lee, S.R., Horton Jr., J.W., Walker, R.J., 2006. Confirmation of a meteorite component in impact-melt rocks of the Chesapeake Bay impact structure, Virginia, USA — evidence from osmium isotopic and PGE systematics. Meteoritics and Planetary Science 41, 819–833.

Leroux, H., Doukhan, J.-C., 1993. Dynamic deformation of quartz in the landslide of Köfels, Austria. European Journal of Mineralogy 5, 893–902.

Leroux, H., Reimold, W.U., Doukhan, J.-C., 1994. A TEM investigation of shock metamorphism of quartz from the Vredefort Dome, South Africa. Tectonophysics 230, 223–239.

Leroux, H., Warme, J.E., Doukhan, J.-C., 1995. Shocked quartz in the Alamo Breccia, southern Nevada: evidence for a Devonian impact event. Geology 23, 1003–1006.

Leung, I.S., Abbott, D.H., 2003. MARID suite minerals in ejecta layer from Ewing Crater (Core PLDS-111P) in the central equatorial Pacific (abstract). EOS, Transactions of the American Geological Union 84 (46), 379; Fall Meeting, Supplement, Abstract P52A-0471.

Liu, L., Zhang, J., Green II, H.W., Jin, Z., Bozhilov, K.N., 2007. Evidence of former stishovite in metamorphosed sediments, implying subduction to >350 km. Earth and Planetary Science Letters 263, 180–191.

Lowe, D.R., Byerly, G.R., 1986. Early Archean silicate spherules of probable impact origin, South Africa and Western Australia. Geology 14, 83–86.

Lowe, D.R., Byerly, G.R., Asaro, F., Kyte, F.J., 1989a. Geological and chemical record of 3400-million-year-old terrestrial meteorite impacts. Science 245, 959–962.

Lowe, D.R., Byerly, G.R., Kyte, F.T., Shukolukov, A., Asaro, F., Krull, A., 1989b. Spherule beds 3.47–3.24 billion years old in the Barberton Greenstone Belt, South Africa: a record of large meteorite impacts and their influence on early crustal and biological evolution. Astrobiology 3, 7–48.

Luczaj, J., 1998. Argument supporting explosive igneous activity for the origin of "cryptoexplosion" structures in the midcontinent United States. Geology 26, 295–298.

Lugli, S., Reimold, W.U., Koeberl, C., 2005. Silicified cone-in-cone structures from Erfoud (Morocco): a comparison with impact-generated shatter cones. In: Koeberl, C., Henkel, H. (Eds.), Impact Tectonics. New York, Springer, pp. 81–110.

Lyons, J.B., Officer, C.B., Borella, P.E., Lahodynsky, R., 1993. Planar lamellar substructures in quartz. Earth and Planetary Science Letters 119, 431–440.

MacLeod, K.G., Whitney, D.L., Huber, B.T., Koeberl, C., 2007. Impact and extinction in remarkably complete K/T boundary sections from Demerara Rise, tropic western North Atlantic. Bulletin of the Geological Society of America 119, 101–115.

Magloughlin, J.F., Spray, J.G., 1992. Frictional melting process and products in geological materials: introduction and discussion. Tectonophysics 115, 197–206.

Maier, W.D., Andreoli, M.A.G., McDonald, I., Higgins, M.D., Boyce, A.J., Shukolyukov, A., Lugmair, G.W., Ashwal, L.D., Gräser, P., Ripley, E.M., Hart, R.J., 2006. Discovery of a 25-cm asteroid clast in the giant Morokweng impact crater, South Africa. Nature 44l, 203–206.

Manton, W.L., 1965. The orientation and age of shatter cones in the Vredefort Ring. Annals of the New York Academy of Sciences 123, 1017–1049.

Manzer, D.D., Abbott, D.H., 2003. A large K/T crater in the Gulf of Maine? (abstract). Geological Society of America, 38th Annual Meeting, Northeastern Section, Halifax, Nova Scotia, Canada, March 27–29, 2003. Abstracts with Programs, vol. 35(3), p. 299.

Margolis, S.V., Claeys, P., Kyte, F.T., 1991. Microtektites, microkrystites, and spinels from a late Pliocene asteroid impact in the Southern Ocean. Science 251, 1594–1597.

Marini, F., 2003. Natural microtektites versus industrial glass beads: an appraisal of contamination problems. Journal of Non-Crystalline Solids 323, 104–110.

Marini, F., Rauka, A., 2004. Lechatelierite-bearing microspherules from burning oil-shales (Kivioli, Estonia): contribution to the contamination problem of natural microtektites (abstract). Abstracts, International Field Symposium on Quaternary Geology and Modern Terrestrial Processes, University of Latvia, Riga, Latvia, pp. 39–40.

Mark, K., 1987. Meteorite Craters. University of Arizona Press, Tucson, AZ. 288 pp.

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J., Anderson, R.S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, T., Minckley, C., Richard, P.J.H., Scott, A.C., Shafer, D.S., Tinner, W., Umbanhowar Jr., C.E., Whitlock, C., 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences 106, 2519–2524. doi:10.1073/pnas.0808212106.

Martinez, I., Schärer, U., Guyot, F., 1993. Impact-induced phase transformations at 50–60 GPa in continental crust: and EPMA and ATEM study. Earth and Planetary Science Letters 119, 207–223.

Martini, J.E.J., 1978. Coesite and stishovite in the Vredefort Dome, South Africa. Nature 272, 715–717.

Martini, J.E.J., 1991. The nature, distribution, and genesis of the coesite and stishovite associated with the pseudotachylite of the Vredefort Dome, South Africa. Earth and Planetary Science Letters 103, 285–300.

Martos, S.H., Abbott, D.H., Elkinton, H.D., Chivas, A.R., Breger, D., 2006. Impact spherules from the craters Kanmare and Tabban in the Gulf of Carpentaria (abstract). Abstracts with Programs — Geological Society of America 38 (7), 299.

Marvin, U.B., 1986. Meteorites, the Moon, and the history of geology. Journal of Geological Education 94, 140–165.

Marvin, U.B., 1990. Impact and its revolutionary implications for geology. In: Sharpton, V.L., Ward, P.D. (Eds.), Global Catastrophes in Earth History. Special Paper, vol. 293. Geological Society of America, Boulder, CO, pp. 147–154.

Marvin, U.B., 1999. Impact from space: the implications for uniformitarian geology. In: Craig, G.Y., Hull, J.H. (Eds.), James Hutton — Present and Future. Geological Society of London Special Publication, vol. 150. Geological Society, London, pp. 89–117.

Masaitis, V.L., 1998. Popigai crater: origin and distribution of diamond-bearing impactites. Meteoritics and Planetary Science 33, 349–359.

Matsunaga, T., Kim, J.K., Hardcastle, S., Rohatgi, P.K., 2002. Crystallinity and selected properties of fly ash particles. Materials Science and Engineering A325, 333–343.

Matton, G., Jebrak, M., Lee, J.K.W., 2005. Resolving the Richat enigma: doming and hydrothermal karstification above an alkaline complex. Geology 33, 665–668.

McCall, G.J.H., 2001. Tektites in the Geological Record: Showers of Glass from the Sky. Geology Society, London. 256 pp.

McDonald, I., 2002. Clearwater East structure: a re-interpretation of the projectile type using new platinum-group element data from meteorites. Meteoritics and Planetary Science 37, 459–464.

McDonald, I., Simonson, B., 2002. PGE anomalies detected in two more 2.5–2.6 billion year-old spherule layers in the Hamersley Basin of Western Australia (abstract). Lunar and Planetary Science 33 abs. #1250 (CD-ROM).

McDonald, I., Andreoli, M.A.G., Hart, R.J., Tredoux, M., 2001. Platinum-group elements in the Morokweng impact structure, South Africa: Evidence for the impact of a large ordinary chondrite projectile at the Jurassic–Cretaceous boundary. Geochimica et Cosmochimica Acta 65, 299–309.

McHone, J.F., Nieman, R.A., Lewis, C.F., Yates, A.M., 1989. Stishovite at the Cretaceous–Tertiary boundary, Raton, New Mexico. Science 243, 1182–1184.

McLaren, A.C., Retchford, J.A., Griggs, D.T., Christie, J.M., 1967. Transmission electron microscope study of Brazil twins and dislocations experimentally produced in natural quartz. Physica Status Solidi 19, 631–644.

Melosh, H.J., 1989. Impact Cratering: A Geologic Process. Oxford University Press, New York, NY. 245 pp.

Melosh, H.J., 2005. The mechanics of pseudotachylite formation in large impact events. In: Koeberl, C., Henkel, H. (Eds.), Impact Tectonics. Springer Verlag, New York, pp. 55–80.

Melosh, H.J., Vickery, A.M., 1991. Melt droplet formation in energetic impact events. Nature 350, 494–497.

Milstein, R.L., 1988. The Calvin 28 structure: evidence for an impact origin. Canadian Journal of Earth Sciences 25, 1524–1530.

Milstein, R.L., 2001. Geology of the Calvin impact structure, Cass County, Michigan (abstract). American Association of Petroleum Geologists Bulletin 85, 1537.

Milton, D.J., 1964. Fused rock from Köfels, Tyrol. Tschermaks Mineralogische und Petrographische Mitteilungen 9, 88–94.

Milton, D.J., 1977. Shatter cones — an outstanding problem in shock mechanics. In: Roddy, D.J., Pepin, R.O., Merrill, R.P. (Eds.), Impact and Explosion Cratering: Planetary and Terrestrial Applications. Pergamon Press, New York, NY, pp. 703–714.

Milton, L.W., 1987. The Hico impact structure of north-central Texas. In: Pohl, J. (Ed.), Research in Terrestrial Impact Structures. Friedrich Vieweg & Sohn, Braunschweig/Wiesbaden, Germany, pp. 131–140.

Milton, D.J., Barlow, B.C., Brett, R., Brown, A.R., Glikson, A.Y., Manwaring, E.A., Moss, F.J., Sedmik, E.C.E., Van Son, J., Young, G.A., 1972. Gosses Bluff impact structure, Australia. Science 175, 1199–1207.

Milton, D.J., Barlow, B.C., Brown, A.R., Moss, F.J., Manwaring, E.A., Sedmik, E.C.E., Young, G.A., Van Son, J., 1996. Gosses Bluff — a latest Jurassic impact structure, central Australia. Part 2: seismic, magnetic, and gravity studies. AGSO Journal of Australian Geology and Geophysics 16, 487–527.

Mittlefehldt, D.W., Hörz, F., See, T.H., Scott, E.R.D., Mertzman, S.A., 2005. Geochemistry of target rocks, impact-melt particles, and metallic spherules from Meteor Crater, Arizona: empirical evidence on the impact process. In: Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), Large Meteorite Impacts III. Special Paper, vol. 384. Geological Society of America, Boulder, CO, pp. 367–390.

Miura, Y., 2000. Shock-wave formation of the Sea of Japan (abstract). Lunar and Planetary Science, 31. abs. #2096 (CD-ROM).

Miura, Y., 2005. Shocked data of silica-rich breccias and X-ray CT images of buried craters at Takamatsu – Kagawa district in Japan (abstract). Lunar and Planetary Science, 36. abs. #2394 (CD-ROM).

Miura, Y., Okamoto, M., Fukuchi, T., 1995. Impact materials of Takamatsu crater in Japan (abstract). Meteoritics and Planetary Science 30, 551–552.

Miura, Y., Rampino, M.R., Kedves, M., Uedo, Y., Maeda, T., 2001. Shocked quartz and diaplectic glass at Miura (Kagawa–Takamatsu) Crater, Japan; new evidence for an impact origin (abstract). Lunar and Planetary Science 32 abs. #1981 (CD-ROM).

Montanari, A., 1986. Spherules from the Cretaceous/Tertiary boundary clay at Gubbio, Italy; the problem of outcrop contamination. Geology 14, 1024–1026.

Montanari, A., Koeberl, C. (Eds.), 2000. Impact Stratigraphy: The Italian Record. Lecture Notes in Earth Sciences, vol. 93. Springer Verlag, New York, NY. 364 pp.

Morrow, J.R., 2007. Shock-metamorphic petrography and microRaman spectroscopy of quartz in upper impactite interval, ICDP drill core LB-07A, Bosumtwi impact crater, Ghana. Meteoritics and Planetary Science 42, 591–609.

Mossman, D., Eigendorf, G., Tokaryk, D., Gauthier-Lafaye, F., Guckert, K.D., Melezhik, V., Farrow, C.E.G., 2003. Testing for fullerenes in geological materials: Oklo carbonaceous substances, Karelian shungites, Sudbury Black Tuff. Geology 31, 255–258.

Müller, W.F., 1969. Elektronenmikroskopischer Nachweis amorpher Bereiche in stosswellenbeanspruchtem Quarz. Naturwissenschaften 56, 279.

Müller, W.F., Defourneaux, M., 1968. Deformationsstrukturen in Quarz als Indikator für Stosswellen: Eine experimentelle Untersuchung an Quarz–Einkristallen. Zeitschrift für Geophysik 34, 483–504.

Müller, R.D., Goncharov, A., Kritski, A., 2005. Geophysical evaluation of the enigmatic Bedout basement high, offshore northwestern Australia. Earth and Planetary Science Letters 237, 263–284.

Myers, S.A., Cygan, R.T., Assink, R.A., Boslough, M.B., 1998. ^{29}Si MAS NMR relaxation study of shocked Coconino Sandstone from Meteor Crater, Arizona. Physics and Chemistry of Minerals 25, 313–317.

Nicolaysen, L.O., Reimold, W.U. (Eds.), 1990. Cryptoexplosions and Catastrophes in the Geological Record, with a Special Focus on the Vredefort Structure. Tectonophysics, vol. 171, pp. 1–422.

Nyström, J.O., Lindström, M., Wickman, F.E., 1988. Discovery of a second Ordovician meteorite using chromite as a tracer. Nature 336, 572–574.

O'Brien, P.J., Zotov, N., Law, R., Khan, M.A., Jan, M.Q., 2001. Coesite in Himalayan eclogite and implications for models of India–Asia collision. Geology 29, 435–438.

Officer, C.B., Carter, N.L., 1991. A review of the structure, petrology, and dynamic deformation characteristics of some enigmatic terrestrial structures. Earth Science Reviews 39, 1–49.

Offield, T.W., Pohn, H.J., 1979. Geology of the Decaturville Impact Structure, Missouri. U.S. Geological Survey Professional Paper, vol. 1042. 48 pp.

O'Keefe, J.A., 1963. Tektites. University of Chicago Press, Chicago. 228 pp.

O'Keefe, J.A., 1976. Tektites and their Origin. Elsevier, New York. 254 pp.

Olson, K.R., Jones, R.L., 2001. Use of fly ash as a time marker in soil erosion and sedimentation studies. In: Scott, D.E., Mohtar, R.H., Steinhart, G.C. (Eds.), Sustaining the Global Farm. Selected Papers from the 10th International Soil Conservation Meeting Held May 24–29, 1999 at Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, pp. 1059–1061.

Orti, L., Di Martino, M., Morelli, M., Cigolini, C., Pandeli, E., Buzzigoli, A., 2008. Non-impact origin of the crater-like structures in the Gilf Kebir area (Egypt): implications for the geology of eastern Sahara. Meteoritics and Planetary Science 43, 1629–1639.

Osae, S., Misra, S., Koeberl, C., Sengupta, D., Ghosh, S., 2005. Target rocks, impact glasses, and melt rocks from the Lonar impact crater, India: petrography and geochemistry. Meteoritics and Planetary Science 40, 1473–1492.

Osinski, G.R., 2003. Impact glasses in fallout suevites from the Ries impact structure, Germany: an analytical SEM study. Meteoritics and Planetary Science 38, 1641–1667.
Osinski, G.R., 2004. Impact melts from the Ries structure, Germany: an origin as impact melt flows? Earth and Planetary Science Letters 226, 529–543.
Osinski, G.R., Spray, J.G., 2001. Impact-generated carbonate melts: evidence from the Haughton structure, Canada. Earth and Planetary Science Letters 194, 17–29.
Osinski, G.R., Spray, J.G., 2003. Evidence for the shock melting of sulfates from the Haughton impact structure, Canada (abstract). Meteoritics and Planetary Science 38, A45.
Osinski, G.R., Grieve, R.A.F., Spray, J.G., 2004. The nature of the groundmass of surficial suevite from the Ries impact structure. Germany, and constraints on its origin. Meteoritics and Planetary Science 39, 1655–1683.
Osinski, G.R., Schwarcz, H.P., Smith, J.R., Kleindienst, M.R., Haldemann, A.F.C., Churcher, C.S., 2007. Evidence for a 200–100 ka meteorite impact in the Western Desert of Egypt. Earth and Planetary Science Letters 253, 378–388.
Osinski, G.R., Spray, J.G., Grieve, R.A.F., 2008. Impact melting in sedimentary targets: an assessment. In: Evans, K.R., HortonJr. Jr., J.W., KingJr. Jr., D.T., Morrow, J.R. (Eds.), The Sedimentary Record of Meteorite Impacts. Special Paper, vol. 437. Geological Society of America, Boulder, CO, pp. 1–18.
Paillou, P., Rosenqvist, A., Malezieux, J.-M., Reynard, B., Farr, T., Heggy, E., 2003. Discovery of a double impact crater in Libya: the astrobleme of Arkenu. Comptes Rendus Geosciences, Academy of Sciences 335, 1059–1069.
Paillou, P., El Barkooky, A., Barakat, A., Malezieux, J.-M., Reynard, B., Dejax, J., Heggy, E., 2004. Discovery of the largest impact crater field on Earth in the Gilf Kebir region, Egypt. Comptes Rendus Geosciences, Academy of Sciences 336, 1491–1500.
Paillou, P., Reynard, B., Malezieux, J.M., Dejax, J., Heggy, E., Rochette, P., Reimold, W.U., Michel, P., Baratoux, D., Razin, P., Colin, J.P., 2006. An extended field of crater-shaped structures in the Gilf Kebir region, Egypt: observations and hypotheses about their origin. Journal of African Earth Sciences 46, 281–299.
Palme, H., 1982. Identification of projectiles of large terrestrial impact craters and some implications for the interpretation of Ir-rich Cretaceous/Tertiary boundary layers. In: Silver, L.T., Schultz, P.H. (Eds.), Geological Implications of Impacts of Large Asteroids and Comets on the Earth. Special Paper, vol. 190. Geological Society of America, Boulder, CO, pp. 223–233.
Palme, H., Grieve, R.A.F., Wolf, R., 1981. Identification of the projectile at the Brent crater, and further considerations of projectile types at terrestrial craters. Geochimica et Cosmochimica Acta 45, 2417–2424.
Planetary Materials. In: Papike, J.J. (Ed.), Reviews in Mineralogy, vol. 36. Mineralogical Society of America, Washington, D.C. chapters individually paginated.
Paquay, F., Goderis, S., Ravizza, G., Claeys, P., 2009. No evidence of extraterrestrial geochemical components at the Bølling–Allerød/Younger Dryas transition. Geological Society of America, Abstracts with Programs, Paper No. 234-3.
Parthasarathy, G., Srinivasan, R., Vairamani, M., Ravikumar, K., Kunwar, A.C., 1998. Occurrence of natural fullerenes in low grade metamorphosed Proterozoic shungite from Karelia, Russia. Geochimica et Cosmochimica Acta 62, 3541–3544.
PASSC, 2009. The Earth Impact Database. Planetary and Space Science Center, University of New Brunswick, Fredericton, Canada. WWW Page, http://www.unb.ca/passc.
Passchier, C.W., Trouw, R.A.J., 2005. Microtectonics. Springer Verlag, New York. 366 pp.
Petaev, M.I., Jacobsen, S.B., Becker, L., 2006. Search for extraterrestrial and impact materials in the P–T boundary samples from Graphite Peak, Antarctica (abstract). Lunar and Planetary Science 37 abs. #2309 (CD-ROM).
Petit, C.W., 2003. A blast from heaven? U.S. News and World Report, December 8, 2003, pp. 76–77.
Pettijohn, F.J., 1957. Sedimentary Rocks. Harper and Brothers, New York, NY. 718 pp.
Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), 2001. Accretion of Extraterrestrial Matter throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, NY. 466 pp.
Philpotts, A.R., 1964. Origin of pseudotachylite. American Journal of Science 262, 1008–1035.
Philpotts, A.R., 1990. Principles of Igneous and Metamorphic Petrology. Prentice-Hall, Englewood Cliffs, N.J. 498 pp.
Pierazzo, E., Herrick, R., 2004. Proceedings of the workshop, Impact cratering: bridging the gap between modeling and observations. Meteoritics and Planetary Science 39, 167–346.
Pierazzo, E., Vickery, A.M., Melosh, H.J., 1997. A reevaluation of impact melt production. Icarus 127, 408–423.
Pilkington, M., Grieve, R.A.F., 1992. The geophysical signature of terrestrial impact craters. Reviews of Geophysics 30, 161–181.
Pinter, N., Ishman, S.E., 2008. Impacts, mega-tsunami, and other extraordinary claims. GSA Today 18 (1), 37–38.
Piperno, D., 2006. Phytoliths: A Comprehensive Guide for Archeologists and Paleoecologists. Altamira Press, New York, NY. 237 pp.
Plado, J., Pesonen, L.J. (Eds.), 2002. Impacts in Precambrian Shields. Impact Studies vol. 1, Springer, Heidelberg. 336 pp.
Poag, C.W., Powars, D., Poppe, L.J., Mixon, R.B., 1994. Meteoroid mayhem on Ole Virginny: source of the North American tektite strewn field. Geology 22, 691–694.
Poag, C.W., Koeberl, C., Reimold, W.U., 2004. The Chesapeake Bay Crater: geology and geophysics of a Late Eocene submarine impact structure. Impact Studies, vol. 4. Springer, Heidelberg. 522 pp.
Poelchau, M.H., Kenkmann, T., 2009. Feather textures — a possible shock feature in quartz diagnostic of low shock pressures. Meteoritics and Planetary Science 44, A170.
Poreda, R.J., Becker, L., 2003. Fullerenes and interplanetary dust at the Permian–Triassic boundary. Astrobiology 3, 75–90.
Powell, J.L., 1998. Night Comes to the Cretaceous. W.H. Freeman Company, New York, NY. 250 pp.
Pufahl, P.K., Hiatt, E.E., Stanley, C.R., Morrow, J.R., Nelson, G.J., Edwards, C.T., 2007. Physical and chemical evidence of the 1850 Ma Sudbury impact event in the Baraga Group, Michigan. Geology 35, 827–830.
Racki, G., Koeberl, C., 2004. Comment on "Impact Ejecta Layer from the Mid-Devonian: Possible Connection to Global Mass Extinctions". Science 303, 471b.
Rajmon, D., 2006. Suspected Earth impact sites (abstract). Lunar and Planetary Science 37 abs. #2372 (CD-ROM).
Rajmon, D., 2009. Impact Database, v. 2009.1. WWW Page, http://impacts.rajmon.cz.
Rampino, M.R., Volk, T., 1996. Multiple impact event in the Paleozoic: collision with a string of comets or asteroids? Geophysical Research Letters 23, 49–52.
Rasmussen, B., Koeberl, C., 2004. Iridium anomalies and shocked quartz in a Late Archean spherule layer from the Pilbara craton: new evidence for a major asteroid impact at 2.63 Ga. Geology 32, 1029–1032.
Raup, D.M., 1986. The Nemesis Affair: a Story of the Death of the Dinosaurs and the Ways of Science. W.W. Norton & Company, New York, NY. 220 pp.
Raup, D.M., 1991. Extinction: Bad Genes or Bad Luck? W.W. Norton & Company, New York, NY. 210 pp.
Read, W.F., 1983. Shatter cones at Glover Bluff, Wisconsin. Meteoritics 18, 241–243.
Read, W.F., 1986. Possible impact spherules from near the base of the middle Ordovician in Northern Illinois. Meteoritics 21, 251–262.
Reimold, W.U., 1991. The geochemistry of pseudotachylites from the Vredefort Dome, South Africa. Neues Jahrbuch Mineralogie Abhandlungen 162, 151–184.
Reimold, W.U., 1995. Pseudotachylite in impact structures — generation by friction melting and shock brecciation? A review and discussion. Earth Science Reviews 39, 247–265.
Reimold, W.U., 1998. Exogenic and endogenic breccias: a discussion of major problematics. Earth Science Reviews 43, 45–47.
Reimold, W.U., 2003. Impact cratering comes of age. Science 300, 1889–1890.
Reimold, W.U., 2007. The impact cratering bandwagon (Some problems with the terrestrial impact cratering record). Meteoritics and Planetary Science 42, 1467–1472.
Reimold, W.U., Colliston, W.P., 1994. Pseudotachylites of the Vredefort Dome and the surrounding Witwatersrand Basin, South Africa. In: Dressler, B.O., Grieve, R.A.F., Sharpton, V.L. (Eds.), Large Meteorite Impacts and Planetary Evolution. Special Paper, vol. 293. Geological Society of America, Boulder, CO, pp. 177–196.
Reimold, W.U., Gibson, R.L., 2005. "Pseudotachylites" in large impact structures. In: Koeberl, C., Henkel, H. (Eds.), Impact Tectonics. Impact Studies, vol. 7. Springer, Heidelberg, pp. 1–53.
Reimold, W.U., Koeberl, C., 2008. Catastrophes, extinctions, and evolution: 50 years of impact cratering studies. Golden Jubilee Memoir of the Geological Society of India, vol. 66, pp. 69–110.
Reimold, W.U., Minnitt, R.C.A., 1996. Impact-induced shatter cones or percussion marks on quartzites of the Witwatersrand and Transvaal Supergroups? South African Journal of Geology 99, 299–308.
Reimold, W.U., Koeberl, C., Johnson, S., McDonald, I., 2000. Early Archean spherule beds in the Barberton Mountain Land, South Africa: Impact or terrestrial origin. In: Gilmour, I., Koeberl, C. (Eds.), Impacts and the Early Earth, Lecture Notes in Earth Science, vol. 91. Springer, Heidelberg, pp. 117–180.
Reimold, W.U., Koeberl, C., Wright, C., McDonald, I., 2001. Comment on "Origin of a late Eocene to pre-Miocene buried crater and breccia lens at Fohn-1, North Bonaparte Basin, Timor Sea: A probable extraterrestrial connection" by J.D. Gorter and A.Y. Glikson. Meteoritics and Planetary Science 36, 747–752 Authors' Reply, pp. 749–751.
Reimold, W.U., Trepmann, C., Simonson, B., 2006. Discussion: Impact origin of the Ramgarh structure, Rajasthan: Some new evidences by M.S. Sisodia et al. Journal of the Geological Society of India 68, 561–563.
Renne, P., Melosh, H.J., Farley, K.A., Reimold, W.U., Koeberl, C., Rampino, M.R., Kelly, S.P., Ivanov, B.A., 2004. Is Bedout an impact crater? Take 2. Science 306, 610–612.
Retallack, G.J., Seyedolali, A., Krull, E.S., Holser, W.T., Ambers, C.P., Kyte, F.T., 1998. Search for evidence of impact at the Permian–Triassic boundary in Antarctica and Australia. Geology 26, 979–982.
Robertson, P.B., 1975. Zones of shock metamorphism at the Charlevoix impact structure, Quebec. Bulletin of the Geological Society of America 86, 1630–1638.
Robertson, P.B., Butler, M.D., 1982. The Kilmichael structure, Mississippi: Evidence for a meteorite impact origin. Journal of Geology 90, 589–601.
Robertson, P.B., Grieve, R.A.F., 1977. Shock attenuation at terrestrial impact structures. In: Roddy, D.J., Pepin, R.O., Merrill, R.P. (Eds.), Impact and Explosion Cratering: Planetary and Terrestrial Applications. Pergamon, New York, NY, pp. 687–702.
Robertson, P.B., Dence, M.R., Vos, M.A., 1968. Deformation in rock-forming minerals from Canadian craters. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 433–452.
Roddy, D.J., 1968. The Flynn Creek crater, Tennessee. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 291–322.
Roddy, D.J., Davis, L.K., 1977. Shatter cones formed in large-scale experimental explosion craters. In: Roddy, D.J., Pepin, R.O., Merrill, R.B. (Eds.), Impact and Explosion Cratering: Planetary and Terrestrial Implications. Pergamon Press, New York, NY, pp. 715–750.
Roddy, D.J., Pepin, R.O., Merrill, R.B. (Eds.), 1977. Impact and Explosion Cratering: Planetary and Terrestrial Implications. Pergamon Press, New York. 1301 pp.
Roedder, E., 1984. Fluid Inclusions. Mineralogical Society of America Reviews in Mineralogy 12 644 pp.
Rogers, A.F., 1946. Sand fulgurites with enclosed lechatelierite from Riverside County, California. Journal of Geology 54, 117–122.
Rose, N.L., 1996. Inorganic fly-ash spheres as pollution tracers. Environmental Pollution 91, 245–252.

Rubin, A.E., 1992. A shock-metamorphic model for silicate darkening and compositionally variable plagioclase in CK and ordinary chondrites. Geochimica et Cosmochimica Acta 56, 1705–1714.

Rubin, A.E., 2003. Post-shock annealing and post-annealing shock in equilibrated ordinary chondrites: Implications for the thermal and shock histories of chondritic asteroids. Geochimica et Cosmochimica Acta 64, 847–858.

Rubin, A.E., Scott, E.R.D., Keil, K., 1997. Shock metamorphism of enstatite chondrites. Geochimica et Cosmochimica Acta 61, 847–858.

Ryder, G., Fastovsky, D., Gartner, S. (Eds.), 1996. The Cretaceous–Tertiary Event and Other Catastrophes in Earth History. Special Paper, vol. 307. Geological Society of America, Boulder, CO. 569 pp.

Salameh, E., Khoury, H., Schneider, W., 2006. Jebel Waqf as Suwwan, Jordan: a possible impact crater — a first approach. Zeitschrift der Deutschen Geologischen Gesellschaft 157, 319–325.

Salameh, E., Khoury, H., Reimold, W.U., Schneider, W., 2008. The first large meteorite impact structure discovered in the Middle East: Jebel Waqf as Suwwan, Jordan. Meteoritics and Planetary Science 43, 1681–1690.

Sawatsky, H.B., 1977. Buried impact craters in the Williston Basin and adjacent area. In: Roddy, D.J., Pepin, R.O., Merill, R.B. (Eds.), Impact and Explosion Cratering. Pergamon Press, New York, pp. 461–480.

Schaal, R.B., Hörz, F., 1977. Shock metamorphism of lunar and terrestrial basalts. Proceedings of the 8th Lunar Science Conference. Pergamon Press, New York, pp. 1697–1729.

Schärer, U., 1998. Dating of impact events. In: Best, D., Froschlé, C. (Eds.), Lecture Notes in Physics, vol. 505. Springer-Verlag, Berlin, pp. 157–183.

Schedl, A., 2006. Applications of twin analysis to studying meteorite impact structures. Earth and Planetary Science Letters 244, 530–540.

Scherler, D., Kenkmann, T., Jahn, A., 2006. Structural record of an oblique impact. Earth and Planetary Science Letters 248, 28–38.

Schmitt, R.T., 2000. Shock experiments with the H6 chondrite Kernouvé: Pressure calibration of microscopic shock effects. Meteoritics and Planetary Science 35, 545–560.

Schmitz, B., Tassinari, M., 2001. Fossil meteorites. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, pp. 319–331.

Schmitz, B., Ellwood, B.B., Peucker-Ehrenbrink, B., El Hassani, A., Bultynck, P., 2006. Platinum group elements and $^{187}Os/^{188}Os$ in a purported impact ejecta layer near Eifelian–Givetian stage boundary, Middle Devonian. Earth and Planetary Science Letters 249, 162–172.

Schnabel, C., Pierazzo, E., Xue, S., Herzog, G.F., Masarik, J., Cresswell, R.G., di Tada, M.L., Liu, K., Fifield, L.K., 1999. Shock melting of the Canyon Diablo impactor: Constraints from nickel-59 contents and numerical modeling. Science 285, 85–88.

Schreyer, W., 1983. Metamorphism and fluid inclusions in the basement of the Vredefort Dome, South Africa: guidelines to the origin of the structure. Journal of Petrology 24, 26–47.

Schüller, A., Ottemann, J., 1963. Vergleichende Geochemie und Petrographie meteoritischer and vulkanischer Gläser. Neues Jahrbuch Mineralogie Abhandlungen 100, 1–26.

Schultz, P.H., Lianza, R.E., 1992. Recent grazing impacts on the Earth recorded in the Rio Cuarto crater field, Argentina. Nature 355, 234–237.

Schultz, P.H., Zarate, M., Hames, W., Camilión, M., King, J., 1998. A 3.3-Ma impact in Argentina and possible consequences. Science 282, 2061–2063.

Schultz, P.H., Zárate, M., Hames, B., Koeberl, C., Bunch, T., Storzer, D., Renne, P., Wittke, J., 2004. The Quaternary impact record from the pampas, Argentina. Earth and Planetary Science Letters 219, 221–238.

Schultz, P.H., Zárate, M., Hames, W.E., Harris, R.S., Bunch, T.E., Koeberl, C., Renne, P., Wittke, J., 2006. The record of Miocene impacts in the Argentine pampas. Meteoritics and Planetary Science 41, 749–771.

Scott, W.H., Hansen, E., Twiss, R.J., 1965. Stress analysis of quartz deformation lamellae in a minor fold. American Journal of Science 263, 729–746.

See, T.H., Wagstaff, J., Yang, V., Hörz, F., McKay, G.A., 1998. Compositional variation and mixing of impact melts on microscopic scales. Meteoritics and Planetary Science 33, 937–948.

Seeger, R., 1968. Origin of the Jeptha Knob structure, Kentucky. American Journal of Science 266, 630–660.

Seeger, R., 1972. Geophysical investigation of the Versailles, Kentucky, Astrobleme. Bulletin of the Geological Society of America 83, 3515–3518.

SEIS, 2006. Suspect Earth Impact Structures, D. Rajmon. Available at: WWW Page, http://web.eps.utk.edu/ifsg_files/SEIS/SEIS_introduction5.pdf.

Self-Trail, J.M., 2003. Shock-wave-induced fracturing of calcareous nannofossils from the Chesapeake Bay impact crater. Geology 31, 697–700.

Shand, S.J., 1916. The pseudotachylyte of Parijs (Orange Free State) and its relation to "trap-shotten gneiss" and "flinty crush-rock". Quarterly Journal Geological Society of London 72, 198–221.

Sharp, T.G., DeCarli, P.S., 2006. Shock effects in meteorites. In: Lauretta, D.S., McSweenJr. Jr., H.Y. (Eds.), Meteorites and the early solar system II. University of Arizona Press, Tucson, AZ, pp. 653–677.

Sharpton, V.L., Schuraytz, B.C., 1989. On reported occurrences of shock-deformed clasts in the volcanic ejecta from Toba caldera, Sumatra. Geology 17, 1040–1043.

Sharpton, V.L., Ward, P.D. (Eds.), 1990. Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality. Special Paper, vol. 247. Geological Society of America, Boulder, CO. 631 pp.

Sharpton, V.L., Dressler, B.O., Herrick, R.R., Schneiders, B., Scott, J., 1996. New constraints on the Slate Islands impact structure, Ontario, Canada. Geology 24, 851–854.

Shoemaker, E.M., 1963. Impact mechanics at Meteor Crater, Arizona. In: Middlehurst, B.M., Kuiper, G.P. (Eds.), The Moon, Meteorites, and Comets. University of Chicago Press, Chicago, IL, pp. 301–336.

Shoemaker, E.M., Chao, E.C.T., 1961. New evidence for the impact origin of the Ries Basin, Bavaria, Germany. Journal of Geophysical Research 66, 3371–3378.

Short, N.M., 1966. Effects of shock pressures from a nuclear explosion on mechanical and optical properties of granodiorite. Journal of Geophysical Research 71, 1195–1215.

Short, N.M., 1968b. Nuclear-explosion-induced microdeformation of rocks: an aid to the recognition of meteorite impact structures. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 185–210.

Short, N.M., 1968a. Experimental microdeformation of rock materials by shock pressures from laboratory-scale impacts and explosions. In: French, B.M., Short, N.M. (Eds.), Shock Metamorphism of Natural Materials. Mono Book Corp, Baltimore, MD, pp. 219–241.

Shukla, A.D., Bhandari, N., Shukla, P.D., 2003. Shocked quartz at the Permian–Triassic boundary (P/T) in Spiti Valley, India (abstract). Conference on Large Meteorite Impacts III, Nördlingen, Germany, August 5–6, 2003. Lunar and Planetary Institute, Houston. abs. #4059 (CD-ROM).

Shukolyukov, A., Lugmair, G.W., 1998. Isotopic evidence for the Cretaceous–Tertiary impactor and its type. Science 282, 927–929.

Shukolyukov, A., Lugmair, G.W., Koeberl, C., Reimold, W.U., 1999. Chromium in the Morokweng impact melt: evidence for extraterrestrial components and type of impactor (abstract). Meteoritics and Planetary Science 34, A107–A108.

Shukolyukov, A., Kyte, F.T., Lugmair, G.W., Lowe, D.R., Byerly, G.W., 2000. The oldest impact deposits on Earth — First confirmation of an extraterrestrial component. Impacts and the Early Earth. . In: Gilmour, I., Koeberl, C. (Eds.), Lecture Notes in Earth Science, vol. 91. Springer Verlag, Heidelberg, pp. 99–115.

Shukolyukov, A., Lugmair, G., Becker, L., Macisaac, C., Poreda, R., 2004. Extraterrestrial chromium in the Permian–Triassic boundary at Graphite Peak, Antarctica (abstract). Lunar and Planetary Science 35 abs. #1875 (CD-ROM).

Sibson, R.H., 1975. Generation of pseudotachylyte by ancient seismic faulting. Geophysical Journal of the Royal Astronomical Society 43, 775–794.

Silver, L.T., Schultz, P.H. (Eds.), 1982. Geological Implications of Impacts of Large Asteroids and Comets on the Earth. Geological Society of America, Boulder, CO, Special Paper 190, 528 pp.

Simkin, T., Siebert, L., 1994. Volcanoes of the World. Geoscience Press, Tucson, Arizona. 349 pp.

Simonson, B.M., 1992. Geological evidence for a strewn field of impact spherules in the early Precambrian Hamersley Basin of Western Australia. Bulletin of the Geological Society of America 104, 8219–8839.

Simonson, B.M., 2003. Petrographic criteria for recognizing certain types of impact spherules in well-preserved Precambrian successions. Astrobiology 3, 49–65.

Simonson, B.M., Davies, D., 1996. PGEs and quartz grains in a resedimented Late Archean impact horizon in the Hamersley Group of Western Australia (abstract). Lunar and Planetary Science 27, 1203–1204.

Simonson, B.M., Glass, B.P., 2004. Spherule layers — records of ancient impacts. Annual Reviews of Earth and Planetary Science 32, 329–361.

Simonson, B.M., Beukes, N.J., Hassler, S., 1997. Discovery of a Neoarchean impact spherule horizon in the Transvaal Supergroup of South Africa and possible correlations to the Hamersley Basin of Western Australia (abstract). Lunar and Planetary Science 28, 1323–1324.

Simonson, B.M., Davies, D., Wallace, M., Reeves, S., Hasler, S.W., 1998. Iridium anomaly but no shocked quartz from Late Archean microkrystite layer: Oceanic impact ejecta? Geology 26, 195–198.

Simonson, B.M., Koeberl, C., McDonald, I., Reimold, W.U., 2000. Geochemical evidence for an impact origin for a Late Archean spherule layer, Transvaal Supergroup, South Africa. Geology 28, 1103–1106.

Simonson, B.M., Byerly, G.R., Lowe, D.R., 2004. The early Precambrian record of large extraterrestrial impacts. In: Eriksson, P., Alterman, W., Catuneanu, O. (Eds.), The Precambrian Earth: Tempos and Events. Elsevier Publishing Corp, New York, NY, pp. 27–45.

Sisodia, M.S., Lashkari, G., Bhandari, N., 2006. Impact origin of the Ramgarh structure, Rajasthan: Some new evidences. Journal of the Geological Society of India 67, 423–431.

Skála, R., Jakeš, P., 1999. Shock-induced effects in natural calcite-rich targets revealed by X-ray powder diffraction. In: Dressler, B.O., Sharpton, V.L. (Eds.), Large Meteorite Impacts and Planetary Evolution II. . Special Paper, vol. 339. Geological Society of America, Boulder, CO, pp. 205–214.

Smit, J., 1999. The global stratigraphy of the Cretaceous–Tertiary boundary impact ejecta. Annual Reviews of Earth and Planetary Science 27, 75–113.

Smith, D.C., 1984. Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. Nature 310, 641–644.

Smith, K., 2004. The North Sea Silverpit Crater: impact structure or pull-apart basin? Journal of the Geological Society of London 161, 593–602.

Snoke, A.W., Tullis, J., Todd, V.R. (Eds.), 1998. Fault-Related Rocks: A Photographic Atlas. Princeton University Press, Princeton, N.J.. 617 pp.

Snyder, F.G., Gerdemann, P.E., 1965. Explosive igneous activity along an Illinois–Missouri–Kansas axis. American Journal of Science 263, 465–493.

Sokol, E.V., Kalugin, V.M., Nigmatulina, E.N., Volkkova, N.I., Frenkel, A.E., Maksimova, N. V., 2002. Ferrospheres from fly ashes of Chelyabinsk coals: chemical composition, morphology, and formation conditions. Fuel 81, 867–876.

Spencer, L.J., 1933. Meteoritic iron and silica-glass from the meteorite craters of Henbury (central Australia) and Wabar (Arabia). Mineralogical Magazine 23, 387–404.

Spevack, S.C., Morrow, J.R., Spevack, B.Z., 2007. 3-D seismic and well log analyses of the Victoria Island Structure, a potential buried impact crater, San Joaquin County, California (abstract). Lunar and Planetary Science 38 abs. #1033 (CD-ROM).

Spray, J.S., 1995. Pseudotachylite controversy: Fact or friction? Geology 23, 1119–1122.

Spray, J.G., 1997. Superfaults. Geology 25, 579–582.

Spray, J.G., 1998. Localized shock- and friction-induced melting in response to hypervelocity impact. In: Grady, M.M., Hutchison, R., McCall, G.J.H., Rothery, D.

(Eds.), Meteorites: Flux with Time and Impact Effects. Special Publication, vol. 140. Geological Society, London, pp. 195–204.
Spray, J.G., Thompson, L.M., 1995. Friction melt distribution in a multi-ring impact basin. Nature 373, 130–132.
Spry, A., 1969. Metamorphic Textures. Pergamon Press, New York, NY. 350 pp.
Stähle, V., 1973. Cordierite glass formed by shock in a cordierite-garnet–gneiss from the Ries crater, Germany. Earth and Planetary Science Letters 18, 385–390.
Stähle, V., Altherr, R., Koch, M., Nasdala, L., 2008. Shock-induced growth and metastability of stishovite and coesite in lithic clasts from suevite of the Ries impact crater (Germany). Contributions to Mineralogy and Petrology 155, 457–472.
Stevenson, J., Mancuso, J., Frizado, J., Truskoski, P., Kneller, W., 1990. Solid pyrobitumen in veins, Panel Mine, Elliot Lake District, Ontario. Canadian Mineralogist 28, 161–169.
Stewart, S.A., Allen, P.J., 2002. A 20-km-diameter multi-ringed impact structure in the North Sea. Nature 418, 520–523.
Stewart, S.A., Allen, P.J., 2005. 3D seismic reflection mapping of the Silverpit multi-ringed crater, North Sea. Bulletin of the Geological Society of America 117, 354–368.
Stöffler, D., 1966. Zones of impact metamorphism in the crystalline rocks of the Nördlinger Ries Crater. Contributions to Mineralogy and Petrology 12, 15–24.
Stöffler, D., 1971. Progressive metamorphism and classification of shocked and brecciated crystalline rocks at impact craters. Journal of Geophysical Research 76, 5541–5551.
Stöffler, D., 1972. Deformation and transformation of rock-forming minerals by natural and experimental shock processes: I. Behavior of minerals under shock compression. Fortschritte der Mineralogie 49, 50–113.
Stöffler, D., 1974. Deformation and transformation of rock-forming minerals by natural and experimental shock processes: II. Physical properties of shocked minerals. Fortschritte der Mineralogie 51, 256–289.
Stöffler, D., 1984. Glasses formed by hypervelocity impact. Journal of Non-Crystalline Solids 67, 465–502.
Stöffler, D., Grieve, R.A.F., 2007. Impactites, Chapter 2.11, In: D. Fettes, J. Desmons (Editors.), Metamorphic Rocks: A Classification and Glossary of Terms, Recommendations of the International Union of Geological Sciences. Cambridge University Press, Cambridge, UK, pp.82–92, 111–125, and 126–242.
Stöffler, D., Langenhorst, F., 1994. Shock metamorphism of quartz in nature and experiment: I. Basic observation and theory. Meteoritics 29, 155–181.
Stöffler, D., Keil, K., Scott, E.R.D., 1991. Shock metamorphism of ordinary chondrites. Geochimica et Cosmochimica Acta 55, 3845–3867.
Stöffler, D., Artemieva, N.A., Ivanov, B.A., Hecht, L., Kenkmann, T., Schmitt, R.T., Tagle, R.A., Wittman, A., 2004. Origin and emplacement of the impact formations at Chicxulub, Mexico, as revealed by the ICDP deep drilling at Yaxcopoil-1 and by numerical modeling. Meteoritics and Planetary Science 39, 1035–1067.
Stone, D.S., 1999. Cloud Creek: A possible impact structure on the Casper Arch, Wyoming. Mountain Geologist 26, 211–234.
Storzer, D., 1992. Microtektite hunting and mineral wool shot (abstract). Lunar and Planetary Science 23, 1373–1374.
Sulovsky, P., 2002. Mineralogy and chemistry of conventional and fluidized bed coal ashes. Bulletin of the Czech Geological Survey 77, 1–11.
Surenian, R., 1988. Scanning electron microscope study of shock features in pumice and gneiss from Koefels (Tyrol, Austria). Geologische and Paläontologische Mitteilungen 15, 135–143.
Surovell, T.A., Holliday, V.T., Gingerich, J.A., Ketron, C., Haynes C.V. Jr., Hilman, I., Wagner, D.P., Johnson, E., Claeys, P., 2009. An independent evaluation of the Younger Dryas extraterrestrial impact hypothesis. Proceedings of the National Academy of Sciences U S A. 106, 18155–18158.
Switzer, G., Melson, W.G., 1972. Origin and composition of rock fulgurite glass. Smithsonian Contributions to the Earth Sciences 9, 47–51.
Symes, S.J.K., Sears, D.W.G., Akridge, D.G., Huang, S., Benoit, P.H., 1998. The crystalline lunar spherules: Their formation and implications for the origin of meteoritic chondrules. Meteoritics and Planetary Science 33, 13–29.
Tagle, R., Hecht, L., 2006. Geochemical identification of projectiles in impact rocks. Meteoritics and Planetary Science 41, 1721–1735.
Talwani, P., Wildermuth, E., Parkinson, C.D., 2003. An impact crater in northeast South Carolina inferred from potential field data. Geophysical Research Letters 30, 19-1–19-4. doi:10.1029/2003GL017051.
Taylor, T.N., 1981. Paleobotany: An Introduction to Fossil Plant Biology. Mc-Graw-Hill Book Co., New York, NY. 589 pp.
Taylor, R., Abdul-Sada, A.K., 2000. There are no fullerenes in the K–T boundary layer. Fullerene Science and Technology 8, 47–54.
Taylor, S., Lever, J.H., 2001. Seeking unbiased collections of modern and ancient meteorites. In: Peucker-Ehrenbrink, B., Schmitz, B. (Eds.), Accretion of Extraterrestrial Matter throughout Earth's History. Kluwer Academic/Plenum Publishers, New York, NY, pp. 205–219.
Taylor, S., Lever, J.H., Harvey, R.P., 1998. Accretion rate of cosmic spherules measured at the South Pole. Nature 393, 899–903.
Therriault, A., Gratz, A., 1995. Planar deformation features in quartz grains from mixed breccia of the Avak structure, Alaska (abstract). Lunar and Planetary Science 26, 1403–1404.
Therriault, A., Lindström, M., 1995. Planar deformation features in quartz grains from the resurge deposit of the Lockne structure, Sweden. Meteoritics 30, 700–703.
Thompson, L.M., Spray, J.G., 1994. Pseudotachylitic rock distribution and genesis within the Sudbury impact structure. In: Dressler, B.O., Grieve, RA.F., Sharpton, V.L. (Eds.), Large Meteorite Impacts and Planetary Evolution. Special Paper, vol. 293. Geological Society of America, Boulder, CO, pp. 275–287.
Thompson, L.M., Spray, J.G., 1996. Pseudotachylyte petrogenesis: constraints from the Sudbury impact structure. Contributions to Mineralogy and Petrology 125, 359–374.
Thomson, K., 2006. Overburden deformation associated with halokinesis in the southern North Sea: implications for the origin of the Silverpit Crater. Visual Geoscience 9, 39–47.
Trefil, J.S., Raup, D.M., 1990. Crater taphonomy and bombardment rates in the Phanerozoic. Journal of Geology 98, 385–398.
Treiman, A.H., Treado, P., 1998. Martian maskelynite? Raman spectra of plagioclase-composition glasses from ALH 84001, EETA 79001, and ALHA77005 (abstract). Lunar and Planetary Science 29 abs. #1196 (CD-ROM).
Trepmann, C.A., 2008. Shock effects in quartz: compression versus shear deformation — an example from the Rochechouart impact structure, France. Earth and Planetary Science Letters 267, 322–332.
Trepmann, C.A., Spray, J.G., 2005. Planar microstructures and Dauphine twins in shocked quartz from the Charlevoix impact structure, Canada. In: Kenkmann, T., Hörz, F., Deutsch, A. (Eds.), Large Meteorite Impacts III. Special Paper, vol. 384. Geological Society of America, Boulder, CO, pp. 315–328.
Trepmann, C.A., Spray, J.G., 2006. Shock-induced crystal-plastic deformation and post-shock annealing of quartz from crystalline target rocks of the Charlevoix Structure, Canada. European Journal of Mineralogy 18, 161–173.
Tschermak, G., 1872. Die Meteoriten von Shergotty und Gopalpur. Sitzungsberichte der Akademie der Wissenschaften in Wien. Mathematisch-Naturwissenschaftliche Klasse. Abteilung I 66, 122–146.
Tullis, J., Christie, J.M., Griggs, D.T., 1973. Microstructures and preferred orientation of experimentally deformed quartzites. Bulletin of the Geological Society of America 84, 297–314.
Tuttle, O.F., 1949. Structural petrology of planes of liquid inclusions. Journal of Geology 57, 331–356.
Turtle, E.P., Pierazzo, E., O'Brien, D.P., 2003. Numerical modeling of impact heating and cooling of the Vredefort impact structure. Meteoritics and Planetary Science 38, 293–303.
Tyburczy, J.A., Ahrens, T.J., 1986. Dynamic compression and volatile release of carbonates. Journal of Geophysical Research 91, 4730–4744.
Veneva, L., Hoffmann, V., Jordanova, D., Jordanova, N., Fehr, T., 2004. Rock magnetic, mineralogical, and microstructural characterization of fly ashes from Bulgarian power plants and the nearby anthropogenic soils. Physics and Chemistry of the Earth 29, 1011–1023.
Vermeesch, P.M., Morgan, J.V., 2004. Chicxulub central crater structure: Initial results from physical properties measurements and combined velocity and gravity modeling. Meteoritics and Planetary Science 39, 1019–1034.
Vernon, R.H., 1975. Metamorphic Processes: Reactions and Microstructure Development. John Wiley and Sons (Halstead Press), New York, NY. 243 pp.
Vernon, R.H., 2004. A Practical Guide to Rock Microstructure. Cambridge University Press, New York, NY. 594 pp.
Vernooij, M.G.C., Langenhorst, F., 2005. Experimental reproduction of tectonic deformation lamellae in quartz and comparison to shock-induced planar deformation features. Meteoritics and Planetary Science 40, 1353–1361.
Verschuur, G.L., 1996. Impact! The Threat of Comets and Asteroids. Oxford University Press, New York, NY. 237 pp.
von der Borsch, C.C., 1971. Glassy objects in Tertiary deep-sea clays cored by the Deep Sea Drilling Project. Marine Geology 10, 5–14.
von Frese, R.R.B., Potts, L.V., Wells, S.B., Leftwich, T.E., Kim, H.R., Kim, J.W., Golynsky, A.V., Hernandez, O., Gaya-Piqué, 2009. GRACE gravity evidence for an impact crater in Wilkes Land, Australia. Geophysics, Geochemistry, Geosystems 10, Q02014. doi:10.1029/2008GC002149.
Vrana, S., 1987. The Sevetin astrobleme, southern Bohemia, Czechoslovakia. Geologische Rundschau 76, 505–528.
Vuorelainen, Y., Tornroos, R., 1986a. Platinum-group element alloy spherules from alluvial deposits in Finnish Lapland. Neues Jahrbuch für Mineralogie Monatshefte 1986, 423–432.
Vuorelainen, Y., Tornroos, R., 1986b. Man-made Pt–Pt–As spherules after sperrylite from alluvial deposits in Finnish Lapland. Canadian Mineralogist 24, 523–528.
Waddington, E.D., Dence, M.R., 1979. Skeleton Lake, Ontario — evidence for a Paleozoic impact crater. Canadian Journal of Earth Sciences 16, 256–273.
Walkden, G., Parker, J., Kelley, S., 2002. A Late Triassic impact ejecta layer in southwestern Britain. Science 298, 2185–2188.
Walzebuck, J.P., Engelhardt, W.V., 1979. Shock deformation of quartz influenced by grain size and shock direction: Observations on quartz-plagioclase rocks from the basement of the Ries Crater, Germany. Contributions to Mineralogy and Petrology 70, 267–271.
Wang, K., 1992. Glassy microspherules (microtektites) from an Upper Devonian limestone. Science 256, 1547–1550.
Wang, K., Chatterton, B.D.E., 1993. Microspherules in Devonian sediments: origins, geological significance, and contamination problems. Canadian Journal of Earth Sciences 30, 1660–1667.
Wdowiak, T.J., Armendarez, L.P., Agresti, D.G., Wade, M.L., Wdowiak, S.Y., Claeys, P., Izett, G., 2001. Presence of an iron-rich nanophase material in the upper layer of the Cretaceous–Tertiary boundary clay. Meteoritics and Planetary Science 36, 123–133.
Weiss, L.E., 1972. The Minor Structures of Deformed Rocks: A Photographic Atlas. Springer-Verlag, New York, NY. 431 pp.
Wenk, H.-R., Lonardelli, I., Vogel, S.C., Tullis, J., 2005. Dauphiné twinning as evidence for an impact origin of preferred orientation in quartzite: An example from Vredefort, South Africa. Geology 33, 273–276.
Whitehead, J., Grieve, R.A.F., Spray, J.G., 2002. Mineralogy and petrology of melt rocks from the Popigai impact structure, Siberia. Meteoritics and Planetary Science 37, 623–647.
Wieland, F., Reimold, W.U., Gibson, R.L., 2006. New observations on shatter cones in the Vredefort impact structure, South Africa, and evaluation of current hypotheses for shatter cone formation. Meteoritics and Planetary Science 41, 1737–1759.
Wignall, P., Thomas, B., Willink, R., Watling, J., 2004. Is Bedout an impact crater? Take 1. Science 306, 609–610.

Williams, D.J., Johnson, W., 1980. A note on the formation of fulgurites. Geological Magazine 117, 293–296.
Wilshire, H.M., Howard, K.A., Offield, T.W., 1971. Impact breccias in carbonate rocks, Sierra Madera, Texas. Bulletin of the Geological Society of America 82, 1009–1018.
Wilshire, H.M., Offield, T.W., Howard, K.A., Cummings, D., 1972. Geology of the Sierra Madera cryptoexplosion structure. Pecos County, Texas. U.S. Geological Survey Professional Paper 599-H. 42 pp.
Windolph, J.F., 1993. Possible impact origin for Permo–Carboniferous sedimentary basins in the USA. Douzième Congrès International de la Stratigraphie et Géologie du Carbonifère et Permien, Buenos Aires, 22–27 September 1991. Comptes Rendus, vol. 1, pp. 455–466.
Wirth, R., Vollmer, C., Brenker, F., Matsyuk, S., Kaminsky, F., 2007. Inclusions of nanocrystalline hydrous aluminum silicate Phase Egg in superdeep diamonds from Juina (Mato Grosso State, Brazil). Earth and Planetary Science Letters 259, 384–399.
Wittmann, A., Kenkmann, T., Schmitt, R.T., Stöffler, D., 2006. Shock-metamorphosed zircon in terrestrial impact craters. Meteoritics and Planetary Science 41, 433–454.
Wolfe, S.H., Hörz, F., 1970. Shock effects in scapolite. American Mineralogist 55, 1313–1328.
Xie, Z., Sharp, T.G., DeCarli, P.S., 2006. Estimating shock pressures based on high-pressure minerals in shock-induced melt veins of L chondrites. Meteoritics and Planetary Science 41, 1883–1896.
Xu, D., Yan, Z., 1993. Carbon isotope and iridium event markers near the Permian/Triassic boundary in the Meishan section, Zhejiang province, China. Palaeogeography, Palaeoclimatology, Palaeobiology 104, 171–176.
Xu, D., Ma, S., Chai, Z., Mao, X., Sun, Y., Zhang, Q., Yang, Z., 1985. Abundance variations of iridium and trace elements at the Permian/Triassic boundary at Shangsi in China. Nature 314, 154–156.
Xu, D.-Y., Zhang, Q.-W., Sun, Y.-W., Yan, Z., Chai, Z.-F., He, J.W., 1989. Astrogeological events in China. Van Nostrand Reinhold, New York, NY. 264 pp.
Yang, W.H., Kirkpatrick, R.J., Vergo, N., McHone, J., Emilsson, T.I., Oldfield, E., 1986. Detection of high-pressure silica polymorphs in whole-rock samples from a Meteor Crater, Arizona, impact sample using solid-state silicon-29 nuclear magnetic resonance spectroscopy. Meteoritics 21, 117–124.
Yin, H., Huang, S., Zhang, K., Yang, F., Ding, M., Bi, X., Zhang, S., 1989. Volcanism at the Permian–Triassic boundary in south China and its effects on mass extinction. Acta Geologica Sinica 2, 417–431.
Yin, H., Huang, S., Zhang, K., Hansen, H.J., Yang, F., Ding, M., Bie, X., 1992. The effects of volcanism on the Permo–Triassic mass extinction in south China. In: Sweet, W.C., Zunyi, Y., Dickens, J.M., Hongfu, Y. (Eds.), Permo–Triassic Events in the Eastern Tethys. Cambridge University Press, New York, pp. 146–157.
Zolensky, M., 1998. The flux of meteorites to Antarctica. In: Grady, M.M., Hutchison, R., McCall, G.J.H., Rothery, D.A. (Eds.), Meteorites: flux with time and impact effects. Special Publication, vol. 140. The Geological Society, London, pp. 93–104.