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# The importance of being cratered:
# The new role of meteorite impact as a normal geological process

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**Abstract**–This paper is a personal (and, in many ways, incomplete) view of the past development of impact geology and of the newly recognized importance of impact events in terrestrial geological history. It also identifies some exciting scientific challenges for future investigators: to determine the full range of impact effects preserved on the Earth, to apply the knowledge obtained from impact phenomena to more general geological problems, and to continue the merger of the once exotic field of impact geology with mainstream geosciences.

Since the recognition of an impact event at the Cretaceous-Tertiary (K-T) boundary, much current activity in impact geology has been promoted by traditionally trained geoscientists who have unexpectedly encountered impact effects in the course of their work. Their studies have involved: 1) the recognition of additional major impact effects in the geological record (the Chesapeake Bay crater, the Alamo breccia, and multiple layers of impact spherules in Precambrian rocks); and 2) the use of impact structures as laboratories to study general geological processes (e.g., igneous petrogenesis at Sudbury, Canada and Archean crustal evolution at Vredefort, South Africa). Other research areas, in which impact studies could contribute to major geoscience problems in the future, include: 1) comparative studies between low-level (≤7 GPa) shock deformation of quartz, and the production of quartz cleavage, in both impact and tectonic environments; and 2) the nature, origin, and significance of bulk organic carbon ("kerogen") and other carbon species in some impact structures (Gardnos, Norway, and Sudbury, Canada).

## INTRODUCTION: A BACKWARD GLANCE

As the 21st century begins, meteorite impact is finally getting plenty of respect. The bombardment of planetary surfaces by large external objects, a catastrophic process long ignored by scientists, is now receiving serious attention from both professional geologists and the general public (e.g., Reimold 2003; Milani 2003). The existence and power of such impacts has been demonstrated beyond doubt by the 1994 impacts of Comet Shoemaker-Levy-9 on Jupiter (Spencer and Mitton 1995), and the role of such bombardments in shaping the surfaces of other planets is now widely accepted (e.g., Taylor 1982, 1992).

On our own planet, more than 150 structures, with diameters of 0.1–200+ km, have now been recognized as the results of the impacts of extraterrestrial objects (Grieve 1991, 1998). A few very large impact structures, with diameters of hundreds of km, represent intense and sudden deformation of immense volumes of the Earth's crust (Grieve and Therriault 2000). These structures include Sudbury (Canada) (diameter: 250 km, age 1.85 Ga) (Grieve et al. 1991; Stöffler et al. 1994), Vredefort (South Africa) (diameter: 300 km, 2.02 Ga) (Nicolaysen and Reimold 1990; Reimold and Gibson 1996; Brink et al. 1997; Therriault et al. 1997a; Gibson and Reimold 2001), and Chicxulub (Mexico) (diameter: 180 km, 65.0 Ma) (Sharpton et al. 1993, 1996; Morgan et al. 1997).

The increasing recognition of impact structures themselves has been accompanied by the realization that impact events produce major geological effects that go far beyond the production of craters. Impact events generate large quantities of molten rocks (impact melts) (Dence 1971; Grieve et. al. 1977; Grieve and Cintala 1992; Dressler and Reimold 2001), which, in larger structures, may form coherent bodies hundreds to thousands of km$^3$ in volume. Many impact structures are the sites of significant ore deposits and hydrocarbon accumulations, which are associated either with the impact event itself or with impact-produced deformation of the target rocks (Grieve and Masaitis 1994; Reimold and Gibson 1996; Donofrio 1997; Johnson and Campbell 1997).

The effects of impact events have been shown to extend far beyond the craters themselves. A large impact event is associated with at least 1 major biological extinction, at the Cretaceous-Tertiary (K-T) boundary 65 Ma ago (Alvarez et al. 1980), and the possible implication of impact events in other extinctions is now an active area of investigation (Ryder et al. 1996; Koeberl and Macleod 2002; Buffetaut and Koeberl 2002). Large impact events also have the potential to produce major geological effects unrelated to extinctions: tsunamis, extreme atmospheric disturbances, short- and long-term climate changes, and the distribution of crater ejecta over regional to global distances. Nor is the current concern about impact-generated extinctions is not limited to past events—the protection of human civilization (and perhaps of humanity itself) from future impact events is a major topic of discussion among scientists (Gehrels 1994; Remo 1997), the public (e.g., Chapman and Morrison 1989; Verschuur 1996), and policy analysts (e.g., Milani 2003).

(In this paper, for simplicity, I use the terms meteorite and meteorite impact in a very general sense to designate an event in which any extraterrestrial object, regardless of size, composition, or source, penetrates the Earth's atmosphere and strikes the Earth's surface at cosmic velocities and the collision of which generates intense shock waves that excavate a hypervelocity impact crater. For details and more specialized terminology, see, e.g., Melosh [1989], Grieve [1991], and Hörz et al. [1991].)

The increasing recognition of meteorite impacts as a significant geological process is reflected in a large number of recent workshops and publications by the Geological Society of America (Silver and Schultz 1982; Sharpton and Ward 1990; Dressler et al. 1994; Ryder et al. 1996; Koeberl and Anderson 1996; Dressler and Sharpton 1999; Koeberl and MacLeod 2002) and by other organizations (e.g., Grady et al. 1998). Since 1993, the European Science Foundation (ESF) has supported a large number of workshops on various aspects of impact geology, with the resulting publication of several benchmark volumes including a new "Impact Studies" series by Springer-Verlag (Gilmour and Koeberl 2000; Montanari and Koeberl 2002; Buffetaut and Koeberl 2002; Plado and Pesonen 2002; Koeberl and Martinez-Ruiz 2003). The rare treatments of meteorite impact geology in standard geoscience textbooks (e.g., Philpotts 1990, chap. 14–9; Hibbard 1995, chap. 24) are now complemented by several more specialized volumes (French and Short 1968; Roddy et al. 1977; Melosh 1989; French 1998).

Today's students may be surprised to learn that there was a time, within living memory, when the discipline of impact geology did not exist and that major scientific battles were fought to establish its validity and to bring it into mainstream geology (e.g., Marvin 1986, 1990; Hoyt 1987; Mark 1987). In 1960, when I began a Ph.D. thesis on a fairly traditional geoscience subject—the metamorphism of banded iron formations—the present state of meteorite impact geology could not have been predicted by any scientist, advisory committee, or government funding agency.

True, meteorite impacts were accepted at that time, and about a dozen circular features (all less than 4 km in diameter) were acknowledged as impact structures (French 1968a; Grieve 1998), but in terms of large and geologically significant effects, the impact process was generally ignored. The hypothesis that impacts could form large geological features was not considered, except in a few perceptive and generally overlooked publications (Boon and Albritton 1937, 1938; Daly 1947; Dietz 1947, 1959; Baldwin 1949). Two long-simmering debates about the impact origin of Meteor Crater (Arizona) and the Ries (Germany) were continuing, relatively unnoticed, on the geological sidelines. However, within the established geoscience community, the active debate about the origins of the Sudbury and Vredefort structures involved only internal mechanisms. And, with very rare exceptions (e.g., de Laubenfels 1956; McLaren 1970), impact events were not included among the many active and competing explanations for the extinction of the dinosaurs.

Over the past 40 years, it has been fascinating to watch as meteorite impact geology expanded from virtually nothing to its present form. I have thoroughly enjoyed my involvement as an occasional contributor (in between a mostly administrative career), as a frequent editor, and as a constant and amazed spectator. I am very grateful to the Meteoritical Society and its members for the award of the Barringer Medal, and I appreciate the opportunity, in this paper, to explore the gradual entry of meteorite impact into mainstream geology, to discuss some current studies, and to point out some research areas for new people to explore. Despite the exciting and rapid progress during the last 4 decades, I do not feel that we have fully identified the effects of meteorite impact on our own planet and its life-forms. I think, as I have thought for the last 40 years, that the most exciting discoveries lie ahead.

This paper is not intended to be either a complete history or a complete review of the field. Meteorite impact geology is now old enough to have generated some of its own histories (Hoyt 1987; Mark 1987; French 1990b; Marvin 1990, 1999; Glen 1994; Lowman 2002, chap. 5) as well as some excellent popular books and memoirs (Hsü 1986; Raup 1986, 1991; Verschuur 1996; Alvarez 1997; Powell 1998; Poag 1999).

This paper is a personal view, but I am grateful to many with whom I have been fortunate to work in an area of science inhabited by enthusiastic, imaginative, friendly, and generous people. I owe debts to more colleagues than I can name for ideas, support, data, information, specimens, and art work, but any errors, omissions, or oversights in this paper are entirely my own.

## THE REVOLUTION FROM OUTSIDE: 1960–1980

It seems appropriate that the revolution in meteorite impact geology came, like the impacting bodies themselves, from the outside. The field did not develop within the established geoscience community, and the first systematic studies of terrestrial impact craters were largely a byproduct of the space program, the Apollo landings on the Moon, and the unmanned exploration of the planets. The chief contributors to the small field of impact studies in the early 1960s were astronomers (Ralph Baldwin, Carlyle Beals) and a very few geologists (Robert Dietz, Eugene Shoemaker).

The origin of meteorite impact geology outside the field of established geosciences was one condition that hampered (and perhaps still hampers; see Marvin 1990, 1999) the general acceptance of impact by traditionally trained geoscientists. There were other problems. Philosophically, meteorite impacts were a "catastrophic" mechanism that seemed in conflict with the basic and long-accepted "uniformitarian" principles of geology (Marvin 1986, 1990, 1999; Glen 1994). (For a counter-argument to this "conflict," see French [1968a, 1990b].)

However, philosophy aside, it is important to remember that terrestrial impact studies developed in the shadow of 2 other simultaneous revolutions in the 1960s. The development of plate tectonics not only involved virtually all the established geoscience community but also emphasized again the importance of gradual, not catastrophic, change in geological processes. At the same time, the Apollo Program and unmanned planetary exploration established that meteorite impact craters were a major feature of geology in the solar system, but (except for limited human explorations on the Moon) planetary impact craters were not studied by the traditional methods of field geology: field mapping, geophysical surveys, drilling, and sample return. The results of lunar and planetary cratering studies were not widely applied to terrestrial geology nor were they rapidly introduced into the geological mainstream.

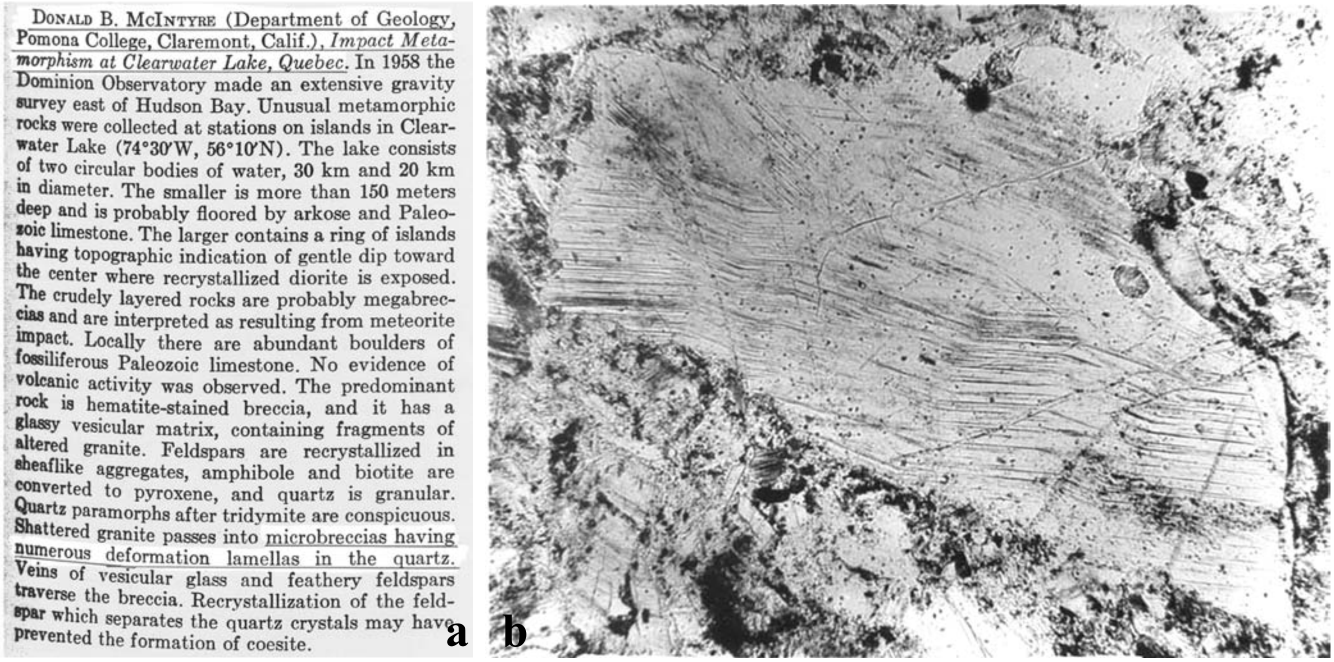
Against this general background, an early period of impact geology can be conveniently bracketed between the years 1960 (the discovery of natural coesite [Chao et al. 1960]) and 1980 (publication of the "Alvarez paper" on the K-T extinction [Alvarez et al. 1980]). The years 1960–1963 are especially important, and with the clear vision provided by hindsight, we can identify in these years the precursors of the great revolution that was to follow.

The most important development during this period was the recognition of unique and geologically durable petrographic and mineralogical effects that could be used to unambiguously identify geologically old impact structures. Prior to 1960, unambiguous identification of a meteorite impact structure required the discovery of actual meteorites associated with the crater. This criterion could only be applied to very young and relatively small craters, in which the meteorites had survived not only the impact but the subsequent terrestrial weathering. (Robert S. Dietz had argued long before 1960 [Dietz 1947, 1959] that shatter cones, unusual conical fractures in the rocks of "cryptoexplosion" structures, were also the unique products of meteorite impact, but this view was not generally held in 1960. Dietz' arguments, however, gradually became accepted during the 1960s and 1970s, especially when shatter cones were found to be associated with petrographic features, such as planar deformation features [PDFs] in quartz, that recorded the presence of even higher shock pressures. Today, well-developed shatter cones are generally accepted as definite impact criteria, although their formation is still as poorly understood as it was in 1960.)

The discovery of the high-pressure silica minerals coesite (Chao et al. 1960; Shoemaker and Chao 1961) and stishovite (Chao et al. 1962) in impact structures provided evidence for the production of extremely high pressures in near-surface crustal rocks, pressures so high that a meteorite impact was required. For the first time, geologists had a durable geological criterion to identify meteorite impact structures so old that the meteorites themselves no longer survived, and it became possible to establish the impact origin of large structures as ancient as 2 Ga old (Martini 1978, 1991).

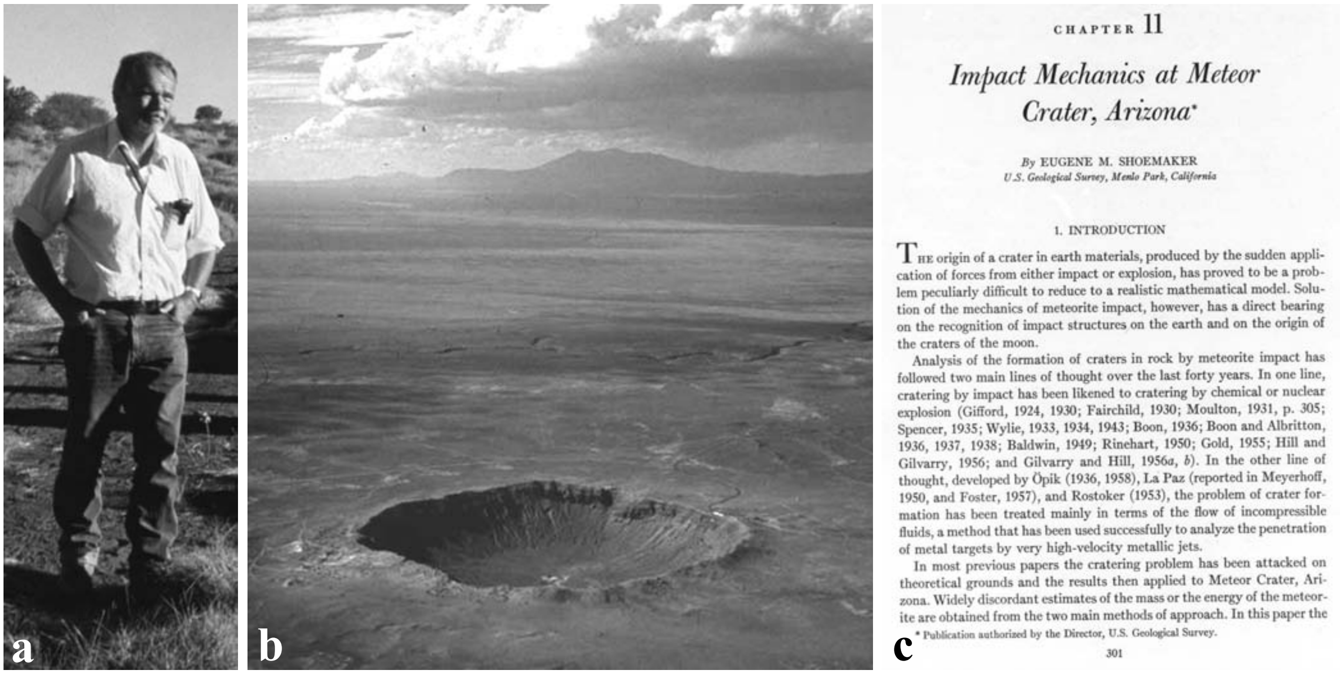
At the same time, a little-noticed abstract appeared, describing unusual microscopic "planar features" developed in quartz from the Clearwater Lakes structure in Canada (McIntyre 1962) (Fig. 1). These features consisted of multiple sets of thin, closely-spaced parallel lamellae filled with glassy material when fresh, decorated with small fluid inclusions when devitrified, and oriented parallel to a few specific low-index planes in the quartz crystal structure. Subsequent studies established that these features are uniquely produced by high shock pressures and that their occurrence is restricted in nature to meteorite impact sites. These features in quartz, after passing through several changes in terminology, have emerged as the *planar deformation features* (PDFs) that are now probably the most-used petrographic indicator of shock and meteorite impact (for reviews, see Alexopoulos et al. [1988]; Grieve et al. [1990, 1996]; Stöffler and Langenhorst [1994]).

1963 can be argued as the year in which impact geology became a real scientific discipline, complete with established methods of study, accumulating evidence of geologically important impacts, theories to explain the observations, and even scholarly debates in prestigious journals. That year saw the publication of Ralph Baldwin's *The measure of the Moon* (Baldwin 1963), a benchmark book that presented an impressive amount of data and evidence for both lunar and terrestrial impact cratering. The appearance of Baldwin's book was accompanied by that of another major volume (Middlehurst and Kuiper 1963), which included at least 3 landmark papers: Shoemaker's geological study of Meteor Crater (Shoemaker 1963) (Fig. 2), Dietz' accumulated evidence for shatter cones as an impact criterion (Dietz



Donald B. McIntyre (Department of Geology, Pomona College, Claremont, Calif.), *Impact Metamorphism at Clearwater Lake, Quebec.* In 1958 the Dominion Observatory made an extensive gravity survey east of Hudson Bay. Unusual metamorphic rocks were collected at stations on islands in Clearwater Lake (74°30′W, 56°10′N). The lake consists of two circular bodies of water, 30 km and 20 km in diameter. The smaller is more than 150 meters deep and is probably floored by arkose and Paleozoic limestone. The larger contains a ring of islands having topographic indication of gentle dip toward the center where recrystallized diorite is exposed. The crudely layered rocks are probably megabreccias and are interpreted as resulting from meteorite impact. Locally there are abundant boulders of fossiliferous Paleozoic limestone. No evidence of volcanic activity was observed. The predominant rock is hematite-stained breccia, and it has a glassy vesicular matrix, containing fragments of altered granite. Feldspars are recrystallized in sheaflike aggregates, amphibole and biotite are converted to pyroxene, and quartz is granular. Quartz paramorphs after tridymite are conspicuous. Shattered granite passes into microbreccias having numerous deformation lamellas in the quartz. Veins of vesicular glass and feathery feldspars traverse the breccia. Recrystallization of the feldspar which separates the quartz crystals may have prevented the formation of coesite.

Fig. 1. The recognition of unique shock-produced "deformation lamellae" or planar deformation features (PDFs) in quartz in the 1960s was a critical development in the identification of ancient meteorite impact structures: a) first published description of "deformation lamellae" identified in breccias from the Clearwater West impact structure, as an abstract in the *Journal of Geophysical Research* (McIntyre 1962) (reproduced by permission of the American Geophysical Union); b) photomicrograph of quartz grain in breccia from Clearwater West, showing multiple sets of PDFs (McIntyre 1968, Fig. 6). Plane-polarized light. The quartz grain is about 1.4 mm long.



CHAPTER 11

*Impact Mechanics at Meteor Crater, Arizona*[*]

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1. INTRODUCTION

The origin of a crater in earth materials, produced by the sudden application of forces from either impact or explosion, has proved to be a problem peculiarly difficult to reduce to a realistic mathematical model. Solution of the mechanics of meteorite impact, however, has a direct bearing on the recognition of impact structures on the earth and on the origin of the craters of the moon.

Analysis of the formation of craters in rock by meteorite impact has followed two main lines of thought over the last forty years. In one line, cratering by impact has been likened to cratering by chemical or nuclear explosion (Gifford, 1924, 1930; Fairchild, 1930; Moulton, 1931, p. 305; Spencer, 1935; Wylie, 1933, 1934, 1943; Boon, 1936; Boon and Albritton, 1936, 1937, 1938; Baldwin, 1949; Rinehart, 1950; Gold, 1955; Hill and Gilvarry, 1956; and Gilvarry and Hill, 1956*a*, *b*). In the other line of thought, developed by Öpik (1936, 1958), La Paz (reported in Meyerhoff, 1950, and Foster, 1957), and Rostoker (1953), the problem of crater formation has been treated mainly in terms of the flow of incompressible fluids, a method that has been used successfully to analyze the penetration of metal targets by very high-velocity metallic jets.

In most previous papers the cratering problem has been attacked on theoretical grounds and the results then applied to Meteor Crater, Arizona. Widely discordant estimates of the mass or the energy of the meteorite are obtained from the two main methods of approach. In this paper the

[*] Publication authorized by the Director, U.S. Geological Survey.

301

Fig. 2. Studies of Meteor Crater, Arizona in the 1960s played a major role in developing the field of impact geology by establishing the geological mechanisms of meteorite impact and by identifying the high-pressure silica minerals coesite and stishovite produced by shock pressures: a) Eugene Shoemaker, one of the founders of impact geology, shown in the field in Australia in 1990; b) aerial view of Meteor Crater (diameter 1.2 km), showing the uplifted rim of sedimentary target rocks and the hummocky patches of ejecta around the crater; c) title page of Eugene Shoemaker's benchmark study on the geology and origin of Meteor Crater (Shoemaker 1963) (used by permission of the University of Chicago Press, Chicago, Illinois).

1963a), and Beals' early description of the few Canadian impact structures (Beals et al. 1963) that would soon grow to a population of more than 2 dozen. Finally, a "duelling review papers" issue of the *American Journal of Science* presented, to a wide geoscience community, the accumulated evidence and arguments for the impact origin (Dietz 1963b) versus the internal formation (Bucher 1963) of so called "cryptoexplosion" structures.

By 1980, the condition of meteorite impact research had changed drastically. The unique physical conditions of impact events were increasingly appreciated, and the terms impact metamorphism (Chao 1967) and shock metamorphism (French 1968a; French and Short 1968; Stöffler 1972, 1974) had been coined to describe the unique effects produced in target rocks by the high pressure shock waves associated with meteorite impact events. The use of shock effects, especially shatter cones and PDFs, immediately produced a rapid increase in the number of known impact structures, partly through the discovery of shock effects in long-known "cryptoexplosion" structures and partly through the discovery of new structures from their shock effects. The number of known impact structures more than tripled (from 15 to 50) between 1960 and 1968 (French 1968a, Fig. 3) and reached nearly 100 by 1980 (Grieve 1998, Fig. 1) (Fig. 3). Origin by meteorite impact was established, not without considerable controversy, for the large and long-debated structures at Sudbury, Canada (Dietz 1964; French 1967, 1968b; Guy-Bray 1972) and Vredefort, South Africa (Dietz 1961; Hargraves 1961; Manton 1965; Carter 1965; Martini 1978). In addition, it was recognized that the impact process could, nearly instantly, generate large volumes of molten impact melt (Dence 1971; Grieve et al. 1977), which then spread out to form an important and often puzzling lithology within the crater. These impact-produced igneous rocks, in turn, often provided additional evidence for impact in the form of anomalously high concentrations of siderophile and other elements (e.g., Ir) derived from the projectile itself (Palme 1982; Koeberl 1998).

## CRATERS INTO THE MAINSTREAM (1980–PRESENT)

The classic "Alvarez paper" (Alvarez et al. 1980), together with nearly-simultaneous publications by other workers (Ganapathy 1980; Smit and Hertogen 1980), provided the first geochemical evidence for a connection between a large impact event and the major biological extinction at the K-T boundary 65 Ma ago. With these papers, impact cratering entered (or, perhaps more accurately, blasted its way into) the geological mainstream. The hypothesis of an impact-produced extinction, and the accumulating evidence for its correctness, could be criticized and debated by mainstream geoscientists, but it could no longer be ignored.

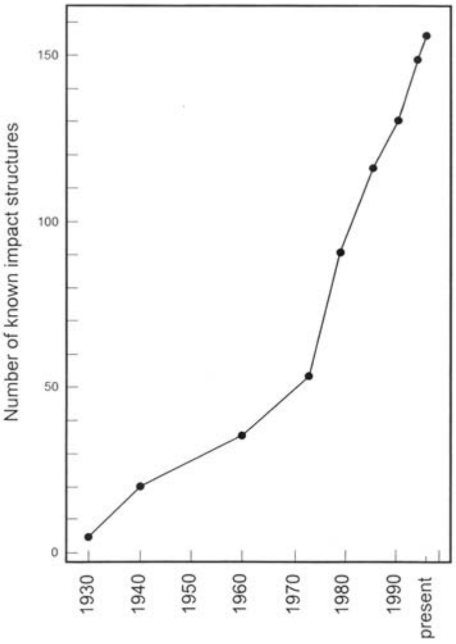

Fig. 3. Graph of the cumulative number of established terrestrial meteorite impact structures as a function of time since 1930 (from Grieve 1998, Fig. 1). The sharp increase in discovery rate after 1960 reflects the increasing use of unique and durable petrographic and mineralogical effects (PDFs, high-pressure silica minerals) to identify old impact structures. More than 150 established impact structures are now known, and the rate of discovery has remained roughly constant at 3–4/yr since 1960.

It is not necessary to describe here the details of this discovery at the K-T boundary and its geological, biological, historical, and philosophical implications. These details now fill up a huge amount of scientific literature, including numerous special publications (e.g., Silver and Schultz 1982; Ryder et al. 1996; Koeberl and MacLeod 2002), and there have been many historical studies, both scientific (Raup 1986; Hsü 1986; Glen 1994) and popular (Verschuur 1996; Powell 1998), as well as personal memoirs (Alvarez 1997).

For the purpose of this paper, the importance of the K-T discoveries is that they mark the start of a period in which studies in impact geology are being done by traditionally trained geologists, often much to their surprise, as they have unexpectedly been confronted with impact structures and impact phenomena in the course of what started out to be more general and traditional studies. Serendipity often plays a major role; geologists find impact effects in the course of looking for something else. (This was even true for the original K-T studies themselves; the Alvarez group analyzed iridium levels in the K-T boundary clay in an attempt to measure the duration of the extinction, not to search for evidence of an impact event itself [Alvarez 1997, pp. 63–69]).

Since 1980, other major impact effects have been recognized in the geological record, most of them discovered by geologists who started out to study other problems. A few of these discoveries are summarized below. These examples, and many others like them, are important for several reasons: 1) they have expanded and increased the importance of impact in the terrestrial geologic record; 2) they have automatically expanded the small community of active impact geologists; 3) they indicate that many more impact structures and impact effects remain to be recognized; and 4) they provide models and methods for future studies of impact events in the geological record.

## The Chesapeake Bay Crater

This 85 km-diameter subsurface structure underlies much of lower Chesapeake Bay and the contiguous parts of Maryland and Virginia (Fig. 4a). Although it is now recognized as the largest known impact structure in the United States, its existence was totally unsuspected until recently, when it was recognized by Wylie Poag and his colleagues of the U.S. Geological Survey (Poag et al. 1994, 2003; Poag 1999) in the course of geophysical surveys and drilling related to problems of the regional submarine geology and water supply. Recognition of the structure was based on studies of an unusual rock type, the Exmore breccia, encountered within the crater during drilling. Discovery of shocked quartz, containing PDFs, in the breccia (Koeberl et al. 1996) established the impact origin of both the breccia and the structure.

The Chesapeake Bay crater has since been the focus of active studies (Poag 1996, 1997; Poag et al. 2003) driven both by scientific questions and by the importance of the structure in influencing the regional water supply of the highly populated area in which it occurs. The structure appears to be of the "peak-ring" type (Fig. 4b), consisting of an outer rim 85–90 km in diameter, marked by concentric inward-dipping normal faults, a flat-floored annular trough, an irregular inner peak-ring, and an inner basin about 30 km in diameter.

There are strong indications that the effects of the Chesapeake Bay crater may extend much further. Its measured stratigraphic age is 35 Ma, identical to that of the Eocene-Oligocene boundary, at which there is a small but significant biological extinction. The age also suggests that the crater might be the source of the widespread North American tektite strewnfield (Poag et al. 1994; Koeberl et al. 1996). The age of the Chesapeake Bay crater, however, is also virtually identical to that of the 100 km-diameter Popigai structure in Russia, and the timing of the 2 impact events and their relations to the extinction and the tektite strewnfield are still topics for active study (e.g., Montanari and Koeberl 2000, pp. 80–83, 130–136; Whitehead et al. 2000; Poag et al. 2003).

## The Alamo Breccia

The Alamo breccia, a large deposit of anomalous breccia in southern Nevada, is now interpreted not as the filling of a large impact structure but as the widespread effect of a much smaller impact event (Warme and Sandberg 1996; Warme and Kuehner 1998). The Alamo breccia is a major geological formation (Fig. 5a). It ranges in thickness from 1 to 130 m and extends over an area of at least 140 × 70 km (Morrow et al. 1998) or at least several 1000 km$^2$. Until recently, the Alamo breccia was regarded as an anomalous high-energy unit (Fig. 5b) occurring in a thick section of otherwise continuous quiet-water Devonian carbonate platform sediments. More recent conventional geological mapping (Warme and Sandberg 1996; Warme and Kuehner 1998), combined with the discovery of small amounts of shocked quartz in the unit (Leroux et al. 1995), have established the Alamo breccia's connection with an impact event.

Because of its wide geographic extent, the Alamo breccia is unlikely to be a typical crater-filling breccia similar to the

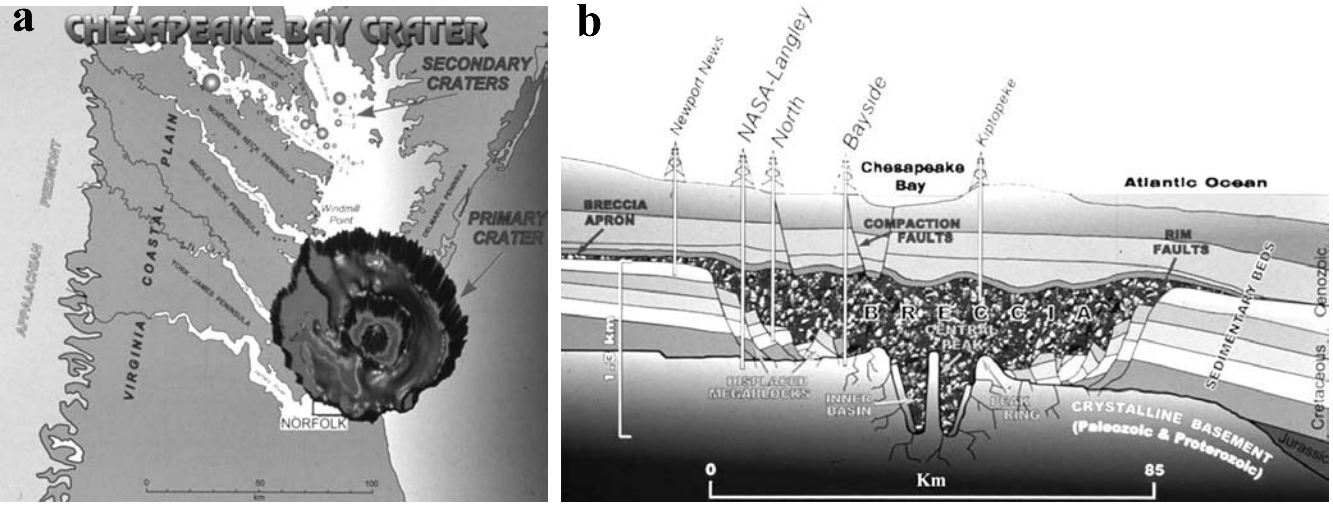

Fig. 4. The Chesapeake Bay impact structure, buried beneath the eastern coastal plain of the United States, was discovered in the course of geological and geophysical studies focused on the regional subsurface stratigraphy and water supply (Poag et al. 1994; Poag 1999): a) location map of the structure, showing the primary structure (diameter 85 km) and possible secondary craters to the north; b) schematic cross-section of the structure developed from seismic studies and drilling. The structure contains a central peak ring and an inner basin. (Figures courtesy of Wiley Poag, U.S. Geological Survey.)

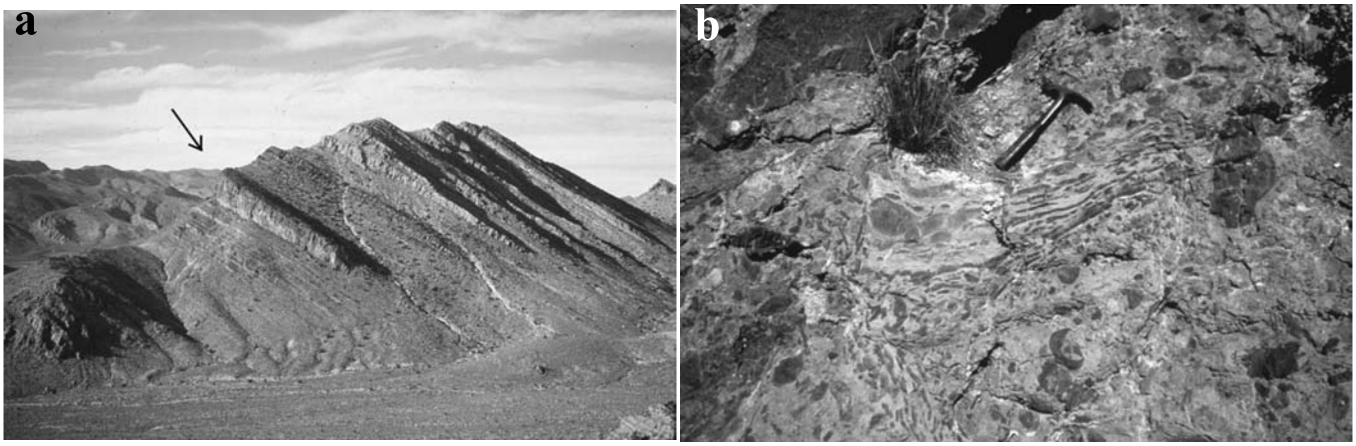

Fig. 5. The Alamo breccia, Nevada, a thick unit of megabreccia in a series of otherwise fine-grained, quiet-water carbonate rocks, has been identified as the consequence of the major collapse of a sedimentary basin due to seismic and marine effects associated with an impact event (Warme and Sandberg 1996; Warme and Kuehner 1998): a) large exposure of the Alamo breccia layer in a thick sequence of fine-grained marine carbonate rocks in the West Pahranagat Range, Nevada. The Alamo breccia (arrow), 55 m thick at this locality, is the leftmost of several cliff-forming units in the section (from Warme and Sandberg 1996, Fig. 1; used by permission of the Geological Society of America); b) outcrop of Alamo breccia, showing a unit of megabreccia composed of carbonate clasts up to several m long in a poorly sorted clastic matrix. The geological hammer is ~30 cm long. (Figures courtesy of John Warme, Colorado School of Mines.)

Exmore breccia of the Chesapeake Bay crater (see above). Instead, current interpretations (Warme and Sandberg 1996; Warme and Kuehner 1998) regard it as a new type of impact-related deposit, formed by the sudden and catastrophic collapse of a large region of a sedimentary platform as a result of seismic waves and tsunamis generated by the formation of a relatively small impact crater, perhaps 20–25 km across, which has still not been identified. Formation of a 25 km crater is a relatively common event over geological time; several such structures can be expected to form every million years over the whole Earth (e.g., Grieve and Shoemaker 1994). Similar impact-produced breccias, as yet unidentified, could, therefore, be present in the geological record, especially in sequences of platform sediments.

### Distal Ejecta: Records of Young and Old Impact Events

The recognition of a large impact event at the K-T boundary has also focused attention on distal ejecta (fine-grained material from impact craters that may be carried to continental or global distances). The fact that such material could be preserved and remain recognizable over geological time was demonstrated by the K-T boundary studies, in which the 1–2 cm-thick global ejecta layer was identified (Alvarez et al. 1980) more than a decade before the source crater itself was established by the recognition of shock effects (Hildebrand et al. 1991; Sharpton et al. 1992).

Despite the apparent fragility of distal ejecta layers in the geological environment, several such layers have been identified and linked to known impact structures several 100 km away (Gostin et al. 1986; Williams 1986; Izett et al. 1993; Sturkell et al. 2000; Montanari and Koeberl 2000, chap. 3), while the strewnfields of tektites from impact structures extend as far as several 1000 km from their source craters (Montanari and Koeberl 2000, chap. 2). These discoveries indicate that such distal ejecta layers, which may contain both shocked quartz grains and glassy spherules of impact melt, may be an important component in the sedimentary record (Grieve 1997; Montanari and Koeberl 2000).

Distal ejecta layers in the geologic record also provide the potential to recognize impact events with craters that have not been identified or may not even be preserved. An especially exciting research area has been opened by the discovery of possible ancient distal ejecta layers, typically 2–30 cm thick and composed of recrystallized glassy spherules, in Archean and Proterozoic rocks of South Africa and Australia (Lowe and Byerly 1986; Lowe et al. 1989; Simonson 1992; Simonson and Hassler 1997; Simonson et al. 1999, 2002; Byerly et al. 2002) (Fig. 6). The interpretation of these layers is complicated by their alteration and recrystallization and by the apparent absence of shocked quartz associated with the spherules. As a result, the impact origin of these layers is still debated, especially for some of the South African ones (Koeberl and Reimold 1995; Reimold et al. 2000; Shukolyukov et al. 2000). The evidence for impact appears stronger for: 1) several Australian spherule layers ~2.5 Ga old, at least 1 of which is a clearly exotic unit in fine-grained dolomite (Simonson and Hassler 1997) and several of which display small but definite iridium anomalies (Simonson et al. 1998, 2000; McDonald and Simonson 2002); and 2) the so called “Monteville layer” in South Africa (Simonson et al. 2000).

## WHAT NOW? IMPACT CRATERS AS GEOLOGICAL TOOLS

The present status of meteorite impact in geology reflects the fact that several major battles have been fought and won,

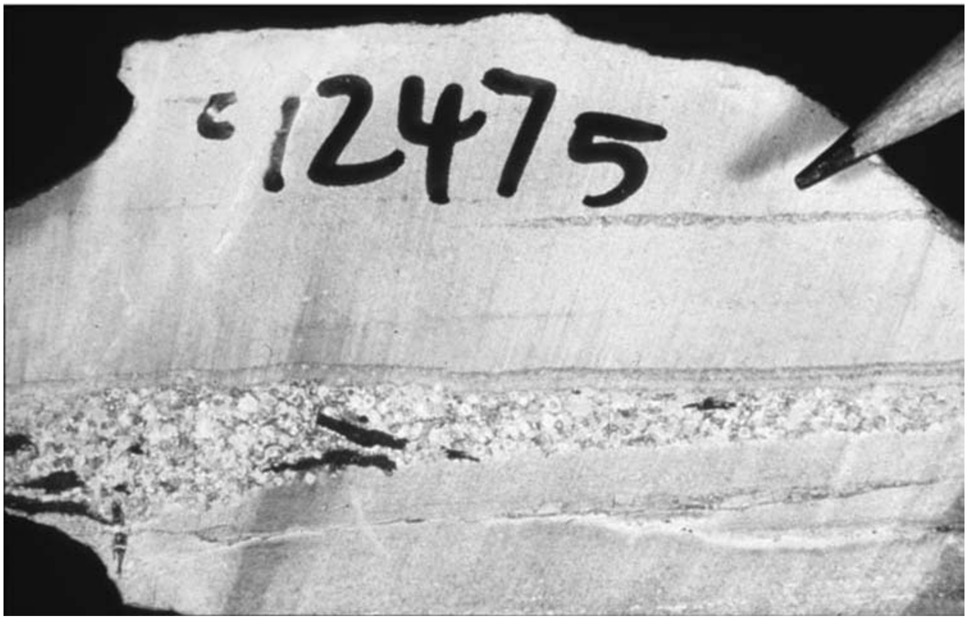

Fig. 6. Layers of mm-size recrystallized spherules, interpreted as glassy bodies ejected from ancient impact events, have been found in Archean and Proterozoic rocks at several locations in Australia and South Africa. This sample, from the Hamersley Range, Australia contains a thin layer of spherules (light colored), which record a sudden depositional event between beds of weathered shale. (The spherules have been stained yellow to identify the secondary K-feldspar that they contain.) The long dimension of figure is ~5 cm. (Figure courtesy of Bruce Simonson, Oberlin College.)

and essentially, controversy over several important issues no longer exists. Large meteorite impacts do occur, and unique geological and petrographic criteria exist to identify the resulting impact structures. Such impacts are now accepted as major geological processes on the Earth—when they occur, they can have major geological and biological effects.

Now what? Where will the small but growing community of impact geologists turn in developing their science further?

I will offer a possibly heretical remark: simply finding new meteorite impact structures is no longer enough. Geologists must now begin to use impact structures and to place them into the wider context of geology. Future studies should aim at more than identifying structures and even using them to understand cratering mechanics. We should use the impact craters themselves to explore more general geological problems, thus bridging the gaps that still exist between impact cratering and other areas of geology.

I think this process has already started. In several recent studies, established and traditionally trained geologists have accepted meteorite impact and have begun to use established impact structures and their effects to probe major problems in terrestrial geology. The few examples below, including some studies I have been involved in, are not a complete list but indicate a growing and important trend in the geosciences.

## Impact Craters: A "Lab Experiment" in Igneous Petrology

During an impact event, a large fraction of the total kinetic energy of impact is expended in heating and melting target rock, producing a volume of impact melt that cools to form igneous rocks associated with the crater (Dence 1971; Grieve et al. 1977; Grieve and Cintala 1992; Dressler and Reimold 2001) (Fig. 7). Recently, some igneous petrologists (Marsh 2002; Zieg and Marsh 2001, 2002) have realized that such impact melt units are an ideal "natural lab experiment" in the generation, cooling, and crystallization of large bodies of igneous rocks because they are free of many of the complicating problems associated with internally generated igneous rocks. Impact melt bodies are: 1) formed by the wholesale and instantaneous melting of a volume of rock; 2) formed from generally accessible and chemically characterized target rocks; 3) emplaced virtually instantly; 4) subject to uniform and monotonic cooling in place; and 5) not affected by subsequent intrusions of related melts.

Although suitably large units of impact melt are found in several impact structures (Dence 1971; Dressler and Reimold 2001), the Sudbury structure (Canada) has been the focus of intensive study. In addition to a wide array of impact phenomena (Grieve et al. 1991; Grieve 1994; Stöffler et al. 1994), Sudbury also contains a unit of igneous rocks (the Sudbury igneous complex [SIC]) 2–3 km thick, which is now generally accepted as entirely composed of impact melt (Dickin et al. 1999). In addition to the general advantages of impact melts for study, the SIC has 2 additional advantages: 1) the complete section of the original melt body is still preserved between the shocked rocks of the crater basement and the crater-fill breccias (Onaping formation) above it; and

Fig. 7. Large volumes of target rocks can be melted in impact events, and the resulting melt is emplaced in the crater as units of igneous rocks. This impact melt, from Lake Mistastin, Canada (Grieve 1985), forms a cliff about 80 m high in the central part of the structure. The upper part of the melt layer has been removed by erosion, but the remainder displays two tiers of columnar jointing, a structure which is also typical of internally generated igneous rocks. (Photograph courtesy of R. A. F. Grieve, National Resources Canada.)

2) because of the immense Cu-Fe-Ni ore bodies associated with the SIC, the body has been intensively sampled, drilled, and analyzed.

Since its recognition as an impact melt (Grieve et al. 1991; Grieve 1994; Stöffler et al. 1994; Dickin et al. 1999), the units of the SIC have been intensely characterized, and the extent of in-place differentiation has been explored and debated (Lightfoot et al. 1997a, 1997b, 2000; Therriault et al. 2002). These problems have important implications for evaluating the origin and extent of differentiation in internally generated terrestrial igneous bodies. They also have a wider planetary importance for resolving controversies over whether the chemically diverse suite of lunar impact melts collected in the Apollo missions reflects chemical differences in the crustal target rocks or in-place differentiation of large impact melt units associated with the major maria (Grieve et al. 1974; Warren et al. 1996).

Sudbury has also helped to explore cooling and crystallization mechanisms in igneous rocks. The SIC, and its well-established conditions of formation, have provided important data to develop general crystal size distribution (CSD) models for the crystallization of igneous bodies (Marsh 2002; Zieg and Marsh 2002), as well as a crystallization model for the SIC itself, involving bulk differentiation and cooling in discrete regions of a superheated impact melt sheet (Zieg and Marsh 2001).

## Low-Level Quartz Deformation: Shock and Tectonic Effects

The deformation of quartz is a fundamental problem in both traditional geology (tectonics and dynamic metamorphism; e.g., Fairbairn 1949; Carter 1968; Spry 1969) and in shock and impact studies (Alexopoulos et al. 1988; Stöffler and Langenhorst 1994; Grieve et al. 1996; Huffman and Reimold 1996). The extreme differences between the conditions of normal dynamic metamorphism and those of shock metamorphism, especially in peak stresses and strain rates (Carter 1968; Stöffler 1972; Huffman and Reimold 1996), are reflected in the distinctly different microstructures produced in quartz in each regime. In impact studies, shock-produced planar deformation features (PDFs) formed at high pressures (≥5 GPa) and high strain rates have been a critically important criterion for recognizing impact structures because of their unique characteristics, wide distribution, extensive preservation, and easy identification.

To date, field and experimental studies of shock-metamorphic features in quartz have concentrated on the unique features (e.g., PDFs) formed at high shock pressures (≥5 GPa), which are diagnostic for meteorite impact. However, in natural impact structures, such shock pressures, and the resulting PDFs, are restricted to relatively small regions of the parautochthonous crater floor or to discrete lithic and mineral clasts in the crater-fill breccia deposits and ejecta (Dence 1968; Grieve 1991). Much larger volumes of the crater, chiefly in the surrounding basement rocks, are subjected to lower pressure shock waves (e.g., 0.1–5 GPa; Kieffer and Simonds 1980; Melosh 1989, chap. 5). This situation raises 2 important questions: 1) What deformation features in quartz are produced by shock waves at pressures <5 GPa?; and 2) Can such features (like PDFs) also be used as unique and diagnostic indicators of shock waves and meteorite impact? This problem is especially important for identifying deeply eroded impact structures in which the more highly shocked rocks near the surface may have been completely eroded away (Grieve 1991, 1998).

Several deformation features in quartz, apparently produced at shock pressures of 5–7 GPa, have already been identified (Stöffler and Langenhorst 1994): basal deformation lamellae (Carter 1965, 1968), Brazil twinning parallel to the base (Leroux et al. 1994; Joreau et al. 1996), and multiple sets of parallel planar fractures (PFs) or cleavages (Bunch and Cohen 1964; Carter 1968; Robertson et al. 1968; Kieffer 1971; Stöffler and Langenhorst 1994; French et al. 1997; Koeberl et al. 1998). However, virtually no information exists on quartz deformation in rocks subjected to still lower shock pressures (e.g., <5 GPa) where the peak stresses (but not the strain rates) may be similar to those produced under tectonic conditions. The problem is further complicated by the absence of experimental techniques that can address the large gap (between pressures of about 0.1–10 GPa and strain rates of $10^2$–$10^6$ $sec^{-1}$) that separates the conditions of hypervelocity impact from those of rapid, but more normal, geological deformation (Fig. 8) (Huffman and Reimold 1996, Fig. 1).

The behavior of quartz in this range between shock deformation and normal dynamic metamorphism (Fig. 8) is a challenge for both impact and non-impact petrologists. What happens to quartz subjected to stress-strain conditions between the impact and non-impact environments of volcanism or tectonic deformation? Can new experimental methods be devised to explore this region? Can deformation features in quartz be used to reconstruct the physical conditions in this region? Are any unique shock deformation features developed that could then be used to recognize deeply eroded impact structures?

One approach to this problem is to study, in detail, deformation features that occur in both impact and non-impact settings. Cleavage in quartz is an obvious candidate. It occurs as multiple parallel sets (also called PFs) in impact structures (Fig. 9a) (see references above). Cleavage also has been produced in non-shock experiments, both involving fracturing under ambient conditions (e.g., Bloss 1957; Bloss and Gibbs 1963) and in confining conditions at high strain rates (Christie et al. 1964) (Fig. 9b). There are rare reports of quartz cleavage in natural non-impact environments (e.g., Frondel 1962, pp. 104–111 and references therein), but virtually none of them have been described in detail.

The probable impact structure at Rock Elm, Wisconsin (Cordua 1985; French and Cordua 1999; French et al. 2004) illustrates both the problems and potential for detailed studies of cleavage in quartz. The structure consists of a circular, 6.5 km-diameter area of anomalously deformed rocks in a region of otherwise flat-lying Ordovician and older sediments, and it contains a central uplift in which normally deep-seated Cambrian sandstone is exposed. These geological features appear typical for a meteorite impact structure in sedimentary rocks, and there is no evidence for origin by endogenic mechanisms such as igneous activity or salt dome intrusion (Cordua 1985).

However, the Rock Elm structure is old (probably >400 Ma) and deeply eroded; any distinctive highly shocked rocks originally in the central uplift have apparently been removed by erosion. No shatter cones or typical PDFs have yet been found in the rocks exposed in the central uplift. Instead, quartz in the sandstone shows 2 kinds of deformation features (Fig. 9c): 1) multiple parallel sets of cleavages (PFs); and 2) possible PDFs, often originating from the cleavage planes. Both features are oriented at specific planes within the quartz crystal, and their occurrence, especially that of the PFs, strongly indicates an impact origin for the structure (French and Cordua 1999; French et al. 2004). However, in Rock Elm, as at established impact structures, these features probably reflect low shock pressures (e.g., 5–7 GPa), and several questions remain to be explored. How, and under what conditions, does cleavage develop in natural quartz? Can cleavage be produced naturally in quartz in non-impact (e.g., volcanic, tectonic) environments? Can the presence of multiple cleavage sets be used as an independent criterion for shock and meteorite impact?

## Crater Age Measurements from Erosion Levels?

My studies of the Rock Elm structure led me directly into another major problem in impact geology: determining the ages of terrestrial impact structures. Accurate isotopic measurements of impact crater ages are important not only for interpreting the local geological history but for accumulating statistical data about the impact rate and its possible variations over geological time (Grieve 1991, 1998).

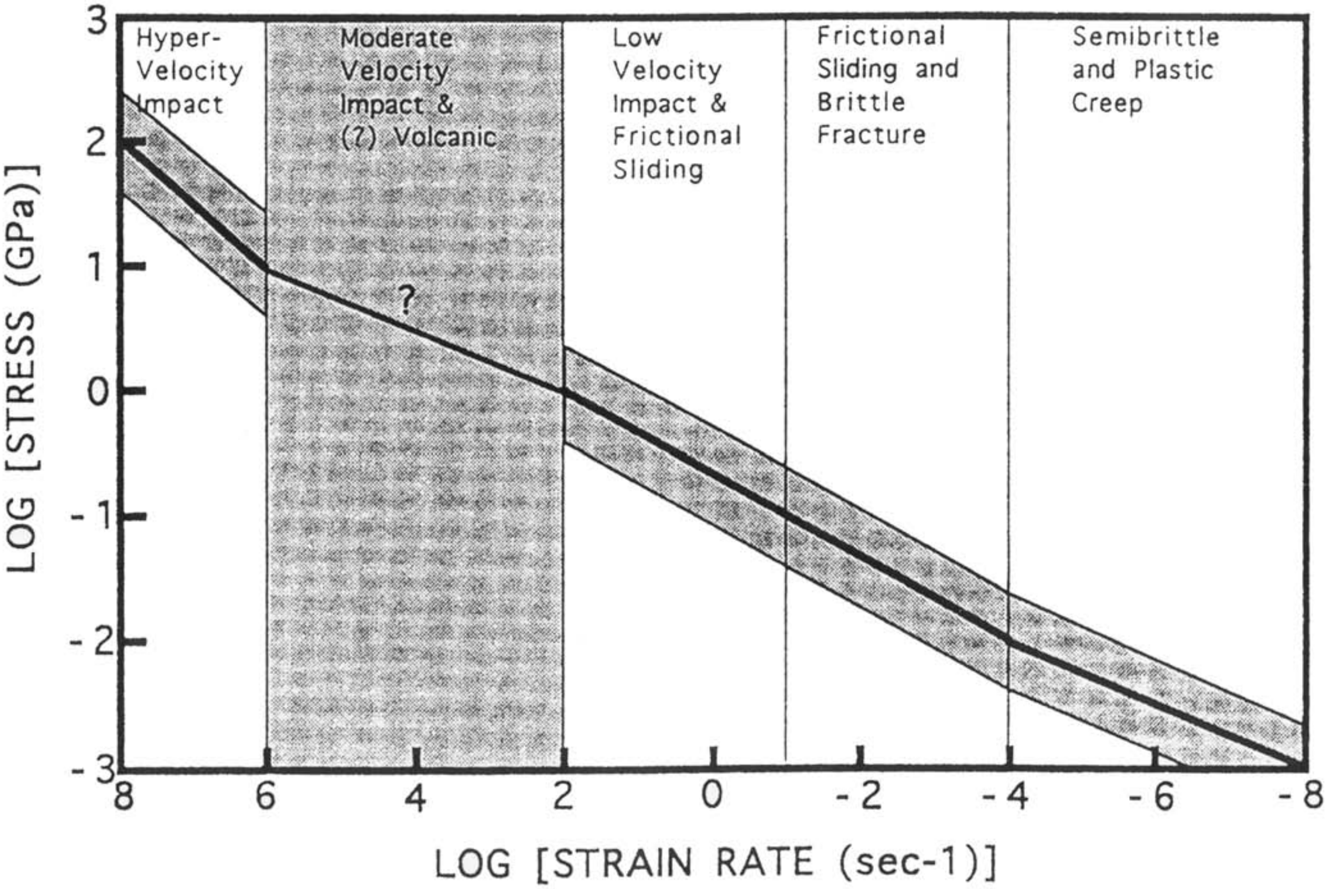

Fig. 8. A major challenge for future field work and experiments is to bridge the gap that exists between the conditions of meteorite impact and those of more normal geological deformation. On this stress-strain graph (Huffman and Reimold 1996, Fig. 1) (reproduced by permission of Elsevier Publishing Company), the high stress, high strain rate domain of meteorite impact (upper left) is separated from the lower stress, lower strain rate domain of other geological processes (lower right). The large gap between the 2 domains (note the logarithmic scale) still has to be explored by field studies of impact structures and by new experimental techniques.

However, many impact structures, especially deeply eroded ones in sedimentary rocks, are hard to date because they lack suitable impact melts or related breccia units (Bottomley et al. 1990; Deutsch and Schärer 1994).

The Rock Elm structure is typical in these respects (French and Cordua 1999; French et al. 2004). No lithologies suitable for isotopic age dating have been identified yet, and the age of the structure has been constrained only between Middle Ordovician (the age of the youngest preserved rocks involved in the deformation) and Pleistocene (the structure is overlain by glacial till), a spread of 400–500 Ma. Similar large uncertainties exist for many other impact structures in sedimentary rocks, especially in the mid-continent regions of the United States (Grieve et al. 1995).

In the absence of isotopic ages, it still may be possible to reduce such large age uncertainties for impact structures formed in sedimentary rocks. Grieve (1991, p. 191) pointed out that the present form of an eroded impact structure can be used to estimate the amount of post-impact erosion because impact structures, regardless of size, have a fixed topographic form and generally (if not precisely) known geometrical characteristics (Melosh 1989, chap. 5; Grieve 1991, 1998). These features are summarized in Fig. 10, a schematic cross-section for the Rock Elm structure, which shows both the standard impact crater parameters and the amount of post-impact erosion ($\Delta h$). The age of the impact can then, in principle, be calculated by combining estimates of: 1) the amount of post-impact erosion ($\Delta h$); and 2) the time interval ($\delta t$) originally required for deposition of the now eroded section of sedimentary rocks, the top of which would ideally have been the ground surface at the time of impact. This time interval can be roughly estimated from depositional rates ($r_s$) calculated for preserved sedimentary sections in the region. (The value of $r_s$ is the net depositional rate calculated from the preserved sedimentary section and does not include the effects of erosion during the time interval.) The time interval represented by the eroded section is then $\delta t = \Delta h/r_s$; subtracting this time interval from the ages of the youngest preserved rocks deformed by the impact can provide an estimate of the age of the impact.

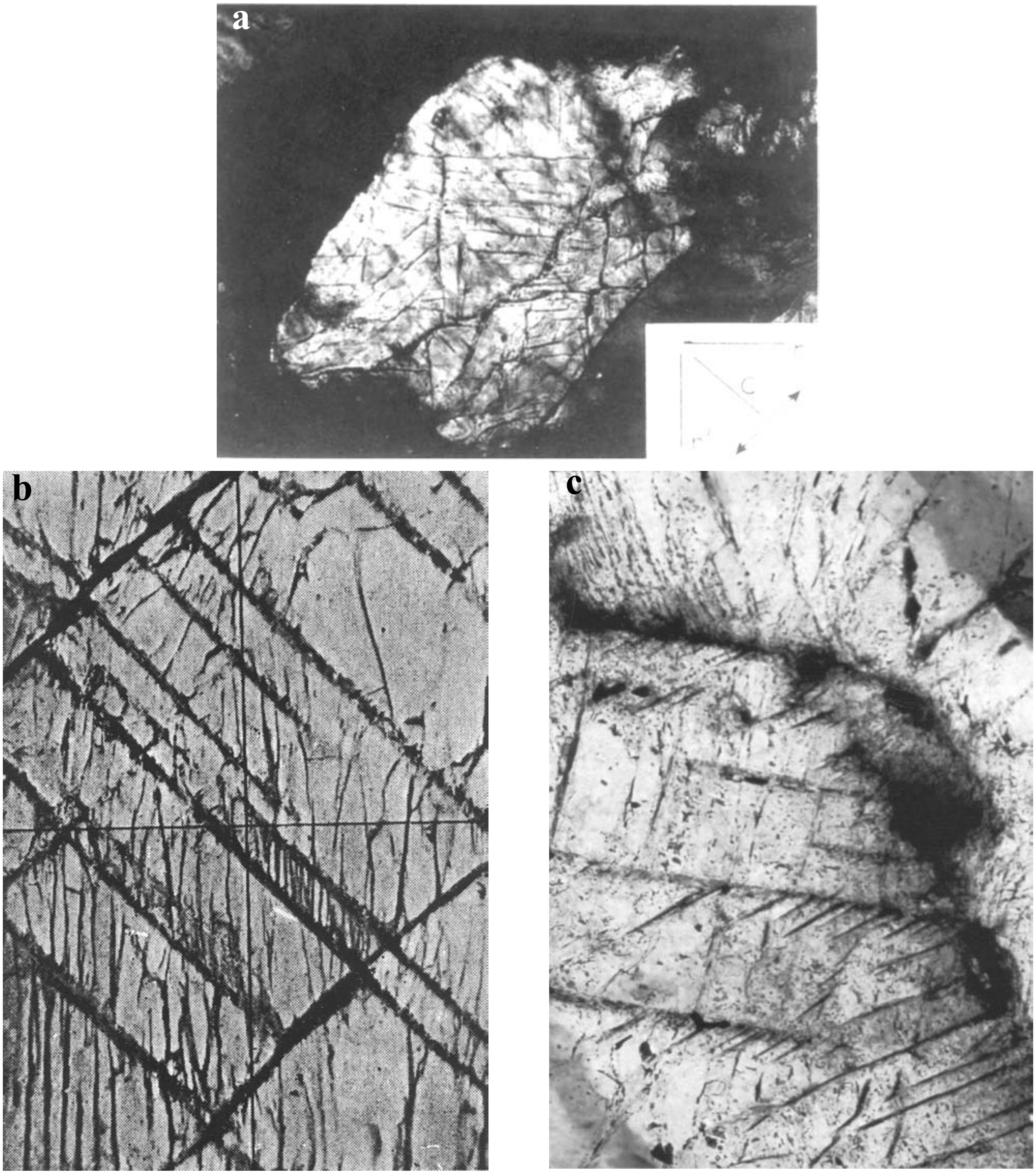

Fig. 9. Cleavage in quartz is commonly observed in meteorite impact structures and only rarely (if at all?) in terrestrial rocks from non-impact settings. The study of cleavage formation in both impact and non-impact environments may provide better information about the conditions of low-intensity shock deformation in impact events: a) multiple sets of parallel cleavage (PFs) in a shocked quartz grain from the Coconino sandstone at Meteor Crater, Arizona (Bunch and Cohen 1964, Plate 2, Fig. 1) (reproduced by permission of the Geological Society of America). The long dimension of quartz grain is about 0.5 mm; b) multiple cleavage sets produced in static pressure experiments on single crystal quartz at approximately 2.6 GPa (Christie et al. 1964, Plate 2b) (reproduced courtesy of the *American Journal of Science*). The long dimension of the field of view is about 1.5 mm; c) multiple sets of cleavage (PFs), accompanied by possible PDFs, in quartz from the Rock Elm structure, Wisconsin (French et al. 2004). Cleavages (PFs) appear as thicker, longer, and more widely-spaced parallel planes. Possible PDFs are narrower, shorter, and more closely spaced parallel planes; these features often originate from PF surfaces to form a kind of “feather structure” in the quartz. The long dimension of field of view is about 2 mm.

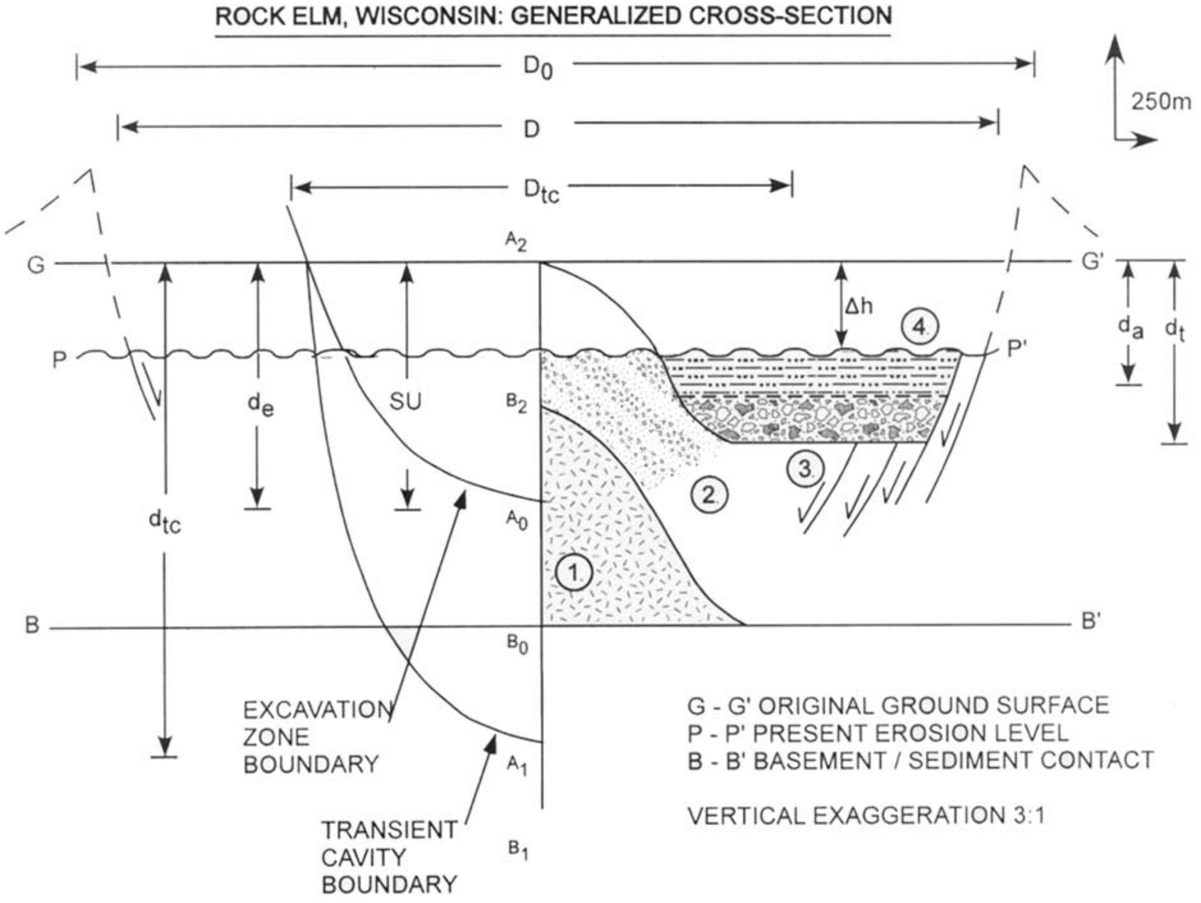

Fig. 10. Because impact structures have characteristic geometric shapes, their appearance can be used to estimate such geological factors as post-crater erosion and age. This schematic cross-section of the Rock Elm structure, Wisconsin (French et al. 2004) shows the idealized geology (right side) and typical crater parameters (left side); the vertical exaggeration is 3:1. Geological units involved in the structure (right side) are: 1) uplifted Precambrian basement rocks (not exposed); 2) overlying Paleozoic sandstones and carbonates; 3) crater fill breccias (not exposed); 4) crater fill sediments. The line G-G' indicates the original ground level at the time of impact; B-B' indicates the original contact between the Precambrian basement and the overlying sediments; and P-P' indicates the present erosion surface. The dashed line indicates the original rim of the structure. Typical crater parameters are indicated at left and above: $D_0$ = original diameter; D = present diameter at the current ground level; $D_{tc}$ = transient cavity diameter; $d_{tc}$ = transient cavity depth; $d_e$ = depth of excavation zone; $d_a$ = apparent depth of final (present) structure, from the original ground surface to the top of the crater fill breccias; $d_t$ = true depth of the final structure, from the original ground surface to the original crater floor; SU = stratigraphic uplift. The point $A_0$, originally in the center of the crater just beneath the excavation zone, is driven downward (to point $A_1$) during formation of the transient cavity and then rebounds with the central uplift to point $A_2$. The point $B_0$, located beneath the center of the transient cavity at the basement-sediment contact, moves in a similar manner, being driven downward (to $B_1$) during transient cavity formation and then rebounding (to $B_2$) with the rest of the central uplift. (For details on these parameters, see Melosh [1989], chapters 2, 5, and 7; Grieve 1991). A key parameter for a deeply eroded structure like Rock Elm is Δh, the vertical amount of erosion of the target stratigraphy from the original ground surface since the crater formed.

This method has been applied to narrow the current uncertainty for the age of the Rock Elm structure (French et al. 2004) (Fig. 11). Post-impact erosion at Rock Elm is estimated at 200–300 m on the basis of general morphological models and comparisons with other well-preserved impact structures (French et al. 2004). Estimates of regional sedimentation rates during the relevant time provide surprisingly consistent values of 5–8 m/Ma, giving δt values of 30–50 Ma. For preserved Middle Ordovician target rocks 480 Ma old, calculated impact ages are 420–440 Ma. Despite the large uncertainties in the estimated values of Δh and $r_s$, the results strongly indicate that the Rock Elm structure is almost certainly >400 Ma old and probably ~430 Ma old, which is a significant improvement on the previous age constraints.

These results, though uncertain, are valuable as a check on future paleontologic and isotopic dating if suitable material can be found. They may also constrain a possible stratigraphic interval in surrounding sediments, where ejecta from the Rock Elm structure might be found. More generally, similar calculations might be successfully applied to other old impact structures in sedimentary rocks, particularly to

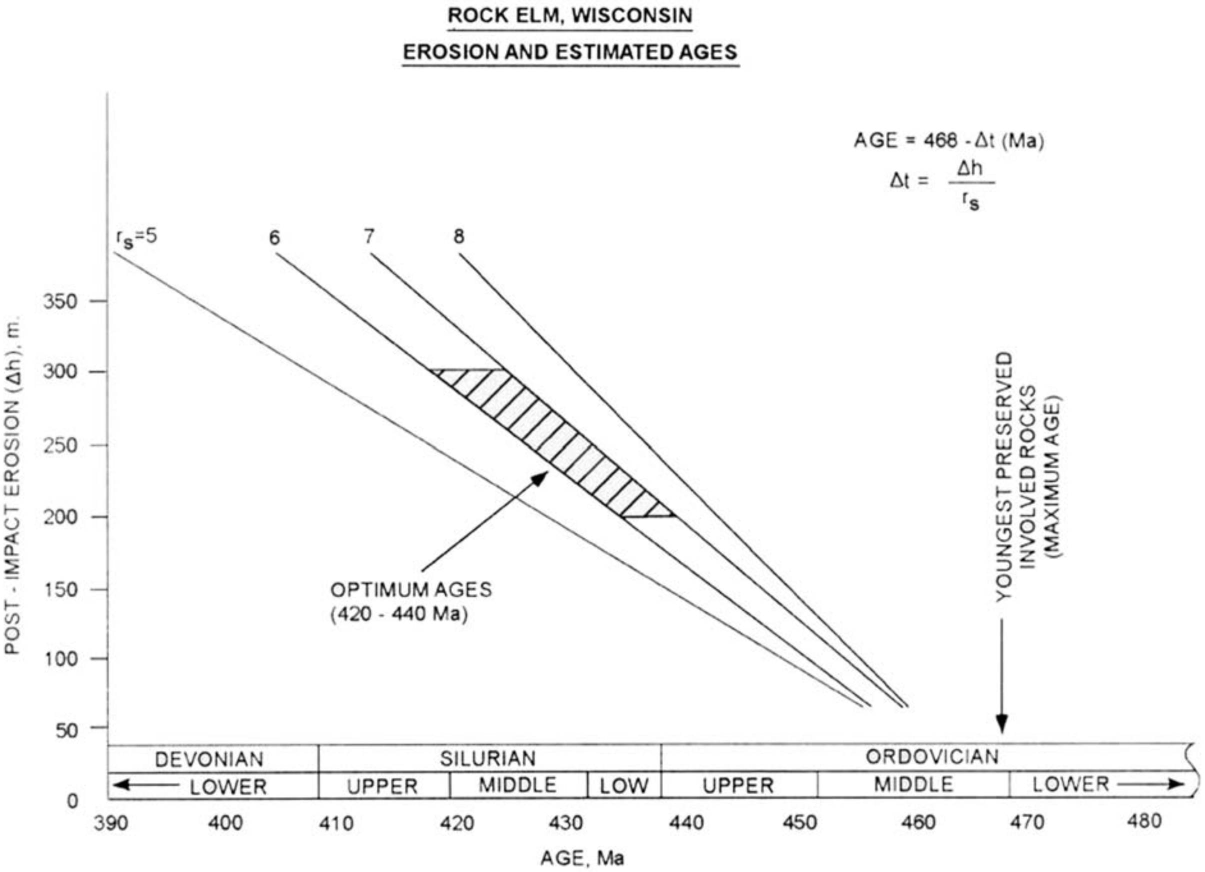

Fig. 11. Diagram showing the calculated age of the Rock Elm structure (Wisconsin) from estimates of pre-impact sedimentation rate and post-impact erosion (French et al. 2004). The diagram plots estimated values of the thickness of sediments eroded after impact (Δh) against geological age for various values ($r_s$) of the rate of pre-impact accumulation of the eroded sediments. The maximum age of Rock Elm is ~470 Ma, the age of the youngest exposed rocks involved in the structure. Average values of $r_s$ (6–7 m/Ma) and Δh (200–300 m) indicate that the thickness of eroded sediments represents 30–50 Ma of time, giving an age for the structure of 420–440 Ma.

structures developed in the platform sediments of the United States midcontinent region.

## WHAT NEXT? SOME OBVIOUS AREAS FOR FUTURE RESEARCH

The field of impact geology has finally reached the level of maturity where we can not only recognize a large number of unsolved problems but can also define specific investigations to attack them (e.g., French 1998, chap. 8; Montanari and Koeberl 2000, pp. 152–156). However, a major difficulty is that the number of exciting problems far exceeds the current number of active workers. To call attention to these problems and to stimulate work on them, a brief and incomplete menu of topics for future workers is presented below. It is not intended to be a complete list; instead, it describes topics that have already been recognized, the importance of which has been well-established, and that seem poised to yield exciting future discoveries.

The research problems that can be identified today have several factors in common: 1) they have already produced important and exciting scientific results, and they have the potential for even more exciting discoveries in the future; 2) many of them involve the interplay between impact events and more normal, internally produced geological processes; 3) they can, therefore, contribute to solving some major problems about the Earth and its history; 4) many key studies can be done with established geoscience methods and existing techniques; 5) they tend to promote the involvement of established geoscientists in impact-related activities; and 6) because of their scientific and public interest, these problems provide the current impact community with both the opportunity and the responsibility for efforts in communication and education to both scientists and the general public.

### Identification of New Impact Structures

Despite the large number of currently known impact structures (>150; Grieve 1998), many preserved terrestrial impact structures on our planet have still not been identified. Several hundred impact structures with diameters ≥10 km remain to be discovered on the land areas of the Earth (Trefil and Raup 1990; Grieve 1991); a large fraction of them will be subsurface structures.

In some ways, the simple identification of new impact structures is less difficult, and less important, than it used to be. Given the availability of suitable shocked samples, recognition of impact structures is relatively easy, almost literally "an exercise for the student." Nevertheless, the continued search for and identification of new impact structures is an important and fundamental activity. The current terrestrial database for preserved impact structures is strongly biased toward small, young structures (Grieve 1991, 1998; Grieve at al. 1995), It is especially important to expand the database of well-dated impact structures to explore unresolved questions about the impact rate, its possible variations, and the existence of impact "clusters" or comet "showers" in the past (e.g., Grieve et al. 1985, 1988).

Other biases in the current database also require the discovery and study of new impact structures. Most of our current database has been collected from impact structures in coherent target rocks, both crystalline and sedimentary. Many of our current cratering models and shock metamorphic criteria (e.g., PDFs), and their use in shock barometry, are based largely on studies of impact craters in crystalline rocks. Discovery of more impact structures should provide new examples of craters and shock metamorphism produced in different targets and different environments: basalts and other lava flows, carbonate and noncarbonate sedimentary target rocks, and unconsolidated sediments. Such impact structures will provide important insights into the effects of target properties on impact processes as well as new shock criteria.

New impact structures may also provide new variations on general impact themes. One example is the recent recognition in Argentina of a group of small craters (Rio Cuarto, Argentina) that appear to reflect the effects of highly oblique, low angle impacts into young unconsolidated sediments (Schultz and Lianza 1992; Aldahan et al. 1997). Although the impact origin of these features is still controversial (Bland et al. 2002), there are several other possible craters present in the same region (Schultz et al. 1998). Even these small features have significant geological implications, especially for deciphering the recent (Pliocene and younger) regional stratigraphy and for possible local extinctions.

## Marine Impact Craters

Impact craters formed partly or completely in the ocean floor are a special category of craters, which are now receiving significant recognition (e.g., Gersonde et al. 1997; Smelror et al. 2001; Dypvik and Jansa 2003). In some respects, this attention is long overdue. The predominance of seas, both shallow and deep, over the Earth during geological time insures that craters formed in marine environments (either on relatively shallow continental shelves or on deep-ocean abyssal plains) should greatly outnumber (by >2:1) those formed on land.

The number of preserved oceanic impact craters will be reduced by 2 factors: 1) the ocean floors are relatively young (<250 Ma) and preserve only that part of the Earth's impact record; 2) deep water will shield the ocean bottom from the impact of smaller projectiles (approximately <1 km in diameter) so that the resulting crater will be formed entirely in the water layer and is not preserved. Identification of deep-ocean impact structures is further restricted by the currently limited geologic knowledge of the ocean floor, the absence of systematic searches, and the difficulties of sample recovery from suspected sites.

Even so, marine impact craters are still under-represented in the current database. In addition to the Chesapeake Bay crater, USA (see above), 2 other established submarine structures are known from continental shelf regions, Montagnais, Canada (Jansa and Pe-Piper 1987) and Mjølnir, Norway (Dypvik et al. 1996; Tsikilas et al. 1999), both of which were discovered during hydrocarbon exploration. An unusual multi-ring structure (Silverpit) 20 km in diameter, of possible impact origin, has recently been identified by geophysical techniques on the bottom of the North Sea (Stewart and Allen 2002). Only a single deep water impact event has been identified so far, a Pleistocene impact of an object 1–4 km in size, named Eltanin, which produced impact melt droplets and significant disturbances of the bottom sediments but did not form a recognizable crater (Gersonde et al. 1997).

Fortunately, a growing number of impact structures on land have been identified as having formed in water of widely varying depths (e.g., Lindström et al. 1996), and it is now possible to make comparisons between them and subaerial impact structures (Ormö and Lindström 2000; Poag et al. 2003). A key factor in such marine impacts is the ratio, h/d, of the water depth (h) to the projectile diameter (d). For shallow water impacts (i.e., low h/d ratio), the water is irrelevant, and the resulting crater is virtually identical to a subaerial one. For deep water (high h/d ratio), the crater excavation zone is entirely in the water layer; no permanent crater is formed, although there may be significant disturbances of the bottom sediments by rapidly-moving water currents and tsunamis (Gersonde et al. 1997; Ormö and Lindström 2000; von Dalwigk and Ormö 2001; Dypvik and Jansa 2003).

The most significant differences between subaerial impacts and impacts in water occur at intermediate values of h/d. In such a situation, both the overlying water and a significant amount of underlying target rock are ejected during crater formation. The ejected water then returns to the impact site as a *resurge*, eroding the new crater rim and producing a crater fill sequence that is different from that in subaerial craters (Lindström et al. 1996; Ormö and Lindström 2000; von Dalwigk and Ormö 2001). Tsunamis formed by the ejected water can also produce distinctive erosional and depositional effects at large distances from the impact point itself (Dypvik and Jansa 2003).

Current studies emphasize the recognition of now-terrestrial impact structures originally formed under a water layer (Lindström et al. 1996; Ormö and Lindström 2000), the identification of impact-produced resurge sediments by shock metamorphic features (Therriault and Lindström 1995; von Dalwigk and Ormö 2001), and the application of computer models to both theoretical (Shuvalov 2002; Artimieva and Shuvalov 2001) and actual (Shuvalov et al. 2002) impact structures formed in deep water. Research areas for the future include examination of sediments surrounding the crater to identify geological and biological effects of impact (Dypvik and Attrep 1999; Smelror et al. 2002; Dypvik and Jansa 2003), the general examination of marine sedimentary sequences for impact signatures (Grieve 1997), and the systematic search for new impact structures beneath the present oceans.

## Impacts and Other Extinction Events

The association between impacts and major biological extinctions, now generally accepted for the K-T extinction (e.g., Ryder et al. 1996, and papers therein), is being actively explored at other recognized extinction boundaries (Sharpton and Ward 1990; Ryder et al. 1996; Montanari and Koeberl 2000; Buffetaut and Koeberl 2002; Koeberl and MacLeod 2002). So far, no match has been made between any other significant extinction and evidence for a coincident major impact event. A minor extinction recognized at the Eocene-Oligocene boundary ~34 Ma ago (Montanari and Koeberl 2000, pp. 130–136, 250–278) was apparently preceded (by 1–2 Ma) by 2 nearly simultaneous major impact events that formed the large Chesapeake Bay (USA) and Popigai (Russia) structures and that distributed 2 discrete layers of impact ejecta ~35.5 Ma old into the sedimentary record (Montanari et al. 1993; Clymer et al. 1996; Montanari and Koeberl 2000, pp. 130–136; Poag et al. 2003).

Proposed correlations of older extinctions have not yet been well-established. Shocked quartz with PDFs has been reported from the Triassic-Jurassic boundary, approximately 200 Ma old (Bice et al. 1992), at which another significant extinction is located. However, a firm connection between the shocked quartz and the actual extinction boundary has been difficult to establish (see Montanari and Koeberl 2000, pp. 151–152). A layer of possibly impact-produced spherules has been found close to the major Frasnian-Famennian (F/F) extinction boundary in the Late Devonian (~364 Ma) (Claeys et al. 1992), but a close correlation between the extinction and possible impacts at that time has not yet been established. The impact associated with the formation of the Alamo breccia (see above) appears to be ~3 Ma older (for details, see Montanari and Koeberl [2000], pp. 148–150 and references cited therein).

The extinction at the Permian-Triassic boundary ~250 Ma ago involved the greatest loss of life in any of the extinctions recorded in the geological record, ~85% of all living species (Erwin 1993). Not surprisingly, much effort has been spent in the search for evidence of a major impact at this location, but reports of impact signatures at the boundary are still controversial and not widely accepted. The studies have been hampered by the absence of Permian-Triassic sections on the younger ocean floors, by the rarity of good stratigraphic sections on land, and by the absence to date of well-verified impact indicators, such as Ir enrichments or PDFs in quartz, at the boundaries so far sampled (Retallack et al. 1998; Montanari and Koeberl 2000, pp. 150–151). The report of fullerenes ($C_{60}$ polymorphs or “buckyballs”) containing anomalous He at the boundary (Becker et al. 2001) remains ambiguous, the more so because the reported presence of fullerenes in impact structures (Becker et al. 1994) has not yet been generally accepted as a diagnostic impact criterion (see Farley and Mukhopadhyay 2001; Buseck 2002).

The search for impact evidence at other extinction boundaries is an active, expanding, and multidisciplinary research area, which combines impact geology, paleontology, sedimentology, and stratigraphy. Out of this complexity may come more and improved stratigraphic sections, a better understanding about the causes of extinction events, a wider range of geological criteria for impact, and an improved knowledge of the biostratigraphic history of the Earth.

## Distal Ejecta Layers

The discovery of the layer of distal ejecta from the Chicxulub crater associated with the K-T extinction (Alvarez et al. 1980; Alvarez et al. 1995) demonstrated that such ejecta could be transported over global distances and preserved over geological periods of time. As a result, searches for similar ejecta layers have been undertaken, and several such layers have now been identified in sedimentary rocks at regional or even global distances from known (and unknown) impact structures (Grieve 1997; Montanari and Koeberl 2000, chap. 3), and distal ejecta from other known impact structures continue to be identified (Sturkell et al. 2000; Montanari and Koeberl 2000, p. 152).

Early identifications involved ejecta transported hundreds of km from the Acraman (Australia) structure (Williams 1986; Gostin et al. 1986) and from the Manson (Iowa) structure (Izett et al. 1993). It is now generally accepted that the long-studied tektites (Koeberl 1986, 1990) and microtektites (Glass 1967, 1968, 1990) are also distal ejecta from impact craters (Montanari and Koeberl 2000, chap. 3). An especially active research area has been created by the discovery of recrystallized glassy spherules of probable impact origin in Proterozoic and Archean sediments (see discussion above).

More recently, impact ejecta layers have been identified close to (but not exactly at) the Eocene-Oligocene (34 Ma) and Frasnian-Famennian (364 Ma) boundaries, both of which are marked by significant extinctions (see discussion above). Another ejecta layer has recently been recognized in the Late Triassic (Walkden et al. 2002). The measured age for the layer (214 Ma) is close to that of several established impact structures (Spray et al. 1998). Current uncertainties in the age determinations are too large to establish a firm connection between the ejecta layer and any of the structures.

It is now clear that distal crater ejecta constitute an important component of impact-produced material and that they can also provide important tools for stratigraphy and time correlation (Grieve 1997). Numerous problems remain (Montanari and Koeberl 2000, chap. 3): 1) discovering other distal ejecta units in the stratigraphic record; 2) identifying (if possible) specific ejecta layers with specific craters, using mineralogical and geochemical criteria (e.g., Whitehead et al. 2000); and 3) searching for ejecta layers from impact events that occurred on the early Earth 3.5–4 Ga ago, especially those for which the original craters are no longer preserved or recognizable.

## Impact Melts: Comparative Petrological and Petrogenetic Studies

Bodies of melted target rock, ranging in size from sub-mm glassy spherules to coherent crystalline units hundreds of m to km thick, are an important product of impact events (Dence 1971; Grieve et al. 1977; Dressler and Reimold 2001; Whitehead et al. 2002). Such impact melt rocks can provide several types of independent evidence for the impact origin of the structures in which they are found: 1) shock effects in xenoliths of target rock (French et al. 1970); 2) anomalously high contents of siderophile elements derived from the projectile (Palme 1982; Koeberl 1998); 3) matches between unusual chemical compositions in the impact melt and in the associated target rocks (e.g., French and Nielsen 1990).

Because impact melts form under physically and chemically constrained conditions, impact melts can be used as valuable analogues (“terrestrial laboratory experiments”) to study the generation, emplacement, cooling, and crystallization of melt bodies produced under both impact and non-impact conditions (see also discussion above). Although few large impact melt bodies have been studied in detail yet, the SIC body in the Sudbury structure, Canada has been a special focus of studies aimed at understanding the details of formation of the SIC itself (Lightfoot et al. 1997a, b, 2000; Therriault et al. 2002) and exploring the mechanisms of crystallization for such large bodies in general (Marsh 2002; Zieg and Marsh 2001, 2002).

Although the SIC is the largest body of impact melt so far identified, several other structures contain thick (hundreds of m) impact melt layers that could provide information about impact processes on smaller scales, e.g., Manicouagan (Canada), Popigai (Russia), and Morokweng (South Africa) (see Dressler and Reimold 2001, and references therein).

Despite the studies at Sudbury and other structures, terrestrial impact melts still represent a largely unstudied reservoir of preserved information about crater formation, the conditions of target rock fusion, and the emplacement, mixing, cooling, and crystallization of both impact melts and non-impact endogenous igneous rock bodies (Dressler and Reimold 2001). A major unstudied problem is the degree of mixing involved in impact melt formation and the degree of chemical heterogeneity preserved in impact melt bodies. Early studies concluded that larger impact melt bodies are well-mixed, homogeneous combinations of the exposed target rocks involved in crater formation (Dence 1971; Grieve 1975, 1978; Grieve et al. 1977). However, more recent studies indicate that large chemical variations, some reflecting fractionation and inhomogeneous distribution of the projectile, can exist in smaller (cm-size) impact melt bodies ejected from small craters (See et al. 1998; Hörz et al. 1989, 2002). The mechanisms of melting and mixing involved in impact melt formation also need to be explored further; one approach is to assess the degree of chemical heterogeneity preserved in small, rapidly cooled bodies of impact melt that occur in small impact structures (e.g., Grieve 1978) or as small dikes in the basements of larger structures (e.g., the Vredefort Granophyre at Vredefort [South Africa]; Reimold et al. 1990; French and Nielsen 1990; Therriault et al. 1997b) or Sudbury (Canada) (e.g., Tuchscherer and Spray 2002).

A related question involves the origin and preservation of chemical heterogeneity in very large impact melt bodies. Do such variations result from incomplete mixing of a range of chemically different target rocks? Or, do they represent the results of mineralogical and chemical differentiation, in place, during cooling? A special focus has been the SIC, which has long been known to be composed chiefly of 2 distinct units, an upper silicic granophyre (“micropegmatite”) and a lower gabbro (“norite”) (e.g., Lightfoot et al. 1997a, b, 2000; Therriault et al. 2002). Such studies are also important for understanding the amount of chemical heterogeneity that can be produced in nonterrestrial impact melts and, thus, for resolving whether certain lunar igneous rock types reflect endogenic magmatic processes or have been formed by differentiation of large bodies of impact melt produced during formation of the mare basins (e.g., Grieve et al. 1974; Taylor et al. 1991; Warren et al. 1996).

The formation of terrestrial impact melts may also have important implications for understanding the production of biological extinctions from major impact events. Studies of the K-T impact event and the Chicxulub crater indicate that oxides of carbon and sulfur produced by decomposition of sedimentary target rocks could have been a major contributor to environmental effects and the resulting extinctions (Kring 1993; Pope et al. 1994, 1997). However, the recent discovery of immiscible carbonate-rich melts associated with impact melts and breccias in other structures (Graup 1999; Osinski and Spray 2001) suggests that some of the $CO_2$ in carbonate target rocks may be retained in the impact structure, as carbonatitic melts and will not be dispersed into the atmosphere to produce significant environmental effects. The formation and significance of these carbonate-rich impact melts are not yet clearly understood; one problem still to be resolved is the inconsistency between the apparent abundance of such melts and a number of experimental shock wave studies (Martinez et al. 1995; Agrinier et al. 2001) that suggest that little melting of carbonate should occur in impact events, even at high shock pressures. A better understanding of impact-produced carbonate melts may also provide important comparative information about the origin and emplacement of similar, but internally generated, terrestrial carbonatite magmas (e.g., Tuttle and Gittins 1966; Bell 1989; Bell et al. 1998). The recent recognition of anhydrite-bearing impact melts at the Haughton (Canada) structure (Osinski and Spray 2003) suggests that similar melting and retention mechanisms may also be involved in the production of sulfur oxides from sulfate-bearing sedimentary rocks.

## Post-Impact Processes: Hydrothermal and Sedimentary Settings

Some of the closest links between impact structures and traditional geology arise not from the direct effects of the impact event itself but from the subsequent long-term actions of geological processes in the resulting impact structure.

The sudden formation of an impact structure creates a major perturbation on the geological landscape by introducing a large amount of energy into what is a single location on the Earth's surface. Mechanical energy, reflected in deformation and brecciation of the target rocks, can create important sites for the later introduction of ore deposits and hydrocarbons (Grieve and Masaitis 1994; Donofrio 1997; Johnson and Campbell 1997). In addition, impacts produce a significant amount of near-surface heat, both from the initial shock wave (short-term) and from cooling of impact melts and glass-rich impact breccias (long-term). The introduction of available fluids into this near-surface thermal anomaly may produce extensive hydrothermal activity and may even lead to the formation of hydrothermal ore deposits.

The presence of such post-impact hydrothermal activity has long been recognized by its effects on the chemistry of impact melts and breccias (e.g., the introduction and/or exchange of alkalis) (Dence 1971; French et al. 1997). Later studies have identified specific post-impact hydrothermal units, such as veins and similar bodies, in numerous impact structures (Newsom et al. 1986; McCarville and Crossey 1996; Boer et al. 1996; Kirsimäe et al. 2002; Naumov 2002). Such units provide important information about post-impact conditions in and around impact structures and also have significant implications for the study and sampling of impact deposits on Mars (e.g., Allen et al. 1982; Newsom et al. 2001).

An impact event produces a shallow basin. Depending on the regional geological conditions at the time of impact, this basin may be immediately filled with sediments. This sedimentary fill may be preserved from erosion, thus providing a sedimentary and climatic record not otherwise available in the region (Grieve 1997). Some impact craters have already become the sites of important studies of post-impact stratigraphy, paleontology, and paleoclimatology (Beales and Lozej 1975; Partridge et al. 1993), but important opportunities are still provided by other impact structures that have crater-filling sediments that have not yet been studied in detail, e.g., Gardnos (Norway) (French et al. 1997) and Bosumtwi (Ghana) (Koeberl et al. 2002).

These studies have even wider implications for more general problems in Earth history, especially for the origin of life on the early Earth. The combined products of an impact event—a shallow basin, heat, and hydrothermal fluids—may create exactly the type of "warm little pond" envisioned for biological synthesis or even the origin of life (Farmer 2000; Kring 2000; Osinski et al. 2001). Although such original environments may no longer be available to study, study of preserved impact structures and their crater-filling deposits may provide detailed information about whether and how post-impact crater environments could have served as sites for the origin of terrestrial life (Cockell et al. 2001, 2002; Cockell and Lee 2002)

## Impacts and the Early Earth

Studies of impact craters on the Moon and other planets have demonstrated that the impact rate 3.9 Ga ago must have been orders of magnitude greater than the present observed rate (Taylor 1982, 1992; Ryder 1990). Impacts of large extraterrestrial objects would have been a major supplier of energy and chemicals to the primordial Earth (Grieve 1980). The large community of traditional geologists involved in problems of Precambrian history, continent formation, and the origin of life needs to be more aware of impact processes and their implications and to include them in their future studies.

Possible effects of major impacts on the early Earth have been widely discussed (e.g., Gilmour and Koeberl 2000). These include: 1) introduction of "precursor" biological chemicals to the Earth; 2) creation and modification of the Earth's early atmosphere (Kastaing 1990); 3) the "impact frustration" of developing life by impact-produced extinctions (Oberbeck and Fogelman 1990; Gogarten-Boekels et al. 1995); 4) generation of regional or even global near-surface melting; and 5) creation of continental nuclei and early proto-plate tectonics (Grieve 1980; Frey 1980; Glikson 1993, 2001).

The implications are exciting, but further investigations face major problems. The geological record is largely absent;

preserved crustal rocks are generally ≤3.8 Ga, and there are few crustal indicators of older events. The oldest known impact structures are only ~2 Ga old. Detailed studies of these problems will have to be done by a mixture of speculation and exploration. Possible approaches include: 1) examine older crustal regions (≥3.0 Ga) and their sediments for as yet unnoticed signs of impact (e.g., Weiblen and Schultz 1978; Koeberl et al. 2000), including a more thorough search for and study of Archean impact spherule layers; 2) develop methods for identifying impact structures in deformed and metamorphosed Precambrian terranes using structural (e.g., Kenkman et al. 2000), metamorphic (Gibson and Reimold 2000; Lana et al. 2003), and geochemical (Schoenberg et al. 2002) information; and 3) study ancient impact structures, both known and possible, as models for larger and older ones. The fact that many such studies will have negative results (e.g., French 1990a; Koeberl et al. 2000; Ryder et al. 2000) should not prevent them from being carried out.

## CARBON IN IMPACT STRUCTURES

Of the many areas in which impact geology has come into contact with traditional geological studies, one of the most interesting (to me, at least) involves the occurrence of carbon species and organic materials in impact structures and their rocks. In this area, recent impact studies have become connected with several important and long-established areas of geology: carbon mineralogy, carbon chemistry, organic geochemistry, and Precambrian geology. The problems of carbon in impact structures also have important implications for more recent interdisciplinary questions, such as the original sources of biological chemicals, the nature of early biological environments, the nature of the impact process, and the effects of impacts on the early Earth.

The occurrence of specific carbon compounds in impact structures has recently received considerable attention (Gilmour 1998). Impact-produced diamonds, created by shock metamorphism of graphite in target rocks, have now been recognized at several impact structures (Masaitis et al. 1972; Koeberl et al. 1997; Masaitis 1998; Masaitis et al. 1999; Gilmour 1998, 1999; Abbott et al. 2001). Widely distributed, finely crystalline "nanodiamonds," possibly produced by chemical vapor deposition (CVD) reactions during impact, have been reported from at least 2 impact sites (Carlisle and Braman 1991; Hough et al. 1995, 1997). The occurrence of fullerenes or "buckyballs" ($C_{60}$ and related compounds), originally reported from the Sudbury (Canada) impact structure (Becker et al. 1994), has been used more widely as an impact criterion (Becker et al. 2001), but these observations, and the existence of impact-produced fullerenes themselves, remain controversial (e.g., Bunch et al. 1999; Heymann et al. 1999; Taylor and Abdul-Sada 2000; Farley and Mukhopadhyay 2001; Buseck 2002).

A less appreciated observation is that high contents of carbonaceous material ("organic" carbon or kerogen) are found in impact breccias and post-impact sediments associated with two impact structures (Table 1), the small Gardnos (Norway) structure (French et al. 1997; Gilmour et al. 2003) and the much larger Sudbury (Canada) structure (French 1968b; Pye et al. 1984). The nature of the carbon in these structures, and the reasons for the absence of organic carbon in impact structures generally, presents a group of problems that need to be investigated in detail.

Gardnos is a small (D = 5 km) structure in southern Norway (French et al. 1997). The structure is not unusual except for the high organic carbon contents (0.1–>1 wt%) present in brecciated subcrater rocks, melt-bearing breccias within the crater, and post-impact crater-fill sediments. The exposed target rocks, which typically contain 5–10 times less carbon, cannot be the source of the carbon, and no other source has been definitely identified yet. The carbon has an isotopic signature in the terrestrial "biological" range ($\delta C^{13} = -25$ to $-30$ permil) (French et al. 1997; Gilmour et al. 2003), suggesting possible derivation from a layer of now-eroded black shale, but other explanations more closely connected with the impact event itself (meteoritic components, unusual chemical reactions in the impact plume, etc.) need to be explored.

The largest known reservoir of impact-related carbonaceous material is in the Sudbury structure (Canada) (French 1968b, and references therein; Guy-Bray 1972; Pye

Table 1. Characteristics of carbon-bearing impact structures: Gardnos (Norway) and Sudbury (Canada).

| Feature | Gardnos, Norway | References[a] | Sudbury, Canada | References[a] |
|---|---|---|---|---|
| Diameter (km) | 5 | 1 | approx. 250 | 3, 4 |
| Age (Ma) | 400–900 | 1 | 1,850 | 4 |
| Carbon location | Allochthonous breccias; brecciated basement rocks | 1 | Allochthonous breccias (Onaping fm.) | 4, 5, 6 |
| Volume of C-bearing impactites (km$^3$) | 2.7 | 1 | 1,700 | 5, 7 |
| Typical C contents (wt%) (average) | 0.3–1.0 (0.65) | 1 | 0.3–0.9 (0.65) | 6, 7, 8 |
| Total C present (gm) | $5 \times 10^{13}$ | 1 | $3 \times 10^{16}$ | 5 |
| | | | $3 \times 10^{17}$ | 8 |
| Exotic C species | Diamonds | 2 | Diamonds | 9 |
| | | | Fullerenes ($C_{60}$)(?) | 10 |

[a] References: 1) French et al. 1997; 2) Gilmour 1999; 3) Gilmour 1999, personal communication; 4) Pye et al. 1984; 5) Stevenson 1972; 6) Avermann et al. 1994; 7) Bunch et al. 1999; 8) Heymann et al. 1999; 9) Masaitis et al. 1999; 10) Becker et al. 1994.

et al. 1984) (Fig. 12). Most of the Sudbury carbon occurs as poorly-characterized carbonaceous organic material ("kerogen") in a distinctive unit of crater-filling impact breccia, the Onaping formation. In the black, carbon-rich upper part of the unit (Muir and Peredery 1984; Avermann 1994; Bunch et al. 1999; Heymann et al. 1999), carbon contents of 0.1–1 wt% are typical. This "Black Onaping" is a large and significant unit, even in the wider context of Precambrian organic geochemistry, with a thickness of nearly 1 km and a preserved volume of ~2000 km$^3$. The carbonaceous material is widely distributed in the breccia, occurring in a black opaque matrix with clasts of target rocks and glassy melt fragments (Fig. 13).

Despite the significant amount of carbonaceous material present in the Gardnos and Sudbury impact structures, especially in the latter, the nature, composition, and origin of the material have not been explored in detail. The sources of the carbonaceous material have not been established, and several possibilities exist: 1) carbon-rich target rocks (e.g., "black shales") could provide material with the observed "biological" $\delta C^{13}$ values (–25 to –34 permil) (French et al. 1997; Bunch et al. 1999), but such units have not been observed in place at either Gardnos or Sudbury. (If such units were the source, then the possible transformations of the original carbonaceous material by the impact conditions would constitute another interesting and unexplored group of impact-related problems.); 2) meteoritic carbon compounds, which have typical $\delta C^{13}$ values of −10 to −20 permil (Kerridge 1985; Grady and Wright 2003) could also be present in significant amounts without producing changes in the bulk isotopic composition; 3) carbonaceous compounds might be produced by unspecified reactions during impact, involving the atmosphere, the hydrosphere, or carbonate target rocks (e.g., Hochstim 1965), although, so far, there is no evidence that such reactions have occurred in any impact event; 4) carbon could be generated by post-impact biological activity in the impact basin and introduced into the basin-filling impact breccias (Heymann et al. 1999); and 5) carbon could also be introduced during post-impact metamorphism, possibly long after impact (French et al. 1997).

The linkages between carbon and impact geology are potentially important, multidisciplinary, and exciting. It is surprising that the wide range of problems has been so little explored as yet. Aside from the preliminary studies on carbonaceous material at Gardnos and Sudbury (see discussion above), only a few investigators have begun to explore the effects of shock waves and the impact environment on carbonaceous target materials (Mimura 1995; Zbik et al. 2000; Hofman et al. 2001; Vishnevsky and Palchik 2002).

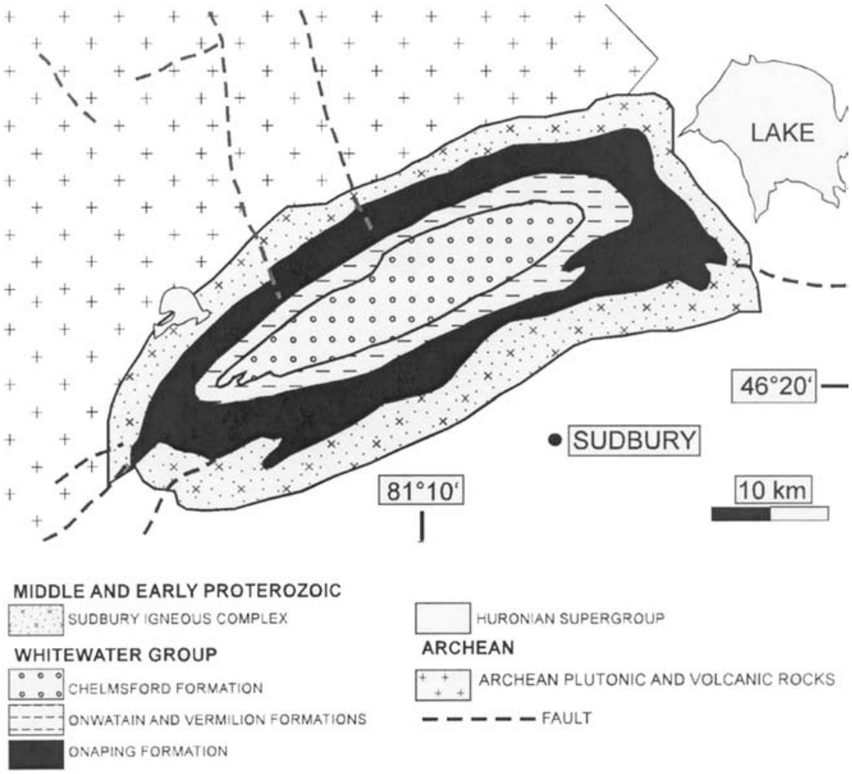

Fig. 12. Simplified geological map of the Sudbury structure (Canada) showing the carbon-bearing impact breccia (Onaping formation; black) and the overlying crater-fill sediments (modified from Ames et al. 1998, Fig. 1; reproduced by permission of the Geological Society of America). The upper part of the Onaping formation (so-called "Black Onaping") is a carbon-rich unit approximately 1 km thick, has an estimated volume of ~1700 km$^3$, and a present outcrop area of about 16,700 km$^2$. The unit contains approximately 0.5 wt% C or a total carbon content of about $10^{14}$ kg.

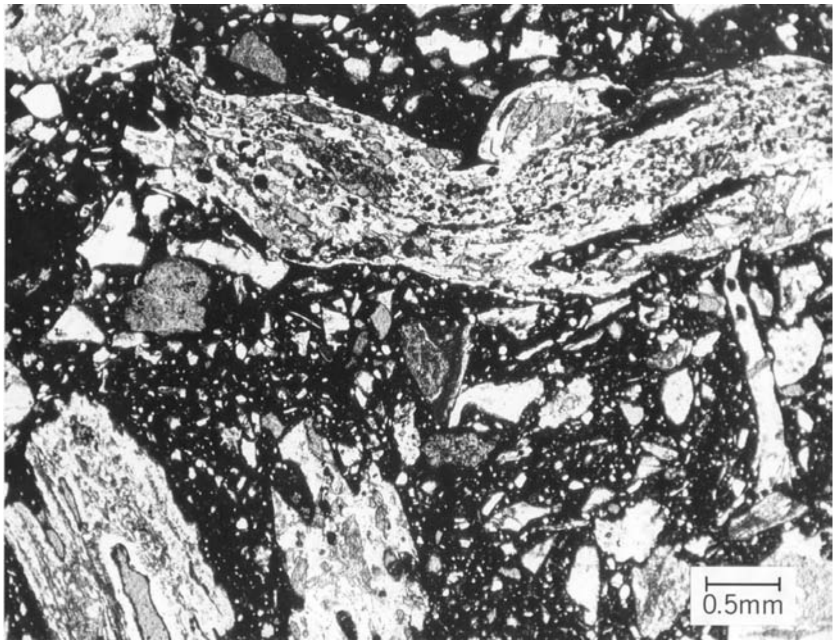

Fig. 13. Photomicrograph of a thin section of the "Black" Onaping formation, a crater-filling impact breccia from the Sudbury structure (Canada). (French 1967, 1968b). The "Black" Onaping formation is a black, poorly sorted breccia containing target rock and mineral fragments, together with vesicular, flow-banded fragments of impact glass, in an opaque carbonaceous matrix. The unit has been metamorphosed to greenschist facies; no isotropic glasses remain, and the rock is now composed chiefly of quartz, feldspar, chlorite, and green amphibole. Despite metamorphism, original textures are clearly preserved. Clast fragments smaller than 25 μm can still be distinguished, and PDFs can be detected and measured in quartz clasts.

It seems to me that the Sudbury structure, in particular, is a ripe and obvious target for detailed and systematic multidisciplinary studies of the Onaping formation and its carbon, studies that should combine geology, petrology, carbon chemistry, and organic geochemistry. Sudbury is an ideal site for such studies. Although deformed after impact, Sudbury preserves the general structure of the original impact basin, as well as a wide variety of impact lithologies, both in the subcrater basement and in the crater-fill deposits. The structure contains a large amount of carbon. Diamonds and possible fullerenes have already been identified in carbonaceous material from the Onaping formation. The Onaping Formation and related units are accessible, well-exposed, and well-drilled. So far, studies have focused on the detection of specific carbon species (diamonds and fullerenes) and not on a systematic study of the total carbon inventory.

Exploring the nature and origin of the Sudbury carbon will shed important light on the details of the impact event itself and the post-impact history. As a random speculation, I suggest that Sudbury might even provide a preserved Precambrian analogue for the kind of "warm little pond" environment in which an impact structure could have sheltered and promoted the early development of life. Perhaps the Vermillion formation (Rousell 1984; Ames et al. 1998), a base-metal-bearing unit located just above the Onaping formation, contains traces of a biological fauna that developed in the basin after the major impact effects had subsided.

## SO BACK TO WORK

The field of impact geology, once on the far fringes, has now established a solid and respectable position in the geoscience mainstream. The once-exotic area of impact crater studies is now becoming an important part of the study of our own planet and its history. In this process, the field has changed and grown, moving from the simple identification of individual impact structures to exploring the effects of impacts in the geological record.

Impact geology is a multidisciplinary field. Its problems and potential discoveries now spread over a wide range of disciplines: structural geology, igneous petrology, geochemistry, isotopics, geophysics, and Precambrian history, to name a few. Impact geology also has major implications for the fields of biology, paleontology, and stratigraphy, and it is a key component of the relatively new discipline of astrobiology.

Today's so called "impact geology community" needs, in a sense, to abolish itself by bridging the artificial gaps that have existed between impact studies and the established areas of "mainstream" geology. There should no longer be a mental gap between "impact geologists" and other geologists. There should only be geologists who study impact craters for the same reasons that other geologists study volcanoes, earthquakes, mountains, and tectonic plates—to probe the problems of the Earth, its past, and its present.

I hope that this paper will excite more scientists, both geoscientists and others, to get involved in the problems of impact geology, and I hope it will provide some useful background to help them get started. The field is still young, exciting, and unpredictable, and the unexpected will continue to play a major role in its development. I am glad that I cannot predict what will happen next or what discoveries may be made. The impact research of the future will involve new and closer looks at the existing terrestrial geological record. It will involve looking at once-studied rocks again and seeing them in new ways. The results will be exciting, stimulating, and sometimes unexpected. Now that I, like Mark Twain, am "on the verge of being an old man," I look forward to being involved in what comes next.

*Dedication*–This paper is dedicated to Prof. Robert B. Hargraves (1928–2003), a long-time friend and colleague, who was one of the first young geologists to move into impact geology in the 1960s. His early studies of shatter cones at Vredefort (South Africa) helped construct the foundation for the present general acceptance of the impact origin of that structure, and he subsequently combined impact geology with geophysics and planetary science to produce a valuable and rewarding career.

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*Editorial Handling*—Dr. E. Pierazzo and Dr. R. Herrick

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