

Observations and interpretations at Vredefort, Sudbury, and Chicxulub: Towards an empirical model of terrestrial impact basin formation

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Abstract—The structural, topographic and other characteristics of the Vredefort, Sudbury, and Chicxulub impact structures are described. Assuming that the structures originally had the same morphology, the observations/interpretations for each structure are compared and extended to the other structures. This does not result in any major inconsistencies but requires that the observations be scaled spatially. In the case of Vredefort and Sudbury, this is accomplished by scaling the outer limit of particular shock metamorphic features. In the case of Chicxulub, scaling requires a reasoned assumption as to the formation mechanism of an interior peak ring. The observations/interpretations are then used to construct an integrated, empirical kinematic model for a terrestrial peak-ring basin. The major attributes of the model include: a set of outward-directed thrusts in the parautochthonous rocks of the outermost environs of the crater floor, some of which are pre-existing structures that have been reactivated during transient cavity formation; inward-directed motions along the same outermost structures and along a set of structures, at intermediate radial distances, during transient cavity collapse; structural uplift in the center followed by a final set of radially outward-directed thrusts at the outer edges of the structural uplift, during uplift collapse. The rock displacements on the intermediate, inward and innermost, outward sets of structures are consistent with the assumption that a peak ring will result from the convergence of the collapse of the transient cavity rim area and the collapse of the structural uplift.

INTRODUCTION

Impact structures are the result of the hypervelocity impact of an asteroidal or cometary body with a planetary surface. They are ubiquitous surface features on all of the terrestrial planets and impact is now recognized as a fundamental geologic process in the solar system (e.g., Taylor 2001). This is most evident on bodies that have retained portions of their early crust, such as the Moon, where there is abundant evidence that impact was a dominant process in early crustal and surface evolution. The most obvious features of the lunar surface are the traces of the large multi-ring basins, which, by virtue of their size, had the most profound effect of all impact structures on lunar surface and crustal evolution (Spudis 1993). Unfortunately, details of the formation of such large impact structures are among the least understood aspects of our current knowledge of cratering mechanics.

Impact is a highly transient event, involving extremely high pressures, temperatures, and strain rates, all of which make impact processes inherently difficult to study. Over the years, understanding of cratering mechanics has evolved from a combination of observations from sources ranging from remote-sensed planetary data, the results of relatively small-scale impact experiments, nuclear and other high energy explosions, geological and geophysical observations at terrestrial impact structures and the results of various computation, most recently hydrocode, models (e.g., Pierazzo and Herrick 2004). Observations from the terrestrial impact record, however, are currently the only source of ground-truth information on the three-dimensional lithological and structural character of natural impact structures.

The three largest known terrestrial impact structures, Vredefort (South Africa), Sudbury (Canada), and Chicxulub (Mexico), all have some evidence for various expressions of ring forms. They had similar target characteristics, namely,

several kilometers of (meta-) supracrustal rocks overlying granitoid crystalline basement. At Vredefort, McCarthy et al. (1986) noted a series of concentric anticlinal and synclinal structures that extend out to a diameter of some 300 km from the central uplifted core of basement rocks. At Sudbury, evidence has been presented for annular zones characterized by an apparent increase in the occurrence of pseudotachylitic breccia and there are claims of rings of lineaments in Landsat imagery north of the Sudbury Igneous Complex (SIC), which have been equated with various attributes related to transient cavity formation and subsequent modification (Spray et al. 2004). At Chicxulub, there are ring structures in the potential field geophysical data that have been related to crater structure. The interpretative models derived from these data, however, are very different in detail (cf. Pilkington et al. 1994; Espindola et al. 1995; Sharpton et al. 1996). Nevertheless, the interpretation of offshore reflection seismic data leaves no doubt as to the existence of an inner topographic peak ring with a diameter of ~80 km at Chicxulub (Morgan and Warner 1999a and 1999b; Turtle et al. 2005).

Previously, some degree of commonality between Vredefort, Sudbury, and Chicxulub had been noted, but how the various “rings” at the individual structures were physically or genetically related to each other, and to the topographic rings observed in large impact basins on the other terrestrial planets, was not explicit at the time (Grieve and Theriault 2000). Apart from intrinsic observational uncertainties, it has become clear that there were also ambiguities in terminologies, e.g., in the definition, or lack of definition, of terms such as diameter, between previous works dealing with morphometric aspects of these structures. Recently, Turtle et al. (2005) reviewed many of the previous aspects of the ambiguities in terminology regarding the morphology of complex impact structures and, specifically, reviewed the situations at Vredefort, Sudbury, and Chicxulub. In response to their plea to avoid semantic misunderstanding by being consistent and explicit, their recommended terminology is used here. The definitions that are applicable here are paraphrased as:

Rim (or final crater) diameter: diameter of the outermost slump block not concealed (by ejecta) at a complex crater.

Apparent crater diameter: diameter of the outermost ring of (semi-) continuous concentric faults.

Peak-ring diameter: diameter of the peak of an internal, topographic ring that rises above the apparent crater floor.

Turtle et al. (2005) also noted that it is the apparent crater diameter that is generally the only measurable diameter at the majority of terrestrial impact craters because of the effects of erosion. The ambiguities in diameter estimates due to erosion and insufficient definitive information have been noted previously (e.g., Grieve and Shoemaker 1994) and the past general use of the term diameter, particularly by the first author, has been generally in reference to apparent crater

diameter (Turtle et al. 2005). In addition to using the terminology of Turtle et al. (2005), we have assumed from the outset that all three structures originally had a similar ring basin morphology, i.e., they originally displayed an inner peak ring, crater rim, and one or more outer faulted rings exterior to the rim (Turtle et al. 2005).

The assumption of a ring basin form is based largely on the indication of a ring form for Chicxulub (Morgan and Warner 1999a and 1999b) and the fact that the three structures are of similar size. In addition, similar-sized structures identified in radar imagery of Venus, which has a surface gravity close to that of the Earth, are classified as multi-ring structures (e.g., Alexopoulos and McKinnon 1994). Whether these three terrestrial structures are, by definition, multi-ring basins or peak-ring basins is somewhat a moot point. The assumption is that these three terrestrial impact structures are likely to have had originally the same form. The structures have been eroded to different levels, which is in terms of increasing erosion: Chicxulub, Sudbury, Vredefort.

Here the salient observations and interpretations of these observations at each structure are initially reviewed. Then, assuming that these three structures expose different levels and aspects of the third dimensional character of a terrestrial impact basin, observations from all three structures are used to constrain and expand interpretations at any one structure and to test for the degree of internal consistency. Finally, all the observations and interpretations are melded together in an attempt to build a composite empirical model of a terrestrial impact basin with an inner peak ring.

THE STRUCTURES

Vredefort, South Africa

The Vredefort impact structure has a central, structurally uplifted area 80–90 km in diameter, known as the Vredefort Dome. The dome consists of a central core of Archean basement gneisses and migmatites, surrounded by an annular collar of sub-vertical to overturned supracrustal late Archean-early Proterozoic metasedimentary and metavolcanic strata (Fig. 1). The dome is, in turn, surrounded by a series of broad concentric anticlinal and synclinal structures that extend out to the so-called Rand Anticline in the north, which is the limit of the eroded remnant of the Witwatersrand Basin, and, possibly, beyond (Fig.1; McCarthy et al. 1986, 1990). The Rand Anticline also marks the limit of the occurrence of substantial pseudotachylitic and cataclastic breccias believed, because of geochronological data and their massive occurrence, to be associated with the Vredefort structure (Reimold and Gibson 2005). Details of the geology and an entrance to the voluminous literature on Vredefort can be found in Gibson and Reimold (2001). Evidence for impact includes shock metamorphic features such as shatter cones (e.g., Hargraves 1961), planar deformation features (PDFs) in

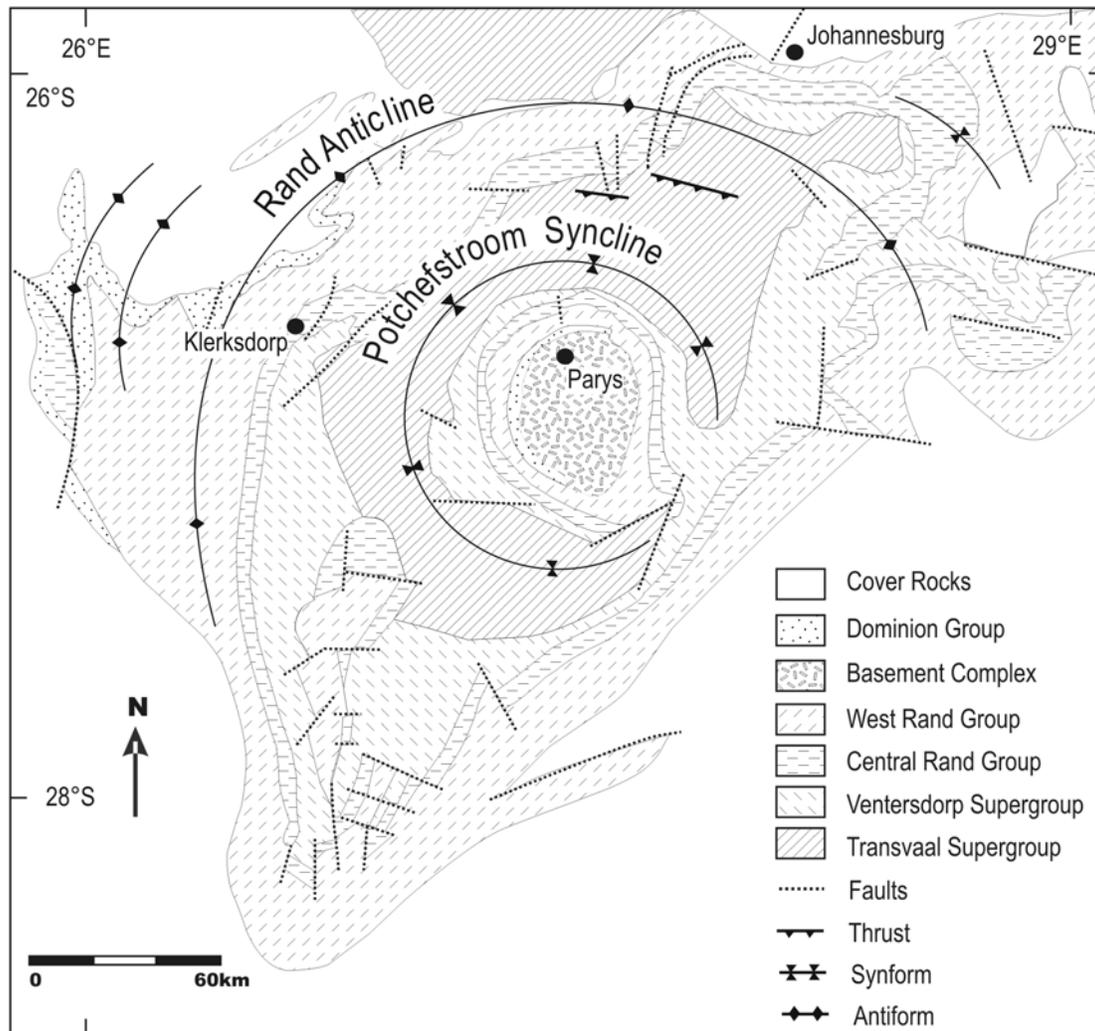


Fig. 1. Schematic geological map of the Vredefort impact structure and environs, with the outcrop of the Karoo cover rocks removed. Also shown are some of the circumscribing structures (e.g., Rand Anticline, Potchefstroom Syncline, and others) identified by McCarthy et al. (1986, 1990).

quartz (e.g., Carter 1965; Leroux et al. 1994), shock deformation of zircon (Kamo et al. 1996; Reimold et al. 2002), the occurrence of coesite and stishovite (Martini 1978), and evidence for a small meteoritic component in impact-melt rocks (Koeberl et al. 1996).

Vredefort is eroded below the original floor of the impact structure and allochthonous impact lithologies are limited to nine radial and concentric dikes of impact-melt rock, known as Vredefort Granophyre, in the crystalline core (Therriault et al. 1996a) and pseudotachylitic breccia dikes, and networks (Dressler and Reimold 2004; Reimold and Gibson 2005). Erosion has removed the coherent impact-melt sheet and has been estimated to be in the range of 5 to 10 km (McCarthy et al. 1990; Gibson et al. 1998; Gibson and Reimold 2001). Kamo et al. (1996) determined a U-Pb age from zircons in the granophyre and pseudotachylitic breccia of ~2020 Ma, which has been confirmed by more recent results, for the age of the Vredefort impact event.

Reasoned estimates of the amount of original structural uplift and the apparent diameter of the Vredefort impact structure are 20–30 km and 250–300 km, respectively (Therriault et al. 1997; Gibson and Reimold 2001; Henkel and Reimold 1998). Turtle et al. (2005) estimated that the original final crater diameter at Vredefort was ~120–200 km. Where the structure is not covered by post-impact, Karoo Supergroup cover rocks, i.e., in the north and west, remote-sensing imagery indicates radial and concentric features out to a radial distance of ~125 km (Phillips et al. 1999). Concentric structures are also evident in synoptic topographic data sets, such as from the Shuttle Radar Topography Mission (SRTM), over Vredefort (Fig. 2). At such a size, the effects of the Vredefort impact structure encompass the entire Witwatersrand Basin and the associated world-class goldfields (Grieve 2005; Reimold et al. 2005). There has been some post-impact deformation at Vredefort, with shortening in a NW-SE direction in the outer regions. The central area,

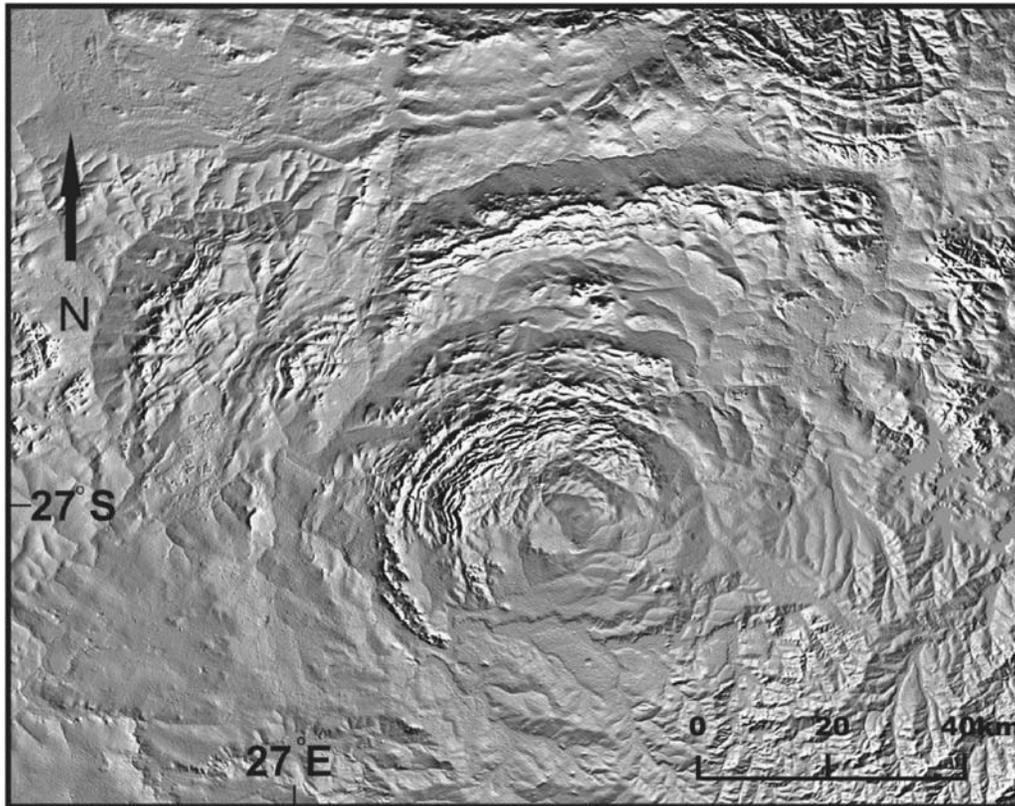


Fig. 2. Grayscale synoptic image of the topography in the area of the Vredefort impact structure, based on the Shuttle Radar Topographic Mission. Image has been illuminated from the center to emphasize arcuate structures surrounding the center of Vredefort.

however, has only been mildly affected by post-impact deformation (Henkel and Reimold 1998). Simpson (1978) was one of the first to recognize and investigate Vredefort-related structures exterior to the Vredefort Dome in the form of the Potchefstroom Synclinorium (Fig. 1). McCarthy et al. (1986, 1990) extended these surface-based geological observations to define more radially distant, but what they believed to be related, anticlinal and synclinal structures (Fig. 1; see also Fig. 1 in McCarthy et al. 1990).

There is also considerable subsurface information available at Vredefort from underground mapping, drill holes, and vibroseismic surveys related to the mining activity. Although most of this information is proprietary, there is a limited amount in the public domain and it serves to build a picture of movements and structures related to the Vredefort impact. For example, in the vicinity of the Western Areas Gold Mine, some 60 km north of the basement core-collar rocks contact of the Vredefort Dome, Killick et al. (1988) noted multiple stages of movement along a Proterozoic-aged bedding plane fault zone, with the latest stage being thrusting that is manifested by pseudotachylitic breccia related to the Vredefort impact. More recent work (e.g., Trieloff et al. 1994; Reimold and Colliston 1994) has confirmed the extensive development of Vredefort-aged pseudotachylitic breccia throughout the northern and northwestern parts of the Witwatersrand Basin along bedding-parallel fault zones,

such as the Ventersdorp Contact Reef (VCR), the feature investigated by Killick et al. (1988).

Similarly, Fletcher and Reimold (1989) reported on more than one generation of pseudotachylitic breccia associated with pre-Vredefort structures that are tangential to the Vredefort Dome. In particular, they examined structures in the north and northwest portion of the Witwatersrand Basin, such as the Black Reef Decollement Zone (BRDZ) and Master Bedding Plane Fault (MBPF), with the latter trending parallel to the Rand Anticline (Fig. 1), some 60 km northwest of the core-collar boundary of the "Vredefort Dome". Like the other main bedding plane-parallel fault zones in the Witwatersrand strata, the MBPF dips some 20° to the southeast and strata above the fault have been moved a residual distance of 6–18 km towards the center of the Vredefort structure. The second generation of breccia associated with the BRDZ was attributed to inward "gravity slides" contemporaneous with the uplift and folding of the central collar rocks during the impact event (Fletcher and Reimold 1989).

Brink et al. (1997) extended these observations through the added interpretation of industry vibroseismic data to build a more synoptic view of the entire Witwatersrand Basin. They identified concentric folds and several zones of faulting around the entire Vredefort Dome. Slickenslide orientations in the thrusts in the northwest quadrant of the Basin clearly indicated an overall radial direction of movement, with

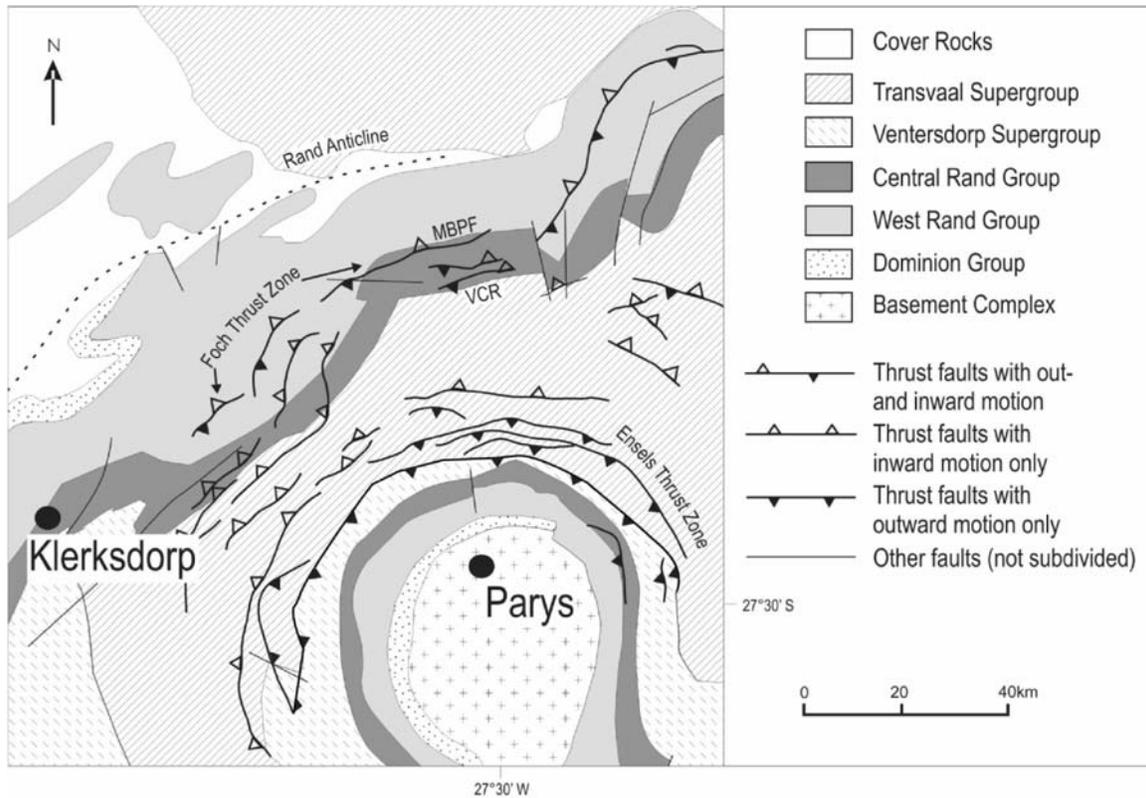


Fig. 3. Schematic geologic map of the northern and western quadrants of the Vredefort impact structure. Also shown are some of the partially circumscribing and arcuate structures and their sense(s) of movement, based largely on the interpretation of industry reflection seismic data (see text for details). The Foch and Ensels Thrust Zones noted by Brink et al. (1997, 2000) and Master Bedding Plane Fault (MBPF) and Venterdorp Contact Reef Fault (VCR) are identified. Note the structures indicated are generally recognized only in the subsurface through geophysics (mostly reflection seismics), drilling and mine workings. Area shown is limited but equivalent structures surround the entire Vredefort structure in both industry data and the work of Brink et al. (1997, 2000). See text for details.

respect to the center of the Vredefort Dome. Brink et al. (1997) also noted the reactivation of pre-existing structures, such as the MBPF, and that the sense of motion on thrusts was outward away from the dome. There are some exceptions, however, such as the Potchefstroom Fault, where the orientations of pre-existing structures were such that their reactivation by the Vredefort impact event resulted in strike-slip motions.

Brink et al. (1997) used these observations to create a model in which the centrifugal motions on these thrusts were due to the outward acceleration of the target rocks during transient cavity formation at Vredefort. They originally attributed none of the motions to the modification stage of the impact event, although they did note, but did not comment on, the occurrence of related motions that were towards the center of Vredefort along inward-dipping normal faults that splay off and join several of these individual outward thrusts. They also noted that outward thrusting in the inner zone (so-called Ensels Thrust Zone; Fig. 3) around the Vredefort Dome occurred after the uplift and local overturning of the collar rocks around the basement core, an observation also made by Simpson (1978). In more recent work, however, Brink et al. (2000) acknowledged rock displacement towards the center

of Vredefort along the BRDZ, exterior to the inner Ensels Thrust Zone, and on the MBPF (Fletcher and Reimold 1989), interior to and then joining their second zone of outward thrusting (so-called Foch Thrust Zone). They attributed these centripetal displacements to the modification stage of the Vredefort impact event.

Thus, the public domain literature can be summarized as cumulatively indicating that there are a series of circumferential thrusts around the basement core at Vredefort. The innermost (Ensels Thrust Zone in the terminology of Brink et al. 1997) structures are concentric and inward dipping. They postdate the uplift and overturning of the collar rocks and indicate outward motion. These inner structures are surrounded by thrusts or thrusts with splayed and converging faults (the Foch Thrust Zone in the terminology of Brink et al. 1997) that indicate at least two generations of movement (Fletcher and Reimold 1989), initially outward and then inward (Ellis and Reimold 1999). In some cases, this initial outward-directed thrusting exploited pre-existing structures tangential to the center of Vredefort. This is particularly evident where massive pseudotachylitic breccias have formed on pre-impact structures, such as the BRDZ, MBPF, and VCR Fault Zone (Killick et al. 1988; Fletcher and Reimold 1989;

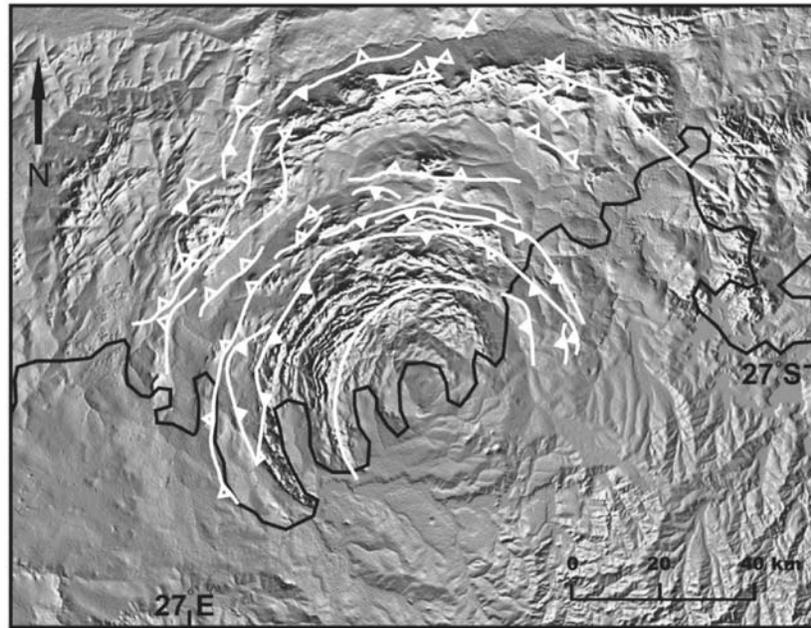


Fig. 4. Enlargement of Fig. 2 focused on Vredefort, with the outcrop of the Karoo (south of the black line) and the structures of Fig. 3 shown. Note the general spatial correspondence between topographic and geologic structures and the lack of Vredefort-related topographic structures in the area of Karoo cover rocks.

Killick and Reimold 1990). In cases where pre-existing structures were more radial, e.g., the Bank and West Rand Faults in the north (Fletcher and Reimold 1989) or the Sugarbush Fault in the east (Brink et al. 1997), motions induced by the Vredefort event were more strike-slip than thrusting.

This general interpretation of the published literature is largely supported, with slight differences, by a detailed confidential report from the industry (S. Ellis, personal communication, 2005), which is based on the interpretation of reflection seismic and potential field data, constrained by geologic and drill hole information. In this industry report, there is clearly more complexity than noted in the earlier public domain work of Brink et al. (1997, 2000). For example, several additional thrusts are identified, in addition to the two major zones of thrusts described by Brink et al. (1997, 2000), and some of these thrusts, which are intermediate in radial distance between the so-called Ensels and Foch Thrust Zones (Brink et al. 1997, 2000), apparently record only one increment of impact-related radial motions that are predominantly inward, toward the center of Vredefort. These intermediate-distance thrusts are reverse faults and dip away from the Vredefort Dome. At depth, they appear to detach from the inward-dipping thrusts, such as the BRDZ and MBPF, and are relatively concentric in plan view, e.g., one of the innermost of these reverse faults is correlated between seismic lines in a concentric trace over ~90 degrees of arc.

The pattern of these thrusts at Vredefort is illustrated in Fig. 3, which is limited to the north and west quadrants, for reasons of industry confidentiality. This is also the area where

there is no covering by post-impact (180–250 Ma) Karoo Supergroup sedimentary rocks. Impact-related structures are consequently better delineated in the SRTM data in this quadrant (e.g., Fig. 4), although these impact-related structures circumscribe the entire Vredefort Dome (Brink et al. 1997, 2000; S. Ellis, personal communication, 2005). The additional number of motions on individual thrusts and reverse faults, spaced a few (~5–10 km) kilometers apart, apparent in industry data and the lack of specific spatial concentrations in the numbers of such structures (Fig. 3) are consistent with the observation that there are no specific spatial/radial concentrations in the development of Vredefort-related pseudotachylitic breccia exterior to the basement core (Dressler and Reimold 2004). Although forward modelling of the potential field data at Vredefort has been used to constrain the impact event and the extent of impact-related crustal movements at the regional scale (Henkel and Reimold 1998), they do not provide the level of detail on structural features afforded by the reflection seismic data.

While there is a sense of movements of crustal blocks on the scale of kilometers along discrete impact-induced and impact-reactivated structures, at the resolution of the seismic data, this does not appear to be the case in the crystalline core of the Vredefort Dome. Although exposures are limited, Lana et al. (2003) failed to identify fault-bounded blocks in the crystalline core at Vredefort. Based on the structural continuity of Archean metamorphic mineral fabrics, they concluded that the required displacements were achieved by small-scale (mm–cm) differential rotations and slip. They further suggested that the pervasive network of veins of

pseudotachylitic breccia may have provided the means for large-scale continuous rock flow during structural uplift. The originally deepest rocks of the crystalline core of the Vredefort Dome are from mid-crustal levels (Lana et al. 2003), and there is a progressive increase in recorded post-impact temperatures from ~300 °C in the outer collar rocks to >700 °C, and locally as high as 1000 °C, in the central core due to the geothermal gradient prior to impact-induced uplift and shock heating (Gibson et al. 1998; Gibson 2002; Gibson and Reimold 2005). These high temperatures may have also assisted in mechanical strength degradation during structural uplift and modification.

Lana et al. (2003) also suggested that sub-horizontal, pre-impact Archean mineral fabrics in the crystalline rocks in the core of the Vredefort Dome record a net differential rotation from the impact event. In particular, the fabrics are steeply dipping close to the collar rocks and parallel the post-impact attitude of the collar rocks. By contrast, toward the central portion of the crystalline core, the fabrics rotate back to a sub-horizontal attitude. Such a shallow attitude of post-impact structures in the center of eroded and exposed structural uplifts is not a feature of smaller terrestrial complex craters, e.g., at Gosses Bluff (Milton et al. 1996). Given that the collar rocks at Vredefort display the expected steep dips that are observed in structural uplifts at other smaller terrestrial complex craters, the sub-horizontal mineral fabrics in the center of the crystalline core are likely a primary function of some additional aspect of the structural uplift process at Vredefort.

Sudbury, Canada

The Sudbury impact structure comprises the so-called Sudbury Basin, the enclosing Sudbury Igneous Complex (SIC), and the surrounding brecciated and fractured Archean and Proterozoic rocks of the Superior and Southern provinces of the Canadian Precambrian Shield (Giblin 1984). As with Vredefort, aspects of its origin have been controversial, particularly with respect to the origin of the SIC. Although written prior to most of the current understanding of Sudbury as an impact structure, Pye et al. (1984) is the most extensive volume on the geology of the Sudbury area. More recent studies at Sudbury, combined with developments in the understanding of large terrestrial impact structures, have led to the general working hypothesis that the basic observations at Sudbury can be accounted for by impact, followed by tectonic deformation and erosion. It is now widely accepted that the SIC represents the differentiated impact-melt sheet within the impact structure (Grieve et al. 1991; Dickin et al. 1999; Therriault et al. 2002). Estimates of the apparent crater diameter are mostly in the ~150–200 km range (Stöffler et al. 1994; Grieve et al. 1991), but some recent estimates range up to 260 km (Tuchscherer and Spray 2002; Spray et al. 2004). Turtle et al. (2005) estimated the original final crater diameter at Sudbury to have been ~130–180 km.

The evolution in the scientific reasoning concerning Sudbury and the SIC is outlined in Naldrett (2003) and an entrance to the more recent literature can be found in Grieve (2006). Evidence for impact includes shock metamorphic features, such as PDFs in quartz and feldspar in the crystalline footwall rocks north of the SIC and in clasts in the overlying Onaping Formation (French 1968; Dence 1972), and shatter cones, particularly in the Huronian metasedimentary rocks that form part of the southern footwall of the SIC (Guy-Bray and Geological Staff 1966). Most recently, there have been claims of the detection of a meteoritic component in the Onaping Formation at Sudbury (Mungall et al. 2004) and the discovery of preserved distal shocked ejecta from Sudbury some 650–900 km to the west of the structure (Addison et al. 2005).

The age of the Sudbury impact event is ~1.85 Ga (Krogh et al. 1984). The amount of erosion that has taken place since the impact event is estimated at 5–6 km for the parautochthonous basement rocks north of the SIC (Thompson et al. 1998), similar to the lower estimate at Vredefort. The current geological situations at Sudbury and Vredefort, however, are not directly comparable. The impact event at Sudbury occurred in an active orogenic belt and the impact structure was folded and then faulted by northwest-southeast shortening during the Penokean orogeny (Rousell 1984; Riller 2005). The net result is that the most obvious current expression of the center of the structure is the elliptical ~30 × 60 km Sudbury Basin bounded by the folded SIC, which dips ~30° to the south in the so-called North Range and is subject to relatively high-angle reverse faulting (South Range Shear Zone) in the so-called South Range (Fig. 5; Milkereit et al. 1992, 1994).

This deformation and folding of the SIC has resulted in the preservation of the entire impact sequence from the parautochthonous, locally brecciated, target rocks of the crater floor, through the impact-melt sheet (SIC), to the post-impact sediments within the central Sudbury Basin. External to the folded SIC and the Sudbury Basin, however, erosion has removed essentially all allochthonous impact lithologies, except the so-called Sudbury Breccia and several radial and concentric dikes of impact melt (offset dikes), and exposed the parautochthonous rocks of the crater floor (Dressler 1984).

As noted, the most conspicuous geologic feature of the Sudbury structure is the outcrop of the SIC. The SIC has been traditionally subdivided into a basal contact Sublayer, Norite, Quartz-Gabbro and Granophyre lithologies (e.g., Naldrett et al. 1970), but it is actually, on average, granodioritic in composition and its lithological phases are more felsic than this traditional nomenclature suggests (Therriault et al. 2002). The composition of the offset dikes varies between dikes (Grant and Bite 1984) and along the strike of an individual dike (Tuchscherer and Spray 2002), but is broadly similar to that of the so-called Norite of the SIC.

Like Vredefort, Sudbury is the site of a world-class

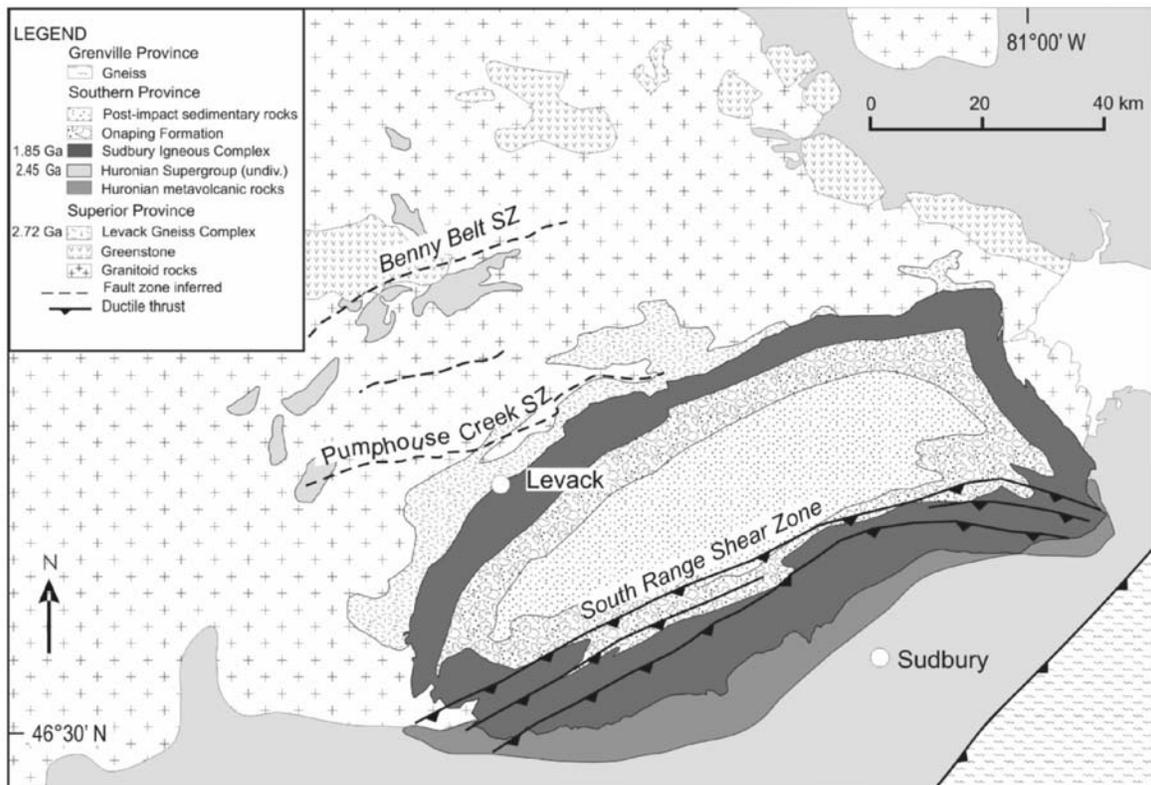


Fig. 5. Schematic geologic map of the Sudbury area. Note the elliptical outcrop pattern of the Sudbury Igneous Complex (SIC), due to post-impact, Penokean folding and thrusting, e.g., the South Range Shear Zone. Note also the outcrop of the uplifted high-grade Levack Gneiss Complex immediately to the north of the North Range of the SIC and the arcuate outcrop pattern on down-dropped outliers of originally near-surface Huronian Supergroup rocks at a greater radial distance in the North Range footwall. Also indicated are the Benny Belt and Pumphouse Creek Shear Zones. See text for details.

mining camp. In the case of Sudbury, the ores are Cu-, Ni- and PGE-rich sulfides associated physically with the base of the SIC, the immediate footwall and the Offset Dikes (Grieve 2005; Reimold et al. 2005). Thus, although there is a large proprietary database on Sudbury held by industry, it is much more spatially limited than at Vredefort. Away from the immediate SIC-footwall contact, systematic geologic mapping covers only ~30% of the area at scales of 1:30,000 or larger (Spray et al. 2004) and was conducted largely at a time when impact-related structures at Sudbury were not a focus (e.g., Card 1968, 1978; Card and Meyn 1969). The structural situation is further complicated by the fact that the Sudbury structure has been extensively tectonized following the impact (Riller 2005; Klimczak et al. 2007).

The extent of this post-impact deformation was only appreciated following a north-south reflection seismic traverse across the SIC and the Sudbury Basin, in the course of a LITHOPROBE transect, which indicated significant northwest thrusting of the South Range of the SIC (e.g., Milkereit et al. 1992; Boerner et al. 2000). This extensive ductile shearing and brittle faulting corresponds at the surface to the South Range Shear Zone (Fig. 5; Shanks and Schwerdtner 1991; Riller et al. 1998). Although there has been some potential field modelling at Sudbury, it has been

largely in the form of two-dimensional profiles along the LITHOPROBE transect. They were also designed more to determine whether or not models of the potential field data were compatible with the seismic interpretation than as an independent set of interpretations (e.g., McGrath and Broome 1994). Unfortunately, in general, differentiation between pre-impact and impact-induced deformation is not possible in the geophysical data at Sudbury (Boerner et al. 2000). Due to the high degree of post-impact tectonization in the South Range of the SIC, observations in the footwall outside the North Range offer the best opportunity to decipher impact-related structures.

Although sometimes referred to as pseudotachylite (Thompson and Spray 1994), the local term Sudbury Breccia encompasses a variety of breccia types, including clastic and pseudotachylitic breccias, as well as breccias that have been recrystallized due to the thermal metamorphic effects of the SIC (Müller-Mohr 1992; Rousell et al. 2003). Sudbury Breccia is concentrated in a 5–15 km inner zone around the SIC but is known up to a distance of 80 km northeast from the lower contact of the SIC. As at Vredefort, there is evidence for more than one generation of Sudbury Breccia, which have been equated with both the transient cavity formation and subsequent modification stages of crater formation (Thompson

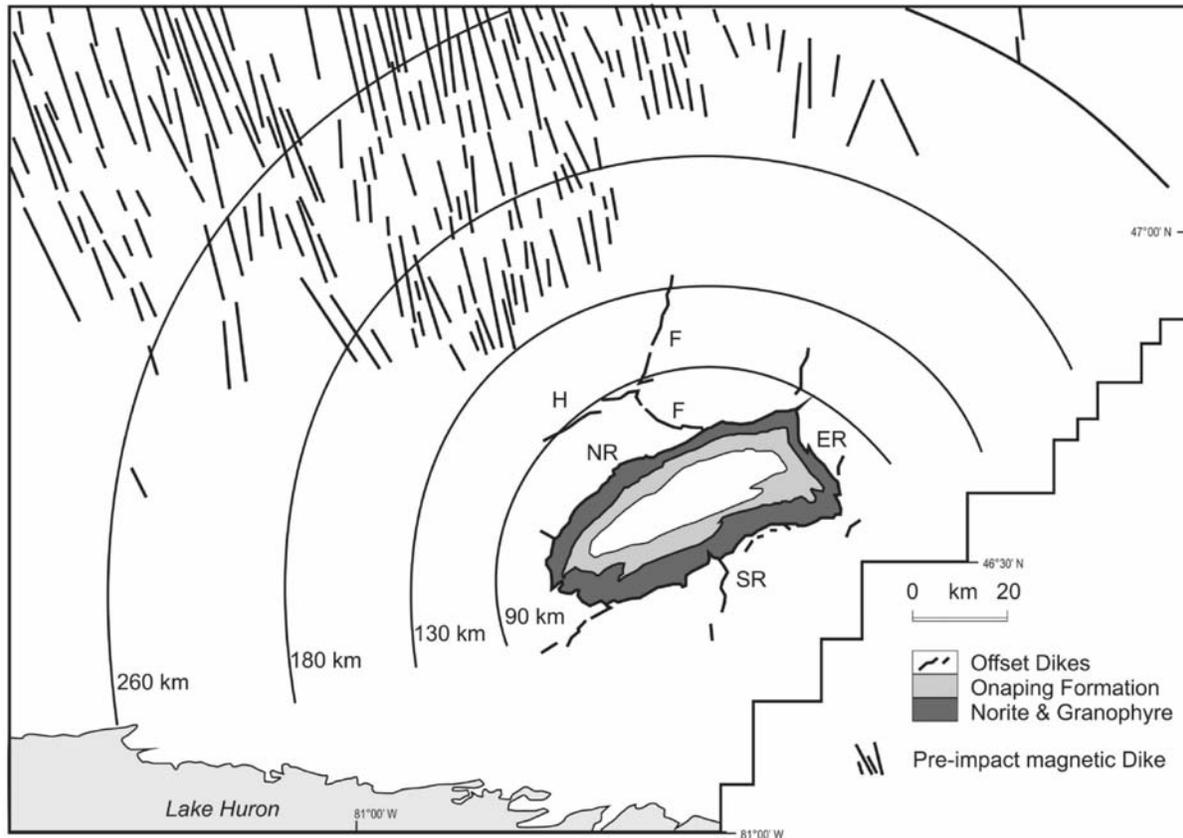


Fig. 6. Sketch map of location of pre-impact Matachewan diabase dikes that have a preserved magnetic signature and the locations of the postulated “rings” at Sudbury, according to Spray et al. (2004). See text for details. Also shown are the locations of the so-called offset dikes, which have intruded from the SIC into the footwall. Foy (F) and Hess (H) offset dikes are indicated. NR, ER, and SR are the North, East, and South ranges of the SIC, respectively. Diagram is after Spray et al. (2004).

and Spray 1994). In addition to the concentration close to the SIC, there are claims of zones several kilometers wide of increased breccia development north of the SIC at radial distances of ~25, 40, and 80 km from the North Range of the SIC (Spray 1997; Thompson and Spray 1994; Rousell et al. 2003).

Spray et al. (2004) suggested the presence of four rings in the North Range footwall (Fig. 6), at diameters of 90 km (structural uplift), 130 km (transient cavity), 180 km, and 260 km (estimated original final crater diameter), respectively, on the basis of fieldwork, geophysics, and remote sensing, with the three inner rings corresponding roughly to the zones of increased Sudbury Breccia development (Thompson and Spray 1994). These ring diameters, however, depend to a large degree on the estimated location of the original center of the impact structure, which is not explicitly defined but appears to be based on the lineament analysis of Landsat MSS imagery by Butler (1994). Similarly, the specific “ring” features (Fig. 6) are those of Butler (1994). Butler’s (1994) analysis defined a series of arcuate lineaments at Sudbury. Based on what he considered the most obvious and continuous band of lineaments, he defined an original center

to the impact structure, located now south of the current position of the South Range of the SIC. This placed this band of lineaments at a diameter of 130 km (Fig. 6). The locations of the other “rings,” however, do not correspond to similar obvious bands of lineaments and were actually assigned a location, which was based on a square root of two scaling of the 130 km diameter “ring” by Butler (1994). While such arbitrary scaling biases the interpretation of the Sudbury impact structure towards that of a multi-ring basin, it also reduces considerably the potential genetic significance of the so-called “rings”. Spray et al. (2004), however, also noted that pre-impact Matachewan dikes apparently lose their pre-impact magnetic signature at the 130 km diameter “ring” (Fig. 6), which also marks the termination of the radial Foy offset dike of the SIC, and that the outcrop of the concentric Hess offset dike roughly occurs at and follows the 90 km diameter “ring”.

Examination of the 90 m resolution SRTM data of the Sudbury area reveals little in the form of arcuate features in the footwall of the North Range of the SIC. Even when illuminated from the center of the Sudbury Basin to emphasize arcuate topographic features (Fig. 7),

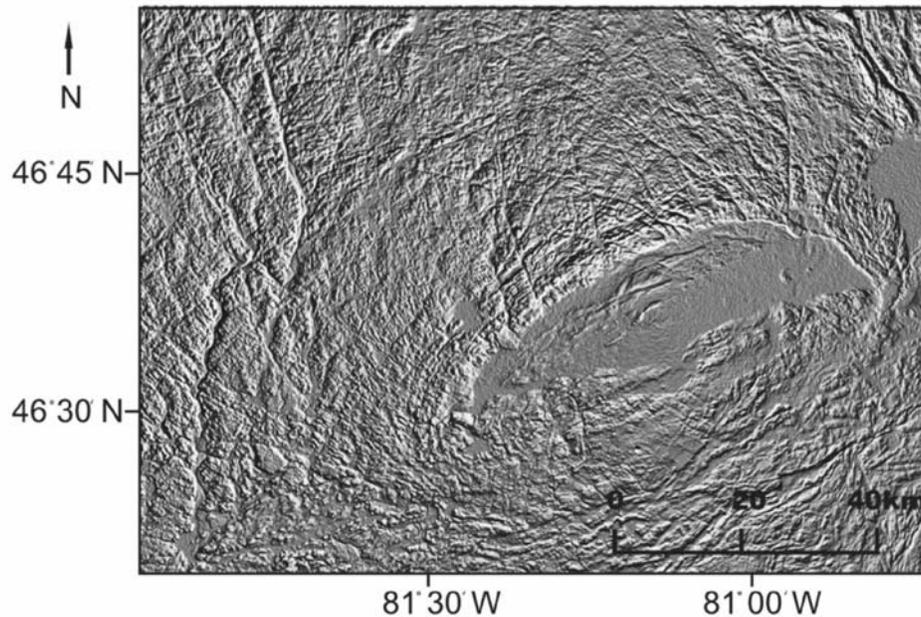


Fig. 7. Grayscale synoptic image of the topography, based on the SRTM, in the area of the Sudbury impact structure. Image has been illuminated from the center to emphasize arcuate structures as at Vredefort (cf. Fig. 2), but such structures are generally not apparent. Topographic features related to the SIC and dikes and post-impact faults are most evident; however, the rings identified in Fig. 6 are not evident. The lack of observable arcuate impact-related features is ascribed to the effects of post-impact tectonism and, more importantly, glacial sculpting to form the current surface.

circumscribing impact-related residual topographic features are not evident at Sudbury beyond the outcrop pattern of the SIC itself. This is most likely due to the preferential erosional effects of glaciation, particularly with respect to linear faults and dikes (Fig. 7). Similarly, topographic features corresponding to either the Landsat or Sudbury Breccia “rings” of Butler (1994) and Thompson and Spray (1994), respectively, are not obvious.

The Huronian outliers west and north of the SIC lie between the 90 and 130 km diameter “rings” of Spray et al. (2004) (Fig. 6). Recent examination of these outliers indicates that they are fault-bounded on their distal margins from the SIC and the faults are invariably occupied by pseudotachylitic breccia, ranging up to ~25 m thick (Mungall and Hanley 2004). This is consistent with the interpretation that the outliers are preserved due to downward and inward-directed faulting, possibly during collapse and modification of the transient cavity at Sudbury (Dence 1972). This is generally inconsistent with the Spray et al. (2004) interpretation, which places these Huronian outliers radially between the trace of the collapsed transient cavity rim (130 km) and the structural uplift (90 km). That is, these Huronian rocks were originally inside the trace of the transient cavity, where they would be subject to excavation. Their preservation and structural character are more consistent with being originally in the final annular trough (Dence et al. 1977), where they would be preserved from erosion due to down-faulting during transient cavity modification.

Northwest of the SIC, these Huronian outliers are

associated with an outlier of Archean greenstone terrain known as the Benny Belt, which has a shear zone as its southern margin. This shear zone has been traced for over 30 km and is sub-parallel to the North Range of the SIC (Fig. 5; Card 1994; Kellet and Rivard 1996). There is another shear zone (Pumphouse Creek) with the same general trend and length closer to the SIC, at the northerly contact of the Levack Gneiss Complex and the Cartier Granite (Fig. 5; Fueten et al. 1992; Card 1994). What were assumed to be shear zones, spaced ~5–10 km apart, were imaged in the LITHOPROBE reflection seismic data from a single line north of the SIC. These seismic data included a third reflector, interpreted to be tectonic in origin, intermediate in distance between the Benny Belt and Pumphouse Creek shear zones (Fig. 5; Moon and Miao 1997; Boerner and Milkereit 1999). This reflector has no currently known geologic surface expression. Although Boerner and Milkereit (1999) proposed that structures such as the Benny Belt and Pumphouse shear zones pre-date the impact, the presence of pseudotachylitic breccia suggests that these shear zones were (re)activated as a consequence of the impact at Sudbury (Fueten et al. 1992). Kellet and Rivard (1996) also noted an overprinting fabric on the pseudotachylitic breccia that suggests some post-impact Penokean deformation on the faults in the Benny Belt shear zone.

Thus, although the structural observations are nowhere as numerous, nor as detailed, compared to Vredefort, there does appear to be similar evidence for impact-related movement on what may have been pre-existing structures at

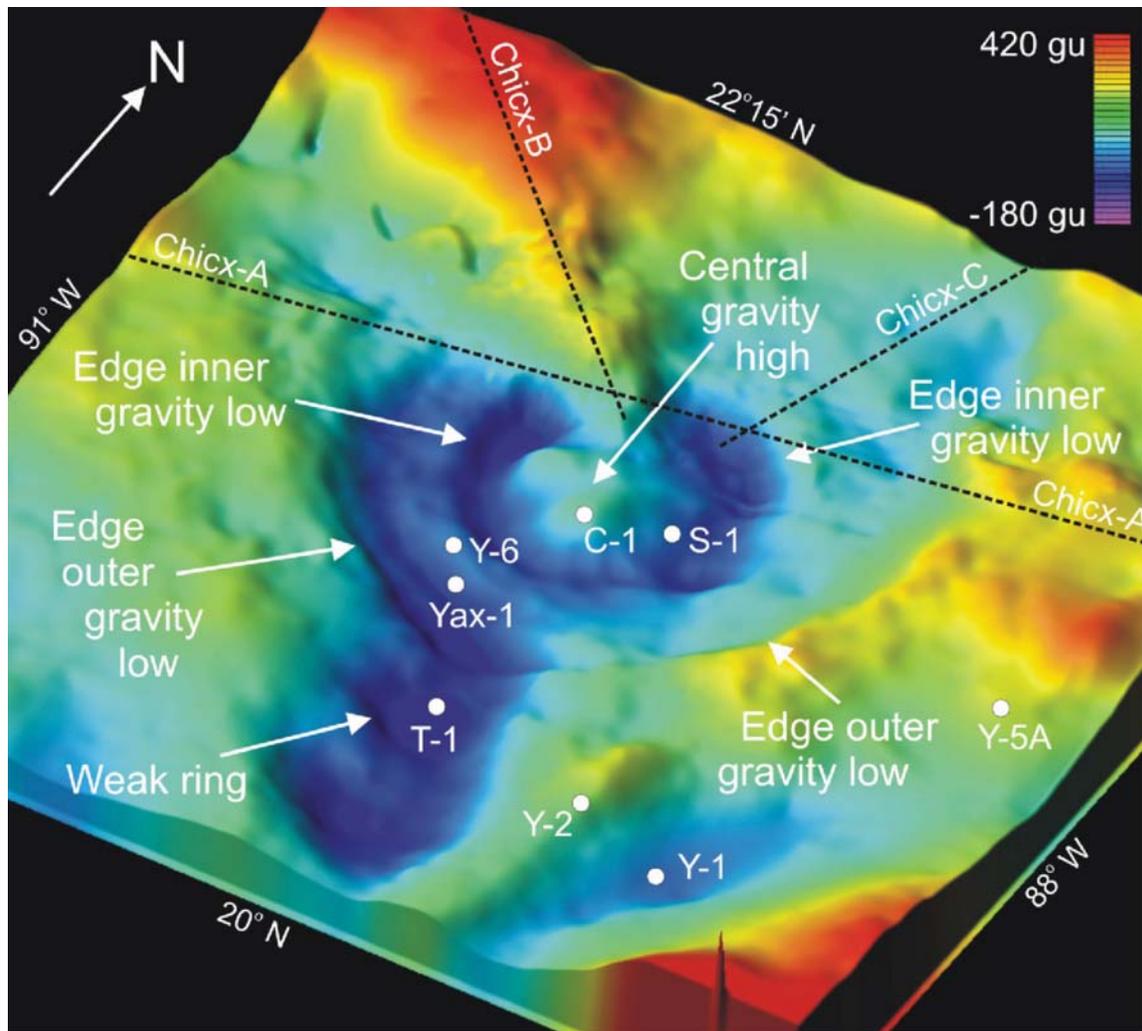


Fig. 8. Grayscale Bouguer gravity image of the Chicxulub impact structure compiled by Styles (2006). Specific gravity features related to the structure are identified, as are the locations of the marine seismic reflection profiles acquired in 1996 (Black dashed lines). White dots are onshore drill sites, with the results from T-1, Y-6, C-1, S-1 and the ICDP drill site, Yax-1 mentioned in the text.

Sudbury. Similarly, the arrangement of a structurally uplifted central area surrounded by a synclinal feature in which there is evidence for movement towards the center is common to both structures. If there is discordance in observations between Sudbury and Vredefort, it is the assertion that there are zones of increased pseudotachylitic breccia at Sudbury (Thompson and Spray 1994), but not at Vredefort (Dressler and Reimold 2004). Given the relatively arbitrary spacing of three out of the four “rings” of Spray et al. (2004) at Sudbury and the vast difference in the level of regional geologic information available from Vredefort compared to Sudbury, it is possible, however, that this difference may be more apparent than real.

Chicxulub, Mexico

Unlike Vredefort and Sudbury, Chicxulub is almost completely preserved. It is, however, buried by up to 2 km of

Tertiary sedimentary rocks and its morphology is known only from interpretations of geophysical data and onshore drilling (e.g., Fig. 8). Due to burial and the relatively flat topography of the area (<50 m elevation difference over a distance of 150 km), the SRTM data do not lend themselves to the type of processing and interpretation that was carried out for Vredefort and Sudbury. The only clear expression of the onshore portion of the structure is a semi-circular ring of sinkholes (cenotes), with a diameter of ~160 km (Pope et al. 1993). There are, however, distinct potential field anomalies associated with Chicxulub, including a series of semi-continuous and roughly circular features in the gravity and magnetic data (Sharpton et al. 1993; Pilkington et al. 1994; Hildebrand et al. 1995).

The most distinct and continuous ring in the gravity data is the outer edge of a gravity low at ~100 km diameter. It surrounds a central gravity relative high, which is offset to the southwest of the crater center (Fig. 8). There is also another

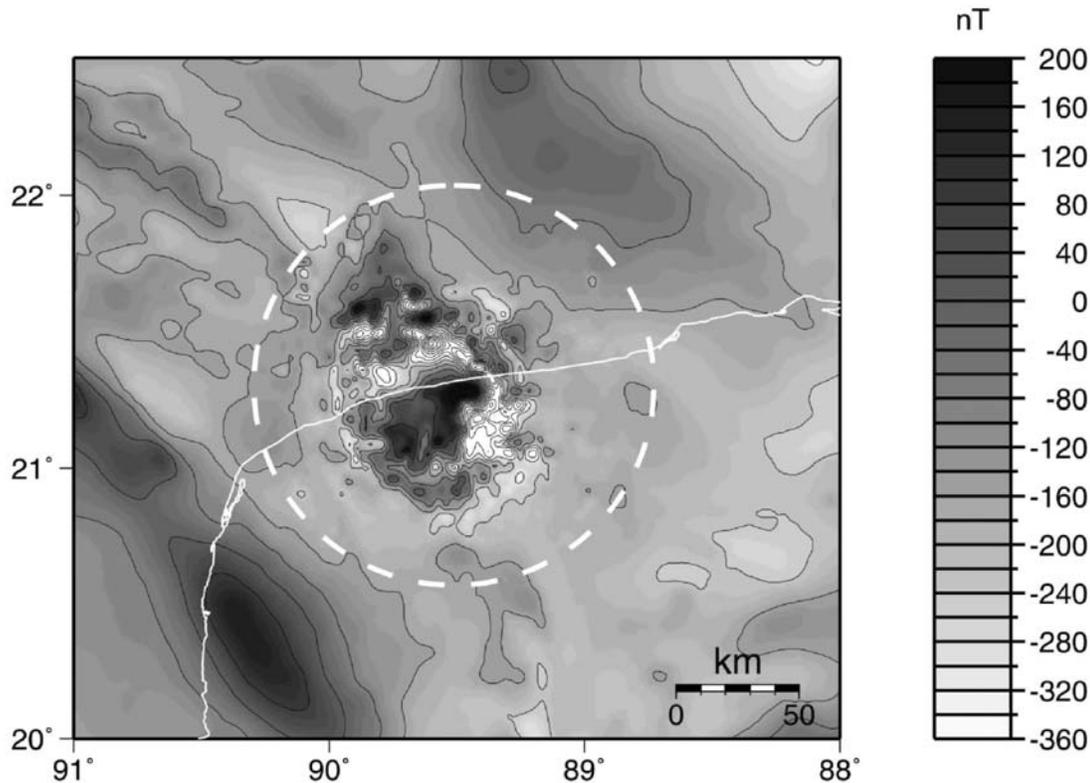


Fig. 9. Grayscale magnetic (reduced to the pole) image of the Chicxulub impact structure from Pilkington and Hildebrand (2000). The magnetic field is characterized by a long-wavelength central high (>500 nT, 40 km in diameter), surrounded by a ring of spatial localized high-amplitude (100 nT) anomalies out to 90 km diameter. See text for details and interpretation. The location of the original rim of the impact structure (dashed white line) and the coast (solid white line) are indicated.

circular feature defined by the outer edge of a gravity low at ~ 180 km diameter (Fig. 8), but this feature is poorly defined in the offshore half of the crater. It coincides roughly with the cenote ring in the eastern onshore half of the structure, but lies 5–10 km outside the cenote ring in the western portion. There are also some less well-defined, discontinuous rings in the gravity data outside the 180 km diameter ring (faint ring in Fig. 8). The main large-amplitude magnetic anomaly has a diameter of ~ 90 km (Fig. 9), lying just inside the 100 km diameter gravity low anomaly.

Argon-argon dating of impact-melt rock from Chicxulub, obtained in the course of exploration drilling for hydrocarbons, and of tektite-like glasses from Cretaceous-Tertiary boundary sediments, indicates that they are coeval, with an age of ~ 65 Ma (Swisher et al. 1992). Various types of breccias intersected in drill cores from within Chicxulub contain target rock clasts displaying shock metamorphic effects up to impact melting (e.g., Sharpton et al. 1996; Stöffler et al. 2004). Based on onshore drill cores, the post-impact Tertiary sediments are known to increase in thickness from a few hundred meters outside the cenote ring in wells T-1, Y-1, Y-2, Y5a to 800 m in Yax-1, and more than a kilometer in wells Y-6, S-1, C-1 (see Fig. 8 for locations of wells; Ward et al. 1995). Marine seismic reflection data across the offshore portion of the impact structure (Fig. 10) confirm

that the Tertiary basin deepens at diameters of <180 km (Camargo and Suárez 1994).

Initially, there was considerable debate about the size and morphology of Chicxulub based on the interpretation of the potential field, particularly gravity, data. Estimates ranged from ~ 170 to ~ 295 km for the final crater diameter (e.g., Hildebrand et al. 1991, 1995; Sharpton et al. 1993; Pilkington et al. 1994; Espindola et al. 1995). Some degree of consensus was only reached after Chicxulub had been imaged by a marine reflection seismic survey (Fig. 10; Morgan et al. 1997), which indicated that it was a multi-ring basin, with an inner topographic peak and one or, possibly, two outer ring structures in the form of faults at diameters of ~ 195 km (monocline, normal fault with a throw of ~ 400 – 500 m into the structure and a dip of $\sim 30^\circ$) and ~ 240 km (outward directed thrust). A schematic diagram of the crater structure is shown in Fig. 11.

One striking feature of the marine seismic reflection data is the downward offset of blocks of Cretaceous sediments as they are tracked from the rim area toward the center of the structure. Figure 10 shows an example from the northwest of the crater, where reflectors that are interpreted as base Cretaceous anhydrites (Camargo and Suárez 1994) are seen to deepen from ~ 1.5 s to ~ 4 s TWTT between 78 and 40 km radial distance (terrace zone in Fig. 10). The start of this terrace

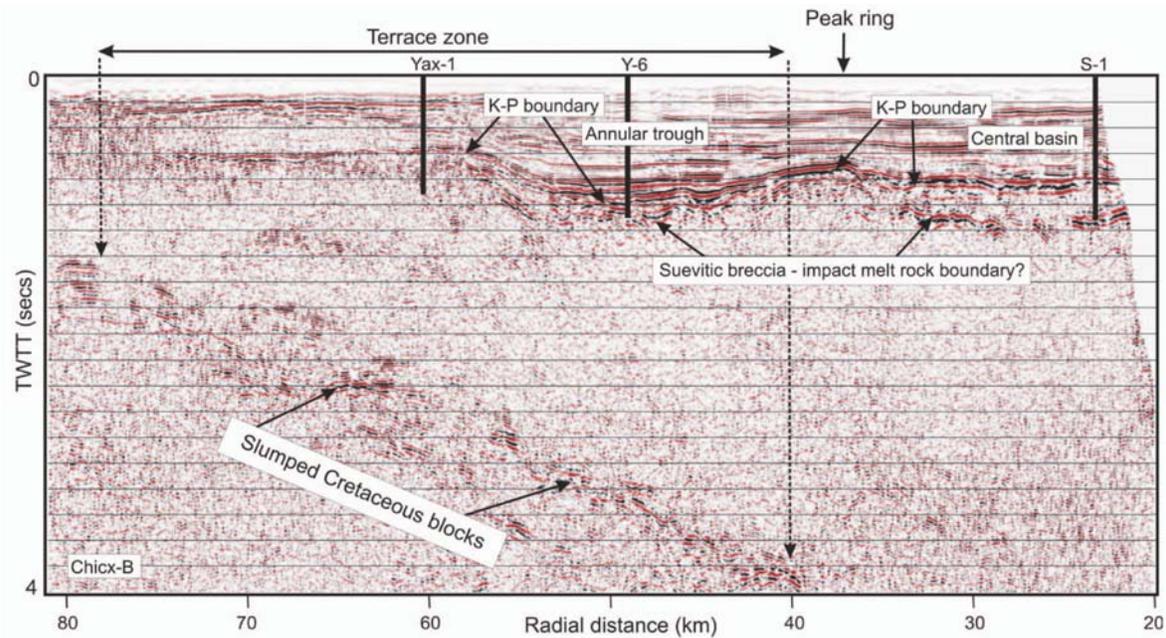


Fig. 10. Marine reflection seismic profile Chicx-B (see Fig. 8 for location). Onshore drill holes (Yax-1, Y-6, and S-1; see Fig. 8 for location) are projected onto the profile at the equivalent radial distance from the crater center. Low-frequency reflections are interpreted as the boundary between suevitic breccia and impact-melt rock, on the basis of their occurrence at a similar depth to this contact in onshore holes S-1 and C-1. Bright reflectors, which are interpreted as Cretaceous anhydrites (Camargo and Suárez 1994; Morgan et al. 1997), are tracked from ~1.5 s to 4 s TWTT between 78 and 40 km radial distance, and lie beneath the peak ring. See text for details.

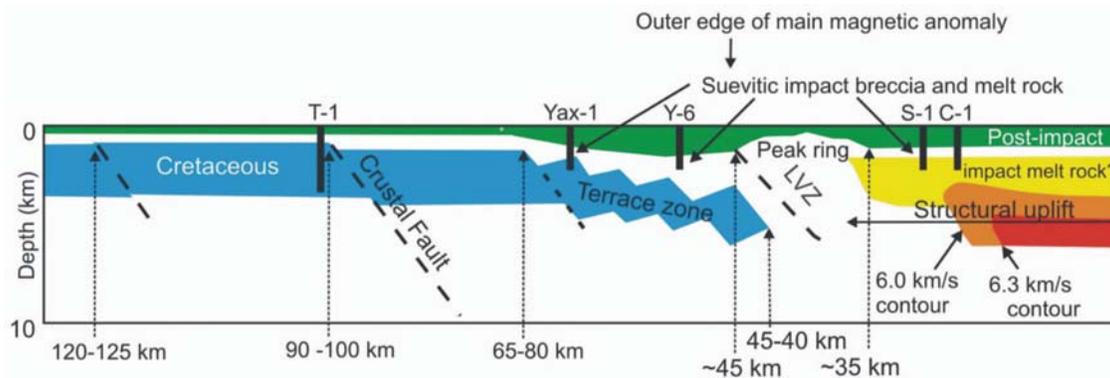


Fig. 11. Schematic cross section of the Chicxulub impact structure, based largely on the interpretation of reflection seismic data, supplemented by drill hole (T-1, Yax-1, Y-6, S-1, and C-1) information. Also included is seismic velocity information, indicating a low-velocity zone (LVZ) dipping inward under the peak ring and >6.0 km/s velocities in the central area, which are interpreted to indicate the presence of crystalline basement in the structural uplift. See text for details.

zone (first significant downward offset) occurs between 65 and 80 km radius, and its inner boundary lies between 40 and 45 km radius, several kilometers below the apparent crater floor. The inner edge of the terrace zone lies directly beneath an inner peak ring on several seismic reflection profiles. On a number of reflection profiles, bright, inward-dipping reflectors run from the outer edge of the peak ring to the inner edge of the terrace zone (Morgan et al. 2000).

Whereas the relationship between observations from the marine reflection data and interpretations of the potential field data are unclear with respect to the outer limits of the Chicxulub structure, the relationship is more consistent

around the inner topographic peak ring. The extent of the inner gravity ring (~100 km in diameter) and the main magnetic anomaly (~90 km in diameter, see Fig. 9) both lie close to the outer edge of the peak ring and the uppermost extension of the inward-dipping reflector (Fig. 11). Inboard of the dipping reflectors, the seismic data are interpreted to indicate structural uplift and thick sequences of impactites. Outboard of the dipping reflectors, drill hole results and interpretations of the seismic data combine to indicate a thinner impactite sequence overlying the collapsed transient cavity rim material. These combined observations have led to better agreement on the size of the original transient cavity

(Hildebrand et al. 1998; Morgan et al. 2000) than on final crater diameter. The final crater diameter at Chicxulub has generally been quoted as ~180 km, primarily on the basis of the outer edge of the gravity low (Hildebrand et al. 1998), and between 180 and 200 km on the basis of faults in the target rock observed on marine seismic reflection data (e.g., Fig. 11; Morgan et al. 1997).

The peak of the inner topographic ring (arrow in Fig. 10) imaged in the seismic data has an average diameter of ~80 km (Morgan et al. 1997; Morgan and Warner 1999a and 1999b). Prior to the collection of the marine reflection data, Pilkington et al. (1994) and Sharpton et al. (1996) located the peak ring at diameters of 70 and 100 km to coincide with an observed gravity low and high, respectively. These interpretations reflected their potential field models that the peak ring is formed from allochthonous breccia (Pilkington et al. 1994) and crystalline basement (Sharpton et al. 1996), respectively. Observations in the reflection seismic data show that the peak ring actually extends across both these gravity features, with the center of the peak ring corresponding roughly to a point of inflexion in the gravity data. The topographic peak ring in the seismic data has a width of 5–10 km, as expressed on the apparent crater floor, and rises up to 600 m above the apparent floor of the structure (Fig. 10; Morgan et al. 1997; Morgan and Warner 1999a and 1999b). In the east, the peak ring is deeper, broader, and more topographically subdued. Similarly, the definition of the “ring” potential field anomalies is more subdued in the eastern portion of Chicxulub (e.g., Fig. 8), raising the possibility of some degree of asymmetry to the original structure and/or post-impact tilting of the crater floor (Bell et al. 2004).

The inner peak ring is identified in the seismic data by a high-amplitude reflector with a rough surface that is overlapped by post-impact sedimentary fill (Fig. 10). Below its surface, there are few coherent reflectors within the interior of the ring. The structural and lithological character of the topographic peak ring is unknown. It is coincident at its outer margin with an inward dipping, low-velocity-zone (LVZ) in the seismic data (Fig. 11), where the overall P-wave velocity contrast with the surrounding rocks is 100–500 m s⁻¹, between the depths of 1 and 7 km (Morgan et al. 2000). The uppermost part of this LVZ has been interpreted as suevitic impact breccia or megabreccia; whereas, the lowermost part is more likely to represent highly fractured crystalline basement (Vermeesch 2006).

The closest existing drill hole exterior to the position of the topographic peak ring is Y-6, which is 5–10 km outside the ring (Figs. 10 and 11). It bottomed at 1641 m in dolomite breccia, after passing through what is interpreted to be ~130 m of suevitic breccia and ~360 m of impact-melt rock (Stöffler et al. 2004). S-1 and C-1 are the closest drill holes (~10–15 km) interior to the position of the topographic peak ring (Figs. 8, 10, and 11). They bottomed at 1530–1580 m, after passing through what is interpreted to be ~360 m of suevitic breccia

and ~110 m of impact-melt rock (S-1) and ~175 m of suevitic breccia and ~330 m of impact-melt rock (C-1) (Stöffler et al. 2004). Therefore, none of these drill holes provide constraints on the nature of the peak ring at Chicxulub. Although the drilling information does not constrain the nature of the topographic peak ring, they do indicate that impact-melt lithologies occur both within the inner crater basin and radially beyond the peak ring.

The most distal drill hole within the structure is the ICDP hole Yax-1 (Figs. 8, 10 and 11), at a radial distance of ~60 km SSW of the center. It passed through ~800 m of post-impact Tertiary fill, followed by ~100 m of suevitic breccia and impact-melt rocks. It bottomed in what is believed to be a down-dropped block of Cretaceous target rocks, at least 600 m thick, which is cut by clastic and impact-melt veins and dikes (Wittmann et al. 2004; Tuchscherer et al. 2004). A low-frequency reflector is observed inside the peak ring at the same depth as the boundary between suevitic breccia and impact-melt rock in C-1 and S-1 (Morgan et al. 2000). Similar, but less coherent, reflectors are observed within the annular trough (Fig. 10), and may also represent the boundary between layers of suevitic breccia and impact-melt rock.

As at other complex terrestrial impact structures (e.g., Scott and Hajnal 1988; Henkel and Reimold 1998), structural mapping by seismic reflection is limited by the loss of coherent reflectors from parautochthonous rocks in the center of Chicxulub (Fig. 10). As noted earlier, interpretations of the potential field, specifically gravity, data over Chicxulub have been divergent, particularly with respect to estimating the final crater diameter (cf. Hildebrand et al. 1991, 1995; Sharpton et al. 1993; Pilkington et al. 1994; Espindola et al. 1995). One of the more recent attempts to define structural elements at Chicxulub from potential field data has been a three-dimensional magnetic model (Pilkington and Hildebrand 2000). The magnetic signature of Chicxulub has the form of three concentric zones, with a center coincident with that of the crater-related gravity anomaly. The inner magnetic zone consists of a broad, high-amplitude (>500 nT) anomaly, which is ~40 km in diameter (Fig. 9) and is interpreted as the signature of crystalline basement rocks structurally uplifted to within ~3 km of the surface. It is roughly coincident with the central gravity high (Pilkington and Hildebrand 2000) and a zone of high seismic velocity. This central anomaly is surrounded by an ~90 km diameter zone with a number of more spatially localized, large-amplitude (100s nT), short-wavelength, dipolar anomalies, which tend to occur in partially concentric patterns (Fig. 9). This is followed by a zone with an irregular outer margin and a maximum diameter of ~180 km, which contains relatively low-amplitude (<25 nT), short wavelength anomalies (Fig. 9).

The short-wavelength, high-amplitude anomalies (<90 km in diameter) are modeled as local magnetized zones at depths of 1–1.5 km, due to magnetic sources at the top of the impact-melt sheet and/or suevitic breccias (Pilkington and

Hildebrand 2000). These short-wavelength anomalies exhibit reverse polarity, with an inclination essentially coincident with the Late Cretaceous paleopole for North America (Steiner 1996), i.e., the same polarity interval (chron 29 r) as the impact event. The anomalies are attributed to hydrothermal activity, resulting in the production of ferromagnetic minerals with a remanent magnetization of 4–5 A m⁻¹ (Pilkington and Hildebrand 2000), compared to that of the relatively low remanently magnetized (0.08–0.60 A m⁻¹) bulk of the impact-melt rocks (Steiner 1996). The magnetic sources are largely confined to two partially concentric zones at ~40 km and ~90 km diameter, which have been inferred to be zones of increased hydraulic permeability (Pilkington and Hildebrand 2000).

This ~90 km diameter zone is coincident with the location of the inward dipping reflector (Fig. 11), which may represent the boundary between relatively intact slumped blocks of Cretaceous and highly fractured peak-ring material (Morgan et al. 2000; Vermeesch 2006). This is consistent with a model of increased fluid circulation related to the physical discontinuity between the inner edge of the down-faulted terrace zone and the topographic peak ring. The strong reflectivity of this dipping reflector may be related to the precipitation of mineral phases through enhanced hydrothermal circulation. The inner ~40 km diameter zone of anomalies is interpreted as due to hydrothermal activity at the interface of the impact-melt sheet and the basement structural uplift (Pilkington and Hildebrand 2000).

Based on the central high gravity and magnetic anomalies, Hildebrand et al. (1998) included a structural uplift zone with a diameter of 40–50 km in their forward modelling of the potential field data. Their model depicts a structural uplift of basement rocks that is surrounded by a megabreccia zone, which is, along with a core of uplifted basement rocks, cumulatively ~80 km in diameter at its top and of lesser width (~60 km) at a depth of 16 km. Given the relative paucity of measured densities and density contrasts at Chicxulub, the model by Hildebrand et al. (1998) may be too complex in detail. Additional gravity modeling by Vermeesch and Morgan (2004) showed that gravity data over the structural uplift at Chicxulub cannot uniquely constrain its shape and that many models will fit the gravity data equally as well. Whereas gravity data can only provide information on the maximum distance (but not depth or direction) to a subsurface density anomaly, seismic velocity data have both directional and depth control. Hence, a velocity model that has been determined using both a three-dimensional velocity and combined three-dimensional velocity-density inversion (Vermeesch and Morgan 2008) has been used to interpret the central crater structure in Fig. 11. An advantage of using this particular inversion technique is that the starting model has no structure and the final model is, thus, objective within the constraints of the model parameters.

Observations at terrestrial complex impact structures,

where the parautochthonous rocks of the structural uplift are exposed at the level of the crater floor or below (including Vredefort and Sudbury), do not indicate a wide, identifiable megabreccia zone surrounding a core of more coherent uplifted basement. In keeping with these observations, it is more likely that the density changes corresponding to this discrete megabreccia zone in the Hildebrand et al. (1998) model are either due to lateral and depth variations in the degree of fracturing and disruption of the basement rocks of the structural uplift, and/or to a change in mineralogy. According to scaling relationships and current general understanding of large crater formation, such as at Chicxulub, the material at the center of the structural uplift would originate from the lower crust and the material that surrounds it from the mid to upper crust. The typical seismic velocity of lower crustal rocks is >6.3 km s⁻¹ and this is consistent with velocities observed within the center of the crater at depths of >5 km (Fig. 11; Christeson et al. 2001; Morgan et al. 2002). These high-velocity rocks are surrounded by rocks with velocities that slowly decrease to ~5.8 km s⁻¹ (Fig. 11). Such velocities are more typical of upper continental crust (Mooney et al. 1998). In support of this, the majority of crystalline basement clasts within the impact breccias at Chicxulub are granitic (Kettrup and Deutsch 2004), with calculated average velocities of around 6 km s⁻¹ (Vermeesch 2006).

Based on the above reasoning, the gravity expression of the entire structural uplift at Chicxulub actually has a diameter of 70–80 km, which is more consistent with that derived from the seismic interpretation (Morgan et al. 2000; Vermeesch and Morgan 2004; Vermeesch 2006). As this is close to the diameter of the inner topographic ring, it suggests a potential role for the structural uplift in inner ring formation. Whatever the case, the structural model of Chicxulub by Hildebrand et al. (1998), based on potential field data, requires revision, as it depicts density contrasts due to this megabreccia zone extending to depths of 16 km. The maximum gravity anomalies over terrestrial impact structures are limited to ~300 g.u. (Basilevsky et al. 1983; Pilkington and Grieve 1992), corresponding to the preservation of the effects of impact-induced fracturing and reduced densities to a maximum depth of ~8 km, below which fractures are expected to be essentially closed by lithostatic pressure (Perrier and Quiblier 1974).

INTEGRATION OF OBSERVATIONS AT ALL THREE STRUCTURES

Both observations and their interpretations in geoscience focus on what has been previously recognizable and generally known (Grieve and Therriault 2004). Thus, observations are never completely objective nor are the models based on these observations. One of the strengths of the terrestrial impact record is the potential to combine observations from several

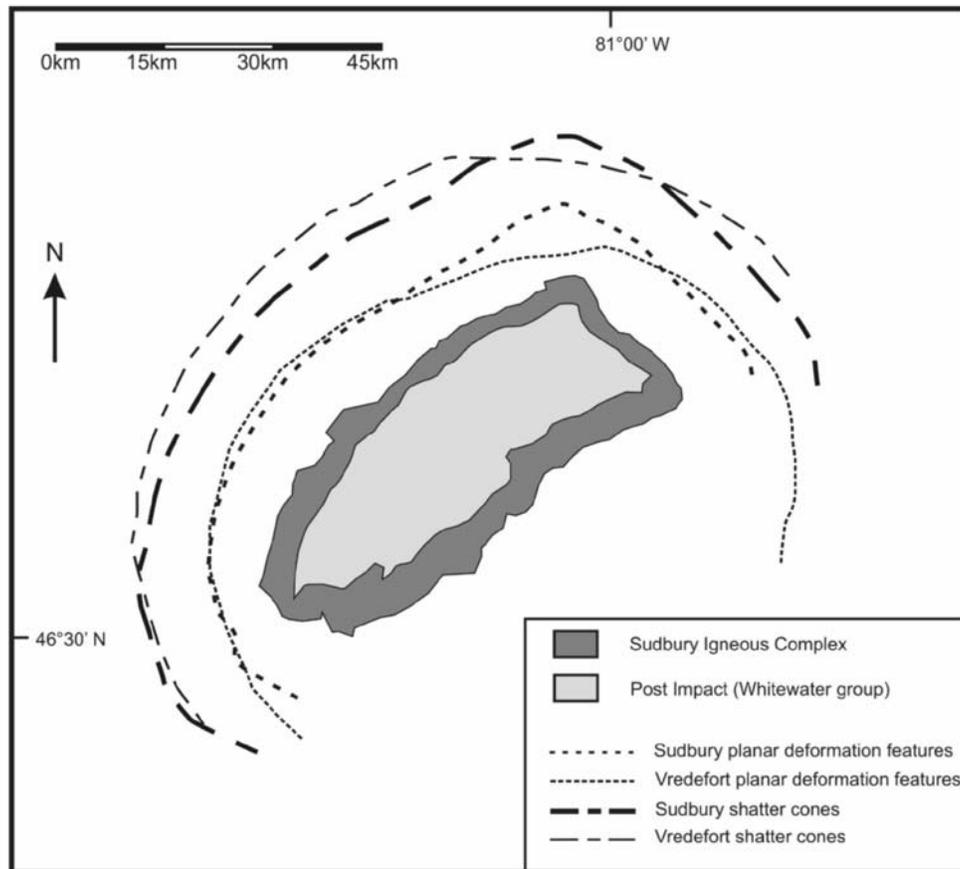


Fig. 12. Outer limits of the occurrence of shatter cones and PDFs in quartz at Vredefort scaled to and overlain on the location of the equivalent features at Sudbury. Such an empirical scaling method was used to scale and locate the potential occurrence of other Vredefort structures (e.g., thrusts) to Sudbury. See Fig. 13.

structures of similar size, but exposed to different levels, to build composite three-dimensional structural and lithological models of terrestrial impact structures. In the case here, however, the available terrestrial sample is very small and the quantity, quality, and intrinsic nature of the observations and interpretations is highly variable between the three structures under consideration. In addition, there is no single observation that can spatially link the structural and topographic characteristics of all three structures.

In order to use the more detailed observations from Vredefort and for their comparison with the relatively few equivalent observations at Sudbury, the spatial distribution of the structural data from Vredefort was dimensionally scaled and overlain onto the Sudbury geology. As neither structure has a recognizable rim, deriving common points for dimensional scaling in transferring the Vredefort data to Sudbury was done by scaling the relative spatial distribution of shatter cones and PDFs in quartz at Vredefort to their equivalent distribution in the least post-impact-deformed sector, i.e., the northern footwall sector, at Sudbury (Fig. 12). Using this scaling, the spatial pattern of “Vredefort-derived” structures was transferred to Sudbury. When done so, they largely lie in the northern footwall outside the SIC. The

relative position of the inward-dipping, outward-directed innermost “Vredefort-derived” thrusts are, in the case of Sudbury, close to the North Range-footwall contact (Fig. 13). The spatial distribution of the most distant “Vredefort-derived” structures extends out to the 130 km “ring” of Spray et al. (2004), but not beyond (Fig. 13).

By analogy with Vredefort, this would suggest that the larger estimates for the original final crater diameter of Sudbury (e.g., Tuchscherer and Spray 2002; Spray et al. 2004) may be overestimates. The intermediate, inward-directed “structures,” derived from scaling the Vredefort structures, correspond spatially to the area of Huronian outliers at Sudbury and the locations of the few identified deformation zones at Sudbury, e.g., the Benny Belt and the Pumphaouse Creek structures (Fig. 13). The locations of the “Vredefort-derived” structures in the NE lobe and so-called East Range of the SIC are such that some of the innermost zone of the outward-directed thrusts cut the SIC in its present location. In as much as the northeast lobe of the SIC represents a fold (Klimczak et al. 2007) and the SIC in the East Range has been extensively deformed by the Penokean orogeny, e.g., it dips $\sim 70^\circ$ towards the center of the Sudbury Basin (Riller 2005), and given the relatively crude nature of

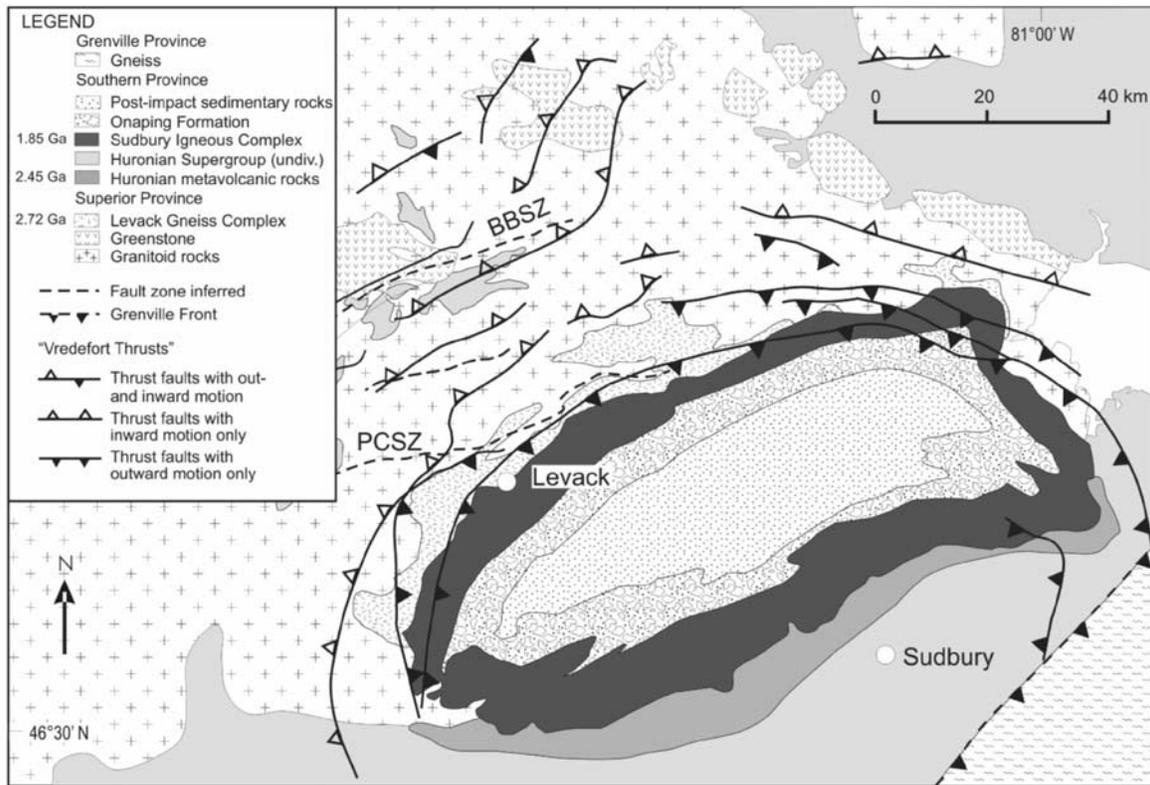


Fig. 13. Potential locations of Vredefort-derived structures transferred to Sudbury using the approximate geometric scaling derived from Fig. 12. Using this scaling the location of the center of Vredefort places the original center of the Sudbury impact structure just west of the city of Sudbury. BBSZ-Benny Belt Shear Zone. PCSZ-Pumphouse Creek Shear Zone. See text for details.

the scaling of Vredefort structures to Sudbury, this is not necessarily an inconsistency.

Conversely, at the relatively uneroded Chicxulub structure, there is no measure of the deep structure or the distribution of shock metamorphic features in the parautochthonous rocks of the crater floor to tie with observations at Vredefort (and Sudbury). Unlike Vredefort and Sudbury, however, Chicxulub has topographic features corresponding to the original rim, annular trough, inner peak ring, and central basin. Although all three structures have been imaged by reflection seismic data, the Sudbury structure was imaged by only a single transect across the central portion of the structure. Furthermore, the marine seismic transects of Chicxulub are not comparable in the level of detail and subsequent interpretation to the numerous land transects at Vredefort, which are tied to both surface and subsurface geological observations. We are constrained, therefore, to build upon the initial assumption that all three structures originally had a ring basin form to extend the integration of observations at the individual structures, while checking for internal consistency.

Recent numerical models of transient cavity modification in large-scale impact events feature outward collapse of an over-heightened central structural uplift and its interference with the inward displacement of the collapsing

transient cavity rim area. The final kinematic indicators of one such model are shown in Fig. 14 (Kenkmann et al. 2000). They indicate that the parautochthonous target rocks undergo sub-vertical collapse in the transient cavity rim area, inward sub-horizontal movement beneath the annular trough and upward and outward movement in the central structural uplift. Other recent models have also included the modification of the transient cavity and several have focused on the formation of Chicxulub (e.g., O'Keefe and Ahrens 1999; Pierazzo and Melosh 1999; Morgan et al. 2000; Ivanov and Artemieva 2002), with generally the same result, although they use different parameterization and vary in detail.

The hydrocode model of Collins et al. (2002) for peak-ring formation indicates, specifically, that the outward collapsing structural uplift overrides the inward collapsing transient cavity rim area to form an inner topographic peak. The interpretation of the reflection seismic data (Morgan et al. 2000) and the interpretation that the seismic and gravity data at Chicxulub can be reconciled to indicate that the structural uplift in the crater floor extends out to the inner topographic ring are generally consistent with this type of model (Vermeesch and Morgan 2008). In addition, in a recent study of the Houghton impact structure, albeit a smaller 23 km diameter structure in a dominantly sedimentary target, Osinski and Spray (2005) reported structural data that

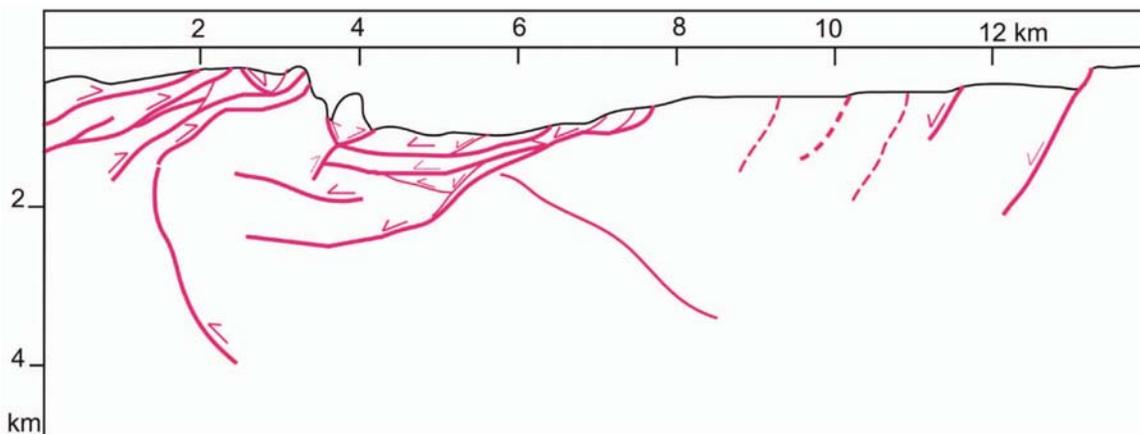


Fig. 14. Interpretation of fault/thrust distribution and final sense of movement in parautochthonous rocks of crater floor inferred from numerical model of formation of a large complex terrestrial crater, after all movement has stopped. Some of the faults may be activated more than once. Taken from Kenkmann et al. (2000).

indicate complex interactions between an outward-collapsing central structural uplift and inward-collapsing transient cavity walls. This resulted in a structural ring of uplifted, intensely faulted strata with a diameter of ~10–13 km.

Thus, the initial assumption of an inner ring at Vredefort and Sudbury is extended here to include the working hypothesis that such a ring is, in principle, the result of the convergence of inward and outward displaced materials during transient cavity modification. In this context, the structural data from Vredefort would suggest that the most likely manifestation of the location of such a ring, at the current level of erosion, is at the convergence of movements between the outward-directed, inward-dipping thrusts of the inner zone surrounding the Vredefort Dome (Ensels Thrust Zone in the terminology of Brink et al. 1997, 2000) and the inward-directed, outward-dipping reverse faults at intermediate radial distances in the industry data (Fig. 3). The extension and scaling of this assumption for Vredefort to Sudbury would place such an inner ring immediately exterior to the North Range of the SIC (Fig. 13). This suggests that what is dominantly preserved at Sudbury, the SIC and its interior Sudbury Basin, may represent the inner basin of the original ring structure and that, possibly, the structure of the topographic peak ring played a role in localizing post-impact Penokean deformation at Sudbury. If this interpretation is correct, the parautochthonous lithologies of the crater floor that occur inward of the position of the peak ring will be part of the structural uplift and, conversely, those that occur exterior to the peak ring will be higher stratigraphic level units from the collapsed wall and rim areas of the transient cavity.

At Sudbury, the dominant lithology inward of the postulated position of the peak ring are the Levack gneisses (Fig. 13), which are granulite facies gneisses partially retrograded to amphibolite facies. Uranium-lead ages on zircon grains define a formation age for the Levack gneisses of ~2.72 Ga, with shocked and partially reset variants

defining a discordia with a lower intercept age of ~1.84 Ga, the time of impact at Sudbury (Krogh et al. 1984). Krogh et al. (1984) also detected some 2.65 Ga zircons, which Riller (2005) interpreted as the time of exhumation of the granulites from their original depths of 28–21 km to shallower crustal levels of 5–11 km (James et al. 1992). Preliminary ^{40}Ar - ^{39}Ar ages on amphibole separates from the Levack gneisses are, however, consistent with the decompression textures and retrograde amphibolite metamorphism (James et al. 1992) being the result of uplift in the Sudbury impact event (N. Wodicka, Geological Survey of Canada, personal communication, 2003). Exterior to the postulated position of the inner topographic peak ring at Sudbury, the parautochthonous rocks of the crater floor are upper greenschist to lower amphibolite Archean granite-greenstones and include the partial ring of down-faulted Huronian outliers in the northwest quadrant (Fig. 13). Thus, the postulated position of the inner ring at Sudbury is generally consistent with the current spatial distribution of “deeper” (structural uplift) and “shallower” (transient cavity rim) parautochthonous lithologies in the footwall of the North Range of the SIC.

If the postulated position of the inner ring, derived from Chicxulub, is used to also scale, from Chicxulub, a position for the original final crater diameter at Sudbury, the estimated final crater diameter is ~150 km. This estimate is apparently consistent with an earlier estimate of 150–200 km (Grieve et al. 1991). The situations, however, are not exactly equivalent. In estimating the original apparent diameter of Sudbury, Grieve et al. (1991) estimated radial distances of the occurrence of particular impact-related features from the North Range of the SIC (assuming no tectonic shortening external to the North Range) and added 30 km to account for the original (unshortened) radial distance of the North Range of the SIC from the center of the structure (assumed to be the center of the Sudbury Basin). Here, however, original radial distances are estimated from a center that was defined from

the center of the Vredefort structure (taken as the center of the Vredefort Dome, 4 km north of Inlandsee), when the location of particular shock metamorphic features from Vredefort were scaled to coincide with the relative location of the equivalent shock-metamorphic features at Sudbury.

This center, so defined, lies south of the present position of the South Range of the SIC, just west of the city of Sudbury. Interestingly, the location of the original center of the Sudbury Structure, as estimated here from scaling Vredefort observations, is within a few kilometers (<5 km) of the estimated location of the original center by Butler (1994), based on his lineament analysis. According to the definitions of Turtle et al. (2005), the Grieve et al. (1991) diameter estimate, with its more northerly center within the Sudbury Basin, and more recent estimates (e.g., Grieve 1994; Deutsch et al. 1995; Tuchscherer and Spray 2002; Spray et al. 2004) would more correctly be an estimate of the apparent crater diameter at Sudbury and be greater than the original final crater diameter. Recently, Pope et al. (2004) undertook a comparison of Sudbury and Chicxulub and, by analogy, estimated the original final crater diameter of Sudbury to have been 130–140 km.

At Chicxulub, drill holes C-1 and S-1 indicate impact-melt-bearing lithologies (suevitic breccia and impact-melt rock) of unknown thickness (>500 m) interior to the inner topographic ring (e.g., Kring et al. 2004), which is consistent with the occurrence of the SIC interior to the postulated position of the inner topographic ring at Sudbury. Geophysical modelling has suggested a thickness of ~3–4 km for the inner impact-melt sheet at Chicxulub (Sharpton et al. 1993; Pilkington et al. 1994; Snyder and Hobbs 1999; Morgan et al. 2000), similar to the thickness of the SIC (~3 km, if the basal member of the overlying Onaping Formation is included as part of the impact-melt sheet [Grieve and Cintala 1992]) at Sudbury. Although the geophysical modelling includes both potential field and seismic data, it is difficult to assess the true independence of the estimated melt sheet thickness in the interior basin at Chicxulub based on geophysics from the known thickness of the SIC. Similarly, drill holes exterior to the inner topographic rim, Y-6 and Yax-1 (Figs. 8, 10, and 11), at Chicxulub also indicate the presence of impact-melt-bearing lithologies (~100–500 m thick, e.g., Stöffler et al. 2004). Based on these observations, the original impact-melt bearing lithologies (now represented only by the SIC) at Sudbury would have extended beyond the original inner peak ring to, at least, a diameter of 120–130 km.

As noted earlier, Spray et al. (2004) observed that the magnetic signature of the pre-impact, 2.47 Ga Matachewan dike swarm terminates at a diameter of 130 km in the North Range footwall at Sudbury. They ascribed this to the impact event, through demagnetization due to either shock or thermal effects from an overlying impact-melt sheet. Recent numerical calculations by Ugalde et al. (2005), with synthetic vertical magnetic dikes, indicate the complete destruction of their magnetic signature due to thermal and shock effects out

to a radial distance approaching the final rim of their model craters. In the case of Sudbury, the radial termination of the magnetic signatures of the Matachewan dikes at 130 km diameter (Fig. 6) is consistent with the estimated original final crater diameter of 150 km for Sudbury, based on scaling of the relative location of the inner topographic ring and final crater diameter from Chicxulub. The termination of the magnetic signature of the Matachewan dikes coincides with the known termination of the radial Foy offset dike (Fig. 6; Spray et al. 2004), which makes the suggestion that the termination of the magnetic signatures also marks the extent of the original impact-melt sheet an attractive working hypothesis (Pilkington and Hildebrand 2003).

The relative spatial information for the inner ring and original rim at Chicxulub was also scaled to Vredefort by scaling and locating the equivalent to the topographic peak ring from Chicxulub between the inner thrusts indicating outward motion (Ensels Thrust Zone) and the intermediate distant reverse faults indicating inward motion (Fig. 15). With the exception of some radial structures in the far north, in the area of Johannesburg, the concentric and tangential thrusts related to the formation of the Vredefort structure lie within the estimated position of the original rim at Vredefort, based on the scaled Chicxulub data (Fig. 15). This is a broadly consistent picture, as the impact-generated and impact-reactivated structures related to outward motions during transient cavity formation and inward motions related to transient cavity modification should largely lie within the final crater diameter. Based on this approach, the estimated original final crater diameter, according to the definition of Turtle et al. (2005), at Vredefort is ~180 km.

This estimate of the final crater diameter for Vredefort is closer to that of the model crater diameter of Turtle and Pierazzo (1998) of 120–200 km. If the seismically imaged structures exterior to the rim at Chicxulub are similarly scaled, the outer limit of impact-related deformation at Vredefort is ~300 km in diameter, which corresponds to the apparent rim diameter estimates of Therriault et al. (1997) and Henkel and Reimold (1998), using the definitions of Turtle et al. (2005). This estimate of ~300 km in apparent diameter corresponds to the estimate of the outer limit of deformation related to Vredefort, according to Turtle et al. (2005). Based on the observations at Chicxulub and the interpretation from Sudbury, regarding the original diameter of the impact-melt sheet, scaling to Vredefort suggests that the original melt sheet at Vredefort was ~145–155 km in diameter.

TOWARDS A COMPOSITE EMPIRICAL KINEMATIC MODEL

There are two basic but reasoned assumptions in this work. First, all three structures had initially the same form, which included an inner topographic peak ring. This is based on the occurrence of such a ring at Chicxulub and the belief that the structures had similar original final crater diameters.

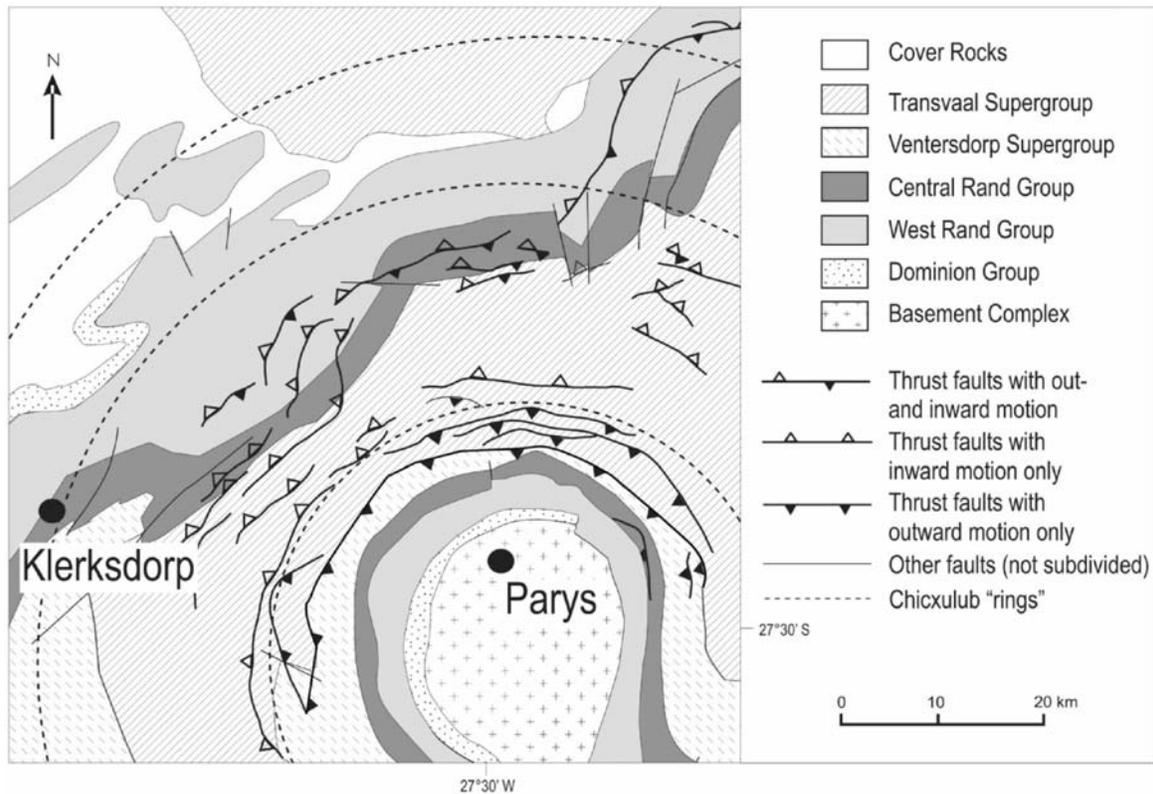


Fig. 15. Potential location of the original peak ring (inner dashed circle) and crater rim (intermediate dashed circle) at Vredefort, based on their occurrence at Chicxulub. Outermost dashed circle corresponds to the location of the external crustal fault at Chicxulub (see Fig. 11). See text for the assumptions made in scaling from Chicxulub to Vredefort.

Chicxulub has an “observable” final crater diameter in the seismic data of ~180 km, according to the definition in Turtle et al. (2005). The integration and comparison of observation undertaken above suggests that the original final crater diameter for Vredefort was ~180 km and for Sudbury was ~150 km. The Sudbury estimate is the least constrained, because of the extensive post-impact deformation. As there is no single observed characteristic or parameter that is common to all three structures, there is also a second model assumption, namely, the topographic peak ring is a reflection of the convergence of inward-moving material from the collapse of the transient cavity rim and wall area and outward-moving material from the collapse of an over-heightened structural uplift during the modification stage of the cratering process. Although there is no single proof, observations and interpretations at the individual structures, and the results when these are extended and integrated between structures, as outlined above, are generally consistent with these assumptions.

Although, in hindsight, it is not surprising, given the detailed shapes of terrestrial impact structures at the surface (e.g., the “squarish” outline of Barringer crater, Arizona [Shoemaker and Kieffer 1974]), the polygonal shape of aspects of Manicouagan and other terrestrial complex impact structures (Morrison 1984)), the evidence from Vredefort

indicates that transient cavity formation clearly exploited pre-existing structures in the target rocks. In particular, pre-existing structures tangential to the radial motions in transient cavity formation developed into thrusts, accomplishing outward-directed material displacements. The perception of the major motions in this process is as discrete packages of target rocks, with scales of several kilometers. Although there are clearly differential movements, the sense is of a degree of overall coherency with respect to the original spatial arrangement of the target lithologies. This does not preclude movement at finer scales. The similar composition of pseudotachylitic breccia veins and their host rocks and the observation of relatively minor displacements (generally less than 0.5 m) across such veins at Sudbury and Vredefort would, however, seem to argue against major individual motions at smaller scales (Dressler and Reimold 2004).

The structures examined here provide little information on details of the original rim area immediately after the modification of the transient cavity, with the exception that the reflection seismic data indicate near-surface lithologies down-dropped inward of the rim at Chicxulub. At the resolution of the Chicxulub seismic data, these blocks would appear to have lateral dimensions on the order of ~10 km near the rim and become progressively smaller in dimension (~5 km) close to the inner peak ring. This decrease in block

dimensions inward of the rim is also observed in reflection seismic data from Haughton, although the much more detailed land-based data from Haughton also suggest a large number of relatively minor displacements and discrete normal fault scarps within the down-dropped blocks (Scott and Hajnal 1988).

Similarly, the Chicxulub data supply limited data on the dip of these faults, except that the most obvious faults near the surface are steep and may become listric at depth (Gulick et al. 2008). In agreement with this, the Haughton data suggest a fault dip of around 60° closest to the surface, becoming more listric with depth (Scott and Hajnal 1988). This corresponds well with observations on the inner rim structure of smaller impact structures such as Tswaing and Bosumtwi (Brandt and Reimold 1999; Reimold et al. 1998). Whatever the case, the Vredefort data clearly indicate that motions in the parautochthonous rocks of the true crater floor from transient cavity rim and wall area collapse are along inward-dipping, listric faults, at least at upper to middle crustal depths. In some cases, particularly at the greater radial distances from the center, motions were along the same pre-existing structures in the crater floor that were exploited previously, during outward-directed motions in the formation of the transient cavity. A similar observation with the same structures being exploited in both the formation and the modification of the transient cavity has been made recently at the Haughton impact structure (Osinski and Spray 2005).

Both the Vredefort and Sudbury structures display the classic pattern of the upturning of lithologies and the exposure of deeper stratigraphic levels in the parautochthonous rocks of the crater floor, as the center of the structure is approached (Lana et al. 2003; Riller 2005; Wieland et al. 2005). This is characteristic of the process of structural uplift in transient cavity modification at complex impact structures (Grieve and Theriault 2004). Under the basic initial assumption of the original form of these structures, this is consistent with the model assumption that structural uplift is an intimate participant in the physical process(es) that result in an inner topographic ring, as suggested by recent hydrocode calculations (e.g., Collins et al. 2002; Ivanov 2005). A requirement in such models (e.g., Ivanov and Kostuchenko 1997; Kenkmann et al. 2000) is reduced target rock strength due to such processes as acoustic fluidization (Melosh 1989). It is not clear what the evidence would be for such a process at the mid-crustal levels exposed in the crystalline core of Vredefort. At these levels, movement appears to have been accomplished by cumulative small-scale differential rock displacements (shearing and rotation) that is facilitated by pervasive pseudotachylitic breccia veining and high post-shock temperatures (Lana et al. 2003; Dressler and Reimold 2004; Gibson and Reimold 2005).

The collar rocks at Vredefort indicate that uplift and rotation to near vertical to overturned attitudes, with the variation likely due to the effect of a pre-impact regional dip

(Lana et al. 2003; Wieland et al. 2005), occurred prior to the outward-directed radial thrusting (Simpson 1978; Brink et al. 1997). The former is indicative of the well-known inward and upward kinematics in the parautochthonous rocks of the crater floor observed in structural uplifts at the centers of smaller terrestrial impact structures (Grieve and Theriault 2004). There is, however, a net difference in the final result of uplift here, compared to smaller complex terrestrial impact structures. The planar mineral fabrics in the crystalline core are steep and similar to the attitude of the collar rocks only in the outermost part of the crystalline core of the Vredefort Dome, adjacent to the collar of supracrustal rocks. In contrast, in the central portion of the core, the planar mineral fabrics are sub-horizontal (Lana et al. 2003), suggesting a further set of movements, beyond the inward and upward movements that characterize the structural uplifts of smaller terrestrial impact structures.

Similarly, the evidence for the later-stage outward motions manifest in the outer portion of the structural uplift as inward-dipping thrusts, such as those at Vredefort, is generally not observed at smaller terrestrial complex impact structures. The indicators for outward motions observed by Osinski and Spray (2005) around the structural uplift at the smaller Haughton structure are not exactly equivalent to these late-stage motions in the structural uplift at the larger structures under consideration here. The structures at Haughton that indicate outward motion dip away from the center, are extensional, and are believed to be related to the structural uplift undergoing late-stage adjustments to the collapsed transient cavity and the formation of the annular trough (Osinski and Spray 2005). The outward-directed, inward-dipping thrusts at Vredefort are consistent with a model of a structural uplift that collapses back down its central axis into a modified transient cavity. The modified transient cavity no longer has the capacity to accommodate the “excess” volume of the collapsing structural uplift, which is then redirected outwards in a radial direction.

This model involving “excess” volume of the structural uplift has similarities to a model to explain the transition from complex central peak craters to central peak basins, which have a central peak and a topographic peak ring, on the Moon (Hale and Grieve 1982). Unlike on the Moon, the greater amount of impact melting, relative to transient cavity dimensions at similar-sized terrestrial impact structures, results in the impact-melt volume reaching below the floor of the transient cavity at structures with the sizes under consideration here (Grieve and Cintala 1992). Following structural uplift and cavity modification, this material of the transient cavity floor will fail to be ultimately manifested as a topographic central peak, as it has no mechanical strength and can not result in a positive topographic feature.

The radial motions from structural uplift collapse occur, at least in their later stages, by discontinuous deformation along specific dislocations. This is not necessarily at odds

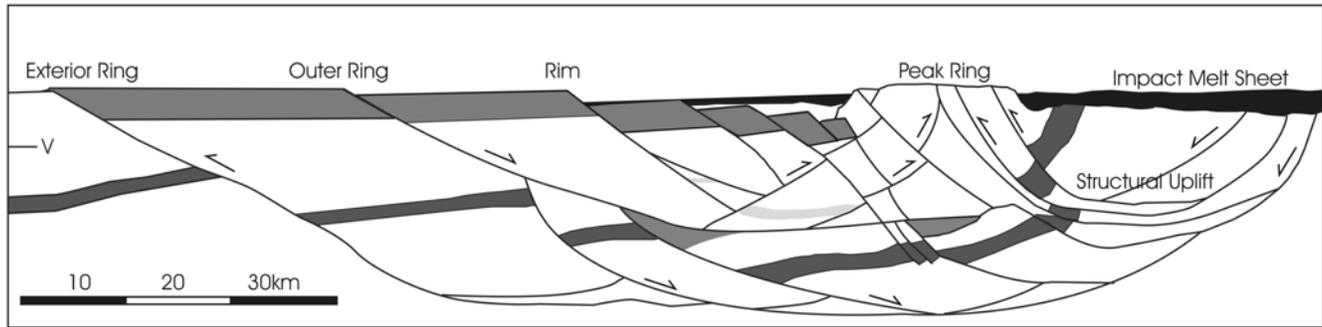


Fig. 16. Schematic cross section of half space of the integrated empirical model of a terrestrial ring basin, with no vertical exaggeration. Model is generally consistent with the observations and interpretations in the text, concerning the characteristics and interpretations at Vredefort, Sudbury, and Chicxulub. “V” on depth scale is approximate current level of erosion at Vredefort. Erosional level for Chicxulub is essentially the upper surface of the model structure. The inner Sudbury Basin has an erosion level similar to Chicxulub. Exterior to the Sudbury Basin and the SIC, the erosional level at Sudbury is more comparable to that at Vredefort. See text for details and model assumptions.

with the sense of bulk coherent flow of overriding low-strength material in the collapsing structural uplift in model calculations (e.g., Collins et al. 2002). Localization of strain concentrated along very narrow zones and discrete displacements are, in fact, a feature of the apparent smooth average strain and bulk coherent flow of model calculations (Collins et al. 2004). The situation, however, may be different in the core of the structural uplift, as suggested by the lack of discrete structures and the sub-horizontal impact-related mineral fabrics in the center of the core at Vredefort (Lana et al. 2003). It is not clear whether the outward-dipping, radially inward-directed reverse faults, which emanate from the listric faults in the crater floor at Vredefort, had already formed during the collapse of the transient cavity wall. Whatever the case, the combination of opposed radially directed shortening by the two sets of structures with opposite dip will lead to a circular zone of compression at this radial distance and the potential to create positive topography in the form of a ring.

At the higher stratigraphic levels of Chicxulub, the inner topographic ring lies stratigraphically above and slightly inward of the last identifiable blocks of Cretaceous strata down-dropped cumulatively some 4–6 km in the collapse of the transient cavity rim area. There are a number of prominent reflectors (structures?) with an inward dip of 30° , which run stratigraphically between the outer edge of the inner topographic ring and the inner edge of the last identifiable down-dropped Cretaceous block at Chicxulub (Fig. 10; Brittan et al. 1999). Inward of the dipping reflectors is the low-velocity zone with a similar inward dip (Morgan et al. 2000), which is interpreted to be due to a megabreccia or fractured basement of the structural uplift (Vermeesch and Morgan 2004). The low velocity zone can be traced to depths of ~ 7 km. The observations and interpretations regarding the process of peak ring formation at Vredefort and Chicxulub are broadly compatible with the representation of the same process. A composite synoptic structural cross section of the final form of such a terrestrial ring basin, compatible with the

observations and interpretations of the three structures under consideration, particularly Chicxulub and Vredefort for the near-surface and deeper sections, respectively, is illustrated in Fig. 16.

Once transient cavity modification is complete, the impact melt will pool on the crater floor both inside and outside the inner topographic ring. On the basis of the SIC at Sudbury, the resultant impact-melt sheet within the inner topographic ring would be ~ 3 km thick and would most likely differentiate into more felsic and more mafic lithologies. It is interesting that both Vredefort and Sudbury have impact-melt dikes with equivalent (radial and concentric) orientations in the parautochthonous rocks of the crater floor, suggesting possibly common genesis and emplacement processes (Therriault et al. 1996b). The offset dikes at Sudbury have somewhat evolved and varying compositions. The data of Tuchscherer and Spray (2002) indicate that most distal chilled variants are closest in composition to the average SIC composition and the most proximal variants have the most evolved composition. This is indicative of successive tapping of the overlying melt sheet for dike material as the melt sheet differentiated. If the Granophyre melt dikes at Vredefort also represent an evolved composition, with respect to the average composition of the original impact-melt sheet, it may explain the somewhat diverse results of mixing models of potential target rock components (Therriault et al. 1997; Reimold and Gibson 2006). Assuming gravity scaled impact-induced topography, similar-sized multi-ring basins on Venus (Alexopolous and McKinnon 1994) suggest the immediate post-impact apparent depth of these terrestrial ring basins, with final crater diameters of ~ 150 – 200 km, would be ~ 1 km (Sharpton 1994).

CONCLUDING REMARKS

This contribution has garnered observations and interpretations of those observations from three separate sources: Vredefort, Sudbury, and Chicxulub, under the

assumption that they all had the same morphology as impact structures. The lack, however, of a single common physical attribute that could be carried through all three structures has required a working hypothesis be assumed, regarding the formation of an inner topographic ring at these structures. With this assumption, scaling of the various attributes of individual structures to all structures yields a generally self-consistent picture with no obvious spatial, structural, or lithological anomalies. The general lack of major inconsistencies in creating the final composite kinematic model of a terrestrial ring basin is a positive outcome, but the model can only be considered as support for the initial working hypothesis. By its nature, the composite model is similar to the end results of some recent hydrocode models. It is internally consistent with the formation of an inner topographic ring through the convergence of the outward collapse of an over-heightened structural uplift and the inward collapse of the transient cavity rim area but, by its inherent nature, is not proof.

The composite empirical model, which is heavily influenced by the structural interpretations at Vredefort, does differ in one detail from the results of hydrocode models. In the hydrocode models (e.g., Collins et al. 2002; Ivanov 2005), the inwardly collapsed transient cavity rim units largely dip towards the center of the structure and are overridden by units from the collapsed structural uplift to form the inner ring. At the erosional level of Vredefort, however, interpretations of seismic data for the empirical model suggest that the inner ring occurs at the convergence of outwardly dipping structures in the collapsed transient cavity units and inwardly dipping structures in the collapsed structural uplift units (Fig. 16). This divergence may be the result of differences in the relative timing of the inward collapse of transient cavity and outward collapse of structural uplift units between the empirical and hydrocode models. Alternatively, it may be a function of the reliance on the structural data from Vredefort and its current level of erosion (see Fig. 15 in Ivanov 2005) in the empirical model.

The structural data from Vredefort are compatible with a structural uplift collapsing back down its axis and the excess volume of material moving radially outward along a series of discrete thrusts. Another principle facet of the model is the extent to which block movements in the formation and modification of the transient cavity rim area exploited pre-existing structures in the target rocks. This is particularly prevalent for pre-existing structures with tangential geometries to the radial sense of movement, which develop as thrusts. In addition, the same structures can be exploited for both transient cavity formation and subsequent modification. Finally, the absence of a residual or remanent central topographic peak from the process of peak-ring formation can be attributed to those materials that could ultimately constitute such a central peak (the uplifted transient cavity floor) being within the original volume of impact melt at terrestrial impact events of this magnitude.

Testing of the robustness of the working hypothesis and the composite model will require further observational data. Although there are thresholds in the formation of particular elements of crater morphology with event size, the processes of transient cavity modification likely represent a continuum. It is possible, therefore, that detailed structural/lithological information from other (smaller) terrestrial impact structures can provide some additional constraints and tests. This may be particularly true at impact structures in weaker sedimentary targets with good stratigraphic controls, such as the recent study at Haughton (Osinski and Spray 2005). Ideally, however, there should be an effort to gather new and relevant observations at the three structures in question. For example, a future focus at Sudbury could include geologic mapping in the northern footwall of the SIC to confirm or deny the existence of structures equivalent to those imaged at Vredefort. At Vredefort, there is potential for the future release of the vast amounts of yet undisclosed data held by industry, which could provide further constraints. At Chicxulub, a future focus should be the determination of the exact lithological and structural nature of the inner topographic peak ring. While additional geophysical studies will help, a true quantum step in determining the exact nature and understanding the formational process will require drilling of the inner topographic peak ring at Chicxulub.

Finally, the potential formation of a zone of inward-dipping thrusts, equivalent to those at Vredefort as the result of the collapse of the initial structural uplift, may have implications for the ultimate nature of the post-impact tectonic deformation at Sudbury. Such thrusts, with the appropriate geometry, could be reactivated during the overall NW-SE shortening by the subsequent Penokean orogeny. There are recent suggestions of such thrusting in the North Range of the SIC, as indicated by missing sections of the SIC-induced thermal aureole in the northern footwall, in the vicinity of the SIC (Boast and Spray 2006). Similarly, impact-related thrusts with other geometries could be reactivated as strike-slip structures in the Penokean, which might account for such faults cutting and displacing the SIC in the East Range (Grieve et al. 2005). As many of the ore deposits at Sudbury occur at or near the base of the SIC, the potential existence and reactivation of such structures have implications for future exploration strategies at Sudbury.

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REFERENCES

- Addison W. D., Brumpton G. R., Vallini D. A., McNaughton N. J., Davis D. W., Kissin S. A., Fralick P. W., and Hammond A. L. 2005. Discovery of distal ejecta from the 1850 Ma Sudbury impact event. *Geology* 33:193–196.
- Alexopoulos J. S. and McKinnon W. B. 1994. Large impact craters and basins on Venus, with implications for ring mechanics on the terrestrial planets. In *Large meteorite impacts and planetary evolution*, edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. GSA Special Paper 293. Boulder: Geological Society of America. pp. 29–50.
- Basilevsky A. T., Ivanov B. A., Florensky K. P., Yakovlev O. I., Fel'dman V. I., Granovsky I. V., and Sadovsky M. A. 1983. *Impact craters on the Moon and planets*. Moscow: Nauka Press 200 p. In Russian.
- Bell C., Morgan J. V., Hampson G. J., and Trudgill B. 2004. Stratigraphic and sedimentological observations from seismic data across the Chicxulub impact basin. *Meteoritics & Planetary Science* 39:1089–1098.
- Boerner D. E. and Milkereit B. 1999. Structural evolution of the Sudbury impact structure in the light of seismic reflection data. In *Large Meteorite Impacts and Planetary Evolution II*, edited by Dressler B. O. and Sharpton V. L. GSA Special Paper 339. Boulder: Geological Society of America. pp. 419–429.
- Boerner D. E., Milkereit B., and Davidson A. 2000. Geoscience impact: A synthesis of studies of the Sudbury structure. *Canadian Journal of Earth Sciences* 37:477–501.
- Boast M. and Spray J. 2006. Superimposition of a thrust-transfer fault system on a large impact structure: Implications for Ni-Cu-PGE exploration at Sudbury. *Economic Geology* 101:1583–1594.
- Brandt D. and Reimold W. U. 1999. The geology and geophysical signature of the Pretoria Saltpan (Tswaing) impact structure. In *Investigations into the origin, age, and paleoenvironments of the Pretoria Saltpan*, edited by Partridge T. C. Council for Geoscience Memoir 85. pp. 6–34.
- Brink M. C., Waanders F. B., and Bisschoff A. A. 1997. Vredefort: A model for the anatomy of an astrobleme. *Tectonophysics* 270:83–114.
- Brink M. C., Waanders F. B., and Bisschoff A. A. 2000. The Foch Thrust-Potchefstroom Fault structural system, Vredefort, South Africa: A model for impact-related tectonic movement over a pre-existing barrier. *Journal of African Earth Sciences* 30:99–117.
- Brittan J., Morgan J. V., Warner M., and Marin L. 1999. Near-surface seismic expression of the Chicxulub impact crater. In *Large Meteorite Impacts and Planetary Evolution II*, edited by Dressler B. O. and Sharpton V. L. GSA Special Paper 339. Boulder: Geological Society of America. pp. 269–279.
- Butler H. R. 1994. Lineament analysis of the Sudbury multiring impact structure. In *Large Meteorite Impacts and Planetary Evolution*, edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. GSA Special Paper 293. Boulder: Geological Society of America. pp. 319–330.
- Camargo Z. A. and Suárez R. G. 1994. Evidencia sísmica del cráter impacto de Chicxulub. *Boletín de la Asociación Mexicana de Geofísicos de Exploración* 34:1–28.
- Card K. D. 1968. Geology of the Denison-Waters area, District of Sudbury. *Ontario Geological Survey Report* 60. 63 p.
- Card K. D. 1978. Geology of the Sudbury-Manitowlin area. *Ontario Geological Survey Report* 166. 238 p.
- Card K. D. 1994. Geology of the Levack gneiss complex, the northern footwall of the Sudbury structure, Ontario. Geological Survey of Canada Paper 1994-C. pp. 269–278.
- Card K. D. and Meyn H. D. 1969. Geology of the Leinster-Bowling area. Ontario Department of Mines Geological Report 65. 40 p.
- Carter N. L. 1965. Basal quartz deformation lamellae—A criterion for recognition of impactites. *American Journal of Science* 263:786–806.
- Christeson G. L., Nakamura Y., Buffler R. T., Morgan J., and Warner M. 2001. Deep crustal structure of the Chicxulub impact crater. *Journal of Geophysical Research* 106:21,751–21,769.
- Collins G. S., Melosh H. J., Morgan J. V., and Warner M. R. 2002. Hydrocode simulations of Chicxulub crater collapse and peak-ring formation. *Icarus* 157:24–33.
- Collins G. S., Melosh H. J., and Ivanov B. A. 2004. Damage and deformation in numerical impact stimulations. *Meteoritics & Planetary Science* 39:217–231.
- Dence M. R. 1972. Meteorite impact craters and the structure of the Sudbury basin. Geological Association of Canada Special Paper 10. pp. 7–18.
- Dence M. R., Grieve R. A. F., and Robertson P. B. 1977. Terrestrial impact structures: Principal characteristics and energy considerations. In *Impact and explosion cratering*, edited by Roddy D. J., Pepin R. O., and Merrill R. B. New York: Pergamon Press. pp. 247–275.
- Deutsch A., Grieve R. A. F., Avermann M., Bischoff L., Brockmeyer P., Buhl D., Lakomy R., Müller-Mohr V., Ostermann M., and Stöffler D. 1995. The Sudbury structure (Ontario, Canada): A tectonically deformed multi-ring impact basin. *Geologische Rundschau* 84:697–709.
- Dickin A. P., Nguyen T., and Crocket J. D. 1999. Isotopic evidence for a single impact melting origin of the Sudbury Igneous Complex. In *Large meteorite impacts and planetary evolution II*, edited by Dressler B. O. and Sharpton V. L. GSA Special Paper 339. Boulder: Geological Society of America. pp. 361–371.
- Dressler B. O. 1984. The effects of the Sudbury event and the intrusion of the Sudbury Igneous Complex on the footwall rocks of the Sudbury structure. In *The geology and ore deposits of the Sudbury structure*, edited by Pye E., Naldrett A. J., and Giblin P. E. Special Volume 1. Toronto: Ontario Geological Survey. pp. 97–136.
- Dressler B. O. and Reimold W. U. 2004. Order or chaos? Origin and mode of emplacement of breccias in floors of large impact structures. *Earth Science Reviews* 67:1–64.
- Ellis S. and Reimold W. U. 1999. Post-Transvaal supergroup age thrusting related to the collapse phase of the Vredefort impact event: Examples from the western ring basin area (abstract). *Meteoritics & Planetary Science* 34:A34.
- Espindola J. M., Mena M., de la Fuente M., and Campos-Enriquez J. O. 1995. A model of the Chicxulub impact structure (Yucatán, Mexico) based on its gravity and magnetic signatures. *Physics of the Earth and Planetary Interiors* 92:271–278.
- Fletcher P. and Reimold W. U. 1989. Some notes and speculations on the pseudotachylites in the Witwatersrand Basin and Vredefort Dome, South Africa. *South African Journal of Geology* 92:223–234.
- French B. M. 1968. Sudbury structure, Ontario: Some petrographic evidence for an origin by meteorite impact. In *Shock metamorphism of natural materials*, edited by French B. M. and Short N. M. Baltimore: Mono Books. pp. 383–412.

- Fuerten F., Seabright A., and Morris B. 1992. A structural transect across the Levack Gneiss Cartier Batholith Complex, northwest of the Sudbury structure. Lithoprobe Abitibi Transect Report 33. pp. 11–15.
- Giblin P. E. 1984. History of exploration and development of geological studies and development of geological concepts. In *The geology and ore deposits of the Sudbury structure*, edited by Pye E., Naldrett A. J., and Giblin P. E. Special Volume 1. Toronto: Ontario Geological Survey. pp. 3–24.
- Gibson R. L. 2002. Impact-induced melting of Archean granulites in the Vredefort Dome, South Africa. 1: Anatexis of metapelitic granulites. *Journal of Metamorphic Geology* 20:57–70.
- Gibson R. L. and Reimold W. U. 2001. The Vredefort impact structure, South Africa (The scientific evidence and a two-day excursion guide). *Council for Geoscience Memoir* 92. Pretoria: Council for Geoscience. 111 p.
- Gibson R. L. and Reimold W. U. 2005. Shock pressure distribution in the Vredefort impact structure, South Africa. In *Large meteorite impacts III*, edited by Kenkmann T., Hörz F., and Deutsch A. GSA Special Paper 384. Boulder: Geological Society of America. pp. 339–349.
- Gibson R. L., Reimold W. U., and Stevens G. 1998. Thermal-metamorphic signature of an impact event in the Vredefort Dome, South Africa. *Geology* 26:787–790.
- Grant R. W. and Bite A. 1984. Sudbury quartz diorite offset dykes. In *The geology and ore deposits of the Sudbury structure*, edited by Pye E., Naldrett A. J., and Giblin P. E. Special Volume 1. Toronto: Ontario Geological Survey. pp. 275–301.
- Grieve R. A. F. 1994. An impact model of the Sudbury structure. In *Proceedings of the Sudbury-Norilsk Symposium*, edited by Lightfoot P. C. and Naldrett A. J. Special Volume 5. Toronto: Ontario Geological Survey. pp. 119–132.
- Grieve R. A. F. 2005. Economic natural resource deposits at terrestrial impact structures. In *Mineral deposits and Earth evolution*, edited by MacDonald I., Boyce A. J., Butler I. B., Herrington R. J., and Polya D. A. Special Publication 248. London: The Geological Society. pp. 1–29.
- Grieve R. A. F. 2006. *Impact structures in Canada*. GEOText 5. Geological Association of Canada. 210 p.
- Grieve R. A. F. and Cintala M. J. 1992. An analysis of differential impact melt crater scaling and implications for the terrestrial impact record. *Meteoritics* 27:526–538.
- Grieve R. A. F. and Shoemaker E. M. 1994. The record of past impacts on Earth. In *Hazards due to comets and asteroids*, edited by Gehrels T. Tucson: The University of Arizona Press. pp. 417–462.
- Grieve R. A. F. and Theriault A. M. 2000. Vredefort, Sudbury, Chicxulub: Three of a kind? *Annual Review of Earth and Planetary Sciences* 28:305–338.
- Grieve R. A. F. and Theriault A. M. 2004. Observations at terrestrial impact structures: Their utility in constraining crater formation. *Meteoritics & Planetary Science* 39:199–216.
- Grieve R. A. F., Stöffler D., and Deutsch A. 1991. The Sudbury Structure: Controversial or misunderstood? *Journal of Geophysical Research* 96:22,753–22,764.
- Grieve R. A. F., Riller U., and Klimczak C. 2005. Potential new constraints on deformation at the Sudbury impact structure (abstract). 15th Conference on Deformation Mechanisms, Rheology and Tectonics. Zurich: ETH. p. 97.
- Gulick S., Barton P., Christeson G., Morgan J., McDonald M., Mendoza K., Pearson Z., Surendra A., Urrutia J., Vermeesch P. M., and Warner M. 2008. Importance of pre-impact crustal structure for the asymmetry of the Chicxulub impact crater. *Nature Geoscience* 1:131–135.
- Guy-Bray J. and Geological Staff. 1966. Shatter cones at Sudbury. *Journal of Geology* 74:243–245.
- Hale W. S. and Grieve R. A. F. 1982. Volumetric analysis of complex lunar craters: Implications for basin ring formation. Proceedings, 13th Lunar and Planetary Science Conference. *Journal of Geophysical Research* 87:A65–A76.
- Hargraves R. B. 1961. Shatter cones in the rocks of the Vredefort ring. *Geological Society South Africa Transactions* 64:147–154.
- Henkel H. and Reimold W. U. 1998. Integrated geophysical modeling of a giant, complex impact structure: Anatomy of the Vredefort structure, South Africa. *Tectonophysics* 281:1–20.
- Hildebrand A. R., Penfield G. T., Kring D. A., Pilkington M., Camargo Z. A., Jacobsen S. B., and Boynton W. V. 1991. A possible Cretaceous-Tertiary boundary impact crater on the Yucatán Peninsula, Mexico. *Geology* 19:867–871.
- Hildebrand A. R., Pilkington M., Connors M., Ortiz-Aleman C., and Chavez R. E. 1995. Size and structure of the Chicxulub crater revealed by horizontal gravity gradients and cenotes. *Nature* 376:415–417.
- Hildebrand A. R., Pilkington M., Ortiz-Aleman C., Chavez R. E., Urrutia-Fucugauchi J., Connors M., Graniel-Castro E., Camargo Z. A., Halpenny J. F., and Niehaus D. 1998. Mapping Chicxulub crater structure with gravity and seismic reflection data. In *Meteorites: Flux with time and impact effects*, edited by Grady M., M. Hutchison R., McCall G. J. H., and Rothery D. A. Special Publication 140. London: The Geological Society. pp. 153–173.
- Ivanov B. A. 2005. Numerical modelling of the largest terrestrial meteorite craters. *Solar System Research* 39:381–409.
- Ivanov B. A. and Kostuchenko V. N. 1997. Block oscillation model for impact crater collapse (abstract). *Lunar Planetary Science* 28:631–632.
- Ivanov B. A. and Artemieva N. A. 2002. Numerical modeling of the formation of large impact craters. In *Catastrophic events and mass extinctions: impacts and beyond*, edited by Koeberl C. and MacLeod K. G. GSA Special Paper 356. Boulder: Geological Society of America. pp. 619–630.
- James R. S., Sweeney J. M., and Peredery W. 1992. Thermobarometric studies on the Levack gneisses—Footwall rocks to the Sudbury Igneous Complex (abstract). International Conference on Large Meteorite Impacts and Planetary Evolution. LPI Contribution #790. p. 41.
- Kamo S. L., Reimold W. U., Krogh T. E., and Colliston W. P. 1996. A 2.023 Ga age for the Vredefort impact event and a first report about shock metamorphosed zircons in pseudotachylitic breccias and Granophyre. *Earth and Planetary Science Letters* 144:369–388.
- Kellet R. L. and Rivard B. 1996. Characterization of the Benny deformation zone, Sudbury, Ontario. *Canadian Journal of Earth Sciences* 33:1256–1267.
- Kenkmann T., Ivanov B. A., and Stöffler D. 2000. Identification of ancient impact structures: Low-angle normal faults and related geological features of crater basements. In *Impacts and the early Earth*, edited by Gilmour I. and Koeberl C. Lecture Notes in Earth Sciences, vol. 91. New York: Springer Verlag. pp. 271–309.
- Kettrup B. and Deutsch A. 2004. Geochemical variability of the Yucatán basement: Constraints from crystalline clasts in Chicxulub impact impactites. *Meteoritics & Planetary Science* 38:1079–1092.
- Killick A. M. and Reimold W. U. 1990. Review of the pseudotachylites in and around the Vredefort “Dome,” South Africa. *South African Journal of Geology* 93:350–365.
- Killick A. M., Thaites A. M., Germs G. J. B., and Schoch A. E. 1988. Pseudotachylite associated with a bedding-parallel fault zone between the Witwatersrand and Ventersdorp Supergroup, South Africa. *Geologische Rundschau* 77:329–344.
- Klimczak C., Wittek, A., Doman, D., and Riller U. 2007. Fold origin of the NE-lobe of the Sudbury Basin, Canada: Evidence from

- heterogeneous fabric development in the Onaping Formation and the Sudbury Igneous Complex. *Journal of Structural Geology* 29:1744–1756.
- Koeberl C., Reimold W. U., and Shirley S. B. 1996. Re-Os isotope study of the Vredefort granophyre: Clues to the origin of the Vredefort structure, South Africa. *Geology* 24:913–916.
- Kring D. A., Hörz F., Zürcher L., and Urrutia-Fucugauchi J. 2004. Impact lithologies and their emplacement in the Chicxulub crater: Initial results from the Chicxulub Scientific Drilling Project, Yaxcopoil, Mexico. *Meteoritics & Planetary Science* 39:879–897.
- Krogh T. E., Davis D. W., and Corfu F. 1984. Precise U-Pb zircon and baddeleyite ages for the Sudbury area. In *The geology and ore deposits of the Sudbury structure*, edited by Pye E., Naldrett A. J., and Giblin P. E. Special Volume 1. Toronto: Ontario Geological Survey. pp. 431–448.
- Lana C., Gibson R. L., and Reimold W. U. 2003. Impact tectonics in the core of the Vredefort Dome, South Africa: Implications for central uplift formation in very large impact structures. *Meteoritics & Planetary Science* 38:1093–1107.
- Leroux H., Reimold W. U., and Doukhan J. -C. 1994. A TEM investigation of shock metamorphism in quartz from the Vredefort Dome, South Africa. *Tectonophysics* 230:223–239.
- Martini J. E. J. 1978. Coesite and stishovite in the Vredefort Dome, South Africa. *Nature* 272:715–717.
- McCarthy T. S., Charlesworth E. G., and Stanistreet I. G. 1986. Post-Transvaal structural features of the northern portion of the Witwatersrand basin. *Transactions of the Geological Society of South Africa* 89:311–324.
- McCarthy T. S., Stanistreet I. G., and Rob L. J. 1990. Geological studies related to the origin of the Witwatersrand basin and its mineralization—An introduction and a strategy for research and exploration. *South African Journal of Geology* 93:1–4.
- McGrath P. H. and Broome H. J. 1994. A gravity model for the Sudbury structure along the Lithoprobe seismic line. *Geophysical Research Letters* 21:955–958.
- Melosh H. J. 1989. *Impact cratering, a geologic process*. Oxford: Oxford University Press. 245 p.
- Milkereit B. and the Sudbury Working Group. 1992. Deep geometry of the Sudbury structure from seismic reflection profiling. *Geology* 20:807–811.
- Milkereit B., Green A., Wu J., White D., and Adam E. 1994. Integrated seismic and borehole geophysical study of the Sudbury Igneous Complex. *Geophysical Research Letters* 21:931–934.
- Milton D. J., Glikson A. Y., and Brett R. 1996. Gosses Bluff: A latest Jurassic impact structure central Australia. Part 1: Geological structure, stratigraphy, and origin. *Journal of Australian Geology and Geophysics* 16:453–486.
- Moon W. M. and Miao X. G. 1997. Crustal structure northwest of the Sudbury meteorite impact structure. *Geoscience Journal* 1:189–201.
- Mooney W. D., Laske G., and Masters T. G. 1998. Crust 5.1: A global crustal model at 5 × 5 degrees. *Journal of Geophysical Research* 103:727–747.
- Morgan J. V. and Warner M. 1999a. Chicxulub: The third dimension of a multi-ring impact basin. *Geology* 27:407–410.
- Morgan J. V. and Warner M. 1999b. Morphology of the Chicxulub impact: Peak-ring crater or multi-ring basin? In *Large meteorite impacts and planetary evolution II*, edited by Dressler B.O. and Sharpton V. L. GSA Special Paper 339. Boulder: Geological Society of America. pp. 281–292.
- Morgan J. V., Warner M., and the Chicxulub Working Group, 1997. Size and morphology of the Chicxulub impact crater. *Nature* 390:472–476.
- Morgan J. V., Warner M. R., Collins G. S., Melosh H. J., and Christeson G. L. 2000. Peak ring formation in large impact craters. *Earth and Planetary Science Letters* 183:347–354.
- Morgan J. V., Christeson G., and Zelt C. 2002. 3D velocity tomogram across the Chicxulub crater: Testing the resolution. *Tectonophysics* 355:217–228.
- Morrison G. G. 1984. Morphological features of the Sudbury structure in relation to an impact origin. In *The geology and ore deposits of the Sudbury structure*, edited by Pye E., Naldrett A. J., and Giblin P. E. Special Volume 1. Toronto: Ontario Geological Survey. pp. 513–522.
- Mungall J. E. and Hanley J. J. 2004. Origins of outliers of Huronian supergroup within the Sudbury structure. *Journal of Geology* 112:59–70.
- Mungall J. E., Ames D. E., and Hanley J. J. 2004. Geochemical evidence from the Sudbury structure for crustal redistribution by large bolide impacts. *Nature* 429:546–548.
- Müller-Mohr V. 1992. Breccias in the basement of a deeply eroded impact structure, Sudbury, Canada (extended abstract). *Tectonophysics* 216:219–226.
- Naldrett A. J., Bray J. G., Gasparriani E. L., Podolsky T., and Rucklidge J. C. 1970. Cryptic variation and petrology of the Sudbury Nickel Irruptive. *Economic Geology* 65:122–155.
- Naldrett A. J. 2003. From impact to riches: Evolution of geological understanding as seen at Sudbury, Canada. *GSA Today* 13:4–9.
- Osinski G. R. and Spray J. G. 2005. Tectonics of complex crater formation as revealed by the Houghton impact structure, Devon Island, Canadian High Arctic. *Meteoritics & Planetary Science* 40:1813–1834.
- O’Keefe J. D. and Ahrens T. 1999. Complex craters: Relationship of stratigraphy and rings to impact conditions. *Journal of Geophysical Research* 104:27,091–27,104.
- Perrier R. and Quiblier J. 1974. Thickness changes in sedimentary layers during compaction history: Methods for quantitative evaluation. *American Association of Petroleum Geologists Bulletin* 58:507–528.
- Phillips M. E., Bussell M. A., McDonald I., Hart R. J., and Andreoli M. A. G. 1999. A remote sensing and geological investigation of the Vredefort impact structure (South Africa), using Landsat Thematic Mapper imagery (abstract). *Meteoritics & Planetary Science* 34:A92–A93.
- Pierazzo E. and Melosh H. J. 1999. Hydrocode modeling of Chicxulub as an oblique impact event. *Earth and Planetary Science Letters* 165:163–176.
- Pierazzo E. and Herrick R. 2004. Proceedings of the workshop, Impact cratering: Bridging the gap between modeling and observations. *Meteoritics & Planetary Science* 39:167–168.
- Pilkington M. and Grieve R. A. F. 1992. The geophysical signature of terrestrial impact craters. *Reviews of Geophysics* 30:161–181.
- Pilkington M. and Hildebrand A. R. 2000. Three-dimensional magnetic imaging of the Chicxulub crater. *Journal of Geophysical Research* 105:23,479–23,491.
- Pilkington M. and Hildebrand A. R. 2003. Transient and disruption cavity dimensions of complex terrestrial impact structures derived from magnetic data. *Geophysical Research Letters* 30: doi:10.1029/2003GL018294.
- Pilkington M., Hildebrand A. R., and Ortiz-Aleman C. 1994. Gravity and magnetic field modeling and structure of the Chicxulub crater, Mexico. *Journal of Geophysical Research* 99:13,147–13,162.
- Pope K. O., Ocampo A. C., and Duller C. E. 1993. Surficial geology of the Chicxulub impact crater, Yucatán, Mexico. *Earth, Moon and Planets* 63:93–104.
- Pope K. O., Kieffer S. W., and Ames D. E. 2004. Empirical and theoretical comparisons of Chicxulub and Sudbury impact structures. *Meteoritics & Planetary Science* 39:97–116.
- Pye E. G., Naldrett A. J., and Giblin P. E., eds. 1984. *The geology and ore deposits of the Sudbury structure*. Special Volume 1. Toronto: Ontario Geological Survey. 604 p.

- Reimold W. U. and Colliston W. P. 1994. Pseudotachylites of the Vredefort Dome and the surrounding Witwatersrand Basin, South Africa. In *Large meteorite impacts and planetary evolution*, edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. GSA Special Paper 293. Boulder: Geological Society of America. pp. 177–196.
- Reimold W. U. and Gibson R. L. 2005. “Pseudotachylites” at large impact structures. In *Impact tectonics*, edited by Koeberl C. and Henkel H. Berlin-Heidelberg: Springer. pp. 1–53.
- Reimold W. U. and Gibson R. L. 2006. The melt rocks of the Vredefort impact structure: Petrography and geochemistry, and implications for impact cratering and Witwatersrand evolution. *Chemie der Erde* 66:1–35.
- Reimold U. W., Brandt D., and Koeberl C. 1998. Detailed structural analysis of the rim of a large complex impact crater: Bosumtwi crater, Ghana. *Geology* 26:543–546.
- Reimold W. U., Leroux H., and Gibson R. L. 2002. Shocked and thermally metamorphosed zircon from the Vredefort impact structure, South Africa: A transmission electron microscopic study. *European Journal of Mineralogy* 14:859–868.
- Reimold W. U., Koeberl C., Gibson R. L., and Dressler B. O. 2005. Economic mineral deposits in impact structures: A Review. In *Impact tectonics*, edited by Koeberl C. and Henkel H. Berlin-Heidelberg: Springer. pp. 479–522.
- Riller U. 2005. Structural characteristics of the Sudbury impact structure, Canada: Impact induced and orogenic deformation—A review. *Meteoritics & Planetary Science* 40:1723–1740.
- Riller U., Schwerdtner W. M., and Robin P. -Y. F. 1998. Low-temperature deformation mechanism at a lithotectonic interface near the Sudbury Basin, eastern Penokean Orogen. *Tectonophysics* 287:59–75.
- Rousell D. H. 1984. Structural geology of the Sudbury Basin. In *The geology and ore deposits of the Sudbury structure*, edited by Pye E., Naldrett A. J., and Giblin P. E. Special Volume 1. Toronto: Ontario Geological Survey. pp. 83–96.
- Rousell D. H., Fedorovich J. S., and Dressler B. O. 2003. Sudbury Breccia (Canada): A product of the 1850 Ma Sudbury event and host to the footwall Cu-Ni-PGE ores. *Earth Science Reviews* 60: 147–174.
- Scott D. and Hajnal Z. 1988. Seismic signature of the Houghton structure. *Meteoritics* 23:239–247.
- Shanks W. S. and Schwerdtner W. M. 1991. Structural analysis of the central and southwestern Sudbury structure, Southern Province, Canadian Shield. *Canadian Journal of Earth Sciences* 28:411–430.
- Sharpton V. L. 1994. Evidence from Magellan for unexpectedly deep complex craters on Venus. In *Large meteorite impacts and planetary evolution*, edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. GSA Special Paper 293. Boulder: Geological Society of America. pp. 19–28.
- Sharpton V. L., Burke K., Camargo Z., Hall S. A., Lee D. S., Marin L. E., Suárez R., Quezada M., Spudis P. D., and Urrutia-Fucugauchi J. 1993. Chicxulub multi-ring impact basin: Size and other characteristics derived from gravity analysis. *Science* 261: 1564–1567.
- Sharpton V. L., Marín L. E., Carney J. L., Lee S., Ryder G., Schuraytz C., Sikora P., and Spudis P. D. 1996. A model of the Chicxulub impact basin based on evaluation of geophysical data, well logs, and drill core samples. In *The Cretaceous-Tertiary event and other catastrophes in Earth history*, edited by Ryder G., Fastovsky D., and Gartner S. GSA Special Paper 307. Boulder: Geological Society of America. pp. 55–74.
- Shoemaker E. M. and Kieffer S. W. 1974. Guidebook to the geology of Meteor Crater, Arizona. Meteoritical Society Annual Meeting Guidebook 37. 66 p.
- Simpson C. 1978. The structure of the rim synclinorium of the Vredefort Dome. *Transaction of the Geological Society of South Africa* 81:115–121.
- Snyder D. B. and Hobbs R. W. 1999. Deep seismic reflection profiles across the Chicxulub crater. In *Large meteorite impacts and planetary evolution II*, edited by Dressler B. O. and Sharpton V. L. GSA Special Paper 339. Boulder: Geological Society of America. pp. 263–268.
- Spray J. G. 1997. Superfaults. *Geology* 25:627–630.
- Spray J. G., Butler H. R., and Thompson L. M. 2004. Tectonic influences on the morphometry of the Sudbury impact structure: Implications for terrestrial cratering and modeling. *Meteoritics & Planetary Science* 39:287–301.
- Spudis P. D. 1993. *The geology of multi-ring impact basins*. Cambridge: Cambridge University Press. 263 p.
- Steiner M. B. 1996. Implications of magneto-mineralogic characteristics of the Manson and Chicxulub impact rocks. In *The Cretaceous-Tertiary event and other catastrophes in Earth history*, edited by Ryder G., Fastovsky D., and Gartner S. GSA Special Paper 307. Boulder: Geological Society of America pp. 89–104.
- Stöffler D., Deutsch A., Avermann D., Bischoff M., Brockmeyer L., Buhl D., Lakomy R., and Müller-Mohr V. 1994. The formation of the Sudbury structure, Canada: Towards a unified impact model. In *Large meteorite impacts and planetary evolution*, edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. GSA Special Paper 293. Boulder: Geological Society of America. pp. 303–318.
- Stöffler D., Artemieva A., Ivanov B., Hecht L., Kenkmann T., Schmitt R. T., Tagle R. A., and Wittmann A. 2004. Origin and emplacement of the impact formations at Chicxulub, Mexico, as revealed by the ICDP deep drilling at Yaxcopoil-1 and by numerical modeling. *Meteoritics & Planetary Science* 39:1035–1067.
- Styles E. 2006. Chicxulub: An analysis of new gravity data, Masters project, Imperial College London, UK. 122 p.
- Swisher C. C., Grahales-Nishimura J. M., Montanari A., Margolis S. V., Claeys Ph., Alvarez W., Renne P., Cedillo-Pardo E., Florentin J. M., Maurasse R., Curtis G. H., Smit J., and McWilliams M. O. 1992. Coeval $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 65.0 million years ago from Chicxulub crater melt rock and Cretaceous-Tertiary boundary tektites. *Science* 257:954–958.
- Taylor S. R. 2001. *Solar system evolution: A new perspective*. Cambridge: Cambridge University Press. 484 p.
- Therriault A. M., Reimold W. U., and Reid A. M. 1996a. Geochemistry and impact origin of the Vredefort Granophyre. *South African Journal of Geology* 100:115–122.
- Therriault A. M., Ostermann M., Grieve R. A. F., and Deutsch A. 1996b. Are Vredefort Granophyre and Sudbury offsets birds of a feather? (abstract). *Meteoritics & Planetary Science* 31:A142.
- Therriault A. M., Grieve R. A. F., and Reimold W. U. 1997. Original size of the Vredefort structure: Implications for the geological evolution of the Witwatersrand Basin. *Meteoritics & Planetary Science* 32:1788–1795.
- Therriault A. M., Fowler A. D., and Grieve R. A. F. 2002. The Sudbury Igneous Complex: A differentiated impact-melt sheet. *Economic Geology* 97:1521–1540.
- Thompson L. M. and Spray J. G. 1994. Pseudotachylitic rock distribution and genesis within the Sudbury impact structure. In *Large meteorite impacts and planetary evolution*, edited by Dressler B. O., Grieve R. A. F., and Sharpton V. L. GSA Special Paper 293. Boulder: Geological Society of America. pp. 275–288.
- Thompson L. M., Spray J. G., and Kelley S. P. 1998. Laser probe argon-40/argon-39 dating of pseudotachylite from the Sudbury structure: Evidence for post-impact thermal overprinting in the North Range. *Meteoritics & Planetary Science* 33:1259–1269.

- Trieloff M., Reimold W. U., Kunz J., Boer R. H., and Jessberger E. K. 1994. ^{40}Ar - ^{39}Ar thermochronology of pseudotachylite at the Ventersdorp Contact Reef, Witwatersrand Basin. *South African Journal of Geology* 97:365–384.
- Tuchscherer M. G. and Spray J. G. 2002. Geology, mineralization and emplacement of the Foy offset dike, Sudbury. *Economic Geology* 97:1377–1398.
- Tuchscherer M. G., Reimold W. U., Koeberl C., Gibson R. L., and de Bruin D. 2004. First petrographic results on impactites from the Yaxcopoil-1 borehole, Chicxulub structure, Mexico. *Meteoritics & Planetary Science* 39:899–930.
- Turtle E. P. and Pierazzo E. 1998. Constraints on the size of the Vredefort impact crater from numerical modeling. *Meteoritics & Planetary Science* 33:483–490.
- Turtle E. P., Pierazzo E., Collins G. S., Osinski G. R., Melosh H. J., Morgan J. V., and Reimold W. U. 2005. What does crater diameter mean? In *Large meteorite impacts III*, edited by Kenkmann T., Hörz F., and Deutsch A. GSA Special Paper 384. Boulder: Geological Society of America. pp. 25–42.
- Ugalde H. A., Artemieva N., and Milkereit B. 2005. Magnetization of impact structures—Constraints from numerical modeling and petrophysics. In *Large meteorite impacts III*, edited by Kenkmann T., Hörz F., and Deutsch A. GSA Special Paper 384. Boulder: Geological Society of America. pp. 1–24.
- Vermeesch P. 2006. Geophysical study of the Chicxulub impact crater. Ph.D. thesis, Imperial College London, UK. 418 p.
- Vermeesch P. M. and Morgan J. V. 2004. Chicxulub central crater structure: Initial results from physical property measurements and combined velocity and gravity modeling. *Meteoritics & Planetary Science* 39:1019–1034.
- Vermeesch P. M. and Morgan J. V. 2008. Structural uplift beneath the Chicxulub impact crater. *Journal of Geophysical Research* 113: B07103, doi:10.1029.
- Ward W. C., Keller G., Stinnesbeck W., and Adatte T. 1995. Yucatán subsurface stratigraphy: Implications and constraints for the Chicxulub impact. *Geology* 23:873–876.
- Wieland F., Gibson R. L., and Reimold W. U. 2005. Structural analysis of the collar of the Vredefort Dome, South Africa—significance of impact-related deformation and central uplift formation. *Meteoritics & Planetary Science* 40:1537–1554.
- Wittmann A., Kenkmann T., Schmitt R. T., Hecht L., and Stöffler D. 2004. Impact-related dike breccia lithologies in ICDP drill hole Yaxcopoil-1, Chicxulub impact structure, Mexico. *Meteoritics & Planetary Science* 39:931–954.
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