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Tectonic influences on the morphometry of the Sudbury impact structure: Implications for terrestrial cratering and modeling

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Abstract–Impact structures developed on active terrestrial planets (Earth and Venus) are susceptible to pre-impact tectonic influences on their formation. This means that we cannot expect them to conform to ideal cratering models, which are commonly based on the response of a homogeneous target devoid of pre-existing flaws. In the case of the 1.85 Ga Sudbury impact structure of Ontario, Canada, considerable influence has been exerted on modification stage processes by late Archean to early Proterozoic basement faults. Two trends are dominant: 1) the NNW-striking Onaping Fault System, which is parallel to the 2.47 Ga Matachewan dyke swarm, and 2) the ENE-striking Murray Fault System, which acted as a major Paleoproterozoic suture zone that contributed to the development of the Huronian sedimentary basin between 2.45–2.2 Ga. Sudbury has also been affected by syn- to post-impact regional deformation and metamorphism: the 1.9–1.8 Ga Penokean orogeny, which involved NNW-directed reverse faulting, uplift, and transpression at mainly greenschist facies grade, and the 1.16–0.99 Ga Grenville orogeny, which overprinted the SE sector of the impact structure to yield a polydeformed upper amphibolite facies terrain. The pre-, syn-, and post-impact tectonics of the region have rendered the Sudbury structure a complicated feature. Careful reconstruction is required before its original morphometry can be established. This is likely to be true for many impact structures developed on active terrestrial planets.

Based on extensive field work, combined with remote sensing and geophysical data, four ring systems have been identified at Sudbury. The inner three rings broadly correlate with pseudotachylyte (friction melt) -rich fault systems. The first ring has a diameter of ~90 km and defines what is interpreted to be the remains of the central uplift. The second ring delimits the collapsed transient cavity diameter at ~130 km and broadly corresponds to the original melt sheet diameter. The third ring has a diameter of ~180 km. The fourth ring defines the suggested apparent crater diameter at ~260 km. This approximates the final rim diameter, given that erosion in the North Range is <6 km and the ring faults are steeply dipping. Impact damage beyond Ring 4 may occur, but has not yet been identified in the field. One or more rings within the central uplift (Ring 1) may also exist. This form and concentric structure indicates that Sudbury is a peak ring or, more probably, a multi-ring basin. These parameters provide the foundation for modeling the formation of this relatively large terrestrial impact structure.

INTRODUCTION

Much of our knowledge of impact structures and the cratering process has come from the study of planetary bodies other than Earth. In particular, the Moon (e.g., Howard et al. 1974; Pike 1974) and Mars (e.g., Pike 1980) have served us well. Compared to Earth, these bodies possess simpler crustal structure. In addition, they preserve more of their earlier histories and, hence, a more extensive cratering record. In the case of the Moon, its surface has been pulverized, fragmented, and locally melted via bombardment to yield a relatively homogenized megaregolith, which is up to 10 km, or more, in thickness (e.g., Heiken et al. 1991). Impact structures on the Moon can survive for geologically long periods because of the decreased impact flux with time and due to an absence of tectonic and erosional processes. For Mars, its larger size has rendered it tectonically and volcanically active for longer than the Moon (e.g., the basaltic and lherzolitic shergottite meteorites from Mars yield primary igneous ages between 475 and 165 Ma; McSween 2002). Nevertheless, Mars retains much of its earlier bombardment history in the Noachian terrains of the southern highlands. This heavily cratered terrain reveals little evidence of faulting, folding or regional tectonics that have overprinted the impact structures.

Earth and Venus, in marked contrast, are dynamic planets. It is estimated that the average age of the venusian surface is 200–600 Ma (Strom et al. 1994). Approximately 70% of the Earth's surface comprises oceanic lithosphere that is <200 Ma in age. Resurfacing of the oceanic realm occurs via plate construction at spreading centers and destruction at plate margins by subduction. Much of the continental lithosphere has been reworked via plate collisions and intraplate igneous activity, metamorphism, and erosion. This means that Earth's inventory of impact structures is limited (currently ~170; Earth Impact Database 2003, versus >42,000 on Mars; Barlow 2000). Moreover, those that have survived are typically not in pristine condition. Terrestrial impact structures are commonly partly eroded and/or deformed. Exceptions include those structures that were rapidly buried following their formation and/or are geologically young (e.g., <20 Ma in age). In addition to destructive processes, which act to erase Earth's impact record, a dynamic planetary surface can influence the hypervelocity collision process due to target heterogeneities. Such influences may include the reactivation of pre-existing fault systems, the generation of new faults at lithological and terrain boundaries, the variable mechanical responses of different terrain types to extreme pressures and temperatures, and the interference of impact-induced strain fields with target strain regimes.

In this work, we examine the influence of pre-impact tectonic processes on the generation of the Sudbury impact structure. We also assess how post-impact processes have modified this structure. This study has implications for understanding the generation of large impact craters on tectonically active planets and for identifying those parameters that are important for the numerical modelling of the cratering process for strained, heterogeneous targets. Our evidence is primarily based on the interpretation of field observations, regional geophysics, and remote sensing data. Our reconstruction of the Sudbury impact structure facilitates an approximate resolution of its crater dimensions.

THE SUDBURY IMPACT STRUCTURE

The 1.85 Ga Sudbury structure is now recognized as one of the largest impact structures on Earth, comparable in size to the 2.02 Ga Vredefort structure of South Africa (~300 km diameter, based on the maximum radius of damage; Therriault et al. 1997). Moreover, Sudbury is the more complete of the two, comprising impact-damaged basement rocks (Archean to Paleoproterozoic age), through footwall breccias and impact melt sheet (Sudbury igneous complex: SIC), fallback-flowback (Onaping formation) to overlying sedimentary cover (Onwatin and Chelmsford Formations), the latter being unique to the Sudbury basin (Fig. 1). Sudbury is also important in that melt sheet intrusions are preserved as radial and concentric offset dykes in the footwall (e.g., Wood and Spray 1998; Tuchscherer and Spray 2002). Thus, it provides a complete sequence through a relatively large impact structure from basement through to post-impact cover rocks. However, Sudbury is also one of the oldest of the terrestrial impact structures and, as a result, it has been deformed and metamorphosed. Two syn- to post-impact orogenies directly affect the structure: the Penokean and Grenville (discussed below). These have caused NNW-directed, relatively high-angle reverse faulting within the SIC, and high grade overprinting of the structure's SE sector (Figs. 1 and 2). Combined with erosion, post-impact deformation has obscured Sudbury's original form and size.

Traditionally, the Sudbury structure has been divided into the Sudbury basin, which includes the SIC and overlying units, the North Range, South Range, and East Range (Fig. 1). More intense faulting and metamorphism in the South Range makes its reconstruction in the southern sector difficult, while the North Range is less deformed and less altered by post-impact processes. The East Range also appears to have undergone significant post-impact modification, and includes the 37 Ma Wanapitei impact structure (Dence and Popelar 1972), which is largely coincident with Lake Wanapitei (Fig. 1). Compounding the difficulty of unravelling the geology of the Sudbury structure is the fact that much of the region has not been mapped with a view to disclosing impact-related features. Some areas have not been mapped at all. Although the Ontario Geological Survey has produced numerous township reports with maps at ~1:30,000 scale that show good geological detail, these do not cover the whole structure.

PRE-IMPACT CONTEXT

The 1.85 Ga Sudbury impact event affected an already complicated tectonic region and the structure now straddles the present day erosional boundaries between three different Precambrian provinces. Archean Superior Province rocks occur to the N and NE of the structure. These are unconformably overlain by the Paleoproterozoic Huronian Southern Province rocks to the S, E, NE and, locally, the N. The late Mesoproterozoic Grenville Province lies astride the impact site to the SE (Table 1, Fig. 2).

The Archean rocks immediately N of the SIC are characterized by the upper amphibolite to granulite facies

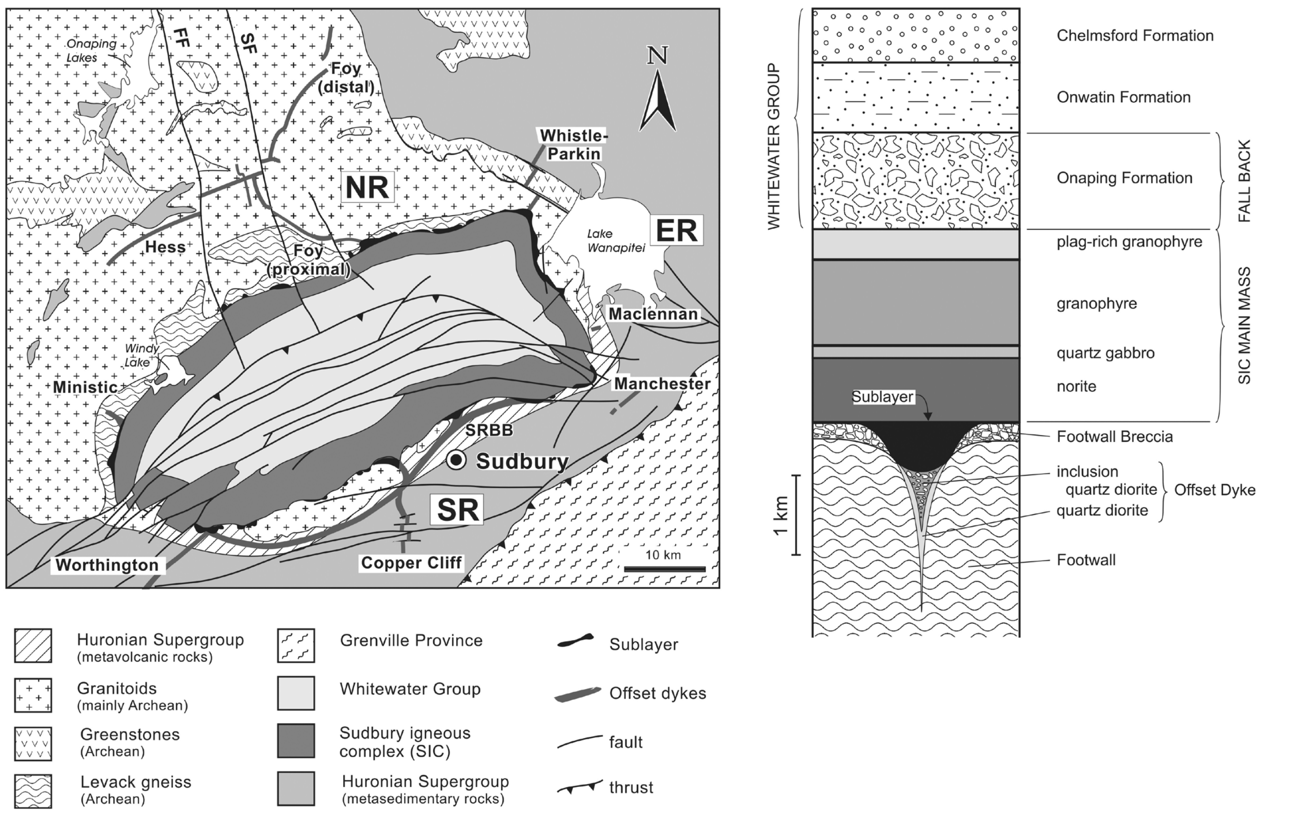

Fig. 1. Simplified geology of the central portion of the Sudbury impact structure. Cross-section is an idealized, scaled reconstruction through footwall, Sudbury igneous complex (SIC) and overlying units. NR = North Range, SR = South Range, ER = East Range, SRBB = South Range Breccia Belt, FF = Fecunis Lake Fault, SF = Sandcherry Creek Fault.

Levack gneiss and associated anatectic Cartier granitoids formed during the Kenoran orogeny at 2.69–2.64 Ga (Krogh et al. 1984; Meldrum et al. 1997). Beyond this, the structure of this part of the Superior terrain is not well mapped. The Abitibi terrain farther N is dominated by E-W trending, 30–50 km wide Archean mesozonal batholiths, accompanied by subordinate synformal greenstone belts. In the Timmins-Kirkland Lake area, prominent regional shear zones and folds include a NW- to WNW-striking set that, locally, predates a NE- to ENE-striking trend (Jackson and Fyon 1991). These structures are themselves overprinted by NE-, NW-, and NNE-striking brittle faults associated with the formation of the Paleoproterozoic Cobalt Embayment (NE of Sudbury) and the Phanerozoic Timiskaming Rift (Jackson and Fyon 1991). This includes the Vermilion River Fault that forms the present western margin of the embayment (VRF in Fig. 2). Although the Timiskaming Rift (TRF in Fig. 2) was active during Phanerozoic times, coarse clastic Proterozoic sedimentary rocks restricted to the graben indicate that these rift faults were operating as early as the Paleoproterozoic (Jackson and Fyon 1991).

North of Sudbury, the NW margin of the Abitibi greenstone belt coincides with the NE-trending Montreal River-Ivanhoe Lake faults (MR-IRF in Fig. 2). These are part of the regionally extensive Kapuskasing Structural Zone, a predominantly NNE-trending Neoarchean-Paleoproterozoic intracratonic overthrust (Percival and Card 1983). Intrusion of the extensive NNW-trending basic Matachewan and N-trending Hearst dyke swarms occurred at 2.47 and 2.45 Ga, respectively (Fig. 2; Heaman 1997). This was contemporaneous with emplacement of the 2.49–2.475 Ga gabbro-anorthosite East Bull Lake Intrusive Suite (Krogh et al. 1984), and the 2.47 Ga Murray granite (Krogh et al. 1996). These two events were probably coincident with the earliest bi-modal volcanism and sedimentation that marked the beginning of Huronian Supergroup deposition (Table 1). Rhyolites of the Copper Cliff formation, close to the base of the Huronian sequence in the Sudbury area, yield a U-Pb zircon age of 2.45 Ga (Krogh et al. 1984). This result is identical, within error, to the above intrusive ages. These igneous events mark the onset of a tectonically active geological period in the region (Table 1); a period that can be correlated with global-scale continental rifting and breakup of Archean cratons characteristic of the inception of the Proterozoic eon.

The Huronian Supergroup of the Sudbury region comprises a sequence of sedimentary and bi-modal volcanic rocks formed during passive and active rifting at a glacier-bearing continental margin (Bennett et al. 1991). The

Table 1. Summary of tectonic, igneous and metamorphic events affecting the Sudbury region.

Event	Age (Ga)	Product(s)	Selected references
Kenoran orogeny	2.69–2.64	Levack gneiss (amphibolite to granulite facies, retrogressed granulite textures), Cartier granitoids via Levack anatexis	Jackson and Fyon (1991) Meldrum et al. (1997)
East Bull Lake Plutonic Suite	2.49–2.475	Gabbro-anorthosite differentiated intrusions (some ultramafic units)	Krogh et al. (1984) James et al. (2002)
Matachewan dykes Hearst dykes	2.47 2.45	NNW to N parallel dyke swarms (possible failed rift) commonly within 5° of the strike of the later Onaping Fault Swarm	Heaman (1997)
Murray granite	2.47	Granite pluton(s)	Krogh et al. (1996)
Passive rifting	>2.45 (age of Copper Cliff rhyolite)	Initiation of Huronian Supergroup deposition, clastic sedimentation along with basaltic (pillow lavas) to acid igneous lavas.	Krogh et al. (1984) Zolnai et al. (1984)
Active rifting	2.3–2.2?	Continued Huronian Supergroup deposition. Thicker sequences, more volcanics and interpreted foredeep deposits south of the present trace of the Murray Fault Zone. Faults exhibited early normal sense.	Zolnai et al. (1984)
Blezardian orogeny	2.4–2.2? 2.33	Folding, metamorphism and melting (Creighton and Skead granitoids): may be related to amphibolite facies metamorphism of early Huronian around Frood Mine.	Stockwell (1982) Riller et al. (1999) Frarey et al. (1982)
Nipissing Diabase intrusions (Sudbury gabbro)	2.2	Differentiated basaltic sheets (ultramafic to granophyre, common pyroxenite layers). Sheets were intruded into folded Huronian, and were, in turn, refolded.	Corfu and Andrews (1980)
Biscotasing dykes	2.17	NE-SW trend	Buchan et al. (1993)
Early Penokean orogeny	~1.9–1.85	Greenschist facies north of, and up to amphibolite facies metamorphism south of, Murray Fault Zone. Thrusting, faulting, folding, and metamorphism paralleling the Flack Lake Fault, Murray Fault Zone, and associated faults	Holm et al. (2001)
Hypervelocity impact	1.85	Generation of ~260 km diameter impact structure	This work
Late Penokean orogeny	1.85–1.8?	Greenschist to sub-greenschist facies, NNW-directed high-angle thrusting in the South Range of the SIC, transpression and minor folding	Holm et al. (2001)
Killarney magmatic (and possible metamorphic) event	1.75–1.70	Cutler granite Eden Lake pluton Grenville Front Tectonic Zone intrusions	Davidson et al. (1992) Corfu and Easton (2000)
Chieflakian event	1.47–1.44	Granite plutonism and metamorphism in the Britt Domain of the Grenville, within the Grenville Front Tectonic Zone	Easton (1992) Corfu and Easton (2000)
Sudbury dykes (Mackenzie dykes)	1.24	WNW-trending basic dykes, generated from a centre near Victoria Island	Krogh et al. (1987)
Abitibi dykes	1.14	ENE trending	Krogh et al. (1987)
Grenville orogeny	1.16–1.12 1.04–1.02 ~0.990	Upper amphibolite facies locally in Grenville Front Tectonic Zone	Jamieson et al. (1992) Krogh (1989)

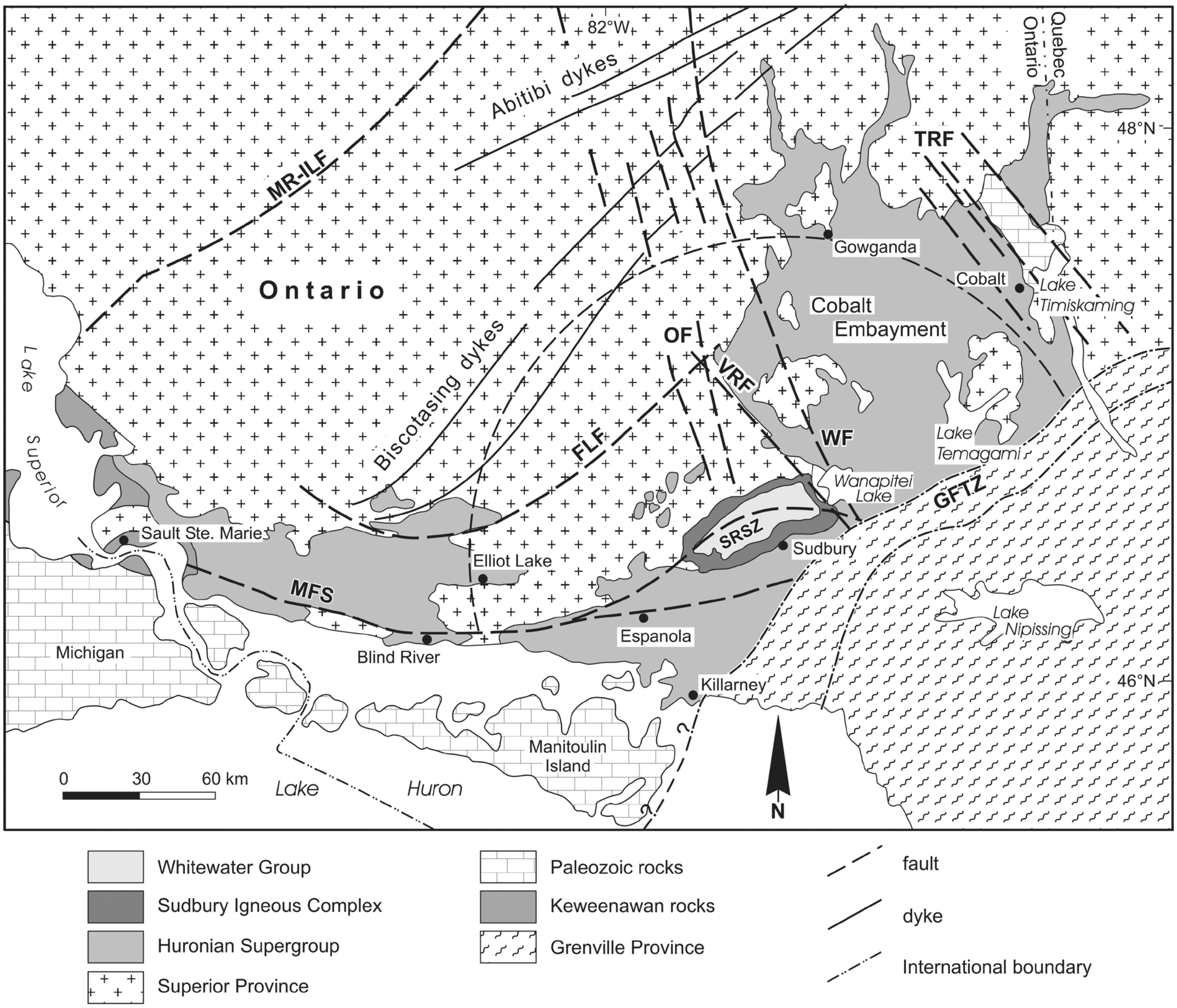

Fig. 2. Regional geological context of the Sudbury impact structure. MR-ILF = Montreal River-Ivanhoe Lake Fault System, MFS = Murray Fault System, FLF = Flack Lake Fault, OF = Onaping Fault System, VRF = Vermilion River Fault, WF = Upper Wanapitei River Fault, TRF = Timiskaming Rift Fault System, GFTZ = Grenville Front Tectonic Zone. Dashed part circle indicates probable final rim diameter of the Sudbury impact structure (~260 km). The Keweenawan rocks constitute a volcano-sedimentary supergroup that accumulated during Mesoproterozoic rifting at 1.11 to 1.09 Ga (Sutcliffe 1991).

sedimentary rocks record a sequence that thickens to the S, with deposition occurring in fault-controlled basins. Deposition commenced at ~2.47–2.45 Ga (constrained by the age of the Copper Cliff rhyolites), and ceased some time before the intrusion of the 2.2 Ga Nipissing diabase (Corfu and Andrews 1986; Noble and Lightfoot 1992). The rocks of the Huronian Supergroup were then subjected to several phases of deformation, and up to amphibolite facies grade metamorphism. The timing of these phases is not well defined. Some deformation clearly occurred pre-Nipissing, as indicated by the 2.2 Ga Nipissing intrusives cutting early folds within the Huronian (Robertson 1977). Pre-Nipissing deformation may correlate with the so called 2.4–2.3 Ga Blezardian orogeny and amphibolite facies conditions (Stockwell 1982; Riller and Schwerdtner 1997). Intrusion of the Creighton granite at 2.33 Ga (Frarey et al. 1982) may be associated with this deformation event. The bulk of deformation and metamorphism probably occurred post-Nipissing during the Penokean orogeny (Holm et al. 2001).

Onaping Fault System

The NNW-trending Onaping Fault System constitutes a major lineament set in the Sudbury region (Fig. 2). The Onaping faults are generally straight, indicating a high angle disposition. They are known to offset the 2.167 Ga, NE-trending Biscotasing dikes by 7–8 km of sinistral wrench displacement (Buchan and Ernst 1994). A similar sense of movement is seen where the Sandcherry Creek and Fecunis Lake Faults intersect the SIC, where they displace the SIC by <0.5 km (Fig. 1). The Onaping faults displace the 1.24 Ga Sudbury dykes, but generally only by a few tens of m. Notably, these faults do not displace the 1.14 Ga Abitibi dykes (Fig. 2). A parallel, and probably related, lineament is the Upper Wanapitei River Fault (WF in Fig. 2). This fault continues to the N as the Mattagami River Fault (Buchan and Ernst 1994), making it several hundred km in total length. This fault has offset Archean granite-greenstone terrains by 7–9 km of sinistral wrench movement (Buchan and Ernst 1994). Moreover, the Wanapitei section of this fault, or a related splay, may be responsible for controlling the shape of the East Range margin of the SIC (Fig. 1). Southward extension of the Onaping Fault System correlates with offset aeromagnetic anomalies associated with highly magnetic units (probably Levack gneiss) in the basement beneath the SIC and Huronian sedimentary rocks of the Southern Province. Conversely, there appears relatively little offset within the overlying SIC itself, especially S of the Penokean orogenic front. Overall, the Onaping Fault System was probably initiated in the late Archean, and was active by early Proterozoic times. Most of the displacement on these faults is pre-impact, and the faults are not responsible for causing major post-impact deformation of the Sudbury structure. However, it appears that they were important in controlling deeper level (basement) structure beneath the SIC. They may have also exerted influence on the present strike of the East Range, and facilitated isostatic (vertical) adjustments within the structure following impact.

Murray Fault System

The Murray Fault System has a WNW trend in the W of the region, swinging round to an ENE trend in the E, and an E and NE trend through the Sudbury basin, where it evolves to include the South Range Shear Zone (SRSZ in Fig. 2; Riller et al. 1998). The related Flack Lake Fault is subparallel to the Murray and roughly mimics its arcuate shape, striking consistently NE in its eastern sector (Fig. 2). These faults have had complicated pre- and post-impact histories, manifest in different types of fault behavior over a period >1 Ga in duration. The earliest movement phase appears to have facilitated rifting. This was accompanied by deposition of the Paleoproterozoic sediments and volcanics of the Huronian. These rocks reveal a southward thickening of sediment accompanied by a transition from fluvial to turbiditic deposits, increased volcanism across the Murray and Flack Lake Faults, and associated parallel structures. This suggests that the faults were originally listric normal and related to rifting of the Archean continental margin during the early Proterozoic (Zolnai et al. 1984). Subsequently, during the Blezardian and Penokean compressional events (Table 1), folding and metamorphism took place, the intensity and trends of which parallel these faults, indicating their regional influence. An abrupt change in metamorphic grade occurs across the Murray Fault in the W of the impact structure (W of Espanola; Fig. 2). Here, unmetamorphosed to subgreenschist facies rocks occur to its N, but garnet amphibolite facies rocks are developed to its S. This indicates a major phase of reverse fault movement on the Murray that was probably initiated before impact. Changes in metamorphic grade across the Murray Fault E of Espanola are less marked, suggesting that the fault may have undergone scissor displacement, with greater uplift occurring on its S side in the W.

Along with the Onaping faults, the Murray Fault System constitutes a pre-impact target flaw manifest as a fracture-fault grid composed of NNW-trending lineaments meshed with E- to NE-trending lineaments. This fault mesh did not appear to facilitate syn-impact wrench movement, but probably accommodated mainly vertical displacements beneath the evolving impact structure. Such flaws, if built into impact computer simulations for Sudbury, would more realistically represent the target state under conditions of shock loading, and especially unloading following excavation.

SYN-IMPACT CONTEXT

Hypervelocity impact occurred at 1.85 Ga into a continental margin terrain that was actively undergoing late stage deformation and metamorphism as part of the Penokean orogeny (Table 1).

Pseudotachylyte (Sudbury Breccia)

Sudbury provides some of the world's best examples of pseudotachylyte associated with impact structures. Although the type locality for pseudotachylyte is the Vredefort impact structure of South Africa (Shand 1914; Reimold 1995; Spray 1998a), Sudbury contains the largest known pseudotachylyte body: the South Range Breccia Belt, which is up to 1 km wide and 45 km long (Spray 1997; Scott and Spray 1999, 2000). This belt is also host to one of the world's largest Cu-Ni-platinum group element deposits—the Frood-Stobie orebody (Grant and Bite 1984). Pseudotachylyte occurs throughout the Sudbury structure and it has been used as an indicator of crater dimensions (Spray and Thompson 1995) . It is also one of the primary products of impact-induced bulk and discrete target deformation, and is therefore fundamental to understanding the impact process.

Pseudotachylyte at Sudbury occurs in a number of different forms and settings (Dressler 1984; Rousell et al. 2003). It has been suggested that pseudotachylytes in impact structures are generated by two main processes (Spray 1998b): 1) shock wave-rock interaction with the formation of the so called S-(shock) type pseudotachylyte, and 2) tectonic activity (e.g., gravity driven faulting, wrench faulting, thrust faulting) with the formation of the so called E-(endogenic) type pseudotachylyte. E-type pseudotachylytes in impact structures are generated by the same mechanism as pseudotachylytes in seismogenic fault systems of purely endogenic origin. Table 2 summarizes features characteristic of these two pseudotachylyte end members.

S-type Pseudotachylyte

In the context of the impact process, S-type pseudotachylytes are generated due to the interaction of the shock and rarefaction waves with the target lithologies. Because shock wave velocity is dependent on the density of the medium through which it moves, the incipient smooth shock front will become convoluted as it encounters different rock types. Thus, the hemispherical shock front evolves from a balloon-like smoothness on its inception to a cauliflower-like roughness. Because of the roughness of the evolving shock wave, the target rocks are, on rarefaction, effectively torn and sheared due to offset between the leading and trailing shock fronts. This leads to displacement, frictional melting, and the formation of S-type pseudotachylytes, which are typically <2 mm in thickness. In addition, S-type pseudotachylytes can be associated with the development of high pressure polymorphs, such as stishovite (e.g., Martini 1978; Spray et al. 1995). Moreover, there may be an element of shock-induced decompression melting involved in their formation. High-pressure polymorph occurrence is restricted to the veins and vein margins, so it is clear that the polymorphs are generated due to extreme shock-induced temperature and pressure excursions (i.e., well beyond that suffered by the bulk target). S-type pseudotachylyte is restricted to shock metamorphosed systems (as in certain shock veins in meteorites) and, therefore, they are not developed by purely endogenic processes (Table 2).

At Sudbury, a zone extends from the margins of the SIC in the North Range to ~15 km beyond the SIC that is pervaded by S-type pseudotachylyte veins. It is difficult to determine their distribution S of the SIC because of the increased amount of post-impact deformation in the South Range. Although similar effects are seen, their distribution in the S is disrupted by faulting. In the less deformed and less faulted North Range, S-type veins typically occur every 50 cm and they form a crude mesh (at high angles to one another), with individual offsets of <2 mm (this is equivalent to a total strain of 2 m per km of target rock). Beyond the ~15 km distance from the SIC, S-type pseudotachylytes are less common. The occurrence of S-type pseudotachylytes generally coincides with the development of shatter cones (Gibson and Spray 1998); both phenomena may be formed by similar conditions of shock wave-rock interaction. It would appear that S-type pseudotachylytes accommodate a degree of bulk deformation within the inner zones of the impact structure. At Sudbury, we correlate this inner S-type pseudotachylyte-rich zone with the central uplift (discussed later), the boundaries of which are marked in the North Range by the Hess Offset (Fig. 1).

E-type Pseudotachylytes

E-type pseudotachylyte post-dates S-type pseudotachylyte, and generally forms veins >1 cm thick, up to spectacular dyke-like bodies 1 km wide (Spray 1998b). E-type pseudotachylyte can reach very large thicknesses in impact structures because the fault systems that generate them can undergo very large displacements (e.g., >100 m) in a single slip event. This type of faulting has been referred to as superfaulting (Spray 1997), and it is a characteristic of impact structures, especially where the margins of a transient cavity in larger complex structures undergo collapse to form terraces and fault scarps. E-types do not generate high pressure polymorphs, unless supplanting an earlier S-type fracture-fault system, from which E-types may spawn. Even then, the residual heat of the larger E-type may be sufficient to eradicate any indications of high shock pressures. E-type pseudotachylyte is formed by frictional melting during the modification stage of the impact process in response to gravity driven processes. Within the inner S-type pseudotachylyte-rich zone of the Sudbury impact structure, large E-type (tens of m width) bodies occur at the Hardy Pit of the McCreedy West Ni-Cu deposit in the North Range (Thompson and Spray 1996), and they also define the southern border of the Murray and Creighton granites as the so called South Range Breccia Belt (Scott and Spray 2000). Meter-wide E-types are also exposed in Archean target rocks along roadcuts on Highway 144 between Windy Lake and just

Table 2. Distinctions between S-(shock) and E-(endogenic) type end member pseudotachylytes.

	S-type	E-type
Typical thickness	<2 mm	>2 mm
Displacement	<1 cm	>1 cm
Mode of occurrence	Fine pervasive networks	Dyke-like bodies and larger disrupted zones
Injections off main generation surface	Uncommon	Common
High pressure polymorphs (e.g., stishovite)	Can be present	None, unless inherited from S-type
Distribution in impact structures	Prevalent in central uplift	Ubiquitous, and can define concentric (ring) systems
Global occurrence	Restricted to systems shocked to >5 GPa	Common in endogenic seismogenic faults (e.g., destructive plate boundaries) and impact structures

N of Cartier. Beyond 15 km from the SIC contact in the North Range, the larger E-type pseudotachylytes are not as common (Thompson and Spray 1994).

A study of E-type pseudotachylyte distribution along a radial transect in the North Range (along Highway 144 and parallel trails) indicates that its distribution is systematic and not random (Thompson and Spray 1994, 1996; Spray and Thompson 1995). Several zones of enhanced pseudotachylyte development have been identified. These broadly correspond to concentric ring systems at 25–35 km, 42–48 km and 78–80 km beyond the SIC (Spray and Thompson 1995). This is not to say that pseudotachylyte forms a continuous zone within these rings, but that its occurrence is more common within these concentric systems. Post-impact offset (e.g., via Onaping Fault System reactivation) can displace original contacts and so disrupt a ring at the field scale. Also, the thickness of pseudotachylyte can be highly variable along strike, ranging from dykes several m in width down to 1 cm or less fracture-fault veins. When combined with limited rock exposure, it remains difficult to trace out these enhanced zones at ground level. However, detailed contour mapping of the percentage of pseudotachylyte at the outcrop scale can reveal major E-type belts (Lloyd Howell, Falconbridge Exploration, personal communication).

E-type pseudotachylyte is typically generated at lithological or terrain boundaries, or wherever there is a ductility contrast between rock types. Thus, it is commonly developed along contacts between basic dykes and more acid or sedimentary host rocks, and where Huronian metasedimentary rocks are juxtaposed with Archean granitoids and gneisses. It is also common between different lithological units within the Huronian metasedimentary sequence. This association with lithological boundaries may be due to the different shock impedance values of contrasting rock types (i.e., the shock wave velocity is dependent on the density of the medium through which it passes). Because of the velocity change induced in a shock wave encountering a rock with contrasting density, a shear system can be created, which can subsequently transform from an S-type to an E-type pseudotachylyte as the impact process evolves to the modification (gravity driven) stage. E-type pseudotachylyte is also found along reactivated fault systems (i.e., pre-existing weaknesses become the focus of displacement), and it can be observed to line the margins of some of the offset dykes, which occupy radial and concentric fracture-fault systems. The common association of E-type pseudotachylyte with lithological discontinuities means that it rarely defines continuous occurrences at the scale of observation in the field. Some of the largest E-type occurrences are associated with transient cavity collapse and associated slumping and terrace formation. In this case, E-type pseudotachylytes can form along the scalloped, arcuate fault scarps (Spray 1997). At the larger scale of observation, the gross distribution of the E-type variant defines concentric ring structures beyond the central core of the crater, as independently supported by remote sensing and geophysical studies.

Remote Sensing and Geophysical Data

Landsat multi-spectral scanning (MSS) images have been used to establish lineament sets in the Sudbury region based on the work of Butler (1994). The rings can be identified N of the Murray Fault-South Range Shear Zone (MFS and SRSZ in Fig. 2), but not S of it, although E-type pseudotachylyte is observed in the field S of the South Range Shear Zone. The Landsat data reveals 4 main ring structures, labelled 1–4 in Fig. 3, which have their collective centers located just S of the SIC and W of the Copper Cliff offset dyke. Ring 1 correlates with the Hess concentric offset dyke and a major change in strike of the Foy dyke, where it naturally divides into proximal and distal segments (PF and DF in Fig. 3). Ring 1 has a radius of ~45 km. The Foy dyke continues just N of Ring 2: the Whitefish Falls—Venetian Lake ring of 65 km radius. Ring 3, the East Bull Lake—Temagami ring, is 90 km radius, and Ring 4, the Elliot Lake—Gowganda ring (final rim diameter), is 130 km radius. A very large E-type pseudotachylyte zone strikes N-S along the Serpent River, 5 km W of the town of Spanish, and large E-type pseudotachylytes occur in the northern part of Lake Temagami to the NE, striking SE. These occurrences correlate with Ring 3 at ~90 km from the putative ring center.

Using data from the Geological Survey of Canada, Fig. 4 depicts the distribution of pre-impact magnetic dykes of the 2.47 Ga Matachewan swarm and post-impact magnetic dykes of the 1.24 Ga Sudbury swarm. This data is superimposed on the ring system of Fig. 3. The notable feature of this map is the termination of the Matachewan magnetic signature on reaching Ring 2. Demagnetization due to shock is a common feature of impact structures (Pilkington and Grieve 1992). We can use this effect to infer that the core of the structure out to Ring 2 (radius 65 km) has had its magnetic signature erased. This places Ring 2 as a shock isobar of >1 GPa for the erasure of pre-existing remnant magnetization, or >10 GPa for the reduction of magnetic susceptibility (Cisowski and Fuller 1978). It is also possible that the apparent magnetic erasure is due to the thermal effects of an overlying impact melt sheet (i.e., due to heating above the Curie point of the magnetic minerals). If so, this provides a constraint on the original diameter of the impact melt sheet.

POST-IMPACT OVERPRINTING

At least two syn- to post-1.85 Ga orogenic events have affected the region: the Penokean and the Grenville.

The Penokean Orogeny

The Penokean (1.87–1.82 Ga in the Lake Superior region;

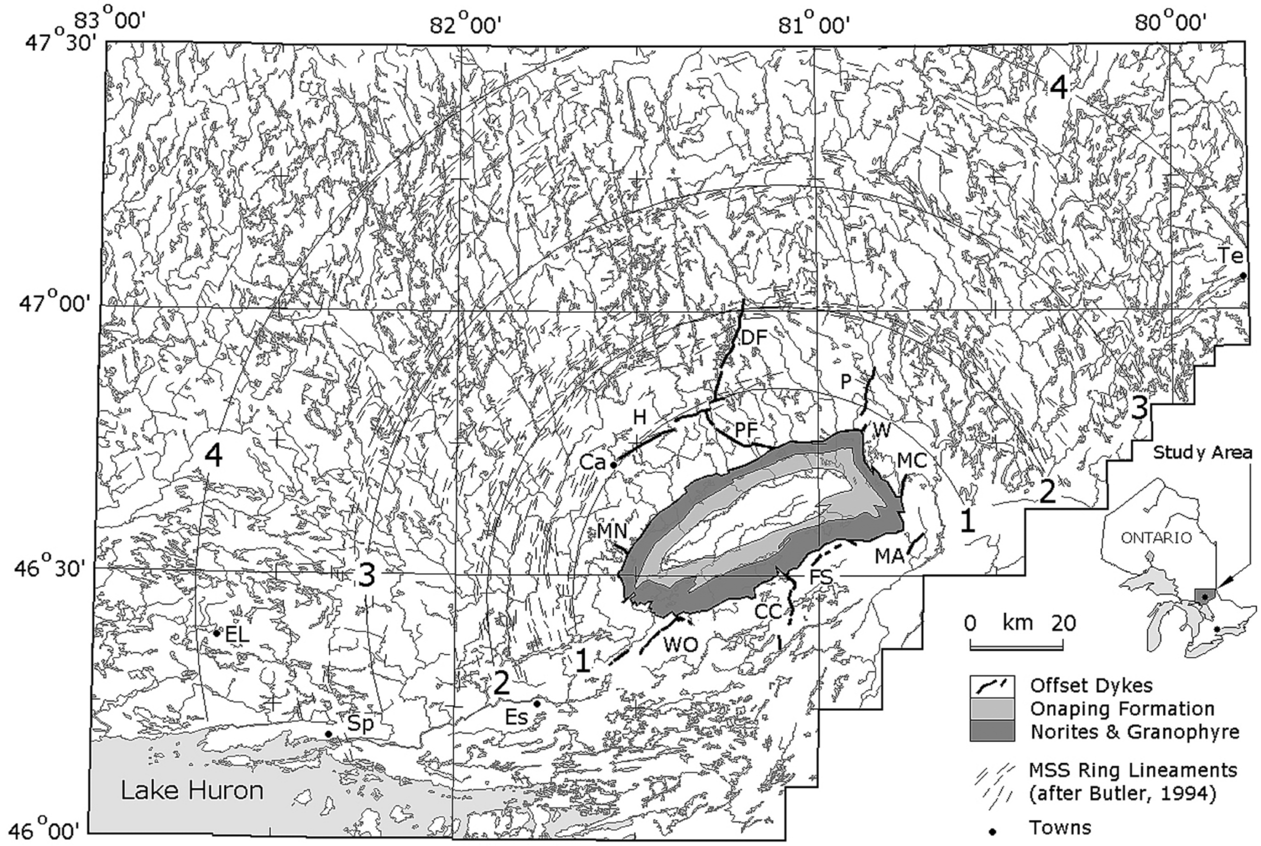

Fig. 3. Location of concentric lineament structures (1–4) based on Landsat multi-spectral scanning (MSS) data (after Butler 1994). Offset dykes: WO = Worthington, CC = Copper Cliff, FS = Frood-Stobie (part of the South Range Breccia Belt), MA = Manchester, MC = Mclellan, W = Whistle, P = Parkin, PF = Proximal Foy, DF = Distal Foy, H = Hess. Towns: EL = Elliot Lake, Sp = Spanish, Es = Espanola, Ca = Cartier, Te = Temagami.

Holm et al. 2001) involved NNW-directed reverse faulting with dextral shear (transpression) at mainly greenschist facies grade (Riller et al. 1999). Any evidence of higher grades of metamorphism is pre-impact (and not necessarily Penokean), because amphibolite facies rocks are cut by impact-generated pseudotachylyte. The main effects of the Penokean are felt in the South Range, where NNW-directed reverse faulting generated the South Range Shear Zone (SRSZ of Fig. 2). Correlation of the Murray Fault System with the Great Lakes tectonic zone to the W (Sims et al. 1980) indicates that, during the later stages of the Penokean orogeny, the Murray Fault acted as a dextral transpressive system in its western sector and, to a lesser degree, with the same sense in its eastern sector. The extent to which the Penokean orogeny distorted the Sudbury structure and changed the original shape of the SIC is a debatable point. It has been suggested that rocks from the South Range were transported northward over basement lithologies (e.g., Roest and Pilkington 1994), with telescoping occurring at least as far N as the South Range Shear Zone. However, in this part of the Penokean orogen, vertical tectonics may have dominated, with only minor shortening occurring via high-angle reverse faulting. There is a lack of rotation of offset dykes, which all maintain a subvertical dip, despite their variable strike around the SIC (Fig. 1). Notwithstanding the relative roles of vertical versus low-angle thrust tectonics, the South Range Shear Zone can be envisaged as the remains of the Penokean Front, at least as currently exposed. There is, however, evidence for some Penokean faulting continuing into the North Range: the metamorphic aureole around the SIC is overthrust and obscured in places (Boast and Spray 2002). This overthrusting occurs via NW-trending transfer faults.

The Grenville Orogeny

The Penokean was followed by the Grenville orogeny at 1.16–0.99 Ga (Krogh 1989; Jamieson et al. 1992; Haggart et al. 1992). This affected the SE sector of the impact structure to yield a polydeformed upper amphibolite facies terrain with local evidence of anatexis (Corfu and Easton 2000). However, early Proterozoic mafic rocks, granitoids and East Bull Lake-type gabbro-anorthosite intrusives occur within the 10–40 km-wide Grenville Front Tectonic Zone (GFTZ, Fig. 2), and these retain U-Pb zircon ages of ~2.47 Ga (Easton and

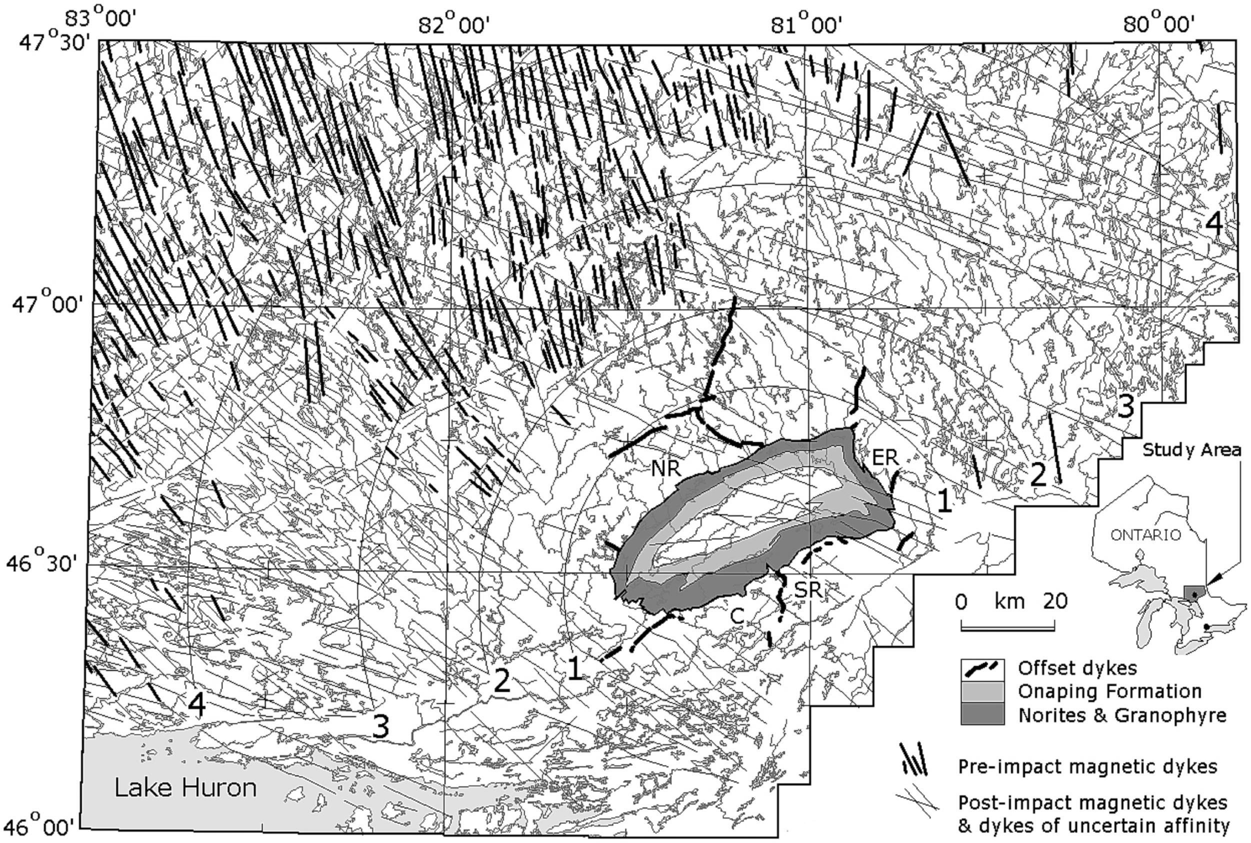

Fig. 4. Distribution and intensity of magnetic dykes of the pre-impact Matachewan and post-impact Sudbury swarms in relation to ring structure. The Matachewan dykes lose their magnetic signature on approaching Ring 2 and they are magnetically "invisible" within Ring 2. This is attributed to shock- and/or thermally induced demagnetization at 1.85 Ga. The post-impact Sudbury dykes are not demagnetized. NR = North Range, ER = East Range, SR = South Range, C = Copper Cliff.

Murphy 2002). This indicates that the GFTZ did not achieve temperatures above the blocking temperature of zircon (~700°C) in the Sudbury region. Grenville deformation resulted in NW-directed reverse faulting and folding in the SE sector, and limited reactivation of pre-existing fault systems NW of the Grenville Front. For example, laser probe ^{40}Ar-^{39}Ar dating of pseudotachylyte from the Flack Lake Fault yields an age of ~1 Ga (Fig. 2. Thompson et al. 1998), suggesting that this fault was also reactivated during the Grenville orogeny. The same may well have occurred with the Murray Fault, although reactivation beyond the Grenville Front at ~1 Ga appears to have involved only minimal displacement (i.e., meters).

MORPHOMETRIC CONSTRAINTS

Given the complex geology of the region, defining the form and size of the Sudbury impact structure is not an easy task. However, we can use a number of constraints to help define: 1) the final rim diameter D_{fr}; 2) the maximum radial extent of melt sheet dykes that penetrate the footwall (Fig.1), which indicates a likely radius of the original impact melt sheet (assuming that melt sheet dykes were fed vertically from above, at least in their more distal portions); 3) the diameter of the shock- and/or thermally demagnetized core zone (Fig. 4), which correlates with shock pressures >1 GPa for the erasure of pre-existing remnant magnetization, and >10 GPa for the reduction of magnetic susceptibility (Cisowski and Fuller 1978). Removal of a remnant magnetization in footwall rocks can also occur by heating magnetic minerals above their Curie points due to the presence of overlying superheated impact melt; 4) the radii of concentric ring systems, as defined by E-type pseudotachylyte-rich fracture-fault systems and by lineaments seen in remote sensing imagery (Fig. 3), which indicate an approximate maximum damage diameter for the structure and the type of complex crater generated (i.e., peak ring, multi-ring).

Field studies indicate that E-type pseudotachylytes coincide with three of the four rings recognized by remote sensing. The outermost ring (Ring 4) has not yet been verified in the field. However, its signature, as based on remote sensing data, is manifest, and we correlate this with the apparent crater diameter at ~260 km. Because the amount of erosion in the North Range since impact is relatively minor (<6 km; Thompson et al. 1998), and because the concentric fault systems appear to dip steeply, we suggest that the apparent crater diameter is approximately coincident with the final rim diameter D_{fr}.

The maximum established radius of the longest melt sheet dyke is 65 km, although this is not the proven end of the dyke. This radius approximately coincides with Ring 2 as defined by lineament imagery and E-type pseudotachylyte concentration. It also coincides with the limit of erased remnant magnetization as seen in the 2.47 Ga Matachewan dykes (Fig. 4). We interpret this to be the probable radius of the inner floor of the structure, within which the impact melt sheet was principally confined.

A definitive, most distal structural disturbance that can be unequivocally attributed to impact has not been established in the field to date. Such a feature may be subtle and limited to a monocline, with or without faulting (Fig. 5). Given the complexity of the regional geology and age of the Sudbury impact structure, this feature may never be discovered or even survive. For this reason, the maximum radius of impact-induced damage is not normally used in scaling crater dimensions, except perhaps for the youngest of terrestrial craters, and those exposed on planets devoid of erosional/burial processes.

The above evidence suggests that Sudbury has an apparent crater diameter of ~260 km (with a comparable final rim diameter) and a melt sheet diameter of ~130 km. The latter corresponds to the demagnetized core. The core zone comprises a 90 km diameter central uplift and a surrounding 20 km-wide annular trough. In the North Range, this trough coincides with downfaulted Huronian outliers and Archean greenstones, and a change in strike and vertical offset in the Foy dyke (Tuchscherer and Spray 2002). The central uplift is circular and bounded, at least in part, by a concentric zone of enhanced pseudotachylyte development. This innermost ring structure also coincides with the location of the Hess Offset in the North Range (Wood and Spray 1998). Beyond this, the margin of the melt sheet-core zone, as defined by Ring 2, is likely to involve terrace collapse with the development of complex structural features (Fig. 6).

Table 3 presents calculated dimensions for the transient cavity, central uplift and amount of structural uplift. There is found to be close agreement between those dimensions determined from the ground and remote sensing data, and those calculated from terrestrial impact crater data sets. The suggested diameter of Ring 2, at 130 km diameter, could be on the low side compared to the calculated figures. However, what is observed now is the collapsed transient cavity and not the original transient cavity diameter.

SUMMARY

1. Pre-, syn-, and post-endogenic tectonic effects on the 1.85 Ga Sudbury impact structure have been assessed in an attempt to reconstruct the morphometry of this

Table 3. Calculated values for transient cavity diameter, central uplift diameter, and structural uplift based on a final rim diameter of 260 km for the Sudbury impact structure.

Relationship[a]	Source	Result (km)
$D_{tc} = 0.5–0.65\ D_{fr}$	Grieve et al. (1981)	130–169
$D_{tc} = 1.23\ D_{fr}^{0.85}$	Croft (1985)	139
$D_{tc} = 0.57\ D_{fr}$	Lakomy (1990)	148
$D_{cu} = 0.31\ D_{fr}^{1.02}$	Therriault et al. (1997)	90
$SU = 0.086\ D_{fr}^{1.03}$	Grieve and Pilkington (1996)	26

[a]D_{tc} = transient cavity diameter; D_{fr} = final rim diameter = 260 km; D_{cu} = central uplift diameter; SU = structural uplift.

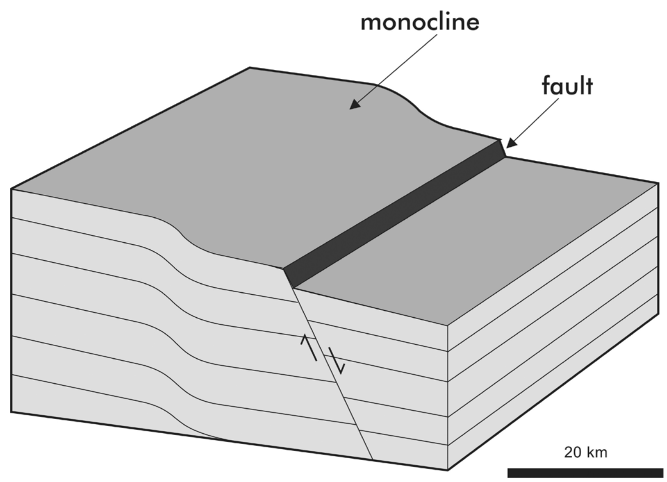

Fig. 5. The maximum damage diameter of an impact structure is defined by the most distal damage effect recorded in the target rocks. This may take the form of a monocline or fault lying beyond the final rim diameter. The center of the impact structure is to the right of the block diagram.

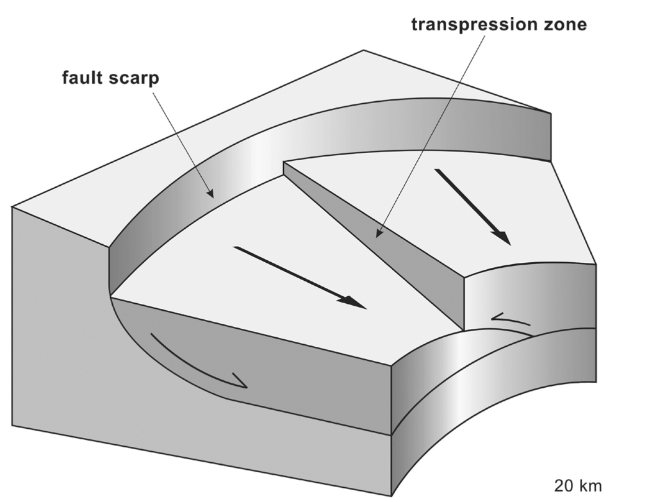

Fig. 6. The location of Ring 2, at 65 km radius from the center of the impact structure, is likely to be additionally defined by superfaulting and the development of collapsed terraces. The inward movement of pie-shaped blocks requires them to locally overlap and form transpression zones.

important terrestrial crater. Two major fault systems existed in the target rocks prior to impact: a) the NNW-trending Onaping system, which exhibits pre-impact sinistral wrench displacements of several km; and b) the ENE- to NE-trending Murray system, which facilitated Huronian sedimentary basin formation via normal, extensional faulting during the early Paleoproterozoic (~2.47 Ga), followed by reverse and dextral wrench movement during the subsequent Blezardian and Penokean orogenies. The Murray Fault System is considered to represent the tectonic front of the Penokean orogen, and this cuts through the center of the Sudbury basin as the South Range Shear Zone. The Onaping and Murray Fault Systems are basement lineaments that controlled continental margin tectonics during late Archean to Paleoproterozoic times. It is likely that they were reactivated during impact to create an underlying, and now largely concealed, fault grid consisting of vertically displaced blocks (on the km- to tens of km-area scale). These were active during post-impact isostatic adjustment of the impact structure, especially along the pre-impact Penokean mountain front in the South Range and a transverse Penokean belt in the East Range, where gravity driven adjustments were protracted, even as the melt sheet cooled (as indicated by multiple intrusive relations between the SIC components).

2. Lineament analysis, based on Landsat MSS data and regional geophysics, indicates the presence of four main ring structures. These are recognized N of the Penokean Front, but not definitively S of it (Fig. 7). The rings occur at the following radii from their projected center: Ring 1 at 45 km, Ring 2 at 65 km, Ring 3 at 90 km and Ring 4 at 130 km. The ring spacing at Sudbury conforms to a $\sqrt{2}$ proportion, as originally noted by Hartmann and Kuiper (1962) for the Moon. With the exception of Ring 4, these rings are found to broadly correspond in the field to zones of enhanced E-type pseudotachylyte development (Spray and Thompson 1995). No attempt has yet been made to search in the field for pseudotachylyte in association with Ring 4. North of the Penokean Front, the ring structures have not undergone major offset by post-impact deformation, which indicates that post-1.85 Ga wrench faulting was not significant (i.e., <<1 km) within the North Range. The presence of at least two rings outside what was the transient cavity would suggest that Sudbury is a multi-ring impact structure, as has been previously proposed (Dressler 1984, Spray and Thompson 1995; Deutsch et al. 1995). However, because of our sparse terrestrial crater inventory, we have limited understanding of central peak, peak ring and multi-ring basins on Earth, and their respective transition diameters.

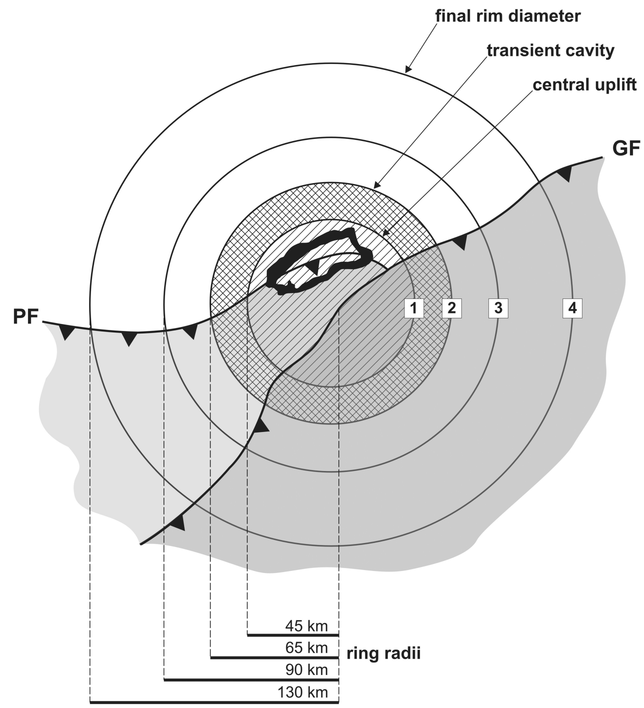

Fig. 7. Attempted reconstruction of the Sudbury impact structure. Four main rings are defined: 1 = Hess Offset ring (central uplift), 45 km radius; 2 = Whitefish Falls-Venetian Lake ring (approximate transient cavity diameter), 65 km radius; 3 = East Bull Lake-Temagami ring, 90 km radius; 4 = Elliot Lake-Gowganda ring (final rim diameter), 130 km radius. The southern half of the crater is overprinted by Penokean and Grenville tectonometamorphic terrains, the edges of which are demarked by the Penokean Front (PF) and Grenville Front (GF), respectively. The present form and location of the SIC is superposed with the proposed original morphometry.

3. Within Ring 1 (i.e., within the area defined by an original radius of 45 km), the rocks are pervaded by S-type pseudotachylytes and the rocks can be extensively shatter coned. Away from the thermal effects of the hot remnant SIC (i.e., beyond 1–2 km from the SIC-footwall contact), planar deformation features (PDFs) are developed in quartz up to 10 km beyond the currently exposed SIC. Together, these features indicate a minimum shock pressure of 5 GPa for the outer limit of the core rocks bounded by Ring 1. The development and distribution of decorated PDFs in quartz suggests shock pressures of 10 or more GPa (French 1998) in the inner 80 km of the core. Ring 1 coincides with the concentric Hess offset dyke in the North Range and certain large E-type pseudotachylyte bodies. Rocks within Ring 1 are interpreted to constitute the central uplift of the Sudbury impact structure. The amount of structural uplift is calculated to be ~26 km (Table 3). Reconstruction of this deformed core, based on extrapolation from the more intact northern margin, indicates a diameter of 90 km for the central uplift. The current interpretation of the South Range Breccia Belt places it well within the central uplift, and as defining the southern margin of a possible

inner central core zone made up of Paleoproterozoic granites (Murray and Creighton). This is contrary to earlier suggestions in which it was interpreted as a collapsed terrace feature (Spray 1997; Scott and Spray 2000). It is now considered more probable that the SRBB was generated as a piston-like superfault that facilitated movement of an inner core within the central uplift.

4. The region between Rings 1 and 2 constitutes an annular trough of ~20 km width. Within this trough are preserved Huronian metasedimentary rocks and Archean greenstone sequences, which have been downfaulted relative to Levack gneisses and Cartier granitoids of the central uplift and similar lithologies beyond the trough. Downfaulting beyond Ring 1 is also indicated by a marked shift in trend, grain size, and chemistry of the Foy offset dyke (Tuchscherer and Spray 2002). We interpret the central core (central uplift) and annular trough to roughly coincide with the original transient cavity, given that some collapse of this cavity may well have occurred along the inward-facing walls of Ring 2 during modification stage tectonics (Fig. 6). This constitutes a transient cavity diameter of ~130 km. We believe that the impact melt sheet would have originally occupied much of this area (i.e., out to Ring 2). The proposed transient cavity broadly coincides with a zone of shock- and/or thermally induced demagnetization, as indicated by the destruction of the highly magnetic signature of the 2.47 Ga Matachewan dykes (Fig. 4). This requires shock pressures >1 GPa, or thermal resetting above the Curie point of the magnetic phase(s). Generation of a transient cavity of this size would correlate with a projectile diameter of ~20 km for an impact velocity of 20 km/s (i.e., an asteroid body), according to the scaling model of Schmidt and Housen (1987).
5. Given that Ring 4 is the furthest recognizable feature found to date associated with the Sudbury impact structure, we take this to represent the apparent crater diameter. Due to limited post-impact erosion in the North Range and the steep dip of the ring faults, this is probably comparable to the final rim diameter. This ring is yet to be ground-truthed in the field. However, using accepted formulae for deriving final rim diameters from the central uplift D_{cu} and transient cavity D_{tc} dimensions, we find that the position of Ring 4 is in agreement with the calculated values (Table 3). This means that the Sudbury impact structure probably had a final rim diameter of ~260 km, and so affected a target area of at least 53,000 km^2, given that damage effects may extend beyond the final rim. We note that much of this morphometric information comes from rocks N of the Penokean Front (Fig. 7). South of this front, the amount of overprinting by the Penokean and Grenvillian orogenies makes it difficult to reconstruct the original form of the crater.
6. This work emphasizes the importance of integrating ground-based field work with remote sensing and geophysical data for understanding large terrestrial impact structures that are exposed at surface. For many impact structures, pre-existing structural grain and syn-impact strain fields in the target rocks may be important in controlling the cratering process. For Sudbury, high-angle NNW (Onaping type) and ENE (Murray type) lineament sets may have been coupled as a pre-existing fault grid that should be built in as flaws in target reconstructions. The Penokean strain field involved a NNW-directed compression and was active at the time of impact. These structural features should be considered when modeling the Sudbury impact event.
7. By using information from the more intact North Range, it has been possible to crudely reconstruct the probable morphometry of the Sudbury impact structure. However, given the vast area involved (>50,000 km^2), the limited rock exposure (estimated to be ~20% at best) and the lack of detailed geologic mapping in the region (~30% has been mapped at 1:30,000 scale), our geological knowledge of the structure remains incomplete. In order to address this, it will be necessary to implement a systematic mapping program that is specifically designed to address the critical morphometric features of this impact structure. From a modeling perspective, we hope that this preliminary attempt to quantify some of the more critical physical dimensions of the Sudbury structure will help pave the way for future computational modeling of the Sudbury impact event. In this respect, observational information needs to be integrated with theoretical modeling in an iterative manner, with the one being used to enhance the value of the other in the light of both, to a greater or lesser extent, being subjective methods.

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