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Empirical and theoretical comparisons of the Chicxulub and Sudbury impact structures

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Abstract–Chicxulub and Sudbury are 2 of the largest impact structures on Earth. Research at the buried but well-preserved Chicxulub crater in Mexico has identified 6 concentric structural rings. In an analysis of the preserved structural elements in the eroded and tectonically deformed Sudbury structure in Canada, we identified ring-like structures corresponding in both radius and nature to 5 out of the 6 rings at Chicxulub. At Sudbury, the inner topographic peak ring is missing, which if it existed, has been eroded. Reconstructions of the transient cavities for each crater produce the same range of possible diameters: 80–110 km. The close correspondence of structural elements between Chicxulub and Sudbury suggests that these 2 impact structures are approximately the same size, both having a main structural basin diameter of ~150 km and outer ring diameters of ~200 km and ~260 km. This similarity in size and structure allows us to combine information from the 2 structures to assess the production of shock melt (melt produced directly upon decompression from high pressure impact) and impact melt (shock melt and melt derived from the digestion of entrained clasts and erosion of the crater wall) in large impacts. Our empirical comparisons suggest that Sudbury has ~70% more impact melt than does Chicxulub (~31,000 versus ~18,000 km^3) and 85% more shock melt (27,000 km^3 versus 14,500 km^3). To examine possible causes for this difference, we develop an empirical method for estimating the amount of shock melt at each crater and then model the formation of shock melt in both comet and asteroid impacts. We use an analytical model that gives energy scaling of shock melt production in close agreement with more computationally intense numerical models. The results demonstrate that the differences in melt volumes can be readily explained if Chicxulub was an asteroid impact and Sudbury was a comet impact. The estimated 70% difference in melt volumes can be explained by crater size differences only if the extremes in the possible range of melt volumes and crater sizes are invoked. Preheating of the target rocks at Sudbury by the Penokean Orogeny cannot explain the excess melt at Sudbury, the majority of which resides in the suevite. The greater amount of suevite at Sudbury compared to Chicxulub may be due to the dispersal of shock melt by cometary volatiles at Sudbury.

INTRODUCTION

The 2 largest, best-preserved impact structures on Earth are Chicxulub in Mexico and Sudbury in Canada; the only other known impact structure of comparable size is the deeply eroded (and possibly larger) Vredefort crater in South Africa (e.g., Grieve and Therriault 2000). While Chicxulub and Sudbury are both large structures with structural features 200 km or more in diameter, they differ markedly in their degree of preservation and surface exposure. Chicxulub is nearly perfectly preserved but deeply buried (~1 km in the center), and only the outer edge of its ejecta blanket is exposed. In contrast, Sudbury is eroded and tectonically deformed but has a well-exposed section of the crater fill, melt sheet, and footwall structures. Surface exposures are discontinuous at Sudbury, but numerous drill cores and abundant geophysical data are available. Despite these differences, recent research now provides sufficient data from each structure to support their detailed comparison presented in this paper. The unique value to this comparison is that structural geophysical data from the well-preserved Chicxulub crater can be used as a guide in interpreting the relatively deformed and eroded

Sudbury structure, and lithological data from the well-exposed Sudbury structure can be used as a guide in interpreting geophysical data from the poorly exposed Chicxulub crater.

The focus of this paper is on the volumes of melt rock and melt-rich breccia (suevite) derived from field and theoretical studies. Theoretical studies have shown that the volume of melt produced upon impact shock compression and release (shock melt) is approximately proportional to the kinetic energy of the impact (e.g., Ahrens and O'Keefe 1987; Bjorkman and Holsapple 1987; O'Keefe and Ahrens 1994; Pierazzo et al. 1997), while the size of impact craters is only partly dependent on kinetic energy (e.g., Melosh 1989, p. 121; O'Keefe and Ahrens 1994). This super-heated shock melt can digest entrained clasts, and thus, the total impact melt volume can greatly exceed the shock melt volume (e.g., Simonds and Kieffer 1993, p. 14,323). Therefore, no simple relationship exists between crater size and impact melt volume, and craters of similar size can have significantly different amounts of melt. This difference can be acute when asteroid impacts are compared to comet impacts, since comets typically have higher impact velocities (v_i) and energy (and shock melt volume) scales with v_i^2.

In this paper, we first use field data to estimate the amount of impact melt lithologies at both structures and then apply a model of shock melt production in asteroid and comet impacts to a comparison of melt volumes from the 2 impact structures. Our comparison of Chicxulub and Sudbury benefits from the good preservation of ejecta at Chicxulub and the extensive exposures of a complete basin fill sequence at Sudbury. We combine data from the 2 structures to produce an estimate of melt production in large impact craters that is more complete than previously possible.

We alert the reader that while we maintain a high degree of precision in the presentation of our volume calculations in the tables presented, this is done solely to facilitate reproducibility of the calculations. The high precision does not imply that these quantities can be estimated with a high degree of accuracy, and we use rounded numbers when assessing the implications of our estimates.

CRATER SIZE AND STRUCTURE

Chicxulub Structure

Although Chicxulub is buried (~200 m at the rim and 1000 m in the floor) and has only subtle surface features (Pope et al. 1993, 1996), its well-preserved features were first revealed by geophysical studies (gravity, magnetic, and seismic) coupled with data from a few exploratory oil wells (e.g., Sharpton et al. 1993, 1996; Pilkington et al. 1994; Camargo and Suarez 1994; Espindola et al. 1995; Hildebrand et al. 1995; Ward et al. 1995). More recently, a major offshore seismic study by the British Institutions Reflection Profiling Syndicate (BIRPS) and associated programs produced a wealth of information on the size and structural elements of Chicxulub (e.g., Morgan et al. 1997, 2002; Hildebrand et al. 1998; Brittan et al. 1999; Christeson et al. 1999, 2001; Morgan and Warner 1999a, b; Snyder and Hobbs 1999). These recent geophysical studies have been complimented by scientific drilling near the rim (e.g., Urrutia-Fucugauchi et al. 1996; Sharpton et al. 1999) and inside the crater (e.g., Dressler et al. 2003). The latter drilling inside the crater (Yaxcopoil-1 core) was finished after our analysis was largely complete. The preliminary data from the Yaxcopoil-1 core are consistent with our interpretation; however, these data have not been included in our analysis.

The dimensions of the main structural elements of the Chicxulub crater are summarized in Table 1 and shown in Figs. 1 and 2. Much of the past debate about the size of Chicxulub derives from the fact that different names have been given to the same concentric structural element by different authors. Despite the differences in nomenclature, the data summarized in Table 1 demonstrate that there is a general consensus on the diameters of the major structural elements. To avoid adding further confusion to the nomenclature, we have numbered the concentric structural elements (rings), beginning with the peak ring, as ring 1 through ring 6 and refer to these structures by their numbered rings.

Ring 1 (almost universally referred to as the peak ring) is a broad (~12 km wide), irregular, concentric ridge averaging ~80 km in diameter and extending several hundred meters above the buried crater floor. Ring 2 corresponds with the wall

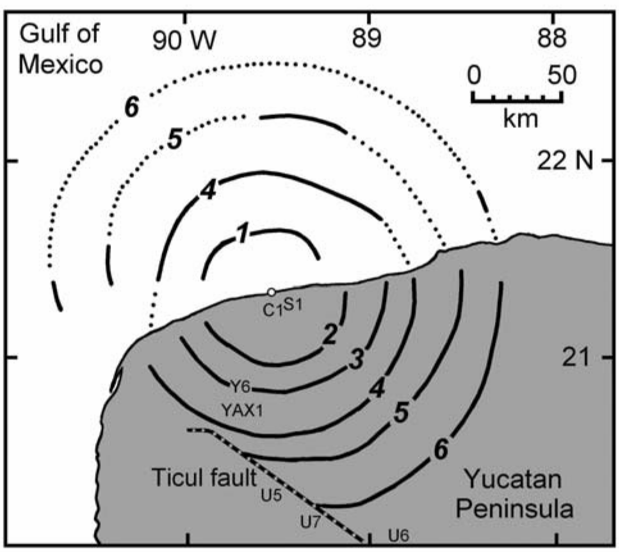

Fig. 1. Structural rings of the Chicxulub crater. The offshore rings (solid lines) are based on seismic profiles and are taken from Morgan and Warner (1999a). The onshore rings (solid lines) are based on topography and karst features and are taken from Pope et al. (1996). The dotted lines give inferred extensions of the rings. The ring characteristics described in Table 1. The approximate locations of the drill cores mentioned in the text (S1, C1, Y6, etc.) are shown.

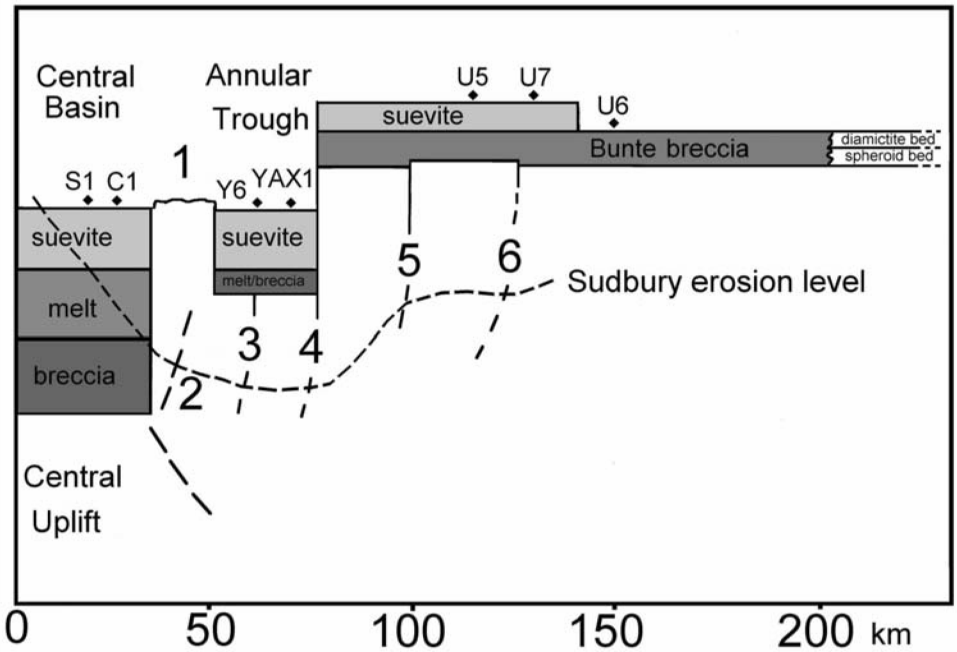

Fig. 2. Schematic profile (right half only) of the structure of the Chicxulub crater. The 6 structural rings described in Table 1 and shown in Fig. 1 are shown. The geometries of the crater fill and ejecta units are described in Table 2. The locations of the drill cores mentioned in the text (S1, C1, Y6, etc.) are marked with diamonds. Note that unit thicknesses are not shown to scale. Recent drilling near the outer edge of the annular trough indicates that the suevite and melt breccia sequence at YAX1 is much thinner (~100 m) than that found at Y6 (~500 m). Bunte breccia is impact breccia free of melt fragments, as in the Bunte breccia of the Ries crater in Germany. Based on the proposed close similarities between the Chicxulub and Sudbury structures, the approximate trace of the current erosion level in the northern part of the Sudbury structure is shown.

of the collapsed transient cavity represented by the boundary between the crater fill and in situ target rock. Ring 2 appears to lie beneath the peak ring. Ring 3 is a major concentric normal fault within the terrace zone of the collapsed transient cavity rim and is associated with down-dropped blocks of Mesozoic sediments. Ring 4 is also a major concentric normal fault that demarcates the outer edge of the main basin formed by the collapse of the transient cavity rim. Ring 5 is a concentric fault that has relatively minor offset in the upper Cretaceous sediments (400–500 m) but extends through the entire crust to the Moho. Ring 6 is a concentric blind thrust fault that produced subtle dome-like folds in the upper Cretaceous sediments. The root of this thrust fault merges with the deep crustal fault of ring 5. There is a growing consensus that ring 5 (~200 km diameter) should be used as the final diameter of Chicxulub (e.g., Snyder and Hobbs 1999; Morgan et al. 2000), although in the past, rings 4 (~150 km) and 6 (~250 km) have been referred to as the "rim" by Morgan and Warner (1999a, b) and Pope et al. (1996), respectively.

Chicxulub Transient Cavity

Based on the structural information from the BIRPS studies, Morgan et al. (1997) used marker beds in the sedimentary strata of the target rocks to reconstruct a diameter of 85 km for the transient cavity at a depth of 3.5 km. They then used the Z model (z = 2.7) for crater formation (Maxwell 1977) to extrapolate the 85 km diameter to the pre-impact surface, arriving at a transient cavity diameter of 90–105 km. This error margin reflects a range of assumptions about the shape of the parabolic transient cavity. The 90–105 km diameter assumes a collapsed transient cavity wall angle of 30° to 45° (from the horizontal). More extreme angles of 60° and <30° have been proposed, which give a possible range of 80 km to 110 km, respectively, for the Chicxulub transient cavity (Hildebrand et al. 1998; Morgan et al. 2002). Most models of transient cavity formation produce rather steep crater walls (e.g., O'Keefe and Ahrens 1999; Ivanov and Artemieva 2001). Therefore, the shallower angle (≤30°) and the larger cavity diameter (110 km) are probably not appropriate for estimating transient cavity diameters, especially for energy scaling, but are included in our analysis for completeness. The best estimate for the Chicxulub transient cavity diameter is probably the 90–105 km range proposed by Morgan et al. (1997).

Sudbury Structure

Sudbury is one of the most studied terrestrial impact craters (e.g., Grieve et al. 1991; Golightly 1994; Stöffler et al. 1994; Deutsch et al. 1995; Dressler and Sharpton 1999; Naldrett 1999; Grieve and Therriault 2000). Nevertheless,

Table 1. Comparison of Chicxulub and Sudbury structural features.

Chicxulub feature	Chicxulub diameter (km)[a]	Sudbury diameter (km)[b]	Sudbury feature
Ring 1			
Peak ring[c]	66–94 (80)	–	Eroded away
Peak ring[d]	72–94 (80)		
Ring 2			
Collapsed transient cavity[c]	85	65–85	Pseudotachylite zone (large)[e]
Collapsed transient cavity[f]	80	85	Innermost Huronian block[g]
First inner trough[h]	78–86 (82)	81–85	Maximum distance shocked quartz[i]
Ring 3			
Inner ring[c]	110	105–115	Abundant Huronian blocks[i]
Second inner trough[h]	114–134 (124)	115–125	Pseudotachylite zone (large)[e]
Ring 4			
Crater rim[c]	136–164 (145)	130–140	Landsat lineament (strong)[j]
Edge of collapsed terraces[f]	130	141–149	Pseudotachylite zone (large)[e]
Edge of basin[h]	160–172 (166)		
Edge of deep basin[d]	130–164		
Ring 5			
Outer ring[c]	195–200	190	Landsat lineament (weak)[k]
Restored rim[f]	195	225–229	Outer Pseudotachylite zone (small)[e]
Normal fault[f]	194–220		
Outer trough[h]	194–218 (206)		
Ring 6			
Exterior ring[c]	250	270	Maximum extent Landsat lineaments[k]
Ring fracture[f]	240–300 (250)		
Crater rim[h]	248–268 (258)		

[a]Mean diameters are shown in parentheses where provided in the reference noted.
[b]Sudbury diameters based on a diameter of 65 km for the undeformed outer edge of the melt sheet (Deutsch and Grieve 1994).
[c]Morgan and Warner 1999a, b.
[d]Brittan et al. 1999.
[e]Thompson and Spray 1994.
[f]Snyder and Hobbs 1999.
[g]Ontario Geological Survey 1984.
[h]Pope et al. 1996.
[i]Grieve et al. 1991.
[j]Dressler 1984.
[k]Butler 1994.

some debate remains over its size, largely because post-impact erosion and tectonic deformation have obscured the original shape of the impact structure but also because, as at Chicxulub, there are several roughly concentric structural elements, and nomenclature for these elements has not been standardized. The dimensions of the main structural elements of the Sudbury structure are summarized in Table 1 and shown in Fig. 3. Structural elements are defined following the approach of Grieve et al. (1991) and correspond to the distribution of pre-impact Huronian sediments and volcanics, shocked quartz, and pseudotachylite zones (breccias with a devitrified glassy matrix) found along shear zones and faults (e.g., Thompson and Spray 1994). The distribution of Huronian sediments is key because these sediments would have been largely removed within the transient cavity (see discussion below). We also include the information from analyses of Landsat satellite images (Dressler 1984; Butler 1994). We do not use shatter cones, since recent work suggests that their distribution is not highly sensitive to crater size (Turtle and Pierazzo 1998).

Post-impact deformation and erosion of the Sudbury impact structure has resulted in the formation of an elliptical basin the surface expression of which includes an elliptical ring of impact melt rocks 60 km by 30 km in size (Fig. 3) called the Sudbury igneous complex (SIC). From structural analyses, including attempts to reconstruct the impact structure's original form, it has been concluded that there is considerable southeast-northwest compression but that the southwest-northeast dimension of the original structure is still largely preserved (e.g., Shanks and Schwerdtner 1991; Milkereit et al. 1992; Roest and Pilkington 1994). Thus, the southwest-northeast dimension of the elliptical SIC exposure is close to the original diameter of the melt sheet at its current erosion depth (Grieve et al. 1991). Geobarometry studies of the SIC footwall contact constrain this erosion depth to 4.2–5.8 km (Molnàr et al. 2001). The best estimate of the original diameter of the SIC at a depth

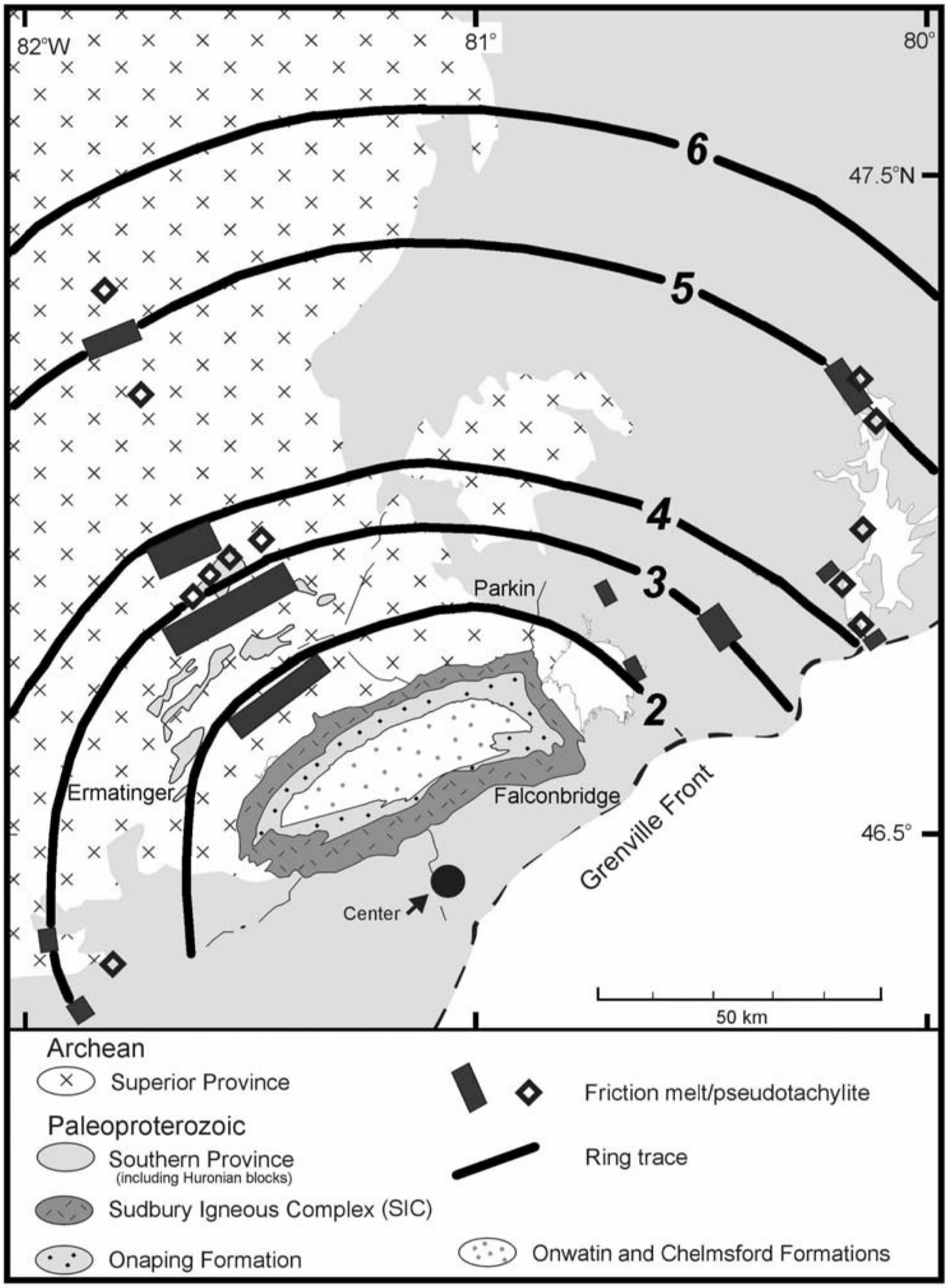

Fig.3. Structural rings of the Sudbury crater. Ring 1 (the peak ring), if it existed, has been eroded away. The locations of rings 2–5 are based on the distribution of friction melt (pseudotachylite, black rectangles) given by Thompson and Spray (1994). The outcrops (diamonds) of friction melt (Sudbury breccia) given by Butler (1994) are also shown. The location of ring 6 is based on the outer limit of concentric lineaments given by Butler (1994). The ring characteristics are given in Table 1. The lightly shaded outcrops of Paleoproterozoic rock between rings 2 and 4, adjacent to and north of Ermatinger, are the Huronian blocks discussed in the text.

of 4.2–5.8 km is 65 km (Grieve and Deutsch 1994). Given this SIC diameter, and following the approach of Grieve et al. (1991), the diameters of the other structural features can be calculated based on their distance from the SIC (Table 1). It is important to keep in mind that these diameters also reflect the diameter at depth and, thus, are for the most part slightly less than the surface diameter of the original feature.

A comparison of the structural elements of the Chicxulub and Sudbury craters presented in Figs. 1 and 3 and Table 1 suggests that there is a striking similarity between the 2 craters. Chicxulub ring 1, the peak ring, was predominantly a surface topographic feature (relief a few hundred meters; Morgan et al. 1997) and, therefore, if it did exist at Sudbury, and we presume it did, it has long since been eroded away by the 4.2–5.8 km of erosion. Evidence for the now-eroded peak ring at Sudbury may exist in the crater-fill sequence, where a megabreccia unit in the basal Garson member of the Onaping Formation is interpreted to represent the collapsed edge of the peak ring (Ames 1999; Ames et al. 2002). If this interpretation is correct, the buried (1.4 km) inner edge of the Sudbury peak ring resides at a diameter of ~60 km (the outer diameter of the preserved Onaping formation), which compares favorably with the 66–72 km diameter of the inner edge (at the surface) of the Chicxulub peak ring (Table 1). The other structural features at Chicxulub are deep seated, and thus, if similar structures are present at Sudbury, they should be detectable despite the erosion. The 65 km diameter of the Sudbury Igneous Complex (SIC) represents the minimum possible diameter of the collapsed transient cavity (ring 2) at a depth of about 4.2–5.8 km, as all target rocks have been ejected or melted inside this diameter. Projecting the walls of the collapsed Chicxulub transient cavity imaged by the seismic data (Christeson et al. 2001) to a depth of 6 km produces a similar diameter of ~70 km. Similarly, the diameter of the innermost zone of pseudotachylite at Sudbury (65–85 km) correlates well with the proposed collapsed transient cavity wall at Chicxulub at a depth of 3.5 km (Table 1).

The other major structural features at Sudbury also have counterparts at Chicxulub. A large pseudotachylite zone, lineaments visible on Landsat images, and abundant Huronian blocks at Sudbury correspond in distance and structure to Chicxulub ring 3 and its associated down-dropped blocks of Cretaceous sediments. The outermost large pseudotachylite zone with a prominent set of concentric lineaments at Sudbury corresponds with Chicxulub ring 4, the edge of the main impact basin. A minor pseudotachylite zone and a relatively weak zone of lineaments at Sudbury correlate with ring 5 at Chicxulub, which is a deep fault but one with minor offset. Finally, the outer boundary of impact-related features (lineaments) identified by Butler (1994) at Sudbury correlates with Chicxulub ring 6, the outermost structural feature. To help clarify the comparison of the 2 impact structures, the approximate trace of the Sudbury erosion levels is plotted on the Chicxulub schematic profile in Fig. 2.

Sudbury Transient Cavity

We can place constraints on the size of the transient cavity at Sudbury using the same technique applied by Morgan et al. (1997) for Chicxulub. The Sudbury impact site, like the one at Chicxulub, was composed of sedimentary (and volcanic) rocks, the Huronian Supergroup, overlying crystalline basement. Nevertheless, the Sudbury geology is more complex than that of Chicxulub, as the Huronian thicknesses were highly variable, and the sediments were metamorphosed and tectonically deformed before impact. The Sudbury field analysis is rendered less definitive by these factors, but it still provides useful constraints.

We can estimate the maximum diameter of the Sudbury transient cavity by determining the minimum distance from the SIC to intact blocks of Huronian sediments. This approach is based on the view that the Huronian would be completely removed within the transient cavity, at least within the excavation zone estimated by the Z model. The excavation depth obtained from the application of the Z model is about 12 km for a transient cavity diameter of 100 km (Morgan et al. 1997). Thus, near the center of the transient cavity, most if not all of the Huronian sediments (the maximum thicknesses of which were about 12 km, see below) would be ejected if the transient cavity diameter was ~100 km. Nearer to the rim, however, complete removal of the sediments would depend on the sediment thickness and the angle of the cavity wall.

The Huronian sediments in the Sudbury area increase in thickness from north to south and from west to east (Card et al. 1984). At the east end of the Sudbury impact structure, in the Parkin township near Wanapitei Lake, the thickness is estimated to be ~8 km (Dressler 1982). Southwest of the structure, in the Falconbridge township, the Huronian is >10.7 km thick and perhaps as much as 12 km thick (Card et al. 1977). Huronian sedimentary blocks in the Ermatinger township (and extending 50 km to the northwest) in the northern part of the Sudbury structure are thinner. These blocks mostly lack the basal formations of the Hough Lake and Elliot Lake groups and have locally truncated formations (Ontario Geological Survey 1984; Rousell and Long 1998), and therefore, the Huronian in this area was only about 5–6 km thick (Golightly 1994; Cowen et al. 1999).

In Table 2 the distances from the SIC to the closest preserved Huronian block are given for the Ermatinger, Parkin, and Falconbridge townships (Fig. 3) together with the estimated Huronian thickness. Calculations are then given for the maximum possible transient cavity diameter, assuming the angle of the collapsed transient cavity wall is 30°, 45°, or 60° from the horizontal. These are maximum values because, in the north, erosion may have stripped away closer blocks and because, in the south, the Huronian abuts the SIC, which would allow for any cavity smaller than that in Table 2. The minimum possible transient cavity diameter derived from the 65 km diameter of the SIC, its estimated depth of 4.2–5.8 km, and the same range of wall angles are also given in Table 2. These minimum diameters are almost certainly significantly smaller than the actual transient cavity, as Chicxulub crater reconstructions indicate that the melt sheet lies well within the transient cavity wall at depth (Christeson et al. 2001). The results of the maximum diameter calculations are similar for the 3 areas and show a consistent pattern of shorter distances between the SIC and Huronian with greater thickness. This consistency supports the view that, while tectonic deformation is significant in the region, it has not greatly distorted the geometry for these calculations. Given the calculations in Table 2, the constraints on the transient cavity diameter of Sudbury are 70–92 km for a 60° wall angle, 73–

Table 2. Estimates of the maximum and minimum Sudbury transient crater diameter. Maximum diameter estimates are based on the estimated pre-erosion thickness of Huronian deposits, the proximity of preserved blocks to the SIC, and wall angle. Minimum diameter estimates are based on SIC and wall angle alone. The original diameter of the SIC at the present erosion depth is assumed to be 65 km.

Huronian thickness or SIC depth (km)	Huronian distance from SIC (km)	Angle of transient cavity wall	Transient cavity diameter (km)
Ermatinger township (thickness 5–6 km)[a]			
5	10	60	91
5	10	45	95
5	10	30	102
6	10	60	92
6	10	45	97
6	10	30	106
Parkin township (thickness 8 km)[b]			
8	5	60	84
8	5	45	91
8	5	30	103
Falconbridge township (thickness 11–12 km)[c]			
11	0	60	78
11	0	45	87
11	0	30	103
12	0	60	79
12	0	45	89
12	0	30	107
SIC (at a depth of 4.2–5.8 km)[d]			
4.2	–	60	70
4.2	–	45	73
4.2	–	30	80
5.8	–	60	72
5.8	–	45	77
5.8	–	30	85

[a]Golightly (1994); Cowen et al. (1999).
[b]Dressler (1982).
[c]Card et al. (1977).
[d]Molnàr et al. (2001).

95 km for a 45° wall angle, 80–107 km for a 30° wall angle, and an overall range of 70–107 km.

Another technique to estimate the size of the transient cavity is proposed by Turtle and Pierazzo (1998), who combined data on the radial extent of shocked quartz with computer impact models to estimate the size of the Vredefort impact structure in South Africa. Their model calculations suggest that, for a transient cavity 80–100 km in diameter, the 5 GPa isobar at a depth of 4–6 km lies at a radial distance of 39–53 km (corresponding diameters of 78–106 km). They propose that the 5 GPa isobar represents the minimum pressure at which planar deformation features form in quartz (e.g., Grieve et al. 1996). Shocked quartz in the footwall of Sudbury extends 8–10 km from the SIC (Grieve et al. 1991), which corresponds to a diameter of 81–85 km. Interpolating between these 2 model calculations gives a Sudbury transient cavity diameter of 81–84 km, which falls within the estimates noted above. This is consistent with the conclusion that, at shallow depths, the 5 GPa isobar roughly corresponds with the transient cavity wall (Turtle and Pierazzo 1998). We can use this shocked quartz-based estimate to provide a more reasonable minimum diameter for Sudbury, giving a probable range (rounded to the nearest 10 km) of 80–110 km for the Sudbury transient cavity. Given that we favor the steeper cavity wall angles (45° to 60°), and that the most reliable stratigraphic data come from the Ermatinger township, the best estimate of the Sudbury transient cavity diameter is 91–97 km.

The conclusion to be drawn from this analysis is that Sudbury and Chicxulub are very similar impact structures. They both have a main basin of ~130–170 km in diameter and outer structural rings at ~190–230 and at ~250–270 km. This interpretation of the final crater structure at Sudbury and Chicxulub is consistent with the reconstructions of transient cavity diameters, which cover the size range of 80–110 km for both craters. The scaling relationships proposed by Croft (1985) give a final crater diameter of ~136–198 for this range of transient cavity diameters, which encompasses the diameters of rings 4 and 5 in Table 1. As noted previously, both ring 4 (Morgan and Warner 1999a, b) and ring 5 (Snyder and Hobbs 1999; Morgan et al. 2000) have been interpreted as the rim at Chicxulub. Which of these structural features should be called the rim can be debated, but such a debate has no bearing on our conclusion that the 2 craters are very similar in size and structure. For this paper this conclusion is important in 2 major respects: 1) we can combine data from the 2 craters to construct a more complete picture of a large impact crater than has been possible from studies of either crater alone; and 2) we can model the 2 craters as having the same range of transient cavity diameters.

Volume of Melt at Chicxulub

Estimates of the volume of impactites and their melt content for Chicxulub are presented in Table 3. For inside the crater, these estimates are based on a simplified crater geometry based on the data in Table 1 and on lithological data from 3 Petroleos de Mexico (PEMEX) exploratory wells (C1, S1, and Y6; Figs. 1 and 2). Our reconstruction of the total volume of the central basin and annular trough at Chicxulub is approximately 18,000 km^3 (Table 3), which matches well with recent 3-D gravity modeling of the crater (Ebbing et al. 2001). Estimates of the volume and melt content of impactites outside the crater (Table 3) are based on three Universidad Nacional Autonoma de Mexico (UNAM) cores (U5, U6, and U7; Figs. 1 and 2), ejecta blanket outcrops, and published data from distal ejecta. Here too, our volume estimates are based on simple circular geometries for the ejecta bodies multiplied by an average thickness. Given the relatively small amount of melt in the distal ejecta, inaccuracies introduced by the use of these simplified geometries are minor.

PEMEX wells Chicxulub 1 (C1) and Sacapuc 1 (S1) are near the center of the crater, and Yucatan 6 (Y6) is at a radius of about 60 km (Fig. 2). Wells C1 and S1 sampled 200–300 m of suevite overlying impact melt (Ward et al. 1995; Sharpton et al. 1996). Impact melt samples from C1 contain 5% or less unmelted clasts (Schuraytz et al. 1994; Claeys et al. 1998). Well Y6 sampled about 200 m of suevite overlying about 300 m of melt-rich breccia containing about 65% melt and 35% unmelted clasts of target rock (Schuraytz et al. 1994; Claeys et al. 1998). Well Y6 bottomed in ~8 m of anhydrite,

Table 3. Geometry and melt content of Chicxulub impact rocks.

Location	Radial distances (km)	Thickness (km)	Volume (km^3)	% melt	Melt volume (km^3)
Inside crater rim					
Central basin					
Suevite	0–35	0.2	769	50	385
Melt rock	0–35	1.0	3,848	97	3,733
Melt breccia	0–35	2.5	9,621	65	6,254
Subtotal					10,372
Annular trough					
Suevite	50–75	0.2	1,963	50	982
Melt breccia	50–75	0.2	1,963	65	1,277
Subtotal					2,259
Total inside					12,631
Outside crater rim					
Bunte breccia[a]	75–200[b]	0.2	21,598	0	0
Suevite near rim	75–140	0.15	6,586	40	2,634
Albion fm. diamictite bed	200–370[b]	0.015	4,566	10	456
Albion fm. spheroid bed	200–500[b]	0.002	1,319	20	264
Proximal microtektites[c]	500–1000	0.0001	236	100	236
Distal microtektites[c]	1000–4000	0.00001	471	100	471
KT fireball[d, e]	Global	0.000003	1,520	100	1,520
Total outside[d]					5,581
Total impact melt[d]					18,212
Total shock melt[d, f]					14,456

[a]Bunte breccia is an impact breccia free of melt fragments, type locality is the Ries crater in Germany.
[b]The 200 km radius boundary assumed here is poorly constrained; observations limit it to between 140–340 km.
[c]Estimates based on data in Smit (1999).
[d]Includes vapor.
[e]Estimates from Pope (2002). All other estimates based on discussions in the text.
[f]See text for calculation of shock melt.

but whether the anhydrite is a large clast in a thicker melt and breccia sequence or if it represents the base of the melt sheet at this location is not clear. Probably, the latter is correct, as the base of Y6 lies close to the top of Cretaceous slump blocks identified in the seismic data (Morgan et al. 2000). The melt content of the suevites inside the crater has not been published, but we assume it is 10% higher than the 40% melt we estimate for the suevites cored near the rim of the crater (see discussion below). We note that these interpretations of the Y6 well are consistent with the drilling at Yaxcopoil-1 (YAX1; Figs. 1 and 2), which is located nearer to the outer edge of the annular trough and intersected only ~100 m of suevite and melt-rich breccia (Dressler et al. 2003). Recent work by Ames et al. (Forthcoming) indicates that the YAX1 suevites and breccias contain 60–95% altered blocky glass. This is slightly higher than our estimate (50–65%; Table 3), but this higher melt content is compensated in part by the apparent thinning of the impact units in the outer trough.

Inside the Chicxulub crater, geophysical data provide some insight into the character and distribution of melt at depth. Tomographic inversion of the seismic data, coupled with the gravity data, indicates the presence of a melt body about 40–50 km in diameter and 1.3 km thick in the center of the crater (Christeson et al. 1999, 2001). This is presumably the melt sheet sampled in C1 and S1, which is about 97% melt (Schuraytz et al. 1994). This same geophysical analysis detected a smaller melt body (<1 km thick) near the outer edge of the collapsed transient cavity (at about a diameter of 90 km). These 2 proposed melt bodies match well with 2 concentric zones of magnetic anomalies interpreted as zones of hydrothermal alteration (Pilkington and Hildebrand 2000), presumably from fluids circulating near the edge of the melts. These melt bodies, when combined, are roughly equivalent to a 1 km-thick melt sheet with a diameter of 70 km (Fig. 2; Table 3). Further analyses of the seismic data by Morgan et al. (2000) suggests that there may be a much thicker sequence of melts extending more than 2 km below the central melt body noted above (total melt thickness ~3.5 km). Nevertheless, the seismic velocities in these melt rocks are far less than that found in the SIC of Sudbury and are comparable to those measured in the melt-rich breccias cored in Y6 (Morgan et al. 2000). Thus, this thick sequence of melts may be clast-rich, and we assume, as in the breccias in Y6, that it is 65% melt. Furthermore, this thick sequence of melt breccias contains no evidence of layering (Morgan et al. 2000) like that found in the differentiated SIC at Sudbury (Milkereit et al. 1994), which has a distinct seismic reflector between the basal norite and overlying granophyre.

Outside the Chicxulub crater, impact melts are a significant component in suevitic ejecta that extend from the crater rim (Urrutia-Fucugauchi et al. 1996; Sharpton et al. 1999) to central Belize, 480 km south (Pope et al. 2000). X-ray fluorescence (XRF) analyses of the UNAM cores near the rim (Fig. 2) indicate that there is ~180 m of suevite with 50–60% silicate material at a radius of 115 km (U5) and ~130 m of suevite with 20–40% silicate material at a radius of 130 km (core U7) (Sharpton et al. 1999). Detailed petrographic analyses have not been published for these cores, but preliminary observations indicate that most of the silicate material is altered glass, with a minor portion of unmelted basement (Corrigan 1998). Our own brief macroscopic examination of the cores in February 2003 (Pope, unpublished data) noted that the suevites in U5 and U7 contain ~30% altered glass lapilli and bombs and an unestimated amount of fine ash in the matrix (matrix is 60–70%). Given the XRF data and our own observations, we estimate the average melt content of the suevites in the UNAM cores to be 40%. Coarse ejecta with little to no altered glass are found below the suevites in U7 and in the core U6 at a radius of 150 km (Urrutia-Fucugauchi et al. 1996; Sharpton et al. 1999). Farther from ground zero (340–360 km from the crater center), in northern Belize and southern Quintana Roo, the 1–2 m of basal fine ejecta (Albion formation spheroid bed) contains ~20% altered glass, and the overlying 8–15 m of coarse ejecta (Albion formation diamictite bed) contains ~10% altered glass (Ocampo et al. 1996; Pope et al. 1999). In central Belize, only the basal fine ejecta unit contains significant altered glass (Pope et al. 2000). At greater distances, impact melts in the form of cm to mm layers of microtektites are distributed as far away as 4000 km, and microkrystites (micro-spherules probably representing condensates from impact vapor) are found globally (e.g., Smit 1999).

The volume of impact melt (+ vapor) produced at Chicxulub is estimated in Table 3, the total of which is ~18,000 km^3. The geometries of the melt bodies are fairly well constrained by the geophysics. Likewise, the melt content of the suevites is constrained by the core data and distal surface exposures. From the melt volumes in Table 3, we estimate that about 30% of the total melt + vapor produced at Chicxulub was ejected (24% if you exclude vapor), which is similar to that predicted by theoretical calculations (Kring 1995; Warren et al. 1996).

The most significant potential error in the melt estimates lies in the melt volume in the lower portion of the central basin at Chicxulub. In the unlikely case that this central melt sheet was composed of 100% melt, about 18% would be added to the final melt estimates (total ~21,600 km^3). In the more likely case that this melt sheet is entirely melt breccia (e.g., Morgan et al. 2000), the final estimates would be about 7% less (total ~17,000 km^3). The other reasonable sources of error, such as a slightly different shape of the crater (e.g., a central basin of 80 km instead of 70 km) or slightly greater or lesser percentages of melt in the suevites (~30–60%), produce melt volumes that mostly vary less than 10%. Since some of these errors could be cumulative, a conservative range of melt volumes for Chicxulub is ±20% or about 14,600–22,000 km^3.

Volume of Melt at Sudbury

Several authors have estimated the volume of impact melt at Sudbury. Most studies focus on the main melt mass of the SIC, which has a diameter of ~65 km and a thickness of ~2.5 km at the current erosional depth (e.g., Grieve et al. 1991). This estimated thickness is based on outcrop and drill core. Geophysical data suggest there may be a slight thickening (~3 km) of the melt sheet toward the center (e.g., Wu et al. 1995). Grieve et al. (1991) estimate an SIC volume (including the Basal member of the Onaping) of 8,000–8,500 km^3, while Wu et al. (1995) suggest a volume of 8,500–15,000 km^3. Stöffler et al. (1994) considered the SIC, melt in the suevites (Onaping formation), and melt in a reconstructed annular ring trough, from which they estimated the total melt at between 11,550–13,300 km^3. This estimate greatly underestimated the amount of melt in the suevites, which contain about ~55% melt not the 10% used in the Stöffler et al. (1994) calculations. None of the previous melt estimates for Sudbury considered the melt once present outside the crater in the form of suevites, microtektites, and microkrystites as we have for Chicxulub (Table 3). The estimate of melt from the suevite once present inside Sudbury comes from recent studies of the Onaping formation, which is comprised of a basal Garson member of limited distribution overlain by the basin-wide Sandcherry and Dowling members (e.g., Ames et al. 1997, 2002; Ames 1999). This member terminology for the Onaping replaces the previous one of Basal, Gray, Green, and Black members (e.g., Muir and Peredery 1984; Brockmeyer 1990). In this paper, we refer to the Sandcherry and Dowling members of the Onaping formation as suevite. The Sandcherry member is 300–500 m thick and contains >60% altered glass fragments and about 25–30% fine-grained matrix, while the Dowling member comprises the upper ~1000 m of the suevite and contains 25–40% altered glass fragments and ~60% fine-grained matrix (Ames et al. 1997, 2002). Presumably some and perhaps most of the matrix is also melt in the form of fine ash. Only the upper 140–220 m of the Dowling member show evidence (normal graded beds) of reworking (Ames et al. 2002). Thus, the bulk of the Onaping is considered here as primary impact deposit. Given these estimates of glass fragments and fine ash, we conservatively estimate an average melt content of 55% for the ~1400 m-thick Sudbury suevite.

We present our estimate of the melt volume of the Sudbury crater in Table 4. This estimate is based on the conclusion drawn above that Chicxulub and Sudbury have a similar basic structure (Table 1). In our melt calculations, we assume that the geometries of the melt bodies at Sudbury are the same as those in the better-preserved Chicxulub (e.g., the same diameter and shape but different thickness). We use actual data from Sudbury on the thickness and melt content of these bodies. For melt bodies that have been completely eroded away, we use scaling relationships from Chicxulub. Melt volumes for the Sudbury central basin are derived from comprehensive data on the thickness and melt content coupled with the geometry extrapolated from Chicxulub. We assume that the suevite was the same thickness in the Sudbury annular trough as it is in the central basin because this is most probably the case at Chicxulub. The melt thickness underlying the suevite in the annular trough is assumed to be the same in both craters but with a higher melt content (100%) at Sudbury. This assumption is based on the massive amount of pure melt in the adjacent central basin (SIC) and the fact that melt in the annular trough starts out as part of the main melt sheet and is only separated from the main mass late in the cratering process after the uplift of the peak ring. The amount of melt outside the crater is derived from scaling of

Table 4. Geometry and melt content of Sudbury impact rocks.

Location	Radial distances (km)	Thickness (km)	Volume (km^3)	% melt	Melt volume (km^3)
Inside crater rim					
Central basin[a]					
Suevite (Onaping fm.)	0–35	1.4	5,387	55	2,963
Melt rock (SIC)	0–35	2.5	9,621	100	9,621
Subtotal					12,584
Annular trough[a]					
Suevite	50–75	1.4	11,436	55	6,290
Melt rock	50–75	0.3	2,945	100	2,945
Subtotal					9,235
Total inside					21,819
Outside crater rim[b]					9,620
Total impact melt[c]					31,439
Total shock melt[c, d]					27,250

[a]Assumed to have an identical size as estimated for Chicxulub, based on comparisons in Table 1.
[b]Assumes 30.6% of the total melt + vapor is ejected based on data from Chicxulub in Table 3.
[c]Includes vapor.
[d]See text for calculation of shock melt.

melt inside and outside of Chicxulub. Our impact melt estimates for Sudbury, as well as Chicxulub, do not include the melt matrix of breccia dikes and pseudotachylite zones in the crater basement, which are considered volumetrically to be an only minor component.

We estimate that Sudbury produced about 31,000 km^3 of impact melt (+ vapor), which is significantly more than the ~18,000 km^3 we estimate for Chicxulub. Given our methods of scaling to achieve this volume, there is no direct way to estimate the error margin for Sudbury. If we adopt the ±20% applied to Chicxulub, the range for the Sudbury melt volume would be 25,000–38,000 km^3. Note, however, that it is not appropriate to compare the lower end of the Sudbury range (25,000 km^3) with the upper end of the range for Chicxulub (22,000 km^3) since many of the factors that would increase the melt volume in one crater would also increase the estimate in the other given the scaling methods we used.

One source of the difference in estimated melt volumes between the 2 craters is that Sudbury has a much thicker blanket of suevite inside its central basin, resulting in ~2500 km^3 more melt. This difference in suevite thickness (1.4 km at Sudbury and 0.2 km at Chicxulub) between the 2 craters is well-constrained by core and geophysical data from Chicxulub and outcrop and core data from Sudbury. Despite the presence of a much thicker melt sheet at Sudbury compared to Chicxulub, our estimates for the total melt plus melt breccia (excluding the suevite) in the central basin of the 2 craters is similar (~10,000 km^3). The largest discrepancies in melt volumes between the 2 craters are for suevites inside the annular trough and for the melt outside the crater, which by our estimates contain ~5300 km^3 and ~4000 km^3 more melt, respectively, at Sudbury. Since the Sudbury estimates of melt outside the central basin are based on our reconstructions not observations, the large difference in melt volumes between the 2 craters must be viewed with some caution. Nevertheless, the major difference in suevites inside the central basin is well constrained, and since the suevites are dominated by debris initially ejected from the crater that fell back in, it is reasonable to assume that, at Sudbury, the suevite thickness would be similar in the central basin and annular trough as it is at Chicxulub. We conclude that either Sudbury has about 70% more melt than Chicxulub, or the two craters had a drastically different distribution of suevite inside and outside the central basin.

Impact Melt and Shock Melt Volumes

Before we can compare the melt volume estimates with the model results in the next section, a distinction must be made between the impact melt observed in the field and the shock melt calculated by theory (Simonds and Kieffer 1993, p. 14,323). The importance of this distinction and the problems that arise in trying to quantify it are also discussed in See et al. (1998), who imply the same distinction in melt products but define the concept in terms of primary mixing (referring to the mixing of melts produced by the initial shock) and secondary mixing (referring to the interaction of solid clasts with hot melts). Shock melt is melt that is produced directly upon decompression from high pressure and is generally superheated. “High pressure” is defined by the particular Hugoniot and release adiabats for the minerals, rocks, and volatile components involved. Shock melt is the melt produced near the meteorite under appropriate conditions of high pressure and temperature; it is the quantity calculated in impact models at present. Impact melt includes not only shock melt formed in the high-pressure region near the meteorite trajectory but also material entrained by erosion as the evolving melt sheet flows along the transient cavity walls and by the entrainment of other shocked debris that was launched into the air but fell back into the evolving melt sheet. The superheated shock melt can readily melt much of this entrained material. Shock melt is thus “bulked up” by digestion of strongly, moderately, and weakly shocked material to become impact melt.

We can estimate the relative proportions of shock melt and impact melt at Chicxulub and Sudbury by examining the distribution of melt in each crater and by making a simple assumption that the melt that remains inside the crater can digest 50% of its volume in shocked but unmelted lithic clasts. This assumption comes from the work of Simonds and Kieffer (1993), who estimated that the impact melt sheet at the Manicouagan impact structure (100 km diameter) had digested about 50% of its volume in target rock. This estimate is based on the mass of residual unmelted quartz in the impact melt and the assumption that all other components from the entrained clasts (such as feldspars, amphiboles, and biotite) were melted. These Manicouagan data are compatible with recent studies of the impact melts inside the Popigai crater (100 km diameter) in Siberia (Whitehead et al. 2002; Kettrrup et al. 2003). Geochemical models cannot reproduce the observed volumetric proportions of the SIC by differentiation from a single homogeneous melt body, but these proportions can be explained if there was significant digestion at the top and base of the SIC (e.g., Ariskin et al. 1999; Naldrett 1999). Geochemical studies of the Onaping formation, SIC, and offset dikes in the crater footwall also show that that bulking up of the shock melt by assimilation of footwall rocks can explain the different chemistries of these 3 units (Ames et al. 2002).

The shock melt available to entrain and digest clasts of target rock does not include the melt ejected out of the crater, or the suevite melt in the crater, which was initially ejected and fell or flowed back in (Kieffer and Simonds 1980). The non-suevite melt inside Sudbury totals 12,566 km^3 (melt from the central basin and the assumed annular trough, Table 4), which, given our 50% bulking assumption, represents 8,377 km^3 of shock melt and 4,189 km^3 of digested clasts (we have kept extra significant figures here so that the reader can reproduce the results, but we drop them in our summary of this section). Subtracting this digested clast melt volume from the total melt + vapor (31,439 km^3) gives a total shock melt + vapor volume of 27,250 km^3, which indicates that bulking increases the shock melt + vapor volume by about 15%. For Chicxulub, the non-suevite melt inside the crater totals 11,265 km^3, which, given our 50% bulking assumption, represents 7,509 km^3 of shock melt and 3,756 km^3 of digested clasts. Subtracting this digested clast melt volume from the total melt + vapor (18,212 km^3) gives a total shock melt + vapor volume of 14,456 km^3. Thus, it is estimated that bulking increases the shock melt + vapor at Chicxulub by about 26%. In summary, our estimates of the volume of shock melt produced at the 2 craters, assuming an error margin of ±20%, are ~12,000–17,000 km^3 for Chicxulub and ~22,000–33,000 km^3 for Sudbury. Taking mean values of 14,500 km^3 for Chicxulub and 27,000 km^3 for Sudbury, 85% more shock melt was produced at Sudbury compared to Chicxulub (compared to 70% more impact melt). This greater percentage of shock melt compared to impact melt derives from the greater amount of suevite at Sudbury, which contains primarily shock melt (e.g., Ames et al. 2002).

ANALYTICAL ESTIMATES OF MELT PRODUCTION

Calculation of Volumes of Shock Melt

Shock melt volumes have been calculated by a number of methods, including laboratory methods that are limited to velocities significantly lower than those expected for planetary collisions and theoretical models that can extrapolate to higher impact velocities. Theoretical approaches have been both analytical and numerical, involving massive computations. These 2 approaches represent end members in the need for simplicity and ease of calculation (the analytic models) and the need for accurate representation of many parts of the process—including both thermodynamic and fluid-dynamic—which the analytical models cannot provide (the massive computer models). "The ideal case would be an analytical model that gives results in good agreement with the numerical simulation" (Pierazzo et al. 1997, p. 408). In this paper, we develop a modification of an earlier analytical method (Kieffer and Simonds 1980) that uses a hypothesis (outlined below) introduced by Melosh (1989, p. 60–66) and reproduces the detailed computationally calculated volumes of melt + vapor by Pierazzo et al. (1997). The model revision and calibration against Pierazzo et al. (1997) is summarized in the Appendix. We then apply this model to examine the influence of different projectiles and velocities on the amount of melt produced at Chicxulub and Sudbury.

The basic controversy has been whether or not the volume of impact melt scales with the momentum of the projectile or its energy. O'Keefe and Ahrens (1977, 1982a, 1982b) presented computations that can be summarized in a relatively simple equation in which the shock melt volume is proportional to the impact energy:

$$M_M/M_P = 0.14\ v_i^2/\varepsilon_m$$

where M_M is the mass of shock melt produced, M_P is the mass of the impacting projectile, v_i is the impact velocity, and ε_m is the internal energy for melting. This equation is based on impacts of iron, gabbro, anorthosite, and ice projectiles on gabbro, as well as anorthosite targets. A similar equation holds for the relative mass of vapor produced with the coefficient 0.14 replaced by 0.4 and the internal energy for melting replaced by the internal energy for vaporization. The melting equation is valid for impact velocities above 12 km/s; the vapor equation is valid for velocities above 35 km/s. Melosh (1989, p. 64–66, p. 122–123) discusses some of the physical differences between the melting and vaporization models.

Grieve and Cintala (1992, their Fig. 2) used a modified version of the Gault-Heitowitz formulation and obtained melt volumes that scaled with energy in agreement with O'Keefe and Ahrens (1977). Similar results for more generalized calculations were reported in Cintala and Grieve (1998, their Fig. 6). Bjorkman and Holsapple (1987) proposed a scaling law, applicable only when the projectile and target are composed of the same material and are not porous, of the form:

$$V_M/V_{pr} \propto (E_M/v_i^2)^{-3\mu/2}$$

where V_M is the volume of shock melt, V_{pr} is the volume of the projectile, E_M is the internal energy of melting, v_i is the impact velocity, and μ is a scaling constant. If $\mu = 1/3$, the scaling is by momentum; if $\mu = 2/3$, the scaling is by energy. Bjorkman and Holsapple's conclusion was that $\mu = 0.55–0.6$, intermediate between the 2 end members but closer to the energy scaling law. We return to this conclusion because our results for μ are in the middle range of μ as proposed by Bjorkman and Holsapple.

Relatively few computer simulations have been done to address this problem. The sum of melt (+ vapor) produced in computer simulations (Pierazzo et al. 1997) of a dunite projectile into a variety of targets (excluding ice-ice impacts) gave a least square fit for μ of:

$$\mu = 0.708 \pm 0.039$$

This value of μ was interpreted as being in good agreement with energy scaling, although it is nominally higher than the value of 0.66 for energy scaling. The effect of calculating (melt + vapor) instead of melt alone was not discussed, but at the shock pressures generated in their simulations, relatively little vapor is produced in dunite impacts and, therefore, this effect should not be significant. We test our model against these simulations in the Appendix.

The revisions introduced here are based on a point noted by Melosh (1989, p. 60–66) but that was not developed in detail at the time and on results in Pierazzo et al. (1997) regarding depth of energy release, radius to peak pressure isobars, and shape of melt volumes. As discussed in the Appendix, the method of Kieffer and Simonds (1980) can then be reproduced with the final result that the non-dimensional pressure decay versus non-dimensional distance is:

$$dX/dR=\{-3X + 3X(Xn + 1)^{-1/n} + 4/n - (4n)(Xn + 1)^{-1/n} + 2/[n(1 - n)][-1 + (Xn + 1)^{1 - 1/n}]\}*$$

$$\{R[1 - (nX + 1)^{-1/n} + X(nX + 1)^{-1 - (1/n)}]\}^{-1}$$

where $X = P/K_0$, $R = r/R_0$, P is pressure, K_0 is the bulk modulus, r is radial distance from the center of energy deposition R_0, and n is the bulk modulus derivative. The form of the analytic equations is the same as in Kieffer and Simonds (1980) with changes in the coefficients.

As shown in Table A1, the results are in good agreement with the results of Pierazzo et al. (1997). Especially given the differences in form of equation-of-state, computational models, and criteria for melting, the agreement between the values of melt + vapor for the 2 models is excellent. Furthermore, the energy scaling coefficient, μ, defined above from the Bjorkman and Holsapple (1987) equation, is 0.59 ± 0.03 for our model, which is within the values of 0.55 and 0.60 found by Bjorkman and Holsapple as being slightly under the absolute energy scaling value of 0.66. For Pierazzo et al. (1997), the value of μ averages about 0.708 ± 0.039, slightly higher than the value for energy scaling.[1] Thus, within the limits of current controversy over the value of this parameter, we conclude that our simple analytical model does accomplish the goal stated by Pierazzo et al. (1997) of presenting an "analytical model that gives results in good agreement with the numerical simulation."

Application of the Model to Chicxulub and Sudbury

Using the pi-scaling law (Schmidt and Housen 1987) to define transient cavity diameters as specified by Melosh and Beyer (1998), we use the Kieffer-Simonds model to calculate shock melt production in comet and asteroid impacts. We calculate 5 examples each of impacts that would produce 80, 90, 100, and 110 km diameter transient cavities (Table 5). In all cases, the target density is assumed to be 2.65 g/cm^3, the asteroid density is 3.0 g/cm^3, and the comet density is 0.9 g/cm^3. For equations of state, we use granite for the target, ice for the comet, and diabase for the asteroid. Equation-of-state parameters are given in Table B1 of Kieffer and Simonds (1980). We take 50 GPa as the melting isobar for granite (approximate mid-point between incipient [46 GPa] and complete [56 GPa] melting; Pierazzo et al. 1997, their Table I). The results are summarized in Table 6.

[1]This significant difference in μ between our values and those of Pierazzo et al. derive from the rather small differences in melt volumes presented in Table A1. At 20 km/s, our values are systematically higher than Pierazzo et al., with exceptions for the large projectiles, and at 40 km/s, our values are systematically lower.

Effects of Impact Angle

The results of our modified Kieffer-Simonds model are for a vertical (90°) impact—statistically nearly an impossible event. Thus, we need to adjust our results to a more probable range of impact angles (45° is the most probable). While melt production in oblique impacts is not fully understood, recent work with 3-D numerical models provides some insights. Studies by Pierrazo and Melosh (2000) and Ivanov and Artemieva (2001) suggest that, compared to a 90° impact (vertical), there is ~20% reduction in melt for a 45° impact and ~50% reduction for a 30° impact. Artemieva and Ivanov (2001, 2002) investigated changes in the volume of the transient cavity with different impact angles. They found that, for impact velocities over 20 km/s and impact angles from 90° to 30°, there was little change in transient crater volume for asteroid impacts. Data presented for comet impacts by Artemieva and Ivanov (2002) suggest that there may be a transient crater size dependence on impact angle along the lines indicated by experimental work (Gault and Wedekind 1978), which demonstrated a reduction in crater size as a function of the sine of the impact angle. In Table 7, we present shock melt volumes for our various impact scenarios adjusted for impact angle, assuming little to no crater size dependence

Table 5. Projectile radius (km) for given transient cavity diameter (Dtc) and asteroid or comet velocity, based on the pi-scaling law (Schmidt and Housen 1987) as specified by Melosh and Beyer (1998).

Dtc	80 km	90 km	100 km	110 km
Asteroid velocity	Projectile radius (km)			
20 km/s	5.4	6.3	7.2	8.1
25 km/s	4.8	5.6	6.4	7.2
30 km/s	4.3	5.0	5.7	6.5
Comet velocity	Projectile radius (km)			
40 km/s	6.1	7.1	8.2	9.2
50 km/s	5.4	6.3	7.2	8.1

Table 6. Kieffer-Simonds model calculations of shock melt + vapor volume (V_{m+v}) for various transient cavity diameters (Dtc) and asteroid and comet impact velocities (vertical impact).

Dtc	80 km	90 km	100 km	110 km
Asteroid velocity	V_{m+v} (km^3)			
20 km/s	7,721	11,548	17,251	24,564
25 km/s	7,681	11,878	17,796	25,950
30 km/s	7,734	12,093	18,026	26,742
Comet velocity	V_{m+v} (km^3)			
40 km/s	20,289	33,048	48,415	69,657
50 km/s	21,555	33,195	50,038	75,389

TAble 7. Corrections to Kieffer-Simonds model calculations of shock melt + vapor volume (V_{m+v}) for impact angle (rounded to the nearest 1000 km^3).

Dtc	80 km		90 km		100 km		110 km	
	45°	30°	45°	30°	45°	30°	45°	30°
Impact angle	0.8 V_{m+v}	0.5 V_{m+v}	0.8 V_{m+v}	0.5 V_{m+v}	0.8 V_{m+v}	0.5 V_{m+v}	0.8 V_{m+v}	0.5 V_{m+v}
Asteroid velocity								
20 km/s	6,000	4,000	9,000	6,000	14,000	9,000	20,000	12,000
25 km/s	6,000	4,000	10,000	6,000	14,000	9,000	21,000	13,000
30 km/s	6,000	4,000	10,000	6,000	14,000	9,000	21,000	13,000
Comet velocity								
40 km/s	18,000	11,000	26,000	17,000	39,000	24,000	56,000	35,000
50 km/s	18,000	11,000	27,000	17,000	40,000	25,000	60,000	38,000

on impact angle (≥30°). Given that there may be such dependence for comets, the oblique comet melt volumes in Table 7 may be low by a factor of ~2–3.

COMPARISON OF SUDBURY AND CHICXULUB

Melt Volumes and Asteroid Versus Comet Impacts

A comparison of the impact model shock melt volume calculations in Table 7 with the empirical estimates of shock melt volumes from Chicxulub (~14,500 km^3) suggests that Chicxulub is probably an asteroid impact. Nevertheless, if one accepts the smaller transient cavity diameters (80–90 km) and the full range of possible shock melt volumes (12,000–17,000 km^3), then an oblique comet impact can be accommodated. An oblique Chicxulub comet impact cannot be accommodated if one assumes a dependence of crater size on impact angle as discussed above. Independent evidence exists to support the hypothesis that Chicxulub was an asteroid impact. First, the mass of the impactor implied by the large content of meteoritic material in the distal ejecta (e.g., the famous Ir anomaly at the Cretaceous-Tertiary [K-T] boundary) cannot be reconciled with the size of the crater if the impact velocity exceed ~45 km/s (Vickery and Melosh 1990; Pope et al. 1997). Second, both the chemistry of a possible fragment of the impactor found in the Pacific (Kyte 1998) and the Cr isotopic signature of the meteoritic debris in the K-T boundary (Shukolyukov and Lugmair 1998) are consistent with a carbonaceous chondrite impactor. Third, analyses of He isotope data from the K/T boundary show no evidence of comet showers (Mukhopadhyay et al. 2001). None of these pieces of evidence is conclusive, but taken together with our analysis of impact melt, they favor the Chicxulub asteroid impact hypothesis. If Chicxulub is an asteroid impact, then the transient cavity diameter is unlikely to be much smaller than 100 km given our estimates of shock melt volume.

A comparison of the shock melt volume calculations in Table 7 with the empirical estimates of shock melt volumes from Sudbury (22,000–33,000 km^3) suggests that Sudbury is probably a comet impact. Nevertheless, if one accepts the largest possible transient crater diameter (110 km) and an impact angle >45°, then an asteroid impact can be accommodated.

While our analysis of impact melts at Chicxulub and Sudbury is not definitive with regard to asteroid versus comet impacts, the most parsimonious explanation for the large difference in melt volumes is that Chicxulub was an asteroid impact and Sudbury was a comet impact. This proposed asteroid versus comet scenario fits well with our best estimates of the shock melt volumes and transient crater sizes for Chicxulub (14,500 km^3 and ~90–105) and Sudbury (27,000 km^3 and ~91–97 km).

Effects of the Geothermal Gradient

While we favor the asteroid versus comet explanation for the apparent differences in melt volume between Chicxulub and Sudbury, there are other possible factors. Warren et al. (1996) suggest that the thicker melt sheet at Sudbury compared to Chicxulub is due to "pre-heating" of the target rocks by the Penokean Orogeny, as Penokean deformation south of Sudbury in the Great Lakes region is roughly contemporaneous with the 1.85 Ga Sudbury impact. The metamorphic facies of the Penokean deformation at Sudbury are greenschist (Card et al. 1984; Riller and Schwerdtner 1997), which suggests that at some point prior to impact, temperatures of the target rocks were ~400 °C. This is consistent with an elevated geothermal gradient. To explore further the possible effects of "pre-heating" of the target rock at Sudbury, we developed a first order calculation of increased melting due to a relatively extreme elevated geothermal gradient of 33.3 °C/km (Warren et al. [1996] proposed 30–40 K/km). Thus, at 15 km, the temperature would be 500 °C, and at 30 km, the temperature would be 1000 °C, near our assumed melting temperature for the target rocks of 1100–1200 °C (e.g., Wyllie 1977). Shock melt is formed when the release adiabat crosses the melting curve upon decompression. At 15 km, a temperature increase of approximately 700 °C is required to melt the rocks, and at greater depths, a lesser increase is required. The temperature increase upon release from 25 GPa is ~500 °C (McQueen et al. 1967). Therefore, we make a simple approximation of the excess melt produced in pre-heated rock by assuming that, in addition to the melt + vapor formed above 50 GPa, all material below 15 km that is shocked to >25 GPa also melts. For the 3 asteroids impacts considered in Table 6, the total (melt + vapor) increases by 25–27%, far short of the 70% increase needed to account for the excess Sudbury melt volume. If this increase in melt volumes is applied to our model shock melt volumes, Sudbury must still have a 110 km diameter transient cavity to accommodate an asteroid impact. These results are for a vertical impact, and since the depth of melting is less in the more likely case of an oblique impact (Pierazzo and Melosh 2000), these percentages are best considered maximum values. Furthermore, the extreme geothermal gradient used in this calculation is also likely a maximum, since several studies suggest that Penokean deformation was waning at the time of impact (e.g., Card et al. 1984; Riller and Schwerdtner 1997; Cowan et al. 1999). Therefore, we conclude that if Sudbury were an asteroid impact, the excessive amount of impact melt cannot be readily explained by the effect of preheating of the target rocks by the Penokean Orogeny.

Another factor related to the geothermal gradient that has been proposed to explain melt rocks at Sudbury is impact-triggered pressure-release melting of deep crustal rock beneath the transient cavity (Dressler and Sharpton 1999; Dressler and Reimold 2001). While this hypothesis has not been rigorously developed, recent impact simulations and field studies do shed light on the importance of the melting in the central uplift. Ivanov and Deutsch (1999) modeled the perturbation of the geothermal gradient due to shock heating and uplift of the deep crustal rock in a Sudbury-size impact. Their model predicts that a central core of rock 5 km in diameter and 40 km deep can be heated to >1200 °C. Presumably, some or most of this rock would melt. Empirical support for such melting is found at the Vredefort impact structure in South Africa, which may be similar in size to Sudbury and Chicxulub or slightly larger (e.g., Grieve and Therriault 2000). Deep erosion of the central uplift at Vredefort exposes a 5 km diameter plug of melt rock with quench textures indicative of rapid cooling (Gibson et al. 2002), which matches well with the Ivanov and Deutsch (1999) calculations for a Sudbury-size impact. Both the impact simulation and the Vredefort field data indicate that the melt rock in the central uplift formed and cooled quickly and, thus, probably did not mix appreciably with the shock melt. Despite this apparent importance of melting in the central uplift (perhaps producing as much as 3000 km^3 of melt), neither our empirical estimates of impact melt nor our model calculations of impact melt include this factor, so the relative amounts of melt at Sudbury and Chicxulub are not affected. Thus, if pressure release melting occurred in the central uplift of Sudbury and Chicxulub, it cannot explain the large discrepancy in melt volumes.

Effects of Volatiles

Most of the excess melt at Sudbury compared to Chicxulub resides in the suevite not the melt sheet. Therefore, it is likely that the differences in melt volumes of the 2 craters is in some way linked to suevite formation. Kieffer and Simonds (1980) noted that craters formed in targets with a significant amount of sediments produced much more suevite than craters with little or no sedimentary cover. They proposed that this difference was caused by the dispersal of impact melt when the volatiles (e.g., CO_2, SO_2, H_2O) that were initially incorporated in the melt effectively exploded, blowing the melt into the air where it mixed with solid ejecta and fell back as suevite. Therefore, another factor to consider when comparing Sudbury and Chicxulub is the differences in the volatile content of the target rock. Both locales probably had a shallow sea overlying the rocks (e.g., Pope et al. [1997] for Chicxulub; Peredery and Morrison [1984] for Sudbury), but we do not believe this was a major factor in melt production. Chicxulub had an upper layer of porous, water saturated sedimentary rock, ~2.5–3 km thick, composed of about 56% carbonate, 30% sulfate, and 14% water (Pope et al. 1997). Sudbury had as much as ~5–12 km of sedimentary and volcanic rocks (Card et al. 1977, 1984; Dressler 1984), which were partially metamorphosed (thus, probably non-porous), and a thin veneer of carbonaceous argillites found as lithic fragments in the upper 1 km of suevite (Ames 1999). In general, these rocks probably contained little water, perhaps ≤1%. Both impacts had granitic crust below the sedimentary cover. The depth of melting for our asteroid and comet impact scenarios was sufficiently shallow (~30 km) to incorporate significant amounts of the sedimentary cover in the shock melt, although, clearly, most of the melt came from the crystalline basement at both craters.

The sedimentary cover at Sudbury was not as volatile-rich as the one at Chicxulub, and thus, the dispersal of melt may not have been as great. Chicxulub suevite with 10–30% melt (Albion formation) is found hundreds of km from the crater in Belize (Ocampo et al. 1996; Pope et al. 1999, 2000), which may reflect the dispersal by volatiles in the target rock. Perhaps the large amount of suevite inside Sudbury reflects the fact that there were insufficient volatiles to blow much melt out of the crater. If this were true, then we have overestimated the amount of melt at Sudbury since our ejected melt estimates are based on scaling from Chicxulub. Such a scenario is unlikely to be a major factor, however, because our estimates of the amount of melt ejected at Chicxulub and Sudbury (24.3%, excluding vapor) are not excessive and are in line with most theoretical estimates. Furthermore, we know of no impact simulations where a significant amount of melt is not ejected. The greater thickness of sediments at Sudbury cannot readily explain the difference in suevite because these sediments were likely much drier than at Chicxulub.

We propose that the larger amount of suevite at Sudbury may be related to the same factor we propose is responsible for the larger amount of melt—a comet impact. The cometary water volume in our impact calculations (~700–1,000 km^3, assuming a comet volume of 50% ice) greatly exceeds the volume of target water (~200 km^3) vaporized in the Chicxulub impact, and in fact, the comet water mass equals or exceeds the total volatile mass (CO_2, SO_2, H_2O) released by a Chicxulub asteroid impact (Pope et al. 1997; Pierazzo and Melosh 1999). Thus, the larger amount of suevite at Sudbury is compatible with a massive dispersal of shock melt by cometary volatiles.

CONCLUSIONS

Analyses of geological and geophysical data from the Chicxulub and Sudbury impact structures indicate that they had similar transient cavity diameters, and have a similar final crater structure. These similarities in size and structure, when coupled with observations of impact melt at the 2 craters, suggest that Sudbury has about 70% more impact melt than Chicxulub, and 85% more shock melt. This greater amount of melt is readily, but perhaps not uniquely, explained with an analytical model where Chicxulub was formed by an asteroid impact and Sudbury by a comet impact. The difference in melt volumes can be explained by differences in crater size only if the extremes in the possible range of impact parameters are invoked. Most of the excess melt at Sudbury resides in the suevite, and this greater amount of suevite at Sudbury compared to Chicxulub may be due to the dispersal of shock melt by cometary volatiles.

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APPENDIX: REVISION OF THE KIEFFER AND SIMONDS (1980) EQUATION FOR CALCULATION OF MELT VOLUMES

Melosh (1989, p. 64–66) pointed out that the Gault-Heitowit (1963) model embedded in the Kieffer and Simonds (1980) model produced an overly rapid pressure attenuation. He attributed the problem to 2 assumptions: 1) that the initial energy was assumed to be deposited in an expanding hemisphere at the site of energy deposition; and 2) that the waste heat is probably overestimated by the assumptions about the Hugoniot and release adiabat. Kieffer and Simonds (1980) used a sphere, instead of a hemisphere, for energy deposition, but this does not solve the problem pointed out by Melosh. In either an expanding sphere or hemisphere, the attenuation varies with r^3, which gives the overly steep attenuation of the earlier models.

Melosh pointed out that computer simulations were showing—and still show—that the initial energy of the meteorite is deposited in an expanding shell of finite thickness rather than a hemisphere or a sphere. The energy decay rate in an expanding shell depends only on r^2 instead of r^3, and thus, the overly steep attenuation in the earlier models is avoided. We incorporate this revision of assumptions below.

Modifying the Gault and Heitowitz (1963) formulation, we assume that the expanding total energy is reduced by the waste heat in an expanding spherical shell (this formulation is explained in greater detail in Kieffer and Simonds [1980] and is not repeated here. In this reformulation, the thickness of the expanding shell occurs on both sides of an equation for energy (Equations 28 and 32 in Kieffer and Simonds [1980]), and so the thickness of the shell does not need to be specified. Pressure decay with radial distance from the crater is calculated from Hugoniot and release adiabat properties, with the assumption that, for non-porous and non-volatile rocks, the Hugoniot is an adequate approximation to the release adiabat. Volumes inside specified isobars are calculated to obtain volumes of vapor + melt. In cases where the hemisphere defined by the isobars extends above the original target surface, the segment above the target surface is subtracted from the total volume (following standard procedure; e.g., Pierazzo et al. 1997).

All steps in Kieffer and Simonds (1980) can then be reproduced with the final result that the non-dimensional pressure decay versus non-dimensional distance is:

$$dX/dR = \{-3X + 3X(Xn + 1)^{-1/n} + 4/n - (4n)(Xn + 1)^{-1/n} + 2/[n(1 - n)][-1 + (Xn + 1)^{1 - 1/n}]\} * \{R[1 - (nX + 1)^{-1/n} + X(nX + 1)^{-1 - (1/n)}]\}^{-1}$$

where $X = P/K_0$, $R = r/R_0$, P is pressure, r is radial distance from the center of energy deposition, R_0 is the radius of the initial volume of energy deposition, K_0 is the bulk modulus, and n is the bulk modulus derivative of the target material. The form of this equation is the same as in Kieffer and Simonds (1980, Equation 34) with changes only in the coefficients.

Other parts of the Kieffer and Simonds (1980) model were either kept identical as described or slightly modified as noted here. Peak pressures are calculated from one-dimensional calculations of peak shock pressures for given impact conditions, (confirmed as a valid approximation by Melosh [1989, p. 63] and Pierazzo et al. [1997, p. 415]).

A depth of penetration as calculated by Kieffer and Simonds (1980) is taken as the center of energy deposition. This represents an oversimplification of a complex, time-dependent process that this analytic model cannot resolve. The detailed computer simulations show that the energy deposition starts with formation of an isobaric core, somewhat similar to the concept of a volume of initial energy deposition used by Gault and Heitowit (1963) and Kieffer and Simonds (1980). The depth to the isobaric core, and its radius, are functions of velocity. The Kieffer and Simonds (1980) model results tend to give a penetration depth somewhat greater than calculated depths to the isobaric core of the computer simulations. However, the computer simulations show that, as the energy is propagated out in an expanding shell, the isobars do not remain centered on the isobaric core when, for example, melting conditions are obtained (for example, see Pierazzo et al. [1997, Fig. 7]). The spheres are centered at depths as great as several km deeper than the isobaric core. The depth of penetration calculated by Kieffer and Simonds (1980) gives a reasonable center for the expanding isobars, and so the original approximation is kept here.

The only other parameter changed in this revision is the ratio of the radius of the sphere of energy deposition to the radius of the meteorite. In the original Kieffer and Simonds (1980) work, this ratio varied from 1–1.2 for relatively similar projectile/target properties to 1.9 for very different materials (iron impacting ice, for example; Tables 2a, 2b, and 2c in Kieffer and Simonds [1980]), and the parameter did not show a velocity dependence. Examination of the calculations of the ratio of the isobaric core to the meteorite radius may vary from less than 1 to greater than 1 for identical materials (Pierazzo et al. 1997, Fig. 8) but clusters around 1 for the velocity range of interest. No work is available to see how this ratio varies for impacts of non-identical projectile and target compositions, but clearly, there is a lot of scatter in the values from the computer simulations. Thus, to simplify the model, we have set this value to 1 for all simulations. The absolute volumes of melt can change by as much as a factor of 2 if this ratio is increased to, for example, 1.2, but the calibration discussed below suggests that the arbitrary value of 1.0 gives excellent results. A parametric study of this dependence should be included if more sophisticated analytical models along this line are developed.

To test this revised model, we compare impacts of dunite projectiles into dunite targets with computer simulations of shock melt volumes (Pierazzo et al. 1997, their Table VI, p. 420). To directly compare results of this revised Kieffer-Simonds model with the Pierazzo et al. (1997) results, it is first necessary to find comparable equation-of-state parameters. Pierazzo et al. (1997) used an ANEOS equation-of-state, while Kieffer and Simonds (1980) used a Birch-Murnaghan equation of state (to allow the analytical formulation). Pierazzo (2001, private communication) provided the equivalent parameters to compare the ANEOS equation-of-state to the Birch-Murnaghan equation-of-state. The parameters ρ (density), c (a constant), s (the slope of the averaged shock-velocity particle-velocity curves), K_0 (the effective bulk modulus), and n (the bulk modulus pressure derivative) are:

$\rho = 3.32$ g cm^{-3}
$c = 6.6 \times 10^5$ cm s^{-1}
$s = 0.86$
$K_0 = 1.479 \times 10^{12}$ (dyn cm^{-2})
$n = 4s^{-1} = 2.44$

Specific isobars are chosen in the Kieffer-Simonds model to represent boundaries between conditions of melting or vaporization upon release from those isobars. For the calculation presented here, the 140 GPa isobar was chosen for melting of dunite (approximate mid-point between incipient [135 GPa] and complete [149 GPa] melting; Pierazzo et al. 1997, their Table I). The zone of partial melting is small and, compared to the other uncertainties in comparing the 2 models, should not be a large effect. The volume inside a sphere defined by the 140 GPa isobar minus any cap that is above ground zero is assumed to consist of melt + vapor. This volume is compared with the melt + vapor calculations of Pierazzo et al. (1997), and the good agreement between the results is shown in Table A1.

Table A1. Revised Kieffer-Simonds model (KSM) results compared to Pierazzo et al. (1997) (PVM) results of melt + vapor volume (V_{m+v}) for impact velocities of 20 km/s and 40 km/s.

Projectile diameter (km)	V_{m+v} (km^3) at 20 km/s		V_{m+v} (km^3) at 40 km/s	
	KSM	PVM	KSM	PVM
0.2	0.02	0.02	0.06	0.09
0.5	0.32	0.26	1.09	1.31
1	2.6	2.5	8.8	10.7
2	20.9	19.2	71.5	83.3
3	71	67	242	291
4	168	163	576	698
6	567	583	1,947	2,451
10	2,631	2,935	9,034	10,918