the Vredefort rocks. This methodology enables the maintenance of strict control over the spatial, compositional, and crystallographic relationships of the deformed material. The brown, optically isotropic nature of the pseudotachylite belies an essentially pure silica composition. As has been previously noted [2], minor K-feldspar, aluminosilicate (kyanite?) and primary mica are the significant nonsilica mineral phases. Backscattered electron imaging demonstrates complex relationships among the silica phases. Stishovite replacement by quartz (Fig. 1) often takes the form of tensile veinlets suggesting reconversion during shock wave relaxation. Coesite most commonly occurs as acicular grains and is widely dispersed at a fine scale throughout quartz. Reconverted quartz (Fig. 2) from both presumed melt and polymorphs can be remarkably fine-grained, e.g., ≤200 nm grain diameters. Preservation of crystalline material of such small grain size would appear to preclude significant postformation thermal anneals, or otherwise requires extremely sluggish transformation kinetics.

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FLOOR-FRACTURED CRATER MODELS OF THE SUDBURY STRUCTURE, CANADA. R. W. Wichman and P. H. Schultz, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

Introduction: The Sudbury structure in Ontario, Canada, is one of the oldest and largest impact structures recognized in the geological record [1]. It is also one of the most extensively deformed and volcanically modified impact structures on Earth [2–4]. Although few other terrestrial craters are recognized as volcanically modified, numerous impact craters on the Moon have been volcanically and tectonically modified [5] and provide possible analogs for the observed pattern of modification at Sudbury. In this study, we correlate the pattern of early deformation at Sudbury to fracture patterns in two alternative lunar analogs and then use these analogs both to estimate the initial size of the Sudbury structure and to model the nature of early crater modification at Sudbury.

Structure Descriptions: Two patterns of deformation can be distinguished at Sudbury: (1) an early sequence centered on the Sudbury Igneous Complex [6] and (2) several later episodes of regional deformation that cut basin-controlled features, i.e., are insensitive to the impact structure. The Main Igneous Complex presently defines an elliptical ring about 60 km long and 27 km across. This norite/micropegmatite layered intrusion has a crystallization age of ~1850 Ma, which is commonly assigned to the time of impact [7]. It also feeds an extensive sequence of offset dikes in the surrounding basement rocks radial and concentric to the undeformed structure [6]. The radial dikes are the most evenly distributed and, although disrupted by later deformation, they can extend up to 30 km from the edge of the Main Igneous Complex. The less extensive concentric dikes mostly occur south of the structure where they are typically about 3–10 km from the Main Complex [6]. Lastly, basin-centered concentric lineaments can be identified in satellite images 20–30 km north and west of the structure [8]. Unfortunately, deformation along the Grenville front to the south and at the Wanapitae Impact to the east masks any similar trends elsewhere around the basin.

Similar patterns of crater-centered radial and concentric fractures are observed in lunar floor-fractured craters. Since these patterns appear to be partly controlled by the original impact structures, however, two alternative lunar analogs (i.e., complex craters and two-ring basins) can be identified for the Sudbury dike pattern. The first compares Sudbury to the central peak crater Haldane in Mare Smythii. Haldane is a multiringed structure with an outer rim diameter of 40 km and an uplifted central "floor plate" separated from this rim by a wide (~5 km) moat structure [5,9]. Concentric fractures occur near the edge of the floor plate, in the moat and in a well-defined annulus 9–16 km beyond the crater rim. Radial fractures are typically restricted to the central plate and moat regions, but one set east of the crater extends over 10 km beyond the crater rim in association with additional concentric fracturing. Crater counts indicate that both the crater and the superposed fracture systems formed at nearly the same time, whereas volcanism in Haldane appears to be coeval with other basalt units in Mare Smythii. These volcanic units are primarily located along the outer fracture ring and in the crater moat structure [9].

The alternative analogy compares Sudbury with the lunar two-ring basin Schrodinger. Schrodinger is ~300 km in diameter with a broad interior ring surrounding a central floor region ~100 km in diameter. Roughly concentric fractures occur along the interior ring structure, whereas radial fractures typically extend from the inner ring toward the outer crater wall. Volcanic activity within the basin is limited, but a dark-haloed pit on one of the innermost concentric fractures indicates minor pyroclastic activity.

Comparison: The dike patterns at Sudbury thus can be interpreted in three ways. First, if the Sudbury Igneous Complex marks the location of the crater rim, the radial offset dikes might correspond to the fractures extending beyond the eastern rim of Haldane. The even distribution of these dikes around Sudbury, however, then requires a uniformly tensile regional stress field, which is inconsistent with the onset of the Penokean Orogeny shortly after the impact [10]. Further, since the Igneous Complex probably represents an impact melt unit [11], the edge of this unit is more likely to reflect the edge of the basin floor than the crater rim.

In the second interpretation, the radial offset dikes correspond to radial fractures observed in the Haldane moat. In this case, the concentric dikes and the Sudbury Igneous Complex would mark the edge of an uplifted floor plate, while floor uplift could produce a uniformly tensile stress field within the crater rim [12]. In addition, the absence of an uplifted central peak complex at Sudbury requires detachment of the impact melt from the central peaks during uplift. Although rare, such detachments are observed on the Moon, where a few craters (e.g., Billy, Camoens) show evidence for a "foundered central peak complex" [5,12].

Third, the Sudbury dike pattern also matches the pattern of fracturing in the two-ring basin Schrodinger. The radial offset dikes are identified with the pattern of radial fractures occurring in the outer floor region at Schrodinger, whereas the concentric offset dikes correlate with the inner sequence of concentric fractures along the interior peak ring. Due to the close proximity of the Igneous Complex to the concentric offset dikes, this interpretation suggests that the Sudbury basin may preserve much of the original central impact melt sheet consistent with [11].

Discussion: The comparison of Sudbury to lunar floor-fractured craters thus provides two alternative models for the initial Sudbury structure. Further, the apparent correlation of crater floor fractures to specific elements of the original crater structure allows estimation of crater sizes for these two models. For the Haldane analogy, since radial fractures are confined to the crater interior, the extent of the radial offset dikes from the original basin center indicates a minimum Sudbury diameter of ~100–120 km. If the Sudbury basin contains a down-dropped central peak complex, the size of the Sudbury Igneous Complex then provides a maximum estimate for the crater size. Since strain analyses of deformation in the Sudbury basin indicate original basin dimensions of 60 km by 40 km [3], the basal diameter of the Sudbury central peak structures was probably no more than 35–40 km. Using morphometric relations for unmodified lunar craters [13], these values indicate a maximum crater diameter of ~120–140 km.

Alternatively, the Schrodinger analogy indicates a larger multiring structure. Since radial fractures are confined to the outer crater floor in this model, the extent of the radial offset dikes provides a minimum basin diameter of ~130–140 km (corresponding to a basin floor diameter of ~100–120 km). The maximum size of the original Sudbury Igneous Complex (~55–60 km), however, also can be related to the basin rim diameter. If this value represents the initial size of the central basin floor, the rim crest diameter becomes approximately 170–180 km, which is comparable to the recent estimate of 180–200 km derived from the distribution of preserved shock features around Sudbury [11,14]. Although erosional loss of the Igneous Complex might accommodate an even larger basin structure, the inferred location of the inner basin ring relative to the concentric offset dikes probably precludes any drastic increase in this estimate.

The interpretation of Sudbury as a floor-fractured crater or two-ring basin also provides two alternative models for early crater modification at Sudbury. First, most lunar floor-fractured craters apparently reflect deformation over a crater-centered laccolithic intrusion [5,12]. Since geophysical studies suggest the presence of a tabular ultramafic body beneath Sudbury [15], such an intrusion also may be the cause of deformation at Sudbury. The timing of dike formation at Sudbury, however, limits the potential melt sources of such an intrusion and requires direct interaction of the Sudbury impact with either a contemporaneous orogenic melt or with an orogenic thermal anomaly. Second, isostatic uplift of the basin floor could induce floor fracturing through flexure [16]. In this case, the dike magmas could be derived primarily from the impact melt sheet rather than from a mantle melt, but isotope analyses of the Sudbury ores still suggest a small (10–20%) component of mantle-derived melts [17].

In either case, interaction of the Sudbury impact with the Penokean Orogeny can be inferred. Since both crater-centered intrusions and isostatic relaxation should be favored by enhanced temperature gradients, this is consistent with the higher heat flows and greater volcanism characteristic of orogenic settings. It also may explain why the majority of terrestrial impacts in more cratonic settings show little evidence of floor fracturing. Since high heat flows were apparently common during the early Archean, however, volcanic crater modification may have been more common at this time. Such early impact structures, therefore, may not resemble the more recent impact structures preserved in the terrestrial impact record. Instead, like Sudbury, they may be preserved primarily as complexes of (possibly anomolous) igneous intrusions.

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S82-46 N93-10194 475248

VARIATION IN MULTIRING BASIN STRUCTURES AS A FUNCTION OF IMPACT ANGLE. R. W. Wichman and P. H. Schultz, Department of Geological Sciences, Brown University, Providence RI 02912, USA.

B7720314

Introduction: Previous studies have demonstrated that the impact process in the laboratory varies as a function of impact angle [1–3]. This variation is attributed to changes in energy partitioning and projectile failure during the impact [2,3] and, in simple craters, produces a sequence of progressively smaller and more asymmetric crater forms as impact angle decreases from ~20° [1]. Crater shapes appear to be constant for higher impact angles. Further studies have compared the unique signatures of oblique impacts observed in the laboratory to much larger impacts on the Moon and Mercury [3–5] as well as Venus [6]. At the largest basin scales, the asymmetry of the transient cavity profile for highly oblique impacts results in an asymmetric lithospheric response [7]. Since transient cavity asymmetry should decrease with increasing impact angle, therefore, comparison of large impact basins produced by slightly different impact angles allows calibration of the effects such asymmetries may have on basin formation.

Basin Comparison: Although only Crisium shows a distinctly elongated basin outline, both the Crisium and Orientale basins on the Moon apparently resulted from oblique impacts. Both basins possess an asymmetric basin ejecta pattern (see [8] for a review), and both basins also exhibit features predicted [7] for collapse of an oblique impact cavity: a gravity high offset from the basin center [9–11] and a set of similarly offset basin ring centers [7]. Based on the crater outlines and ejecta distributions in laboratory impact experiments, Crisium probably represents an impact event at ~10–15° off the horizontal [3], whereas the ejecta pattern and more circular basin outline at Orientale more closely resemble laboratory impacts at ~15–25°.

Three primary differences can be identified between the Crisium and Orientale basin structures. First, the Cordillera scarp in Orientale has a relief of ~4–6 km [12], whereas the outer basin scarp at Crisium is poorly defined and has a maximum relief of only ~1–2 km. Second, Orientale shows two distinct massif rings (the inner and outer Rook Montes) separated by a nearly continuous trough structure, whereas the massif ring at Crisium is only disrupted by a medial system of discontinuous troughs [13–15]. The distribution of massif topography is also different. The highest massifs in Orientale are in the Outer Rooks, but the highest massif elevations in Crisium occur in the innermost massifs bounding the central mare. Third, although mare volcanism in both basins has developed along the massif troughs and along the base of the outer basin scarps, such peripheral volcanism appears to be less extensive in Orientale (Lacus Veris, Autumnae) than in Crisium (Lacus Bonitatis, Mare Spumans, Undarum, Anguis).

Despite these differences, both Crisium and Orientale possess a common pattern of basin modification: an innermost steplike rise bounds the central mare; the massif ring(s) are split by a sequence of concentric troughs, and, in both cases, the outer basin scarp is most prominent uprange. Further, the occurrence of peripheral mare