

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 multi-ring 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 anomalous) igneous intrusions.

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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.

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, Autumnnae) 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

volcanism is similar. Although peripheral ponded mare units do occur downrange in Crisium (Mare Spumans, Undarum, Anguis), these units can be correlated with impacts by hypervelocity decapitated projectile fragments from the Crisium impactor [3]. We interpret these fundamental similarities between Crisium and Orientale to be common signatures of basin formation at oblique impact angles, whereas the observed differences are attributed to variations in cavity collapse as a function of impact angle.

Discussion: As discussed by [3,5,6], smaller complex craters (20–100 km) with asymmetric ejecta patterns typically exhibit offset central peaks and more extensive wall slumps uprange, reflecting the distinctive asymmetry of crater profiles for oblique impacts. Similarly, the differences in basin appearance between Crisium and Orientale provide insight into the effects of impact angle on cavity collapse during basin formation. First, the progression from discontinuous concentric troughs in the Crisium massif ring to a split massif ring at Orientale is consistent with increasing failure of the transient cavity rim at higher impact angles. In addition, the outer Crisium scarp is lower than the Cordillera scarp, whereas the inner Crisium massifs are much higher than the inner Rook massifs. These topographic differences also support greater slumping during cavity collapse with increased impact angles. Even the changing expression of the innermost ring structures (from a mare bench ~200 m high in Crisium [16] to a combination of scarps and massifs in Orientale [8]) may reflect such variations in basin collapse, if the relation of rim failure to interior uplift resembles that observed in smaller terrestrial craters [17].

Second, the greater restriction of uprange peripheral volcanism in Orientale also can be related to greater cavity collapse. If reduced cavity collapse indicates reduced cavity equilibration, isostatic uplift after the impact should increase with decreasing impact angle. Since flexural stresses during such uplift are tensile at depth outside the basin region [7], conditions for structurally controlled dike formation will then depend on impact angle. For a given basin size, therefore, basins formed by highly oblique impacts should induce greater flexural stresses than higher-angle impacts; hence, magma columns should be more likely to reach the surface along peripheral basin faults resulting from lower-angle impacts.

Third, the greater prominence of the basin scarps uprange of both Crisium and Orientale may reflect the asymmetry of oblique impact cavities. In the ring tectonic model of basin scarp formation [18,19], the outer scarp reflects lithospheric failure over mantle flow into the collapsing cavity. For an axisymmetric flow field, therefore, the basin scarp should be equally well developed around the basin periphery. The uprange offset in deepest projectile penetration at low impact angles [1], however, should modify the pressure gradients driving mantle flow during cavity collapse. Since both wall slopes and cavity depths are reduced downrange [1], the volume of mantle flow into an oblique transient cavity may be predominantly derived from beneath the basin rim uprange. In addition, since projectile failure should reduce the energy of later (downrange) cavity excavation in an oblique impact, peak shock pressures also should be centered closer to the point of initial contact (uprange); thus shock disruption and acoustic fluidization could be enhanced uprange of the transient cavity.

The observed settings of the peripheral mare units in Crisium and Orientale provide further support for the inferred asymmetry of cavity collapse. Although tectonically controlled mare units consistently develop along uprange scarps in Crisium and Orientale, peripheral volcanism downrange of Crisium apparently requires intersection of the ring fault with an impact structure. This observation suggests that magma column heights are greatest uprange of

Crisium and Orientale, which is consistent with greater scarp failure in these regions. In addition, however, the uprange offset in oblique impacts of the mantle uplift and deepest impactor penetration could produce such an asymmetry by shifting the mantle melt reservoirs uprange and by shifting the center of basin uplift and the associated flexural stress fields.

Conclusions: Variations in impact angle can produce differences in the appearance of multiring impact basins. Comparison of Orientale to the more oblique impact structure at Crisium also suggests that these differences primarily reflect the degree of cavity collapse. The relative changes in massif ring topography, basin scarp relief, and the distribution of peripheral mare units are consistent with a reduction in degree of cavity collapse with decreasing impact angle. The prominent uprange basin scarps and the restriction of tectonically derived peripheral mare units along uprange ring structures also may indicate an uprange enhancement of failure during cavity collapse. Finally, although basin ring faults appear to be preferred pathways for mare volcanism [16,20–22], fault-controlled peripheral mare volcanism occurs most readily uprange of an oblique impact; elsewhere such volcanism apparently requires superposition of an impact structure on the ring fault.

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SELF-ORGANIZED ROCK TEXTURES AND MULTIRING STRUCTURE IN THE DUOLUN CRATER. Wu Siben and Zhang Jiayun, Institute of Mineral Deposits, Chinese Academy of Geological Science, Beijing 100037, China.

The Duolun impact crater is a multiring basin located 200 km north of Beijing [1,2]. From the center to the edge of the crater there are innermost rim, inner ring, outer rim, and outermost ring. The 5-km-diameter raised innermost rim, 80 to 150 m above the surrounding plain, is located in the cratering center and consists of volcanic rock (andesite, etc.). The prominent 70-km-diameter ring, which is encircled by the Luan river, the Shandian river, and their tributaries, is a peripheral trough now occupied by the Lower Cretaceous coal-bearing formation, etc. The 82-km-diameter outer rim, 200 to 250 m above the plain, consists of Archean metamorphic rocks