
**Introduction:** Laboratory cratering experiments have shown that the size, shape and profile of an excavated simple crater change with impact angle [1]. Since these changes reflect fundamental changes in the impact process [1,2,3], comparable changes in shape and profile should occur for transient cavities in larger basin-forming impacts. Although such changes in transient cavity shape are obscured by cavity collapse, the asymmetric profile of an oblique impact cavity can produce recognizable features in the final basin structure. Further, the effect of basin structures and topography on later volcanism also may change the distribution and character of basin-centered volcanism with impact angle.

The lunar Crisium basin can be used to illustrate the effects of an oblique crater profile on cavity collapse structures and subsequent volcanism in a multi-ring basin. The Crisium basin (figure) is perhaps the best example of a well preserved, low angle impact basin on the Moon [3,4]. The elliptical massif ring and the asymmetric pattern of basin ejecta (not shown) are comparable to features in smaller oblique impacts [4] and the broad mare shell breaching the eastern massifs is consistent with models of projectile failure at low impact angles [2,3]. In addition to these signatures of an oblique impact, however, Crisium differs in appearance from other mare basins on the Moon. The broad, plateau-like massifs are much more prominent than similar features elsewhere [5,6], whereas the outermost basin (Cordillera-equivalent) scarp is poorly developed [4]. These differences may reflect changes in the degree and character of basin collapse as a function of impact angle.

**Cavity Collapse:** Decreasing laboratory impact angles below ~30° changes the final profile of simple craters in sand in two ways [1]: 1) cavity volume decreases relative to projectile size and 2) the cavity nadir moves progressively uprange of the cavity center. At very low angles (<15°), a broad shallow shelf develops in the downrange crater wall as well [1,3]. If similar transient cavity profiles occur at basin scales, cavity asymmetry should shift the mantle uplift beneath a basin uprange of the cavity center. The resulting mascons and gravity anomalies will be similarly offset. Further, if ring scarps formation reflects lithospheric failure over mantle flow into this uplift [7,8,9], the ring scarps also could reflect the offset mantle uplift. For an axisymmetric mantle flow field, these scarps presumably would be centered on the mantle uplift.

Such offset basin structures can be clearly identified at Crisium. Regional gravity data show a pronounced gravity high over western Crisium [10,11] and gravity models indicate a mantle uplift centered on ~17N, 58E [12,13]. In contrast, the average mare center (presumed to reflect the basin center) lies at ~17N, 59E. The centers of the basin ring pattern are also offset from this basin center. The innermost basin ring corresponds closely in size and center to the modeled mantle uplift, whereas the highest basin massifs and the outermost basin scarp are both centered ~20 km west of the average mare center. Only the oblong massif ring as a whole seems centered on the mare.

The reduced cavity volume relative to projectile size in an oblique impact also may affect cavity collapse. Excavation cavities decrease in volume as the vertical component of impact velocity [1]; consequently, an oblique impact requires a larger impactor than a basin of the same size formed at a near-vertical impact angle. Conversely, since a near-vertical basin is deeper/bigger for a given impactor, it may produce more lithospheric failure. Although the precise size relation of Crisium to its impactor is unclear, the Crisium structure is consistent with limited cavity collapse. Not only is the outer basin scarp poorly developed, but its diameter is unusually large relative to the massif ring when compared to other lunar basins. This combination suggests that collapse of the transient rim was less extensive at Crisium than in higher angle impacts, possibly accounting for the prominence and breadth of the Crisium massifs as well. Since Crisium is comparable in size to other mare basins, however, limited cavity collapse cannot represent an effect of impact angle on the Crisium cavity size. Rather it may reflect the reduced peak shock pressures of an oblique impact [2] and a consequent reduction in either the extent of lithospheric disruption or the duration of acoustic fluidization around the impact. Alternatively, cavity asymmetry may modify the conditions of basin collapse, precluding the classical assumption of symmetrical failure and subsidence along the transient cavity rim.

**Mare Volcanism:** The history of basin volcanism at Crisium provides further constraints on the initial basin structure. Although Mare Crisium contains a thick sequence of chemically distinct basalt units [14], a number of thinner peripheral mare units also occur at higher elevations along the massif ring [14] and outer basin scarp (figure). These peripheral units can be correlated with early basalts in Mare Crisium [14,15], but only the oldest basalts occur at all elevations. Later basalt units appear to be confined to progressively lower elevations closer to the central basin. This progression suggests a transition from early, structurally controlled volcanism to later, topographically controlled volcanism. The range in early
Lithospheric Failure and Basin Volcanism in Crisium: Wichman, R.W. and Schultz, P.H.

Mare elevations further suggest that magmatic conditions initially varied with location in the basin. Hydrostatic magma column models indicate an initial hydrostatic efficiency in the peripheral mare ~4% greater than in the central mare. This variation may partially reflect a contrast in conduit tortuosity between peripheral fault zones and a central breccia. The progressive restriction of volcanism into the basin interior, however, then requires decreasing flow efficiencies in the peripheral conduits over time.

Although the evolution of volcanism at Crisium could reflect changing magma sources beneath the basin, these changes also can be related to changing basin-centered stress fields. If limited cavity collapse at Crisium produced a relatively deep central basin, isostatic equilibration would induce flexural uplift around the basin with extensional stresses along the base of the lithosphere outside the central basin region. Such stresses give mantle melts access to both the peripheral basin faults and the central basin and favor magma escape from the mantle. As mare basalts fill the central basin, however, the mare load counteracts the mass deficit of the basin, reducing the peripheral tensile stresses and associated volcanism. Regional compression due to planetary cooling could also reduce these stresses. Eventually, development of a super-isostatic mare load reverses the initial stress patterns and concentrates volcanism around the central mare load as proposed by 16,17.

This model accounts for two other aspects of the volcanic record at Crisium. First, the role of mare emplacement in equilibrating the central cavity can explain why Mare Crisium, despite its thickness, has no associated load-induced fractures. Second, the inferred stress fields may be consistent with the chemistry of the mare basalts. From lunar spectra, the initial basalts are moderately titaniferous and Mg-rich [14,18], whereas later basalts sampled by Luna 24 are Ti-poor and Fe-rich [14]. If the early melts escaped rapidly from the mantle, they probably represent smaller equilibrium melt fractions and would be enriched in melt-compatible elements like Ti. Later, as tensile stresses decayed, magma escape rates would diminish. This should lead to 1) larger equilibrium melt fractions in the depleted melt source and 2) concentration of melt near the base of the crust where melt equilibration and fractionation could produce the observed Fe-enrichments [19, 20].

Implications: Both the basin structures and volcanic record at Crisium thus indicate two effects of oblique angle impacts on multi-ring basin formation. First, the asymmetry of an oblique impact cavity concentrates cavity collapse uprange of the basin center. Second, cavity collapse in oblique multi-ring basins may be less extensive than in near-vertical impact basins of the same size. Consequently, the variation between mare basins on the Moon in both basin appearance and distribution of volcanism may reflect variations in both the respective impact angles and in post-impact modification. Although ring scar formation is limited to large impact events, cavity collapse in smaller impacts may show similar effects. In particular, the shifting center of collapse may explain both enhanced uprange wall failure in large craters and circularization of scarp-bounded oblique multi-ring basins on Venus [21,22].

Figure 1. Sketch map of the Crisium basin showing distribution of volcanism relative to massif ring and outer scarp. Stars indicate floor-fractured craters.