**AN INCONVENIENT VIEW: INTERPRETING HOW SHOCK-INDUCED FRACTURES INFLUENCE IMPACT CRATER DEVELOPMENT.** Michael R. Dence, 824 Nesbitt Place, Ottawa, K2C 0K1, Canada, mrdence@magma.ca

**Introduction:** One of the most interesting outcomes of the first Bridging the Gap workshop was the renewed attention given to the role of fractures in crater development. It was realized early in the study of hypervelocity impact craters that, like omelets, making craters in strong materials requires breakage. Indeed using gravity surveys to measure the volume fractured gave one way of estimating the energy of an impact [1]. However, relatively little attention has since been given to the role fractures play in crater formation as analysis concentrated on shock melting and metamorphism and other manifestations of the early compression phase of impact events. By comparison, fractures are inconveniently difficult to observe and to quantify as a means of gaining insight into the subsequent stages of the crater-forming process.

A critical ingredient has now been provided through the experimental investigation of dynamic tensile fracturing and fragmentation by Ai and Ahrens [2], who measured shock pressures at standard temperature and pressure for the onset of fracturing and for complete fragmentation (brecciation) of two strong crystalline rocks and Coconino sandstone. Their results complement observations [3, 4] that indicate that in crystalline rocks the limit of fragmentation down the axis of natural craters occurs at much higher shock pressures than in the laboratory. Furthermore, from [3], shock pressure at the fragmentation limit (P in GPa) increases regularly with increasing crater size (D in km) as $P = 3.5\ D^{0.5}$. Putting these results together suggests that in strong materials crater size is controlled by dynamic fracturing. This in turn is limited by the intrinsic dynamic tensile strength of the target modulated by the confining pressure of the overburden as the transient cavity grows.

**Differences between craters formed in crystalline and sedimentary rock targets**: About a third of known terrestrial impact craters are formed in crystalline rocks, the rest entirely in sedimentary rocks or where a thick sequence of sediments overlies a crystalline basement. Crystalline rocks in general are relatively homogeneous whereas sedimentary rocks are commonly heterogeneous, weaker and more porous, with consequent effects on the rapidity of shock pressure attenuation [5], the partition of energy and limits of fragmentation.

Moreover, crystalline rock craters on Earth exhibit a relatively gradual change in form with increasing size from simple through central peak to peak-ring forms, as seen in craters on other rocky planets. This argues for a general similarity in crater mechanics with differences largely due to the effects of gravity. On the other hand, in sedimentary rocks there is an abrupt change from simple crater form exemplified by Barringer crater (1.2km) to a pronounced central peak form as seen in Steinheim and Flynn Creek, each about 3.5km across. Sedimentary rock craters are rarely more than 150m deep while those formed in crystalline rocks may exceed depths of 400-600m. In addition, in complex craters formed in crystalline rocks, the ratio of the amount of uplift to the final crater diameter as estimated from shock metamorphism data is about 1:5 whereas for most craters formed in sedimentary rocks the ratio is 1:8 to 1:10. Such differences argue for the dominant role of a different mechanism in sedimentary than in crystalline rocks an obvious candidate being movement on planes separating strata of contrasting physical properties.

**Observations of Fractures in Natural Craters:** The relative homogeneity of crystalline rocks makes them the preferred venue for the analysis of the role of fractures in impact crater formation. Beyond the near-field region where high shock pressures result in total melting, rocks that show the standard effects of shock metamorphism bear little evidence of shear deformation. The subsequent release from compression, on the other hand, produces several sets of tensile fractures, best seen in simple craters. These include closely spaced, sub-horizontal fractures and steeply inclined circular fractures. Widely spaced radial fractures may also exist. The remarkable regularity of these fractures in plan and cross-section indicates that the stress field generated by the impact completely dominates the pattern of deformation. Crater structure is generally not strongly influenced by anisotropy of composition or fabric in the target rocks or obliquity of impact except in the far field and in the distribution of ejecta.

*Sub-horizontal fractures:* These are most clearly observed at the crest of the rim, as exposed at the New Quebec/Pingualuit (3.2km) crater. There they resemble sheet jointing fractures spaced a few centimeters apart that cut the regional gneissosity at high angles. They were apparently sub-horizontal when formed then subsequently tilted during uplift of the rim. The resulting bilaterally symmetric pattern [6] suggests, by analogy with experiments, oblique impact from the southeast. Fractures of this type are inferred to have formed down axis as the initial shock wave was reflected from the trailing edge of the impactor and the free surface. As the transient crater developed they produced fragmentation with the formation of breccia to the limit dictated by the dynamic tensile strength of the target rocks and the confining pressure.

*Spheroidal fractures:* Drilling at the 3.8km Brent crater has shown that the breccias within this simple crater are bounded by a fracture zone that is circular in plan and conforms to a spherical segment in cross-section [3,4]. It is steeply inclined at the original surface and curves inwards towards the crater center at the base of the breccia lens. Near surface it is expressed as the boundary between breccias filling the crater and the fractured crater wall. At depth it changes into a shear along which sheets of weakly shocked and fractured gneiss from the crater walls slid towards the center. A possible sequence of events is that it was initiated as one of a set of circular tensional fractures generated by release of the initial shock pressure. The excavation of the transient cavity consumes the innermost fractures of the set until the cavity attains its maximum dimensions. The remaining fractures continue to propagate in response to the changing stress field around the cavity. The resulting spheroidal shears allow the cavity walls to slump towards the center of the crater.

*Radial fractures:* Although radial fractures are generally expected around an impact site there is little direct evidence that they exist. Weak depressions in the rim of the New Quebec crater may be underlain by radial fractures spaced at ~10-15° intervals, that appear not to extend to any great depth or have much influence on the subsequent development of the crater.

**Late stage influence of fractures:** In simple craters the final crater form would seem to arise from the relative timing of the growth of sub-horizontal and spheroidal fracture systems. Where the spheroidal fractures reach the toe of the crater floor before there is significant upward expansion of the floor of the transient cavity a simple crater results. Any tendency for the center to rise is suppressed by the weight of the thick lens of breccia cascading from the crater walls. The timing is different in larger craters. Expansion of the floor exceeds the rate of propagation of the primary spheroidal shear planes and their point of convergence occurs below the crater floor. As a result the segment above the converging shears is carried upwards to form a central peak and a complex crater is formed. In crystalline rock craters of intermediate size (4 to ~30 km final diameter) the rocks of the central peak are strongly fractured as they converge in the center. In the largest complex craters, this secondary fracturing is dominant towards the margins and the rocks of the central peak are preserved as large blocks with little internal deformation that moved on widely spaced zones of intense shearing lubricated by friction melts.

In craters formed in sedimentary rocks the presence of pre-existing sub-horizontal bedding planes allows movement to take place with relatively limited formation of new fractures. Thus collapse occurs rapidly and relatively completely once a critical size is attained.

**Final remarks:** To integrate the role of fractures into impact crater models more information on relevant physical properties is needed. This includes a more extensive database of the dynamic tensile strength and related properties of common rocks. In addition, data on the rate of formation and propagation of dynamic fractures is required as well as on the rate at which rocks expand after release from shock compression.

***References:***

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