WHAT CAN WE LEARN ABOUT IMPACT MECHANICS FROM LARGE CRATERS ON VENUS? William B. McKinnon and J. S. Alexopoulos, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis MO 63130, USA.

More than 50 unequivocal peak-ring craters and multiringed impact basins have been identified on Venus from Earth-based Arecibo, Venera 15/16, and Magellan radar images. These ringed craters are relatively pristine, and so serve as an important new dataset that will further understanding of the structural and rheological properties of the venusian surface and of impact mechanics in general. They are also the most direct analogues for craters formed on the Earth in Phanerozoic time [1].

The inner rings and crater rims of venusian peak-ring craters (or basins) are morphologically similar to inner rings and crater rims, respectively, of peak-ring craters on the Moon, Mars, and Mercury. As is observed for mercurian ringed basins, ring diameter ratios decrease from ≥ 3.5 to 2 (or less) with increasing crater diameter. On Venus, the transition from central-peak crater to peak-ring crater is well defined at around 40 km diameter. Decreasing ring diameter ratios with increasing peak-ring crater diameter are consistent with a hydrodynamic origin for peak rings, i.e., collapse and expansion of the uplifted central peak. The large but finite ring ratios at the transition and, on other terrestrial planets, the simultaneous presence of central peaks and rings in many of these transitional structures imply that central rings rise from the collapsing shoulders of central peaks, i.e., that they are a wave-breaking phenomena in oversteepened and unstable central peaks (cf. photographs in [2]). The viscosities of fluidized crater material implied by central-peak to peak-ring transition diameters on the terrestrial planets are more or less proportional to crater diameter, D, indicating that the scale dependence of viscosity, η, may dominate gravity in the formation of peak-ring craters. This approximately linear dependence, $\eta \approx 9$ (D/km) GPa-s, is compatible with fluidization by strong acoustic or seismic vibrations. It implies a nearly constant ratio $\lambda_d/D \approx 1/80$ to 1/20, where λ_d is the dominant wavelength of the acoustic field, depending on the sound speed in agitated rubble adopted (0.5–2 km/s). In terms of scaling, the originally generated λ/D spectrum may be expected to be roughly invariant with respect to final crater size. For lower sound speeds, the dominant wavelength λ_d could be a large fraction of the crater depth, which may imply leakage of lower frequencies and damping of higher ones [3]. Impactor diameter and λ_d would also be comparable for the lower sound speed above, given presently accepted crater scaling relations.

Important interplanetary differences remain; martian crust in particular appears to be more easily fluidized by impact. We also do not consider the shock melt hypothesis of [4] here, but note that the increasing amount of melt compared to ejected mass in larger structures might be expected to result in decreasing effective viscosity with size. The interiors of most of the peak-ring craters appear generally smooth (similar to the surrounding plains), as evidenced by the radar-dark returns in Arecibo and Magellan images. This may be attributed to the presence of impact melt deposits or to postimpact volcanism. The increasing incidence of bright floors among the youngest craters (i.e., those with dark parabolic deposits [5]) suggests that volcanism may be the more correct choice, but postimpact differentiation and eruption from a large melt sheet should also be considered.

Of the four largest ringed structures identified on Venus so far, Klenova (144 km diameter), Lise Meitner (148 km), and Mead (270 km) exhibit what we interpret to be major asymmetric inner (intermediate for Klenova) and outer mountain rings, possibly representing fault scarps similar to the Outer Rook and, especially, the Cordillera ring of Orientale, respectively. Furthermore, Klenova exhibits an inner peak ring analogous to Orientale's Inner Rook, whereas Meitner exhibits a possible additional, exterior, scarplike partial or transitional ring. A recent Magellan image of Meitner does not equivocally show this outer segment as a scarp, but the radar geometry was poor for determining this. Mead exhibits no inner peak ring, but may be the structurally clearest example of "mega-terrace" collapse yet observed on the terrestrial planets. Adjacent ring diameter ratios for the three multiringed basins range from ~1.6 between the most prominent rings of Klenova and Meitner to ~1.4 for Klenova's peak ring, Meitner's partial ring, and Mead. These ratios are similar to those observed for Orientale and other lunar multiringed basins. Thus we interpret all three venusian structures to represent Orientale-type multiringed impact basins. Isabella (~170 km diameter) is also a ringed basin, but it is severely volcanically flooded; much of the intermediate ring and all of the inner ring are defined by isolated but concentrically arranged massifs.

Although multiringed basins on Venus occur at much smaller diameters than on the other terrestrial planets (except perhaps the Earth), effective viscosities are low enough at depth to allow inward asthenospheric flow, which in the model of [6] can cause radial extensional stress and circumferential faulting in the overlying lithosphere, block rotation, and ring formation. The differing rheologies of Venus crust and mantle may play a role in the creation of Cordilleran-style ring faulting. The large differential stresses associated with the deep transient crater precursors to Klenova, Meitner, and Mead are sufficient to have driven solid-state power-law flow of venusian upper mantle rock at low effective viscosity (not only low enough to define an asthenosphere on the collapse timescale, but a lower viscosity than that of overlying shock-fluidized lithosphere). For the two smaller multiringed basins, sufficiently low viscosities may have only been possible if accessible mantle temperatures were close to or at the peridotite solidus. This is not geologically implausible, as the abundant widespread basaltic volcanism on Venus implies that its mantle temperature profiles exceed the solidus at numerous locations and the asthenosphere may in fact be defined by pressure-release partial melting, but alternative possibilities include enhanced flow rates in mantle rocks due to plasticity or viscous flow in a weaker crustal asthenosphere. Analogous arguments can be made with respect to multiple ring formation on the Moon. Effective viscosity estimates imply that ring tectonics on the terrestrial planets may in fact work most readily within a sufficiently thick, soft crustal layer.

Finite-element simulations of basin collapse and ring formation along the lines of [7] were undertaken in collaboration with V. J. Hillgren (University of Arizona). These calculations, summarized in [1], used an axisymmetric version of the viscoelastic finite element code TECTON, modeled structures on the scale of Klenova or Meitner, and demonstrated two major points. First, viscous flow and ring formation are possible on the timescale of crater collapse for the sizes of multiringed basins seen on Venus and heat flows appropriate to the planet. Second, an elastic lithosphere overlying a Newtonian viscous asthenosphere results mainly in uplift beneath the crater. Inward asthenospheric flow mainly occurs at deeper levels. Lithospheric response is dominantly vertical and flexural. Tensional stress maxima occur and ring formation by normal faulting is predicted in some cases, but these predicted rings occur too far out to explain observed ring spacings on Venus (or on the Moon). Similar distant tensional stress maxima were reported by

[7], who found that in order to generate a ring fault at a distance of ~1.4 crater radii, it was necessary to restrict asthenospheric flow to a channel at depth, one overlying a stiffer mesosphere. It is tempting to assign this asthenospheric channel to a ductile lower crust, as discussed above. Alternatively, an effectively stiffer mesosphere may be a natural consequence of truly non-Newtonian rebound. Much work remains to be done on this problem.

Overall, these estimates and models suggest that multiringed basin formation is indeed possible at the scales observed on Venus. Furthermore, due to the strong inverse dependence of solid-state viscosity on stress, the absence of Cordilleran-style ring faulting in craters smaller than Meitner or Klenova makes sense. The (1) apparent increase in viscosity of shock-fluidized rock with crater diameter, (2) greater interior temperatures accessed by larger, deeper craters, and (3) decreased non-Newtonian viscosity associated with larger craters may conspire to make the transition with diameter from peak-ring crater to Orientale-type multiringed basin rather abrupt.

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SUDBURY PROJECT (UNIVERSITY OF MÜNSTER–ONTARIO GEOLOGICAL SURVEY): (5) NEW INVESTIGATIONS ON SUDBURY BRECCIA. V. Müller-Mohr, Institute of Planetology, University of Münster, Wilhelm-Klemm-Str. 10, W-4400 Münster, Germany.

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Sudbury breccias occur as discordant dike breccias within the footwall rocks of the Sudbury structure, which is regarded as the possible remnant of a multiring basin [1]. Exposures of Sudbury breccias in the North Range are known up to a radial distance of 60–80 km from the Sudbury Igneous Complex (SIC). The breccias appear more frequent within a zone of 10 km adjacent to the SIC and a further zone located about 20–33 km north of the structure.

From differences in the structure of the breccias, as for example the size of the breccia dikes, contact relationships between breccia and country rock as well as between different breccia dikes, fragment content, and fabric of the ground mass, as seen in thin section, the Sudbury Breccias have been classified into four different types.

A. Early breccias with a clastic/crystalline matrix comprise small dikes ranging in size from ~1 cm to max. 20 cm. Characteristic features of these breccias are sharp contacts to country rock, low fragment content (20–30%), local origin of fragments, and an aphanitic, homogenous matrix, which can be related to country rock. Locally corrosional contacts to feldspar minerals and small vesicles filled with secondary minerals are observed.

B. Polymict breccias with a clastic matrix represent the most common type of Sudbury breccia. The thickness of the dikes varies from several tens of centimeters to a few meters but can also extend to more than 100 m in the case of the largest known breccia dike. Contacts with country rock are sharp or gradational. Fragment content (60–75%) is usually of local origin but especially in large dikes allochthonous fragments have been observed. Inclusions of type A breccias reveal the later formation of this type of breccia. The heterogenous matrix consisting of a fine-grained rock flour displays nonoriented textures as well as extreme flow lines. Chemical analysis substantiates at least some mixing with allochthonous material.

C. Breccias with a crystalline matrix are a subordinate type of Sudbury breccia. According to petrographical and chemical differences, three subtypes have been separated. The local origin of the fragments and the close chemical relationship to the country rock point to an autochthonous generation probably through *in situ* frictional processes. For two subtypes the geometry of the dikes and the texture of the matrix indicates that at least some transport of breccia material has occurred. Breccias with a crystalline matrix have never been observed in contact with the other types of breccias.

D. Late breccias with a clastic matrix are believed to represent the latest phase of brecciation. Two subtypes have been distinguished due to differences in the fragment content. Breccias with a low fragment content show a weak lamination and sharp or gradational contacts to country rock. Inclusions of type A breccias are observed. Breccias with a high fragment content are characterized by gradational contacts and are only known from the outermost parts of the structure. Fragments of these breccias are of local origin. A possible correlation of the relative timescale of breccia formation with the phases of crater formation will be discussed.

Shock deformation features, which have been recorded within breccia fragments up to a radial distance of 9 km from the SIC, represent the shock stage I of the basement rocks. Inclusions exhibiting a higher shock stage, such as melt particles or suevitic fragments, which are known from dike breccias of, e.g., the Carswell impact structure, are lacking. This means that the dike breccias of Sudbury as presently exposed are from a deeper level of the subcrater basement than their counterparts of Carswell.

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A HISTORY OF THE LONAR CRATER, INDIA—AN OVERVIEW. V. K. Nayak, Department of Applied Geology, Indian School of Mines, Dhanbad, India.

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The origin of the circular structure at Lonar, India (19°58'N:76°31'E), described variously as cauldron, pit, hollow, depression, and crater, has been a controversial subject since the early nineteenth century. A history of its origin and other aspects from 1823 to 1990 are overviewed. The structure in the Deccan Trap Basalt is nearly circular with a breach in the northeast, 1830 m in diameter, 150 m deep, with a saline lake in the crater floor.

Since time immemorial, mythological stories prevailed to explain in some way the formation of the Lonar structure, which has been held in great veneration with several temples within and outside the depression. Various hypotheses proposed to understand its origin are critically examined and grouped into four categories as (1) volcanic, (2) subsidence, (3) cryptovolcanic, and (4) meteorite impact. In the past, interpretations based on geological, morphological, and structural data were rather subjective and dominated by volcanic, subsidence, and, to some extent, cryptovolcanic explanations [1]. In 1960, experience of the Canadian craters led Beals et al. [2] to first suggest the possibility of a meteorite impact origin of the Lonar crater, and thus began a new era of meteorite impact in the history of the Indian crater.

The last three decades (1960 to 1990) reflect a period of great excitement and activity of the Lonar crater, perhaps owing to an upsurge of interest in exploration of the Moon and other planets.