[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.

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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.

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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.

Application of principles of hypervelocity impact cratering has provided overwhelming evidence for an impact origin of the Indian crater. Among others, shock metamorphic characteristics of basalt, impact glasses, mineralogy, chemistry, geochemistry, and comparison with the Moon's rocks have clearly demonstrated its formation by impact of a meteorite [3–6].

Over the years, the origin of the Lonar structure has risen from volcanism, subsidence, and cryptovolcanism to an authentic meteorite impact crater. Lonar is unique because it is probably the only terrestrial crater in basalt and is the closest analog with the Moon's craters. Some unresolved questions are suggested. The proposal is made that the young Lonar impact crater, which is less than 50,000 years old, should be considered as the best crater laboratory analogous to those of the Moon, be treated as a global monument, and preserved for scientists to comprehend more about the mysteries of nature and impact cratering, which is now emerging as a fundamental ubiquitous geological process in the evolution of the planets [7].

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SUDBURY IGNEOUS COMPLEX: IMPACT MELT OR IGNEOUS ROCK? IMPLICATIONS FOR LUNAR MAGMATISM. Marc D. Norman, Planetary Geosciences, Department of Geology and Geophysics, SOEST, University of Hawaii, Honolulu HI 96822, USA.

The recent suggestion that the Sudbury Igneous Complex (SIC) is a fractionated impact melt [1] may have profound implications for understanding the lunar crust and the magmatic history of the Moon. A cornerstone of much current thought on the Moon is that the development of the lunar crust can be traced through the lineage of "pristine" igneous rocks [2]. However, if rocks closely resembling those from layered igneous intrusions can be produced by differentiation of a large impact melt sheet, then much of what is thought to be known about the Moon may be called into question. This paper presents a brief evaluation of the SIC as a differentiated impact melt vs. endogenous igneous magma and possible implications for the magmatic history of the lunar crust.

Petrologic and geochemical studies of terrestrial impact melts have shown that most of these occurrences cooled quickly, creating homogeneous crystalline rocks with compositions approximating those of the average target stratigraphy [3,4]. Impact melts typically, but not always, have elevated concentrations of siderophile elements relative to the country rock, indicating meteoritic contamination [5,6,7]. Application of these studies to lunar samples has lead to various criteria thought to be useful for distinguishing primary igneous rocks of the lunar highlands crust from the mixtures created by impact melting [2,8,9]. Among these criteria are mineral compositions suggesting plutonic conditions, non-KREEPy incompatible trace-element patterns, and low concentrations of meteoritic siderophile elements. Lunar breccias and impact melts identified as polymict on petrographic grounds usually have incompatible- and siderophile-element signatures indicating KREEP and meteoritic components, so a lack of these components may be taken as evidence that a sample preserves its primary igneous composition, even though its texture may have been modified by cataclasis or annealing.

If the SIC represents melt formed during the impact event that created the Sudbury Basin, then ideas of how large melt sheets behave require revision. The SIC is a noritic-to-granophyric mass of crystallized silicate liquid with mineral and chemical compositions broadly consistent with closed-system fractional crystallization, although greenschist facies alteration has obscured much of the fine-scale record [10]. Despite the Ni and PGE (platinum-group-element) sulfide ores in the SIC, siderophile-element abundances in the silicates are comparable to those of the country rock [11]. PGE patterns in the ores are not chondritic, as they are in many impact melts, but are highly fractionated and similar to those of terrestrial basalts [12]. Osmium isotopic compositions in the ores suggest a significant component of continental crust and are difficult to reconcile with meteoritic contamination [11].

A lunar sample with mineralogic and geochemical characteristics analogous to those of the SIC probably would be judged as "pristine," hence a primary igneous rock. If large impact events can create melt rocks with characteristics indistinguishable from those of layered igneous intrusions and with no detectable meteoritic contamination, then any or all of the pristine lunar highland rocks may not necessarily represent endogenous lunar magmatism but fractionated impact melts. Diverse components would still be required in the lunar crust and/or upper mantle to produce the impressive array of lunar highland rock types, but the connection to major mantle reservoirs that could constrain the planet's bulk composition would be lost. There may be economic implications as well: If the SIC is a fractionated impact melt, then large impact structures become potential exploration targets, both terrestrial and extraterrestrial.

Despite the somewhat unusual, silica-rich bulk composition of the SIC, several characteristics of the complex appear more consistent with endogenous magmatic processes vs. impact melting and *in situ* differentiation. Among these characteristics are (1) petrologic and geophysical evidence suggesting an unexposed mafic or ultramafic mass beneath the SIC, (2) contact relations within the SIC that suggest multiple intrusive events, and (3) possibly abundant water in the SIC magma. In addition, we argue that the silica-rich composition of the SIC does not require impact melting, but can be accounted for by endogenous magmatic processes although the impact event may have influenced the course of the magmatic evolution. These topics are discussed in more detail below.

Petrologic and geophysical evidence favoring an unexposed mafic or ultramafic mass beneath the SIC includes ultramafic xenoliths found in the SIC sublayer [13,14] and gravity and magnetic data [15]. The xenoliths have mineral and trace-element compositions suggesting a petrogenetic connection to the SIC. A basal ultramafic zone would suggest that the SIC is not contained entirely within the impact structure and would create a bulk composition for the SIC unlike that of the proposed target stratigraphy. It would also seem to require a mantle-derived component in the SIC magma, which may be more supportive of an endogenous magmatic origin rather than incorporation of mantle material into the impact melt. If the excavation cavity of the Sudbury impact event was 100–150 km diameter [1], the depth of excavation was probably ≤20 km [16], which would be predominantly or exclusively within the continental crust.