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.

Contact relations between the sublayer and the SIC main mass norite appear to reflect multiple intrusive events although both units may have been mobile simultaneously [14]. Multiple intrusions would seem more consistent with pulses of endogenous magmatism rather than a one-shot impact event although the mechanics of large-scale impact melting remain obscure. Amphibole is present in the SIC norite and may be primary [10]. The presence of water in the melt in amounts necessary to stabilize amphibole (2–5 wt%) may be more consistent with an endogenous magma rather than a superheated impact melt. For example, tektites are among the driest of terrestrial rocks, but their small volume may not be directly analogous to the SIC. It may also be possible that a dry impact melt became hydrated through assimilation of country rock during crystallization.

The bulk composition of the SIC seems to be close to that of an average for the upper crustal target stratigraphy [1], which is a common characteristic of terrestrial impact melts. However, endogenous magmatic processes such as assimilation can incorporate significant amounts of continental crust into more mafic magmas without superheat [17,18]. Such processes can produce igneous rocks with compositional characteristics quite similar to that estimated for the bulk composition of the SIC. For example, many occurrences of Cenozoic volcanic rocks in western North America have bulk compositions close to that of the SIC [19–22].

Even if the SIC is not a direct impact melt, there does appear to be a close association in space and time between the SIC and a major impact event. Dietz [23] and French [24] described features in the Sudbury Basin that they attributed to shock. Their arguments that the Basin is an impact structure are persuasive because there are no known occurrences of similar shock features unequivocally associated with volcanic eruptions. If the Sudbury Basin is an impact structure, it is the largest such structure known on Earth. The noncircularity of the SB has been cited as evidence against an impact origin, although the original shape of the Basin is poorly constrained [25]. Although the original shapes of most impact craters generally are circular, considerable variation in crater outline and morphology can be found. Oblique impacts can produce craters with elongate outlines, as observed on the Moon and Mars [26–29]. An oblique, skipping impact event that created a series of elongated scars was discovered recently in Peru [30]. Fragmentation of the impactor can produce elongated, noncircular crater patterns or multiple events as shown by the Henbury cluster, the Cape York meteorite field, and the East-West Clearwater pair. Erosion and deformation can alter the original shape of an impact basin, e.g., Meteor Crater is somewhat rectangular. The apparent noncircularity of the Sudbury crater is not a strong argument against an impact origin when stacked against the host of shock features clearly associated with the Basin.

Even if the SIC is an endogenously produced magma and not an impact melt, the association of impact events and magmatism may nonetheless have important implications when considering the locus and style of planetary magmatism. The close correspondence in space and time between the impact event and the magmatism that produced the SIC suggests a broadly genetic connection, especially considering the overall paucity of magmatism of similar age (1850 Ma) in the region [31,32]. In order to explain the compositional characteristics of the SIC, it appears necessary to invoke significant mixing of mantle-derived magmas with continental crust. Spatial variations in mineral compositions away from wall rock contacts suggest that the melt was actively assimilating wall rock [10]. Intracrater melt rocks or breccias may have been assimilated by more mafic magmas, which in turn may have been produced by local thermal perturbations or pressure-release melting associated with the impact.

Alternatively, crustal material may have been injected into the mantle, producing a mixed source that melted to give the SIC parent magma. Nyquist and Shih [33] have proposed that regional heterogeneities in the lunar mantle may reflect large impact events that injected crustal material deep into the Moon's interior.

The SIC appears to represent endogenous magmatism although probably localized and influenced by a major impact event and structure. The role of pristine lunar highland rocks as products of endogenous magmatism is correspondingly secure for the moment but the effects of major impact events in localizing and influencing that magmatism remains poorly perceived and probably requires additional missions to the Moon to clarify. Regardless, study of impact events remains of fundamental importance for understanding the formation and evolution of the planets.

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MELTING AND ITS RELATIONSHIP TO IMPACT CRATER MORPHOLOGY.

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Shock-melting features occur on planets at scales that range from micrometers to megameters. It is the objective of this study to determine the extent of thickness, volume geometry of the melt, and relationship with crater morphology.

The variation in impact crater morphology on planets is influenced by a broad range of parameters: e.g., planetary density (ρ), thermal state, strength (Y), impact velocity (U), gravitational acceleration (g),... We modeled the normal impact of spherical