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.

References: [1] Grieve et al. (1991) *JGR, 96,* 22753. [2] Warren and Wasson (1977) *Proc. LSC 8th,* 2215; (1978) *Proc. LPSC 9th,* 185. [3] Phinney and Simonds (1977) *Impact and Explosion Cratering,* 771. [4] Grieve et al. (1977) *Impact and Explosion Cratering,* 791. [5] Morgan et al. (1975) *Proc. LSC 6th,* 1609. [6] Palme et al. (1978) *GCA, 42,* 313. [7] Wolf et al. (1980) *GCA, 44,* 1015. [8] Warner and Bickle (1978) *Am. Mineral., 63,* 1010. [9] Ryder et al. (1980) *Proc. LPSC 11th,* 471. [10] Naldrett and Hewins (1984) *Ontario Geol. Surv. Spec. Vol. 1,* 235. [11] Walker et al. (1991) *EPSL, 105,* 416. [12] Naldrett (1984) *Ontario Geol. Surv. Spec. Vol. 1,* 309. [13] Scribbins et al. (1984) *Can. Mineral., 22,* 67. [14] Naldrett et al. (1984) *Ontario Geol. Surv. Spec. Vol. 1,* 253. [15] Gupta et al. (1984) *Ontario Geol. Surv. Spec. Vol. 1,* 381. [16] Pike and Spudis (1987) *Earth Moon Planets, 39,* 129. [17] Leeman and Hawkesworth (1986) *JGR, 91,* 5901. [18] Moorbath and Hildreth (1988) *CMP, 98,* 455. [19] Gerlach and Grove (1982) *CMP, 80,* 147. [20] McMillan and Duncan (1988) *J. Petrol., 29,* 527. [21] Nixon (1988) *J. Petrol., 29,* 265. [22] Norman and Mertunan (1991) *JGR ,96,* 13279. [23] Dietz (1964) *J. Geol., 72,* 412. [24] French (1970) *Bull. Volcanol,. 34,* 466. [25] Shanks and Schwerdtner (1991) *Can. J. Earth. Sci., 28,* 411. [26] Wilhelms (1987) *U.S. Geol. Surv. Prof. Pap. 1348.* [27] Schultz and Lutz-Garihan (1982) *Proc. LPSC 13th,* 84. [28] Nyquist (1983) *Proc. LPSC 13th,* 785; (1984) *Proc. LPSC 14th,* 631. [29] Mouginis-Mark et al. (1992) *JGR,* in press. [30] Schultz and Lianza (1992) *Nature, 355,* 234. [31] Sims et al. (1981) *Geol. Surv. Can. Pap. 81–10,* 379. [32] Krogh et al. (1984) *Ontario Geol. Surv. Spec. Vol. 1,* 431. [33] Nyquist L. E. and Shih C.-Y. (1992) *LPSC XXIII,* 1007–1008.

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

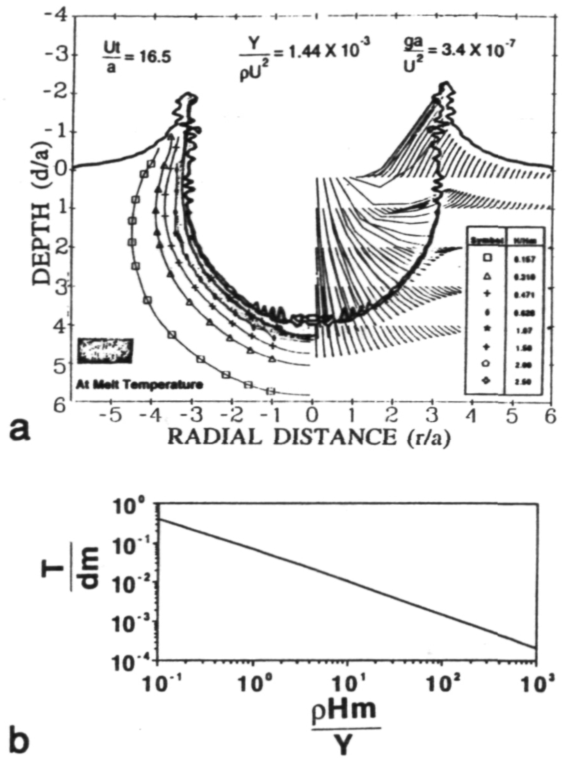

Fig. 1. (a) Melt layer morphology at time of maximum penetration for strength-dominated simple crater. (b) Melt layer thickness/crater diameter at time of maximum penetration as a function of (Cauchy number)$^{-1}$.

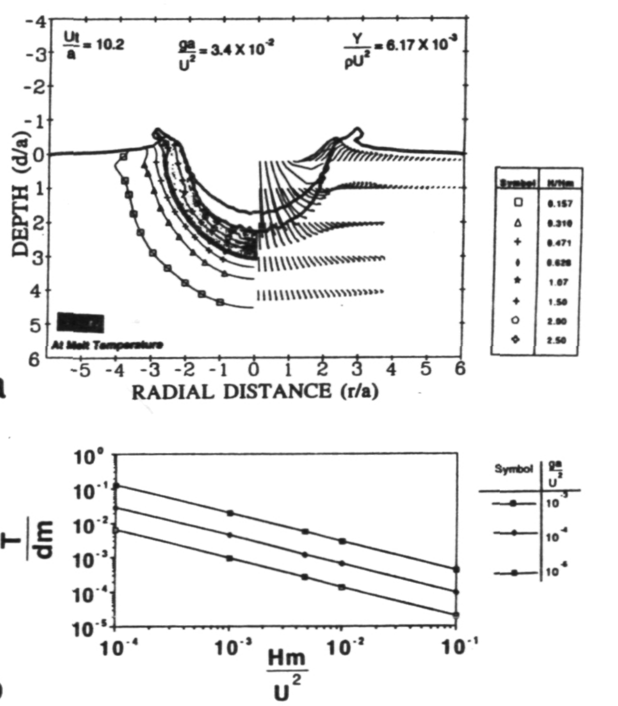

Fig. 2. (a) Melt layer morphology at time of maximum penetration for a gravity-dominated complex crater. (b) Melt layer thickness/crater diameter at time of maximum penetration as a function of (Froude number)$^{-1}$.

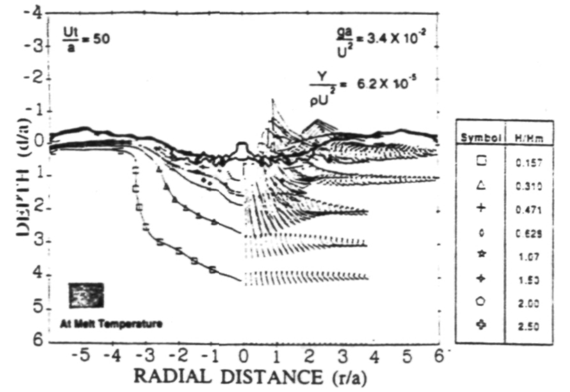

Fig. 3. Melt layer morphology at later times for a gravity-dominated complex crater.

projectiles on a semi-infinite planet over a broad range of conditions using numerical techniques [1]. The scope of the calculations was defined so as to span the range of dimensionless parameters that characterize planetary impacts. These parameters are the inverse Froude number, ga/U^2, inverse Cauchy number, $Y/(\rho U^2)$, melt number, H_m/U^2, and shock weakening number, H_{sw}/U^2. Here H_m is the melt enthalpy (~10^{10} erg/g), and H_{sw} is the enthalpy required to negate the planet's strength (~10^7–10^8 erg/g).

The crater morphological regimes have been described as simple bowl-shaped, flat-floored, multiple-ringed, central peak, and central pit [2]. In the case of simple bowl-shaped craters, the strength of the planet arrests the growth of the crater and is the dominant factor in its shape (Fig. 1). In all the other regimes, gravity arrests the growth and results in a rebounding of the depth and a collapse and propagation of the crater lip (Fig. 2). Multiple rings, peaks, and pits evolve after the rebounding and collapse and are a result of the interplay between the gravitational and strength forces (Fig. 3). The planetary strength is altered by the impact process. The strong shock wave melts, thermally weakens, and fractures the planetary material. We have modeled the melting and thermal weakening and Asphaung et al. [3] are addressing fracturing. We have determined the consequences of these effects on crater morphology scaling using the formalism of Holsapple and Schmidt [4]. Using the result of calculations, we determine the melt layer thickness/crater diameter (T_m/d) for simple and complex bowl-shaped craters. From numerical calculations, we find for simple craters that the quantity T_m/d is dependent only upon the material properties and scales as $[Y/(\rho H_m)]^{-0.28}$ (Fig. 1b). The relative melt layer thickness for craters that are dominated by a shock weakening scale as $(H_m/H_{sw})^{-0.28}$. For gravity-dominated craters and a given crater diameter, $T_m/d \propto (H_m/U^2)^{-0.28}$, so that the relative thickness increases with velocity (Fig. 2b). In addition to the melt layer thickness, we determined the scaling of the depth and total amount of melting for each of the cratering regimes. These results will be presented along with a comparison with terrestrial [e.g., 5] cratering field results.

References: [1] Thompson S. L. (1979) *SAND-77-1339*, Sandia National Labs., Albuquerque, New Mexico. [2] Melosh H. J. (1989) *Impact Cratering, A Geologic Process*, Oxford, New York, 245 pp. [3] Asphaung E. H. et al. (1991) *LPSC XXII*, 37–38. [4] Holsapple K. A. and Schmidt R. M. (1987) *JGR, 92*, 6350–6376. [5] Grieve R. A. F. et al. (1991) *JGR, 96*, 22753–22764.