MELT PRODUCTION IN LARGE-SCALE IMPACT EVENTS: CALCULATIONS OF IMPACT-MELT VOLUMES AND CRATER SCALING. Mark J. Cintala[1] and Richard A. F. Grieve[2], [1]Code SN4, NASA Johnson Space Center, Houston TX 77058, USA, [2]Geophysics Division, Geological Survey of Canada, Ottawa, Ontario K1A 0Y3, Canada.

Along with an apparent convergence in estimates of impact-melt volumes [1–3] produced during planetary impact events, intensive efforts at deriving scaling relationships for crater dimensions have also been yielding results [4]. It is now possible to examine a variety of phenomena associated with impact-melt production during large cratering events and apply them to planetary problems. This contribution describes a method of combining calculations of impact-melt production with crater scaling to investigate the relationships between the two.

Calculations of Impact-Melt Volumes: This study uses melt-volume calculations that treat vertical impacts into a flat target; the projectile and target are described by a modified, material-specific Murnaghan equation of state, the details of which have been described elsewhere [3,5]. It does not use the "constant-energy shell" assumption of Charters and Summers [6] and Gault and Heitowit [7], and yields a closer approximation to the results of more complex, finite-difference models [1,2]. In an attempt to approximate the off-axis stress decay evident in more detailed models of the impact process [1,2,8], the particle velocity in the target behind the shock front is assumed to vary as $\cos^{\beta} \theta$, where β is the ratio of target to projectile compression, and θ is the angle from the axis of penetration (equivalent to the direction of the velocity vector) to the point of interest, measured at the center of flow in the target. Energy is added to the target until the projectile decompresses, whereupon the detached shock front is treated as a thin region whose intensity decays due to entropy production and geometric effects. The results of this procedure in calculating melt volumes for the impact of chondrite (simulated by an artificially dense basalt) into Hardhat granite and Tahawus anorthosite are compared in Fig. 1 to those for anorthosite into anorthosite, using a finite-difference model [1].

TABLE 1. Impact-melt volumes at terrestrial craters.

Crater	D_R (km)	Melt Volume (km^3)
Brent	3.8	2×10^{-2}
Zapadnaya	4.5	1×10^{-1}
Il'nets	8	7×10^{-1}
Kaluga	15	8
Logoisk	17	7×10^{-2}*
Lappajärvi	17	8
Ries	24	2×10^{-1}*
Boltysh	25	11
Mistastin	28	20
W. Clearwater	32	80
Kara	65	480
Manicouagan	100	1200
Popigai	100	1750
Sudbury	200	8000¶

*Values are low probably due to mixed nature of target and presence of volatiles in sedimentary strata [9].

¶Assumes Sudbury Igneous Complex and part of overlying Onaping Formation are a coherent melt sheet [10].

Melt Volumes and Cavity Scaling: Even though it is far from complete, the terrestrial dataset is the best one available for the determination of impact-melt volumes associated with large craters. Values for these volumes for impacts into crystalline rock have been estimated from information culled from the literature (Table 1), and are presented in Fig. 2 against transient-cavity diameters, which were derived from the observed crater diameters with Croft's [11] modification scaling relationship. In order to extrapolate from the terrestrial data to planetary events, provision must be made for the effects of variations in gravity, impact velocity, and target and projectile properties. Calculations were performed for the impact of chondritic projectiles into Hardhat granite, covering a velocity range of 10 to 50 km s^{-1}; chondrites are considered to be representative of silicate impactors, and the velocity range falls within that allowable for the Earth. The scaling relationship as given by

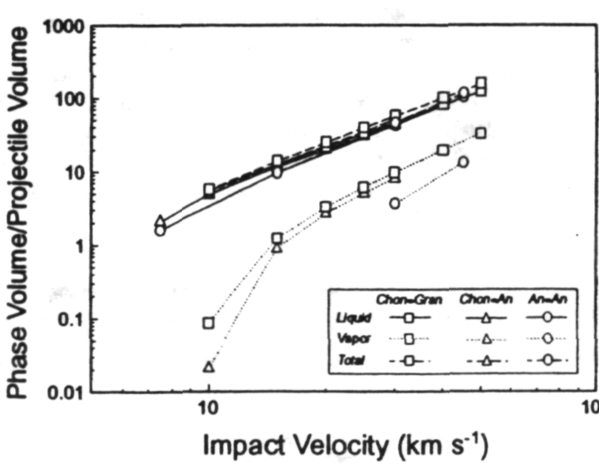

Fig. 1. Volumes of pure melt and pure vapor produced for impacts of chondrites into granite and anorthosite and for anorthosite into anorthosite [1]. The chondrite calculations were performed with the model described above.

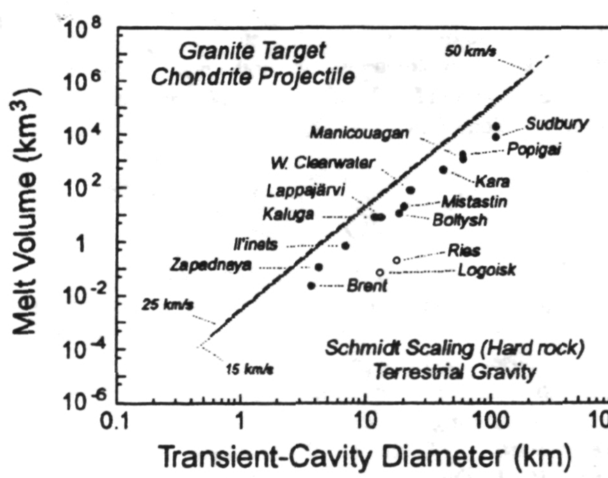

Fig. 2. Comparison between model calculations and actual terrestrial data for craters in crystalline rock. Note the displacement between the three curves and the observed values. Because they were formed in mixed targets, the Ries and Logoisk structures were not included in the analyses.

Schmidt and Housen [4] was then used to estimate transient-cavity diameters for a range of projectile sizes. Since the melt volumes are originally expressed in terms of impactor volume, it is a simple matter to relate the volume of impact melt to the dimensions of the transient cavity as given by the scaling relationship [4]. Three such curves are also included in Fig. 2. It is immediately apparent that the theoretical curves overestimate the quantity of melt by, in some cases, more than an order of magnitude. We believe that this reflects an underestimate of the transient-cavity dimensions rather than an overestimate of melt production for the following reasons: (1) The scaling relationship used for cavity dimensions was formulated partly on the basis of the *final* dimensions of craters formed in sand, which almost certainly represent adjusted transient cavities. (2) The melt-volume estimates are accurate to within a factor of 2, with underestimates being equally likely as overestimates, and thus cannot account for the differences. (3) Melt ejection could account for removal of up to 50% of the total produced at the smallest craters, but will have a vanishingly small effect in the cases of the largest craters in the figure. (4) The melt volumes calculated here, as evidenced by Fig. 1, are in good agreement with those determined from the more complex models. Lacking a detailed physical basis for changing the scaling relationship—which, it must be emphasized, combines with the melt calculations to yield a slope that is statistically indistinguishable from that of the terrestrial data—the model curve is brought into agreement with the terrestrial data simply by multiplying the model relationship for 25 km s^{-1} (the rms terrestrial impact velocity [12]) by a constant. The resulting relationship is

$$D_{tc} = 1.39\left(\frac{\rho_p}{\rho_t}\right)^{\frac{1}{3}} D_p^{0.78} V_i^{0.43} g^{-0.22} \qquad (1)$$

where D_{tc} is the transient-cavity diameters, ρ_p and ρ_t are the projectile and target densities respectively, V_i is the impact velocity, and g is the gravitational acceleration, all in cgs units.

Final Crater Dimensions: Equation (1) can be written for final crater dimensions by direct incorporation of Croft's [11] modification scaling relationship, which can be written as

$$D_R \approx D_Q^{-0.18} D_{tc}^{1.18} \qquad (2)$$

in which D_R is the final rim-crest diameter and D_Q is the diameter of the simple-to-complex transition for the planet (and terrain) in question. Substitution for D_{tc} into equation (1) and solving for D_R yields an equation of the form

$$D_R = k\left(\frac{\rho_p}{\rho_t}\right)^{0.39} D_p^{0.92} V_i^{0.51} \qquad (3)$$

where k is a constant related to g and the value of D_Q. Values for D_Q and k are given in Table 2. Relationships described by equations (1) and (3) are used elsewhere in this volume in relating model melt volumes to observed characteristics of the terrestrial and planetary impact record, and in deriving certain implications of those relationships for the cratering record.

References: [1] O'Keefe J. D. and Ahrens T. J. (1977) *Proc. LSC 8th*, 3357. [2] Orphal D. L. et al. (1980) *Proc. LPSC 11th*, 2309. [3] Cintala M. J. (1992) *JGR, 97*, 947. [4] Schmidt R. M. and Housen K. L. (1987) *Int. J. Impact Eng., 5*, 543. [5] Grieve R. A. F. and Cintala M. J. (1992) *Meteoritics*, submitted. [6] Gault D. E. and Heitowit E. D. (1963) *Proc. 6th Hypervel. Impact Symp.*, 419. [7] Charters A. C. and Summers J. L. (1959) *NOLR 1238*, U.S. Naval Ordnance Laboratory, 200. [8] Thomsen J. M. et al. (1980) *Proc. LPSC 10th*, 2741. [9] Kieffer S. W. and Simonds C. H. (1980) *Rev. Geophys. Space Phys., 18*, 143. [10] Grieve R. A. F. et al. (1991) *JGR, 96*, 753. [11] Croft S. K. (1985) *Proc. LPSC 15th*, 828. [12] Shoemaker E. M. (1977) In *Impact and Explosion Cratering* (D. J. Roddy et al., eds.), 617, Pergamon, New York.

TABLE 2. Planet-specific constants for use in equation (3).

Planet	D_Q (km)	k (cm$^{-0.43}$ s$^{0.51}$)
Mercury	10.0	2.61×10^{-2}
Venus	4.0 (assumed)	2.54×10^{-2}
Earth	4.0	2.24×10^{-2}
Moon	10.9	3.38×10^{-2}
Mars	3.1	3.39×10^{-2}

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Differences in scaling relationships for crater formation and the generation of impact melt should lead to a variety of observable features and phenomena. These relationships infer that the volume of the transient cavity (and final crater) relative to the volume of impact melt (and the depth to which melting occurs) decreases as the effects of gravity and impact velocity increase. Since planetary gravity and impact velocity (Table 1) are variables in the calculation of cavity and impact-melt volumes [1], the implications of the model calculation will vary between planetary bodies; this contribution will address some of those differences. Details of the model calculations of impact-melt generation as a function of impact and target physical conditions have been provided elsewhere [1], as have attempts to validate the model through ground-truth data on melt volumes, shock attenuation, and morphology from terrestrial impact craters [2,3].

Melt Volumes: The volume of impact melt as a function of rim-crest diameter is shown in Fig. 1 for typical impact velocities at the five terrestrial planets [4] (Table 1). In the calculation of rim-crest diameter, a modified version of Schmidt and Housen [5] scaling was used to calculate transient-cavity diameters [3], which were converted to final rim-crest diameters using the "modification scaling" relation of Croft [6]. Chondritic projectiles were used in all calculations, and assumed target materials varied by planet (Table 1). Figure 1 indicates that relative melt volumes at craters of a given

TABLE 1. Variables used in the calculations of impact melting and crater dimensions. All targets were assumed to have a temperature of 273 K except for Venus, for which 700 K was used.

Planet	Target	V_i (km s^{-1})	Gravitational Acceleration (cm s^{-2})
Mercury	Anorthosite	23.6	370
Venus	Diabase	19.3	891
Earth	Granite	17.8	981
Moon	Anorthosite	14.1	162
Mars	Anorthosite	12.4	371