ASSESSING IMPACT MELT VOLUMES CALCULATED WITH DIVERSE ANALYTICAL AND NUMERICAL METHODS. O. Abramov[1], D. A. Kring[2], and S. J. Mojzsis[3,4,5], [1]U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001 (*oabramov@usgs.gov*), [2]Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX, 77058, [3]University of Colorado, Geological Sciences, 2200 Colorado Ave., Boulder, CO 80309-0399, USA, [4]Center for Lunar Origin and Evolution (CLOE), NASA Lunar Science Institute, [5]Laboratoire de Géologie de Lyon, Université de Lyon 1, 69622 Villeurbanne Cedex, France

Introduction: Impact-induced melting is an important planetary process, and several analytical expressions have been developed to estimate the volume of melt produced during the formation of impact craters. Perhaps the simplest and most commonly-used expression is that by Grieve and Cintala [1], derived using an analytical model [2] and verified with observations at terrestrial impact structures [1]. In that expression, melt volume is defined as cD_{tc}^{d}, where c is a material-, velocity-, and gravity-dependent constant, and d is a constant defined as 3.85 for all materials, impact velocities, and surface gravities. However, this model can be improved upon by deriving explicit relationships between melt volume and impact velocity, impact angle, planetary gravity, target and projectile densities, and specific internal energy of melting.

Analytical model 1: A new melt scaling model by Abramov et al. [3] agrees well with the results of Grieve and Cintala [1] in terms of absolute melt volumes predicted, and validates, builds upon, and implements several improvements to that expression. In contrast to the Grieve and Cintala [1] model, melt volumes for both a given crater and a given projectile were derived, with the latter being:

$$V_{melt} = 0.22 E_m^{-0.85} \frac{\rho_p}{\rho_t} D_p^{3} v_i^{1.7} \sin^{1.3}\theta \qquad (1)$$

where E_m is the specific internal energy of the target at shock pressure that results in melting upon release (please refer to ref. [4] for a full definition), and has a value of ~5.2 × 10^6 J kg^{-1} for granite [5], ρ_p is projective density, and D_p is projectile diameter.

Analytical model 2: The initial temperature distribution, representing shock-heating only, is analytically calculated using an expression for specific waste heat (ΔE_w) derived from the Murnaghan equation of state [6,7]:

$$\Delta E_w = \frac{1}{2}\left[PV_0 - \frac{2K_0V_0}{n}\right]\left[1-\left(\frac{Pn}{K_0}+1\right)^{-1/n}\right] + \frac{K_0V_0}{n(1-n)}\left[1-\left(\frac{Pn}{K_0}+1\right)^{1-(1/n)}\right] \qquad (2)$$

where P is the peak shock pressure, K_0 is the adiabatic bulk modulus at zero pressure, n is the pressure derivative of the bulk modulus, and V_0 is the specific uncompressed target volume ($1/\rho_t$). For granite, the uncompressed density ρ_t is 2700 kg/m^3, K_0 is 35.7 GPa, and n is 3.94 [8].

Hydrocode simulations suggest that the center of impact, from which the shock originates, is at a depth equal to approximately the radius of the impactor [5,9] although a small variation with impact velocity is observed. Surrounding the impact center is the isobaric core, a region where shock pressure is constant or slowly decaying [e.g., 10]. The ratio of isobaric core radius to impactor radius shows only a small dependence on impact velocity and projectile and target compositions in hydrocode simulations [5], and is approximately unity [5,9], meaning that the isobaric core and impactor radii are roughly equal. Shock pressure P drops off with distance r according to the power law

$$P = A\left(\frac{r}{R_p}\right)^{-k} \qquad (3)$$

where R_p is the radius of the projectile, k is the decay exponent, and A is pressure at $r = R_p$ [e.g., 9]. A depends on target and impactor properties, and is based here on an estimate by [11], corrected for the impact angle based on the results of [9]:

$$A = \frac{\rho v_i^2}{4}\sin\theta \qquad (4)$$

where ρ is impactor and target density, both of which are assumed to be 2700 kg m^{-3}, consistent with a rocky asteroid striking a planetary crust, v_i is impact velocity, and θ is the impact angle. An impact angle of 45° is used in the present investigation because it is the most probable impact trajectory. The decay exponent k varies with impact velocity:

$$k \approx 0.625 \log(v_i) + 1.25 \qquad (5)$$

with v_i being in kilometers per second [12]. Additional validation of this expression can be found in [9], who concluded, based on CTH hydrocode simulations, that the volumetric pressure decay exponent n_V ($n_V = k/3$) can be considered constant for impacts between 30° and 90°, and has a weighted average value of 0.671. This corresponds to a k of 2.01, and agrees well with the prediction of 2.06 [12] for the 20 km s^{-1} impact investigated by [9].

Melt volumes were derived from the temperature increase (ΔT) in the target predicted by the shock-heating model. To keep the comparison general, a target with no geothermal gradient and a homogeneous initial temperature of 0 °C was assumed. This allows a straightforward comparison to the baseline analytical model 1 expression (Eq. 1) and hydrocode results [9], which do not include effects of target temperature; however, it should be noted that a correction for preexisting target temperature is also given by [3]. The latent heat of fusion was modeled using the approximation of [13] as used by [14] in a study of the Manicouagan (Quebec, Canada) impact melt sheet, replacing the heat capacity C_p in the temperature range between the liquidus (T_L) and the solidus (T_S) with

$$C_p' = C_p + L/(T_L - T_S) \quad (6)$$

where L is the latent heat of fusion (418 J kg^{-1} for granite [15]), and T_S and T_L are solidus and liquidus temperatures, set to 997 and 1177 °C, respectively. Melt was defined as material heated above the average granitic melting temperature of 1087 °C.

Hydrocode models: Several numerical computer codes have been developed that allow three-dimensional simulations of impact events and, thus, oblique impacts, to be investigated, and numerous studies have used hydrocode models to estimate impact melt volumes [e.g., 9,16]. These studies typically either (i) calculate melt volume as the volume of target shocked above a given shock pressure, such as ~50 GPa for granite [e.g., 9], which is conceptually similar to analytical model 2, or (ii) calculate the liquidus temperature as a function of pressure, but usually do not include latent heat [e.g., 17]. The major strength of hydrocodes is the ability to explicitly calculate the shock impact field, which is asymmetric for oblique impacts, whereas analytical methods approximate the shock field as a partial sphere. However, hydrocode studies have yielded average volumetric pressure decay exponents that can be used in analytical approximations (see previous section).

Results: Results of melt volume comparisons are presented in Fig. 1. Melt volumes predicted by analytical methods 1 and 2 differ by less than 20% in Fig. 1a, which presents melt volumes as a function of impactor diameter, with impact angle and velocity held constant. Fig. 1b shows melt volumes as a function of impact velocity, and the two methods differ by almost a factor of two for 10 km s^{-1} impacts; however, this difference decreases with increasing velocity, becoming less than 20% for 20 km s^{-1} impacts.

Fig. 1c shows melt volumes as a function of impact angle for analytical model 1 [3], analytical model 2 (this work), and CTH hydrocode calculations [9]. Melt volume decreases as a function of impact angle at the same rate for both analytical methods, and the absolute difference between the two approaches is again under 20%. It should be noted, however, that both [3] and [9] assumed a density of ~3300 kg m^{-3} for the projectile and ~2700 kg m^{-3} for the target, whereas the present work assumes approximately equivalent densities. If melt volumes are adjusted by a factor of ~1.22 (~3300/~2700, see [3]), it essentially eliminates the ~20% difference described earlier, resulting in a near-perfect match to [3] and a close match to [9].

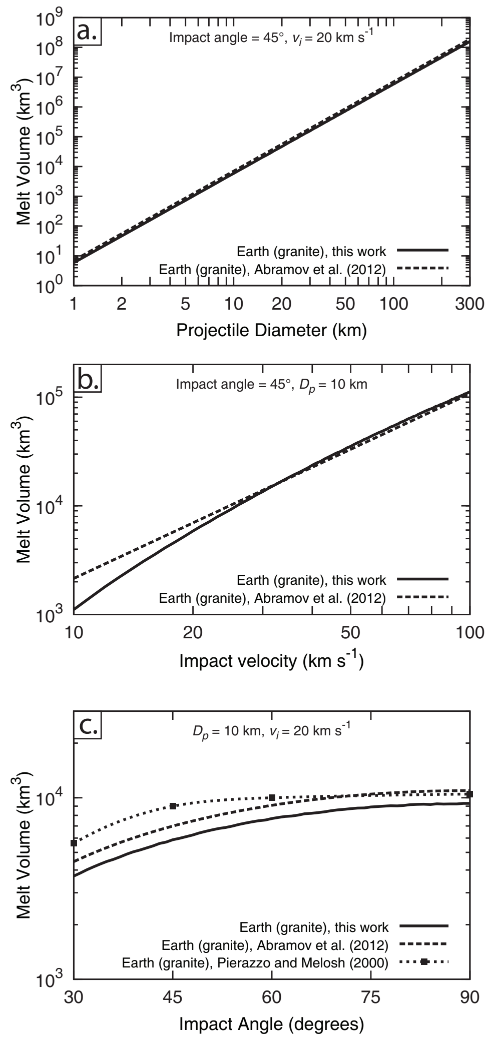

Fig. 1. Melt volume as a function of (a) projectile diameter, (b) impact velocity, and (c) impact angle. Effects of target temperature are not included here.

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