SHALLOW-WAVE APPROACH TO EMPLACEMENT OF LAYERED CRATER EJECTA ON MARS. S. M.Baloga[1], S. A. Fagents[2], L. S. Glaze[3], P. J. Mouginis-Mark[2], [1]Proxemy Research, Gaithersburg, MD, 20882 (steve@proxemy.com), [2]HIGP, University of Hawaii, Honolulu, HI 96822, [3]Planetary Geodynamics Laboratory, Code 698, NASA GSFC, Greenbelt, MD, 20771 (lori.s.glaze@nasa.gov).

Introduction: Many fresh impact craters on Mars have layered ejecta blankets that are distinct from those on the Moon and most other planetary surfaces [1-3]. The three primary categories of roughly symmetric layered ejecta morphologies are single layered (SLE), double layered (DLE), and multi-layered (MLE) [1]. Figures 1 and 2 show two typical cases. Although there are many cratered surfaces in the solar system, layered ejecta deposits are found predominantly on Mars. Consequently, it has long been thought that a volatile presence in the target (e.g., ground water/ice) somehow fluidized the ejecta into a dense overland flow, much like a terrestrial debris flow or catastrophic landslide [e.g., 4-6]. Morphologic studies continue to suggest that the emplacement of the layered deposits resembles a ground-hugging flow [7-8].

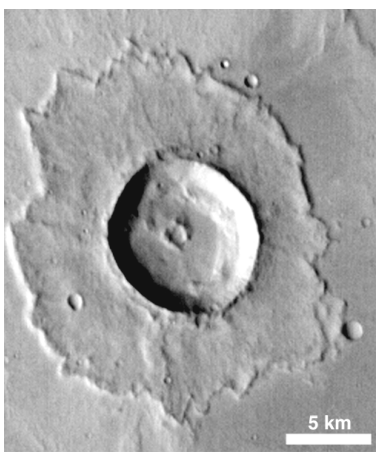

Figure 1. Typical single layer ejecta crater

Only a few elementary models have been proposed to describe the emplacement of the layered ejecta deposits as an overland flow. These formulations have been based on kinematic waves [7], a prototype 'shallow-wave' approximation [8], and granular flow simulations [9]. Such studies aim to explain qualitative features of the deposits (e.g., ramparts) and quantitative characteristics such as transit times, flow velocities, and rheologic parameters. None of the current models provides an explanation for the three different types of morphologies or provides significant inferences about the volatile content in the target. In fact, *Wada and Barnouin-Jha* [9] have recently shown theoretically that some aspects of emplacement could be produced by dry granular flows.

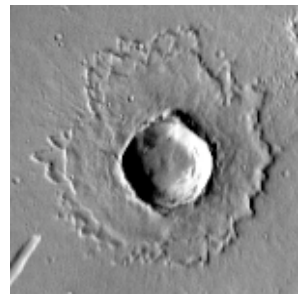

Figure 2. Typical double layer ejecta crater

Shallow-wave Model: The shallow-wave model treats the ejecta as a radially symmetric overland flow with inertia, hydrostatic pressure, and a frictional resistance to flow. Volume and momentum conservation are described by,

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial r} + h\frac{\partial u}{\partial r} = -\frac{uh}{r} \qquad (1)$$

and

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r} + g\frac{\partial h}{\partial r} = -\frac{Cu^2}{h} - \frac{gh}{2r} \qquad (2)$$

where h is flow thickness, u is flow velocity, r and t are radial distance and time, g is gravity, C is a friction factor. The ground-hugging flow is thus treated as a sequence of vertical columns advancing from the crater rim. Each column has a single local value for the flow depth and velocity that changes with time and distance according to the boundary conditions at the crater rim and the dynamics of eqs. (1) and (2). A particularly attractive feature of the shallow-wave formulation is that it permits use of a large body of terrestrial knowledge about the roles of water and particle sizes in catastrophic mass flows.

Matching the qualitative and quantitative features of observed deposits with theoretical predictions from eqs. (1) and (2) constrains *inter alia* the boundary condition relationships (i.e., the form of initial velocity and flow depth) and the friction factor C in (2). The constraint on C can, in principle, be used subsequently to obtain a secondary constraint on the water content and mean particle diameter based on terrestrial experience.

Rigorous numerical solutions of the shallow-wave equations are extremely challenging. The shallow-

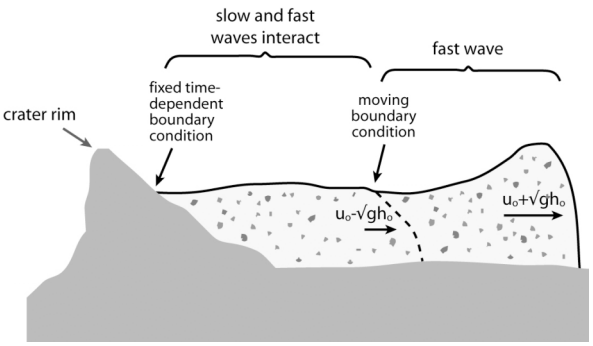

Figure 3. Cartoon illustrating differential propagation of two wave components away from the crater rim. The fast wave outruns the slow wave, but behind the flow front there is a zone where the two waves interact and can produce a variety of flow profiles.

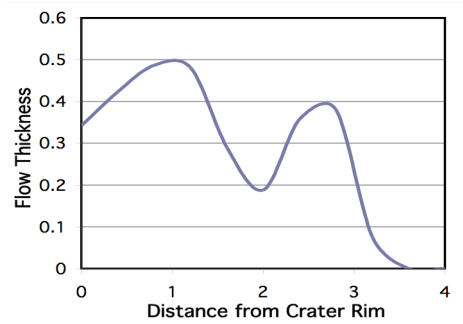

Figure 4. A typical theoretical deposit thickness profile for a DLE crater.

wave equations fundamentally generate two waves. For high exit velocities at the crater rim, both waves propagate forward (see Fig. 3). Complexity in the solution algorithm arises because the faster wave must be matched with time-dependent conditions at the front of the slower wave rather than conditions at the rim.

The most significant finding of the shallow-wave approach is that different flow regimes naturally emerge that correspond to the three basic deposit morphologies (SLE, DLE, and MLE). The input parameters for the model are the initial velocity (u_o), the depth of the flow (h_o) and the degree of frictional resistance to flow (C). The critical groupings of these parameters that differentiate the three types of flow profiles are:

$$\varepsilon = \frac{u_o - \sqrt{gh_o}}{u_o + \sqrt{gh_o}}, \quad \beta = \frac{Cu_o}{2h_o} \qquad (3)$$

The parameter ε represents the ratio of the propagation speeds (u_o-√gh_o and u_o+√gh_o) of the two inherent characteristic wave components of the flow. This parameter measures the kinetic energy of a flow relative to its thickness and its ability to dissipate the energy by removal of pressure gradients. When too much energy is imparted to the flow (high, positive ε) a variety of complex new phenomena emerge such as instabilities, pulses, roll waves and similar phenomena. The time-constant β is a measure of the resistance to flow. This parameter can be related (via C and terrestrial experience) to water content and mean particle diameter for ejecta flows consisting of water and solids.

Various combinations of ε and β produce the broad range of features observed in the layered crater ejecta deposits. Figure 4 shows the case of a high frictional resistance to flow (β=0.9) and characteristic wave com ponents that remain moderately separated (ε=0.55) during emplacement. Such profiles are suggestive of the DLE in Fig. 2.

Preliminary Model Assessment: The initial assessment of the shallow-wave approach is very promising. First, the model suggests reasonable quantitative emplacement times, flow velocities, and deposit dimensions consistent with data, observations, and prior theoretical studies. More importantly, it appears that a wide variety of flow regimes are associated with variations in the boundary conditions and the flow resistance coefficient C. Qualitatively, the shallow-wave approach appears to provide a unifying framework for the interpretation of the three primary styles of ejecta deposits (SLE, DLE, and MLE). Initial estimates of C from comparison of theoretic profiles with ejecta deposits suggest very high fluidities nothing like the values expected from a dense debris flow. The preliminary assessment thus suggests that the fluidizing agent is primarily water vapor rather than liquid, except possibly for the very last phase of ejecta flow emplacement.

References: [1] Barlow, N.G. et al. (2000) *JGR, 105*(E11), 26, 773-26, 733-26. [2] Garvin, J.B. et al. (2000) *Icarus, 144,* 329-352. [3] Barlow, N.G. and Perez, C.B. (2003) *JGR, 108*(E8) 5085. [4] Gault, D.E. and Greeley, R. (1978), *Icarus, 34*, 486-495. [5] Mouginis-Mark, P.J. (1978) *Nature, 272*, 691-694. [6] Melosh, H.J. (1989) Impact Cratering, A Geologic Process, Oxford Univ. Press. [7] Barnouin-Jha, O.S. et al. (2005) *JGR,* 110, E04010. [8] Baloga, S.M. et al. (2005) *JGR, 110*, E10001. [9] Wada, K and Barnouin-Jha, O.S. (2006) *Meteorit. Plan. Sci., 41*, 1551-1569. [10] Bulmer, M.H. et al. (2002) *JGR, 107*, *107*, E001531.