DIAGNOSTIC FEATURES FROM MODELING IMPACT CRATERING IN ICY LAYERED TERRAINS. L. E. Senft and S. T. Stewart, Dept. Earth & Planetary Sci., Harvard U., 20 Oxford St., Cambridge, MA 02138 (lsenft@fas.harvard.edu).

Introduction. Icy and layered surfaces are seen throughout the solar system. In this work, we use numerical simulations to describe and quantify the effects of icy surface and subsurface layers on crater formation. We focus on understanding Martian crater forms because observations of Martian ice-related features and theoretical work on the dynamical history of Mars have illuminated how obliquity variations led to the deposition of ice-rich layers, ranging from 10 m to 1 km thick, on the surface [1, 2]. The impact crater record provides a powerful tool to investigate these layers' properties. Furthermore, icy layers may be a contributing factor to the layered ejecta structures found around the majority of Martian impact craters [e.g. 3].

Method. Cratering simulations are conducted using the shock physics code CTH [4]. We use the rock strength model of Collins et al. [5], which we have implemented into CTH [6]. The equations of state for basalt [7] and H_2O are gridded in Sesame tables. We constructed a new Sesame table for H_2O. This table includes three solid phases (ice Ih, VI, and VII), liquid, and vapor. The EOS of the phases and phase boundaries are determined experimentally [8, 9, 10, 11].

Results. A range of effects from icy layers are seen. Here we illustrate the effects using examples from a single layer of ice. Fig. 1 presents time series from simulations of a 200-m diameter projectile impact onto the Martian surface for different target configurations. In Fig. 1a, the target is homogenous basalt. Crater formation proceeds as expected, with the ejecta curtain forming a smooth inverted cone that sweeps outward (20 s) and the formation of a bowl shaped transient cavity whose walls collapse slightly ("end"). In Fig. 1b, a 100 m surface layer of ice is added. Crater formation proceeds as before, but when the basalt ejecta is laid down near the rim, it compresses the ice layer underneath. This leads to horizontal, non-ballistic motion of the near-surface ice, which thins the icy layer near the rim and thickens it at greater distances.

When the thickness of the surface ice layer is increased to 200 m (Fig. 1d), the proportion of ice relative to basalt in the ejecta blanket increases. The ejection of ice at higher angles than basalt creates a curved profile to the ejecta curtain. If the thickness of the surface ice layer is large enough (400 m, Fig. 1f), than the ice separates from the basalt in the ejecta curtain (2 s). This ejecta curtain structure has also been observed in simulations of marine targets [12]. Also, the icy rim appears to be unstable, flowing into the crater at late times ("end").

Burying the ice layer under a basalt layer produces further morphological variations. Figs. 1c and 1e show a 100 and 200 m ice layer, respectively, buried under a 200 m thick basalt layer. In both cases, the top basalt layer tears away from the underlying surface at early times (2 s). The ejecta trajectories are modified by wave reflections between the layers. The high ejection angles result in a hinge-like evolution of the ejecta curtain. The hinge area then collapses back towards the crater cavity (20 s). Finally, as the hinge slumps, it squeezes the ice layer, resulting in a late-stage icy extrusion into the crater. This ice behaves in a fluid manner because it is warm, however it is largely unmelted.

If the thickness of a buried icy layer becomes large enough (Fig. 1g; a 400 m thick ice layer buried under a 100 m basalt layer), then the actual crater (in the underlying basalt layer) becomes very small and the amount of ice being extruded into the crater at late times becomes very large. As the ice being extruded from all sides of the crater meets, it creates a central uplift which collapses back down in on itself and flows outward at temperatures near the melting point.

Comparison with Observations. Our simulations suggest that several of the features associated with Martian impact craters may be a result of surface or near subsurface icy layers, including:

"Dewatering" Features: Tornabene et al. [13] has recently documented flow features associated with young impact craters of a large size range (~3 to 60 km) and suggest that they are a result of the flow of water into the crater cavity. Our simulations (Figs. 1c, 1e, 1f, and 1g) show warm, thermally weakened ice flowing away from the crater rim and into the crater (as late-stage icy extrusions).

Rim Moats: Our simulations show non-ballistic, horizontal flow of ice away from the crater rim, which may produce observed circum-rim moats (Figs. 1b and 1d) [14].

Layered Ejecta Structures: Non-ballistic trajectories modify the radial distribution of ejecta from a simple power law. Terminal ramparts cannot be directly observed in the simulations because the scale is too small and the physics of debris flows are different from the physics of large-scale impact cratering events. However, simulations can provide the initial conditions for debris flow models.

Lack of Secondary Craters: Boyce and Mouginis-Mark [14] observe a lack of secondary craters around some double layer ejecta craters. Our simulations show that when there is a buried ice layer (Figs. 1c, 1f, and 1g), the ejecta flow can be somewhat impeded, leading to most of the ejecta being deposited close to the crater rim.

Paleolakes: A number of possible paleolakes in Martian craters have been identified [e.g. 15]. Our simulations show warm ice ponded on crater floors (Figs. 1c, 1e, and 1g).

Central Pit Formation: The thermal evolution of liquid water and ice deposits in the crater floor can be used to study the possible formation of central pits by dewatering [16].

Natural Variations: Martian impact craters display large variations in depths, rim heights, and amounts of ejected and uplifted material versus crater diameter [e.g. 17]. Our simulations produce a large range of these measures.

Conclusions. We have performed simulations of impact cratering events into layered icy terrains in order to understand the effect that such layers can have on the impact cratering process and the final crater morphology. The effects can be significant and may explain differences in crater morphologies between planetary surfaces and many of the features seen around Martian impact craters. Finally, note that dry, weak layers may produce some (but not all) of the same morphologies as icy layers, and we are investigating ways to differentiate between the two cases.

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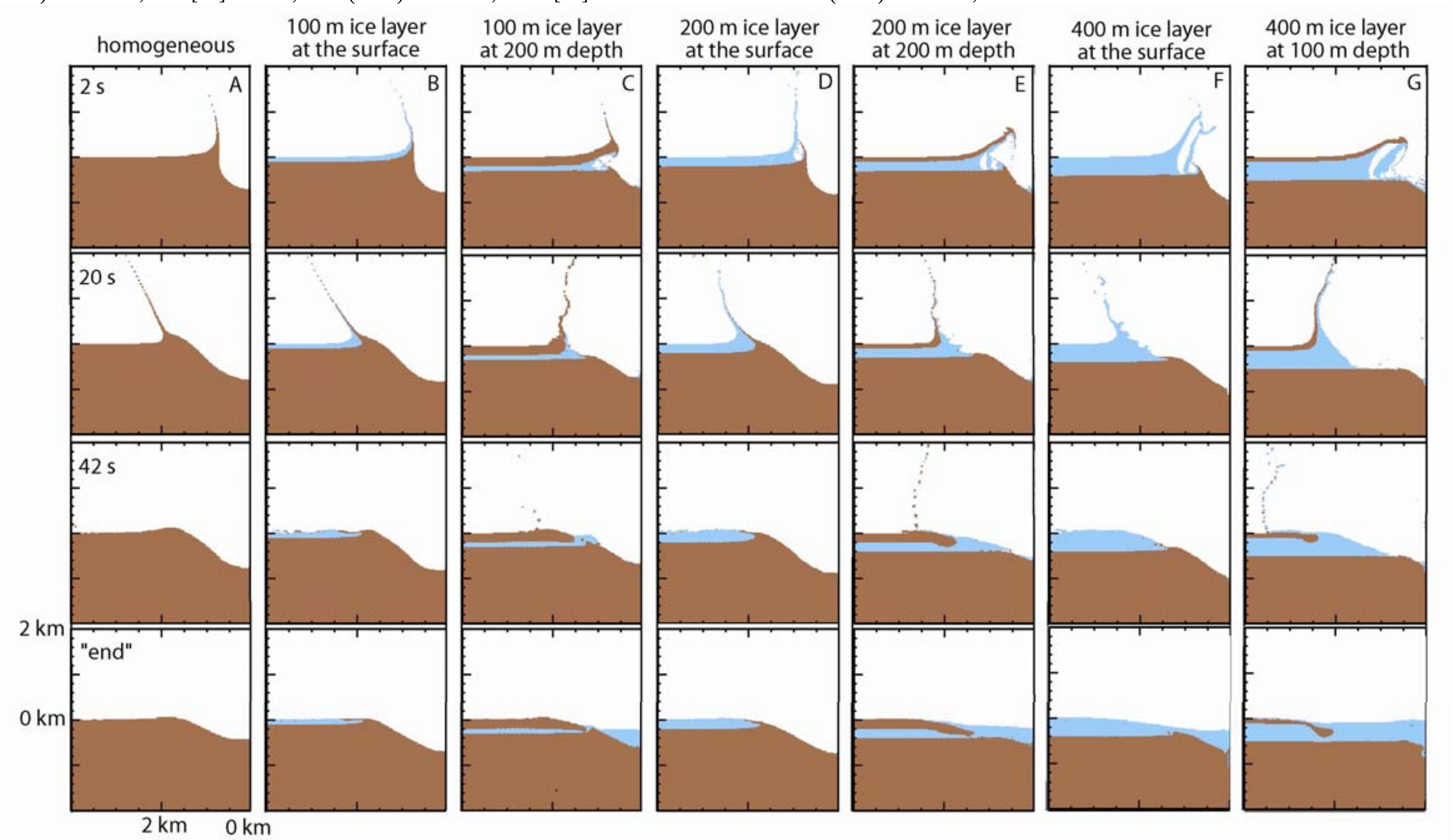

Figure 1. 200-m diameter projectile impact at 10 km/s for different target configurations under Martian gravity (nominal 4.9 km final rim diameter). Cross sections of cylindrically symmetric calculations are shown, where brown represents basalt and blue represents H_2O. Time increases downwards and the scale is the same in all panels. The “end” refers to the time when material has stopped moving appreciably.