SCALING LABORATORY EXPERIMENTS TO NATURAL PLANETARY EXPERIMENTS. P. H. Schultz, Brown University, Department of Earth, Environmental, and Planetary Sciences, 324 Brook Street, Providence, RI 02912 USA, peter_schultz@brown.edu.

Introduction: Laboratory experiments cannot directly replicate actual impact conditions, except at the regolith scale on small bodies with comparable impact speeds. Nevertheless, experiments can be designed to isolate processes that can be extrapolated through models and comparisons with planetary-scale craters, hence challenging the refrain "small laboratory experiments cannot be scaled to planetary-scale impacts." This is a personal review of selected results from laboratory experiments that can be recognized in planetary "experiments." At the outset, I apologize to my colleagues whom I have neglected to highlight.

Extrapolating Experiments: Two broad comparisons illustrate how processes observed at laboratory scales implicate similar processes at much larger scales.

***Atmospheric Effects on Ejecta Emplacement*:** The discovery of very non-Moon-like ejecta deposits on Mars from Mariner 9 prompted two seemingly divergent views of the causative processes: the effect of volatiles at depth [e.g., 1-3] and the role of the atmosphere [4-7]. The flow-like ejecta morphology supported the argument for the role of a fluidizing agent, an interpretation further supported by early experiments [8]. Unfortunately, terminology such as "splosh" craters creates confusion by convolving an interpretation with a description. While the term "Double-Layered Ejecta" (DLE) is intended to mitigate this issue, this term also connotes a specific sequence requiring a process that creates two layers.

The atmospheric model of ejecta emplacement was created in response to two simple questions: what is the effect of the tenuous atmosphere on Mars acting on ejecta trajectories [4], and conversely, what is the effect of the ensemble of ejecta (the curtain) on the atmosphere [9]. Experiments revealed several key processes. First, the advancing ejecta curtain generates intense vortical winds that trail the ejecta curtain but entrain particles below a critical size for a given atmospheric density. Second, the intensity of these winds increases directly with outward speed of the ejecta curtain, which means that aerodynamic drag increases with crater size. Third, ejecta emplacement style changes with increasing atmospheric pressure: from Moon-like, to rampart bordered, to fluid flow, to radial (scouring). Fourth, the effect of entrained water droplets would result in atomization that would then become part of the entrained flow. Fifth, the effect of an atmospheric blast would equilibrate well before the later stages of ejecta emplacement. And sixth, the mode of emplacement is initially ballistic, thereby preserving signatures of the basic ejection process such as the zone of avoidance in oblique impacts.

Consequently, laboratory experiments revealed unexpected atmospheric processes that could be scaled with reasonable assumptions about atmospheric density, ejecta size, and crater size without the need invoke the presence of subsurface water. Moreover, the run-out distance should increase with crater size due to the increasing role of comminution and the degree of degree of entrainment (until much of crater growth exceeded the atmospheric column). As expressed on the surface of Mars, rampart-bordered deposits reflect excavation of bimodal size distributions in the ejecta (e.g., impacts into the ridged plains) with the rampart resulting from ejecta sizes too large for suspension in the flow but small enough to be mobilized until energy losses preclude further transport. Multi-modal ejecta sizes result in flow separation and sequential deposition. Hence, the term DLE is inappropriate because there are not two layers; rather, vortices scour and entrain near-rim ejecta deposits that are re-deposited beyond the inner terminus in an outer deposit. Finally, enhanced run-out flows occur in regions with uni-modal fine ejecta sizes, e.g., silts deposited from outflows or air-fall loess at high latitudes. In the presence of volatiles (e.g., near-surface ice), an atmospheric vapor blast and heat may pre-condition the surface [10] and result in auto–suspension [5].

Subsequent studies isolated different components of the process observed in the laboratory and applied fluid dynamical theory to not only provide greater insight but also provide predictions on ejecta sinuosity applicable to both Mars and Venus [7]. Moreover, computer models reveal the generation of vorticies and the possible effects of the blast [11]. The atmospheric model does not preclude the role of near-surface volatiles. Some studies indicate that volatiles will increase the role of comminution, thereby enhancing atmospheric effects [12], while entrained water may enhance mobility of near near-rim ejecta [13]. Moreover, impacts into ice/dust-rich deposits at mid-latitudes during orbital forcing should result in dramatic changes in morphology due to easily entrained fines, rather than liquid flow [e.g., 5].

***Oblique Impacts*:** Experiments clearly expose key processes resulting from oblique impacts not (yet) fully captured in hydrocode models. Without the planetary record, however, such a statement would be pure speculation. The evolving flowfield and the effects of impactor decapitation are two key processes exposed by experiments and observed on the planets are

Gault and Wedekind's classic study demonstrated that the elongate crater shape does not emerge until impact angles approached 5° from the horizontal [14]. Nevertheless, asymmetries in the distribution of ejecta could be recognized up to angles of 30°, along with a peculiar elongation perpendicular to the trajectory. Later experiments used in-flight measurements that captured asymmetries in ejecta angle and velocity at much higher angles that would otherwise be masked by late-stage processes [15,16]. Other studies directly measured these symmetries in the peak pressure and failure patterns in strength-controlled targets [17-19]. Even though small in scale, these results can be clearly recognized at planetary scales. Such insights proved critical for interpreting the Deep Impact [20] and LCROSS impact experiments [21]. The dimensionless scaling relations developed over the years have proven critical [22-24], not just for making extrapolations but also for focusing on departures from necessary simplifications, such as the point-source assumption. For example, oblique impacts result in a flow-field center that migrates downrange and downward during the coupling phase [24] and contributes to the evolution of ejecta angles and speeds [25], identifiable at large scales [9, 27]. This migration becomes exposed at large scales as cratering efficiency decreases [28]. With this insight, the diameter of the objects responsible for various impact basins could be estimated and crater scaling relations tested [29]. Another implication of the migrating flowfield is the uprange-offset location of the central uplift associated with craters exhibiting distinctive asymmetries in the distribution of ejecta [9]. Although a statistical study of craters on Venus seemed contradictory, it included "failed" experiments (topographic effects and small craters) that diluted the results. Hydrocode models [30] also demonstrated the motion of flow, perhaps accounting for the breached downrange central rings of large basins. For smaller craters, this may be an issue of specifying appropriate conditions leading to termination of the flow due to strength [31].

***Impactor Decapitation*:** At very low impact angles, the fate of the projectile is exposed. As impact angle decreases, so does the peak pressure in the projectile. Rather than being overprinted by the subsequent flowfield in vertical impacts, the fragments of the decapitated projectile continue downrange and produce a distinctive double impact pattern [32]. The same pattern can be recognized at large scales, especially Mars [33]. Subsequent studies argued that such craters represent tidally disrupted bodies and proposed that the distribution on Mars is not anomalous [34]. However, that study globally averaged the distribution, not recognizing that such statistics require isolating units of a given age, which then indicates in a much higher flux of highly oblique impacts on Mars possibly related to ancient satellites [33]. At very large scales, impactor decapitation becomes even more important due to surface curvature and results in distinctive "arrowhead" and "tomahawk" shapes in plan view [36]. Impactor decapitation also enhances the amount of vaporization in carbonate targets due to the increasing role of frictional shear [37, 38].

Conclusions: Laboratory experiments can be used to interpret features found on planetary surfaces, despite the enormous differences in scale because the same fundamental processes operate. But extrapolation requires more than just a one-to-one morphologic comparison. Rather, it requires an understanding of underlying processes, potential differences, and scaling relations. In this sense, laboratory experiments become more than benchmarks for hydrocode models: they actually can guide the models to examine lost or masked details in the impact process.

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