MODELING THE 150-M DIAMETER "CHRISTMAS EVE" IMPACT CRATER ON MARS G. S. Collins[1], K. Miljković[2], N. Wójcicka[1], A Rajšić[2], P. Lognonné[3], C. M. Dundas[4], L. Posiolova[5], T. Kawamura[3], M. Froment[3], Z. Xu[3], Ingrid J. Daubar[6] and the InSight Impacts Working Group. [1]Department of Earth Science & Engineering, Imperial College London, UK, g.collins@imperial.ac.uk. [2]School of Earth & Planetary Science, Curtin University, Perth, Australia. [3]Université Paris Cité, Institut de Physique du Globe de Paris, Paris, France. [4]USGS, Flagstaff, AZ, USA. [5]Malin Space Sciences Systems, San Diego, CA, USA. [6]Brown University, Providence, RI, USA.

Introduction: On Christmas Eve, 2021, a large meteoroid struck Mars in Amazonis Planitia [1]. The impact excavated a ~150-m diameter crater, and produced a spectacular >30-km wide "blast zone" (prominent surface albedo disturbance; Fig. 1). The impact also generated a magnitude 4 marsquake that was detected by the Seismic Experiment for Interior Structure (SEIS) [2] of the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission [3], 3,460 km away (event S1094b). The impact excavated blocks of water ice (Fig. 1); located at 35°N, this is the lowest latitude at which ice has been directly observed on Mars [4].

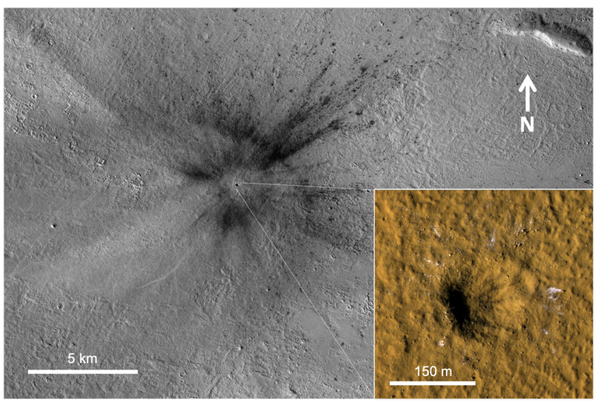

Figure 1: Orbital images of the Christmas Eve impact crater, blast zone and excavated ice. CTX image ID U05_073077_2154_XI_35N170W (main); HiRISE image ID ESP_073077_2155 (inset). Adapted from [1].

The combination of orbital imagery and seismic ground motions observed for this impact provides a unique opportunity to investigate seismic wave and atmospheric blast wave generation by impact on a planet with a thin atmosphere, as well as the excavation of ice from the shallow subsurface. Here we report on numerical simulations of the Christmas Eve impact that inform and enhance these investigations.

Numerical Modelling: Several simulations of the Christmas Eve impact were performed with the iSALE shock physics code [5–7] to investigate: (a) seismic wave generation; (b) crater formation and ice excavation; and (c) atmospheric blast wave generation and decay. Our nominal impact scenario assumed a 5-m diameter stony meteoroid (density 2.9 g/cc) impacting at 12 km/s [1,4]. The asymmetric blast pattern around the crater indicates a shallow impact trajectory. However, for computational expediency, initial simulations approximated the impact as vertical; 3D oblique impact simulations are in progress. The target was represented with a material model appropriate for porous martian regolith or fractured basalt [8, 9], with and without an ice layer. A tabular Mars atmosphere equation of state [10] was used in blast wave decay simulations.

Seismic wave generation: Our numerical simulations show that the impact generated shock wave transitions to seismic waves within a radius of ~120 m [1] and give seismic moments of 0.5×10^{13} to 1.2×10^{13} Nm for impacts in regolith and 2.8×10^{13} to 7×10^{13} Nm for fractured rock, respectively [8, 9]. These estimates are consistent with the observed seismic moment once corrected for seismic properties at shallow source depths [1]. The seismic efficiency is estimated to be 10^{-5} on the basis of scaling relations between seismic moment and crater diameter [11] with an order of magnitude uncertainty.

Crater formation and ice excavation: Our nominal vertical impact simulation produces a crater that is slightly deeper (30 m) and less wide (~130 m) than observed. A better match to observations likely requires a shallower impact angle, and a more massive or faster impactor. Most of the observed ice deposits are in the continuous ejecta between 75 and 140 m of the crater center (Fig. 1, inset). The provenance and state of this proximal ejecta (Fig. 2) were tracked in the simulation with Lagrangian tracer particles that follow points in the material during the impact and cratering flow.

Overturning of strata during excavation and ejecta emplacement of the proximal ejecta implies the uppermost ejecta derives from the greatest depth of origin (Fig. 2). Most proximal ejecta is minimally heated; and most ejecta that originates from below 5-m depth experiences shock pressures exceeding 10 MPa, which is greater than unconfined compressive strength of intact ice. This suggests that the blocks of massive ice around the Christmas Eve crater originated from less than 5 m and perhaps as shallow as 2 m depth [4].

Atmospheric blast efficiency and dust disturbance: Seismic source analysis, as well as the extensive blast zone around the Christmas Eve crater (Fig. 1), suggests that some of the seismic energy may have originated from the impact-induced atmospheric blast wave and then coupled to the ground [1]. To better understand the partitioning of seismic source energy between the direct ground coupling and the atmosphere-ground coupling it is necessary to determine the efficiency of blast wave generation by impacts on Mars.

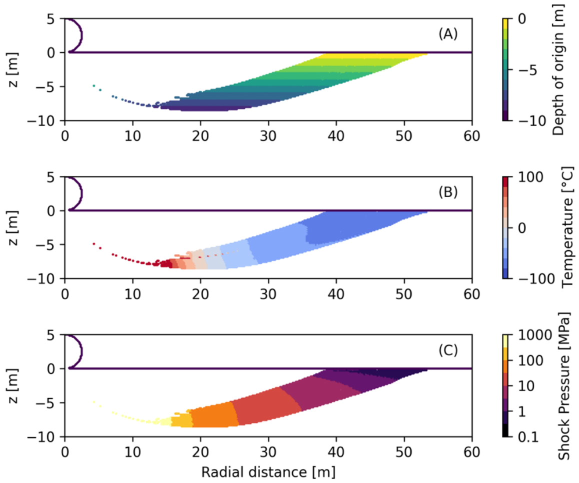

Figure 2: Provenance and shock state of proximal ejecta. The depth of origin (A), peak temperature attained (B) and peak shock pressure (C) of target material ejected by the impact that lands in the continuous ejecta blanket at a range of 75–140 m, is plotted at the material's pre-impact location. The maximum excavation depth is 8 m. More distal ejecta would derive from <5 m depths and closer to the impact point. Semi-circle at upper left is the impactor. From [4].

Numerical simulations of the nominal vertical impact scenario (6.6 kton kinetic energy) with a Mars-like atmosphere were performed to measure blast wave overpressure as a function of distance from the impact (Fig. 3). The decay of overpressure with blast radius is consistent with a 0.01 kton surface explosion based on semi-empirical blast wave theory extrapolated to Mars atmospheric conditions [1, 12]. This implies about 0.2% of the impact energy goes into blast wave, which would produce an atmospheric seismic moment of ~10^{10} Nm and imply an approximate seismic efficiency of ~10^{-8} for the component attributed to atmosphere-ground coupling. If correct, this suggests that most of the seismic energy resulted from direct coupling of the meteoroid with the ground. However, blast wave efficiency may be higher in an oblique impact. High-speed ejecta in the simulation generate bow shocks that enhance the blast amplitude. This process is likely to be more important in an oblique impact scenario where more of the impact energy is partitioned into the high-speed ejecta.

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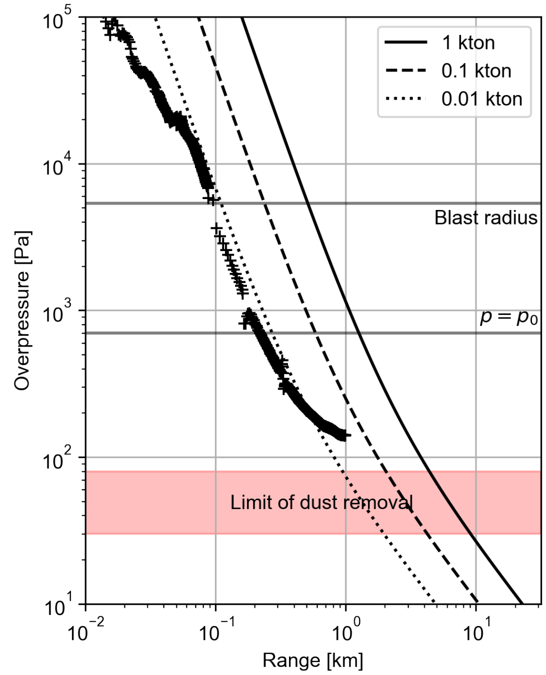

Figure 3: Atmospheric blast wave decay with distance. Simulated overpressure as a function of distance from iSALE simulation (crosses) and semi-empirical blast theory based on nuclear explosion tests [12] scaled to Mars atmospheric conditions (ratio of specific heats = 1.3, surface density = 1.7×10^{-5} kg m^{-3}, reference sound speed = 230 m/s, surface pressure 700 Pa) for three different estimates of blast energy (1 kton TNT equivalent, 4.184×10^{12} J; 0.1 kton and 0.01 kton). Approximate minimum pressure thresholds for removal of surface dust are 30–80 Pa [13].

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