DO MEGA IMPACTS LEAVE CRATERS? CHARACTERIZING MEGA IMPACTS AND THEIR RELATION TO THE MARS HEMISPHERIC DICHOTOMY. Margarita M. Marinova[1], Oded Aharonson[1], and Erik Asphaug[2], [1]Caltech, 150-21, Pasadena, CA 91125, mmm@caltech.edu, oa@gps.caltech.edu, [2]University of California, Santa Cruz, Earth Sciences Dept., Santa Cruz, CA 95064

Introduction: The most clearly visible feature on Mars is the hemispheric dichotomy: the difference in elevation (~4 km), crustal thickness (~30 km), roughness, and impact crater density between the Northern and Southern hemispheres [1,2]. The depression in the northern hemisphere encompasses ~35% of the planet's surface, equivalent to an average diameter of 7700 km [2]. The dichotomy boundary is expressed both as steep scarps and gentle slopes [2,3,4].

Despite the crustal dichotomy's prominent nature, its formation mechanism remains unknown. The possible formation mechanisms fall in the categories of endogenic and exogenic. For endogenic processes, degree-1 mantle convection is often invoked [e.g. 5]. Exogenic scenarios call for a single mega impact [2] or multiple smaller impacts [6]. If the crustal dichotomy is formed by a mega impact, the impact must not shatter the planet or produce sufficient melt to obliterate all surface and crustal evidence of the impact.

We investigate whether the Mars crustal dichotomy may have formed by a single mega impact. This first requires characterizing planetary-scale impacts, which have not been extensively studied; these impacts differ from the thoroughly studied smaller impacts due, in part, to the importance of surface curvature in planetary-scale impacts. Due to surface curvature it is expected that material redistribution, and thus melt distribution, would differ from that resulting from small impacts, and the change in crater properties with impact angle may be more prominent. We focus on the effect of planetary-scale impacts on early Mars. We compare the results of these simulations to observations to evaluate whether a single mega impact may have formed the dichotomy. Particularly, we investigate the depth of penetration of the projectile, the amount of melt produced, and the redistribution of excavated material.

Modeling: We use a fully 3 dimensional Smoothed Particle Hydrodynamics (SPH) model to simulate the impacts. SPH is a Lagrangian model in which an object is represented by particles, where each particle's mass remains constant, but its size, pressure, internal energy, and density change in response to external forces. SPH has been extensively used for simulating the Moon-forming impact [7]. The 3 dimensional nature of the code allows the simulation of impacts at any impact angle. In our simulations we nominally use 200,000 particles, giving a resolution (particle diameter) of about 115 km. The semi-empirical Tillotson Equation of State (EOS) is employed [8]. Figure 1 shows a snapshot of a simulation of a 60 deg impact (measured from the horizontal).

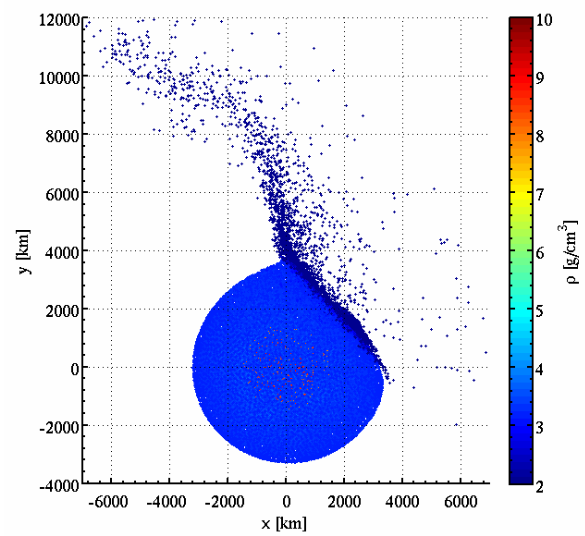

Figure 1. Snapshot of an impact simulation: t = 25 min after impact. Impact parameters: v = 6 km/s, $D_{impactor}$ = 860 km, $E_{impact} = 1.45x10^{29}$ J, D_{crater} ~ 8000 km, impact angle = 60 deg.

Planet Initial Conditions. Mars' initial pressure profile in the simulation is set to hydrostatic. In order to be able to calculate melt production, we require a realistic initial internal energy profile. We assume the surface and core-mantle boundary temperatures from parameterized convection models [9], and impose an adiabatic compression heating profile in the planet to obtain the mantle and core internal energies. Early Mars is likely to have had a convecting mantle and core, resulting in an adiabatic profile. The bulk materials for the mantle and core are taken to be olivine and iron, respectively.

Equation of State: The proper implementation of initial conditions requires using the appropriate materials for the mantle and core. The Tillotson EOS library does not include an olivine-like material, so to match mantle density we create our own olivine EOS. We use the same parameterization and formulation as the Tillotson EOS. Density [10], bulk modulus [11], and heat capacity [12] values were obtained from the literature; all other values were set to the average of available representative materials (basalt, granite, anorthosite lpp & hpp, andesite). Our model of Mars matches the known planet radius and mass, and the pressure profile ($P_{central,model}$ = 50 GPa, similar to ref [13]) and core size ($r_{core,model}$ = 1600 km, within range of ref [14]) are within the expected range.

Depth of Penetration: We calculate the depth of penetration of the deepest 10% of the impactor, which is effectively the depth of the transient impact crater cavity. We consider this depth as it relates to the magnitude of gravity waves that are sent through the planet as a result of the impact. That is, a deep depth of penetration implies large amplitude waves and significant disruption of the planet's surface by these waves.

Melting Criteria: We calculate melt production using two criteria: a high pressure criterion and a low-pressure (energy) criterion. In the high pressure melting criterion, material shocked above its threshold pressure melts upon decompression. This is commonly referred to as pressure melting. For olivine and basalt, the pressure melting threshold is ~75 GPa [15]. The low pressure melting criterion is effectively an energy melting criterion. For particles at low pressure (no more than one particle depth into the planet) we assume that melting occurs when the internal energy exceeds $T_{melt}C_p + H_{fusion}$, where T_{melt} is the melting temperature, C_p is the heat capacity, and H_{fusion} is the heat of fusion for the material. We do not take into account energy melting at depth in the planet and thus we underestimate melt production. We do, however, expect that we take into account all melting occurring close to the planet's surface, thus we can evaluate the extent of preservation of surface and impact features.

Impacts Parameter Space: We simulate impacts with velocities of 6 to 50 km/s (where 5 km/s is Mars' escape velocity and 50 km/s is twice Mars' orbital velocity), impact angles of 90 (perpendicular to the planet surface), 75, 60, 45, 30, and 15 degrees, and impact energies sufficient to create 4000 to 12,000 km craters (following the gravity regime scaling in [2]).

Results: Figures 2 & 3 show some results on the depth of penetration of the impactor and mass of melt produced for an 8000 km crater impacts, for different impact velocities and angles.

Results indicate that slower and vertical impacts penetrate the deepest, thus producing significant gravity waves and the strongest disturbance of the planetary surface. At constant impact energy, the impator's momentum is inversely proportional to the impact velocity, thus slower (higher momentum) impacts penetrate deeper. The smaller depth of penetration of oblique impacts is due to their grazing nature. Thus, faster and lower angle impacts result in less disruption of the planet.

The maximum melt production is for about 15 km/s impacts. In the case of high pressure melting, the low impact velocities (6 km/s) do not generate a shock

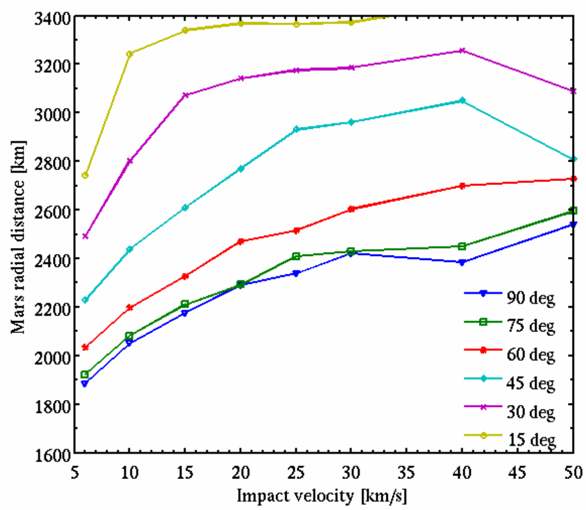

Figure 2. Penetration of deepest 10% of impactor. Colours represent impact angle; r_{core} = 1600 km, R_{Mars} = 3400 km; $E_{impact} = 1.45 \times 10^{29}$ J.

wave upon impact since the sound speed in olivine is comparable to these impact velocities, and therefore the high pressure melting production is negligible. As the impact velocity increases, the shock wave is stronger and therefore produces more high pressure melting. At high velocities we interpret the decrease in melt production as due to the decrease in the impactor size and therefore a smaller volume is exposed to the strong shock. In the low pressure (energy) melting criterion, the melt production is generally constant for all impact velocities, as expected for constant impact

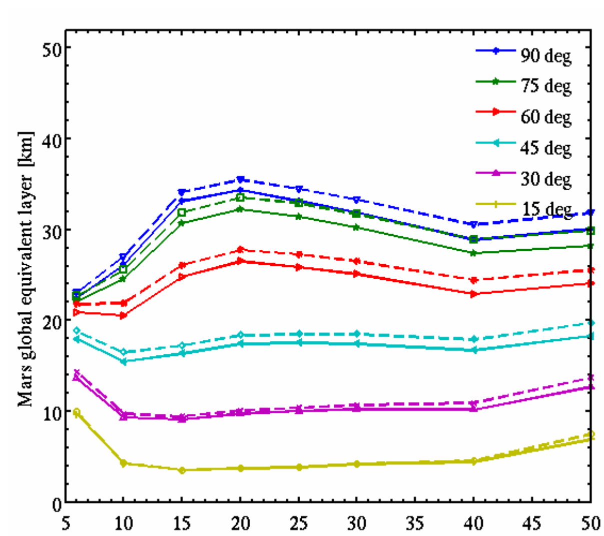

Figure 3. Total melt produced (dashed) and melt retained on the planet (solid) in terms of a global equivalent layer depth on Mars; a few percent of the melt is ejected into space. 10 km depth = 5.1×10^{21} kg. $E_{impact} = 1.45 \times 10^{29}$ J.

energy. However, there is a trend of higher melt production at low impact velocities, which is due to larger, slower impactors depositing energy over a larger volume of the planet. Since the material is already close to its melting point, this increase in internal energy results in larger melt production.

We can visualize the volume of melt produced as a global equivalent layer (GEL) of a given thickness over the surface of Mars (fig. 3). In these units, a vertical impact produces the equivalent of 30-40 km deep melt over the entire planet and oblique impacts (15-30 deg), produce a GEL layer of 5-10 km. While the GEL depths are useful to visualize the total melt volume, they fail to represent the spatial distribution that ultimately determines whether surface features are preserved.

The distribution of melt is a key factor in determining whether a mega impact erases all the evidence of its occurrence. Figure 4 shows snapshots of the distribution of melted and non-melted material at 12 min (a,c) and 2.1 hrs (b,d) after the impact of a 15 km/s impactor at 90 deg (a,b) and 15 deg (c,d). The figures represent slices through the planet. It is seen that in the case of the head-on (90 deg) impact, the depth of penetration is down to the core-mantle boundary, there is significant excavation, and the resulting area with a surface melt pool is extensive. In addition, the excavated material re-impacts the planet, thus covering much of the surface with melt. A melt pool is formed at the antipode of the impact. In the case of the oblique impact, the depth of penetration is smaller, and the resulting melt pool is more restricted. The simulations shown in figure 4 highlight the difference in resulting crater structure, and melt production and distribution due to the change in impact angle. The simulations show that the resulting melt pool in the vertical impact case covers ~85 deg of the planet's circumference while for the oblique, 15 deg impact it spans ~35 deg of the planet's circumference in the downrange direction. Because much of the excavated material reaches

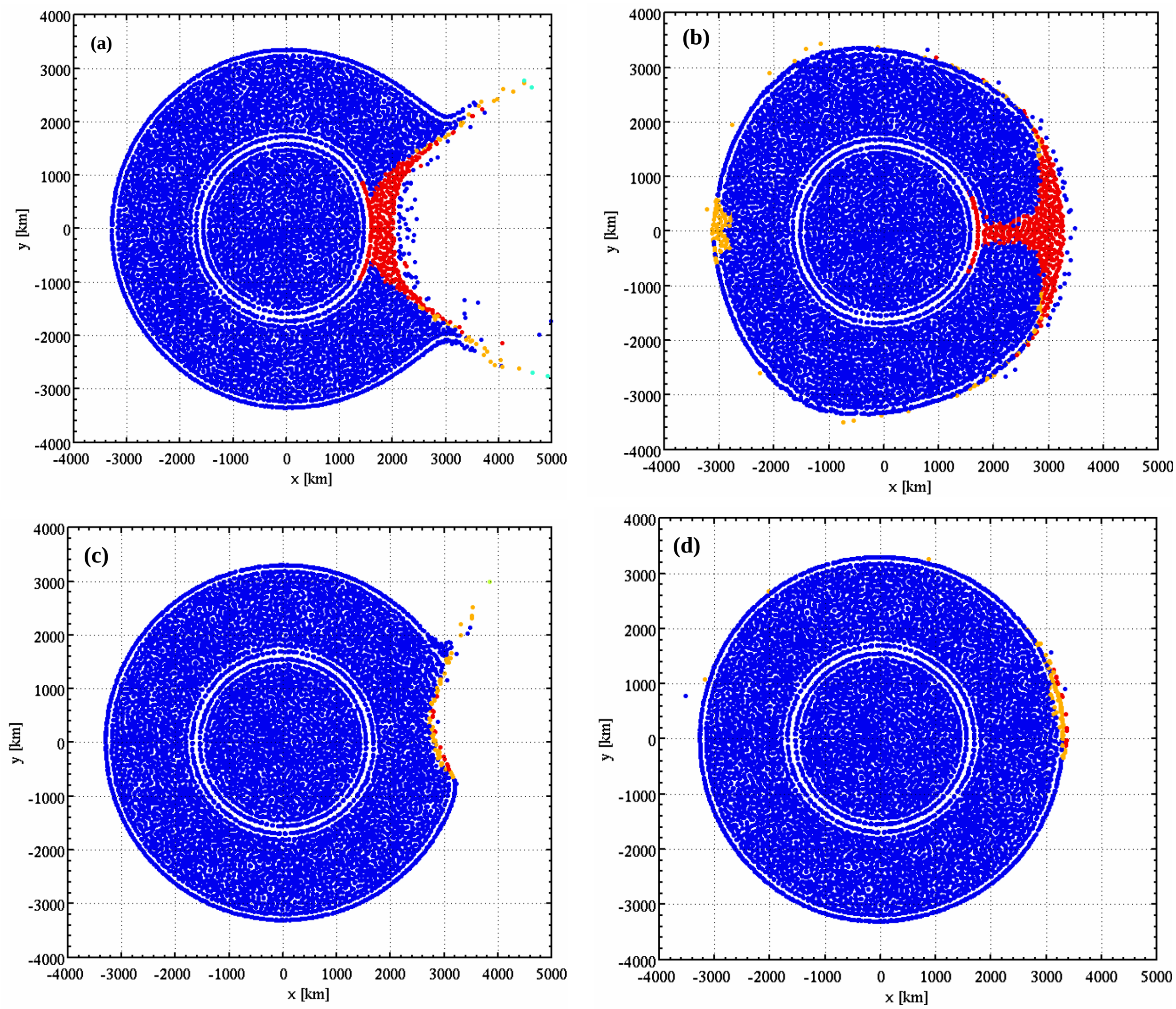

Figure 4. Production and redistribution of melt (red and orange); 15 km/s impact at 90 deg (a,b) and 15 deg (c,d); 12 min (a,c) and 2.1 hrs (b,d) after impact. The head on impact produces more melt and a more extensive melt pool than the oblique impact. $E_{impact} = 1.45 \times 10^{29}$ J.

escape velocity, no significant amounts of material, including melt, re-impact the planet. Thus, at constant energy and for a given impact velocity, the more oblique impacts produce much smaller melt pools and do not distribute molten material over the planet. A similar trend is also apparent as the impact velocity is increased.

Crustal redistribution is another important constraint, since current Mars crustal thickness estimates [1] show no crustal thickening at the highlands - lowlands boundary. Figure 5 shows crustal distribution for a 15 km/s impact at 90 deg and 15 deg impact angle at 2.1 hrs after the impact event (same impacts as shown in figure 4). For the vertical impact there is apparent crustal thickening around the crater, while in the oblique impact there is crustal thickening only on the

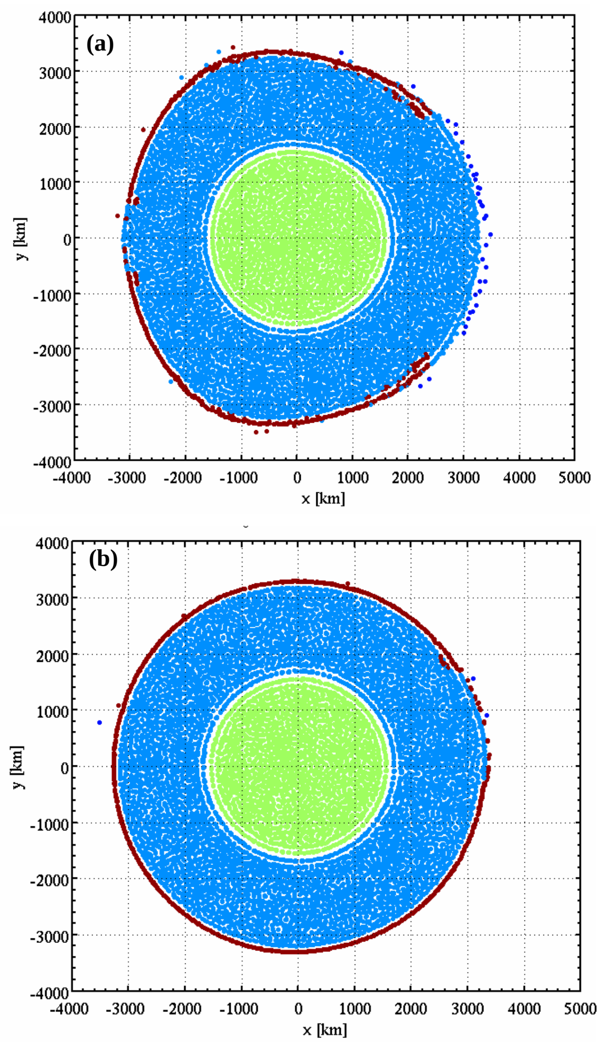

Figure 5. Crustal redistribution from a 15 km/s impact at 90 deg (a) and 15 deg (b). The crust (red), impactor (dark blue), mantle (light blue), and core (green) are shown. The excavation of crust (red) and its thickening around the impact crater are apparent. E_{impact} = 1.45×10^{29} J.

downrange side of the impact crater and the thickening appears to be less than in the vertical impact case. This limited example shows the significant difference in crustal redistribution as a function of impact angle. Further work is needed to determine the crustal thickening from various impacts.

Conclusions: Our simulations provide insight into planetary scale redistribution and melting of crust following mega impacts. As a first order observation, at constant impact energy, we note the large discrepancy between vertical and oblique impacts, where the change in impact angle has a more exaggerated effect than seen in smaller (flat surface) impact events. We see that head-on and intermediate velocity impacts produce the largest amounts of melt and disrupt the planet significantly, while the slowest and head-on impacts distribute melt over much of the surface. Oblique and fast impacts produce less melt and disrupt the planet to a lesser extent, thus allowing a signature of the impact to remain. Our results show that mega impacts need not obliterate the evidence of their occurrence and the possibility of forming the Mars hemispheric dichotomy by an impact should be further examined.

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