# NUMERICAL MODELING OF BASIN-FORMING IMPACTS: IMPLICATIONS FOR THE HEAT BUDGET OF PLANETARY INTERIORS

M. Bierhaus[1], K. Wünnemann[1] and D. Elbeshausen[1], [1]Museum für Naturkunde Leibniz-Institut an der Humboldt-Universität zu Berlin, Invalidenstr. 43, 10115 Berlin Germany, (Michael.Bierhaus@mfn-berlin.de)

**Introduction:** Impact processes are important for the evolution of solar system bodies. Objects of all sizes, ranging from asteroids (including e.g. Vesta), to moons and planets such as Mars are heavily cratered. It has been suggested that the formation of large impact basins, for instance, on Mars (such as Hellas, Argyre) may have significantly affected the dynamics (mantle and core convection) and evolution (plate tectonic, volcanism and generation of an intrinsic magnetic field) of the planetary interior [1-6]. Basin forming impact events generate shock waves, strong enough to travel through a whole planet and deposit heat deep into the planet. In a previous study we showed by 2D numerical models that a Hellas-sized vertical impact increases the temperature of the mantle and the core not only directly underneath the basin, but also antipodal to the point of impact [5,6]. In this study we account for the fact that most impacts occur at an oblique angle of incidence. We carried out a suite of 3D models of inclined impacts using the iSALE-3D hydrocode [10,11]. Besides impact angle and kinetic energy of the impactor other parameters such as the internal thermal structure and the degree of differentiation of the target (planet, moon, asteroid) may also affect how efficient heat can be deposited deep into the target interior by a giant impact event. By means of a systematic parameter study varying the impactor size, velocity and angle, target size and, thus, thermodynamic state and structure we quantify how the interior of a planetary object or asteroid can be heated up by large collision events.

**Shock heating and code validation:** In most hydrocode models peak pressures are used to work out post-shock temperatures. The temperature rise as a result of shock compression and subsequent unloading can be calculated from the peak shock pressure the target was exposed to and specific material parameters [e.g. 12-14]. To test our modeling approach we compare our results with previous studies of shock wave decay at impacts on planar surfaces. Fig 1. shows a good agreement between different hydrocode models of impacts at different velocities.

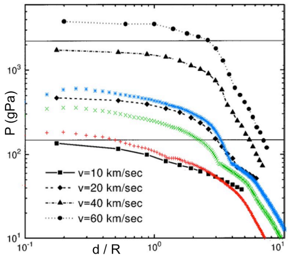
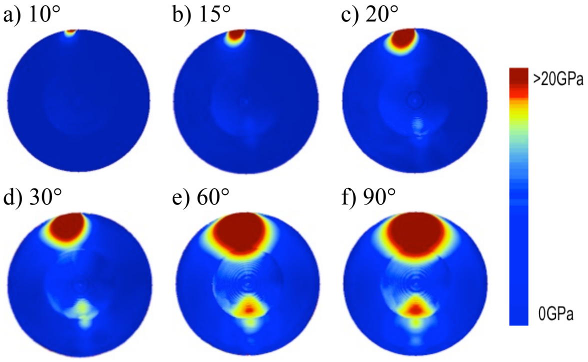


Fig. 1: Comparison of hydrocode models of impacts into a planar surface at different velocities. Coloured results: iSALE; black results: Pierazzo et al. [13]

**Oblique impacts:** In order to investigate how the impact angle influences the amount and the distribution of heat transferred into the planet we carried out a suite of 3D models and varied the angle of impact from 10°-90°. The snapshots in Fig. 2 show the result of an impact of a 200 km projectile on a martian-sized planet (r=3450 km) with a solid iron core of 1725 km radius and a dunitic mantle at different impact angles.


a) 10° b) 15° c) 20°

d) 30° e) 60° f) 90°

Fig 2. Oblique impact of a 200 km projectile with 15 km/s at different impact angles into a Martian sized planet. Shown are the peak pressures reached in the target.

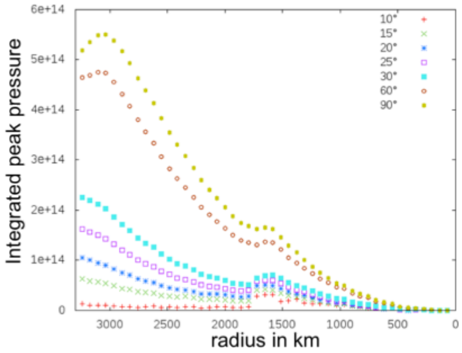


Fig. 3: Integrated peak pressures with planetary radius for different impact angles, proportional to heat transfer into the planet.

Fig. 2 reveals the existence of an area of locally increased peak pressure which is antipodal to the basin centre, not necessarily to the point of impact. For decreasing incidence angles this antipodal feature becomes less significant since the amount and depth of heat transferred into the planet decreases, as shown in Fig. 3. For impact angles smaller than 20° the heat barely reaches the core mantle boundary. The integrated peak pressures in Fig. 3 may suggest the existence of an antipodal feature (see local maximum at a radius of 1500 km) even for very low impact angles. However the missing visibility of this feature for impacts with incidence angle less than 15° in Fig. 2 does not support this assumption.

**Size/gravity dependency of the antipodal feature:** Many of the asteroids in the solar system show impact craters in a size range comparable to basins on a planet. If we assume equal impactor size to target ratios for asteroids the most significant difference is the gravity and, thus, the thermodynamic structure of the target body. Small planetary bodies are relatively cold in comparison to larger planets. Nevertheless, they may be differentiated (e.g. Vesta) indicating that they had been much warmer in the past. We carried out a suite of vertical impact models (90°, 2D cylindrical geometry) with a constant impactor/target size ratio to investigate the effect of a "cold" and a "hot" target. All target bodies are layered with a solid dunitic mantle and a solid iron core. Fig. 4a-f shows the results of heat distribution for different target sizes. In all cases the impactor velocity is 15 km/s and the impactor/target ratio is 2/69. The different cases show that the magnitude of the antipodal feature clearly depends on the absolut size of the target body. For bigger (hotter) targets it is much more pronouncend than for the smaller (colder) objects.

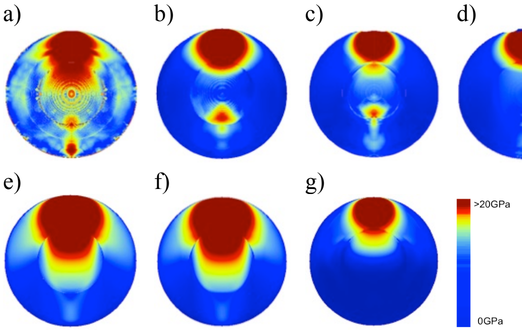


Fig. 4: Peak pressures after impacts with the same impactor/ target ratio but different absolut sizes. a) 13800 km target; b) 6900 km target; c) 5175 km target; d) 3450 km target; e) 690 km target; f) 69 km target; g) 6900 km target without gravity

Fig. 4g shows the same sizes as case b, but gravity is neglected here artificially. Hence, a constant starting temperature and pressure profile is given. The missing antipodal feature suggests that its occurrence strongly depends on the thermodynamic structure of the planetary interior and not only on the curvature of the surface.

**Effect of the core:** Small asteroids tend to be not differentiated and may be approximated by a homogenious sphere. Large asteroids, planetesimals and planets, normally form a separated core, a mantle, and a crust with different thermodynamic properties. In sufficiently large planets the core may be molten. In an additional study we compare the effect of impacts into an undifferentiated pure dunitic planet, a planet with a liquid iron core and a planet with a solid iron core (Fig. 5). The size of the target is kept constant, gravity changes slightly due to the higher density of the iron cores. The heat transfer into the planet is slightly different in all cases. The existence of a core influences the shock wave propagation through the target and, thereby, the distribution of heat. The shape and intensity of the antipodal feature is also affected by the core but it exists in all cases. Therefore we conclude that it is not necessary to have a separated core to get an antipodal feature.

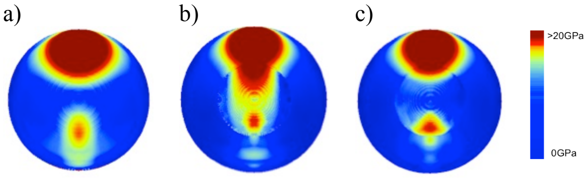


Fig. 5: Peak pressures after an impact of a 200 km projectile at 15 km/s into: a) 6900 km target without core; b) 6900 km target with liquid core; c) 6900 km target with solid core

**Conclusions:** Basin forming impacts affect the interior of the target body by transfering heat into the planet. The amount and distribution of the deposited heat depends on a number of factors: Most obviously, the higher the impact energy, the more heat is deposited into the planet and the more pronounced is the existence of an antipodal feature. The next major parameter is the impact angle. The lower the angle of incidence the less efficient the energy is transferred to the planet and the less deep it is deposited. The latter may be particularly important to assess whether large impacts are capable to affect convection processes in a liquid core and thus, a geodynamo (for example on Mars). Despite the asymmetry of shock wave propagation in oblique impacts, an antipodal feature occurs at impact angles >> 20°. Finally, heat deposition depends on the thermal structure and the existence of a differentiated core and mantle. The models show that the antipodal effect is much more pronounced for bigger warm planetary objects than for cold small bodies where it is almost not existent. The existence and thermodynamic state of the core mainly influences the heat distribution inside the core. A separated core, solid or liquid, leads to shock wave reflections at the core mantle boundary, increasing the heat transfer into the core. An antipodal effect occurs regardless of the existence or thermodynamic state of a separated core.

**Acknowledgements:** We thank B.A: Ivanov and H.J. Melosh for contributing to the development of iSALE. This work was funded by Helmholtz-Alliance "Planetary Evolution and Life"(WP3200).

**References:** [1]Watters W.A. et. al. (2009), *J. Geophys. Res*., 114 [2]Roberts J.H. et. al. (2009), *J. Geophys. Res*., 114 [3]Reese C.C. et. al. (2004), *J. Geophys. Res*., 109 [4]Arkani-Hamed, J. and P. Olson (2010), *Geophys. Res Lett.*,37 [5]Bierhaus M. et. al. (2011), *$42^{st}$ LPSC Abstract #2128* [6]Neumann W. et. al. (2010), *Abstract EPSC2010*-858 [7]Amsden A.A. et al. *Los Alamos National Laboratories Report*, LA-8095:101p, (1980). [8]Ivanov B.A. et al., (1997), *Int. J. Impact Eng.* 17, 375–386. [9]Wünnemann K. et. al. (2006), *Icarus*180 [10] Elbeshausen D. et al. (2009) *Icarus 204*, 716-731. [11] Elbeshausen D. and Wünnemann K. (2011) *Proc. HVIS XI*, 287-301. [12] Gault D.E. and Heitowit E.D.(1963), *6th hypervelocity Impact Symposium* [13]Pierazzo E. et. al. (1997), *Icarus* 127 [14]Ahrens T.J. and O'Keefe J.D. (1977), *Pergamon Press phys. Res*., 109