The fate of sandstone during impact cratering: shock compaction, cataclastic flow, and granular fluidization *Vortrag*

Thomas Kenkmann[1]

Impact of solid bodies is the most fundamental of all processes that have taken place on the terrestrial planets in our Solar system (Shoemaker 1977). On Earth, impact cratering was the dominant geologic process during the period of the early heavy bombardment until 3.8 Ga. A constant asteroid impact flux exists since that time. Although deformation of the crust by meteorite impacts is now subordinate with respect to tectonics, it represents an important, but often underestimated fraction of the bulk crustal deformation. Short-term deformation during hypervelocity impact events differs in many respects from standard tectonics: Unique conditions exist at pressures above the so-called Hugoniot elastic limit (HEL) of a particular mineral or rock. This state of compression is reached in a shock wave that propagates from the point of impact. Shock waves travel at supersonic velocity, heat and irreversibly deform the rock, and cause a residual motion of the material they have passed, which ultimately leads to the formation of parabolically shaped crater cavity of much larger extent than the projectile diameter. At pressure above the HEL minerals are subjected to shock metamorphism. For instance, the HEL of quartz is in the range of 3–5 GPa, pending on crystallographic orientation. With increasing shock pressure, quartz first displays reduction in refraction indices and birefringence (10–35 GPa). Localized amorphization occurs in this pressure interval along certain crystallographic directions and leads to the formation of so-called *Planar Deformation Features* (PDF) in which small stishovite crystals can form. PDFs are among the most important diagnostic features to prove the existence of ancient impact structures. Above 35 GPa quartz is completely transformed to amorphous glass while keeping its initial shape (diaplectic glass). Clusters of coesite can grow within this solid-state glass. Above 50 GPa quartz melted upon pressure release, as indicated by the formation of schlieren and vesicles. Vaporization of quartz is completed at about 100 GPa upon pressure release (Stöffler & Langenhorst 1994). The volume of rock affected by shock metamorphism increases unproportionally strong with increasing crater size. Since pressure decays with increasing distance from the point of impact, the zone of shocked rock is surrounded by a zone in which deformation by strong pressure waves occurs without indications of shock metamorphism. Deformation products of this area comprise cataclasites, monomictic and polymictic breccias, dikes, pseudotachylites, and variously faulted and folded rocks. The period of deformation during initial compression, and the subsequent excavation flow and crater modification at ambient pressure is in the order of seconds to minutes, pending on crater size. However, even in this short period the physical boundary conditions for deformation change in time and space and lead to a complex deformation path in which reversals in motion direction are com-

[1] Institut für Mineralogie, Museum für Naturkunde, Humboldt-Universität Berlin, Invalidenstrasse 43, 10115 Berlin

mon. A general characteristic of deformation during excavation is a radial symmetric, divergent, outward and upward directed flow. This is followed by an inward directed, convergent flow that dominates the gravity-driven crater collapse (Kenkman 2002). Here, the deformation history of porous sandstone during impact cratering is presented. These rocks were investigated experimentally (Kenkman 2006), and in the deeply eroded Upheaval Dome impact crater, Utah (Kenkman 2003, Kenkman et al. 2005). We can distinguish three stages of deformation: (i) deformation above the HEL of quartz, (ii) deformation at confining pressure below the HEL, (iii) deformation at fluctuating ambient pressure during the excavation and modifications stage of the cratering process:

i) Porous rocks behave differently in shock waves with respect to non-porous, dense rocks. Before the rock can be pervasively compressed, the pore space must collapse. Thus, a large amount of shock wave energy is spent for compaction prior to compression. This leads to reduced shock magnitudes, unusually high target heating, and more rapid shock decay. Since volume and size of the crater depend on shock magnitude and the decay in shock pressure with distance, the resulting crater will be smaller than a crater in a dense rock with the same bulk density. In weakly-shocked porous sandstone (<10 GPa) pore closure is accomplished by brittle fracturing of grains, in moderately and strongly shocked rocks, pore space collapse is accomplished by jetting, the extrusion of melted streams of hot SiO_2 material into the pores (Kieffer et al. 1976). PDF formation is relatively rare in porous sandstone. Most of the shock metamorphosed rock volume will be ejected from the crater.

ii) At pressures below the HEL shock metamorphism of quartz does not occur. But the attenuated shock wave still provides a considerable pressure and initiates a cataclastic flow within porous sandstones. Distributed cataclastic flow is defined as a microscopically brittle process in which a material's coherence is reduced by pervasive microcracking that affects the entire rock. The distributed cataclastic flow in the sandstones is initiated by grain crushing, collapse of pore space, and subsequent intergranular shear. An important result of the deformation at high confining pressure is that the cohesive sandstone is transformed to a non-cohesive sand by pervasive, delocalized intergranular cracking. Hence, further deformation is controlled by frictional properties rather than the fracture toughness of the rock.

iii) It is well-known that the strength properties of rocks are temporarily strongly reduced after the shock wave has passed through the rocks. Disturbances of the shock wave lead to strong residual seismic noise and vibrations behind a shock wave; a process which is called acoustic fluidization (Melosh 1979). The basic idea of acoustic fluidization is that seismic vibrations of grains, fragments, or blocks within the target result in fluctuations of the overburden pressure, which leads to slip events in periods of low pressures and reduced frictional strength. In terms of rheology the fluidized rock can be described with the properties of a Bingham plastic material (Melosh & Ivanov 1999), which is characterized by a linear viscous behavior after a yield strength is exceeded. Deformation at such fluctuating ambient pressures allows dilatancy and a rearrangement of grains in periods of unloading. Hence, the cataclastically deformed sandstones behave like unconsolidated sand and most likely deform in a pervasive granular flow. A macroscopic result of granular flow of sandstones during impact crater collapse is the formation of large sandstone dike networks, which occur, e.g. in the center of the Upheaval Dome impact crater, Utah. These dikes show extreme thickness variations, blind terminations and frequent embranchments at nodular-like points and indicate an almost complete loss of internal coherence during deformation. Fluidized sandstone accommodates space incompatibilities that arise from the deformation of more competent target rocks.

References

Shoemaker EM (1977) In: Roddy DJ et al. (eds) Impact and explosion cratering, Pergamon Press, New York, 1–10

Stöffler D & Langenhorst F (1994) Meteoritics, 29, 155–181

Kenkmann T 2002, Geology, 30, 231–234

Kenkmann T, Thoma K & the MEMIN team (2006) LPSC, 37, #1587

Kenkmann T (2003) EPSL, 214, 43–58

Kenkmann T, Jahn A, Scherler D & Ivanov, BA (2005) GSA Spec. Pap, 384

Kieffer SW, Phakey, DP & Christie, JM (1976) Contrib Min Petrol 59, 41–93

Melosh HJ, (1979) J Geophys Res 84, 7513–7520

Melosh HJ & Ivanov BA (1999) Annu. Rev. Earth Planet Sci 27, 385–415