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Particle size distribution and strain rate attenuation in hypervelocity impact and shock recovery experiments

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ABSTRACT

Particle size distribution (PSD) is an often used parameter to describe and quantify fragmentation of deformed rock. Our analyses of shock deformed sandstone show that dynamic fragmentation influences the PSD, expressed as fractal dimension (*D*-value). Image analysis was used to derive fractal dimensions from a hypervelocity impact cratering experiment (2.5 mm steel sphere, 4.8 km/s) and a planar shock recovery experiment (2.5 GPa). The *D*-values in the cratering experiment decrease from 1.74 at the crater floor to 0.84 at a distance of 7.2 mm to the crater floor. The *D*-values found in this experiment are closely related to the microstructural features found at distinct distances from the crater floor. The obtained values are in good agreement with the *D*-values reported for fault zones, impact sites and deformation experiments. The *D*-value measured in the shock recovery experiment is 2.42. Such high *D*-values were usually attributed to abrasive processes related to high strain. Since the strain in our experiment is only ~23% we suggest that at highly dynamic deformation very high *D*-values can be reached at small strain. To quantify this, numerical impact modelling has been used to estimate strain rates for the impact experiment. This is related to the activation of more inherent flaws and fracture bifurcation at very high strain rates $\sim>10^2\ s^{-1}$.

1. Introduction

Brittle failure of rock commonly involves a reduction of particle size. In general, this principle is scale-invariant and only determined by the development of fractures. It has been shown that particle sizes resulting from comminution are properly described by a fractal size distribution (e.g., Turcotte, 1986; Sammis et al., 1987; Marone and Scholz, 1989; Sammis and Biegel, 1989) and the resulting power-law slope in a double-logarithmic plot. This allows quantifying the degree of fragmentation of fault rock (Storti et al., 2003). Using the relation:

$$N(d) \approx d^{-D} \qquad (1)$$

where $N(d)$ is the number of particles larger than the diameter d, and D is the fractal dimension. As the word "fractal dimension" might be misleading when non-fractal processes are involved in the evolution of a self-similar particle size distribution (PSD), we here follow the suggestion of Heilbronner and Keulen (2006) and refer to this number as the *D*-value. Higher *D*-values indicate a larger portion of fine material and, thus, more effective grain comminution.

Several methods have been used to estimate the PSD of faulted rocks. This has included sieving (Anderson et al., 1980), optical microscopy (Biegel et al., 1989), the use of a Coulter counter (An and Sammis, 1994), scanning electron microscopy (Shao and Zou, 1996), laser diffraction (Storti and Balsamo, 2010), and transmission electron microscopy for particles down to 15 nm (Olgaard and Brace, 1983; Chester et al., 2005). PSD are commonly presented on a log–log plot of grain diameter versus frequency plots, with the *D*-value ("fractal dimension") defining the slope of the PSD.

Depending on the methodology, two-dimensional or three-dimensional *D*-values are derived. A three-dimensional distribution is a description of all particles in a given volume (e.g. sieving),

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Table 1
Selection of *D*-values measured for different deformation modes and materials.

Deformation setting	Material	2D *D*-value	Reference
Low strain rate natural deformation			
Natural fault zone	Granite	1.6	Sammis et al., 1987
Natural fault zone	Granite	1.6	Sammis and Biegel, 1989
Natural fault zone	Granite, gneiss	0.8–2.1	Blenkinsop, 1991
Natural fault zone	Arkose	1.6–2.0	
Natural fault zone	Granite	1.4–2.6	An and Sammis, 1994
Natural fault zone	Gneiss	1.6–1.9	
Natural fault zone	Tonalite	1.5–1.9	
Natural fault zone	Schist and gneiss	1.6	Shao and Zou, 1996
Natural fault zone	Granite	1.7–2.3	Monzawa and Otsuki, 2003
Natural fault zone	Carbonate	0.88–2.49	Storti et al., 2003
Natural fault zone	Carbonate	1.09–1.93	Billi and Storti, 2004
Natural fault zone	Granite	2.0	Chester et al., 2005
Natural fault zone	Shale	2.3	Ma et al., 2006
Natural fault zone	Granitoids	1.6–2.4	Keulen et al., 2007
Natural fault zone	Tonalite	1.8	Pittarello et al., 2008
Natural fault zone	Sand	1.64–2.02	Balsamo and Storti, 2011
Natural fault zone	Dolostone	1.49–1.56	Fondriest et al., 2012
Low strain rate tests			
Hydrostatic load 20 MPa	Crushed Ottawa sand	1.4	Marone and Scholz, 1989
Hydrostatic load 100 MPa	Crushed Ottawa sand	1.8	
Shear test	Crushed Ottawa sand	1.6	
Shear test	Artificial gouge	1.6	Biegel et al., 1989
Shear test	Westerly granite	1.6	
Three axial compression	Quartz sandstone	1.9–2.5	Hadizadeh and Johnson, 2003
Three axial compression	Granitoids	1.4–2.3	Heilbronner and Keulen, 2006
Three axial compression	Granitoids	1.4–2.3	Keulen et al., 2007
Rotary shear experiment	Granitoids	1.54–2.26	Stünitz et al., 2010
Three axial compression	Granite	1.13–2.28	Dyer et al., 2012
High strain rate tests			
Impact experiment	Basalt	1.4–1.62	Fujiwara et al., 1977
Chemical explosion		1.42	Schoutens, 1979
Nuclear explosion		1.50	
Impact experiment	Basalt	1.44–1.71	Lange et al., 1984
Natural impact site	Sudbury Breccia	1.2–1.8	Rousell et al., 2003
Natural impact site	Sandstone	1.55	Key and Schultz, 2011
Cratering experiment	Sandstone	0.84–1.74	This study
Shock recovery experiment	Sandstone	2.42	This study

whereas a two-dimensional distribution is a description of all particles encountered by a two-dimensional section through the three-dimensional volume (e.g., from image analysis). Based on the concepts of stereology (Underwood, 1970) it was shown by Turcotte (1986) and An and Sammis (1994) that a given three-dimensional "fractal dimension" can be transformed into a two-dimensional value by subtracting 1. In this study *D*-values taken from the literature have been converted into two-dimensional values. Numerous particle size analyses have been published for natural fault zones in sandstone (Balsamo and Storti, 2011), quartzite (Olgaard and Brace, 1983), quartz-rich crystalline rock (Sammis and Biegel, 1989; Blenkinsop, 1991; An and Sammis, 1994; Chester et al., 2005; Keulen et al., 2007; Pittarello et al., 2008), metamorphic rocks (Blenkinsop, 1991; An and Sammis, 1994; Shao and Zou, 1996), limestones (Storti et al., 2003; Billi and Storti, 2004; Fondriest et al., 2012), and shales (Ma et al., 2006). Also a wide range of data has been obtained for different deformation tests, including sledgehammer blows (Hartman, 1969), explosive testing (Schoutens, 1979; Grady and Kipp, 1987), triaxial loading (Sammis et al., 1986; Marone and Scholz, 1989; Hadizadeh and Johnson, 2003; Heilbronner and Keulen, 2006), shear tests (Biegel et al., 1989; Marone and Scholz, 1989; Stünitz et al., 2010), and impact experiments (Fujiwara et al., 1977).

D-values have been frequently used to compare particle sizes of naturally and experimentally deformed rocks (Sammis et al., 1987; Marone and Scholz, 1989; Blenkinsop, 1991; An and Sammis, 1994; Shao and Zou, 1996; Reches and Dewers, 2005; Wilson et al., 2005; Heilbronner and Keulen, 2006; Keulen et al., 2007; Glazner and Mills, 2012). A compilation of *D*-values for fractured materials is given in Table 1. The *D*-values cover a range between 0.8 and 2.5 for different rock types and loading conditions. Fault gouge material typically has higher *D*-values ($D \approx 2$) than cracked grains deformed without significant displacement ($D \approx 1.6$) (Sammis and King, 2007). It has been suggested that PSD may be related to strain and/or strain rate (Grady and Kipp, 1987; Hadizadeh and Johnson, 2003; Zhou et al., 2005; Stünitz et al., 2010) but no quantitative relation for strain has been found (Keulen et al., 2007). Grady and Kipp (1987) first established a relationship between strain rate and resulting fragment size distribution using controlled blasting experiments with oil shale. The general idea behind this relationship is that at increased strain rates more inherent flaws of the deformed material are activated at the same time. This is due to the limited propagation velocity of a single crack and leads to an increased fracture density and, thus, may influence the *D*-value.

The relationship between strain, strain rate and PSD is of fundamental interest for the investigation of meteorite impact-related damage on Earth and planetary surfaces. It could possibly be used to provide additional constraints to characterize an impact event by quantification of impact damage. A first attempt to relate PSD and damage to impact-induced deformation was made by Fujiwara et al. (1977), who analyzed the destruction of basaltic bodies, and Lange et al. (1984), who analyzed ejected fragments of gabbroic targets. First PSD investigations at natural impact sites were reported by Rousell et al. (2003) for Sudbury, Canada and by Key and Schultz (2011) for Upheaval Dome, Utah. The latter structure was recently confirmed as an impact crater (Buchner and Kenkmann, 2008)

Here, we provide the first-ever spatially resolved PSD measurements for experimental impact events. We compare the PSD of a mesoscopic sandstone target deformed by a hypervelocity impact cratering experiment with the PSD induced in a small sandstone specimen experimentally shocked at 2.5 GPa in a planar shock recovery experiment. Porous sandstone was chosen as target material to account for the ubiquitous porosity of earth and planetary targets. Of the 184 known impact structures on earth ca. 70% occur full or partly on sedimentary rocks which possess varying degrees of porosity (*earth impact database*). Similarly planetary surfaces are covered widely by porous regolith breccias, or even exhibit porous eolian and fluvial sediments. All experiments were performed in the framework of the MEMIN (Multidisciplinary Experimental and Modeling Impact research Network) German Science Foundation research unit at the facilities of the Fraunhofer Institut für Kurzzeitdynamik, Ernst-Mach-Institut (EMI), in Freiburg, Germany. All experimentally deformed materials were analyzed by image analysis of scanning electron microscope (SEM) photomicrographs obtained in back-scattered electron (BSE) mode. To gain more insight in the development of the measured *D*-values, numerical modeling has been used to estimate the decreasing strain rates in the target of the impact experiment. The results are discussed in the context of PSD reported from natural fault zones, rock deformation experiments and impacts.