

Experimental impact cratering: A summary of the major results of the MEMIN research unit

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Abstract—This paper reviews major findings of the Multidisciplinary Experimental and Modeling Impact Crater Research Network (MEMIN). MEMIN is a consortium, funded from 2009 till 2017 by the German Research Foundation, and is aimed at investigating impact cratering processes by experimental and modeling approaches. The vision of this network has been to comprehensively quantify impact processes by conducting a strictly controlled experimental campaign at the laboratory scale, together with a multidisciplinary analytical approach. Central to MEMIN has been the use of powerful two-stage light-gas accelerators capable of producing impact craters in the decimeter size range in solid rocks that allowed detailed spatial analyses of petrophysical, structural, and geochemical changes in target rocks and ejecta. In addition, explosive setups, membrane-driven diamond anvil cells, as well as laser irradiation and split Hopkinson pressure bar technologies have been used to study the response of minerals and rocks to shock and dynamic loading as well as high-temperature conditions. We used Seeberger sandstone, Taunus quartzite, Carrara marble, and Weibern tuff as major target rock types. In concert with the experiments we conducted mesoscale

numerical simulations of shock wave propagation in heterogeneous rocks resolving the complex response of grains and pores to compressive, shear, and tensile loading and macroscale modeling of crater formation and fracturing. Major results comprise (1) projectile–target interaction, (2) various aspects of shock metamorphism with special focus on low shock pressures and effects of target porosity and water saturation, (3) crater morphologies and cratering efficiencies in various nonporous and porous lithologies, (4) in situ target damage, (5) ejecta dynamics, and (6) geophysical survey of experimental craters.

INTRODUCTION

Impact experiments have played a pivotal role for the understanding of the general principles of impact cratering (e.g., Shoemaker et al. 1963; Stöffler et al. 1975; Schultz 1987). As illustrated in Table 1, the range of scales at which experiments were conducted comprises several orders of magnitude: nuclear tests yielded craters at the size of simple natural craters (e.g., Schooner, Nevada test site; 300 m diameter $\varnothing$) and allowed qualitative assessment of processes occurring in a fireball (e.g., Nordyke 1977). Buried high-explosive charges (~ 500 t TNT) yielded craters with $\varnothing \geq 100$ m (e.g., Roddy 1977). Large-scale cratering experiments were mostly designed to constrain the yield of the explosion and to assess the lateral decay of shock pressure. The impact-explosion analogy was investigated in such experiments and provided a basis for the understanding of impact processes (Cooper and Sauer 1977; Oberbeck et al. 1977). These large-scale military experiments of the 1960s and 1970s were gradually replaced by increasingly more powerful and sophisticated numerical simulations (e.g., O’Keefe and Ahrens 1989; Pierazzo et al. 1998; Artemieva and Shuvalov 2008).

A different class of large-scale experiments has been performed in recent years in space research with real-time observations of impact crater formation, impact flashes, and early ejecta. Outstanding examples for this are the observations related to the NASA missions Deep Impact (Comet Temple 1; A’Hearn et al. 2005; Schultz et al. 2013) and LCROSS (impact on the Moon; e.g., Colaprete et al. 2010; Schultz et al. 2010).

Table 1 provides a summary of different dynamic experimental approaches commonly used in impact research. The first subdivision relates to consolidated/solid target material versus unconsolidated/granular target materials. Experiments with unconsolidated granular materials are used to study (1) the effect of gravitational acceleration (e.g., Gault and Wedekind 1977; Schmidt and Housen 1987), (2) the excavation flow field and ejection mechanisms and ejecta emplacement (e.g., Stöffler et al. 1975; Cintala et al. 1999; Barnouin-Jha et al. 2007; Hermalyn and Schultz

2011; Wünnemann et al. 2016), (3) the effect of oblique impacts on crater formation (Gault and Wedekind 1978; Anderson et al. 2004; Ormö et al. 2015), and (4) the role of unconsolidated wet targets (Ormö et al. 2013). Such experiments allow for dimensionless scaling in the gravity regime (e.g., Housen et al. 1983; Holsapple 1993; Holsapple and Housen 2007). Due to the lack of cohesion of the target materials, these experiments require horizontally oriented targets, and thus, a vertical or inclined acceleration setup. NASA’s unique vertical ballistic gun range at the Ames Research Center has been used for this type of experiments (e.g., Gault and Wedekind 1978; Schultz 1987; Crawford and Schultz 1991).

MEMIN, in contrast, has focused on laboratory-scale shock and cratering experiments into solid rocks (Kenkmann et al. 2011a). The launch direction can, thus, be horizontal with the target surface oriented vertically. However, gravity effects cannot be investigated with the horizontal setup. We have further subdivided the dynamic experiments listed in Table 1 into cratering experiments *sensu stricto*, in which hemispherical or “3-D” shock waves are generated, and planar impact experiments in which planar shock waves (“2-D”) are produced. Both setups are used for different purposes. Major goals of cratering experiments into consolidated targets are to reconstruct (1) crater growth, (2) the spatial distribution of subsurface damage and shock metamorphism in craters, and (3) using recording techniques such as high-speed videos to document ejecta dynamics in real time. Moreover, impact-induced damage in the crater subsurface can be correlated with petrophysical and geophysical characteristics measured before and after such experiments (e.g., Polanskey and Ahrens 1990; Ai and Ahrens 2005).

A great challenge is that craters in solid rocks are often only a few centimeters in diameter due to the limiting factors of projectile size and velocity (= impact energy) (e.g., Burchell and Whitehorn 2003). In such experiments, the projectile size is so small that it is often of similar size as the grain size of the target material (mm). Since the pressure pulse duration depends on projectile size, extremely short loading pulses occur in the grain assemblies of the target materials. Scaling the

Table 1. Summary of different dynamic experimental approaches used in impact research.

Material	Setup	Facility	Shock duration		Shock pressures (GPa)	Used to study	Advantages	Disadvantages
				(μsec)				
Solid	Cratering experiments	Gas accelerator			$0 - > 100$ hemispherical spreading	Projectile–target interaction, shock metamorphism, cratering flow field, ejection	Acceleration horizontal, target in upright position	Exact shock pressure hard to quantify, scaling only in the strength regime, high energies required
		Nuclear/explosive devices		> 10	> 100 hemispherical spreading	Shock metamorphism, impact-explosion analogy	Large-scale craters	See (1), point source instead of line source
	Planar impact	Gas accelerator/explosive devices (free sample surface)		$0.1 - 1$	$10 - > 100$ planar shock	Material characterization, fragmentation, Hugoniot data	Hugoniot data	Recovery problematic due to sample fragmentation
		Gas accelerator/explosive devices (embedded sample)		$0.1 - 1$	$10 - 100$ Planar shock (impedance or reverberation technique)	Shock metamorphism under controlled shock conditions	Full recovery, calibration of shock features	Impedance technique: Hugoniot data of sample material must be known for pressure determination; Reverberation technique: somewhat unrealistic owing to multiple reflections and reduced heat production
Granular	Cratering experiments	Laser shock		< 0.001	> 100 planar shock	Shock metamorphism	Extreme pressures, good cost-value ratio fast repetition	Extremely short pulses
		Split Hopkinson pressure bar		No	$0.05 - 0.5$ subshock planar pressure waves	Response to dynamic loading conditions	Response to stress, strain, and strain rate, determination of dynamic increase factor	Recovery problematic due to sample fragmentation
		Membrane-driven/dynamic diamond anvil cell		No	$50 - 100$ loading rate of a few GPa s^{-1}	High-pressure phase transformation, amorphization	In situ, real-time recording via diffraction	Uncontrolled heterogeneous stress field in the chamber, no shock loading
		Gas accelerator			$0 - 60$ hemispherical spreading	Cratering flow field, ejection, crater modification, scaling	Scaling in the gravity regime, ejecta emplacement, effects of oblique impacts	Acceleration vertical or oblique, target must be in horizontal position, Material not representative
		Nuclear/Explosive devices		> 10	> 100 hemispherical spreading	Shock metamorphism, impact-explosion analogy	Large-scale craters	See (1), point source instead of line source

Methodology used in the framework of MEMIN are given in italics.

results of such experiments to nature is particularly difficult and usually only valid for the strength regime of crater formation. To produce much larger experimental craters with a diameter in the decimeter range in solid targets that would allow detailed spatial analysis, it is, thus, essential to use powerful accelerators. The availability of such equipment at the Ernst-Mach Institute (EMI) in Freiburg (Lexow et al. 2013) was a prerequisite for the conception and realization of the MEMIN project.

Planar impact experiments (Table 1) have the advantage over cratering experiments that the magnitude of the shock pressure can be precisely determined and—due to plane-strain conditions—deformation is more homogeneous. Planar impact flyer plates accelerated with light-gas guns are used to derive Hugoniot data of minerals and rocks (e.g., Ahrens 1987; Ahrens and Johnson 1995; Trunin 2001; Zhang et al. 2017). They are important for the construction of equation of states (EOS) at dynamic pressures of up to ~100 GPa and yield primary input parameters for the numerical modeling of impact processes. Hence, they are crucial for accurate simulations. In recent studies particular attention has been paid to porous rocks (Millon et al. 2016; Hoerth et al. 2017) or to the thermodynamic behavior of ice and rock–ice mixtures (Stewart et al. 2008; Kraus et al. 2010).

Planar impact shock recovery experiments may also use explosive devices to accelerate the flyer plates (Table 1) and have played a pivotal role for the calibration of shock-related effects in a variety of minerals and rocks (e.g., Langenhorst and Deutsch 1994; Thoma et al. 2005). Systematic experimental studies have been carried out for a number of minerals and rocks at the EMI (e.g., Müller and Hornemann 1969; Reimold and Stöffler 1978; Deutsch and Schärer 1990; Langenhorst et al. 1992; Langenhorst and Deutsch 1994; Schmitt 2000). A fundamental result is that material undergoes systematic changes with increasing shock pressure, from fracturing, via phase transitions, to melting, and vaporization. Shock recovery experiments in the low-shock regime that have not been investigated systematically in the past formed an important aspect of the MEMIN effort (Kowitz et al. 2013a, 2016).

The main objective of MEMIN has been to comprehensively quantify impact processes by conducting highly controlled experimental cratering campaigns at the laboratory scale, with concomitant multidisciplinary analytical approaches. Central to MEMIN has been the use of powerful two-stage light-gas accelerators capable of producing impact craters in the decimeter size range in solid rocks that allowed detailed spatial analysis of petrophysical, structural, and

geochemical changes in target rocks and ejecta. These experiments were aimed at supplying input data for validating numerical models. A further goal has been to extrapolate the experimental results to strength-dominated simple, bowl-shaped natural craters (Poelchau et al. 2013), in accordance with accepted scaling laws (e.g., Holsapple 1993; Holsapple and Housen 2007), and to improve and validate shock physics codes by conducting numerical experiments (Wünnemann et al. 2011). The two-stage light-gas gun experiments were complemented by conventional high-explosive and “fast” membrane-driven diamond anvil cell experiments with real-time recording of the crystallographic modifications, both aiming at a better understanding of deformation and transformation behavior of quartz and quartzitic target rocks under dynamic conditions.

MEMIN (www.memin.de) is a so-called Research Unit financed by the Deutsche Forschungsgemeinschaft DFG. A DFG Research Unit (Forschergruppe) is made up of a team of researchers working together on a medium- to long-term joint research project, which, in terms of thematic focus, duration, and finances, extends beyond other standard funding options. Research Units carry out intensive, cooperative projects and often contribute to establishing new fields of research in the respective host institutions. The MEMIN team was gathered by the speaker, and consisted of a central project plus eight thematically concerted projects, each of them financed by a grant to its principal investigators. Prior to its foundation, the MEMIN proposal was evaluated in a two-stage screening process by an international panel. In addition, a mid-term and final evaluation are integral parts of funding. In the context of the MEMIN project, 36 researchers collaborated with each other, and so far 13 doctoral and 17 master’s and bachelor’s theses were successfully completed. Connecting university-based research with exceptional experimental facilities and capabilities of external, nonuniversity research organizations like the Fraunhofer Gesellschaft and the Helmholtz Gemeinschaft, offered unique opportunities for these young scientists.

THE ACCELERATION FACILITIES USED FOR MEMIN EXPERIMENTS

The MEMIN research unit used two types of two-stage light-gas accelerators at EMI: the space light-gas gun (SLGG) (Schneider et al. 1995; Schäfer et al. 2006) and the extra-large light-gas gun (XLLGG; Lexow et al. 2013). EMI’s SLGG is designed to reach extreme impact velocities. The pump tube has a length and caliber of 1.8 m and 40 mm respectively, and a launch

tube length of 1.5 m with a caliber of 8.5 mm. A maximum impact velocity of 9.1 km s^{-1} had been attained with this facility (Schneider et al. 1995). In the course of MEMIN, a maximum impact velocity of 7.85 km s^{-1} was achieved (Table 2). The XLLGG accelerator has a length of 37 m and can be set up as a two-stage light-gas gun or single-stage launcher. In the two-stage setup, configurations based on pump tubes with either 100 or 154 mm caliber and lengths between 7 and 22 m are used. Launch tube calibers vary between 25 and 70 mm and length between 6 and 12 m (Lexow et al. 2013) (Fig. 1). Generally, an increase of the accelerated masses goes nonproportionally at the expense of launch velocity. During the MEMIN campaigns with the XLLGG, we used projectiles of 1.0–1.2 cm diameter with masses of 4–7 g at velocities up to 5.5 km s^{-1} . At the SLGG, spherical projectiles of 2.0, 2.5, 4.0, 5.0, and 6.17 mm diameter with masses ranging from 0.22 to 0.36 g were used. The spherical projectiles consisted of different steels, aluminum, basalt, and Campo del Cielo iron meteorite (Table 2). The range of kinetic energies in our experiments varied over more than three orders of magnitude (46–83,000 J). Projectiles were placed in cylindrical Lexan sabots that aerodynamically separate from the projectiles in the blast tank (Fig. 1a). Chamber pressures varied between 1 and ~500 mbar (Poelchau et al. 2013). We used cubes of Seeberger sandstone, Taunus quartzite, Carrara marble, and Weibern tuff as major target rock types. All rocks were carefully selected and originated as dimension stone from quarries. Selection criteria were a homogeneous texture, lack of fractures, and a well-defined and preferably simple mineralogical composition. Anisotropic rocks with bedding planes or foliation were investigated perpendicular and parallel to the layering. The largest craters obtained in $\frac{1}{2}$ cubic meter target blocks of sandstone have diameters up to 40 cm (Kenkmann et al. 2011a; Poelchau et al. 2013). For a description of the planar plate shock recovery experiments we refer to Kowitz et al. (2013b) (Table 3). The split Hopkinson bar experiments are detailed in Zwiessler et al. (2017). The setup of the conducted laser melting experiments (Table 4) and membrane-driven diamond anvil cells are described in Ebert et al. (2017) and Carl et al. (2017), respectively.

PROJECTILE–TARGET INTERACTION

What happens to a projectile in a hypervelocity collision? The initial contact of projectile and target marks the moment in time when the highest pressures and temperatures prevail in the colliding bodies. MEMIN focused on the very early stage of cratering in a number of studies (Ebert et al. 2013, 2014, 2017;

Kenkmann et al. 2013; Hamann et al. 2016a, 2016b). This included the analysis of projectile deformation, melting, and vaporization and subsequent condensation, mixing of target and projectile, and subsequent solidification of projectile residues.

Deformation of Projectiles

The deformation of steel projectiles and the degree of projectile melting and vaporization were investigated at impact velocities between 2.5 and 5.3 km s^{-1} with centimeter-sized steel projectiles and sandstone targets (Kenkmann et al. 2013). This range of velocities is still well below natural impact velocities, and hence, results on heating, melting, and vaporization are not directly comparable with nature. However, the studied impact velocities are typical for small terrestrial crater strewn fields made by iron projectiles such as Henbury or Wabar. The masses of coherent projectile relics that could be recovered ranged from 58 to 92% of initial projectile masses. These relics often had shapes of deformed bowls with convex outer and irregularly formed or concave inner sides (cf. Kenkmann et al. 2013); a serrated, sometimes fragmented rim; and a knobby region in the center of the inner side (Fig. 2a). The overall shape pointed to intense plastic deformation of such projectiles. Microstructural investigation of these projectile relics showed shearing and brittle fracturing at their surfaces. Melting and boiling of iron and silica were evident from the formation of bubbles, droplets, and melt filaments. For one experiment (P1-2808; Table 2), it was estimated that at least 4.4% of the impact energy had been dissipated by heating and melting of the projectile (Kenkmann et al. 2013). Small-scale residues of the projectile were ejected as spherules (Fig. 2b), unmelted fragments, and compound iron-silica aggregates.

Melting and Mixing

The melted and vaporized residues of projectiles showed complex mixing with target material. To mimic high fidelity scenarios, spheres fabricated from the IAB iron meteorite Campo del Cielo were used instead of steel projectiles in several MEMIN experiments (Ebert et al. 2013) (Table 2). Melted residues of these meteorite projectiles could be found in highly shocked ejecta that consist of complex intermingled target and projectile matter. Various amounts of projectile material were mechanically injected into the silicate targets. Heterogeneous melting of sandstone (or quartzite) and projectile occurred, followed by mixing of both melts. This process was found to involve significant interelement fractionation. In target melt, meteoritic Fe

Table 2. MEMIN impact experiments.

Experiment	Target material	Projectile material	v_i (km s ⁻¹)	E (kJ)	d (cm)	D (cm)	d/D	ρ_p/ρ_t	V (cm ³)	Target size (cm)	Chamber pressure (mbar)
A3-5124	Sst. dry	Steel	5.00	0.84	1.15	6.36	0.18	4	8.33	20 × 20 × 20	5
A5-5125	Sst. dry	Steel	5.10	0.87	1.17	6.24	0.19	4	8.80	20 × 20 × 20	100
A6-5126	Sst. dry	Steel	4.80	0.77	1.1	5.76	0.19	4	7.63	20 × 20 × 20	100
A8-5128	Sst. dry (parallel)	Steel	5.10	0.87	0.95	5.06	0.19	4	6.35	20 × 20 × 20	100
D2-3296	Sst. dry	Steel	4.40	39.69	5.19	24.2	0.21	4	629	50 × 50 × 50	~300
D3-3298	Sst. dry	Campo del Cielo	4.56	42.84	5.5	24.1	0.23	3.8	612	50 × 50 × 50	305
D4-3299	Sst. dry	Campo del Cielo	3.50	25.36	4.4	18.4	0.24	3.9	309	50 × 50 × 50	340
D5-3300	Sst. dry	Campo del Cielo	2.50	12.88	3.73	18.5	0.2	3.8	243	50 × 50 × 50	390
P1-2808	Sst. dry	Steel	5.34	58.41	5.6	24.3	0.23	3.4	715	100 × 100 × 50	500
E1-3382	Sst. dry	Steel	4.56	76.03	6.8	36.6	0.19	3.9	1393	80 × 80 × 50	~300
E4-3450	Sst. dry	Steel	4.68	80.34	6.55	36	0.18	4	1703	80 × 80 × 50	275
A11-5181	Sst. 90% sat.	Steel	5.30	0.94	1.43	10.2	0.14	3.6	31.10	20 × 20 × 20	100
A12-5183	Sst. 90% sat.	Steel	5.25	0.93	1.8	9.41	0.19	3.6	34.20	20 × 20 × 20	100
A13-5182	Sst. 50% sat.	Steel	5.25	0.92	1.4	7.48	0.19	3.7	13.40	20 × 20 × 20	100
A15-5185	Sst. dry	Al	6.97	4.35	1.43	10.45	0.14	1.3	42.93	20 × 20 × 20	100
A16-5186	Sst. dry	Al	7.75	0.67	0.64	3.92	0.16	1.3	2.65	20 × 20 × 20	100
P2-2809	Sst. 50% sat.	Steel	5.27	56.91	4.5	28.7	0.16	3.3	1099	100 × 100 × 50	500
E2-3383	Sst. 50% sat.	Steel	4.58	76.81	5.96	33.8	0.18	3.7	1298	80 × 80 × 50	~300
E3-3384	Sst. 50% sat.	Campo del Cielo	4.59	74.66	5.1	40	0.13	3.6	1829	80 × 80 × 50	~300
A20-5339	Quartzite	Steel	5.43	0.99	1.06	5.94	0.18	3.1	7.61	20 × 20 × 20	100
A22-5340	Quartzite	Steel	5.32	0.94	0.98	7.08	0.14	3.1	7.94	20 × 20 × 20	100
E6-3452	Quartzite	Steel	4.71	81.06	5.5	28.5	0.19	3.1	1684	80 × 80 × 40	295
A24-5341	Tuff	Steel	5.57	1.04	2.01	4.23	0.48	5.7	5.67	20 × 20 × 20	100
A25-5342	Tuff	Steel	5.40	0.97	2.27	4.09	0.56	5.7	5.22	20 × 20 × 20	100
E5-3451	Tuff	Steel	4.76	82.73	8.9	21.3	0.42	5.7	674	80 × 80 × 50	270
A26-5343	Tuff wet	Steel	5.48	1.01	1.99	6.43	0.31	7.96	17.93	20 × 20 × 20	100
A30-5610	Carrara marble	Basalt	4.94	4.42	1.26	12	0.105	1.1	43.51	25 × 25 × 25	1.1
A31-5611	Quartzite (parallel)	Basalt	5.46	5.49	—	—	—	1.1	—	20 × 20 × 20	1.2
A32-5612	Carrara marble	Al	7.00	2.16	0.82	7.5	0.11	1	11.58	25 × 25 × 25	0.9
A34-5614	Carrara marble	Campo del Cielo	5.00	0.79	0.56	5.5	0.10	4	5.04	25 × 25 × 25	1
A35-5615	Carrara marble	Al	7.04	2.18	0.87	6	0.15	1	10.76	25 × 25 × 25	0.9
A36-5666	Carrara marble	Al	7.03	2.17	—	—	—	1	12.92	25 × 25 × 25	1.4
A37-5667	Maggia Gneis (perpendicular)	Al	6.93	4.26	—	—	—	—	24.24	25 × 25 × 25	1.9

was selectively enriched over Ni and Co, whereas in coexisting meteoritic droplets and molten margins of projectile fragments, Ni and Co were enriched over Fe.

To better understand the interelement partitioning between projectile and target, spheres of D290-1 steel containing high amounts of Cr, Co, V, Mo, and W were used as projectiles in subsequent MEMIN

experiments. The above elements are below detection limit (quasi absent) in the sandstone and quartzite targets—thus allowing detailed tracing of projectile matter (Ebert et al. 2014). Again, significant interelement fractionation occurred during mixing of projectile and target material. The degree of element enrichment was mainly controlled by the lithophile or

<i>L</i> (mm)	<i>m</i> (g)	<i>P</i> (GPa)	Facility	HSFC ejecta	LSFC ejecta	Spectrometer	Ultrasound	Laser light sheet	Ejecta catcher	Jetting catcher	Publication
2.5	0.067	54	SLGG				x		x		1,11,12,13,24,25
2.5	0.067	55	SLGG	x	x		x		x		1,4,8,10,12,13,14,25
2.5	0.067	50	SLGG	x			x		x		1,4,6,7,9,10,12,13, 14,16,24,25
2.5	0.067	55	SLGG				x		x		1,11,12
10	4.1	43	XLLGG								1,8,12,13,25
10	4.12	45	XLLGG	x			x		x		1,8,9,12,13,14,15,25
10	4.14	29	XLLGG	x			x		x		1,8,12,13,14,17,25
10	4.12	16	XLLGG	x			x		x		1,12,13,14,17,25
10	4.1	59	XLLGG								1,12,13,17,18,19,25
12	7.313	46	XLLGG	x			x		x		1,2,4,5,8,12,13,14, 16,17,23,25
12	7.336	48	XLLGG	x			x		x	x	1,5,8,25
2.5	0.067	–	SLGG	x	x		x		x		1,4,6,8,12,13,14
2.5	0.068	–	SLGG	x	x		x		x		1,2,4,8,12,13,14,23
2.5	0.067	–	SLGG	x	x		x		x		1,4,8,12,13,14
5	0.179	66	SLGG	x	x		x		x		1,2,12,13,23,25
2.5	0.022	79	SLGG	x	x		x		x		1,2,12,13,23,25
10	4.1	–	XLLGG								1,12,13,17,18,19
12	7.323	–	XLLGG	x			x		x		1,4,5,8,12,13, 14,16,17
12	7.087	–	XLLGG	x			x		x		1,2,4,5,8,12,13, 14,17,23
2.5	0.067	84	SLGG	x			x		x	x	1,10,16,20,22,25
2.5	0.067	81	SLGG	x	x		x		x	x	1,10,25
12	7.311	66	XLLGG	x			x		x	x	1,2,16,23,25
2.5	0.067	51	SLGG	x	x		x		x		1,3,10
2.5	0.066	48	SLGG	x	x	x	x				1,3,10
12	7.312	39	XLLGG	x			x		x		1,3
2.5	0.067	–	SLGG	x	x		x		x		1
6.17	0.363	48	SLGG						x	x	
6.18	0.369	–	SLGG	x			x		x	x	
4	0.088	89	SLGG		x				x	x	
2.5	0.064	–	SLGG		x		x		x	x	22
4	0.088	89	SLGG		x		x		x	x	
4	0.088	89	SLGG		x	x	x		x		
5	0.178	–	SLGG		x	x	x		x		

siderophile character of the respective “tracer” element. The silica-rich target melts were strongly enriched in the projectile-derived elements Cr, V, and Fe, but show only minor enrichment of Co, W, and Mo. The different geochemical behavior of the tracer elements led to element ratios in the target melts that differ strongly from the respective element ratios of the projectile.

Therefore, determination of the projectile type via trace element ratios in terrestrial impactites may yield erroneous results as already noted by Attrep et al. (1991) and Mittlefehldt et al. (1992).

The study by Ebert et al. (2014) emphasized the importance of H₂O-bearing phases during impact melting, and showed that subordinate mineral phases in

Table 2. *Continued.* MEMIN impact experiments.

Experiment	Target material	Projectile material	v_i (km s ⁻¹)	E (kJ)	d (cm)	D (cm)	d/D	ρ_p/ρ_t	V (cm ³)	Target size (cm)	Chamber pressure (mbar)
A38-5668	Maggia Gneis (parallel)	Al	7.24	4.65	–	–	–	–	18.25	25 × 25 × 25	1.7
A39-5669	Savonnieres Limestone	Campo del Cielo	3.91	0.48	–	–	–	–	4.71	20 × 20 × 20	1.65
A41-5672	Savonnieres Limestone wet	Steel	4.80	0.72	–	–	–	–	12.54	25 × 25 × 25	100
A42-5695	Carrara marble	Al	2.60	0.60	0.65	5.71	0.11	1	5.93	25 × 25 × 25	120
A43-5696	Carrara marble	Al	3.50	1.09	0.63	5.06	0.12	1	4.57	25 × 25 × 25	120
A44-5698	Carrara marble	Al	4.91	2.14	0.99	7.87	0.13	1	15.65	25 × 25 × 25	120
A45-5699	Carrara marble	Al	2.75	0.05	0.22	1.38	0.16	1	0.12	25 × 25 × 25	120
A46-5700	Carrara marble	Al	3.11	0.06	0.26	1.64	0.16	1	0.19	25 × 25 × 25	120
A47-5701	Carrara marble	Al	4.75	0.13	0.38	2.24	0.17	1	0.49	25 × 25 × 25	120
A48-5702	Carrara marble	Al	3.92	0.09	0.29	1.78	0.16	1	0.27	25 × 25 × 25	120
A49-5703	Carrara marble	Al	4.18	1.55	0.88	7.10	0.12	1	11.26	25 × 25 × 25	120
A50-5708	Carrara marble	Al	6.41	3.64	1.06	10.58	0.10	1	31.06	25 × 25 × 25	120
A51-5709	Carrara marble	Al	6.30	0.25	0.42	2.98	0.14	1	0.96	25 × 25 × 25	120
A53-5711	Carrara marble	Al	7.85	0.37	0.48	3.35	0.14	1	1.28	25 × 25 × 25	120
A54-5712	Sst. 90% sat. (ice)	Steel	5.34	0.91	–	–	–	3.6	–	25 × 25 × 25	120
A56-5714	Carrara marble	Al	6.78	4.08	1.45	10.67	0.14	1	43.70	25 × 25 × 25	120

L = projectile diameter; m = projectile mass; v_i = projectile velocity; E = kinetic energy; P = peak impact pressure estimates for planar impact approximation; d = crater depth; D = crater diameter; ρ_p = projectile density; ρ_t = target density; V = crater volume; m = projectile mass; Sst. = sandstone; Sst. 90% sat. = sandstone saturated with water to 90%; Al = aluminum; SLGG = space light-gas gun; XLLGG = extra-large light-gas gun; HSFC = high-speed framing camera; LSFC = low-speed framing camera; x: measurement and sample collection techniques applied to experiment.

References: 1. Poelchau et al. (2014); 2. Wilk and Kenkmann (2016, Forthcoming); 3. Winkler et al. (2016a, 2016b); 4. Hoerth et al. (2013); 5. Hoerth et al. (2014); 6. Buhl et al. (2013a); 7. Buhl et al. (2013b); 8. Buhl et al. (2014a); 9. Buhl et al. (2014b); 10. Moser et al. (2013a, 2013b); 11. Moser et al. (2014); 12. Dufresne et al. (2013); 13. Poelchau et al. (2013); 14. Sommer et al. (2013); 15. Ebert et al. (2013); 16. Ebert et al. (2014); 17. Kenkmann et al. (2011a); 18. Kenkmann et al. (2011b); 19. Kenkmann et al. (2013); 20. Hamann et al. (Forthcoming); 21. Gulde et al. (2018); 22. Winkler et al. (2016b); 23. Wilk et al. (Forthcoming); 24. Raith et al. (Forthcoming); 25. Güldemeister et al. (2015).

silicate-rich targets can strongly affect the chemical exchange processes. The MEMIN experiments yielded results that are very similar to observations in nature, e.g., at Meteor Crater and the Wabar craters (Kearsley et al. 2004; Mittlefehldt et al. 2005; Hamann et al. 2013) or at Kamil crater (Fazio et al. 2016). Textural evidence of silicate liquid immiscibility in the impactites (including glasses) was (1) spherical droplets of one glass disseminated in a chemically distinct glassy matrix, (2) sharp phase boundaries (menisci) between the two glasses, (3) deformation and coalescence of silicate glass droplets, and (4) occurrence of secondary, nanometer-sized quench droplets in Si-rich glasses (Hamann et al. Forthcoming).

Laser Melting Experiments

Laser melting experiments (Table 4) turned out to be a very useful approach, complementary to impact experiments, to investigate the instantaneous melting,

mixing, and vaporization of projectile and target, and subsequent quenching under postshock P-T conditions (Hamann et al. 2016b; Ebert et al. 2017; Hamann et al. 2018, Forthcoming). Although not capable of creating high shock pressures, the experiments produce superheated melts that thermodynamically, texturally, and mineralogically resemble impact melts formed during adiabatic decompression. In particular, laser-generated melts formed from various combinations of planetary materials (sandstone, iron meteorite, basalt, limestone, marble) resembled true impact melts that occur in terrestrial impact structures (e.g., Kamil, Wabar, Meteor Crater, Haughton etc.; Hamann et al. 2018, Forthcoming) and from the MEMIN impact experiments. Using high-speed imaging, in situ temperature measurements, and petrologic investigations of the irradiated targets, Hamann et al. (2016b) calculated the entropy gains of the laser-generated melts and compared them with the entropy gains associated with the thermodynamic states

L (mm)	m (g)	P (GPa)	Facility	HSFC ejecta	LSFC ejecta	Spectrometer	Ultrasound	Laser light sheet	Ejecta catcher	Jetting catcher	Publication
5	0.178	–	SLGG		x	x	x		x		
2.5	0.063	–	SLGG		x	x	x		x		
2.5	0.063	–	SLGG		x	x			x		
5	0.1771	22	SLGG						x		
5	0.1781	32	SLGG	x				x	x		
5	0.1778	53	SLGG						x		
2	0.0122	24	SLGG	x				x	x		
2	0.0119	28	SLGG						x		
2	0.0119	50	SLGG	x				x	x		
2	0.0119	38	SLGG	x				x	x		
5	0.1772	42	SLGG	x				x			
5	0.1771	78	SLGG	x				x	x		
2	0.0126	76	SLGG	x				x	x		21
2	0.0121	106	SLGG	x				x			
2.5	0.0635	–	SLGG	x				x	x		
5	0.1774	85	SLGG	x				x	x		

produced in hypervelocity impacts at various velocities. The experiments extended the currently attainable postshock temperatures in impact experiments to ranges commensurate with impacts in the velocity range of 4–20 km s^{−1}, and hence allowed study of time scales of petrogenetic processes in impact melts. Laser melting experiments also allowed the determination of cooling rates and reaction times. Ebert et al. (2017) derived reaction times of 0.6–1.4 s for element partitioning and phase-separation processes in their experiments. In the experiments of Hamann et al. (2016b), the centimeter-sized ejected melt bodies cooled and solidified within tens of seconds, thereby constraining time scales for petrogenetic processes (melt mixing and mingling, element partitioning, crystallization, etc.) in ejected impact melt particles of similar size, composition, and thermal history.

Laser melting experiments with carbonate–silicate composite targets were also initiated to investigate the response of carbonates (calcite, dolomite) to superheated silicate melts taken as impact melt analogs

(Hamann et al. 2018). These experiments demonstrate that high-temperature interactions between silicate melts and carbonates at the silicate melt–carbonate interface are complex and extremely fast (tens of seconds), involving degassing of carbonates; formation of Ca- or Ca,Mg-enriched silicate melts; precipitation of Ca- or Ca,Mg-rich silicates; and back-reactions between residual, carbonate-derived oxides, and CO₂. Similar reaction products are also known from, for example, the Haughton (Martinez et al. 1994), Meteor Crater (Hörz et al. 2015), or Chicxulub (Deutsch and Langenhorst 2007) impact structures, and are at odds with the view that melting is the dominant response of carbonates to impact (e.g., Osinski et al. 2007). By combining experimental results with observations of previous studies and thermodynamic considerations of the phase diagrams of calcite and quartz, Hamann et al. (2018) present a working model of impact melting of mixed carbonate–silicate targets. This model suggests that the response of mixed carbonate–silicate targets to shock pressures sufficient to melt coexisting silicates is a

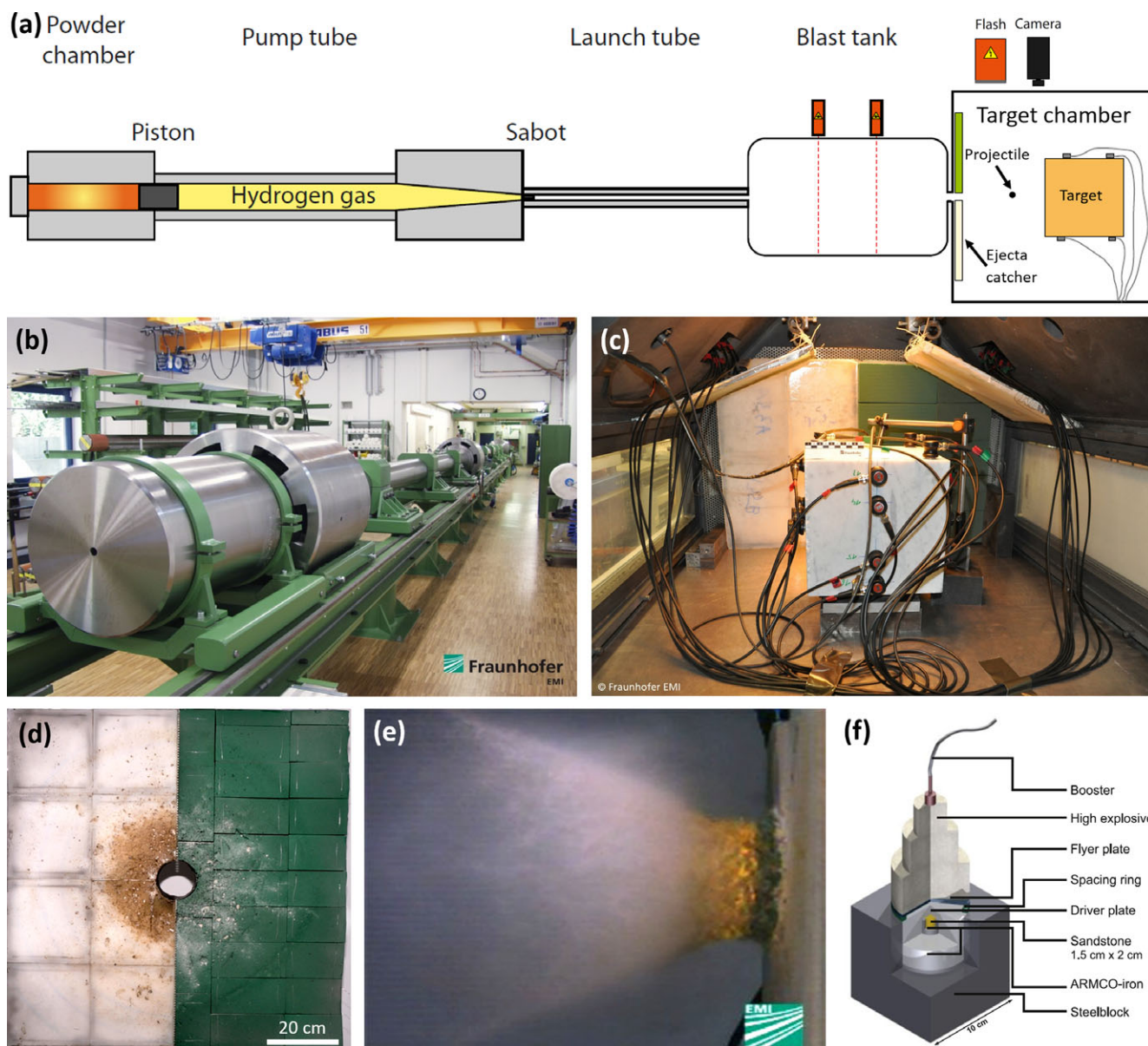


Fig. 1. a) Simplified schematic overview of a two-stage light-gas gun and the experimental setup, viewed from above (modified from Poelchau et al. 2013). b) Powder chamber and pump tube of the two-stage light-gas gun facility (XLLGG) at the Fraunhofer EMI, Efringen-Kirchen, Germany. c) Fully instrumented quartzite target block in the target chamber (SLGG facility). d) Ejecta catcher system (white: Vaseline plates; green phenolic foam plates) with characteristic imprints of the ejecta curtain. e) Ejecta cloud shortly after the impact. Width of the ejecta tube close to the target: ~10 cm. f) Experimental setup for shock recovery experiments (after Kowitz et al. 2013a).

highly idiosyncratic process that possibly involves both melting and decomposition of carbonates depending on a variety of factors (e.g., crater size, peak shock and final postshock pressure, and postshock thermal histories). This has implications for CO₂ emission into Earth's atmosphere following large-scale impacts into mixed carbonate-silicate targets (e.g., O'Keefe and Ahrens 1989; Pierazzo et al. 1998).

EXPERIMENTAL STUDIES ON SHOCK METAMORPHISM

MEMIN was also devoted to better understand mechanisms of shock metamorphism. Special attention was paid to shock effects in quartz at low shock pressures, close to the Hugoniot elastic limit, in both porous and dense rocks. For this purpose, planar

Table 3. MEMIN shock recovery experiments.

Exp. No.	Material	Cylinder (dia $\times$ length) (mm)	High-explosive	D_{fp} (mm)	v_{fp} (km s ⁻¹)	D_{dp} (mm)	p_{dp} (GPa)	p_m (GPa)	Pressure pulse duration (μ s)	Publication
1-01	Sst. L5	15 $\times$ 20	TNT	4	1.57	14.5	12.5	2.5	0.81	1
1-1	Sst. L5	15 $\times$ 20	TNT	4	1.57	6.5	18.4	5.0	1.11	1,4
1-2	Sst. L5	15 $\times$ 20	Comp.B	4	2.03	15.0	25.0	7.5	0.66	1,4
1-3	Sst. L5	15 $\times$ 20	Comp.B	4	2.03	10.0	33.5	10.0	0.87	1,4
1-4	Sst. L5	15 $\times$ 20	Comp.B	3	2.33	8.5	42.5	12.5	0.55	1,4
1-5	Sst. L5	15 $\times$ 20	Comp.B	3	2.33	3.2	48.4	15.0	0.79	1
1-6	Sst. L5	15 $\times$ 20	Comp.B	2	2.76	4.9	57.7	17.5	0.35	1
2-1	Sst. L3	15 $\times$ 20	TNT	4	1.57	14.5	12.5	2.5	0.81	1,2,3,5
2-2	Sst. L3	15 $\times$ 20	TNT	4	1.57	6.5	18.4	5.0	1.11	1,2,5
2-3	Sst. L3	15 $\times$ 20	Comp.B	4	2.03	15.0	25.0	7.5	0.66	1,2,5,6
2-4	Sst. L3	15 $\times$ 20	Comp.B	4	2.03	10.0	33.5	10.0	0.87	1,2,5
2-5	Sst. L3	15 $\times$ 20	Comp.B	3	2.33	8.5	42.5	12.5	0.55	1,2,5,6
2-6	Sst. L3	15 $\times$ 20	Comp.B	3	2.33	3.2	48.4	15.0	0.79	1,2,5
2-7	Sst. L3	15 $\times$ 20	Comp.B	2	2.76	4.9	57.7	17.5	0.35	1,2,5
3-1	Quartzite	15 $\times$ 20	TNT	4	1.57	12.9	13.0	7.5	0.85	1
3-2	Quartzite	15 $\times$ 20	TNT	4	1.57	9.1	16.0	10.0	1.00	1
3-3	Quartzite	15 $\times$ 20	TNT	4	1.57	5.5	20.0	12.5	1.14	1
3-4	Quartzite	15 $\times$ 20	Comp.B	4	2.03	14.7	26.0	15.0	0.66	1
3-5	Quartzite	15 $\times$ 20	Comp.B	4	2.03	11.5	32.0	17.5	0.80	1
4-1	Sst. L3	15 $\times$ 20	TNT	4	1.57	11.0	13.5	5.0	0.93	1
4-2	Sst. L3	15 $\times$ 20	TNT	4	1.57	6.9	17.0	7.5	1.10	1
4-3	Sst. L3	15 $\times$ 20	Comp.B	4	2.03	16.7	22.0	10.0	0.60	1
4-4	Sst. L3	15 $\times$ 20	Comp.B	4	2.03	13.9	28.0	12.5	0.72	1
4-5	Sst. L3	15 $\times$ 20	Comp.B	4	2.03	8.2	35.0	15.0	0.95	1
4-6	Sst. L3	15 $\times$ 20	Comp.B	3	2.33	9.4	42.0	17.5	0.52	1
4-7	Sst. L3	15 $\times$ 20	Comp.B	2	2.76	8.0	48.0	20.0	0.21	1

D_{fp} = thickness of the flyer plate; v_{fp} = velocity of the flyer plate; D_{dp} = thickness of the driver plate; p_{dp} = shock pressure at the base of the ARMCO-iron driver plate; p_m = calculated pressure at the top of the material cylinder.

References: 1. Kowitz et al. (2016); 2. Ebert et al. (2018); 3. Buhl et al. (2013b); 4. Kowitz et al. (2013a); 5. Kowitz et al. (2013b); 6. Mansfeld et al. (2017).

impact shock recovery experiments were performed with a high-explosive setup (e.g., Langenhorst and Deutsch 1994) in the pressure range from 5 to 20 GPa (Kowitz et al. 2013a, 2013b, 2016; Mansfeld et al. 2017; Ebert et al. 2018) (Table 3). Further emphasis was placed on the formation of shatter cones (Kenkmann et al. 2016; Wilk and Kenkmann 2016; Wilk et al. Forthcoming) and high-pressure polymorphs of quartz (Carl et al. 2017, Forthcoming).

The Effect of Porosity

The influence of porosity on shock metamorphism has been greatly appreciated ever since the seminal work by Kieffer (1971) and Kieffer et al. (1976) on

naturally shocked Coconino sandstone from Barringer (Meteor) Crater, AZ, USA. Data on naturally shocked porous, quartz-bearing rocks were discussed in Grieve et al. (1996), emphasizing the lack of a sophisticated pressure calibration. In MEMIN, shock effects in quartz of porous Seeberger sandstone were pressure calibrated (Kowitz et al. 2013a, 2013b; Ebert et al. 2018). Moreover, mesoscale numerical modeling (Güldemeister et al. 2013) yielded explanations for the observed features. The pore space in these experiments was completely closed at 2.5 GPa. Kowitz et al. (2013b) reported on the appearance of diaplectic quartz glass/SiO₂ melt already at 5 GPa. The amount of diaplectic quartz glass/SiO₂ melt increased up to ~80% at 17.5 GPa. It was found that the formation

Table 4. MEMIN laser melting experiments.

Exp. no.	Materials	Emitted power (kW)	Laser intensity (W cm^{-2})	Irradiation time (s)	Traverse length (mm)	Movement speed between laser and target (mm s^{-1})	Laser diameter (mm)	Estimated average cooling rate (K s^{-1})	Publication
LE-F	Sandstone plate	2	2.5×10^5	0.5	–	–	1	–	2
LE-G	Steel plate on top of sandstone plate	2	2.5×10^5	1	10	10	1	–	2
LE-H	Steel plate on top of sandstone plate	2	2.5×10^5	1	10	10	1	–	2
LE-I	Campo del Cielo plate on top of sandstone plate	2	2.5×10^5	1	10	10	1	–	2
887	Campo del Cielo plate on top of sandstone plate	8	2.5×10^4	2	20	10	2.2	~ 120	1,2,3
889	Alternating sequence of sandstone and calcite marble plates	8	2.5×10^4	6	30	5	5.9	~ 106	3
891	Basalt plate on top of limestone plate	8	2.5×10^4	6	30	5	5.9	~ 44	3
892	Basalt plate on top of calcite marble plate	8	2.5×10^4	6	30	5	5.9	~ 44	1,3
893	Powder target (Campo del Cielo, dolomite marble, sandstone)	8	2.5×10^4	2	20	10	5.9	~ 44	3

References: 1. Hamann et al. (2016a, 2016b); 2. Ebert et al. (2017); 3. Hamann et al. 2018, Forthcoming.

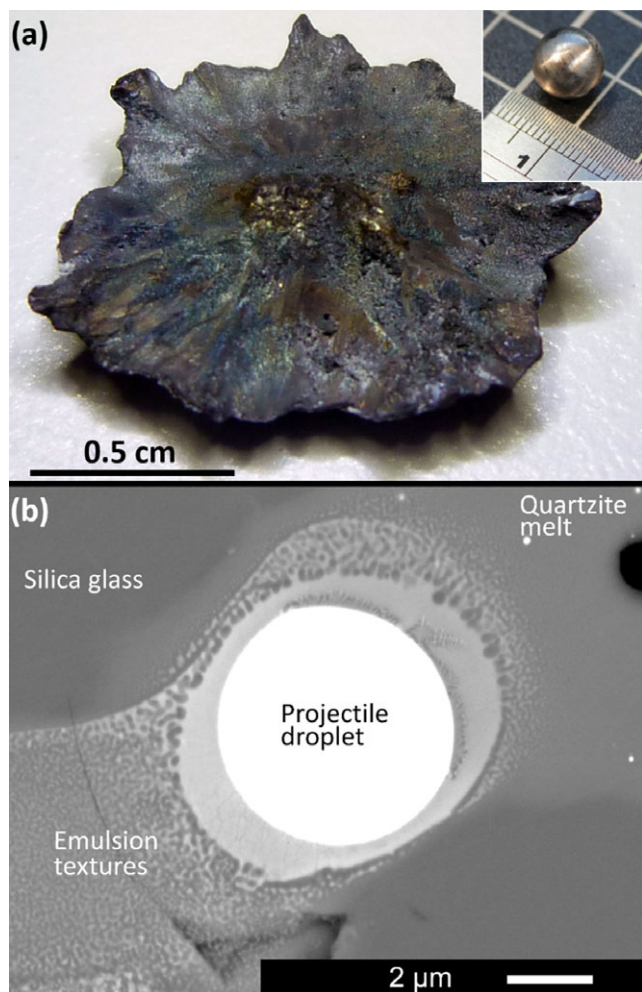


Fig. 2. a) Rear side morphology of a recovered projectile relic (MEMIN experiment E3-3384). The inset shows the original iron meteorite projectile sphere of this experiment. b) Back-scattered electron (BSE) image of a highly shocked quartzite ejecta particle showing typical projectile–target mixing and unmixing textures. Emulsion textures indicate liquid immiscibility during cooling (Ebert et al. 2014; Hamann et al. 2013, Forthcoming).

of SiO_2 melt is spatially related to the occurrence of pores. Collapsing pores locally generated shock pressure amplification up to >4 times the average (nominal) shock pressure experienced by the specimen (Güldemeister et al. 2013; Kowitz et al. 2013b) (Figs. 3a and 3b). For water-saturated rocks, a cataclastic texture (microbreccia) was typical for shock pressures up to 20 GPa. Melting of H_2O -rich sheet silicates played an important role in these experiments. The higher the amount of structural water in these minerals, the higher the shock compressibility of the phyllosilicates and the lower the shock pressure required to induce melting (Ebert et al.

2018). The results of these experiments in combination with numerical modeling could be used to improve the shock classification for porous, SiO_2 -bearing rocks and their shock calibration (see Kowitz et al. 2016).

Experimental Formation of Stishovite in Shock Recovery Experiments

Recovered samples from planar impact experiments with porous sandstone shocked to 7.5 and 12.5 GPa (Kowitz et al. 2013a, 2013b, 2016) (Table 3) showed small melt veins of 0.7–1.5 μm width with a higher electron density than their host-quartz (Fig. 4a). Transmission electron microscopy (TEM) revealed that these veins contain tiny, yet abundant stishovite crystals of less than 150 nm size (Langenhorst et al. 2015; Mansfeld et al. 2017) (Fig. 4b). This was the first evidence for stishovite generated in a low-pressure shock experiment. The occurrence of stishovite as polycrystalline, defect-free crystallites in quenched melt veins indicates genesis by fast crystallization from silica melt at high pressure. Calculations using the Stefan approach described in Langenhorst and Poirier (2000) indicate a crystallization time in the order of tens of nanoseconds. This observation rules out the previous hypothesis that stishovite is a residual product of solid-state transformation and favors stishovite formation by crystallization from impact melt. Calculations demonstrated that the cooling rates are sufficiently high to crystallize stishovite only if the melt veins are only a few micrometers wide.

An Alternative Approach: Dynamic Loading with Diamond Anvil Cells

An apparent mismatch exists when the static stability fields of high-pressure SiO_2 -polymorphs coesite and stishovite are compared to their occurrence in naturally shocked rocks. Coesite is found only in diaplectic SiO_2 glasses that were generated at peak shock pressures of 35–45 GPa (e.g., Stöffler and Langenhorst 1994; Langenhorst and Deutsch 2012). Stishovite, in turn, is observed in rocks that have experienced lower shock pressures than those containing coesite (Stöffler 1971), and commonly occurs in the context of melt pockets (Kieffer et al. 1976; Mansfeld et al. 2017) or melt veins (Langenhorst and Poirier 2000). This apparent discrepancy is explained by the crystallization of the high-pressure SiO_2 -polymorphs at different stages of the decompression path, i.e., at pressures that are well below the peak conditions (Stöffler and Langenhorst 1994; Langenhorst and Deutsch 2012).

Within MEMIN, the formation of high-pressure phases of α -quartz was studied under dynamic and nonhydrostatic conditions in a novel approach utilizing membrane-driven diamond anvil cells at pressures up to 66 GPa, at ambient temperature, and at different loading rates (Carl et al. 2017), and up to 70 GPa at high temperatures (Carl et al. Forthcoming). The phase transformations were recorded in situ and under real-time conditions by synchrotron powder X-ray diffraction at the Extreme Conditions Beamline (ECB, P02.2) at PETRA III, DESY, Hamburg. At compression rates between 0.14 and 1.96 GPa s⁻¹, α -quartz becomes amorphous and partially converts to stishovite between 20.7 and 28.0 GPa. Coesite could not be detected at such conditions. While these experimental data help us to understand the formation of high-pressure phases, we should keep in mind that the compression rates in these experiments were orders of magnitudes slower than in real shock compression.

At elevated temperatures and under nonhydrostatic and disequilibrium conditions, the phase transition from α -quartz to coesite, and the transition from coesite to stishovite were initiated (Carl et al. Forthcoming). Coesite was formed above 760 K in the pressure range 2–11 GPa. At 1000 K, coesite started to transform into stishovite at the same pressure, but this phase transition was not complete at 1160 K. Below 1000 K and during compression, α -quartz becomes amorphous and converts to stishovite between 25 and 35 GPa. Above 1000 K, no amorphization of α -quartz was observed. The ultimate goal of this type of studies is to understand the systematics of phase transformations during slow compression and extrapolating these findings to much faster shock compression in an effort to observe shock waves under real-time conditions. The latter will require even more brilliant light sources such as the European X-ray free electron laser, currently starting operation in Hamburg, combined with shock compression lasers such as the DIPOLE system, currently under construction for the Helmholtz International Beamline for Extreme Fields (HIBEF) located at the high-energy density (HED) instrument.

Experimental Generation of Shatter Cones and Clues to Their Formation

Shatter cones were found by chance in a MEMIN experiment (Kenkmann et al. 2012), which was then followed by a systematic study (Wilk and Kenkmann 2016; Wilk et al. Forthcoming) (Fig. 5). Shatter cones attract specific attention as they are the only macroscopic diagnostic phenomenon of shock observable in the field. The mesoscale MEMIN impact experiments produced several shatter cones that were recovered from ejected

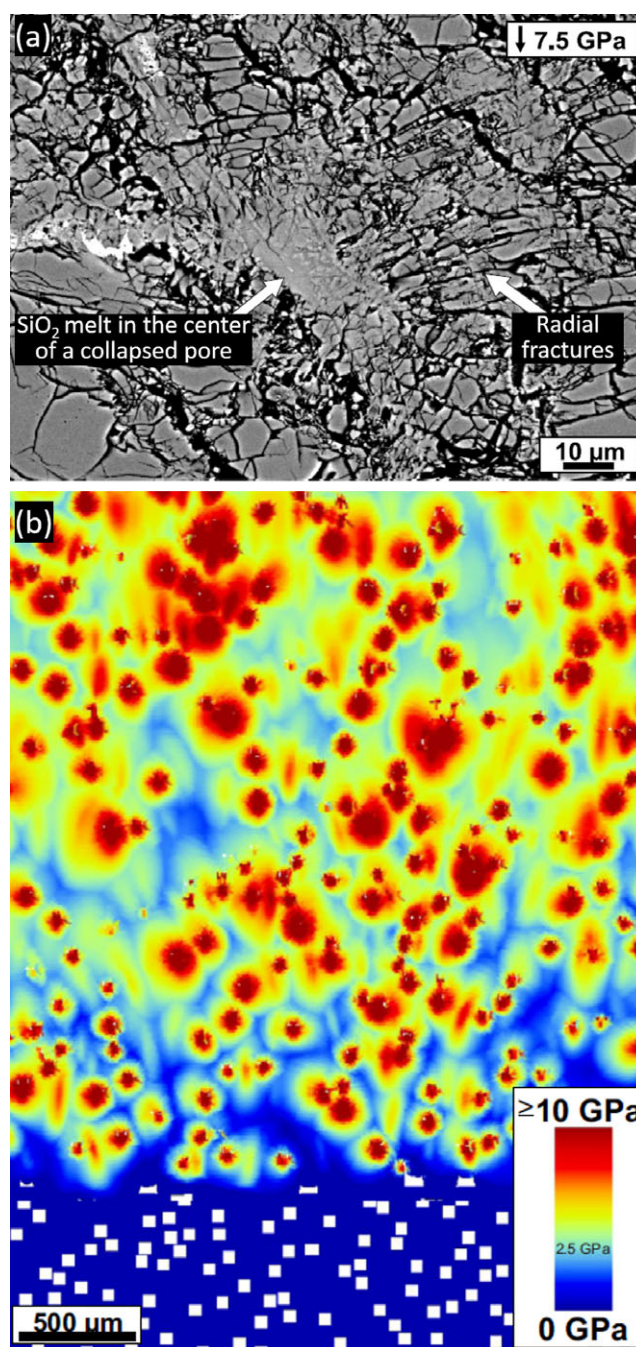


Fig. 3. a) Backscattered electron image of shocked sandstone. Center of a crushed zone at the locus of a pre-existing pore, filled with SiO₂ melt. Localized zones of pressure amplification after shock wave propagation through a representative sample with randomly distributed pores obtained by numerical modeling. The reference pressure (given by the shock pressure that is achieved in the same material with no porosity) is 2.5 GPa (for details see Kowitz et al. 2013a).

fragments. These cone fragments show slightly curved, striated surfaces and conical geometries with apices of 36°–52°. They fulfill the morphological criteria of shatter

cones (e.g., Baratoux and Reimold 2016). They were found in experiments with 20–80 cm sized target cubes of sandstone, quartzite, and limestone, but not in highly porous tuff. These targets had been impacted by aluminum, steel, and iron meteorite projectiles of 2.5–12 mm diameter at velocities of 4.6–7.8 km s⁻¹. No shatter cones were detected after impact experiments with lower impact velocities. A morphometric analysis of the experimentally generated shatter cones with 3-D white light interferometry (Fig. 5b) showed that the cones consist of a system of diverging subcones that intersect each other. Scanning electron microscopy (SEM) of cone surfaces revealed vesicular melt films alternating with smoothly polished surfaces (Wilk and Kenkmann 2016; Wilk et al. Forthcoming) similar to those that had been analyzed on the surfaces of naturally formed shatter cones (e.g., Gibson and Spray 1998; Nicolaysen and Reimold 1999; Pittarello et al. 2015). The paper by Wilk et al. (Forthcoming) provides TEM evidence for amorphous SiO₂ films and documents that fracturing and melt films can be related to the shock loading and unloading phases.

In the framework of MEMIN, a phenomenological model was developed that used the hierarchical arrangement of the subcone ridges of shatter cone surfaces as key for understanding the shatter cone formation process (Kenkmann et al. 2016). This model showed that the overall cone geometry including the apex angle of the enveloping cone and the degree of concavity (horse-tailing) is determined by the convexity of the subcone ridges. Straight cones of various apical angles, constant slope, and constant bifurcation angles form if the subcone convexity is low. Increasing subcone convexity leads to a stronger horse-tailing effect and the bifurcation angles increase with increasing distance from the enveloping cone apex. The model successfully described experimentally formed as well as natural shatter cones (Kenkmann et al. 2016). However, reasons for the curvature of the subcones remain enigmatic and require further micromechanical understanding of dynamic fracture propagation.

Hugoniot Data

Seeberger sandstone was the most frequently used target rock during the MEMIN campaign (Table 2) and most of the mesoscale numerical modeling also related to this rock. Therefore, it was necessary to gather Hugoniot data for this specific rock, in particular for the low-pressure regime, by conducting planar plate impacts up to 7 GPa (Hoerth et al. 2017). A special inverse testing method suitable for rock targets was applied together with a laser interferometer for the measurement of the free-surface velocity of the target plate. The analysis of

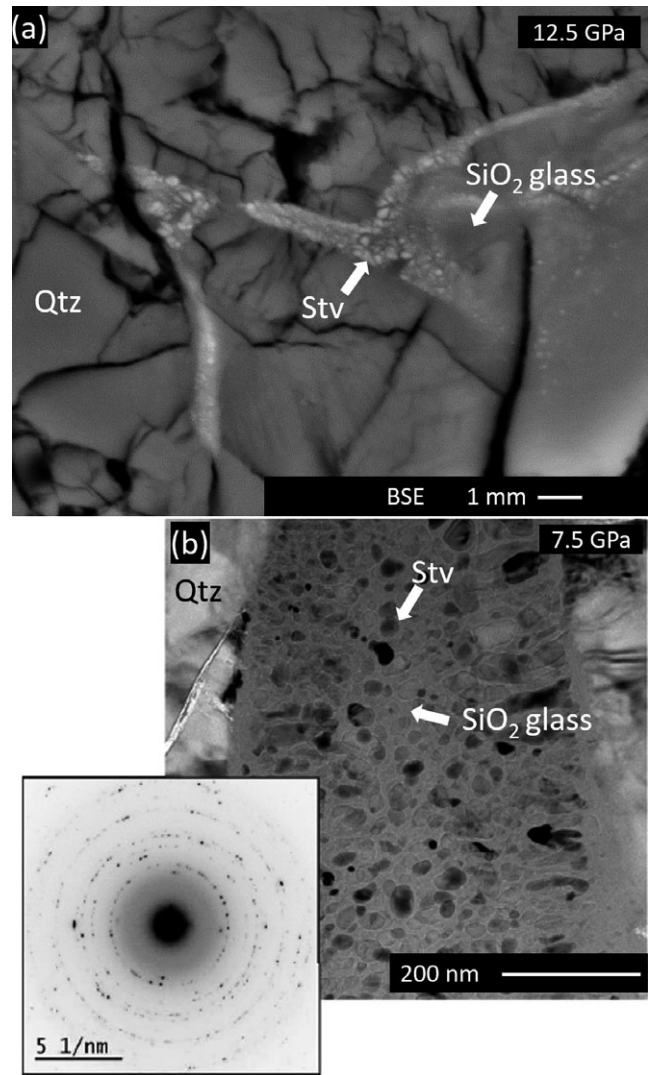


Fig 4. a) Backscattered electron image of shocked sandstone with relatively bright melt veins containing fine-grained stishovite crystals generated in the shock recovery experiment at 12.5 GPa. b) Bright-field transmission electron microscopy (TEM) images and selected area electron diffraction (SAED) pattern (inset) of polycrystalline stishovite aggregates embedded in amorphous vein matrix generated at 7.5 GPa (for details see Mansfeld et al. 2017).

shock wave velocity versus particle velocity indicated pore crushing and significant scattering (Hoerth et al. 2017). Additional Hugoniot data were gathered in the pressure range from 8 to 20 GPa with high-explosive-driven planar impact experiments (Fig. 6) (Holzwarth, personal communication).

CRATER MORPHOLOGIES AND CRATERING EFFICIENCIES

The lithologies used in MEMIN for cratering experiments consisted of quartzite, marble, gneiss,

sandstone, and tuff (Table 2; Fig. 7). Resulting crater diameters were between 1.4 and 40 cm. Their morphometric analyses revealed features that were characteristic for all, regardless of impact conditions. All craters consisted of a central depression roughly corresponding to the transient crater, and an outer spallation zone with areas of incipient spallation (Dufresne et al. 2013). The transient crater dimensions and spallation volumes were reconstructed by fitting quadratic parabolas to crater profiles from digital elevation models (Dufresne et al. 2013; Poelchau et al. 2014). First-order differences between the various craters were expressed by the craters' depth/diameter ratios (Table 2) that range from 0.1 to 0.56. Very shallow craters were obtained for impacts into marble (Winkler et al. 2016b), while deep penetration tubes were formed by impact into high-porosity tuff (Winkler et al. 2016a, 2016b).

Porosity and Water Saturation

MEMIN initially concentrated on sandstone as porous target material to address the influence of porosity and water saturation (Kenkmann et al. 2011a) for a range of impact velocities (Poelchau et al. 2013). Data were compared with nonporous quartzite and tuff of 43% porosity. Results showed that the target's porosity reduces crater volumes and the cratering efficiency relative to nonporous rocks (Poelchau et al. 2014). In the case of the highly porous tuff, an extra-deep, tube-like, quasi-cylindrical cavity developed (Winkler et al. 2016a, 2016b) comparable to funneled craters in highly porous snow (Luther et al. 2017, Forthcoming). Saturation of pore space with water at 50 and 90%, respectively, set off the effects of porosity, with crater size increasing with progressive saturation of target pore space (Dufresne et al. 2013; Poelchau et al. 2013). Craters in water-saturated sandstone were generally shallower and larger in diameter and volume than craters from equivalent impacts into dry, porous sandstone (Kenkmann et al. 2011a; Poelchau et al. 2013). Cratering efficiency, ejection velocities, and spall volume are enhanced if pore water is present (Hoerth et al. 2013; Poelchau et al. 2013, 2014).

Spallation

Except for micrometer-sized projectiles (Price et al. 2010), spallation always occurs in impact cratering experiments with solid rocks but seems to play a subordinate role in natural craters (Kenkmann et al. 2014; Durr et al. 2017). Spallation became more prominent in larger scale experiments at the XLLGG facility—leading to an increase in cratering efficiency

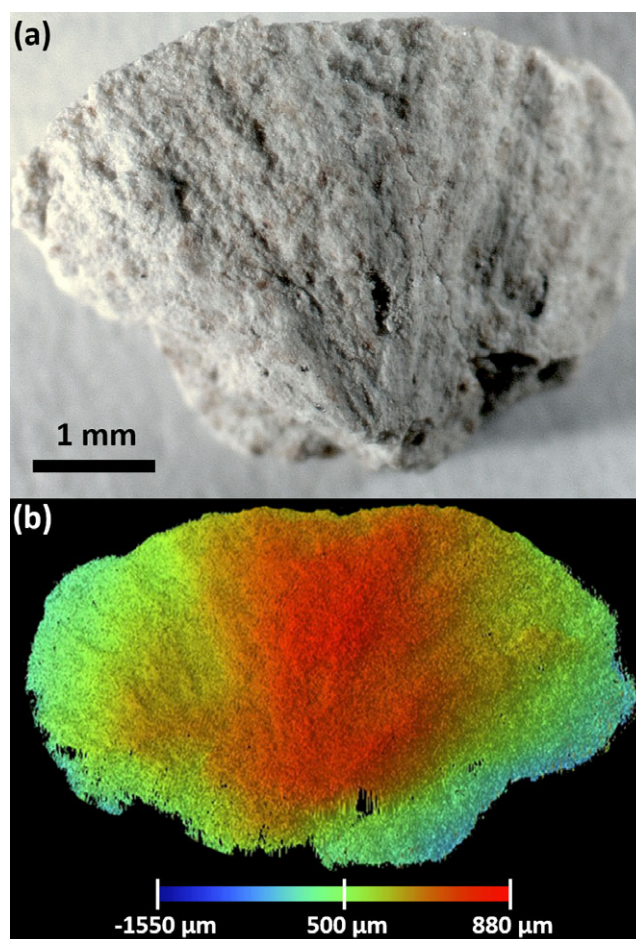


Fig. 5. a) Shatter cone fragment from MEMIN experiment A15 (impact of a 5 mm aluminum sphere onto sandstone with an impact velocity of 6.97 km s^{-1}). b) White light interferometer scan of the shatter cone fragment shown in (a). Note the multiple sets of striae diverging on the curved fracture surface (for details see Wilk and Kenkmann 2016).

with increasing projectile size for constant impact velocities (Poelchau et al. 2013). Owing to enhanced spallation, crater volumes and crater efficiencies for our large-scale experiments were greater than predicted by strength scaling laws (Poelchau et al. 2014). Strength scaling laws were used to determine the reduction of tensile strength in large-scale experiments and showed a decrease by a factor of 1.8–3.6. This strength reduction is explained by three effects, i.e., decrease in strain rate for larger projectiles, prolongation of the pressure pulse, and the Weibull effect (Rinne 2008; Poelchau et al. 2014). The interrelation of these effects is complex. Further variations in spallation are observed between different target materials; a decrease in spall is suggested to be controlled by increased porosity (Poelchau et al. 2014).

Scaling Laws

Pi-group scaling, rooted in dimensional analysis (e.g., Holsapple 1993), is the most successful approach to relate laboratory-scale craters to natural crater structures on planetary surfaces. Experiments are key to determine the so-called scaling parameters, which quantify the functional relationships between impactor properties (diameter, density, and velocity) and transient crater morphometry (diameter, depth, and volume). These parameters depend on material properties such as strength, friction, and porosity (Schmidt and Housen 1987; Wünnemann et al. 2011; Prieur et al. 2017). In addition to these target properties, gravity plays an important role. The effect of gravity can only be investigated at laboratory scales with noncohesive, granular target materials, which, in turn, do not allow studying the effect of strength. A way around this dilemma was to determine scaling parameters for the strength regime from the MEMIN experiments (Poelchau et al. 2013, 2014), and to use the π -group scaling method to delineate the effect(s) of strength in the transitional and gravity regime. Alternatively, numerical modeling was used to scale the experimental results from MEMIN in sandstone and quartzite to crater dimensions where gravity has a significant or dominant effect (Güldemeister et al. 2015). The models show that an effective strength, almost five orders of magnitude smaller than the quasi-static experimentally determined strength of sandstone and quartzite, has to be assumed to accurately predict crater size in the transitional and gravity regime (Güldemeister et al. 2015).

DAMAGE GRADIENTS

Damage in the subsurface of the experimentally produced impact craters was investigated in all target lithologies. Impact damage beneath the crater floor in quartzite is characterized by intense, localized deformation along roughly radial shear zones. In contrast, subsurface deformation in marble is dominated by pervasive and omnipresent fracturing and twinning of calcite that dies out with radial distance from the crater floor (Winkler et al. 2016b). Sandstone targets, in turn, show a zone of pervasive grain crushing and compaction, surrounded by a zone of localized deformation, and beneath the wider spall crater, a zone of incipient spallation (Buhl et al. 2013a). The presence of interstitial pore water leads to the absence of the zone of complete compaction, but the zone of localized deformation becomes larger. The development of concussion fractures is independent of the presence of water. Their radial orientation is consistent with their

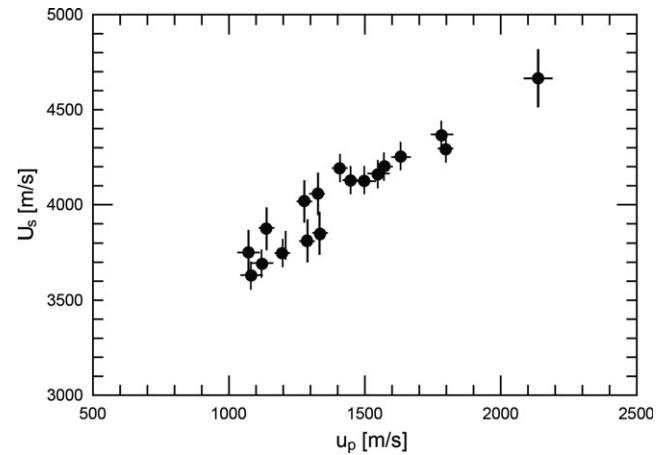


Fig. 6. Shock velocity (U_s)—particle velocity (u_p) data for Seeberger sandstone (layer 3), measured in high-explosive-driven planar impact experiments with manganin detectors (U_s) and photonic Doppler velocimetry (u_p) (Holzwarth, personal communication).

supposed development as tensional Mode I fractures along grain-to-grain contacts and force chains.

Buhl et al. (2013a) suggested that pore water reduces the shock impedance mismatch between grains and pore space, and thus reduces the peak stresses at grain–grain contacts. This effect inhibited profound grain comminution and effective compaction by pore-collapse, but allowed for reduced shock wave attenuation and a more effective transport of energy into the target. Winkler et al. (2016a, 2016b) carried out a systematic study of target damage for craters in highly porous tuff. Here, the deformation in the subsurface included, among other effects, pore space compaction and clast rotation. The subsurface damage extended to 2–3 projectile diameters beneath the crater floor. Based on overprinting relationships and the geometrical orientation of deformation features, a sequence of subsurface deformation events was recognized to comprise (1) matrix compaction, (2) intragranular crack formation in clasts, (3) deformation band formation in the compacted matrix, and (4) tensile fracturing (Winkler et al. 2016a, 2016b).

Strain Rate-Sensitive Particle Size Distribution

Quantification of damage in rocks was done by measuring the particle size distribution of fractured rocks. Dynamic fragmentation under varying strain rates influences the power law of the distribution, expressed as a fractal dimension (D -value) (Buhl et al. 2013b, 2014a). For instance, the D -values in one cratering experiment (A6-5126; Table 2) decreased from 1.74 at the crater floor to 0.84 at a distance

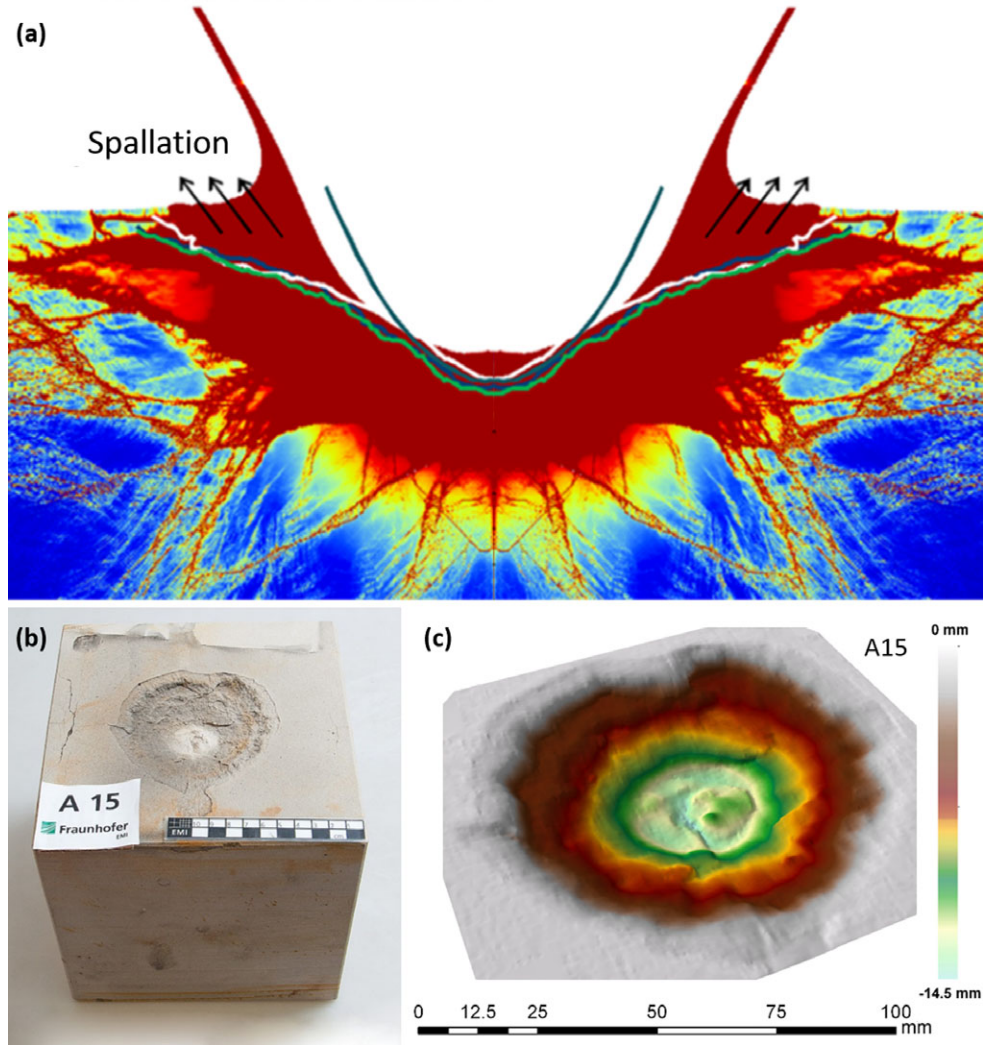


Fig. 7. a) Numerical model of crater formation and crater damage. Colors represent the intensity of damage: blue is undamaged material, red is fully damaged material. The profiles represent the corresponding final experimentally generated crater shapes. The diameter of the final crater in the experiments is enlarged due to spallation, which so far has not been considered in the numerical model. b) Photograph showing the morphological characteristics of a typical crater with a prominent spallation zone (A15-5185). c) Digital elevation model for the crater formed in target block A15.

of 7.2 mm from the crater floor. Comparative analysis of craters of various sizes documented that the extent of subsurface damage is very similar in size, volume, and geometry when normalized to the projectile size (Buhl et al. 2014b). The D -value (2.42) measured in a shock recovery experiment (experiment 2-1; Table 3) was much higher than in the cratering experiments (Buhl et al. 2013b). A value of approximately 2 and lower may indicate that the fragmentation process is mainly surface driven and friction controlled. Higher D -values at low total strain indicate highly dynamic conditions and a strain rate dependency of deformation.

Strain Rate-Sensitive Mechanical Response

The physical response of brittle rocks at high strain rates changes dramatically with respect to quasi-static conditions. Rocks become stiffer and their strength increases. As a measure for the dynamic behavior of a rock and its strain rate dependency, we used the dynamic increase factor (DIF), which is the ratio of the dynamic compressive strength to the quasi-static uniaxial compressive strength (Zwiessler et al. 2017). To investigate deformation in the high strain rate regime experimentally, we used a split Hopkinson pressure bar and measured the stress-strain response of homogeneous,

fine-grained Seeberger sandstone and other lithologies in uniaxial compression at strain rates ranging $10\text{--}100\text{ s}^{-1}$ with respect to the elastic properties and the dynamic uniaxial compressive strength. Seeberger sandstone did not show changes in the elastic properties at high strain rates, but the uniaxial compressive strength was found to be 1.6–1.7 times higher at a strain rate of 100 s^{-1} than under quasi-static conditions (Zwiessler et al. 2017). The onset of dynamic behavior is accompanied by changes in the fracture pattern, changing from single to multiple fracturing up to pervasive pulverization for increasing rates of deformation.

EJECTA DYNAMICS

Ejecta dynamics were closely linked to crater morphology and target damage. We used high-speed framing cameras to record the excavation process and we used custom-designed catchers to determine particle shape and size distribution, ejection velocities and angles, and microstructures (Sommer et al. 2013). Specific attention was paid to the excavation dynamics of dry and water-saturated sandstone targets.

A higher degree of water saturation of the target yielded an increase in total ejecta mass, up to 400% higher mean ejection velocity, and steeper ejecta cone angles, with respect to dry targets (Kenkmann et al. 2011a; Hoerth et al. 2013; Sommer et al. 2013). Moreover, the transient crater grew at a faster rate and reached a larger diameter for water-saturated targets. Power law fits were applied to the crater growth curves and they showed an increase in the scaling exponent with increasing pore space saturation. The values for the scaling exponent μ for the dry sandstones were between 0.49 and 0.56; for the partially saturated sandstones, the values were between 0.56 and 0.64; and for the fully saturated targets, our values were close to 0.66.

The particle size distribution of collected ejecta followed a power law distribution. No influence of impact energy or impact velocity on the particle size distribution was detected (Buhl et al. 2014a), but the presence of pore water further increases the power law exponent. The energy spent for target fragmentation and comminution was calculated to be in the <5% range (Buhl et al. 2014a).

Based on the experimental laser light sheet (LLS) technique as employed by Cintala et al. (1999), we developed and implemented a new methodology to robustly track single ejecta particles with very high accuracy (Gulde et al. 2018). In particular, instead of relying on the challenging correlation of particles via their geometric shape, the novel methodology identifies particles by means of their trajectory. This ultimately allows for a comprehensive description of every

recorded ejecta particle with up to 100 ns temporal and $50\text{ }\mu\text{m}$ spatial resolution. In the present work, a single plane within the ejecta plume was illuminated using a time resolution of 500 ns as well as a spatial resolution of $150\text{ }\mu\text{m}$. By investigating the impact of a 2 mm aluminum sphere at 6.3 km s^{-1} into Carrara marble, Gulde et al. (2018) found that ejecta particles were launched in a short time window of about 0–25 μs and up to a radial distance of 10 mm from the impact location. During this time interval, the transient crater radius grew from 2 ± 1 to 6 ± 2 mm. Ejecta velocities between 70 m s^{-1} and 1 km s^{-1} were observed and a substantial steepening of the ejecta curtain occurred within 15 μs after the impact. Furthermore, we have first indications that the ejecta cone steepening can be derived from the transient crater evolution. Complementary numerical modeling of the ejection process shows that the ejection angle and velocity depend on porosity, friction, and cohesion (Luther et al. 2017). Increasing the coefficient of friction and the porosity of the target material leads to a decrease of ejection velocities and the formation of smaller craters. In addition, the ejection angle decreases with distance for higher coefficients of friction, but remains approximately unchanged with increasing porosity. As a consequence, the characteristics of the ejecta deposits vary for different target properties and the ejecta thickness at the crater rim and how it decreases with distance may be indicative of target properties.

GEOPHYSICAL SURVEYING OF EXPERIMENTAL IMPACT CRATERS

Geophysical signatures rank among the most prominent features that can be observed at terrestrial impact structures, and many of these craters have been initially recognized as local or regional, geophysical anomalies (e.g., Pesonen 1996). The nondestructive geophysical methods applied in the MEMIN project have similarities to geophysical methods used in field studies. Within MEMIN two types of measurements were performed: real-time recording of both supersonic (=shock) and subsonic (= elastic) pressure waves, and postimpact geophysical surveying.

Recording of Seismic Waves

Acoustic emission measurements were carried out to determine the magnitude of compressional waves at various distances from the point of impact and to determine the attenuation rate of the shock and seismic pressure waves for different rock types. Initially, the acoustic emission data recorded in our hypervelocity

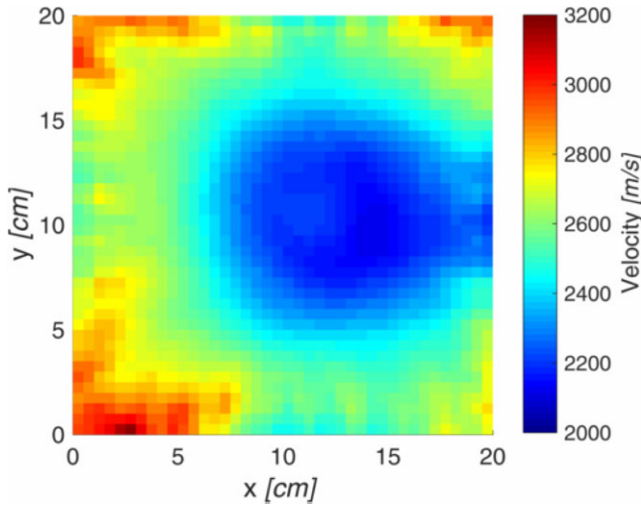


Fig. 8. Cross section obtained from sandstone target A3-5124 at 2 cm depth below the impact surface. The area of reduced p-wave velocity indicates the impact-induced damage. Side spall effects are visible at all four edges of the cross section. The eccentricity reflects the eccentric impact.

impact experiments were used to precisely localize the equivalent depth of burst (Moser et al. 2013a). It turned out that the hypocenter of the hemispherically expanding p-waves was located well above the crater floor, corresponding to the equivalent depth of burst (Holsapple 1993).

To determine the decay behavior of pressure amplitudes as a function of distance, a special type of piezo-resistive sensor was developed and calibrated using a split Hopkinson pressure bar (Hoerth et al. 2014). Pressure amplitudes decreased by three orders of magnitude within the first 250 mm (i.e., 42 projectile radii).

Surprisingly the attenuation for water-saturated sandstone was higher than for dry sandstone. However, this result remains in conflict with numerical studies and the investigations of cratering efficiencies (Kenkmann et al. 2011a; Poelchau et al. 2013). The proportion of the impact energy radiated as seismic energy (seismic efficiency) was of the order of 10^{-3} (Hoerth et al. 2014) in a sandstone target. Numerical modeling allowed for a more systematic investigation of the effect of porosity on seismic efficiency and the attenuation (quality factor Q) of seismic waves with distance. Güldemeister and Wünnemann (2017) found that the seismic efficiency decreased significantly for water-saturated targets by approximately two orders of magnitude (10^{-5}) in comparison to nonporous, dry quartzite (10^{-3}). They found Q -values of <10 , ~ 35 , and 80 for water-saturated (25%), dry porous sandstone, and dry quartzite, respectively.

Nondestructive Analysis of Impact-Induced Geophysical Anomalies

Nondestructive geophysical analysis of rock cubes prior and after the impact experiments focused on ultrasound tomography and vibrational analysis to characterize the damage zone, as well as on micro-computed tomography (μ -CT) measurements to visualize subsurface fractures (Moser et al. 2013b). Micro-computed tomography is capable of tracing large spall cracks and concentric fractures below the crater surface of the experimentally impacted sandstone blocks. Ultrasound tomography revealed a hemispherical damage zone of reduced p-wave velocities beneath the crater (Raith et al. Forthcoming). The p-wave velocity increases from the crater floor toward the edges of the specimen; spall effects at these edges/free surfaces were recognized and eliminated to obtain the radial trends of damage in an infinite half-space target (Raith and Grosse 2016) (Fig. 8).

Also the modulus of elasticity is generally reduced between approximately 9 and 18% (Moser et al. 2013b). The inferred damage zone reaches much deeper than documented for our experimental craters by application of optical and electron optical microscopy (Buhl et al. 2013a). Ultrasound tomography is more sensitive for the detection of “damaged” rock than micro-computed tomography (Moser et al. 2013b; Raith and Grosse 2016).

IMPROVEMENTS OF HYDROCODES AND NUMERICAL MODELS

An important objective of MEMIN was to improve and validate existing hydrocodes by comparison with experimental data. In order to study the influence of pores and water saturation on the shock behavior of sandstone, numerical investigations at the mesoscale were performed using mesh-free Smoothed Particle Hydrodynamics (Durr et al. 2013, 2017; Durr and Sauer 2015) as well as the iSALE shock physics code (Güldemeister et al. 2013, 2015; Kowitz et al. 2013a, 2016) with the ANEOS equation of state tables for quartzite and water. These mesoscale models consider simplified pore geometries in a homogeneous and isotropic quartz matrix (Fig. 3b). The latter was described with an equation of state including phase transitions and a strength model. Two-dimensional planar shock simulations mimicking the planar impact shock recovery experiments were conducted in order to analyze effects of quartz strength and water saturation on pore crushing. A homogenization procedure transforms the mesoscale model to a macroscale model. A sophisticated three-dimensional finite element method

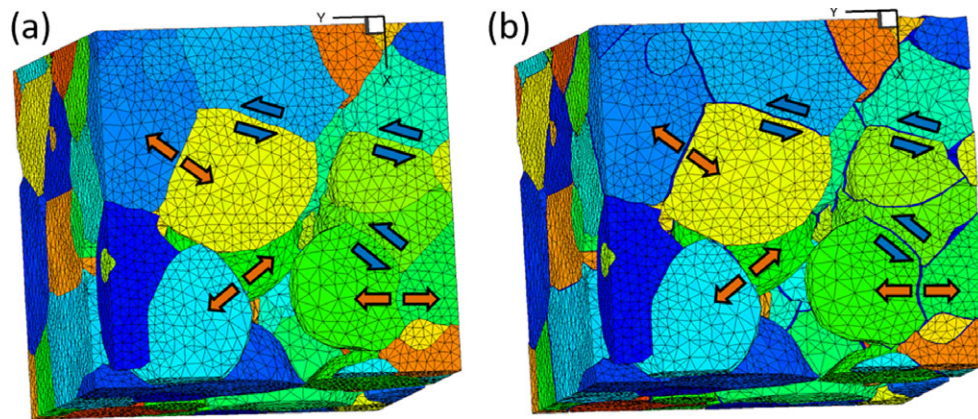


Fig. 9. Mesoscale sandstone structure under uniaxial tensile loading in its initial state (a) and after crack initiation and propagation (b). Grain interfaces undergo combined shear and tensile loading. Blue lines indicate which of the grain boundaries are activated. Arrows indicate the sense of loading.

model (FEM) presented by Durr et al. (2017) is commensurate with a real rock (Fig. 9). The model considers individual grains of various shapes, orientations, and sizes. Shear localization occurs along grain boundaries, and the model includes specific algorithms to treat stress concentrations at propagating fracture tips. The model is capable of calculating stress and strain at the grain scale during and after passage of a shock wave. The macroscale models could be validated against the experimentally formed craters and were used for scaling the experimental results to natural crater sizes. Based on this, Gldemeister et al. (2015) pointed out that scaling relationships (e.g., Holsapple 1993) at natural crater dimensions may not yield accurate results if standard values for the uniaxial compressive strength or cohesion are used. They emphasized that it is important to consider dynamic weakening as a result of the accumulation of damage in rocks.

CONCLUDING REMARKS

The MEMIN research unit has been focused on experimental and numerical cratering processes. MEMIN was conceived as a multi- and interdisciplinary research project, bringing together geologists, mineralogists, geochemists, geophysicists, impact engineers, physicists, and numerical modelers to jointly analyze cratering processes in solid targets. Never before was impact research performed with such close interaction of specialists from such different disciplines. A prime requirement for all experiments was to match natural systems as closely as possible, and to design a series of experiments by systematically varying and isolating only one or very few variables. This approach, in combination with high-end recording techniques and

advanced numerical modeling, allowed us to assign specific observations to physical parameters and processes.

In more detail, the MEMIN team used natural planetary materials as projectiles, e.g., Campo del Cielo iron meteorite, and target lithologies such as sandstone to match porous lithologies on planetary surfaces. Our specific lithologies, some saturated with volatiles, are not only important to understand cratering on Earth but are also of vital interest for cratering processes on Mars or minor bodies with rock-ice mixtures. Variables such as target rheology, including porosity and pore water, and impact energy were systematically investigated in several parametric studies. Thanks to novel and powerful accelerator technologies used by MEMIN, impact cratering experiments could downsize the dimensional gap to natural craters. Numerical simulations validated by the experiments were used as a bridge to the real crater world. We are convinced that the wealth of our results will serve as a solid base for other research groups working in the field of impact processes.

MEMIN conducted fully monitored cratering experiments in solid rocks and yielded craters up to 40 cm in diameter that allowed in situ analysis with high spatial accuracy. The experiments delivered important insights into the very early phase of cratering when projectile and target are shocked, melted, and vaporized, and ejecta curtains form and ejecta are deposited. Various aspects of shock metamorphism were investigated experimentally and by means of mesoscale numerical modeling; special emphasis was paid to the low-pressure shock regime and to porosity; pressure calibration schemes could be developed for both. The formation mechanism and the physical boundary conditions during formation of silica high-pressure

phases and shatter cone development could be significantly narrowed. The detailed, real-time as well as postexperiment analyses of the cratering process and products—including crater growth, target damage, and excavation—gave insights into the cratering process in solid rocks. We are confident that the close interaction of scientists and engineers with very different backgrounds, the enthusiasm of the students, and the availability of various high-end experimental and analytical tools resulted in a significant contribution in the overall understanding of impact cratering.

Here are some highlights of the MEMIN project:

1. Insights in the energy budget of selected impact experiments show that target fragmentation and comminution consumes <5% of the impact energy. Melting and vaporization of projectiles consumes 4–5% at 5.3 km s⁻¹ impact velocity.
2. Significant interelement fractionation occurs during mixing of projectile and target melts.
3. The degree of fractionation is controlled by the lithophile or siderophile character of the respective elements.
4. Target porosity exponentially reduces crater volume and cratering efficiency while it increases crater depth relative to nonporous rocks, and also flattens ejection angles. The combined approach of numerical modeling and cratering experiments lead to improved scaling laws and a better understanding of porosity and strength on crater size scaling.
5. Higher degrees of water saturation in sandstone targets yield an increase in total ejecta mass, up to 400% higher mean ejection velocity, and steeper ejecta cone angles, with respect to dry targets.
6. A new pressure calibration of shock metamorphic features in porous rocks and low shock pressures was established. Localized shock pressure amplification as a consequence of pore space collapse was quantified by mesoscale modeling to be a factor of 4, if not more.
7. For the first time stishovite was experimentally produced in low-pressure shock experiments and this work indicated ultrafast crystallization from silica melt at high pressure.
8. Nondestructive geophysical analysis of targets using ultrasound tomography shows that the damage zones beneath craters is wider than indicated by microstructural inspection at the SEM scale.
9. A novel mesoscale numerical model considers grains of various sizes and shapes and allows for shear localization at grain boundaries.

A large number of impact experiments was fully documented, including all initial technical data and current analysis results and is available to the scientific community. Moreover, we are willing to share samples

from this extraordinary series of impact and melting experiments with interested scientists.

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