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Microstructural Imaging of Shock-Recovered Berea Sandstone and Quartz Sand Using Scanning Electron Microscopy

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Microstructural imaging of shock-recovered Berea sandstone and Quartz sand using Scanning Electron Microscopy

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Abstract. A number of shock-recovery experiments have been performed on Berea sandstone for different conditions: dry, water-saturated, hydrostatically water-pressurized and Helium gas-pressurized. We also conducted experiments with purified quartz sand in dry and water-saturated conditions with a grain size between 212 to 250 μm and 250 to 300 μm to compare with damaged Berea sandstone. The shock stresses in the range between 1.2 to 9.8 GPa were achieved by impacting projectiles accelerated by a single-stage light-gas gun. Different flyer plate thicknesses were used to produce different shock pulse durations. The water-pressurized sandstone targets were hydrostatically pressurized between 7.58–7.79 MPa, whereas the gas-pressure samples were pressurized to 27.5 MPa using helium gas. The microstructural damage of all specimens is being investigated by using scanning electron microscopy (SEM) in order to determine differences for these conditions. In this report we will present the results of the systematic SEM investigations for each experiment. The scientific results and discussions including X-ray computed micro tomography and statistical analysis are presented elsewhere. Overall, we collected around 1600 SEM pictures, which are available in electronic form on Compact Disks (CDs). We also provide the results of the laser particle analysis on the CDs.

1. Introduction

Our motivation for this work comes in part from oil and gas recovery, where explosive shaped charges are used to perforate the wellbore casing to provide connectivity to the surrounding reservoir rock. The perforator jet causes deformation of each perforator tunnel. This so-called crushed zone (*Krueger, 1986, Halleck, 1996*) consist of fines from grain fragmentation, intergrain cracking and metal debris. The fines can significantly reduce the local permeability in the vicinity of the perforation and hinder recovery of hydrocarbon (*Halleck, 1996 and 1997, McLeod, 1983*). In this study, we examine grain fragmentation caused by short duration stress waves similar to perforation loading using a two-stage light-gas gun shown in Fig 1.

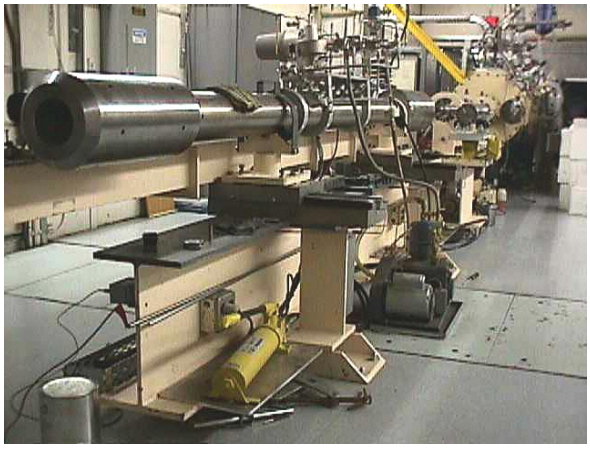

Fig. 1: Two-stage light-gas gun at Lawrence Livermore National Laboratory.

Samples of Berea sandstone and pure quartz sand under dry, water-saturated, water-pressurized, and gas-pressurized conditions were subjected to well-defined impact loading using stress levels up to 10 GPa. Observations of grain damage were obtained from the recovered samples using the SEM. We are focused on basically two issues. First, to get a better understanding of shock induced grain damage and second, to provide quantitative data for correlation with grain/pore scale structure modeling of fragmentation caused by grain-to-grain interactions (*Swift et al., 1998*). A detailed description of computer modeling as well as scientific results and discussions of the shock-recovery experiments are reported elsewhere (*Hagelberg et al., 2000ab, Hiltl et al., 2000abc, Swift et al., 2000ab*).

2. Material description

For the shock recovery experiments we selected Berea sandstone, one of the most commonly used rock standards in petrophysical studies. This sandstone consists primarily of sub-angular, well-sorted quartz grains. Other mineral grains like feldspar, mica and clay aggregates (kaolinite which occurs primarily as flakes, montmorilonite and smectite) are present, together with accessory minerals namely zircon, rutile, magnetite and apatite. Calcite and dolomite cement the mineral grains. Pre-existing cracks were observed in some quartz grains of the undamaged material. We determined the bulk density of cylindrical samples by weighting and measuring several samples in air. The grain density was measured using a helium densitometer and the Archimedes method. The material properties of the sandstone used in this study are listed in Table. 1.

Porosity:	21.9%
Bulk density:	2.077 g/cm^3
Grain density:	2.631 g/cm^3
Average grain size:	0.15 mm

Tab. 1: Material properties of the investigated Berea sandstone.

The purified material for the quartz sand experiments was obtained from J. T. Barker Inc. We sieved the sand to a grain size of 212-250 μm and 250-300 μm, respectively. Material properties of quartz can be found, for example, in *Lide, 1998*.

3. Experimental Setup

The dry, water-saturated, water-pressurized and gas-pressurized recovery experiments have been conducted using a 4 m long single-stage light-gas gun with a bore diameter of 35 mm. The experimental work was performed at Lawrence Livermore National Laboratory. All sandstone samples were confined in an aluminum 6061 (*Lundergan and Herrmann, 1963, Mitchell and Nellis, 1981*) capsule surrounded by a recovery fixture of the same material. The front face thickness of the capsule varies between 3 and 7 mm. Figure 2 shows the target setup for the dry experiments. Aluminum 6061 was selected due to the similar shock impedance to Berea sandstone minimizing the impedance mismatch. Core plugs for the experiments were obtained from a Berea sandstone cylinder (90X70 mm) by using a 22.4 mm and 25.4 mm diameter diamond coring drill. Water was used as a coolant to minimize the grain damage during the drilling process. Slices of approximately 5 mm and 15 mm were sawed from the cored material using a diamond saw. To achieve an accurate flatness the samples were ground and lapped. To avoid that grains pulling away from the edge during the cutting, grinding and lapping process, all samples were confined with a 1 mm thick aluminum 6061 ring.

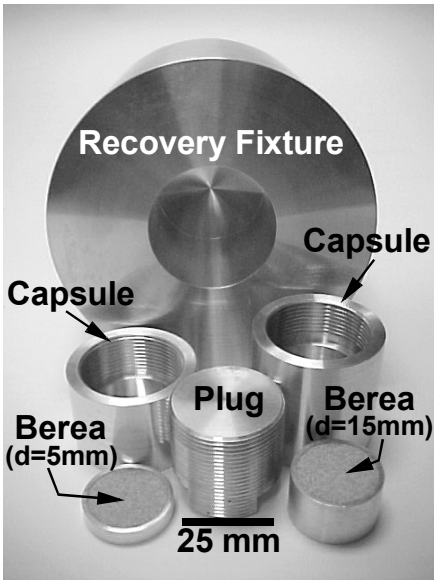

Fig. 2: Parts used to setup the target for dry conditions. Two different sample thicknesses (5 mm and 15 mm) were used.

The correct stress levels of shaped charges, typically between 1-10 GPa (*Lichtenberger, 1995*) , were achieved by accelerating a projectile with expanding helium gas before impacting onto the capsule containing the sandstone target. The helium gas used to pressurize the gas breech is independent from the helium gas we used to gas-pressurize the Berea sandstone. The projectile consisted of a polycarbonate (Lexan®) carrier and a 32 mm in diameter flyer plate; either aluminum 1100, oxygen-free high-conductivity (OFHC) copper or PMMA (Polymethyl methacrylate). We chose two flyer plate thicknesses, approximately 3 mm and 6.25 mm, to produce different shock pulse durations in the sandstone samples. Laser-diode measurments and X-ray photos of the projectile shortly before the impact were taken to determine the velocity of the flyer plate. The achieved impact pressures were calculated using the shock impedance matching method (*Rice et al.(1958)*) by knowing the impact velocity, the Hugoniot equations of state of the flyer plate material (*Lundergan and Herrmann, 1963, Mitchell and Nellis, 1981, Marsh, 1979*) and the container material. Computer simulations show an approximately 35% reduced stress levels in the sandstone material. Fig. 3 illustrates schematically the experimental configuration for the dry samples shortly before the impact. In this report we will list only the impact pressure produced by the accelerated flyer plate.

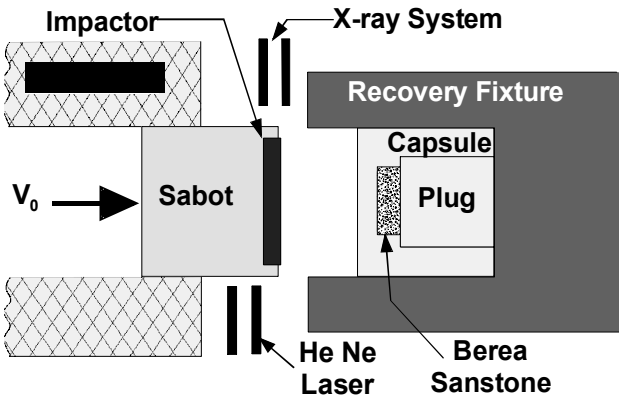

Fig. 3: Schematic setup for the experiments with dry Berea sandstone samples.

To simulate downhole pressure conditions, we applied the water and gas pressure hydrostatically directly to the samples. This was realized by modifying the capsule used originally for the dry samples. Two stainless steel tubes with a diameter of 1.6 mm were fitted in the recovery fixture to the backside of the sealed capsule. A connection was made to two 1 mm boreholes, which end at the surface of the Berea target. A schematic drawing, that shows the experimental setup for water-saturated, water-pressurized and gas-pressurized conditions, is shown in Fig. 4.

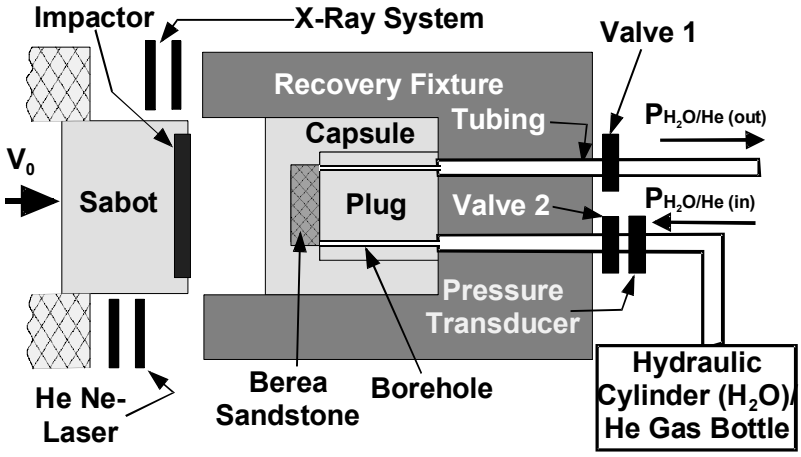

Fig. 4: Schematic setup for water-saturated, water-pressurized and gas-pressurized experiments.

Water-pressurizing the samples was done by pumping approximately 500 ml of de-ionized water through the tubing and the sandstone to make sure that all air bubbles were out of the system. Valve 1 (Fig. 4) was closed and the sample was pressurized up to the desired pressures by using a hydraulic cylinder. The water pressure was measured and controlled by a calibrated pressure transducer. After reaching the correct hydrostatic water pressure valve 2 was closed to avoid any damage to the pressure transducer during the shock experiment. The projectile was then launched into the capsule using the gas gun. For the water-saturated experiments, water with a pressure of 690 kPa was pushed through the targets to make sure that all air bubbles were out of the sandstone before closing valves 1 and 2. We did the same procedure for the water-saturated experiments with quartz sand. For these experiments we used aluminum and stainless steel for the capsules as well as for the recovery fixtures. Figure 5 shows the experimental setup inside the gun tank.

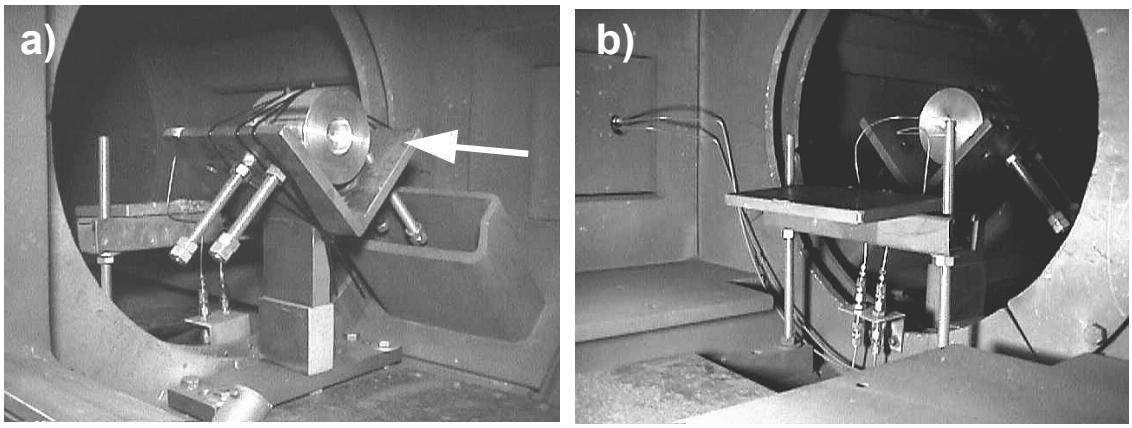

Fig 5: Target holder and Target inside the gun tank for water-saturated, water-pressurized and gas-pressurized conditions. a) front side (arrow indicates impact direction) and b) backside.

4. Sample preparation

Preparing the recovered material plays a major role in the microstructural analysis. Therefore we tested several sample recovery methods and the following procedure is the most successful for our application. First, the capsules were removed from the recovery fixtures using a band saw with a fluid coolant. Then a diamond wire saw, having a wire diameter of 0.3 mm, was used to cut each capsule into two halves. We preferred the wire saw because it makes a precise and smooth cut and therefore reduces the destruction of the original sandstone microstructure. After drying the two samples using an electrical oven at 60 C for 1 hour, a very low viscose epoxy (EPO-TEK 301™) was pressed under vacuum into one of the two capsule halves. After the epoxy was hard and dry another cut was made, 1-2 mm away from the original cut, to get to the undisturbed material. The epoxied samples were then polished and a thin conductive layer of carbon was applied to the samples. This layer is required during SEM analysis to avoid build-up of electric charge due to the electron bombardment. The other half was used for laser particle size analysis. Fig. 6 shows the sample preparation schematically.

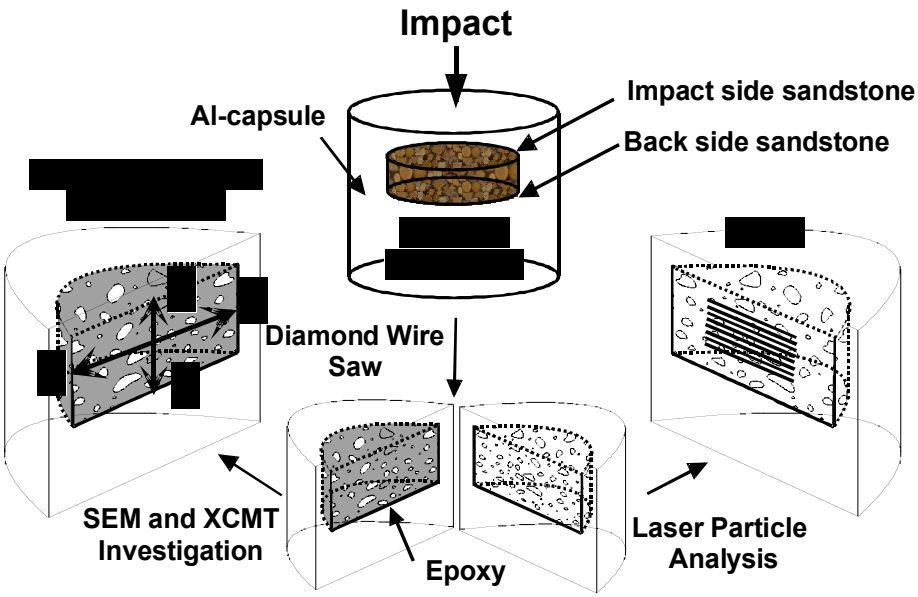

Fig. 6: Shocked capsule preparation technique for SEM and laser particle analysis.

5. Laser particle size measurements

Laser diffraction analyses using the unified scatter technique were performed at Pennsylvania State University. The machine employed for the analysis of the size distribution of the shock-recovered samples throughout this project is the Microtrac-X100 analyzer made by Honeywell Inc., FL/USA. All samples were measured in wet conditions using water as the fluid medium. Sandstone material was sliced from several depths (starting from the capsule impact side moving to capsule back side) with a scalpel (Fig. 6). A mortar and pestle was used to take the shocked Berea sandstone apart to get to the actual grain size. All aggregates with a size greater than 150 μm were sieved out. The sieved material was analyzed three times and the Microtrak software program was used to calculate an average grain size from the collected data. The calculations used to obtain results are based on the theory of optical diffraction by small suspended particles. The measurement system is based on Fourier optics. Laser light is shone through the sample cell, through which a constant flow of sandstone suspension is passed. The particles from the shocked Berea sandstone cause the light to be diffracted, depending on the size of the particle. Small particles diffract more than larger particles. The light is focused on to a detector. The flux pattern from the detector, averaged over a period of time, is deconvolved into a reading of particle

sizes, calculated over discrete size ranges, the ranges given by the size of the detector areas. This measuring system assumes that the particles are completely opaque to the incoming radiation. A correction can be made to the flux pattern, allowing for refraction of light through the particles, provided the refractive index of the material is known. This system assumes that the particles are spherical. The calculation of the particle size is based on the fact that, for particles in the range of sizes corresponding to the wavelength of incident light, the difference in scattering of the vertically and horizontally polarized light is strongly dependent on the ratio of particle size to the wavelength of the incident light. The grain size distributions of the shocked Berea sandstone can be found on the attached CD.

6. X-ray computed micro tomography

Cores with a diameter of 2 mm and approximately 10 mm length were taken from the center part of the samples parallel to the axis of impact. The small Berea cores were analyzed using synchrotron computed micro tomography at Brookhaven National Laboratory with a voxel size of 3.6 and 6 μm, respectively. The XCMT process creates a stack of images each of which lies in the plane perpendicular to the cylinder axis. Figure 7 shows an undamaged Berea sandstone sample and provides an idea of the resolution obtained using XCMT. Figure 8a illustrates a 3D-XMCT image of experiment 608 that was conducted under water-saturated conditions. The resolution for this particular sample was 3.6 μm. Fig. 8b shows the water-pressurized experiment 700 with a resolution of 6 μm. The scales for x, y and z are given in pixels. With XCMT it is possible to distinguish the differences between undamaged Berea sandstone (Fig. 7) and the shock-recovered materials (Fig. 8). Porosity measurements of the two regions give values of 21.0 % and 13.3 % for the undamaged and shocked regions, respectively. The use of X-ray computed microtomography is a useful complement and extension to other techniques like SEM and laser particle analysis. Because of the immense amount of XMCT data a detailed description of the analysis technique as well as a discussions will be reported separately (Hagelberg et al, 2000c).

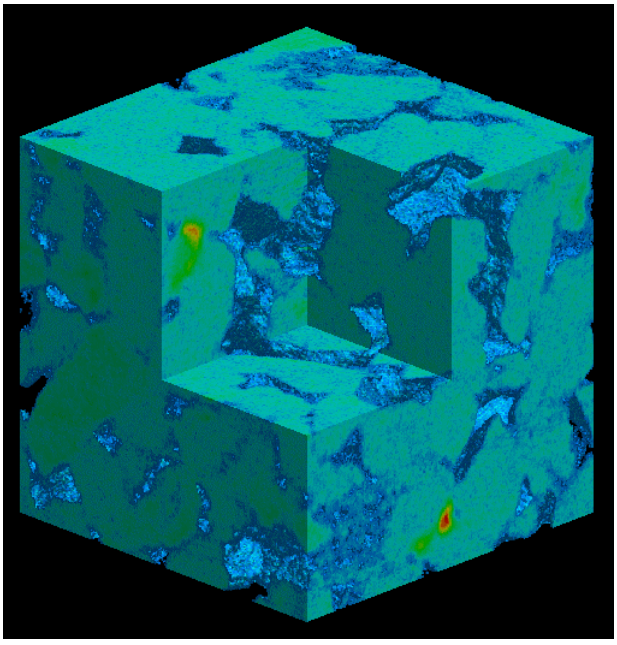

Fig. 7: 3-dimensional XCMT-image of undamaged Berea Sandstone.

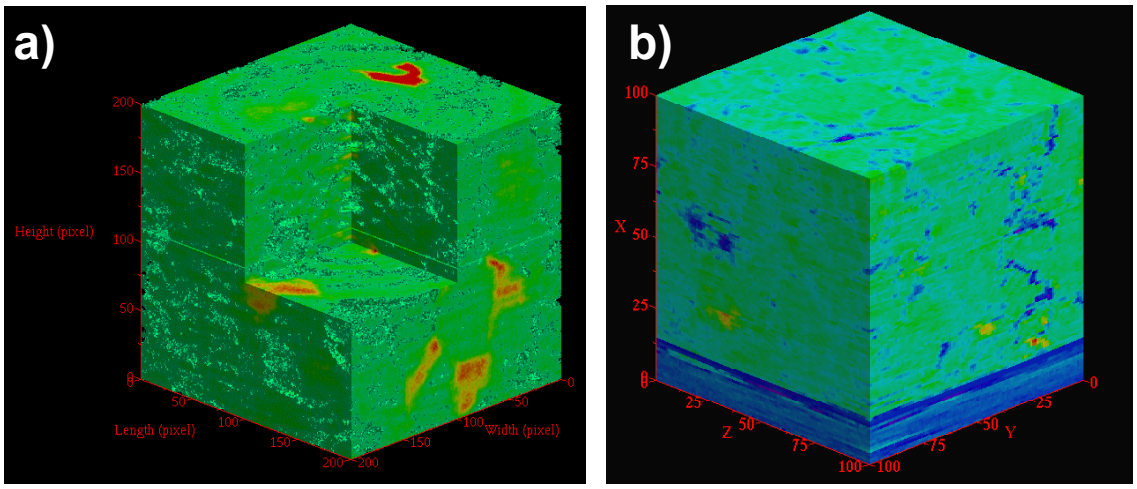

Fig. 8: 3-dimensional XCMT-image of a) experiment 608 (water-saturated) with a resolution of 3.6 μm and b) experiment 700 (water-pressurized) with a resolution of 6 μm. (See Hagelberg et al, 2000c for more details).

7. SEM information

Systematic studies on the shock recovered samples were done at Los Alamos National Laboratory using a Noran Instruments automated digital electron microscope (ADEM) with a voltage of 15 kV and a beam current of 100-300 picoamperes. We collected more then 1600 backscattered electron images (BSE) from all shock-recovered samples. The digital images were recorded mainly at a 1024 x 1024 pixel resolution, but some also at a 512 x 512 resolution using magnifications of 100x and 400x. The gray levels of the images are related to the average atomic number of the minerals. The bigger the density of the material, the brighter it appears. However, different minerals (for example quartz, dolomite and sodium feldspar) can have similar average atomic numbers. To distinguish such minerals more accurately, X-ray analysis has to be used. The pores in the pictures appear dark, because they are filled with a low-density epoxy resin. We scanned each sample along the centerline from point A to point B (where A is the impact side and B the back side of the sandstone sample). On a few selected samples we did also a scan along the line C – D to investigate edge effects. The way we scanned the samples is illustrated in Fig. 6. The images are available in electronic form (tagged image format TIFF) on the attached CDs. The TIFF files are organized in directories having names corresponding to the experimental shot number. The two exceptions are UndamagedTiff and XrayMapsTiff that contain SEM images of the undamaged Berea and x-ray maps for elemental constituent analysis, respectively. Within the directories the TIFF files follow a general naming convention using the experiment number, magnification, and an identifying number. For example 744.401.01.tif refers to shot # 744, magnification 401x, image number 1. For the undamaged Berea the naming convention uses „0k“ to indicate the image comes from undamaged material. Unfortunately, the scanning sequence is not consistent throughout the data. For part of the data the scans start from the impact side of the sample and the rest start at the opposite end. It is easy to check by viewing the endpoint images. On occasion there are two sets of images of the same magnification, or two images saved of the same field of view. In these cases letters are appended to the filename constituents. For example, 608.100.01.tif and 608.100b.01.tif represent two images at 100x, but not of the same area, and saved at two different pixel resolutions (easily distinguished by file size). Or, for example, 696.100.01.tif and 696.100.01a.tif are two versions of the same image, with only a small change in SEM gain between the two. Such duplicate images are few and were kept for only completeness. There are six instances where the image was unsuccessfully saved from the SEM without the operators knowing (the images are blank or partially blank). These are 609.400.26.tif,

700.400.mid1.tif, 700.400.mid4.tif, 701.400.mid2.tif, 743.10.04.tif, and 0k.400.13.tif. Any partial image was kept, but the blank images were discarded.

8. Technical data of the shock-recovered samples

In this section we will list important technical information for each of the shock-recovery experiments performed. Fig. 7 shows a schematic drawing of the capsule dimensions we will use.

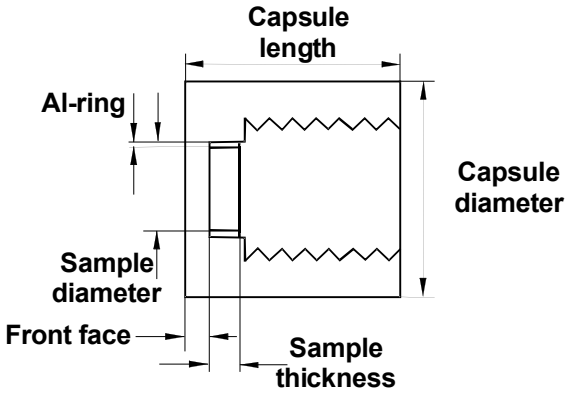

Fig. 7: Schematic drawing of the used capsules.

Experiment 563:

Shot number:	563	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	4.6 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	OHFC copper	Gas breech pressure:	22.10MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	no
Flyer plate weight:	21.98 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	51.1 g	Impact pressure:	9.5 GPa
Projectile velocity	820 m/s	Date:	05/27/1998
Comments:	SEM images: 20 total 400X: 20 pictures named mh.b.90k.c.1 - mh.b.90k.c.20		

Experiment 564:

Shot number:	564	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	4.95 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	17.9 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	2.92 mm	Gap behind flyer:	no
Flyer plate weight:	6.43 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	35.6 g	Impact pressure:	7.0 GPa
Projectile velocity	870 m/s	Date:	5/27/1998
Comments:	SEM images: 24 total 400X: 24 pictures named mh.70k.d.c1 - mh.70k.d.c24		

Experiment 565:

Shot number:	565	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	5.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	13.9 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	2.97 mm	Gap behind flyer:	no
Flyer plate weight:	6.55 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	35.7 g	Impact pressure:	6.1 GPa
Projectile velocity	760 m/s	Date:	05/28/1998
Comments:	SEM images: 26 total 400X: 26 pictures named mh.b.50k.c1 - mh.b.50k.c26.		

Experiment 577:

Shot number:	577	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	4.64 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	11.1 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	no
Flyer plate weight:	6.36 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	32.0 g	Impact pressure:	6.0 GPa
Projectile velocity	750 m/s	Date:	08/07/1998
Comments:	The sample was water-pressurized to 7.24 GPa using the hydraulic cylinder. Note that these samples was gold coated for the SEM. SEM images: 21 total 400X: 21 picture named mh.b.50k.w.g1 - mh.b.50k.w.g26		

Experiment 579:

Shot number:	579	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	4.61 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	17.2 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	no
Flyer plate weight:	6.43 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	35.5 g	Impact pressure:	6.9 GPa
Projectile velocity	850 m/s	Date:	08/17/1998
Comments:	The sample was water-pressurized to 7.54 GPa using the hydraulic cylinder. Note that these sample was gold coated for the SEM. SEM images: 18 total 400X: 18 pictures named mh.b.70k.w.g1 - mh.b.70k.w.g18		

Experiment 605:

Shot number:	605	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	5 mm
Sample thickness:	5.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	13.79 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.03 mm	Gap behind flyer:	no
Flyer plate weight:	6.67 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	35.3 g	Impact pressure:	6.3 GPa
Projectile velocity	780 m/s	Date:	11/02/1998
Comments:	SEM pictures: 8 total 100X: 3 pictures named 605.100.01-04 400X: 4 pictures impact side named 605.400.top1-4		

Experiment 606:

Shot number:	606	Capsule dimensions:	40 mm X 33.8 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	14.8 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	13.79 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.25 mm	Gap behind flyer:	yes
Flyer plate weight:	13.64 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	40.6 g	Impact pressure:	6.1 GPa
Projectile velocity	760 m/s	Date:	11/02/1998
Comments:	SEM images: 106 total 100X: 16 pictures named 606.100.01 – 606.100.16 (side by side vertical scans, bottom to top, then top to bot.) 100X: 46 pictures named 606.100b.01 – 606.100b.46 (vertical scan bottom to top, then three horizontal left to right top, middle, and bottom) 100X: 2 pictures named 606.100p.01, 606.100p.02 (top and bottom at 512 resolution) 400X: 12 pictures named 606.400.r1.01 – 606.400.r3.04 (mosaics of four at top, middle and bottom) 400X: 28 pictures named 606.401.01 – 606.401.28 (vertical scan bottom to top) 400X: 606.401.scale (intended to record a zoom, but didn't work) Note: 606 100x transect 1: (01 - 08) bottom to top; transect 2: (09 - 16) top to bottom.		

Experiment 607:

Shot number:	607	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	3.49 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	yes
Flyer plate weight:	6.63 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	33.7 g	Impact pressure:	3.1 GPa
Projectile velocity	390 m/s	Date:	11/03/1998
Comments:	SEM images: 48 total 100X: 8 pictures named 607.100.01 – 607.100.08 (bottom to top) 100X: 8 pictures named 607.100b.01 – 607.100b.08 (bottom to top, slightly different track) 400X: 32 pictures named 607.401.01 - 607.401.32 (bot. to top)		

Experiment 608:

Shot number:	608	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	14.6 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	13.1 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	yes
Flyer plate weight:	6.56 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	33.8 g	Impact pressure:	6.4 GPa
Projectile velocity	800 m/s	Date:	11/03/1998
Comments:	SEM images: 125 total 100X: 7 pictures named 608.100.01 – 608.100.07 (vertical scan top to bottom) 100X: 1 picture named 608.100a.01 (same as 608.100.01 with (a different gain setting) 100X: 608.100b.01 608.100b.43 (bottom to top plus three horizontal scans, left to right at top, middle, and bottom) 100X: 608.100H1.01 (1024 resolution, bottom), 608.100L1.01 – 608.100L1.19 (512 resolution vertical scan bottom to top plus horizontal scan along bottom) 400X: 608.400.r1.01 through 608.400.r6.04 (24 images) (r1 and r4: top; r2 and r5: middle; r3 and r6 bottom)		

Experiment 609:

Shot number:	609	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	14.7 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	22.06 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	2.98 mm	Gap behind flyer:	yes
Flyer plate weight:	21.47 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	48.50 g	Impact pressure:	9.8 GPa
Projectile velocity	850 m/s	Date:	11/03/1998
Comments:	SEM images: 34 total 100X: 7 pictures named 609.100.01 – 609.100.07 (bottom to top) 400X: 28 pictures named 609.400.01 – 609.400.28 (bottom to top)		

Experiment 610:

Shot number:	610	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	5 mm
Sample thickness:	5.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-pressurized	Ring material	Aluminum 6061
Flyer plate material:	OHFC copper	Gas breech pressure:	22.06 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	2.98 mm	Gap behind flyer:	no
Flyer plate weight:	21.67 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	50.3 g	Impact pressure:	9.7 GPa
Projectile velocity	830 m/s	Date:	11/04/1998
Comments:	The sample was water-pressurized to 7.31 GPa using the hydraulic cylinder. SEM pictures: 7 total 100X: 3 pictures named 610.100.01-03 (top, middle, bottom) 400X: 4 pictures impact side named 610.400.top1-4		

Experiment 611:

Shot number:	611	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	14.5 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-saturated	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	13.79 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.21 mm	Gap behind flyer:	yes
Flyer plate weight:	13.48 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	40.5 g	Impact pressure:	6.1 GPa
Projectile velocity	760 m/s	Date:	11/04/1998
Comments:	SEM images: 94 total 100X: 46 pictures named 611.100.01 – 46 (vertical scan bottom to top, plus 3 horizontal scans left to right top, middle, and bottom) 100X: 7 pictures named 611.100a.01-07 (512 resolution vertical scan bottom to top) 100X: 2 pictures named 611.100b.01 (top and 611.100b.02 (bot) 400X: 27 pictures named 611.400.01 – 26 (vertical scan bottom to top) 400X: 12 pictures named 611.402.r1q1 – 611.402.r3q4 (3 regions – top, middle, and bottom- 4 quadrants each to make mosaics)		

Experiment 613:

Shot number:	613	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	14.7 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-saturated	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	3.45 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	yes
Flyer plate weight:	6.58 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	33.8 g	Impact pressure:	3.1 GPa
Projectile velocity	390 m/s	Date:	11/05/1998
Comments:	SEM images: 46 total 100X: 2 pictures named 613.100a.01-02 (top and bottom) 100X: 10 pictures named 613.100b.01 – 613.100b.10 (vertical scan bottom to top, plus upper right and lower right corners) 400X: 32 pictures named 613.400.01 – 32 (vertical scan bottom to top) 400X: 2 pictures named 613.400.roi1 (region of interesting damage) and 613.400.scale (attempt to record zoom)		

Experiment 615:

Shot number:	615	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	3 mm
Sample thickness:	5.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-saturated	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	13.01 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.00 mm	Gap behind flyer:	yes
Flyer plate weight:	6.56 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	33.7 g	Impact pressure:	6.4 GPa
Projectile velocity	800 m/s	Date:	11/06/1998
Comments:	SEM images: 105 total 50X: 1 picture named 615.050.01 showing interesting results of sample preparation. 100X: 8 pictures named 615.100.01 – 615.100.08 (vertical scan bottom to top; 512 resolution) 100X: 2 pictures named 615.100a.01 (top) and 615.100a.02 (bottom) 100X: 46 pictures named 615.100b.01 – 615.100b.46 (vertical scan bottom to top, plus 3 horizontal scans left to right, top, middle, and bottom; 1024 resolution) 400X: 12 pictures named 615.401.r1.01 to 615.401.r3.04 (top, middle, and bottom regions of 4 images each) 400X: 28 pictures named 615.403.01 – 615.403.28 (vertical scan, bottom to top; 512 resolution) misc: two-50X, two-300X, and four-1200X named 615.p50.01 through 615.p1200.04 to examine some artifacts of sample preparation.		

Experiment 616:

Shot number:	616	Capsule dimensions:	40 mm X 27.0 mm
Sample diameter:	22.4 mm	Capsule front face:	5 mm
Sample thickness:	5.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-pressurized	Ring material	Aluminum 6061
Flyer plate material:	Tantalum	Gas breech pressure:	17.23 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.0 mm	Gap behind flyer:	no
Flyer plate weight:	47.9 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	69.0 g	Impact pressure:	8.6 GPa
Projectile velocity	830 m/s	Date:	11/06/1998
Comments:	The sample was water-pressurized to 7.14 GPa using the hydraulic cylinder. SEM pictures: 6 total 100X: 4 pictures named 616.100.01- 04 (top to bottom) 400X: 2 pictures impact side named 616.400.top1- 2		

Experiment 677:

Shot number:	677	Capsule diameter:	40 mm X 37.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	23.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	N/A
Flyer plate material:	Aluminum 1100	Gas breech pressure:	18.61 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.18 mm	Gap behind flyer:	yes
Flyer plate weight:	13.56 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	38.27 g	Impact pressure:	7.1 GPa
Projectile velocity	870 m/s	Date:	04/30/1999
Comments:	Dry quartz sand experiment with a grain size >212μm <250 μm, porosity 36%, 8.017 cm^3 sand in capsule. SEM pictures: 54 total 100X: 9 pictures named 677.100.01-09 (vertical scan top to bottom) 400X: 5 pictures named 677.402.01-05 27 pictures named 677.401. 06-33 4 pictures impact side named 677.400.top1-4 4 pictures middle part named 677.400.mid1-4 4 pictures back side named 677.400.bot1-4		

Experiment 692:

Shot number:	692	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-pressurized	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	3.6 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.26 mm	Gap behind flyer:	yes
Flyer plate weight:	13.63 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	40.91 g	Impact pressure:	2.7 GPa
Projectile velocity	360 m/s	Date:	09/23/1999
Comments:	The sample was water-pressurized to 7.79 GPa using the hydraulic cylinder. SEM pictures: 73 total 100X: 10 pictures named 692.100.01-10 (vertical scan top to bot.) 100X: 3 pictures named 692.100bot , 100mid, and 100top 400X: 42 pictures named 692.400.01- 42 4 pictures impact side named 692.400.top1-4 4 pictures middle part named 692.400.mid1-4 4 pictures back side named 692.400.bot1-4 2 pictures impact side named 692.400.top1-2 3 pictures middle part named 692.402.mid1-3 2 pictures back side named 692.402.bot1-2		

Experiment 693:

Shot number:	693	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	14.8 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-saturated	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	4.07 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.25 mm	Gap behind flyer:	yes
Flyer plate weight:	13.61 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	40.56 g	Impact pressure:	3.8 GPa
Projectile velocity	490 m/s	Date:	09/23/1999
Comments:	SEM pictures: 62 total 100X: 10 pictures named 693.100.01-10 400X: 40 pictures named 693.400.01-40 4 pictures impact side named 693.400.top1-4 4 pictures middle part named 693.400.mid1-4 4 pictures back side named 693.400.bot1-4		

Experiment 696:

Shot number:	696	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	3 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	3.65 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.20 mm	Gap behind flyer:	yes
Flyer plate weight:	13.46 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	40.40 g	Impact pressure:	3.5 GPa
Projectile velocity	450 m/s	Date:	05/26/1999
Comments:	SEM pictures: 60 total 100X: 10 pictures named 696.100.01-10 400X: 38 pictures named 696.401.01-38 4 pictures impact side named 696.400.top1-4 4 pictures middle part named 696.400.mid1-4 4 pictures back side named 696.400.bot1-4		

Experiment 697:

Shot number:	697	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	3 mm
Sample thickness:	15.0 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	PMMA	Gas breech pressure:	4.17 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.12 mm	Gap behind flyer:	yes
Flyer plate weight:	5.84 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	33.01 g	Impact pressure:	1.4 GPa
Projectile velocity	450 m/s	Date:	06/08/1999
Comments:	SEM pictures: 69 total 100X: 10 pictures named 697.100.01-10 3 pictures named 697.100bot, 697.100mid, 697.100top 400X: 39 pictures named 697.401.01-39 4 pictures impact side named 697.400.top1-4 4 pictures middle part named 697.400.mid1-4 4 pictures back side named 697.400.bot1-4 5 named 697.402bot.01-02, 697.402mid.01, 697.402top.01-02		

Experiment 698:

Shot number:	698	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	3 mm
Sample thickness:	14.97 mm	Capsule material:	Aluminum 6061
Sample condition:	Dry	Ring material	Aluminum 6061
Flyer plate material:	OFHC Copper	Gas breech pressure:	19.03 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.21 mm	Gap behind flyer:	yes
Flyer plate weight:	44.35 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	71.26 g	Impact pressure:	7.8 GPa
Projectile velocity	680 m/s	Date:	06/08/1999
Comments:	Front-part of the capsule came off. The flyer plate sealed the opening and therefore the sandstone target could be recovered. SEM pictures: 10 total 100X: 2 pictures named 698.100.bot, 698.100.top 400X: 8 pictures named 698.401.bot1-4, 698.401.top1-4		

Experiment 700:

Shot number:	700	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	14.8 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-pressurized	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	15.86 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.30 mm	Gap behind flyer:	yes
Flyer plate weight:	13.66 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	40.78 g	Impact pressure:	6.4 GPa
Projectile velocity	793 m/s	Date:	06/08/1999
Comments:	SEM pictures: 94 total 100X: 9 pictures named 700.100.01-09 100X: 9 pictures named 700.100.01p-09p 3 pictures named 700.100bot, 700.100mid, 700.100top 400X: 36 pictures named 700.400.01-36 4 pictures impact side named 700.400.top1-4 4 pictures impact side named 700.400.top1p-4p 2 pictures impact side named 700.400.top.01-02 4 pictures middle part named 700.400.mid1-4 4 pictures middle part named 700.400.mid1p-4p 2 pictures middle part named 700.400.mid.01-02 4 pictures bottom part named 700.400.bot1-4 4 pictures bottom part named 700.400.bot1p-4p 2 pictures bottom part named 700.400.bot.01-02 A series taken at increasing magnification: 700.st100, 700.st400, 700.st801, 700.st1600, 700.st3200		

Experiment 701:

Shot number:	701	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	3 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-pressurized	Ring material	Aluminum 6061
Flyer plate material:	PMMA	Gas breech pressure:	4.13 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.14 mm	Gap behind flyer:	yes
Flyer plate weight:	5.76 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	32.78 g	Impact pressure:	1.3 GPa
Projectile velocity	438 m/s	Date:	06/10/1999
Comments:	The sample was water-pressurized to 7.65 GPa using the hydraulic cylinder. SEM pictures: 64 total 100X: 11 pictures named 701.100.01-11 400X: 41 pictures named 701.400.01-41 4 pictures impact side named 701.400.top1-4 4 pictures middle part named 701.400.mid1-4 4 pictures back side named 701.400.bot1-4		

Experiment 739:

Shot number:	739	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Water-saturated	Ring material	Aluminum 6061
Flyer plate material:	PMMA	Gas breech pressure:	4.13 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	5.93 mm	Gap behind flyer:	yes
Flyer plate weight:	5.62 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	35.01 g	Impact pressure:	1.2 GPa
Projectile velocity	412 m/s	Date:	08/26/1999
Comments:	SEM pictures: 62 total 100X: 10 pictures named 739.100.01-10 400X: 41 pictures named 739.400.01-40 4 pictures impact side named 739.400.top1-4 4 pictures middle part named 739.400.mid1-4 4 pictures back side named 739.400.bot1-4		

Experiment 740:

Shot number:	740	Capsule diameter:	40 mm X 27.2 mm
Sample diameter:	25.2 mm	Capsule front face:	5 mm
Sample thickness:	7.97 mm	Capsule material:	Stainless steel
Sample condition:	Water-saturated	Ring material	N/A
Flyer plate material:	Aluminum 1100	Gas breech pressure:	15.81 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.00 mm	Gap behind flyer:	yes
Flyer plate weight:	6.60 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	36.00 g	Impact pressure:	7.6 GPa
Projectile velocity	662 m/s	Date:	09/09/1999
Comments:	Quartz sand in water-saturated conditions SEM pictures: 52 total 100X: 6 pictures named 740.100.01-06 400X: 46 pictures named 740.401.01-46 2 rows scanned, 23 images each row		

Experiment 741:

Shot number:	741	Capsule diameter:	40 mm X 27.2 mm
Sample diameter:	25.2 mm	Capsule front face:	5 mm
Sample thickness:	7.97 mm	Capsule material:	Stainless steel
Sample condition:	Dry	Ring material	N/A
Flyer plate material:	Aluminum 1100	Gas breech pressure:	15.81 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	3.02 mm	Gap behind flyer:	yes
Flyer plate weight:	6.65 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	35.91 g	Impact pressure:	7.3 GPa
Projectile velocity	640 m/s	Date:	09/10/1999
Comments:	Quartz sand in dry condition SEM pictures: 41 total 100X: 5 pictures named 741.100.01-05 400X: 36 pictures named 741.402.01-36 2 rows scanned, 18 images each row		

Experiment 742:

Shot number:	742	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Gas-pressurized	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	15.81 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.23 mm	Gap behind flyer:	yes
Flyer plate weight:	13.56 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	42.91 g	Impact pressure:	6.2 GPa
Projectile velocity	770 m/s	Date:	09/13/1999
Comments:	The sample was gas-pressurized with helium to 27.56 GPa using a He-gas bottle. SEM pictures: 59 total 100X: 10 pictures named 742.100.01-10 400X: 37 pictures named 742.401.01-37 4 pictures impact side named 742.401.top1-4 4 pictures middle part named 742.401.mid1-4 4 pictures back side named 742.401.bot1-4		

Experiment 743:

Shot number:	742	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	15.1 mm	Capsule material:	Aluminum 6061
Sample condition:	Gas-pressurized	Ring material	Aluminum 6061
Flyer plate material:	Aluminum 1100	Gas breech pressure:	3.65 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.25 mm	Gap behind flyer:	yes
Flyer plate weight:	13.60 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	43.16 g	Impact pressure:	2.6 GPa
Projectile velocity	348 m/s	Date:	09/14/1999
Comments:	The sample was gas-pressurized with helium to 28.96 GPa using a He-gas bottle. SEM pictures: 64 total 100X: 11 pictures named 743.100.01-11 400X: 41 pictures named 743.402.01-41 4 pictures impact side named 743.402.top1-4 4 pictures middle part named 743.402.mid1-4 4 pictures back side named 743.402.bot1-4		

Experiment 744: Berea Sandstone

Shot number:	744	Capsule diameter:	40 mm X 33.8 mm
Sample diameter:	25.2 mm	Capsule front face:	7 mm
Sample thickness:	14.9 mm	Capsule material:	Aluminum 6061
Sample condition:	Gas-pressurized	Ring material	Aluminum 6061
Flyer plate material:	PMMA	Gas breech pressure:	4.14 MPa
Flyer plate diameter:	32 mm	Barrel diameter:	35 mm
Flyer plate thickness:	6.02 mm	Gap behind flyer:	yes
Flyer plate weight:	5.69 g	X-ray taken:	yes
Projectile material:	Lexan	Laser taken:	yes
Projectile weight:	34.82 g	Impact pressure:	1.3 GPa
Projectile velocity	430 m/s	Date:	09/14/1999
Comments:	The sample was gas-pressurized with helium to 27.56 GPa using a He-gas bottle. SEM pictures: 63 total 100X: 10 pictures named 744.100.01-10 400X: 41 pictures named 744.401.01-41 4 pictures impact side named 744.401.top1-4 4 pictures middle part named 744.401.mid1-4 4 pictures back side named 744.401.bot1-4		

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