Drill core from seismically active sandstone gas reservoir yields clues to internal deformation mechanisms

Berend A. Verberne, Suzanne J. T. Hangx, Ronald P. J. Pijnenburg, Maartje F. Hamers, Martyn R. Drury and Christopher J. Spiers

Correspondence to: s.j.t.hangx@uu.nl

This PDF file includes:

Supplementary Text Sections S1-4 Materials and Methods; Microscopes and Analysis Methods Image Processing and Interpretation; Data Processing	ods;
Supplementary Figure S1 Overview of core samples	
Supplementary Figure S2 Lab-test on an SDM-1 core sample (Sw14A) simulating production induced compaction	n-
Supplementary Figure S3 Slochteren Sandstone microstructures	
Supplementary Figure S4 Sectioned layered core samples	
Supplementary Figure S5 Intragranular crack density and descriptors quantifying the grain st distribution (GSD)	ize
Supplementary Figure S6 Hyperspectral cathodoluminescence (CL) mapping	
Supplementary Figure S7 Panchromatic cathodoluminescence (CL) mosaic	
Supplementary Figure S8 Electron backscatter diffraction (EBSD) mapping of quartz and Dauphiné Twin (DT) boundaries	
Supplementary Table S1 List of key data from sectioned ZRP-3a core samples	
Supplementary Table S2 List of key data from sectioned SDM-1 core samples (incl. Sw14A))
Supplementary Table S3 Reactivated healed fractures	
Supplementary Table S4 Quartz area and Dauphiné Twin (DT) boundary length	

S1. MATERIALS AND METHODS

S1.1 Core Samples and Sectioning

We inspected core material from the depleted Zeerijp (ZRP)-3a and from the undepleted Stedum (SDM)-1 well at the core repositories of respectively Shell (Rijswijk, The Netherlands) and NAM (Assen, The Netherlands). We collected fragments from 35 depth intervals in the ZRP-3a core and from 33 depth intervals in the SDM-1 core (Fig. DR1). Samples selected for sectioning (Tables S1 and S2) were first flushed in daily refreshed demineralized water for several days, dried in a hot-air oven (60°C), vacuum-impregnated using an epoxy resin, and then left to harden. Sections I to XVIII are $\sim 500~\mu m$ thick polished sections prepared by D. Doran of the University of Southampton. All other sections are $\sim 30~\mu m$ thin sections, prepared at Utrecht University. Polished sections were sputter-coated with a $\sim 4-6~nm$ thick layer of Pt/ Pd to enable conduction in a scanning electron microscope (SEM). In the case of loose sample fragments (Fig. 2B) a $\sim 10~nm$ thick layer was applied.

All sectioned samples (dimensions 2.5 x4.8 cm) were imaged in full using SEM-backscatter electron (BSE) imaging (e.g., Fig. DR3). Each BSE mosaic is composed of up to 1800 high-resolution BSE images. We chose BSE imaging over light microscopy because of the high quality and detail resolved, and the efficiency of (automatic) data collection. Sections Sg07 and Z22 were additionally mapped using electron dispersive X-ray (EDX) spectrometry, cathodoluminescence (CL) imaging and electron backscatter diffraction (EBSD), and sections Sw14 and Sw14A using only CL and EBSD. Prior to EBSD and CL mapping, sections were repolished using a silica colloid, rinsed, and then coated for 2 seconds using a glow-discharge Carbon evaporator.

S1.2 Lab-Experiment

The experiment consisted of a stress-relaxation test broadly following the procedure described by Pijnenburg et al., 2018, 2019a. Here we used a cylindrical plug, sample Sw14A, which was drilled in a direction parallel to the coring direction from core fragment Sw14 (undepleted SDM-1 well, see Table S2). The experiment was carried out at a temperature of 100°C, an effective confining pressure of 31 MPa, a pore pressure of 8 MPa and a differential stress of 26 MPa, simulating the pressure-temperature conditions of the (depleted) Groningen reservoir (Pijnenburg et al., 2018, 2019; Van Eijs, 2015). Demineralized water (DMW) was used as the pore fluid. The sample was emplaced between two Mg-alloy (AZ-31), cylindrical, spacers, 15 mm long and 25 mm in diameter, which have elastic properties (Young's modulus E = 32 GPa, Poisson ratio v =0.35) close to those of the Slochteren Sandstone (i.e., $E \sim 10$ - 20 GPa, $v \sim 0.2$), thus reducing shear traction on the piston-sample interface during axial compression. To ensure an elastic response of the spacers at the conditions of testing they were pre-compressed at a differential stress of 105 MPa, at the same temperature and pressure conditions as used in the experiment. To reduce friction on the sample-piston interface further, we emplaced a double layer of thin (50 μm) Teflon sheets. The Teflon sheets and Mg-alloy spacers were perforated to facilitate free pore fluid flow. The sample-spacer assembly was jacketed using a fluorinated ethylene propylene (FEP) sleeve, sealed against the top and bottom pistons using steel wire tourniquets. The completed assembly was emplaced into the pressure vessel, and heated to the desired testing temperature of 100°C. During heating, a small confining pressure (P_c) was applied and maintained below the initial effective value of 5 MPa used during testing. After evacuating the pore fluid system for 15 minutes, a pore fluid pressure of 2 MPa was applied, followed by successive steps of increasing first the confining pressure, and then the pore pressure to their

starting values of respectively 13 MPa and 8 MPa, such that the effective confining pressure $(P_c^{\text{eff}} = P_c - P_p)$ never exceeded the starting value of 5 MPa. The sample was left to equilibrate at these conditions for 4 hours.

Starting from $P_c = 13$ MPa, and $P_p = 8$ MPa, the confining pressure was increased in 5 MPa increment steps, while maintaining a constant pore pressure. Each pressurization step was followed by depressurization to the initial value of $P_c^{\text{eff}} = 5$ MPa. We employed a pressurization rate of ± 0.05 MPa/s, chosen such that the rate of change of the mean effective stress was similar to that used during increase of axial stress. Upon achieving the desired confining pressure of 39 MPa, hence an effective confining pressure of 31 MPa, P_c was held constant, while the sample was subjected to axial compression ($\sigma_1 > \sigma_2 = \sigma_3 = \text{fixed } P_c$). During axial compression, the loading piston was advanced, leading to an increase of the differential stress (σ_1 – σ_3) at a near-constant axial strain rate (ε) of $\sim 10^{-5}$ s⁻¹, until the desired differential stress of 26 MPa was achieved. Following piston arrest, a time-dependent decrease of the differential stress of about 1 to 3 MPa occurred. To ensure sample equilibration at (σ_1 – σ_3) ≈ 26 MPa, the sample was axially re-loaded to (σ_1 – σ_3) = 26 MPa, 30 minutes after initial stress relaxation, and again after 70 hours. After a period of several days the differential stress remained constant within the resolution of measurement. Upon termination of the test, the sample was first axially unloaded ([σ_1 – σ_3] = 0 MPa), followed by depressurization to the initial P_c^{eff} value of 5 MPa.

The internal axial load, sample temperature, confining pressure, pore pressure, pore fluid volume change, and axial displacement were logged at 2 Hz during piston advancement intervals, and at 0.1 Hz for ~15 mins into an interval of stress relaxation, using a 16-bit DAQPad National Instruments A/D converter. All sensor voltage signals and displacement data were corrected using calibrations carried out under conditions relevant to those used during the test. During hydrostatic stress-cycles, the inelastic porosity change was obtained by dividing the inelastic change in pore volume, determined upon unloading to $P_c^{\text{eff}} = 5$ MPa, by the initial sample volume. Total shortening (ΔL) of the sample was determined from the difference in piston position between sample-piston touch upon the first axial loading, and final axial unloading, of the sample, at $P_c^{\text{eff}} = 31$ MPa. The total inelastic axial strain is taken $\Delta L/L \times 100\%$, where L is the initial, unconfined length of the plug before the experiment, which was 53.20 ± 0.05 mm as measured using calipers. The length of sample Sw14A after recovery from the experiment measured 53.10 ± 0.05 mm, implying a permanent axial shortening strain of $\sim0.2\%$, consistent with the mechanical data (Fig. DR3).

S2. MICROSCOPES AND ANALYSIS METHODS

Electron microscope imaging was conducted using an FEI Helios Nanolab G3 focused ion beam (FIB)-SEM, an FEI Nova Nanolab 600 FIB-SEM, a Phillips XL-30S SEM, and a JEOL JXA8530F electron microprobe, all installed at Utrecht University. Section-scale BSE micrograph mosaics were mapped in the Helios, using a concentric backscatter detector and FEI mapping software ("Maps"). Each mosaic-tile covers an area 1.18 mm x 0.79 mm with an overlap of 10% between each tile, and was recorded at a resolution of 1536x1024 pixels, at a working distance of 4-5 mm, using a dwell time of 3 μ s, an acceleration voltage of 10 kV, and a beam current of 1.6 nA. During mapping we enabled automatic adjustment of focus and contrast/brightness settings.

Element mapping by electron dispersive X-ray (EDX) spectrometry of sections Z22 and Sg07 was achieved using an Oxford Instruments (OI) X-Max 150 silicon drift detector installed on the Helios, employing an acceleration voltage of 10 kV, beam current of 1.6 nA, and a working

distance of 4 mm. Section-scale mosaics of the spatial element distribution were generated using the EDX operating software OI AZTec, for the elements Al, Ba, Ca, Cl, K, Fe, Mg, Na, Mn, S, and Si. These elements form the main constituents of the sectioned samples investigated here, except for Cl, which we used to represent the background (noise) signal. Mosaic stitching was done within OI AZTec, and each single-element map was exported at 3937x9521 pixel resolution.

Section-scale CL mapping (Fig. DR7) was achieved using panchromatic detectors installed on the Helios (Gatan PanaCL), and on the XL-30S (KE Centaurus). Selected subareas (Fig. DR6) were additionally analyzed by hyperspectral mapping, using an xCLent IV CL spectrometry system installed on the electron microprobe. Using the Helios we employed an acceleration voltage of 10 kV, a beam current of 1.6 nA, while operating at a working distance of 7.4 mm. The dwell time per pixel used was 10 μs for each image. Mapping was achieved using FEI "Maps", employing 10% overlap between each tile. Each tile was recorded at 3072x2048 pixel resolution, covering an area 0.414x0.276 mm² in size (1.34896·10⁻⁷ m/pixel). CL and BSE imaging in the microprobe occurs simultaneously, and was conducted using an acceleration voltage of 15 kV, a beam current of 30 nA, a dwell time of 10 ms and a step size of 0.5-1 μm/pixel.

Electron backscattered diffraction (EBSD) data of sections Sg07, Z22, Sw14 and Sw14A were collected using a Nordlys EBSD detector mounted on the XL30S. Automatic mapping was conducted using OI AZtec operating software, at 20 mm working distance, using a 50 μ m aperture, an acceleration voltage of 30 kV, and a beam current of 2.4 nA. The step size for automatic mapping was 7.000 μ m/pixel for section Z22 and Sw14, 8.000 μ m/pixel for section Sw14A, and 8.167 μ m/pixel for section Sg07.

S3. IMAGE PROCESSING AND INTERPRETATION

Stitching of section-scale BSE mosaics was achieved using the grid/collection stitching plugin (Preibisch et al., 2009) developed for the open source, Java-based image processing software "ImageJ" (Schindelin et al., 2012). Conversion from pixel to length dimensions is done via the pixel resolution ($7.70833 \cdot 10^{-7}$ m/pixel). To obtain levelled contrast between each tile we used a contrast-levelling batch routine (macro) in Adobe Photoshop 2014.1.0. CL micrographs collected using the Helios were first filtered using a bandpass fast-fourier transform built into ImageJ, while CL micrographs obtained using the microprobe did not require filtering. Crystallographic orientation data from EBSD measurements were processed using OI HKL Channel5, only indexing grains consistent with the quartz crystal system. We defined a grain boundary where crystal axes are mis-oriented by >10°, and a Dauphiné twin when the crystal system is rotated $60^{\circ} \pm 2^{\circ}$ about the c-axis <0001> (Tullis, 1970). We removed isolated pixels with a different (apparent) orientation, but a common crystal system to neighboring pixels. Zero-solutions were removed using an iterative nearest-neighbor interpolation.

Stitched BSE mosaics were cropped into domains of characteristic porosity, mineralogy, or grain size distribution (GSD), consistent with mm- to cm-scale sedimentary layering identified from visual inspection. In all, we studied 51 domains in SDM-1 core samples, 56 in ZRP-3a core samples, and 7 in lab-deformed sample Sw14a (Tables S1 and S2). All image processing described below was carried out for each domain separately. The output result was visually inspected for consistency with the input image.

Intragranular crack mapping was achieved using a Wacom IntuosPro pen tablet connected to ImageJ or else to ESRI ArcMaps 2010, tracing each intragranular alignment of black pixels

corresponding with a fracture. Crack mapping was done by multiple individuals, unaware of sample origin, and several maps or portions thereof have been reinterpreted to check reproduction. This revealed reproduction of the number of cracks in each map (N_{cr}) to within $\pm 15\%$, mainly due to interpretative ambiguities. The intragranular crack density (ρ_{cr} in Fig. 3a, Fig. DR6, and Tables S1 and S2) is calculated as $\rho_{cr} = N_{cr}/((A_{map}(1-\phi)))$, where A_{map} is the area of the cropped BSE mosaic (i.e., the domain) used for preparing the crack map overlay, and ϕ is the pore area exposed in the mosaic.

Porosity was determined from thresholding of filtered BSE mosaics (Gaussian blur, pixel radius 2) using the Otsu algorithm (Otsu, 1979). Grain size was measured using the line intercept method, tracing 250 to >1000 line lengths (N_L) across grains for each BSE mosaic, such that the standard error $SE = SD/\sqrt{(N_L)} \le 10$ µm, where SD is the standard deviation of the grain size distribution. The intercept length (1) is scaled via the pixel dimension and converted to grain size (d), using $d = 1.5 \times 7.70833 \cdot 10^{-7} \times l$ (Dell'Angelo and Olgaard, 1995). In sections Sg07 and Z22, which were mapped using EDX, the phase-specific area was determined from summing the cumulative grain area in phase maps prepared from linear combinations of single-element maps (A_{grain}^{phase}) in Fig. 3b) (Verberne and Spiers, 2017). To estimate the K-Feldspar grain area (A_{grain}^{KFS} in Fig. 3c and Tables S1 and S2), we carried out segmentation of the highest grey-level pixel intensities in BSE mosaics. In the Slochteren sandstone, the grains with the highest pixel intensity in BSE images are mainly K-Feldspar, with minor barite and siderite. Prior to segmentation, each mosaic was contrast-levelled, filtered (Gaussian blur, 2px), and subjected to a 3x3 convolution kernel to introduce artificial noise. Trial-and-error showed that this method improved the quality of the output. Segmentation was then carried out using the Multi-Otsu algorithm (Liao et al., 2001) in ImageJ, set to 4 threshold levels. The highest-level segment was filtered using a median ranking filter (15 px) to remove noise, and then converted to a binary image, such that the phase of interest is represented as white pixels against a black background. After removing isolated (black) pixels using the 'fill holes' command in ImageJ, the 'Analyze particles' routine was used, selecting particles of $\geq 3000 \text{ px}^2$ in size, effectively further filtering out random noise. Visual inspection showed a good match between the KFs grains of interest and the segmented output binary image. For each BSE mosaic or domain, a binary file representing the KFS grain area map is multiplied with its corresponding binary crack map. The resulting binary output shows lineaments, each of which represent a crack cutting KFs.

CL mosaics were referenced to the corresponding area in the BSE mosaic (using ESRI ArcMaps 10.3.1 or ImageJ), including the crack map and phase map overlay when available. Intergranular cracks identified in the crack map were inspected for overlap with preexisting healed fractures and overgrowths identified from the CL map. Maps of quartz area and Dauphiné Twins (DT's) prepared using EBSD and exported using OI HKL Channel5, were first converted to bitmaps (Fig. DR7). The quartz area and DT boundary length were calculated by taking the number of pixels in each map, and scaling via the step-size employed. The ratio of DT boundary length over the quartz area is taken to represent the DT density (ρ_{DT} in Table S3).

S4. DATA PROCESSING

S4.1 Student's T-Test Using KFs Crack Populations in ZRP-3a and SDM-1 samples

Crack ratio ($\mu_1 = N_{cr}^{KFs}/N_{cr}^{tot}$) data (Fig. 3c) can be treated as a discrete frequency distribution, F(x), characterized by a population (N), mean (\bar{x}) and standard deviation SD. We test the statistical discernibility between $F^{SDM}(x)$ and $F^{ZRP}(x)$ using an unequal variance, two-tailed t-test (Student, 1908)

$$t = \frac{\vec{x}^{ZRP} - \vec{x}^{SDM}}{\sqrt{\frac{\left[SD^{ZRP}\right]^2}{N^{ZRP}} - \frac{\left[SD^{SDM}\right]^2}{N^{SDM}}}}$$

Where the superscripts refer to data from respectively the SDM-1a and ZRP-3a cores. When t falls below some reference value β , we may conclude that the distributions are statistically discernable at the β -level (or confidence level $(1-\beta)\times 100\%$) (Wonnacott and Wonnacott, 1990). Taking $H_0: \bar{x}^{SDM} = \bar{x}^{ZRP}$ and $H_1: \bar{x}^{SDM} \neq \bar{x}^{ZRP}$ returns a probability $P(T \leq t; H_0) = 0.056 \approx 6\%$, implying that the null hypothesis must be overthrown at the 94% confidence level. This suggests that \bar{x}^{ZRP} is indeed significantly larger than \bar{x}^{SDM} —in line with the visual trend in Fig. 3B.

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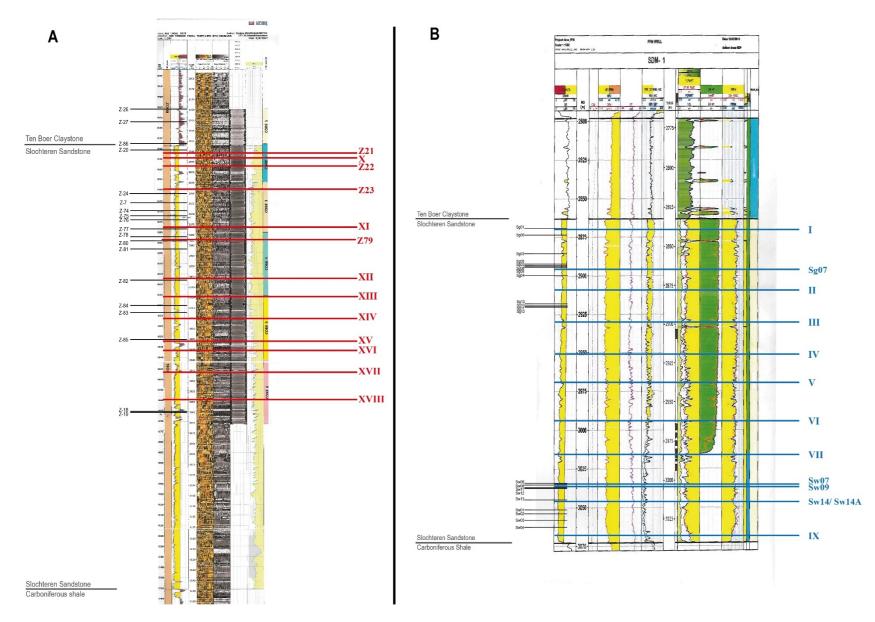


Figure S1. Overview of core samples. (A) Depleted ZRP-3a and (B) undepleted SDM-1 core. Sections in bold.

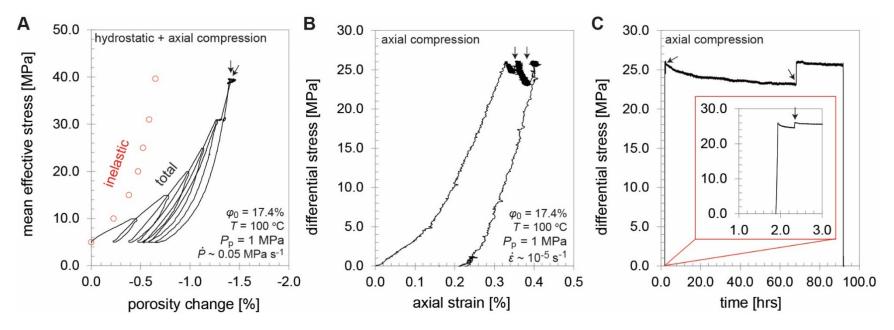


Figure S2. Lab-test on an SDM-1 core sample (Sw14A) simulating production-induced compaction. (A) Mean effective stress versus porosity change. (B) Differential stress versus axial strain, and (C) versus time. φ_0 = starting porosity, T = temperature, P_P = pore fluid pressure, \dot{P} = pressurization rate, $\dot{\varepsilon}$ = axial strain rate. Arrows indicate reloading to a differential stress of 26 MPa.

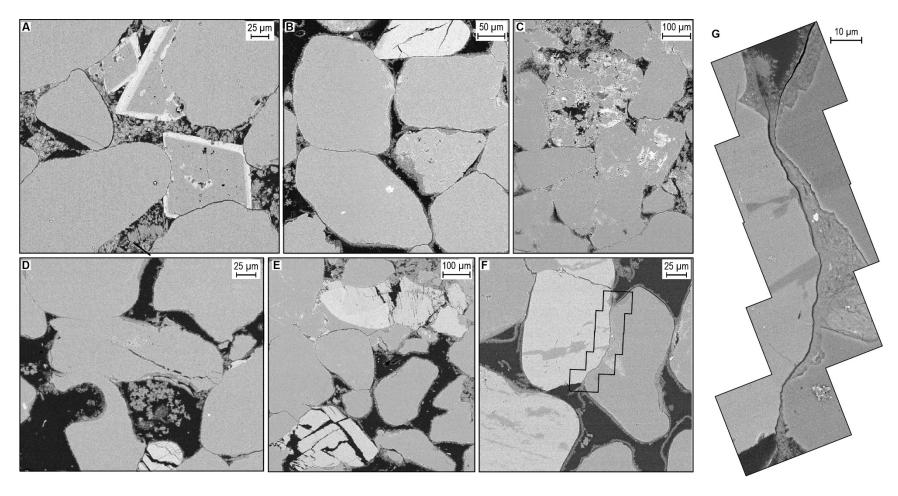


Figure S3. Slochteren Sandstone microstructures. Backscatter electron micrographs, representative for SDM-1 and ZRP-3a core. (A) Intragranular cracks in quartz and carbonate. Zoned crystals are ankerite/ dolomite with a siderite rim. (B) Clay-coated quartz grains and cracked K-feldspar (KFs) (bright grain). (C). Lithic fragment with high intragranular porosity. (D) Intragranular crack. (E) Multiple (cleavage) cracks in KFs. (F) and (G) Clay-rim within a KFs-quartz grain contact.

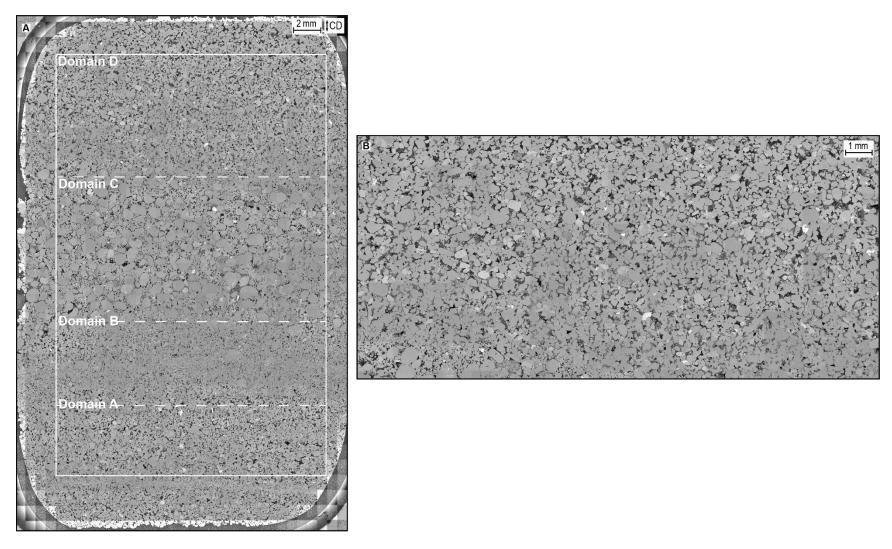


Figure S4. Sectioned layered core samples. (A) Backscatter electron micrograph mosaic of section 1 (SDM-1), highlighting domains A-D used for image analysis. (B) Domain "D". See Tables S1 and S2 for a list of all sectioned samples and domains.

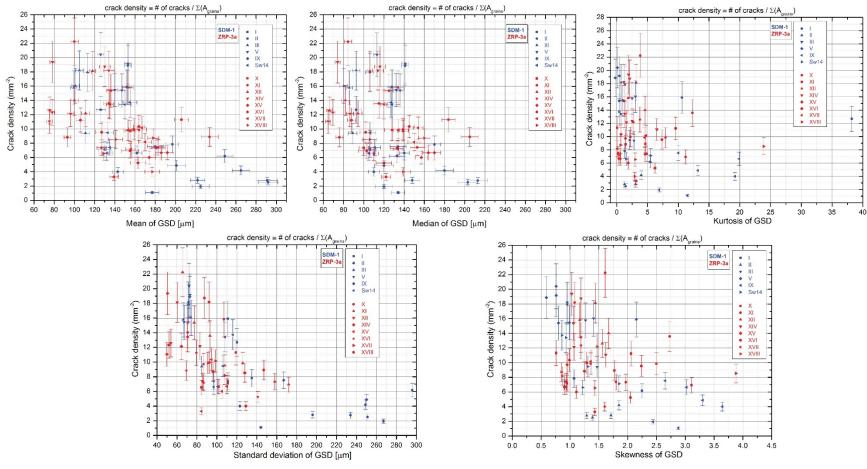


Figure S5. Intragranular crack density and descriptors quantifying the grain size distribution (GSD). Grain size data from linear intercept analysis and crack mapping of each domain (see Tables S1 and S2).

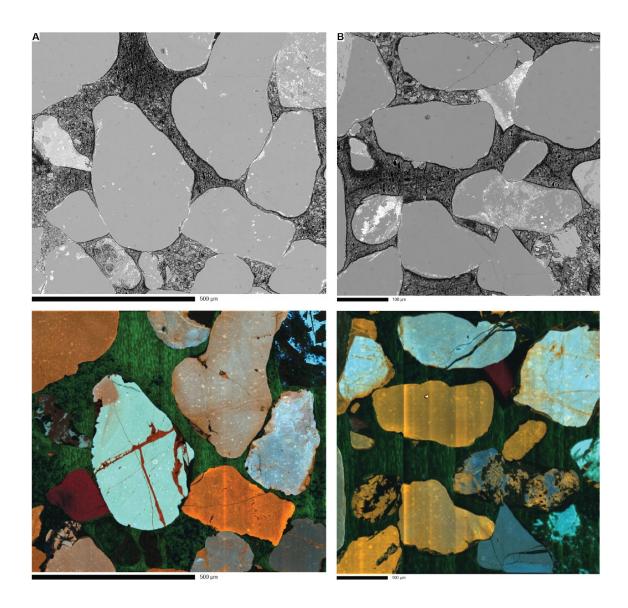


Figure S6. Hyperspectral cathodoluminescence (CL) mapping. The upper row shows backscattered electron micrographs, and the lower row the corresponding RGB CL maps. Collected from section Z22 (ZRP-3a). (A) Central quartz grain (blue CL) shows healed intragranular fractures and overgrowth (red and dark CL). (B) Central uppermost quartz grain shows a reactivated healed intragranular fracture (dark CL).

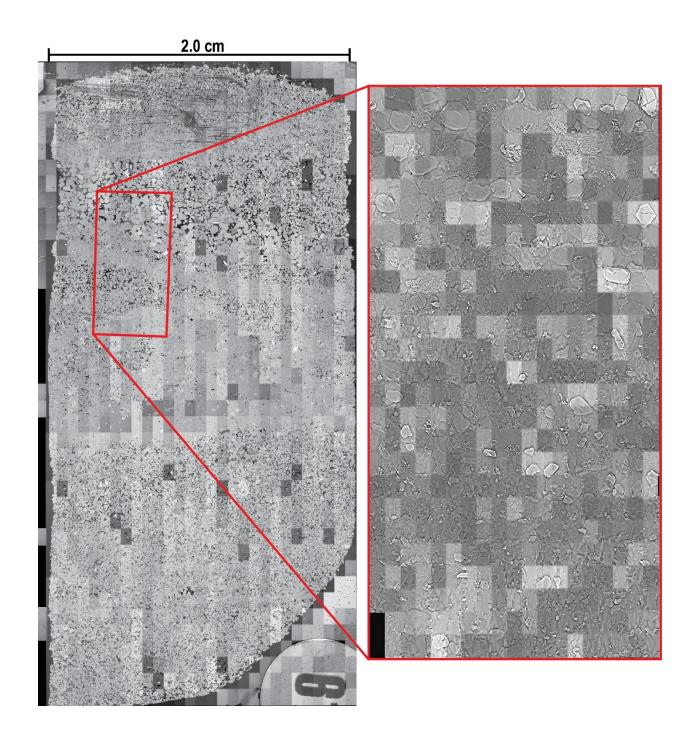


Figure S7. Panchromatic cathodoluminescence (CL) mosaic. A crack map overlay, prepared using the backscatter electron mosaic (left), was used to identify reactivated healed fractures in the CL mosaic (right). Section Z22 (depleted ZRP-3a core).

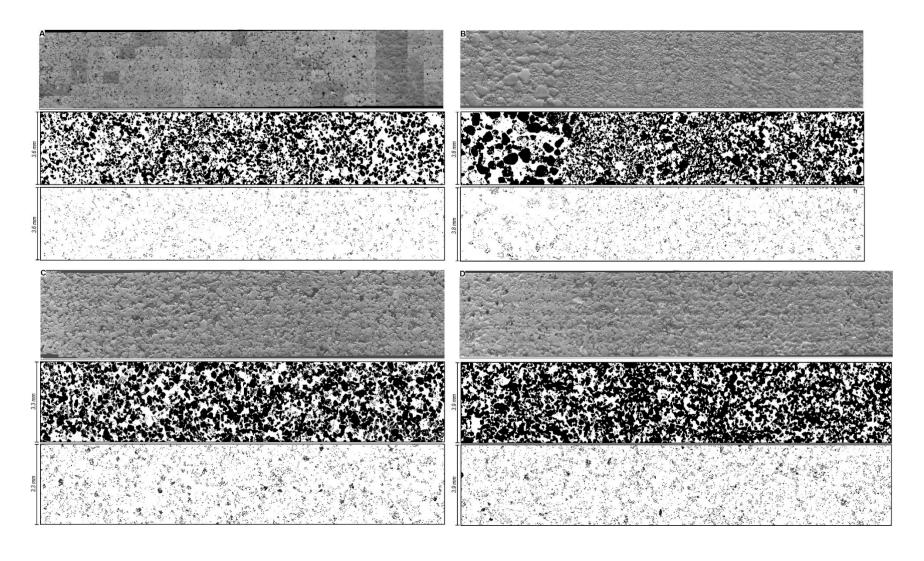


Figure S8. Electron backscatter diffraction (EBSD) mapping of quartz and Dauphiné Twin (DT) boundaries. The top image in each panel is a forescattered electron micrograph of the mapped area, the middle image the quartz area bitmap, and the bottom image the Dauphiné Twin boundary bitmap.

Table S1. List of key data from sectioned ZRP-3a core samples.

	51. List of		A_{map}		φ	A_{KFs}		Median	Mean	SE	SD			$ ho_{cr}$
Section	TVD (m)	Domain		N_{cr}	[%]	[mm ²]	N _{cr} ^{KFs}	[µm]	[µm]	[µm]	[µm]	Skew	Kurt	[mm ⁻²]
Z21	2941.4	full	286	5219	18.3	9.03	556	n/a	n/a	n/a	n/a	n/a	n/a	22.4 ± 3.4
X	2943.5	A	47.8	357	24.9	1.56	43	139	159	5.52	92.7	1.29	2.23	9.9 ± 1.5
		В	73.2	611	26.2	2.94	71	184	206	6.71	119	0.76	0.08	11.3 ± 1.7
		С	52.4	342	26.7	2.29	39	205	234	8.50	147	1.77	4.67	8.9 ± 1.3
		D	21.5	120	24.1	0.51	11	100	127	4.69	85.8	1.80	4.91	7.4 ± 1.1
		Е	25.1	141	24.2	0.98	9	153	183	6.85	111	0.94	0.23	7.4 ± 1.1
Z22	2947.4	1	72.6	1008	19.2									17.2 ± 2.6
		2	13.9	81	9.8									6.4 ± 1.0
		3	31.5	428	17.4	/-	/-	/-	/	/	/-	/-	/-	16.4 ± 2.5
		4	40.2	329	11.9	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	9.3 ± 1.4
		5	46.8	143	6.1									3.3 ± 0.5
		6	86.7	1172	19.5									16.8 ± 2.5
Z23	2958.5	mos1	54.9	815	26.4	n/a	n/o	n/o	m/o	n/o	n/a	n/a	m/a	20.2 ± 3.0
		full	287	6754	22.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	30.5 ± 4.6
XI	2976.6	A	52.0	310	14.0	1.34	54	103	155	8.61	172	3.11	11.2	6.9 ± 1.0
		В	29.2	355	21.0	0.73	38	125	136	3.98	77.3	1.06	1.18	15.4 ± 2.3
		С	32.7	195	18.7	0.55	18	133	181	6.20	158	1.97	4.60	7.3 ± 1.1
		D	44.7	484	20.2	1.04	54	115	134	5.11	93.1	2.73	12.3	13.6 ± 2.0
		Е	36.5	668	17.8	0.76	70	84.4	100	3.76	65.7	1.61	3.84	22.2 ± 3.3
		F	25.1	202	18.4	0.78	25	128	164	7.47	126	2.50	7.93	9.9 ± 1.5
Z79	2982.9	full	278	4810	14.8	7.76	526	n/a	n/a	n/a	n/a	n/a	n/a	20.3 ± 3.0
XII	3001.5	A	52.9	597	19.5	0.42	73	81.7	100	3.86	70.8	1.67	4.60	14.0 ± 2.1
		В	55.1	676	22.5	0.68	42	134	153	5.63	107	1.17	1.85	15.8 ± 2.4
		С	40.6	407	17.7	0.37	41	94.2	111	4.02	83.0	1.47	2.71	12.2 ± 1.8
		D	10.9	116	15.3	0.07	9	66.1	75.5	2.54	53.9	1.56	3.77	12.6 ± 1.9
		Е	32.6	492	16.8	0.43	44	106	118	2.99	60.2	1.44	3.14	18.1 ± 2.7
XIII	3009.8	A	43.8	77	14.0									2.0 ± 0.3
		В	22.0	152	27.5									9.5 ± 1.4
		С	12.6	112	28.1	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	12.4 ± 1.9
		D	69.1	389	29.6									8.0 ± 1.2
		Е	18.1	161	28.1									12.4 ± 1.9
XIV	3020.6	A	11.5	109	14.6	0.16	10	64.7	75.2	2.73	49.9	1.62	6.52	11.1 ± 1.7
		В	27.2	401	19.0	0.58	34	114	134	5.32	92.1	1.08	1.17	18.2 ± 2.7
		С	19.5	315	16.7	0.42	22	74.0	78.3	2.50	50.5	1.03	1.91	19.4 ± 2.9
		D	10.2	107	14.6	0.17	5	69.4	78.0	2.34	51.9	1.19	2.50	12.3 ± 1.8
		Е	26.9	401	20.5	0.48	45	116	130	5.24	87.4	1.19	2.11	18.7 ± 2.8
		F	28.8	289	17.2	0.29	18	86.3	96.2	3.33	64.4	1.07	1.60	12.1 ± 1.8
	2022	G	50.7	564	17.2	0.88	67	120	135	3.38	70.6	1.19	1.33	13.4 ± 2.0
XV	3032	A	61.8	178	12.4	1.96	62	122	139	4.38	84.4	1.43	3.15	3.3 ± 0.5

		В	47.1	386	20.9	0.75	49	145	164	5.32	94.5	0.99	0.69	10.4	±	1.6
		С	29.2	224	21.1	0.65	74	139	155	5.17	86.7	0.95	1.41	9.7	±	1.5
		D	52.5	276	21.2	1.14	39	164	186	5.77	102	0.90	0.35	6.7	\pm	1.0
		Е	42.6	217	15.3	1.41	48	157	174	6.10	105	1.11	1.87	6.0	±	0.9
		F	71.3	375	21.3	1.31	74	170	192	6.14	110	0.93	0.58	6.7	±	1.0
XVI	3035.5	A	32.2	245	13.9	0.38	35	75.9	93.1	3.37	69.4	1.25	1.46	8.8	±	1.3
		В	35.0	280	16.3	0.57	31	102	127	5.88	108	2.24	7.35	9.5	±	1.4
		С	67.9	298	16.3	1.51	39	120	163	7.80	141	2.05	6.23	5.2	±	0.8
		D	50.7	477	16.4	0.50	50	87.9	106	3.99	79.5	2.06	9.56	11.2	±	1.7
XVII	3046	A	64.1	534	17.9	1.88	83	154	167	4.84	98.5	1.36	4.76	10.2	±	1.5
		В	82.9	668	18.2	1.40	99	134	153	4.65	91.0	1.36	4.55	9.9	±	1.5
		С	70.5	436	13.7	1.58	41	134	156	5.05	86.6	0.95	0.51	7.2	±	1.1
		D	39.6	266	17.9	0.75	45	150	170	6.36	108	0.87	0.10	8.2	\pm	1.2
XVIII	3058.7	A	42.5	315	13.1	0.23	17	106	141	6.86	128	3.88	23.9	8.5	\pm	1.3
		В	49.2	168	14.6	0.51	12	139	177	7.24	129	1.60	2.92	4.0	\pm	0.6
		C	59.7	429	17.7	0.57	86	160	178	5.50	96.2	0.85	0.64	8.7	\pm	1.3
		D	43.9	248	13.8	0.44	27	110	129	4.65	84.4	1.43	2.99	6.5	±	1.0

TVD = True vertical depth; A_{map} = area of (cropped) BSE mosaic. N_{cr} = number of intragranular cracks. φ = porosity. A_{KFs} = cumulative area occupied by KFs grains. N_{cr}^{KFs} = number of cracks in KFs grains. Median, mean, SE (standard error), SD (standard deviation), Skew(ness), and Kurt(osis) are quantitative descriptors of the grain size distribution. ρ_{cr} = Intragranular crack density (±0.15 N_{cr}).

Table S2. List of key data from sectioned SDM-1 core samples (incl. Sw14A).

G - 4	TVD ()	D	A_{map}	A T	φ	A_{KFs}	N _{cr} ^{KFs}	Median	Mean	S.E.	SD	CI.	W 4	$ ho_{cr}$
Section	TVD (m)	Domain	[mm ²]	N_{cr}	[%]	$[mm^2]$	IV _{cr}	[µm]	[µm]	[µm]	[µm]	Skew	Kurt	[mm ⁻²]
I	2840.6	A	93.2	1201	18.9	3.50	125	128	152	4.73	111	2.15	10.6	15.9 ± 2.4
		В	101	1102	14.1	2.11	87	92.5	128	4.73	128	4.31	33.2	12.7 ± 1.9
		С	190	1022	13.1	4.47	68	133	249	7.98	296	2.25	5.44	6.2 ± 0.9
		D	166	1063	18.3	6.82	182	170	197	6.19	135	1.07	1.30	7.8 ± 1.2
Sg05	2862.9	mos4	38.7	573	24.7	n/a	n/a	n/a	10/0	n/a	n/a	n/a	n/a	19.7 ± 3.0
		full	257	3679	23.0	17.4	799	11/a	n/a	II/a	n/a	II/a	II/a	18.6 ± 2.8
Sg07	2866.5	1	47.7	252	17.8									6.4 ± 1.0
		2	122	414	10.5									3.8 ± 0.6
		3	29.7	176	15.4									7.0 ± 1.0
		4	48.7	292	15.4	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	7.1 ± 1.1
		5	60.4	356	19.0									7.3 ± 1.1
		6	85.4	436	17.3									6.2 ± 0.9
		7	60.0	387	20.4									8.1 ± 1.2
II	2877.0	A	78.6	194	10.9	2.42	49	213	291	9.82	234	1.29	1.25	2.8 ± 0.4
		В	79.4	179	10.4	1.59	25	203	292	9.39	251	1.39	1.46	2.5 ± 0.4
		C	62.1	238	8.6	2.75	51	180	265	8.75	249	1.85	3.98	4.2 ± 0.6
		D	109	292	3.9	11.4	90	148	222	7.21	196	1.71	3.05	2.8 ± 0.4
III	2898.9	A	36.0	553	15.7	1.54	81	92.5	105	3.71	71.4	0.95	0.71	18.2 ± 2.7
		В	17.8	247	13.4	0.80	41	80.2	101	3.78	74.0	1.41	3.04	16.0 ± 2.4
		C	36.3	545	16.2	1.99	84	106	113	4.12	71.4	0.95	1.36	17.9 ± 2.7
		D	23.0	194	10.2	1.00	29	89.0	111	4.32	84.8	1.47	2.80	9.4 ± 1.4
		Е	24.4	334	13.2	1.09	42	85.6	99.4	3.32	66.2	1.27	2.51	15.8 ± 2.4
IV	2950.6	full	574	n/a	21.2	14.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
V	2938.3	A	51.9	842	20.5	0.81	61	113	126	2.94	72.2	0.76	0.11	20.4 ± 3.1
		В	45.6	673	22.9	0.73	50	141	153	3.37	73.0	0.76	0.40	19.2 ± 2.9
		С	18.0	225	19.0	0.18	11	132	140	3.17	67.1	0.99	0.97	15.5 ± 2.3
		D	78.2	1145	22.4	1.31	111	141	153	3.24	72.9	0.59	-0.24	18.9 ± 2.8
		Е	59.4	723	21.0	0.99	49	136	147	3.17	70.8	0.80	0.41	15.4 ± 2.3
VI	2960.3	full	533	n/a	16.9	5.38	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
VII	2985.6	full	597	n/a	23.3	3.16	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Sw07	3005.0	full	270	742	23.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	3.58 ± 0.5
Sw09	3007.0	full	209	3446	10.9	1.13	99	n/a	n/a	n/a	n/a	n/a	n/a	18.5 ± 2.8
Sw14	3015.4	A	49.9	306	13.9	0.09	3	106	130	6.14	111	1.85	5.52	7.1 ± 1.1
		В	55.0	433	16.9	0.06	2	106	133	5.84	106	1.31	2.11	9.5 ± 1.4
		С	17.5	104	10.1	0.10	3	105	132	5.42	96.8	1.22	1.55	6.6 ± 1.0
		D	50.3	556	19.5	0.19	8	127	155	6.94	116	0.86	0.41	13.7 ± 2.1
		Е	36.0	240	10.1	0.11	1	111	135	5.73	96.7	0.91	0.25	7.4 ± 1.1
		F	49.1	540	18.1	0.07	4	128	150	5.97	108	0.93	0.68	13.4 ± 2.0
IX	3041.1	A	65.8	67	6.8	0.23	2	134	177	6.60	144	2.88	11.5	1.1 ± 0.2

		В	47.9	256	19.5	0.44	4	140	162	4.98	101	3.02	19.9	6.6	±	1.0
		С	42.4	180	12.9	0.22	7	120	201	9.21	250	3.30	13.2	4.9	±	0.7
		D	28.4	99	12.9	0.12	0	110	143	5.66	123	3.64	19.2	4.0	±	0.6
		Е	31.9	194	19.2	0.12	5	134	180	7.97	167	2.65	10.0	7.5	±	1.1
		F	59.3	106	8.1	0.26	6	120	225	8.38	267	2.44	6.91	1.9	±	0.3
Lab-d	<u>eformed</u>															
Sw14A	3015.4	A	61.1	479	13.0									9.0	±	1.4
		В	47.2	220	15.9		n/a	12/2	n/a n/a	n/a n/a		n/a	n/a	5.5	±	0.8
		C	19.8	92	11.2						n/a			5.2	±	0.8
		D	57.8	354	18.3	n/a		11/a						7.5	±	1.1
		Е	32.9	102	10.8									3.5	±	0.5
		F	62.6	404	17.2									7.8	±	1.2
		G	154	801	14.9			177	202	6.96	125	1.25	2.07	6.1	\pm	0.9

TVD = True vertical depth; A_{map} = area of (cropped) BSE mosaic. N_{cr} = number of intragranular cracks. φ = porosity. A_{KFs} = cumulative area occupied by KFs grains. N_{cr}^{KFs} = number of cracks in KFs grains. Median, mean, SE (standard error), SD (standard deviation), Skew(ness), and Kurt(osis) are quantitative descriptors of the grain size distribution. ρ_{cr} = Intragranular crack density (±0.15 N_{cr}).

Table S3. Reactivated healed fractures.

Sample	Domain	A_{map} [mm ⁻²]	N _{cr}	N _{cr} heal	X
Undepleted core					
Sw14	В	55.0	313	95	31.3
	C	17.5	114	51	44.7
	D	50.3	377	111	29.4
	E	36.0	206	63	30.6
Depleted core					
XII	Α	52.9	405	124	30.6
	В	55.1	533	149	28.0
	C	40.6	281	93	33.1
	D	10.9	73	45	61.6
Lab-deformed					
Sw14A	D	45.2	156	68	43.6

 A_{map} = total mapped area. N_{cr} = number of intragranular cracks in quartz mapped. N_{cr}^{heal} = number of cracks overlapping older healed fractures or overgrowths. $X = N_{cr}^{heal} / N_{cr} \times 100\%$.

Table S4. Quartz area and Dauphiné Twin (DT) boundary length.

Sample	A_{map} $[extbf{mm}^{-2}]$	A_{qtz} $[extbf{mm}^{-2}]$	L_{DT} [mm]	$ ho_{DT}$ $[extbf{mm}^{ ext{-}1}]$
Undepleted core				
Sg07	80.7	44.1	417	9.44
Sw14	54.0	30.0	504	16.8
Depleted core				
Z-22	73.6	33.3	354	10.6
Lab-deformed				
Sw14A	62.2	51.0	740	14.5

 A_{map} = total mapped area. A_{qtz} = quartz area. ρ_{DT} = DT density.