Dear Dr. Fusseis,

Our paper makes a very important conceptual contribution, in that it highlights how critically low porosity, combined with evidence that solution-precipitation occurred, means a fault is in a critical state. This may be the control on earthquake recurrence interval of many similar faults. We think that your focus (mirrored and thus doubly weighted by the reviewer, who we note was in the past a member of your research group) on procedural details of the analyses obscures the major contribution of our paper. As demonstrated below, even if we use a different analytical method, the key data that stimulate this concept, which is that the porosity is critically low, will not change. We hope that it is possible to allow this observation inspired concept to be presented to our community, since we expect it to stimulate new and novel research in other fault zones.

Following your request, we have included SEM data to the manuscript. This data is a part of an unpublished PhD thesis, thus we have added that thesis' author, Dr. Risa Matsumura, as a co-author of this manuscript.

Below we have provided a point-by-point response. Line numbers are listed with respect to the manuscript with track changes on.

Best Regards,

Dr. Martina Kirilova

On behalf of co-authors: Virginia Toy, Katrina Sauer, François Renard, Klaus Gessner, Richard Wirth, Xianghui Xiao, and Risa Matsumura

Dear Authors,

Thank you for your reply to my comments. Unfortunately, it does not convince me that your porosity estimates are robust and support your interpretations sufficiently. Your descriptions are neither precise nor detailed enough to allow for a reproduction of your analysis, and I do miss evidence that supports the choices you have made in your data processing. Just a few examples to justify these statements:

What data support your claim that binary thresholding is “more than sufficient for robust porosity segmentation”?

Response: See our answer to point 1 in Dr. Gilgannon's review.

What threshold values did you use, and how were they chosen? Where they the same between all four datasets?

Response: See our answer to point 2 in Dr. Gilgannon's review.

What is the effect of the NLM filter on your porosity quantification?

Response: Non-local means filter reduces noise, and several studies have employed it (e.g. Thomson et al., 2018; Renard et al., 2019). We have now added two sentences at the beginning of section 3.3 that summarize the effect of this filter.

Are your subvolumes statistically representative?

Response: The sub-volume crops in each sample are representative. They were carefully chosen to (i) preserve the typical microstructural characteristics within a sample, and (ii) to exclude ring artifacts or big fractures (obviously induced by coring) as much as possible.

Where all of your pores labelled on the basis of face-connected pores?

Response: All pores were labelled on the basis of face-connected pores. This question was already addressed during the previous round of revisions and the information was added at line 116, but due to further revisions it is now at lines 143 and 147.

What degree of voxel connectivity did you choose to label your pores?

Response: No limit of voxel connectivity was implemented. Limits within Avizo software were introduced purely for visualization purposes as previously noted at line 147.

All of this is critical, as your entire interpretation is based on your segmented porosity data. Your reference to Menegon et al., (2015) and Gilgannon et al. (2017) is to a degree justified, both do indeed use the same thresholding technique. However, we now have significantly more sophisticated algorithms freely available, and they should be used. The significance of the choice of segmentation technique has been demonstrated in a large number of publications.

Response: See our answer to point 1 in Dr. Gilgannon's review.

On the basis of these, I am actually certain that I could analyze your data with a different set of algorithms and arrive at significantly different numbers, which, I think, highlights the principal problem.

Response: See our answer to point 1 in Dr. Gilgannon's review.

We would be interested in the opinion of the Editorial Board whether this statement is in line with the code of conduct of Solid Earth (point 3 in https://www.solid-earth.net/policies/obligations_for_editors.html: "*An editor must respect the intellectual independence of authors*").

As is, I cannot recommend the paper for publication. I do you encourage you to address the concerns raised above, and I would further ask you to consider the review of your revised manuscript provided by James Gilgannon.

Response: Because the second review of Dr. Gilgannon was not submitted as part of the interactive discussion process, all the authors failed to recognize the submission of this review. We now provide a response to Dr. Gilgannon's comments.

I would further ask you to include the detailed microstructural sample description that must form the basis for your interpretation of the porosity in these rocks.

Response: We have added section 3.4, lines 214-220 in section 4.2 and Figure 8.

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Dear Editor,

Please find my general and specific comments below for my review of the revised manuscript by Kirilova et al., titled "Micro- and nano-porosity of the active Alpine Fault zone, New Zealand".

General comments

In their revised manuscript the authors have chosen to retain the manuscript largely as is. The few additions that have been made in the methods section now help the reader not make the mistake I made when first reading the initial submission.

I understand why the authors have been reluctant to change the manuscript as it is well written and has a flow that guides the reader but I do not find the answers to my last comments satisfactory in addressing the fundamental limitations of the data. The chief concern I have is that the porosity segmentation is too simplistic to allow the interpretation that follows in the discussion of a porosity and permeability gradient. In the following specific comments I have tried to clarify why I think that the authors may be over-interpreting their data and as such why I think that the authors should make room for more discussion about the limitations of the data.

To be very clear I think that the work is good and the results can be published but first there is a need for more transparency in the methodological workflow used and how it may affect any interpretations. If the authors wish to make the claims they currently make then I think these must be made more cautiously and with enough information given to allow the reader to evaluate the discussion points. As the manuscript currently stands, the results presented do not allow a gradient in porosity and permeability to be interpreted nor the further interpretation of this that variations in dissolution-precipitation must exist, which are both key discussion points of the current manuscript.

Best,

James Gilgannon

Dear Dr. Gilgannon,

We are grateful for the overall positive and thorough feedback provided here and address the remaining concerns below.

1) the porosity segmentation is too simplistic

Response: We acknowledge the efforts of the reviewer to support his views with the analysis of a synthetic case where images with known porosity are generated. These images are created with a two-step process: 1) an image of known porosity is created, 2) then this image is blurred, an effect that we consider similar to adding noise. Finally, different gray level thresholds are applied and a variability on the estimated porosity is calculated. This example illustrates very well that when the level of noise in an image is increased, a variability in the results of a segmentation technique is encountered (Andrew, 2018). In analysing our data, we proceeded in the opposite way. First, we reduced the noise in the images by applying a non-local-means filter, and then we applied a segmentation technique. This approach ensures that the differences between several segmentation techniques remain small when the level of noise in the images is small (as shown by Figure 3h of Andrew, 2018).

The main limitations of all the possible segmentation methods are data resolution, noise level, and spatial complexity of the materials of interest (e.g. Iassonov et al., 2009; Andrä et al., 2013; Bultreys et al., 2016). Furthermore, the ground-truth/real/absolute porosity is unknown in natural samples imaged with XCT (Hapca et al., 2013), unless measured independently. The thresholding method performs as well as other segmentation techniques (e.g. classification using a supervised machine learning algorithm, watershed) when the level of noise in the images is low, as demonstrated by Figure 3h of Andrew (2018). To our knowledge, there is no segmentation procedure that can be automatically applied to various kinds of samples, without the intervention of a real scientist who can adapt the segmentation procedure to the data set and even then, the estimated porosity will only be an approximation. The method we have chosen is robust and widely used in rock physics (e.g. Iassonov et al., 2009, Fusseis et al., 2014; Qi et al., 2018; Xing et al., 2018; Macente et al., 2018; 2019; Renard et al., 2019) and potential caveats on the choice of the value of the threshold have been identified in other studies (e.g. Andrä et al., 2013).

We identified porosity as the darkest phase on the analyzed synchrotron high-contrast grey-scale images. These images have less noise than data acquired in laboratory (e.g. desktop CT tomographs). In addition, porosity in these samples is represented by separated individual pores, so there were no morphological complications with respect to spatial resolution (e.g. separating fractures such as in Figure S1 in Zhao et al., 2020). Thus, it was straightforward to segment pores by binary thresholding.

More ‘complex’ segmentation methods could be applied as an exercise, similar to what was done by Andrew (2018). This exercise is out of the scope of the present article and would be a study in itself.

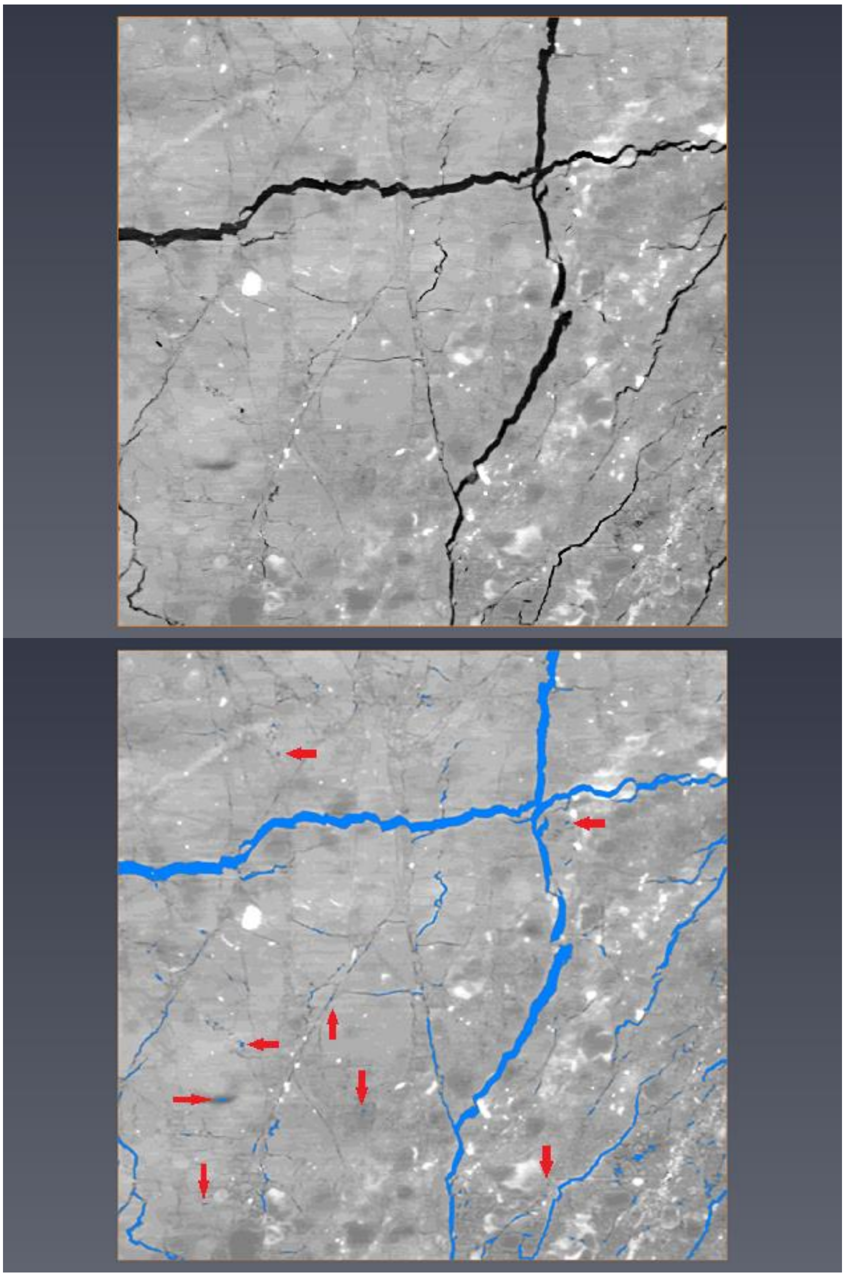
However, because we consider that the reviewer comments necessitate modification of our manuscript, we have added several paragraphs in section 3.3 to justify the choice of our segmentation technique and added two sentences in section 4.1 to estimate a variability of the porosity. We have also added some information on the variability several segmentation techniques could introduce to the estimated porosity: our preferred segmentation procedure indicates porosities in the range 0.1-0.24%. Including 20% variability due to various segmentation techniques (Andrä et al., 2013) would modify this range to 0.08-0.29%. If one considers that the level of noise in the data is low so the analysis of Andrew applies (Figure 3h, 2018), the variability between segmentation procedures would be negligible.

In summary, as we now explain in Section 3.3, different segmentation procedures will not sufficiently modify our results, and thus will not affect the discussion and central conclusions made in the manuscript.

2) need for more transparency in the methodological workflow

Response: We strive to be as transparent as possible about our analyses. Thus, we intend to provide the analyzed datasets in a data repository (most likely via GFZ Dataservices) to accompany the manuscript when it is published. The applied gray level threshold ranges for each sample are different because of a difference in darkness contrast between the samples. The threshold ranges applied to each samples are as follows: DFDP-1B 69_2.54: 0 to 28; DFDP-1B 69_2.57: 0 to 44; DFDP-1B 58_1.9: 0 to 74; DFDP-1B 69_2.48: 0 to 46. On the screenshots below, we display the result of the selected threshold value in sample DFDP-1B 69_2.54, slice 363. This demonstrates that most of the porosity is due to fractures that formed during sample unloading, representative pores are shown with arrows.

Furthermore, to demonstrate the need for polynomial fitting in order to estimate total porosities in these samples we included further explanations in the text at lines 139-161 and an additional table in Supplementary material 1.



3) the results presented do not allow a gradient in porosity and permeability to be interpreted nor the further interpretation of this that variations in dissolution-precipitation must exist, which are both key discussion points of the current manuscript

Response:

Our main conclusions are based on the fact that the total porosities in these samples are extremely low. Even if different segmentation techniques would double these porosity estimates (e.g. Andrä et al., 2013), these numbers will remain very low, well under 1% total porosity. The fact than one sample contains twice the total porosity of others is an observation that deserves discussion. We have further clarified this in the manuscript in lines 289-293. Furthermore, evidence for pressure-solution process in these rocks have been documented in numerous previous studies (Sutherland et al., 2012; Toy et al., 2015;

Schleicher et al., 2015; Williams et al., 2017) and also observed on the TEM images presented in the current manuscript. Therefore, our results are sufficient to support the main conclusion. This conclusion, which is novel and innovative, is not dependent on the absolute value of the segmented porosity.

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Micro- and nano-porosity of the active Alpine Fault zone, New Zealand

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Abstract

Porosity reduction in rocks from a fault core can cause ~~fluid overpressure~~elevated pore fluid pressures, and consequently influence the recurrence time of earthquakes. We investigated the porosity distribution in the New Zealand's Alpine Fault core in samples recovered during the first phase of the Deep Fault Drilling Project (DFDP-1B) by using two-dimensional nanoscale and three-dimensional microscale imaging. Synchrotron X-ray microtomography-derived analyses of open pore spaces show total microscale porosities in the range of 0.1-~~ to~~ 0.244%. These pores have mainly non-spherical, elongated, flat shapes and show subtle bipolar orientation. Scanning and ~~T~~transmission electron microscopy ~~imaging~~ reveal~~s~~ the samples' microstructural organization, where~~that~~ nanoscale pores ornament grain boundaries of the gouge material, especially clay minerals. Our data imply~~ies~~ that: (i) the porosity of the fault core is very small and not connected, (ii) the distribution of clay minerals controls the shape and orientation of the associated pores; (iii) porosity was reduced due to pressure solution processes; and (iv~~ii~~) mineral precipitation in fluid-filled pores can affect the mechanical behaviour of the Alpine Fault by decreasing the already critically low total porosity of the fault core, causing elevated pore fluid pressures~~fluid overpressure~~, and/or introducing weak mineral phases, and thus lowering the overall fault frictional strength. We conclude that the current state of very low porosity in the Alpine Fault core is likely to play a key role in the initiation of the next fault rupture.

1. Introduction

Fault mechanics, fault structure and fluid flow properties of damaged fault rocks are intimately related (e.g. Gratier and Gueydan, 2007; Faulkner et al., 2010). Fault rupture is associated with intense brittle fracturing that enhances porosity, and thus permeability, and therefore also possible rates and directions of fluid propagation within fault zones (e.g. Girault et al., 2018). Conversely, post seismic recovery mechanisms (gouge compaction and pressure solution processes) result in reductions of porosity, permeability and fluid flow ~~propagation reductions~~ (Renard et al, 2000; Faulkner et al., 2010; Sutherland et al., 2012). These processes may cause elevated pore fluid pressures within fault cores, and trigger frictional failure (e.g. Sibson, 1990; Gratier et al., 2003; Zhu et al., 2020). Therefore, the state of porosity within rocks from fault cores can play a key role in fault slip.

The Alpine Fault of New Zealand is late in its seismic cycle (Cochran et al., 2017), so studying it allows us to investigate pre-earthquake conditions that may influence earthquake nucleation and rupture processes. Recently, drilling operations were undertaken in this fault zone to investigate the *in situ* conditions (Sutherland et al, 2012, 2017). Slug tests in the DFDP-1B borehole (Sutherland et al., 2012) and laboratory permeability measurements of core samples (Carpenter et al., 2014) indicate permeability decreases by six orders of magnitude with increasing proximity to the fault. Furthermore, Sutherland et al. (2012) documented a 0.53 MPa fluid pressure difference across the principal slip zone (PSZ) of the fault, which suggests that the fault core has significantly lower permeability than the surrounding cataclasite units. It is therefore interpreted to act as a fault seal that limits fluid circulation within its hanging wall (Sutherland et al., 2012). Permeability variations like this are closely associated with the porosity evolution of fault cores, and thus are likely to affect the fault strength and seismic properties (Sibson, 1990; Renard et al., 2000; Gratier and Gueydan, 2007).

In this study, we investigate the porosity distribution in rocks from the Alpine Fault core and consider the potential effects of this porosity on fault strength. We have measured open pore spaces in these rocks from X-ray computed tomography (XCT) datasets and examined pore morphology by implementing quantitative shape analyses. Lithological and microstructural characteristics of these samples were performed by ~~and~~ using scanning electron microscopy (SEM) and transmission electron microscopy (TEM).

2. Geological setting

New Zealand`s Alpine Fault (Fig. 1a) is a major active crustal-scale structure that ruptures in a large earthquake every 291 ± 23 years, the last one of which occurred in 1717 (Cochran et al., 2017). The fault is the main constituent of the oblique transform boundary between the Australian Plate and the Pacific Plate, accommodating around 75% of the relative plate motion. Ongoing dextral strike-slip at 27 ± 5 mm yr^{-1} along the fault has resulted in a total strike-separation of ~ 480 km over the last 25 Ma (Norris and Cooper, 1995, 2001; Norris and Toy, 2014). In Neogene time, a dip-slip component added to the fault motion has resulted in more than 20 km of vertical uplift of the hanging wall (Norris and Cooper, 1995, 2001; Norris and Toy, 2014). Consequently, rocks comprising the hanging wall of the fault have been exposed in various outcrops, where they can be studied in detail. The amphibolite facies Alpine Schist is the metamorphic protolith of a ~ 1 km thick mylonite zone, which has been exhumed from depth and now structurally overlies an up to 50 m thick zone of brittlely deformed cataclasites and gouges (e.g. Norris and Cooper, 1995, 2001; Norris and Toy, 2014). These rocks have been investigated in outcrops and from samples collected in three boreholes during the two phases of the Deep Fault Drilling Project (DFDP-1A, DFDP-1B and DFDP-2B; Fig. 1a) along the Alpine Fault (Sutherland et al., 2012; Toy et al., 2015; Toy et al., 2017).

Most of the brittle shear displacement along the fault has been accommodated within the fault core, which includes Principal Slip Zone (PSZ) gouges and cataclasite-series rocks (Toy et al., 2015). Both in surface outcrops and drill core samples, the Alpine Fault manifests as a thin (5 to 20 cm thick) gouge zone with a predominantly random fabric of clay-rich material (Toy et al., 2015; Schuck et al., 2020). This cohesive but uncemented layer has a ~~significantly finer~~ grain size significantly finer than the surrounding cataclasite units, which shows that the material was reworked only within this layer, most probably as a result of ultra-comminution due to multiple shear events under brittle conditions (Boulton et al., 2012; Toy et al., 2015). The local presence of authigenic smectite clays (Schleicher et al., 2015) and calcite and/or chlorite mineralization within sealed fractures and in the gouge matrix (Williams et al, 2017) indicate that mineral reactions are restricted to an alteration zone within the fault core (Sutherland et al., 2012; Schuck et al., 2020). The Alpine Fault core has been interpreted to have formed during a cyclical history of mineralization, shear, and fragmentation (Toy et al., 2015). In addition, in the DFDP-1B borehole (Fig. 1b, Sutherland et al., 2012) fault gouges occur at two distinct depths: 128.1 m (PSZ-1) and 143.85 m (PSZ-2), which shows that the slip was not localized within a single gouge layer (Toy et al., 2015).

3. Sample description and analytical methods

3.1 Samples

Porosity analyses were performed on four samples representing PSZ gouges and cataclasites of the Alpine Fault core, which were recovered from the DFDP-1B borehole (Fig. 1b, c; Sutherland et al., 2012). These are DFDP-1B 58_1.9, DFDP-1B 69_2.48, DFDP-1B 69_2.54 and DFDP-1B 69_2.57. Sample nomenclature includes drill core run number, section number, and centimeters measured from the top of each section. These samples were recovered from drilled depth of 126.94 m, 143.82 m, 143.88 m and 143.91 m, respectively.

Detailed lithological and microstructural descriptions of the DFDP-1B drill core were carried out simultaneously with, and after the drilling operations by the DFDP-1 Science Team, and these data were later summarized by Toy et al. (2015). Samples DFDP-1B 58_1.9 and DFDP-1B 69_2.48 belong to foliated cataclasite units (Fig. 1b, c; Toy et al., 2015),~~. These were~~ described as ultracataclasites with gouge-filled shear zones~~s~~ located above PSZ-1 and PSZ-2 respectively. Sample DFDP-1B 69_2.54 represents the gouge layer that defines PSZ-2, whereas sample DFDP-1B 69_2.57 is composed of brown ultracataclasites that belong to the lower cataclasite unit (Fig. 1b, c; Toy et al., 2015).

3.2 X-ray computed tomography (XCT)

We imaged the samples using X-ray absorption tomography, where the signal intensity depends on how electron density and bulk density attenuate a monochromatic X-ray along its path through the material (e.g. Fusseis et al. 2014). We acquired the X-ray microtomography data for this study at the 2-BM beamline of the Advanced Photon Source, Argonne National Laboratories USA in December 2012. The non-cylindrical samples of ~7 mm height and ~ 4 mm diameter were mostly drilled parallel to the foliation, ~~and~~ mounted on a rotary stage, and imaged with a beam energy of 22.5~~0~~ keV. A charge-couple device camera collected images at 0.25° rotation steps over 180°~~ at~~. A~~.~~ sample-detector distance of 70 mm ~~and~~yielded a field-of-view of 2.81 mm. The voxel size (i.e. spatial sampling) was 1.3 µm and the spatial resolution ~~was likely in the~~ ranged ~~between~~from two ~~and~~to three times the voxel size. We have reconstructed the datasets with a filtered back-projection parallel beam reconstruction into 32-bit gray level volumes consisting of ~~2083~~ 2048 * ~~2083~~ 2048 * ~~2083~~ 2048 voxels using X-TRACT (Gureyev et al., 2011).

3.3 Analyses of XCT datasets

Data analyses and image processing were performed using the commercial software ~~package~~ Avizo 9.1™ (Fig. 2). Initially, the datasets were rescaled to 8-bit grey scale volumes for enhanced computer performance. In addition, small volumes of interest were cropped from the whole volume before a non-local means filter was applied to reduce noise (Buades et al., 2005). For each voxel, this filter compares the value of this voxel with all neighboring voxels in a given search window. A similarity between the neighbors determines a correction applied to each voxel (e.g. Thomson et al., 2018).

On the filtered gray-scale images, pores were identified as disconnected materials of ~~as~~~~porosity was identified as~~ the darkest ~~phase~~ grey-scale range (Fig. 2a). The corresponding gray-scale values were thresholded, and the datasets were converted into binary form. This step is called segmentation. Several segmentation techniques exist, from thresholding at a given gray scale value (e.g. Ianossov et al., 2009; Andrew~~ä~~ et al., 2013) to deep learning algorithms (Ma et al., 2020). ~~The choice of one~~It is up to the user to choose the segmentation technique ~~or another~~that is most appropriate to analyze a given dataset~~ is user-dependent~~. To our knowledge, no single segmentation technique can be generalized and universally used independently of the nature of the samples. In the present study, we have chosen a simple segmentation technique by applying a threshold to the gray scale images to separate the void space from the solid. This technique has been used in many studies in the last two decades ~~since the 2000's~~ to characterize porosity in rocks, including some very ~~and was applied in~~ recent studies in rock physics (Macente et al., 2019; Renard et al., 2019). ~~The variability on t~~The segmented porosity volume depends strongly on the choice of the threshold and some studies have ~~reported~~demonstrated that the final porosity estimated by different segmentation methods ~~could~~can vary ~~within an error of~~by 20% (Andrä et al., 2013). ~~A recent study has shown that,~~However, when the level of noise in the data is low, the differences in porosities estimated ~~between variousy~~by different segmentation techniques is negligible (~~Figure 3h in~~ Andrew, 2018). Our data ~~have been~~were acquired at a synchrotron where the parallel beam and high photon flux ensured a low level of the noise in the images. In addition, ~~the~~application of a non-local-means filter applied to our data ~~has~~ reduced the noise level. For these reasons, we consider that ~~the~~it was robust to apply ~~choice of~~ a simple thresholding technique ~~is robust for~~to this dataset ~~and~~but acknowledge that the porosity values we ~~give~~estimate ~~later~~ could ~~have a small error that cannot be estimated becaus~~differ by <20% from ~~the ground truth~~the 'true' porosity of the rock ~~is not known, as discussed in~~(cf. Andrä et al., 2013; Hapca et al., ~~(~~2013).

However, our segmentation procedure~~this threshold range~~ also captured cracks within a sample, which are likely to result from depressurization during core recovery (Fig. 2b). To omit the cracks, we utilized the morphological operation 'connected components' available in the software Avizo 9.1, which allows volumes larger than selected number of connected voxels to be excluded from the binary label images. To each sample we applied upper limits of 20 (43.94 μm^3), 50 (109.85 μm^3), 100 (219.7 μm^3) and 200 (439.4 μm^3) face connected voxels. Total porosities estimates based on these operations are presented as percentages of the sample volume in Supplementary material 1. Unfortunately, this methodology results in either loss of larger pores or inclusion of small cracks depending on the implemented limit of connected components, and thus the calculated porosities include significant bias. Therefore, the operation 'connected components' was used only for visualization purposes, and clusters of 200 face connected voxels were created to show the 3D volumes of segmented pore spaces (Fig. 2c)

~~To omit the cracks, thresholded components with volumes larger than the volume of 200 connected voxels (439.4 μm^3) were excluded from the binary label images by using the morphological operation 'connected components' built available in the software Avizo 9.1. Clusters of connected components were then created to visualize 3D volumes of segmented pore spaces (Fig. 2c).~~

~~Unfortunately, this methodology results in either loss of larger pores or inclusion of small cracks depending on the implemented limit of connected components, and thus calculating totalcalculated porosities includes significant bias.~~ ~~Instead~~Instead, the volumes and shape characteristics of segmented materials (including cracks i.e. without any data limitation) were exported from Avizo software in numerical format, and volume distributions within a sample were plotted on a logarithmic scale ~~in Matlab~~ (Fig. 3). Data up to a specific volume size were fit to a polynomial curve, and then the curve was extrapolated to the X-axis intercept, which is the expected maximum pore size (Fig. 3). For each sample the t~~T~~otal porosit~~ies~~y w~~ere~~as then estimated by integrating the curve, which excludes all volumes on the right side of the curve. Total porosities are presented as a percentage of the whole sample volume (Fig. 3). The implemented equations are ~~presented~~given in Supplementary material 1.

Pore shapes were analyzed on bivariate histograms plotted ~~on Matlab~~ by using the numerical pore characteristics, previously extracted from Avizo software. Only pore volumes between 21.97 μm^3 (10 voxels) and 878.8 μm^3 (400 voxels) were included to avoid bias in the data due to insufficient voxel count and presence of cracks, respectively. Individual pores in our dataset are separated (Fig. 2c).~~For each pore, t~~The covariance matrix of ~~the volume~~each pore was calculated, and the three eigenvalues of this covariance matrix were extracted. These three values correspond to the three main orthogonal directions in each pore (i.e. the longest, medium and shortest axes) and we use them as proxies to describe pore geometry. Thus, their amplitudes provide information on the spatial extension of ~~the~~ a given pore and its shape. The ratio between the medium and largest eigenvalues of each pore defines its elongation (Fig. 4), the ratio between the smallest ~~to~~ and the largest eigenvalues defines~~–~~ its sphericity (Fig. 5), and the ratio of the smallest ~~to~~ and the medium ~~–~~eigenvalues defines its flatness (Fig. 6).

The angles θ and φ that describe the orientation of the longest eigenvalue (i.e. axis) of each pore with respect to the ~~main~~ global orthogonal ax~~e~~is system of the 3D scan were calculated. These angles were translated into trend and plunge and then plotted on a lower hemisphere equal area stereographic projection with a probability density contour to display the distribution of pore unit orientations (Fig. 7).

3.4 Scanning electron microscopy (SEM)

SEM images were collected on Zeiss Sigma-FF-SEM at the University of Otago's Centre for Electron Microscopy. The SEM was operated at a working distance of 8.5 mm, a**n accelerating** voltage of 10 keV and a 120 µm aperture with dwell time of 100µs. EDS maps were created by using Aztec Software (https://www.oxford-instruments.com/products/microanalysis/energy-dispersive-x-ray-systems-eds-edx/eds-for-sem/eds-software-aztec).

3.5 Transmission electron microscopy (TEM)

~~High resolution~~ TEM images were collected on a FEI Tecnai G2 F20 X-Twin transmission electron microscope, located at the German Research Centre for Geosciences (GFZ), Potsdam, Germany (~~Fig. 8~~Fig. 9). The instrument is equipped with field-emission gun (FEG) electron source and high-angle annular dark-field (HAADF) Detector. Images were collected from samples placed on a Gatan double-tilt holder at an accelerating voltage of 200kV. These TEM samples were prepar~~ation was perform~~ed ~~with~~by focused ion beam (FIB) milling at GFZ Potsdam using a HELIOS system operated at an accelerating voltage of 30 kV.

~~3~~4 Results

4.1 XCT-derived characteristics of porosity

All samples contain low total porosities, ranging from 0.1% to 0.24% (Fig. 3). If different segmentation techniques were applied, a variability ~~between~~in the range that Andrew (2018) demonstrated is reasonable, from nearly ~~nearly~~ 0% to ~~(e.g. Figure 3h in Andrew, 2018) to~~ 20%, ~~(Andrä et al., 2013)~~ would correspond to porosities between 0.08% and 0.29% in our samples. ~~However, i~~It ~~should~~ can be noted that the lower cataclasite sample (DFDP-1B 69_2.57) has twice as much pore space (Fig. 3d) as any of the other samples. The characterized pore ~~size~~ volume distributions range over almost three orders of magnitude~~-~~ for all samples (Fig. 3). Furthermore, the expected maximum pore ~~size~~ volume was estimated to be largest in the PSZ-2 sample (DFDP-1B 69_2.54), reaching 862 µm^3 (Fig. 3c). ~~All pores are disconnected to each others.~~

In all samples, shape analyses of pores with volumes between 21.97 µm^3 (10 voxels) and 878.8 µm^3 (400 voxels) demonstrate predominantly elongated (Fig. 4), non-spherical (Fig. 5) and flat pore shapes (Fig. 6). This is particularly pronounced for the smaller pore volumes. The number of elongated pores per sample ~~is increasing~~increases in the upper foliated cataclasites (Fig. 4a and b) with increasing proximity to PSZ-2, where most elongated pores occur (Fig. 4c). Conversely, the lower cataclasite sample demonstrates proportionally fewer elongated pores within the sample (Fig. 4d). The degree of sphericity is uniform for all samples, and pores appear as mainly non-spherical (Fig. 5). Few isolated spherical pores are manifested only by small pore volumes (Fig. 5). A trend of increasing the number of flat pores is observed with increasing sample depth (Fig. 6), and most flat pores are detected in the lower cataclasite (Fig. 6d).

The orientations of the individual pore units show two distinctive peaks with opposite vergence, defining bipolar distributions of pore orientations (Fig. 7). The observed bipolarity is subtle in samples DFDP-1B 58_1.9 (Fig. 7a) and DFDP-1B 69_2.48 (Fig. 7b), and more obvious in samples DFDP-1B 69_2.54 (Fig. 7c) and DFDP-1B 69_2.57 (Fig. 7d).

4.2 Microstructural characteristics of porosity

To demonstrate the microstructural arrangement of the cataclasites, we show representative SEM images from sample DFDP-1B 69_248 (Fig. 8), previously described as a 'lower foliated cataclasite' by Toy et al., 2015. SEM images presented here reveal rounded to sub-rounded crystalline clasts up to 100 µm in diameter (Fig. 8a, b), which consist of ~50 % plagioclase, ~40 % K-feldspar, and ~10 % quartz and are elongated at angles of 0-30° to the foliation. The surrounding matrix material is composed of finer grains (< 30 µm in diameter) of white micas, chlorite, K-feldspar, calcite and Ti-oxide (Fig. 8c). Numerous quartz clasts contain microfractures, filled by calcite and/or chlorite.

TEM characterization of the gouge material from PSZ-2 (sample DFDP-1B 69_2.54) reveals that the Alpine Fault gouges have composition,are composed of comprising angular quartz and/or feldspar fragments (~200 nm in size), wrapped by smaller phyllosilicates (< 100 nm long). This random fabric is ornamented by nanoscale pores (< 50 nm), distributed along all grain and phase boundaries, but especially abundant along within/around clay minerals (Fig. 8Fig. 9a).

The gouge material also demonstrates phyllosilicate-rich areas, defined by an increase in the clay/clast ratio. In these zones, fine (< 100 nm long) and coarser (few µm long) clay grains coexist and are aligned in wavy fabric that surrounds sporadic protolith fragments (Fig. 8Fig. 9b). Pore spaces are again distributed along the boundaries of the constituent mineral grains but some of them are larger (~0.5 µm) withand thin ellipsoidal or elongated shapes (Fig. 8Fig. 9b, c). These pores are commonly associated with inter-clay layer porosity. Large size pores are also observed along quartz-feldspar grainphase boundaries. These latter , where pores are associated with multiple grains and occasionally disrupt grainthe boundaries, thus were labelled asas cracks along boundaries of quartz and/or feldspar grains (i.e. fracture porosity; – (Fig. 8Fig. 9d).

5 Discussion

5.1 Characteristics of porosity within the Alpine Fault core

Porosity analyses of samples from, or in close proximity to the two PSZs encountered in the DFDP-1B drill core reveal total pore volumes between ~0.1% and 0.24% (Fig. 3). These values are significantly lower than the porosity estimates from other active faults in the world, such as: 0.2 to 5.7% total porosity in the core of the Nojima Fault, Japan (Surma et al., 2003) and 0 to 18% in the San Andreas Fault core (Blackburn et al., 2009). The Alpine Fault core contains total pore space volumes, comparable only with the lower porosities in these previous studies. It should be noted that the smallest pore spaces captured in the XCT datasets are 1.3 µm in size due to resolution acquisition constraints, whereas nanoscale porosity was identified on the TEM images. Therefore, the estimated total porosities from XCT data represent only minimum values of the open pore spaces in the Alpine Fault core. However, the addition of nanoscale porosity volumes is unlikely to dramatically affect the final total porosity of these rocks because they comprise a very small total volume.

TEM images presented here mainly focus on nano-scale materials (Fig. 8Fig. 9a, c, d) but were also used to describe the distribution of micro-porosity in these rocks (Figure 8Figure 9b). The pores visible on grain and phase boundaries inOn figure 8figure 9b pores have similar sizes comparable to the small range of pores segmented on XCT images (> 1.3 µm in diameter), and thus we conclude that this is the typical habit of both nano- and micropores within the Alpine Fault core ~~are distributed on grain and phase boundaries, especially of clay minerals~~ (~~Fig. 8~~Fig. 9). In addition, both quantitative micro-porosity shape analyses (Fig. 4, 5 and 6) and nano-pores identified on TEM images (~~Fig. 8~~Fig. 9) reveal that a significant population of pores are predominantly non-spherical with elongated, flat shapes. We attribute this observation to the tendency of these pores to ornament clay minerals where pores are ~~attained~~ distributed and elongated along their (001) planes (~~Fig. 8~~Fig. 9b, c and d).

Foliation in the upper cataclasites is defined by clay-sized phyllosilicates, that become more abundant with proximity to the PSZ (Toy et al., 2015), where a weak clay fabric is developed (Schleicher et al., 2015). This gradual enrichment in clay minerals coincides with the subtle development of bipolar distributions of pore orientations with increasing sample depth (Fig. 7). This observation and the fact that pores are mainly ~~attained~~ distributed along grain boundaries of clays (~~Fig. 8~~Fig. 9) suggest that the distribution of clay minerals also controls pore orientations within the Alpine Fault core. Previously, the phyllosilicate foliation in the Alpine Fault cataclasites has been used to define shear direction (Toy et al., 2015). Thus, we speculate that pore orientations in these rocks are also systematically related to the kinematic framework of the shear zone. If these pores represent remnants of fluid channels, their spatial orientation is likely to reflect the fluid flow directions during deformation. To address this possibility more data for systematic analyses of pore orientations are needed.

5.2 Porosity reduction within the Alpine Fault core

The comparatively lower porosity estimates of the Alpine Fault core than other active faults (e.g. the Nojima Fault, Surma et al., 2003, and the San Andreas Fault, Blackburn et al., 2009) could~~an~~ be attributed to the fact that the Alpine Fault is late in its c. 300 year seismic cycle and the last seismic event occurred in 1717– (Cochran et al., 2017). Thus, ~~W~~we propose that the fault has almost completely sealed. Porosity of ~~the~~ fault cores is ~~considered widely thought~~believed to evolve during the seismic cycle~~,~~ ~~when~~ since fault rupture can cause ~~porosity~~ porosities to increase up to 10% (Marone et al., 1990), and ~~the conse~~subsequent healing ~~by various~~ mechanisms~~,~~ (such as mechanical compaction of the fault gouge and/or elimination of pore spaces within the fault core due to pressure solution processes)~~,~~ ~~lead~~ causes~~to~~ porosity to decrease over time ~~due to mechanical compaction of the fault gouge and/or elimination of pore spaces within the fault core due to pressure solution processes~~ (Sibson, 1990; Renard et al., 2000; Faulkner et al., 2010).– SEM~~TEM~~ data presented here show that fine-grained chlorite and muscovite grains ~~act~~formed as a cement in the cataclastic matrix (Fig. 8c). Our TEM data reveal~~s~~ the abundance of newly precipitated authigenic clays, wrapped around coarser clay minerals (~~Fig. 8~~Fig. 9b). Furthermore, delicate clay minerals form fringe structures (~~Fig. 8~~Fig. 9a), and strain shadows (~~Fig. 8~~Fig. 9c) around larger quartz-feldspar grains. These microstructural observations demonstrate that pressure solution processes operated within these rocks (Toy et al., 2015).

Evidence for pressure solution processes has been previously documented in all units, comprising the Alpine Fault core (Toy et al., 2015). Abundant precipitation of alteration minerals (Sutherland et al., 2012), calcite filled intragranular and cross-cutting veins (Williams et al., 2017), and the occurrence of newly formed smectite clays (Schleicher et al., 2015) indicate extensive fluid-rock reactions. In addition, anastomosing networks of opaque minerals (such as graphite; Kirilova et al., 2017), which define foliation in the upper cataclasites (Toy et al., 2015), have been interpreted to be concentrated by pressure solution processes during aseismic creep (Toy et al., 2015; Gratier et al., 2011). The petrological characteristics of the Alpine Fault core lithologies ~~identify~~ indicate that solution transfer ~~mechanisms likely~~ was~~ere~~ likely the dominant mechanism for pore closure within these rocks.

Porosity estimates presented here are so low that presumably negligible variations in between samples can represent significant gradients in porosity. For example, the increase of total porosity in sample DFDP-1B 69-2.57 with only 0.14%, manifests as twice as many open pore spaces in comparison to the rest of the analyzed samples (Fig. 3). In addition, this is the only footwall sample analyzed here and as ~~aforementioned~~already mentioned in section 3.1 does not contain any gouge material. Post-rupture porosity reduction is known to operate three to four times faster within fine-grained fault gouges than in coarser-grained cataclasites (Walder and Nur, 1984; Sleep and Blanpied, 1992; Renard et al., 2000)~~,~~ which may explain the -porosity differences demonstrated above.~~differences in total porosity~~

~~between the gouge-containing samples and the footwall ultracataclasite – DFDP-1B 69-2.57 (Fig. 3).~~ Furthermore, previous studies documented less carbonate and phyllosilicate filling of cracks in the Alpine Fault footwall cataclasites ~~as compared to~~than in the hanging wall cataclasites (Sutherland et al., 2012; Toy et al., 2015), suggesting more reactive fluids are present and isolated within~~g~~ the hanging wall of the Alpine Fault. Thus, more intense dissolution-precipitation processes took place in the fault`s hanging wall, which very likely resulted in more efficient porosity reduction, as demonstrated by our porosity estimates (Fig. 3).

~~As aforementioned, porosity reduction is known to increase with time after an earthquake event due to post-rupture healing mechanisms (Sibson, 1990; Renard et al., 2000; Faulkner et al., 2010). Thus, the comparatively lower porosity estimates of the Alpine Fault core than other active faults (e.g. the Nojima Fault, Surma et al., 2003, and the San Andreas Fault, Blackburn et al., 2009) can be attributed to the fact that the Alpine Fault is late in its seismic cycle (Cochran et al., 2017).~~

5.3 Effects of porosity on the Alpine Fault strength

~~The extremely~~Very low porosity estimates are presented here (Fig. 3). ~~are consistent with the l~~Very low permeabilities of 10^{-18} m^2 were also measured experimentally in clay-rich cataclasites and gouges from the Alpine Fault zone (Carpenter et al., 2014). In addition, the documented difference of total porosities between the hanging wall and footwall samples (Fig. 3) ~~implies~~ may be interpreted ~~as~~to reflect different intensities~~y~~ of pressure solution processes, and thus ~~compartmented~~ ~~compartmentalisation~~compartmentalization of percolating fluid~~s propagation~~. Our porosity data ~~thus provide independent verification~~ ~~is comparable with of~~show a spatial trend similar to the permeability measurements ~~in that study~~of ~~(~~Carpenter et al.~~,~~ (2014). This observation ~~and~~ yields increased confidence in ~~their~~ the interpretation of Carpenter et al. (2014) of a permeability gradient with distance from the PSZ, which itself acts as a hydraulic seal (Sutherland, et al., 2012). The existence of such a barrier to flow is characteristic for faults undergoing creep and locked faults (Rice, 1992; Labaume et al., 1997; Wiersberg and Erzinger, 2008). However, much higher permeabilities in the surrounding damaged rocks (Carpenter et al., 2014) allow fast propagation of fluids within them and can cause localization of high fluid pressures on one side or the other of a hydraulic seal (Sibson, 1990). Such fluid pressures can enhance gouge compaction and pressure solution processes~~ within the fault core~~, which will eventually introduce zones of weakness and thus may trigger fault slip (Faulkner et al., 2010).

Previous studies and the observations presented here show that fluids were present in the Alpine Fault rocks. Fluid-filled pores represent a favorable environment for mineral precipitation, which can affect the fault strength in two ways: (i) V~~v~~ery small decrease of these critically low total porosities due to mineral precipitation would cause fluid pressurization, which is a well-known fault weakening mechanism described by ~~(~~Byerlee~~,~~ (1990~~;~~) and Sibson~~,~~ (1990)~~). H~~; however, this pressure increase ~~will~~could be slightly offset by inclusion of fluids into new hydrous minerals;~~;~~ (ii) deposition of frictionally weak phases (such as clay minerals and graphite), especially if they decorate grain contacts and/or form interlinked weak layers, would lower the overall frictional strength (Rutter et al., 1976; Niemeijer et al., 2010).

Precipitat~~ion of~~ed authigenic clay minerals ~~was~~ were identified ~~on~~ in our TEM data (~~Fig. 8~~Fig. 9) and also documented by previous studies (Schleicher et al., 2015). As well as having low frictional strengths (Moore and Lockner, 2004), clay minerals may also contribute to the formation of an impermeable seal if they form an aligned fabric, ~~and thus can~~ which can enhance the likelihood of fluid-pressurization in the fault rocks (Rice, 1992; Faulkner et al., 2010). In addition, graphite, which was previously documented in these rocks ~~by previous studies~~ (Kirilova et. al., 2017), may effectively weaken the fault due to mechanical smearing (Rutter et al., 2013) and/or localized precipitation within strained areas (Upton and Craw, 2008). Such graphite precipitation within shear surfaces was previously documented by Kirilova et al. (2017).

In summary, the presence of trapped fluids in the low porosity rocks of the Alpine Fault core possibly controls the mechanical behavior of the fault and could be responsible for future rupture initiation due to fluid pressurization and/or precipitation of weak mineral phases. This hypothesis is further supported by an experimental study showing that the DFDP-1 gouges are frictionally strong in the absence of elevated fluid pressure (Boulton et al., 2014).

6 Conclusions

Analyses of XCT-datasets and TEM images of borehole samples from the core of the Alpine Fault reveal micro- and nanoscale pores, distributed along grain boundaries of the constituent mineral phases, especially clay minerals. The tendency of these pores to ornament clays defines their predominantly non-spherical, elongated, flat shapes and the bipolar distribution of pore orientations. The documented extremely low total porosities (~~from~~ in the range 0.1~~ to~~ - 0.24 %) in these rocks suggest effective porosity reduction and fault healing. Microstructural observations presented here and documented in previous studies indicate that pressure solution processes were the dominant healing mechanism, and that fluids were present in these rocks. Therefore, fluid-filled pores may be places where ~~fluid overpressures~~elevated pore fluid pressures develop, due to further mineral precipitation that decreases the already critically low total porosities.~~–~~ Alternatively, ~~they~~ these pores may also facilitate the deposition of weak mineral phases (such as clay minerals and graphite) that may very effectively weaken the fault. We conclude that the current state of the fault core porosity is possibly a controlling factor on the mechanical behaviour of the Alpine Fault and will likely play a key role in the initiation of the next fault rupture.

Data availability.

Matlab ~~code~~ scripts and numerical data of pore volumes can be found in Supplementary material 1.

Authors contribution

Kirilova reconstructed, processed, and analysed the XCT datasets presented here, interpreted the TEM data and prepared the manuscript. Most of this work was performed during Kirilova's PhD under the academic guidance of Toy. Toy and Gessner collected the XCT data with technical support by Xiao. Renard and Sauer contributed with valuable discussion about XCT data analyses and edited the manuscript. Wirth enabled TEM data acquisition and provided his expertise on TEM data interpretation. Matsumura collected and analyz~~s~~ed the presented SEM data. The final version of this manuscript benefits from collective intellectual input.

Competing interests

The authors declare that they have no conflict of interest.

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Figures

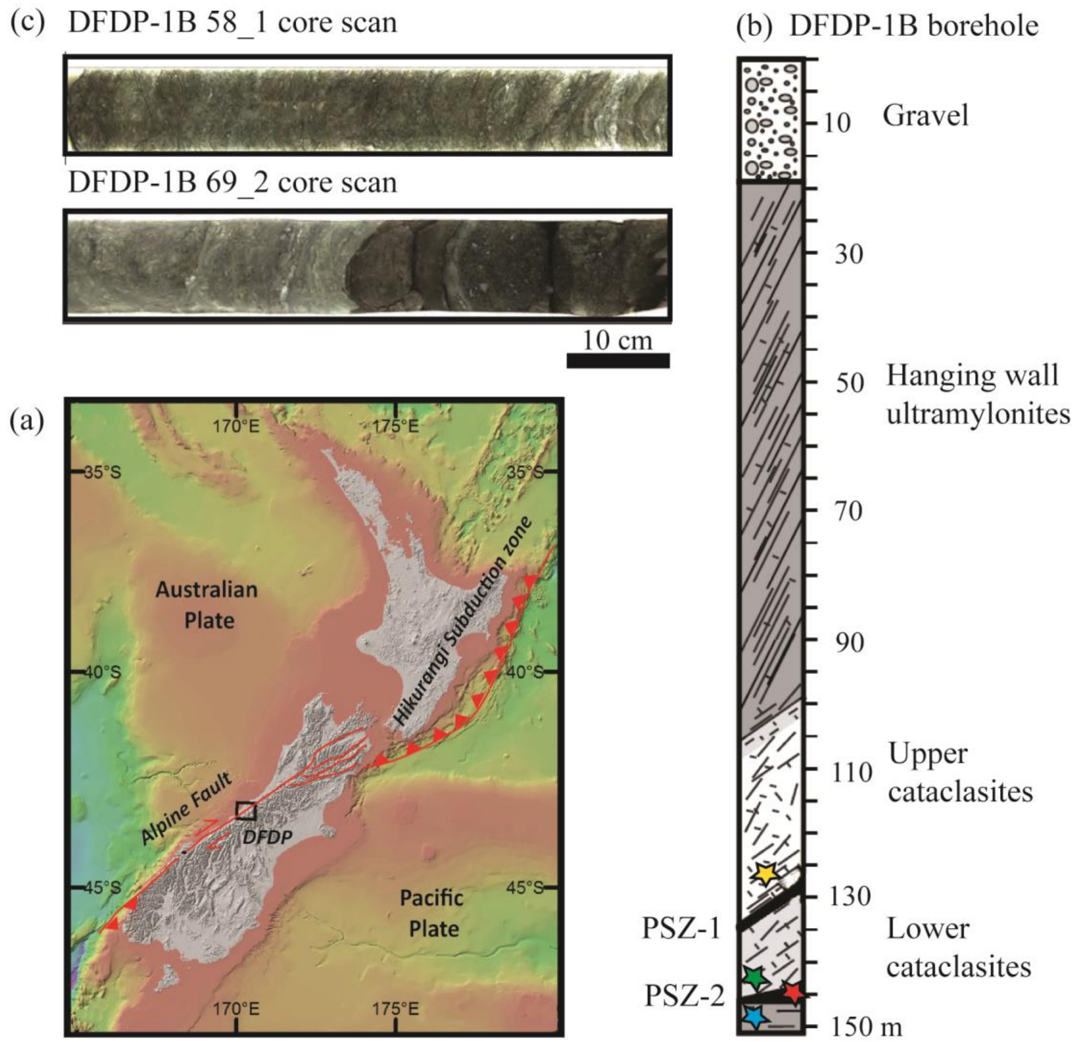


Figure 1. (a) Location map of DFDP drill sites (a bathymetric map compiled by NIWA). Drill site coordinates: 43°17′5″S, 170°24′22″E (b) Schematic diagram of the sampled lithologies in DFDP-1B borehole (modified after Sutherland et al., 2012). (c) Scans of DFDP-1B drill core. Samples were collected from the locations indicated with stars: yellow – DFDP-1B 58_1.9; green – DFDP-1B 69_2.48; red – DFDP-1B 69_2.54; blue – DFDP-1B 69_2.57.

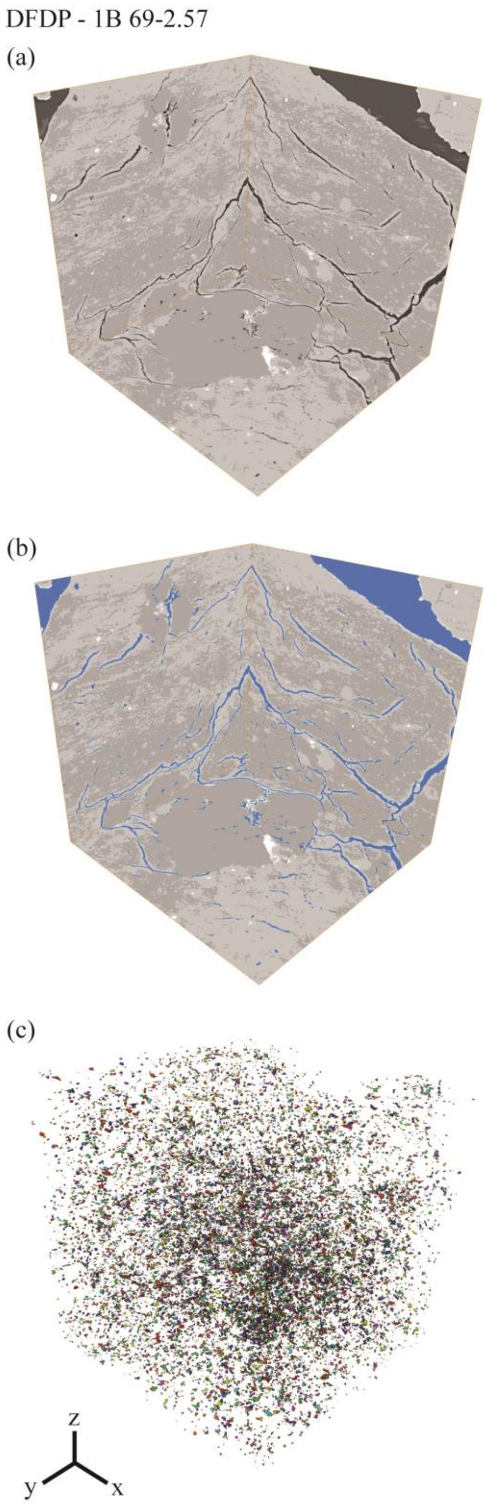


Figure 2. X-ray tomography data processing workflow. (a) Gray scale images in xy, xz and yz directions (b) Threshold of the darkest gray scale phase in each sample, corresponding to voids (pores and fractures); (c) 3D volume of the segmented pore spaces after removal of the fractures due to sample decompaction and coring damaging effects were removed.

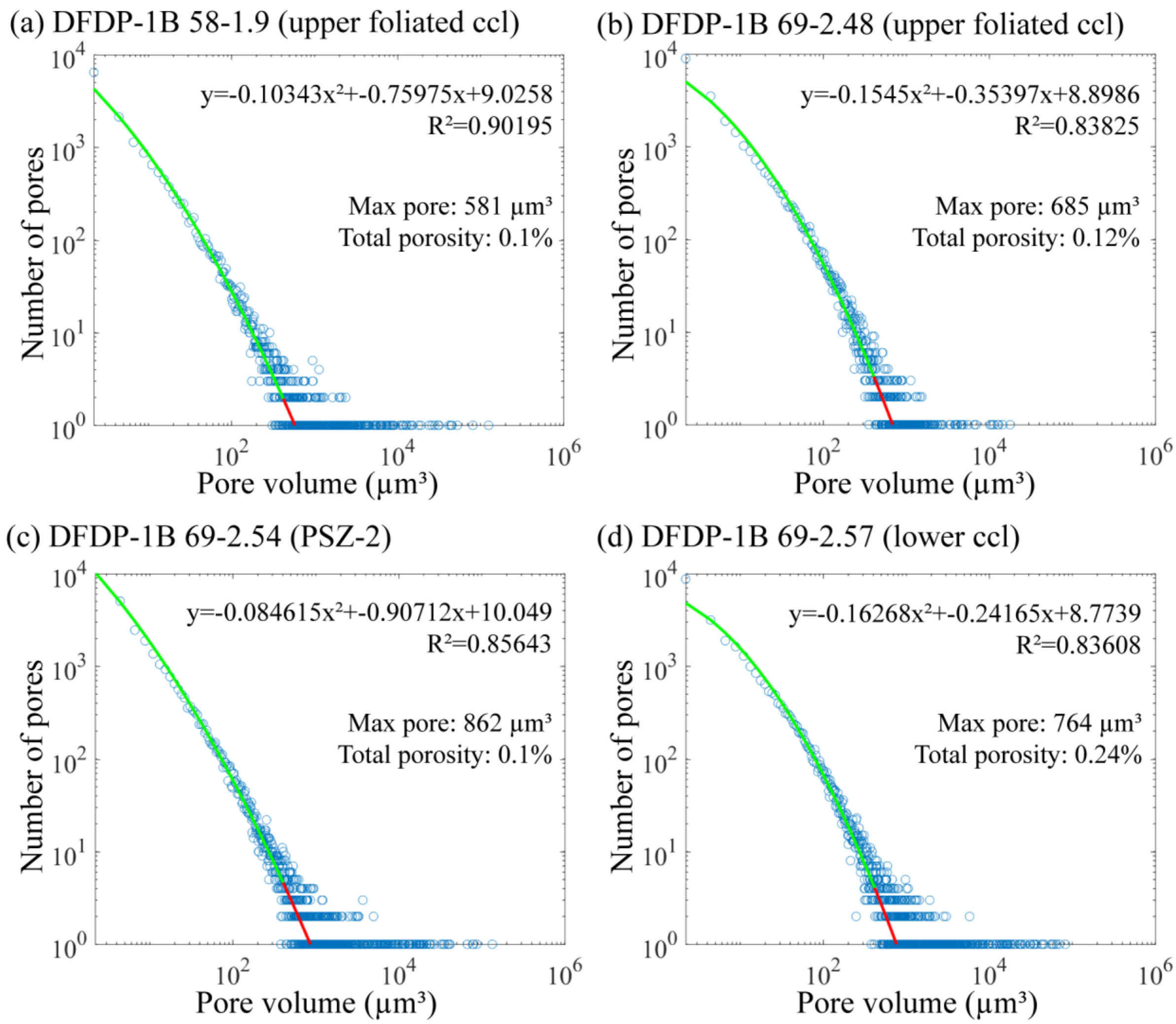


Figure 3. Plots of pore volume versus number of pores for each sample. Estimates of total porosity and size of the maximum expected pore are also shown, as well as the curve fitting function for each dataset.

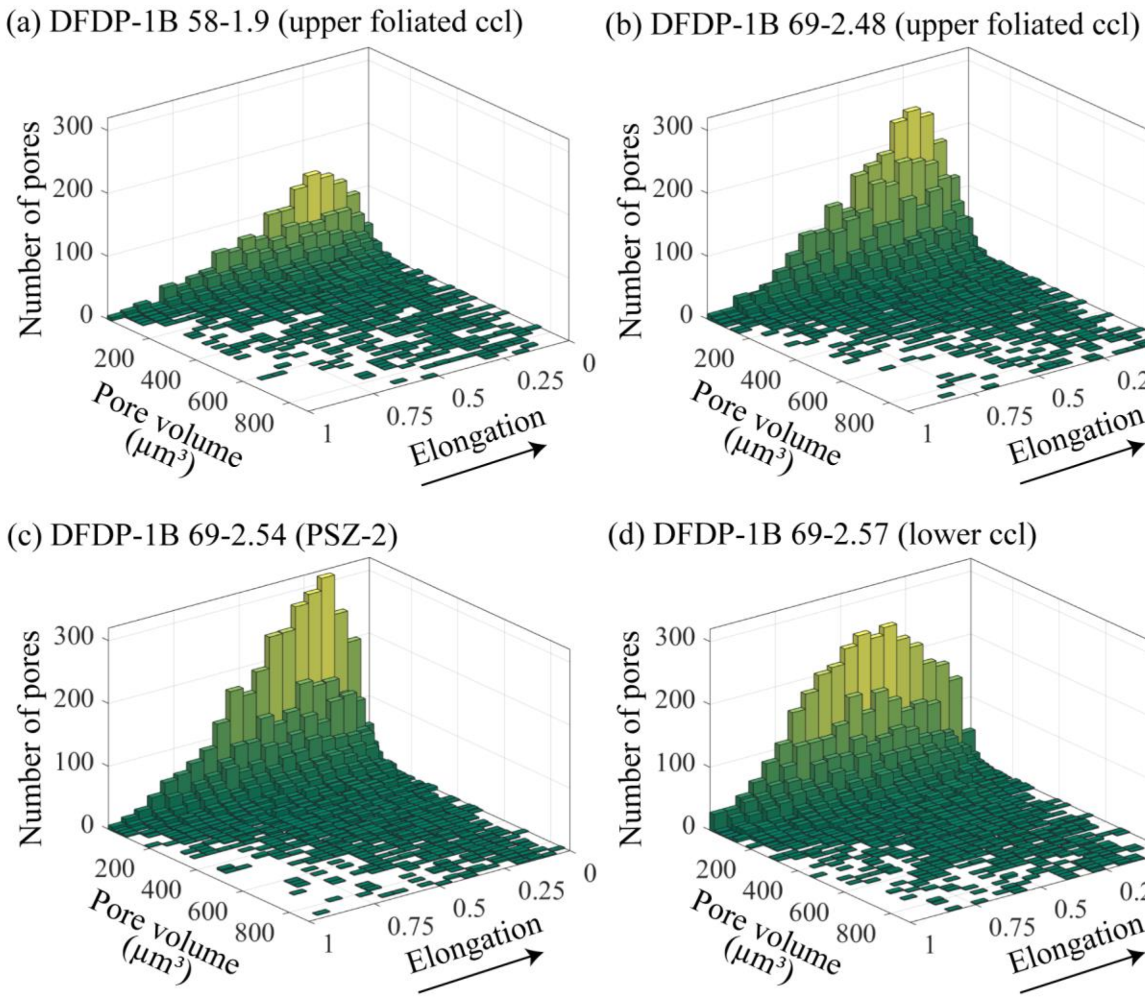


Figure 4. Bivariate histograms showing elongation versus pore volume (μm^3) and number of pores for each sample. The arrow indicates the direction of increasing elongation. Here, the elongation is defined as the ratio between the medium and the largest eigenvalues (i.e. axis) of each pore.

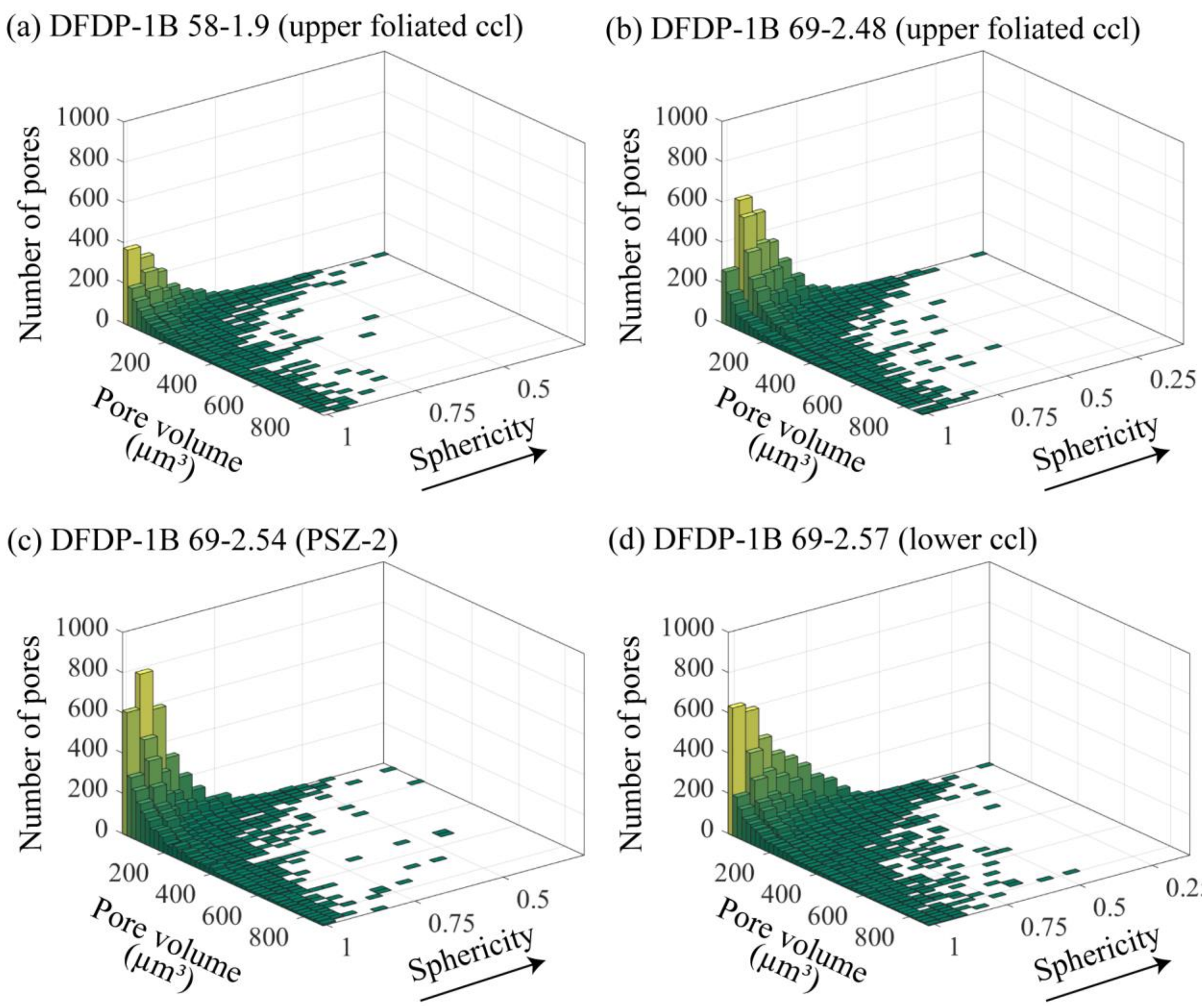


Figure 5. Bivariate histograms showing sphericity versus pore volume (μm^3) and number of pores for each sample. The arrow indicates the direction of increasing sphericity. Here, the sphericity is defined as the ratio between the smallest and the largest eigenvalues (i.e. axis) of each pore.

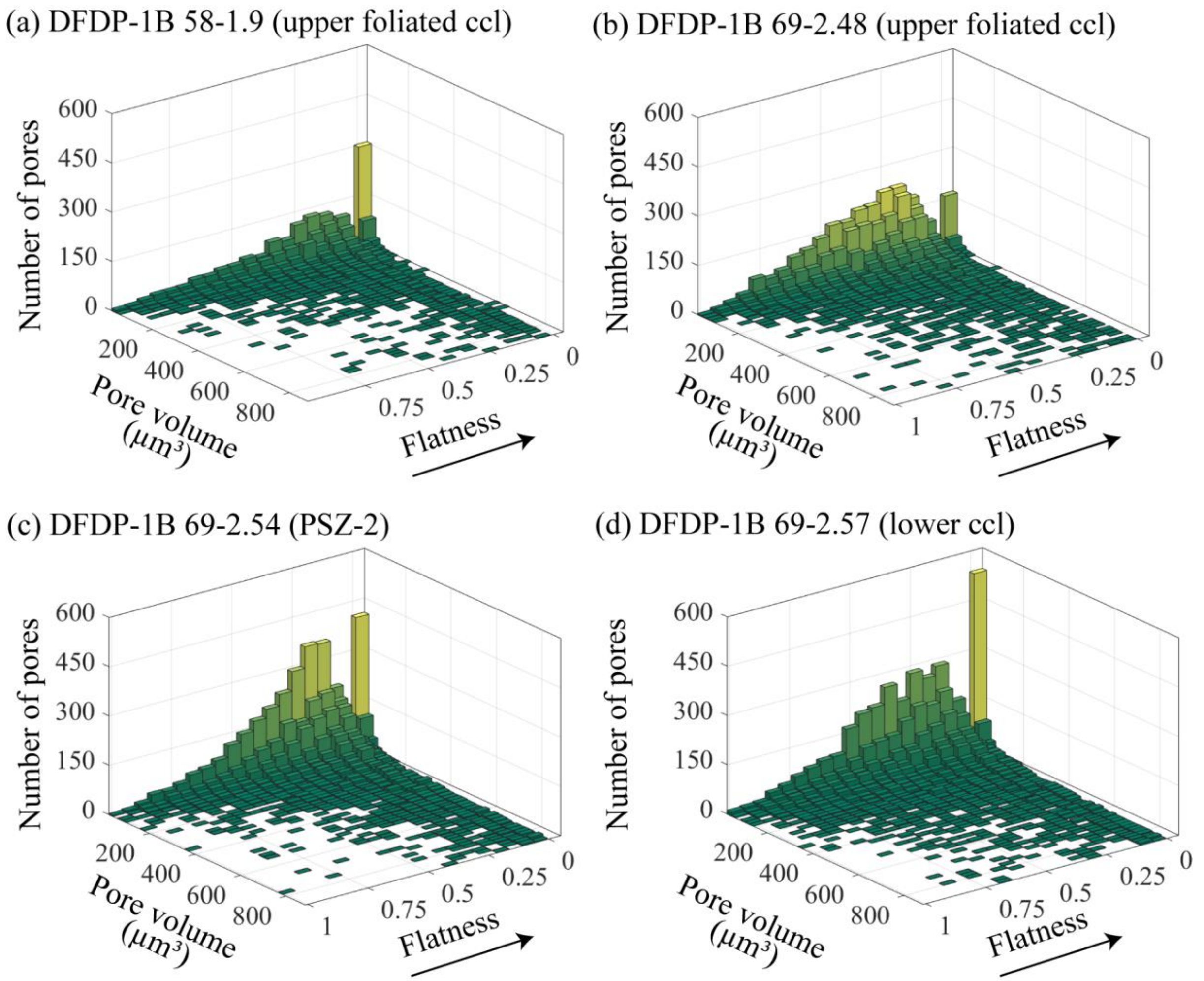


Figure 6. Bivariate histograms showing flatness versus pore volume (μm^3) and number of pores for each sample. The arrow indicates the direction of increasing flatness. Here, the flatness is defined as the ratio of the smallest and the medium eigenvalues (i.e. axis) of each pore.

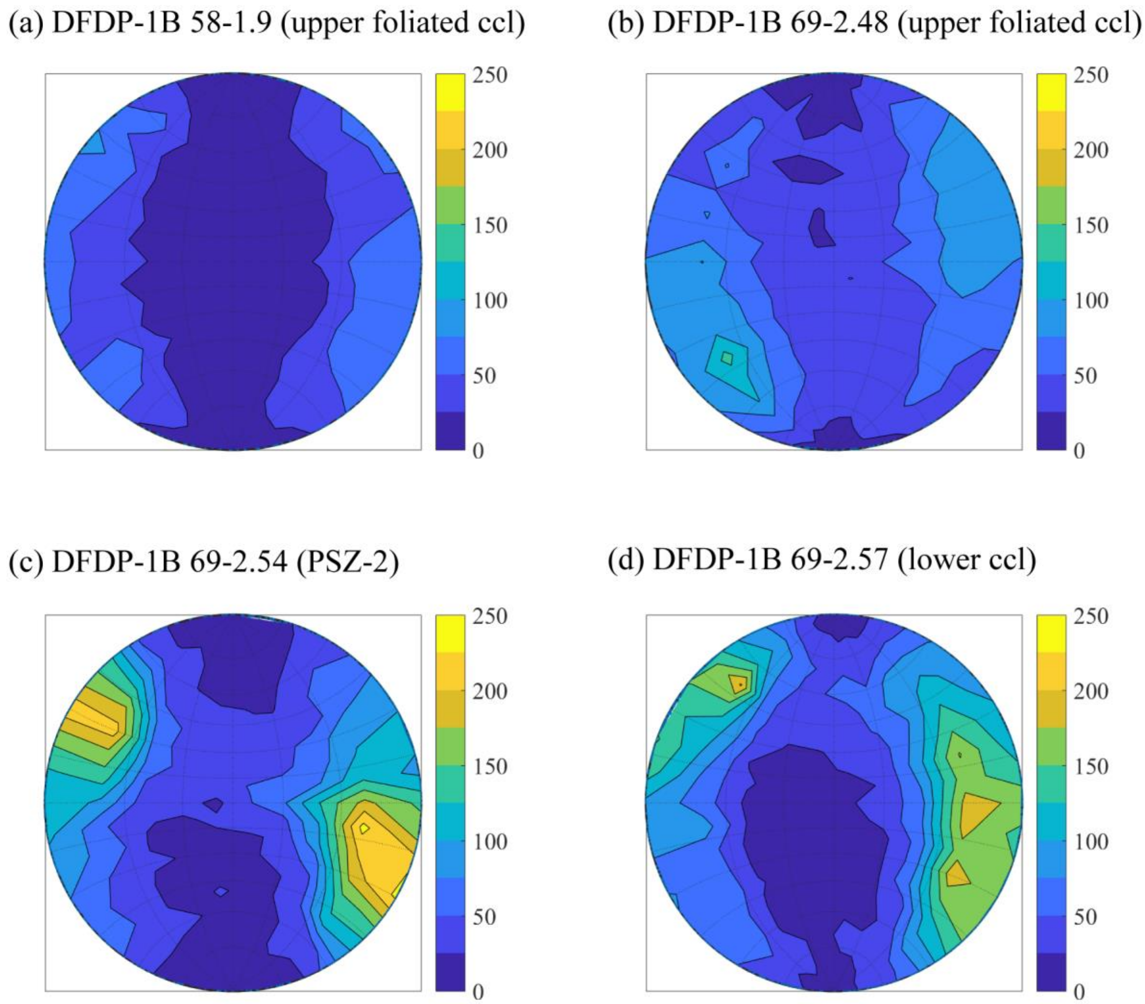


Figure 7. Distribution of pore unit orientations plotted on a lower hemisphere equal area stereographic projection with a probability density contour.

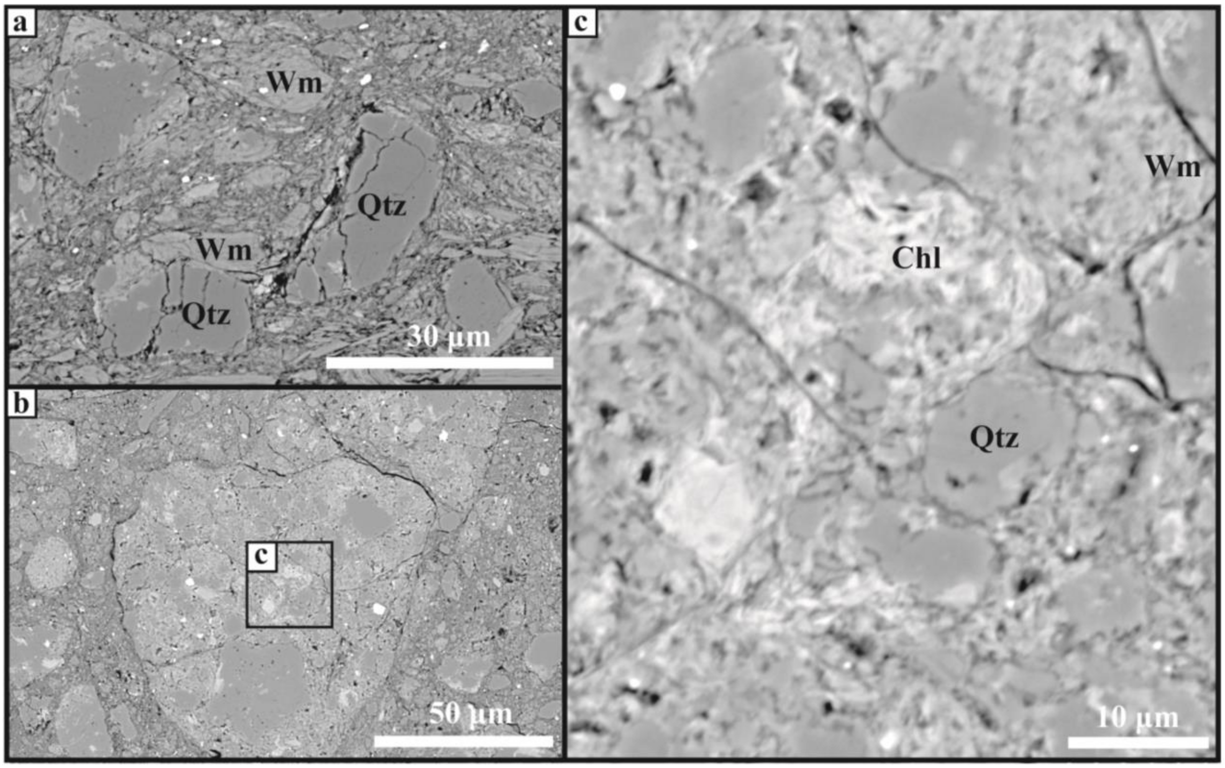
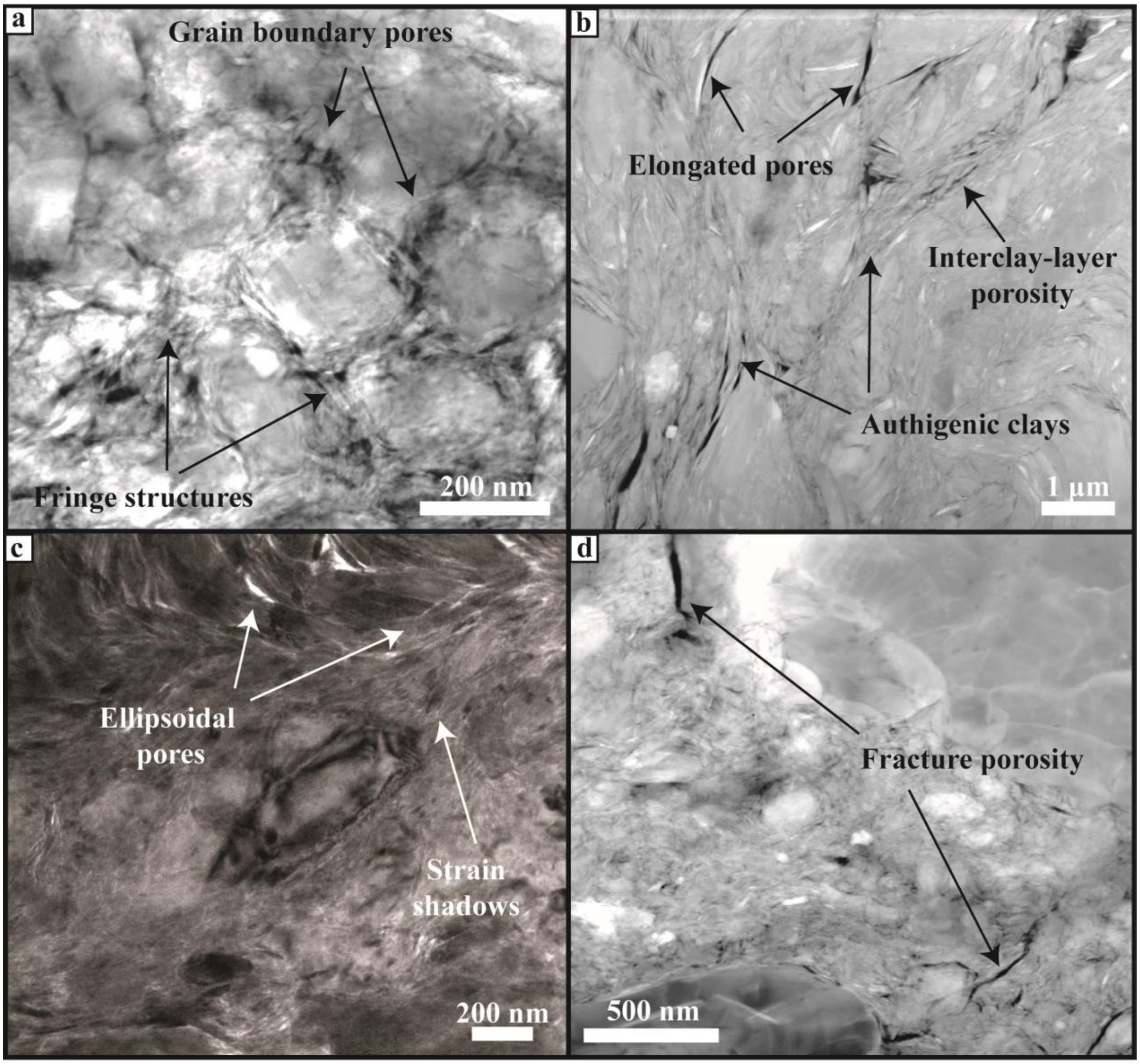


Figure 8. Scanning electron images collected from sample DFDP 1B 69-2.48 showing the existing minearal associations. (a) Sub-rounded and intensly fractured quartz and white mica clasts~~ in association with white mica~~, ~~floating ~~within fine matrix material. (b) Rewor~~d~~ked cataclasite clasts in phyllosilicate-rich ~~layer~~matrix. (c) ~~C~~Fine chlorite and white mica ~~fillings~~aggregates ~~in ~~between quartz clasts. (Qtz = quartz, Wm = white mica, Chl = chlorite).



~~Figure 8~~Figure 9. Transmission electron microscopy images collected ~~from~~ from~~on~~ the gouge sample DFDP-1B 69_2.54 (PSZ-2). (a) and (c) are bright-field (BF) images, where porosity appears as bright contrast areas. (b) and (d) are high-angle annular dark field (HAADF) images, where pores appear as dark contrasts areas. (a) TEM bright-field image of homogeneous fault gouge area. Quartz/feldspar grains, wrapped by fine authigenic clays, displaying fringe ~~structures~~morphlogies. Pores with sub-angular shape distributed along grain boundaries. (b) HAADF image of phyllosilicate-rich gouge area. Co-existence of fine authigenic clays with coarser clay mineral grains. Elongated pores and interlayer porosity. (c) TEM bright-fi~~l~~eld image of ellipsoidal pores in phyllosilicate-rich areas. Examples of strain shadows along quartz/feldspar grains. (d) HAADF image of fracture porosity along grain boundaries of quartz/feldspar grains.