

Alma Mater Studiorum Università di Bologna  
Archivio istituzionale della ricerca

Constraints upon fault zone properties by combined structural analysis of virtual outcrop models and discrete fracture network modelling

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

*Published Version:*

Ceccato, A., Viola, G., Antonellini, M., Tartaglia, G., Ryan, E.J. (2021). Constraints upon fault zone properties by combined structural analysis of virtual outcrop models and discrete fracture network modelling. JOURNAL OF STRUCTURAL GEOLOGY, 152, 1-18 [10.1016/j.jsg.2021.104444].

*Availability:*

This version is available at: <https://hdl.handle.net/11585/831393> since: 2021-09-06

*Published:*

DOI: <http://doi.org/10.1016/j.jsg.2021.104444>

*Terms of use:*

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).  
When citing, please refer to the published version.

(Article begins on next page)

This is the final peer-reviewed accepted manuscript of:

Ceccato, Alberto; Viola, Giulio; Antonellini, Marco; Tartaglia, Giulia; Ryan, Eric J.:  
*Constraints upon fault zone properties by combined structural analysis of virtual outcrop models and discrete fracture network modelling*

JOURNAL OF STRUCTURAL GEOLOGY VOL. 152 ISSN: 0191-8141

DOI: 10.1016/j.jsg.2021.104444

The final published version is available online at:

<https://dx.doi.org/10.1016/j.jsg.2021.104444>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

**When citing, please refer to the published version.**

1    **Constraints upon fault zone properties by combined structural analysis of virtual outcrop**  
2    **models and discrete fracture network modelling**

3    Alberto Ceccato<sup>1</sup>, Giulio Viola<sup>1</sup>, Marco Antonellini<sup>1</sup>, Giulia Tartaglia<sup>1</sup>, Eric J. Ryan<sup>2</sup>

4    <sup>1</sup>Department of Biological, Geological and Environmental Sciences – BiGeA. Alma Mater Studiorum  
5    – University of Bologna – Italy

6    <sup>2</sup>Norwegian University of Science and Technology – Department of Geoscience and Petroleum –  
7    Trondheim – Norway

8    Corresponding Author: Alberto Ceccato (alberto.ceccato@unibo.it)

9    **Abstract**

10    The permeability structure of a fault zone is strongly dependent on the occurrence of meso-scale  
11    fracture patterns within the damage zone. Here, structural analyses of Virtual Outcrop Models (VOM)  
12    integrated with Discrete Fracture Network (DFN) modelling are used to constrain the relationship  
13    between meso-scale fracture patterns and the bulk permeability of a regional-scale fault zone. The  
14    Goddo Fault Zone (GFZ, Bømlo – Norway) is a long-lived extensional fault zone cutting across a  
15    granodioritic body developed during the long-lasting rifting of the North Sea. Fracture geometrical  
16    characteristics and the spatial variation of fracture intensity derived from VOM structural analysis  
17    were adopted as input for stochastic DFN models representing selected portions of the GFZ to  
18    constrain the variability of the structural permeability tensor **K** related to the mesoscopic fracture  
19    pattern. The intensity of fault-related fracture set(s), and the associated structural permeability  
20    computed with DFN models, likely exhibits a decreasing power-law trend within the damage zone  
21    with increasing distance from the fault cores. The orientation of the maximum **K** tensor component  
22    is controlled by the intersection direction of the dominant fracture sets. These results highlight the  
23    fundamental role of mesoscopic fracture patterns in controlling the bulk petrophysical properties of  
24    large fault zones.

25    **Keywords**

26    Fault zone permeability; Virtual Outcrop Model; Permeability tensor; Discrete Fracture Network  
27    modelling.

28

## 1. Introduction

Metamorphic and igneous crystalline basement rocks are characterised by a very low matrix permeability ( $<10^{-4}$  mD), which is related to an inherent low porosity (Achtziger-Zupančič et al., 2017). Their bulk permeability is thus controlled by the so-called structural permeability, i.e. the secondary permeability due to fractures and fault zones (Nelson, 2001). The permeability and hydraulic properties of fault zones are, in turn, controlled by the fault zone structural architecture (Caine et al., 1996). The geometrical arrangement, deformation intensity and size of fault zone domains and brittle structural facies (*sensu* Tartaglia et al., 2020) control whether fault zones behave as conduits or barriers to fluid flow (Bruhn et al., 1994; Faulkner et al., 2010; Bense et al., 2013). Fault architectural elements include (i) the fault core(s), which localises most of the deformation accommodated by fault zones, and (ii) the damage zone, defined as a zone of diffuse micro- to meso-scale fractures surrounding the fault core. At the micro-scale, micro-fracturing and cataclasis affect the matrix properties within fault zone domains, i.e. the bulk permeability of the rock (Evans et al., 1997). The matrix permeability increases proportionally to the micro-fracture intensity within the fault damage zone (Mitchell and Faulkner, 2012; Rempe et al., 2018; Gomila et al., 2021). Intense cataclasis and fluid-rock interaction within fault cores may form fine-grained, phyllosilicate-rich and low-permeability fault rocks (Faulkner, 2004). The main factors controlling fault structural permeability are, instead, fracture intensity and connectivity within the meso-scale fracture networks (Hardebol et al., 2015; Peacock and Sanderson, 2018). In this paper, the term *fracture intensity* refers to both linear fracture intensity  $P_{10}$  ( $\text{m}^{-1}$ ), expressed as the number  $N$  of fractures intersected by a 1D survey scanline of length  $L$  ( $P_{10} = N/L \text{ m}^{-1}$ ), and the volumetric fracture intensity  $P_{32}$  ( $\text{m}^2/\text{m}^3$ ), which quantifies the total surface area of fractures within a given volume of rock (Dershowitz and Herda, 1992). Fracture intensity generally varies across faults/damage zones such that a detailed quantification of the spatial variability of fracture intensity is necessary to evaluate the variation of the hydraulic properties across a fault zone (Martinelli et al., 2020).

54 Here we present field and Virtual Outcrop Model (VOM) structural analyses to quantify the  
55 geometrical parameters of the fracture sets associated with the Goddo Fault Zone (Bømlo,  
56 southwestern Norway). Our results were used as input to Discrete Fracture Network (DFN) modelling  
57 (computed in FracMan 7.9) to quantify the structural permeability related to the meso-scale fracture  
58 network developed across the large-scale Goddo Fault Zone.

59 The analysis of fracture distribution in the VOMs allowed us to constrain the geometry, intensity,  
60 spatial distribution, and organisation of subseismic-resolution-scale (SSRS) structural features  
61 (Wilson et al., 2011; Seers and Hodgetts, 2014; Bisdorn et al., 2017; Biber et al., 2018). Examples of  
62 SSRS structural features include outcrop-scale fracture patterns and local-scale fault zones  
63 characterized by either low seismic impedance or dimensions that are below resolution and thus  
64 undetectable by standard-industry seismic surveys (e.g. fault throw <4-10 m) (Tanner et al., 2019).  
65 In contrast, seismic-resolution scale (SRS) structural features such as the GFZ include fractures and  
66 fault zones that are commonly detected by standard seismic surveys. SSRS structural features are  
67 intrinsic properties of the damage zone of SRS fault zones and deeply affect the local-scale  
68 permeability of reservoir rocks (Damsleth et al., 1998).

69 VOMs produced by Structure-from-Motion (SfM) algorithms on unmanned aerial vehicles (UAV)  
70 imagery are increasingly adopted to document the high-resolution architecture of fault zones and to  
71 retrieve input parameters for quantitative models of meso-scale structural permeability (Romano et  
72 al., 2020; Hansberry et al., 2021; Smeraglia et al., 2021). VOMs generate structural data from large  
73 areas, leading to statistically significant datasets of geometrical fracture properties (Martinelli et al.,  
74 2020). In this study, results from VOM structural analysis are adopted as inputs to stochastic DFN  
75 models aiming to quantify the permeability and its variability due to the meso-scale fracture patterns  
76 that are associated with a fault zone. DFN models make it possible to define the magnitude and  
77 orientation of the principal components of the equivalent permeability tensor  $\mathbf{K}$  in a Representative  
78 Elementary Volume (REV) (Oda, 1988) of the studied fault zone domains.

Ultimately, the focus of this combined structural and modelling approach is to understand and quantify the impact on the rock bulk permeability of variable intensities of SSRS fractures associated with SRS fault zones. Our results have significant implications upon the understanding of the relative variation of permeability (magnitude and orientation of maximum permeability) as a function of the spatially variable intensity of meso-scale fractures close to large-scale fault zones in crystalline basements (e.g. Mitchell and Faulkner, 2012). This is highly relevant as fractured crystalline basement blocks are increasingly becoming the focus of many applied and theoretical studies, also aiming at the sustainable exploitation of georesources (oil, mineral, heat and water) (Lüschen et al., 2015; Achtziger-Zupančič et al., 2016; Ceccato et al., 2021), and at their characterisation as potential sites for anthropogenic waste repositories (Marchesini et al., 2019; Vo Thanh et al., 2019; Prando et al., 2020). The analysis of outcrop analogues of fractured crystalline basement and the analytical/numerical workflow presented here make it possible to improve our understanding of the spatial variation of the permeability tensor, which, in turn, can be of great importance to the development of effective exploration and production strategies for unconventional reservoirs.

## **2. Geological Settings**

The Goddo Fault Zone (GFZ) crops out along the southeastern coast of the Goddo Island (Bømlo, Hordaland, Western Norway; Fig. 1). The fault zone cuts through the Rolvsnes granodiorite, a pre-Scandian granitoid pluton ( $466 \pm 3$  Ma, U/Pb on zircon; Scheiber et al., 2016) intruding the metamorphic units of the Caledonian Upper Allochthon (Gee et al., 2008; Slagstad et al., 2011; Scheiber et al., 2016). The Rolvsnes granodiorite is cut across by a complex network of fractures and fault zones, which records the prolonged brittle deformation history that unfolded during the post-Caledonian orogenic collapse and subsequent multi-stage rifting of the northern North Sea (Scheiber et al., 2016; Scheiber and Viola, 2018). The tectonic history of the area is only shortly summarized in the following, while further details can be found in Scheiber and Viola (2018). Fractures formed

104 during this prolonged tectonic activity can be sorted into three main sets in relation with their relative  
105 timing with the progressive development of the GFZ: (a) Pre-Permian background fractures,  
106 mineralised veins, and shear fractures; (b) GFZ-related fractures and fault zones and (c) fracture  
107 clusters spatially and genetically associated with Cretaceous alteration processes.

108 During Caledonian arc accretion and following continental collision in Silurian-Devonian times, two  
109 dominant conjugate sets of NNW-trending and WNW-trending strike-slip faults developed in  
110 response to a NW-SE-directed compressional stress field. ENE-trending, NW-verging minor thrust  
111 faults also formed. A first phase of NW-SE-directed tectonic extension was recorded by the  
112 reactivation and kinematic inversion of existing structures during mid-Devonian times. Tectonic  
113 quiescence characterised the Late Devonian to Late Carboniferous periods. The variably oriented,  
114 pre-Permian mineralised veins and shear fractures formed during these early stages of brittle tectonic  
115 deformation. They include K-feldspar-quartz-muscovite pegmatitic greisens, epidote and chlorite  
116 veins, and biotite- and muscovite-bearing shear fractures, and likely formed at mid to upper crustal  
117 levels (6-10 km depth).

118 The recent tectonic history of the area was controlled by the multi-stage extensional tectonics related  
119 to the northern North Sea rifting during the Permian to the mid-Cretaceous (Bell et al., 2014). During  
120 this multi-stage history, several sets of normal faults, including the GFZ, formed under variably  
121 oriented extensional stress fields. During Permian to Triassic times (290 to 245 Ma), NW-striking,  
122 top-to-NE normal faults developed in an ENE-WSW-directed extensional stress field. From the Late  
123 Triassic to early Jurassic (210-160 Ma), WNW-ESE-directed extension led to the formation of NNW-  
124 trending, top-to-ENE normal faults as well as to the reactivation of suitably oriented pre-existing  
125 structures. Fracture and fault zones with thick ( $\gg 1$  cm) fault-rock-bearing cores formed only during  
126 this Permo-Jurassic stages of faulting and reactivation (Scheiber and Viola, 2018).

127 During the Early Cretaceous, a set of minor, N-S trending normal (top-to-E) faults and fracture zones  
128 developed in the area in response to far-field stresses related to the extensional tectonics in the



129 northern North Sea and along the Mid-Norwegian Margin. During this latest deformation stage, N-S  
130 to NNE-SSW trending fracture clusters formed at very shallow crustal conditions (<2 km). These  
131 clusters are commonly associated with evidence of fluid-rock interaction that locally transformed the  
132 host Rolvsnes granodiorite into a sandy, non-cohesive aggregate of quartz and clay-minerals (Viola  
133 et al., 2016; Fredin et al., 2017b; Ceccato et al., 2021).

134 The Rolvsnes granodiorite resided at upper crustal levels throughout its entire deformation history,  
135 reaching surficial conditions during the Triassic, as inferred from the formation of weathering  
136 products (saprolite) during the subaerial exposure of the granodiorite in tropical-humid climate  
137 (Fredin et al., 2017b, 2017a).

## 138 *2.1 The Goddo Fault Zone*

139 The GFZ is a long-lived, iteratively reactivated fault zone accommodating several episodes of  
140 extension since the Permian (Viola et al., 2016). The fault zone has a general NNW-SSE strike, and  
141 it is characterised by the occurrence of two main, top-to-ENE, normal fault planes (average Dip/Dip  
142 Dir: 50°/070°), antithetic to the dominant regional sets of W-dipping normal faults and extensional  
143 detachments (Viola et al., 2016; Scheiber and Viola, 2018). Earlier field investigations highlighted  
144 the complex GFZ architecture and fault core structure at the outcrop (Viola et al., 2016; Scheiber and  
145 Viola, 2018; Ceccato et al., 2021). The GFZ outcrop is oriented WSW-ESE along its southern  
146 exposure, and NNW-SSE along its northern exposure (Fig. 2a-c). This exposure is well suited for the  
147 characterisation of the footwall and main fault cores (that crop out along the southern part of the  
148 outcrop), but it does not allow for clear analysis of the hanging wall, with the northern exposure being  
149 almost parallel to the main fault strike (Fig. 2a). The exposed footwall and hanging wall damage  
150 zones are characterised by a variable fracture intensity, the quantification of which is the focus of this  
151 study. The central portion of the GFZ is defined by the occurrence of two parallel main fault cores,  
152 both oriented c. 50°/070° although characterised by different thicknesses and brittle structural facies  
153 associations (Viola et al., 2016; Ceccato et al., 2021). The southern fault core (sFC, Fig. 2) includes:

(i) a polished Principal Slip Surface (PSS), dipping  $50^{\circ}/071^{\circ}$  with dip-slip, normal  $50^{\circ}/070^{\circ}$  slickenlines; (ii) a 5-10 cm thick, massive, well-sorted clay-rich gouge layer, overlain by (iii) a 40-50 cm thick layer of consolidated cataclasite (Fig. 3a). The northern fault core (nFC in Fig. 2; outcrop S<sub>3B</sub> in Ceccato et al., 2021) includes: (i) a PSS dipping  $56^{\circ}/079^{\circ}$ , characterised by dip-slip slickenlines suggesting normal, top-to-ENE kinematics; (ii) a 5-10 cm thick layer of massive, clay-rich gouge; (iii) a 10 cm thick chlorite-bearing phyllonitic gouge, characterised by S-C' microstructures; (iv) a ~2 m thick layer of cohesive cataclasite (Fig. 3b). According to the general scaling relationship between fault core thickness and accommodated fault throw (e.g., Torabi and Berg, 2011) and considering that the fault cores are up to 2 m thick, the GFZ may have accommodated a cumulative normal throw in the order of several hundreds to a thousand meters. This estimate suggests that the GFZ is a good example of an SRS fault zone (Ceccato et al., 2021). The fault zone is locally crosscut by NNE-SSW-striking fracture clusters usually associated with alteration of the host granodiorite (Figs. 2 and 3c) (Viola et al., 2016; Fredin et al., 2017b; Scheiber and Viola, 2018).

Detailed microstructural and geochronological analyses of the brittle structural facies (*sensu* Tartaglia et al., 2020) within the GFZ fault core have allowed us to track its temporal meso- and micro-structural evolution (Viola et al., 2016). The Permian age ( $264.1 \pm 5.4$  Ma) of the phyllonitic gouge, and the Early Jurassic age ( $200.2 \pm 4.1$  Ma) of the clay-rich fault gouge retrieved from K-Ar dating of synkinematic illite suggest that the GFZ recorded a multi-stage activity of extensional faulting and fluid-rock interaction at different temperature conditions at upper crustal levels ( $< 6$  km depth, Scheiber and Viola, 2018). Extensive alteration of the host granodiorite occurred along fracture clusters at high angle to the GFZ during the Early Cretaceous, as inferred from K-Ar dating of authigenic illite ( $125.2 \pm 4.2$  Ma) (Viola et al., 2016).

## 2.2 Fault rock bulk permeability and anisotropy

The petrophysical and geomechanical properties of the GFZ fault rocks have been characterised through in-situ measurements and discussed by Ceccato et al. (2021). The permeability of the fault

179 cores (gouge, cataclasite) and host granodiorite was measured with a New England Research  
180 TinyPerm3 air-minipermeameter. Results are reported in Table 1. Details on methods and data  
181 statistics can be found in Ceccato et al. (2021). The lowest permeability was observed in the host  
182 granodiorite (48 mD on average) and in the fault core directly on PSS along a direction perpendicular  
183 to it (43 mD on average). The highest permeability was observed in the cataclasite (368 mD on  
184 average) measured parallel to the fault strike (NNW-SSE direction). The clay-rich gouge layers  
185 exhibit an intermediate permeability of 96 mD on average. Based on the discussion of literature data,  
186 Ceccato et al. (2021) suggested that the shape of the permeability tensor of gouge and cataclasite is  
187 likely strongly oblate, with the principal minimum permeability component measured perpendicular  
188 to the fault plane and on average three orders of magnitude smaller than the maximum and  
189 intermediate axes of the permeability tensor parallel to the fault plane (Faulkner and Rutter, 1998;  
190 Zhang and Tullis, 1998).

### 191 **3. Workflow and methods**

192 The proposed workflow includes four main steps (Fig. 4): (1) creation of VOMs from UAV imagery;  
193 (2) detection and interpretation of fractures from VOMs; (3) analysis of fracture intensity and spatial  
194 organisation by means of virtual cross-sections and scanlines; (4) stochastic DFN modelling in  
195 FracMan.

#### 196 *3.1 UAV imagery acquisition and Virtual Outcrop Model elaboration*

197 Georeferenced (WGS 84 / UTM zone 31N - EPSG:32631) Virtual Outcrop Models of the GFZ  
198 outcrop were generated using UAV-drone imagery through SfM algorithms. UAV-drone image  
199 acquisition was carried out with a DJI Phantom 4 drone, equipped with a 20 MP camera (CMOS-1  
200 sensor, 24 mm lens) using Ground Station Pro software on an iPad. Two flights were flown on the  
201 GFZ outcrop: (i) an overview survey, acquiring images at low-resolution (1 cm/pxl) and covering the  
202 entire exposed outcrop), (ii) a high-resolution (1-3 mm/pxl) survey of the central fault zone area,  
203 specifically covering the sFC and nFC. The images were taken with 80% front and 60% side overlap

204 while the UAV was in stationary flight. Point clouds, orthophotos and digital surface models were  
205 generated through the analysis of the drone imagery by means of SfM algorithms in ContextCapture  
206 (Bentley Systems Inc.).

### 207 *3.2 Virtual Outcrop Models interpretation and fracture identification*

208 The interpretation of fractures and the structural analysis of the generated VOMs were performed in  
209 CloudCompare (<https://www.danielgm.net/cc/>). The VOMs were plotted in CloudCompare as point  
210 clouds. The point clouds of the two VOMs generated from the two drone flights were combined to  
211 build a single, high-resolution VOM of the GFZ (Fig. 4A). Fracture extraction from the VOMs  
212 required the segmentation of exposed fracture surfaces and the analysis of fracture traces on the  
213 outcrop surface adopting the structural analysis toolkits Facets (Dewez et al., 2016) and Compass  
214 (Thiele et al., 2017) implemented in CloudCompare (Fig. 4B). These toolkits rely on two different  
215 approaches to retrieve a geometrical representation of fracture planes. The Facets tool is designed to  
216 retrieve the planar 3D polygon that best fits the points of a manually selected portion of the point  
217 cloud. The Compass tool allows to either fit a square plane to a selected region of defined radius  
218 around a selected point of a point cloud (Plane tool), or to retrieve the plane that best fits the trace of  
219 a fracture on the outcrop surface (Trace tool). Thus, these tools are efficient in retrieving the  
220 orientation of fracture surfaces and planes when the outcrop topography is irregular and offer a three-  
221 dimensional exposure of fracture planes or traces. We have mainly adopted Facets to analyse the  
222 exposed fracture surfaces, and the Trace tool in Compass to retrieve the orientation of fracture planes  
223 and length from the fracture trace on the outcrop surface. The accuracy of both analytical tools in  
224 retrieving reliable orientation data depends on the resolution of the point cloud and the dimension of  
225 the segmented fracture plane: the smaller the fracture surface/trace, the fewer the points that can be  
226 fitted by the interpretation tools, and thus, the less accurate the retrieved plane orientation (Dewez et  
227 al., 2016; Thiele et al., 2017). Accordingly, the range of fracture length that the tools can analyse is  
228 limited at the lower bound by the resolution of the point cloud, and at the upper bound by the  
229 computational capability of the PC/workstation (Dewez et al., 2016; Thiele et al., 2017). The

230 interpreted planar or linear trace expression of fractures ranges between 10 cm and 5 m. The structural  
231 orientation data exported from Facets and Compass tools were then analysed and plotted with  
232 Stereonet v.11.2.2. (<https://www.rickallmendinger.net/stereonet>). Fracture trace length distributions  
233 were analysed with an ad-hoc MATLAB script adopting the functions for distribution fitting made  
234 available by FracPaQ (Healy et al., 2017; Rizzo et al., 2017).

### 235 *3.3 Analysis of fracture intensity and spatial organisation through virtual cross-sections and* 236 *scanlines*

237 The interpreted fracture traces and segmented polygons were then exported as .dfx meshes and  
238 imported into MOVE (Petex) to identify the dominant fracture sets, analyse their spatial distribution  
239 and the related fracture intensity (Fig. 4). The imported meshes were converted in rectangular fracture  
240 planes displaying the same orientation and horizontal length dimension of the polygons interpreted  
241 from the VOM. In MOVE, the entire fracture plane database was sorted into different orientation sets  
242 through manual segmentation of point clusters formed by the poles to the fracture planes in the  
243 stereographic projections. The fracture intensity ( $P_{10}$ ) was computed for each set on virtual cross-  
244 sections across the GFZ with the aid of virtual scanlines. In the VOM displayed in MOVE, we  
245 selected only the polygons-fractures belonging to a single orientation set. Then, several cross-sections  
246 were traced through the outcrop, oriented perpendicularly to the average strike of the selected fracture  
247 set and cutting across the areas of the VOM populated by the largest density of polygons-fractures  
248 (Fig. 4D). On each section we projected the polygon-fractures occurring within a tabular volume  
249 centred around the cross-section plane (Fig. 4D). In doing so, we assumed that the local intensity and  
250 distribution of meso-scale fractures is constant along fault strike. Virtual scanlines were traced  
251 perpendicular to the main dip angle of projected fractures on each section. The length of scanlines  
252 drawn on each section was limited to a few meters (<2-5 m). Fracture intensities were then computed  
253 by counting the number of fractures intersected and/or occurring in proximity (1-2 m above or below)  
254 to the virtual scanline (Fig. 4E).

255 Finally, to compare results from different scanlines and cross-sections, we projected the virtual  
256 scanlines on a single cross-section to track the variation of fracture intensity for each set across the  
257 profile (Fig. 4F).

### 258 *3.4 Discrete Fracture Network Modelling with FracMan*

259 The quantification of the structural permeability related to meso-scale fracture networks was  
260 performed by stochastic Discrete Fracture Network (DFN) modelling in FracMan 7.9 (Golder  
261 Associates) (Fig. 4G). FracMan allows to compute the permeability related to a specific fracture  
262 network in a rock mass through numerical modelling based on Discrete Fracture Network methods.  
263 The fracture network can be deterministically retrieved from 2D outcrop maps and imported into the  
264 software as trace maps (Antonellini et al., 2014). Alternatively, fracture networks can be generated  
265 with a stochastic approach using statistical parameters describing the geometrical properties of the  
266 fracture network as retrieved from deterministic field measurements (Lei et al., 2017). Here, we adopt  
267 the stochastic approach: the fracture network in the DFN models has been generated using the  
268 parameters describing the statistical distribution of geometrical fracture properties as retrieved from  
269 the analysis of VOMs. The input parameters required for stochastic DFN modelling include (Table  
270 2): (i) the average orientation and orientation variability; (ii) the target  $P_{32}$  local intensity; (iii) a  
271 function describing the shape of the cumulative distribution of some fracture size (length, height,  
272 radius); (iv) the fracture shape.

273 The input  $P_{32}$  for each fracture set in each model was calculated from the measured  $P_{10}$  intensity  
274 retrieved from the virtual scanlines following the approach suggested by Antonellini et al. (2014).  
275 For each fracture set, several DFN models were computed by simulating progressively increasing  $P_{32}$   
276 ( $P_{32} = 0.1; 0.5; 1.0; 2.0; 5.0; 10.0 \text{ m}^2/\text{m}^3$ ) while keeping constant the other geometrical parameters  
277 (orientation, length distribution). For each DFN model at any given  $P_{32}$ , the related  $P_{10}$  was calculated  
278 on virtual scanlines oriented perpendicular to the average fracture plane orientation. By plotting the  
279 different input  $P_{32}$  values and the related measured  $P_{10}$  values on a scatter plot, we retrieved the

280 proportionality coefficient relating  $P_{10}$  and  $P_{32}$  for each fracture set. The proportionality coefficient  
281 subsequently allowed us to calculate the appropriate  $P_{32}$  for each fracture set in each DFN model.

282 Each DFN model consists of a  $100 \times 100 \times 100$  m ( $10^6$  m<sup>3</sup>) volume domain composed of 8000 REV of  
283  $125$  m<sup>3</sup> ( $5 \times 5 \times 5$  m) each (Fig. 4G). Each REV was populated stochastically with selected assemblages  
284 of fracture sets. The elementary block dimensions (cube side length = 5 m) are larger than the  
285 minimum dimensions suggested by Oda (1988) for the definition of a REV, which must be at least  
286 three times larger than the average length of fractures ( $3 \cdot 0.8$ -1m = 2.4-3 m in our case; see Table 2).  
287 The computed volumetric grid, therefore, represents 8000 possible configurations of a  $125$  m<sup>3</sup> REV  
288 of a rock mass populated by a specific assemblage of fracture sets with specific fracture parameters.  
289 By doing so we aimed at analysing the statistical variation of the permeability tensor properties among  
290 the 8000 REV in the  $10^6$  m<sup>3</sup> modelled volume domain. The permeability computation in the DFN  
291 models follows the approach of Oda (1985). The approach of Oda allows retrieving the magnitude  
292 and orientation of the permeability tensor principal components ( $K_1$ ,  $K_2$ ,  $K_3$  with  $K_1 > K_2 > K_3$ ) from  
293 the “crack tensor” describing the geometrical properties of the fractures-discontinuities occurring  
294 within a REV of fractured rock mass. Comparing the magnitude and orientation of the tensor principal  
295 components computed for each of the 8000 REV within the same DFN model, we have retrieved the  
296 statistical variability of  $\mathbf{K}$  components (Fig. 4H-I). The resulting permeability values and permeability  
297 tensor components only refer to the structural permeability, as the matrix permeability of the host  
298 rock is not accounted for in our models.

299

## 300 **4. Results**

### 301 *4.1 Field and VOM outcrop characterization*

302 The structural field analysis of this study was limited to the acquisition of a reliable dataset of fracture  
303 orientations and the identification of the fault zone domains (fault cores and damage zone) (Figs. 2-  
304 3). By comparing the 3D point clouds with field investigations, we could identify the three different

domains composing the GFZ (Figs. 2 and 5): the footwall (FW) damage zone, the central GFZ, and the northern hanging wall (HW) damage zone.

The southern portion of the outcrop exposes the damage zone in the footwall of the main fault plane (main PSS, Fig. 5a-b), which is characterised by rather spaced, up to 20 m long fractures organised in clusters and oriented in two main sets, trending NNE-SSW and ENE-WSW, respectively (Fig. 5c-d). A third set of NW-SE-trending fractures becomes increasingly prominent (Fig. 4d) moving toward the southern fault core (sFC, Figs. 2, 3a, 5a-b). These sets of fractures dip toward either NE or SW (Fig. 5d). The central GFZ includes the Internal Damage Zone (IDZ), the southern (sFC) and northern (nFC) fault cores (Fig. 5e-f). The sFC is defined by a large areal exposure of the main PSS above which a 50-60 cm thick fault core is exposed (Figs. 3a, 5f). The nFC is characterised by a limited exposure of the main PSS, which crops out at the bottom of a thick zone of cataclasites (~2 m thick measured perpendicularly to the PSS). The sFC and nFC bound an Internal Damage Zone (IDZ) characterised by high fracture intensity to the southern and northern side, respectively (Fig. 5g). Five main sets of fractures are recognized in the central GFZ (Fig. 5h): in addition to the previously identified fracture sets, an additional fracture set was observed, which shows the same orientation of the main PSS (on average 50°/070°; Fig. 5h). The northern portion of the outcrop exposes the hanging wall (HW) damage zone (Fig. 5i-j). This portion of the outcrop is characterised by a decreasing fracture intensity moving northward from the nFC and by large (up to 10-15 m wide) volumes of weathered granodiorite ("Alteration zone" in Fig. 5j). These alteration zones are related to NNE-SSW-trending fracture clusters (Viola et al., 2016; Scheiber and Viola, 2018; Ceccato et al., 2021).

#### *4.1.1 Fracture set identification*

The orientations of the segmented fracture surfaces and fracture traces interpreted in CloudCompare were plotted on stereographic projections in MOVE (Fig. 6). The total dataset of interpreted planes includes more than 2300 fractures (Fig. 6a). Clusters of fracture orientations were manually selected and classified into 5 main fracture sets (A-E; Fig. 6b; Table 2) in MOVE. Set A corresponds to the



330 NNE-SSE-trending clustered fractures, mainly observed in the southern footwall damage zone and  
331 within the alteration zones in the northern HW damage zone (Fig. 5i-l). Set B corresponds to WSW-  
332 ENE-trending fractures. Sets C and D correspond to the NW-SE-trending fractures found throughout  
333 the GFZ, dipping toward NE and SW, respectively. Set E fractures have the same orientation of the  
334 main PSS (50°/070°). Sets C and E display a similar orientation but different spatial distributions  
335 (Fig. 5d,h,l) suggesting that they are two distinct fracture sets. The identified fracture sets include  
336 only part of the total number of the interpreted fracture planes, whose orientation distribution is  
337 characterised by a significant background orientation noise (Fig. 6a). Nonetheless, the identified  
338 fracture sets represent a good first approximation of the entire dataset (1806 fractures included in the  
339 interpreted clusters out of 2347 fractures identified from VOMs – 77% of 2347 fractures). The  
340 variability of fracture set orientation was quantified by both the K-Fisher value – for Sets C, D and  
341 E, which display well-clustered orientations – and standard deviations for a uniform distribution – for  
342 Sets A and B, which exhibit very small K-Fisher parameter. This was necessary to better reproduce  
343 the observed orientation distribution in DFN models (see below).

#### 344 *4.1.2 Fracture trace length distribution*

345 The trace length reported here represents the fracture trace persistency and is retrieved from the  
346 projection of either the fracture trace or the horizontal dimension of a fracture plane on the horizontal  
347 plane. Trace length distributions for each set were analysed by the Maximum Likelihood Estimation  
348 method (MLE) and KS-test to obtain the best fit function describing the observed distribution (Rizzo  
349 et al., 2017). The trace length distribution dataset is reported in the Supplementary Data Table T1.  
350 All retrieved fracture trace length distributions range between 0.1 and 5 m in length, and are best  
351 fitted by negative exponential functions. Length ranges, statistical parameters, and the exponential  
352 parameter  $\lambda$  are reported in Table 2.

353 *4.1.3 Intensity and spatial distribution of fracture sets across the GFZ outcrop*

354 Here we report the results of the fracture intensity analysis on the virtual cross-sections and scanlines  
355 for each set of fractures identified within the GFZ. The virtual cross-sections are reported in the  
356 Supplementary Data S1, and the related scanline results are reported in the Supplementary Data Table  
357 T2.

358 *Set A.* The spatial distribution and local  $P_{10}$  of Set A were quantified through virtual scanlines on a  
359 single horizontal section (map view) through the entire GFZ outcrop (Supplementary Data S1-Set A).  
360 Following this, the virtual scanlines were projected again on the vertical cross-section B-B' (Fig. 2a),  
361 oriented N060°W-N120°E to visualize the variability of fracture intensity in a direction perpendicular  
362 to the average strike of Set A (Fig. 7a). Set A fractures mainly occur in clusters with a high fracture  
363 intensity (up to  $P_{10}=6\text{ m}^{-1}$  - Fig. 7a). In the southern portion of the GFZ outcrop (FW) there are three  
364 main Set A clusters, which are on average 10-15 m apart from one another (Fig. 7a). The inter-cluster  
365 granodiorite is characterised by a lower local fracture intensity ( $P_{10}=1\text{ m}^{-1}$  on average). Set A fracture  
366 clusters occur also in the northern GFZ outcrop (HW), where they are associated with alteration zones  
367 (Fig. 5j) (Viola et al., 2016; Scheiber and Viola, 2018; Ceccato et al., 2021).

368 *Set B.* The  $P_{10}$  and spatial distribution of Set B fractures were quantified by means of a single vertical,  
369 N-S oriented cross-section perpendicular to their average strike and across the entire GFZ outcrop  
370 (cross-section C-C' in Fig. 2a, Supplementary Data S1-Set B). Set B fractures are scattered, and they  
371 do not exhibit any obvious preferential spatial distribution. The measured  $P_{10}$  ranges between 0.5 and  
372  $2.5\text{ m}^{-1}$  ( $1.4\text{ m}^{-1}$  on average, Fig. 7a).

373 *Set C.* Spatial distribution and  $P_{10}$  were quantified from multiple NE-SW cross-sections perpendicular  
374 to the main fracture strike (Supplementary Data S1-Set C). Set C fractures crop out along the entire  
375 GFZ exposure.

376 *Set D.* Spatial distribution and  $P_{10}$  were quantified on multiple NE-SW cross-sections (Supplementary  
377 Data S1-Set D). Set D fractures occur mainly in the central and southern portion of the GFZ outcrop,  
378 as small clusters with variable fracture intensity moving from south to north across the outcrop.

379 *Set E.* Spatial distribution and  $P_{10}$  were quantified on multiple N070° cross-sections, perpendicular to  
380 the main fault strike (Supplementary Data S1-Set E). Fracture intensity varies spatially, displaying  
381 larger  $P_{10}$  values close to the main fault cores (sFC, nFC) and progressively decreasing values moving  
382 away from the central fault zone both northward and southward.

383 *Spatial distribution of Sets C, D and E.* To analyse the spatial distribution of  $P_{10}$  for Sets C, D and E,  
384 the variably oriented cross-sections traced for the different sets (Supplementary Data S1), as well as  
385 the related scanlines, were projected onto a cross section oriented N070°E, thus perpendicular to the  
386 strike of the main fault (Fig. 7b). On this cross-section, we assessed the spatial distribution of  $P_{10}$   
387 intensity on a profile perpendicular to the fault dip (black line in Fig. 7b). This allowed for the  
388 relationship between  $P_{10}$  intensity of each fracture set and the distance perpendicular to the main fault  
389 planes to be determined (Fig. 7c). The intensity of Set C fractures does not display any obvious spatial  
390 trend (constant  $P_{10} = 1.1 \text{ m}^{-1}$  on average; Fig. 7c). The diagram in Fig. 7c highlights two different  
391 spatial trends for fracture Sets D and E intensity.  $P_{10}$  for Set D varies from  $0.5 \text{ m}^{-1}$  in the southern  
392 GFZ outcrop up to a maximum of  $5.5 \text{ m}^{-1}$  just north of the nFC outcrop (Fig. 7c). A second peak in  
393 intensity ( $P_{10} = 2.9 \text{ m}^{-1}$ ) is observed next to the sFC. Set D fractures show an increasing intensity  
394 moving from SW to NE across the fault zone, which is best fitted by a power-law function ( $R^2 =$   
395  $0.7702$ ; Fig. 8a-b). The spatial trend of Set E fracture intensity increases next to the two main fault  
396 cores (Fig. 7c), showing  $5.7 \text{ m}^{-1}$  and  $4.5 \text{ m}^{-1}$  close to the sFC and nFC, respectively. The IDZ is  
397 characterised by variable intensity ranging between  $1.2$  and  $1.9 \text{ m}^{-1}$ . In the footwall, fracture intensity  
398 increases quite abruptly from  $<1 \text{ m}^{-1}$  to  $>5 \text{ m}^{-1}$  over less than 5 m from the southern PSS. Conversely,  
399 in the hanging wall, Set E fracture intensity decreases slowly, and  $P_{10}$  values larger than  $2 \text{ m}^{-1}$  are still  
400 observed ~15 m away from the northern PSS (Fig. 7c). The decreasing trend of Set E  $P_{10}$  intensity is

best fitted by a power-law function moving away from the sFC into the FW ( $R^2 = 0.9809$ ; Fig. 8a-b). The decreasing trend of Set E  $P_{10}$  intensity moving away from the nFC into the HW is instead best fitted by a negative exponential function ( $R^2 = 0.88$ ; Fig. 8a), even though data fitting with a power-law function also yielded a statistically meaningful result ( $R^2 = 0.7293$ ; Fig. 8b).

#### 4.2 Discrete Fracture Network models

To track the variation of the magnitude and orientation of the  $\mathbf{K}$  tensor principal components across the fault zone, we computed several DFN models for different combinations of fracture sets and related  $P_{10}$  to simulate the observed fracture networks of selected portions of the GFZ and recreate a synthetic fault zone (Figs. 7b-9a).

The DFN models include (Figs. 7c-9; Table 3): (i) model FW\_1, representing the crystalline basement affected by background fracturing alone in the footwall of the GFZ; (ii) model FW\_2, representing the transition from background fracturing toward the footwall damage zone (Set E  $P_{10} = 1 \text{ m}^{-1}$ ); (iii) model FW\_3, representing the footwall damage zone; (iv) model sFC, representing the damage zone close to the southern fault core (max Set E intensity); (v) model IDZ, representing the Internal Damage Zone; (vi) model nFC, representing damage zone close to the northern fault core; (vii) model HW\_1, representing the hanging wall damage zone affected by the maximum observed Set D intensity; (viii) model HW\_2, representing the intermediate portion of hanging wall damage zone; (ix) model HW\_3, representing the external portion of the hanging wall damage zone without the contribution of Set D. Additionally, we have created a model targeting the permeability properties of the crystalline basement affected by Set A fracture clusters (model Clus in Fig. 9a). The fracture sets, the related  $P_{10}$  intensities and all the fracture parameters adopted for each model computation are listed in Table 2 and 3. We assumed a constant mechanical fracture aperture of  $100 \text{ }\mu\text{m}$  for all the fracture sets in the DFN models. The proportionality coefficients relating  $P_{10}$  with  $P_{32}$  and the adopted  $P_{32}$  values for each fracture set in each DFN model are listed in Table 2 and plotted in Fig. 9a (Supplementary Data S2). An example of the graphical output of a DFN model computation is

426 reported in the Supplementary Data S3. The magnitude and orientation of the permeability tensor  
427 principal components retrieved from the DFN models are reported in Table 4 and Fig. 9.

428 The magnitudes of the principal components of the permeability tensor show a significant variation  
429 across the GFZ (Fig. 9b). The  $K_1$  component ranges between 0.03 mD and 0.13 mD on average,  
430 showing maximum values as high as 0.4 mD and displaying a relative increase of about one order of  
431 magnitude between the least and the most fractured zone (Table 4). The  $K_2$  component shows a  
432 variation trend similar to  $K_1$ . The  $K_3$  component is the least variable component, ranging between  
433 0.01 mD and 0.05 mD. The relative magnitude of the tensor components suggests that in all cases the  
434 shape of the  $\mathbf{K}$  tensor is oblate, having very similar  $K_1$  and  $K_2$  permeability values that are much  
435 larger than  $K_3$  (Fig. 9b). As to the orientation of the  $\mathbf{K}$  principal components (Fig. 9c), the orientation  
436 of the  $K_3$  component is constant for all models, being almost subhorizontal and NE-striking. The  
437 orientation of  $K_1$  varies across the GFZ: in the footwall and in the most distal portions of the GFZ  
438 hanging wall (FW\_1, FW\_2, FW\_3, HW\_3),  $K_1$  plunges 45° eastward, laying subparallel to the  
439 intersection direction between Sets B and E or Sets B and C. In these domains, the  $K_2$  direction is  
440 close to the intersection direction between Sets C and D (Fig. 9c, Supplementary Data S4). In the  
441 central and most fractured portions of the GFZ (sFC, IDZ, nFC, HW\_1, HW\_2), on the other hand,  
442  $K_1$  is almost subhorizontal and NW-trending, laying subparallel to the intersection direction between  
443 Sets D and E (Fig. 9c, Supplementary Data S4). In most cases, the distribution of the entire  $K_1$   
444 orientation dataset defines a girdle spanning almost 90° and overlapping with a similar  $K_2$  girdle  
445 distribution (Supplementary Data S4). This girdle distribution for  $K_1$ - $K_2$  orientations is most  
446 pronounced in the footwall models (FW\_1, FW\_2, FW\_3), while it becomes less pronounced in the  
447 hanging wall models (HW\_1, HW\_2, HW\_3; Supplementary Data S4).

448 The maximum permeability  $K_1$  of fracture clusters (Clus) is equal to 0.11 mD (Fig. 9b) and the  $K_1$ -  
449  $K_2$  principal component vectors rest on a plane parallel to Set A average orientation (Fig. 9c).  
450 Accordingly, the  $K_3$  principal component is equal to 0.04 mD, is subhorizontal, and plunges toward

451 WNW. Overall, the computed principal components of **K** increase linearly with the computed total  
452  $P_{32}$  fracture intensity both within the GFZ and Set A clusters (Fig. 10).

453

## 5. Discussion

In the following, we first discuss the geometry of the SRS GFZ and its SSRS structural features, and then the effects of the geometry on the permeability of the fractured crystalline basement.

### 5.1 Geometry of the Goddo Fault Zone

The GFZ case study offers useful insights into the geometry of SSRS fracture networks associated with SRS fault zones cutting across crystalline basement rocks, which is otherwise difficult if not impossible to do by means of geophysical investigations (e.g., Lüschen et al., 2015). Our results from the GFZ VOM structural analysis revealed the following characteristics:

- (i) The GFZ is characterised by two distinct fault cores probably representing two fault strands with a hard overlap, which have been activated coevally, as it can be inferred from the same assemblage of structural facies with the same probable age in the two fault cores (Viola et al., 2016; Ceccato et al., 2021). However, the limited exposure of the studied outcrop does not allow to fully characterise the large-scale geometry of the GFZ. The two fault strands can either represent two en-echelon segments of a larger-scale normal fault or the same fault core embedding a very large damage zone lithon (the IDZ) (Childs et al., 1995; Fossen and Rotevatn, 2016).
- (ii) The intensity of the ENE-dipping Set E fractures varies from  $<1 \text{ m}^{-1}$  5 m from the main fault zone to  $\sim 6 \text{ m}^{-1}$  adjacent to the main fault cores. If fracture intensity in the most external portions of the GFZ represents the “background” fracture intensity of Set E, we define c.  $1 \text{ m}^{-1}$  as the limit between the background fracture intensity and the GFZ damage zone (Choi et al., 2016; Torabi et al., 2020). The transition from background intensity values to values  $>1 \text{ m}^{-1}$  occurs in the footwall  $\sim 5 \text{ m}$  from the southern fault core. In the hanging wall, the transition to intensity values  $<1 \text{ m}^{-1}$  occurs at  $>20 \text{ m}$  from the nFC (Fig. 7c). The intensity profile displayed by Set E fractures within the footwall and hanging

478 wall suggests that the fault zone is asymmetric, with the damage zone preferentially  
479 developed in the hanging wall of the fault zone.

480 (iii) The width of the fault zone (fault core + damage zone) is on the order of 35-40 m,  
481 consistent with the average width expected for fault zones characterised by fault traces  
482 longer than 100-1000 m with fault cores as thick as 2 m (Wilson et al., 2003; Faulkner et  
483 al., 2006, 2010).

484 (iv) Set E and Set D fractures clearly exhibit a decreasing intensity trend moving away from  
485 the closest “high strain” zones – which are the sFC and nFC for Set E, and the highest  
486 intensity peak along the profile for Set D, respectively (Figs. 7c, 8a-b). Whether related to  
487 the GFZ or not, the decreasing trend is best fitted for both sets by a power-law decreasing  
488 function, which shows, in most cases,  $R^2$  coefficients for a least-square regression (Fig.  
489 8b) higher than those obtained from the fitting through negative-exponential functions  
490 (Fig. 8a). An exponentially decreasing trend is usually described for the density of  
491 microfractures within damage zones with increasing distance from fault cores (Mitchell  
492 and Faulkner, 2009; Ostermeijer et al., 2020). Conversely, intensity variations of meso-  
493 scale (cm-to-m scale) fractures seem to be better described by a power-law decreasing  
494 function as observed within the GFZ (Savage and Brodsky, 2011; Johri et al., 2014;  
495 O’Hara et al., 2017). The observed range of power-law coefficients ( -0.28 – -0.45; Fig.  
496 8b) are consistent with the power-law decay expected for multi-strand fault zones  
497 accommodating >150 m of displacement (Savage and Brodsky, 2011).

498 The GFZ contains thin fault cores (<1 m) embedded within a 35-40 m thick damage zone. The ratio  
499 between damage zone thickness (footwall damage zone + IDZ + hanging wall damage zone = 40 m)  
500 and the total fault zone thickness (damage zone + fault cores = ~42 m) is approximately 0.95,  
501 suggesting that the GFZ represents a zone of distributed deformation behaving as a preferential  
502 distributed conduit for fluid-flow, following Caine et al. (1996). In addition, the distributed



503 deformation occurs mainly in the hanging wall of the GFZ, which is therefore expected to focus fluid-  
504 flow within the hanging wall block.

## 505 *5.2 Geometry of Set A fracture clusters*

506 Set A fracture clusters overprinted the fractured and faulted Rolvsnes granodiorite during Jurassic-  
507 Cretaceous deformation (Viola et al., 2016; Scheiber and Viola, 2018). Set A fractures form 5-7 m  
508 thick clusters, 10-15 m apart and with a  $P_{10}$  fracture intensity  $>5-7 \text{ m}^{-1}$  (Fig. 7a). The clusters mainly  
509 occur in the footwall of the GFZ. However, their occurrence in the hanging wall of the GFZ can be  
510 inferred from the presence of “alteration zones” and linear topographic depressions (gullies) just to  
511 the N/NE of the GFZ (dashed lines in Fig. 2a), which have previously been correlated with fracture  
512 clusters of similar orientation to Set A in the same outcrop (Viola et al., 2016). The “alteration zones”  
513 and gullies are spaced  $\sim 10$  m perpendicular to the strike of the gully. This is similar to the spacing  
514 between Set A clusters observed in the footwall (Fig. 7a). Thus, Set A fracture clusters seem to be  
515 rather homogeneously distributed over the GFZ outcrop, forming high-fracture intensity channels  
516 clustered with a spacing of 10-15 m and separated by low-fracture intensity ( $\sim 1 \text{ m}^{-1}$ ) domains.

517 Fracture clusters are quite common in the crystalline basement of southwestern Norway (Gabrielsen  
518 and Braathen, 2014; Torabi et al., 2018). Observations from the published literature and from the  
519 studied outcrop suggest that the fracture clusters are an ubiquitous feature of the fractured crystalline  
520 basement, yet impossible to detect by commonly adopted seismic investigation methods (Torabi et  
521 al., 2018; Ceccato et al., 2021). Their occurrence, however, controls the hydrology and fluid-flow  
522 within fractured rock masses at different crustal levels and scales (Ogata et al., 2014; Place et al.,  
523 2016; Souque et al., 2019).

## 524 *5.3 Relationship between the geometry of SSRS structures and structural permeability within a SRS* 525 *fault zone*

526 The results of our DFN models highlight the effects of fracture intensity variations on the magnitude  
527 and orientation of the **K** principal components across the GFZ.

- (i) The overall variation in permeability is related to an increase of total fracture intensity  $P_{32}$  from  $3.5 \text{ m}^2/\text{m}^3$  (background intensity) up to  $14.4 \text{ m}^2/\text{m}^3$  across the GFZ outcrop (Fig. 10). The computed increase of c. one order of magnitude in total intensity  $P_{32}$  of fractures longer than  $10^{-1} \text{ m}$  leads to a relative increase of one order of magnitude of the principal maximum ( $K_1$ ) permeability. In all cases, the shape of  $\mathbf{K}$  tensor is strongly oblate ( $K_1 \approx K_2 \gg K_3$ ; Fig. 9c). The magnitude of the  $\mathbf{K}$  principal components increases linearly with the computed total  $P_{32}$ , despite the different assemblage of fracture sets and related intensity characterising each DFN model (Fig. 10, Table 4). Accordingly, the ratios between principal components ( $K_1/K_2$ ,  $K_1/K_3$ ) are almost constant despite the different assemblages.
- (ii) The average orientation of the  $K_1$  principal component is generally subparallel to the intersection directions of the dominant fracture sets (Fig. 9c; Table 3; Supplementary Data S4). The variability of  $K_1$  orientation (cluster vs. girdle distribution) depends on three main factors: (1) the variability in orientation of each fracture set (K-fisher parameters and standard deviations for uniform distributions; Table 2); (2) the similarity of the average orientation of intersecting fracture sets (Table 2), and (3) the relative frequency of fracture sets in each model (Table 3). A well-defined cluster distribution of  $K_1$  orientation occurs when the model is characterised by either two predominant fracture sets (e.g. Set D and E in model HW\_1) or fracture sets exhibiting similar orientations and relative frequencies (e.g. Set B, C and E in model HW\_3). Girdle distributions are, instead, promoted when fracture sets characterised by dissimilar average orientations and a large statistical variation have comparable relative frequency (e.g. Sets B, C, D and E in model FW\_1; Fig. 9c; Table 3; Supplementary Data S4).
- (iii) The asymmetric development of the GFZ damage zone suggests that, even though the magnitude of the  $\mathbf{K}$  components may be comparable throughout the fault zone, the

hanging wall damage zone could be the principal conduit for fault-parallel fluid-flow given the larger volumetric extension compared to the footwall damage zone (Fig. 7c).

- (iv) As observed in many other geological settings, fracture clusters (Set A) may form highly permeable preferential pathways for the flow of fluids derived from either deeper crustal levels (Souque et al., 2019), or surficial, meteoric conditions (Place et al., 2016; McCaffrey et al., 2020).

The structural permeability within the GFZ are particularly enhanced in the hanging wall damage zone, where the direction of maximum permeability ( $K_1$ ) is steered by the intersection direction of the dominant fracture sets therein. The resulting anisotropic permeability and the  $K_1/K_3$  permeability ratio both indicate that the GFZ acts as a combined conduit-barrier favouring fault-parallel fluid-flow rather than fault-perpendicular flow.

#### *5.4 Fault zone bulk permeability*

The fault zone bulk permeability results from the sum of the matrix permeability of the deformed host rock within the fault zone and the superimposed structural permeability related to the meso-scale fracture network. Previous investigations of the GFZ focussed on the in-situ characterisation of the fault rocks matrix permeability (Ceccato et al., 2021). At odds with what would be commonly expected (cf. Bruhn et al., 1994; Caine et al., 1996; Evans et al., 1997; Caine and Forster, 1999; Rawling et al., 2001), the matrix permeability of fault rocks measured by air-minipermeametry (Table 1) is larger than the damage zone structural permeability obtained by DFN modelling (Table 4) under the adopted boundary conditions. The permeability values measured by air-minipermeametry and DFN modelling refer to significantly different sampled volumes ( $\sim\text{cm}^3$  in air-minipermeametry,  $125\text{ m}^3$  for DFN modelling). Therefore, the comparison of permeability values retrieved from these two different methods may be problematic and a straightforward correlation would require dedicated analyses which go beyond the scope of the present paper. However, in terms of relative permeability changes with respect to the undeformed host rock, permeability measurements with air-

578 minipermeametry have revealed that the gouge and cataclasite (matrix) permeability is generally four  
579 orders of magnitude larger than the host rock permeability (measured parallel to the fault plane, Table  
580 1) (Ceccato et al., 2021). In the same way, DFN models suggest that the increase of fault-related  
581 fractures across the GFZ leads to a relative increase in (structural) permeability of one order of  
582 magnitude with respect to the area outside the GFZ damage zone.

583 The occurrence of PSSs and microstructurally anisotropic fault gouges within the fault cores lead to  
584 an oblate permeability tensor, whose major principal axes are oriented parallel to the fault planes  
585 (Faulkner and Rutter, 1998; Zhang and Tullis, 1998). Similarly, petrophysical and microstructural  
586 analyses of the matrix permeability related to microfractures in the damage zone of large-scale fault  
587 zones within crystalline rocks suggest the occurrence of a strongly oblate matrix permeability tensor  
588 whose minimum component ( $K_3$ ) is oriented perpendicular to the main fault planes (Rempe et al.,  
589 2018; Gomila et al., 2021). Our DFN models consistently indicate that the minimum principal  
590 component  $K_3$  of the structural permeability related to meso-scale fractures within the damage zone  
591 is also oriented normal to the main fault planes. The values of  $K_1$  and  $K_3$  within the damage zone  
592 usually do not differ more than one order of magnitude (Fig. 7b). The maximum and minimum  
593 components of the (matrix) permeability tensor within the fault core, however, are expected to differ  
594 by up to four orders of magnitude (Faulkner and Rutter, 1998).

595 Considering the linear relationship between total fracture intensity and the  $\mathbf{K}$  components, the  
596 structural permeability within the damage zone probably decreases following a power-law function  
597 similar to that observed for the fracture  $P_{10}$  intensity moving away from the “high-strain” fault cores  
598 (Figs. 8, 10). However, this is based on a rather limited dataset of permeability data and a more  
599 systematic and detailed characterisation of fracture intensity, effective aperture and related  
600 permeability would be necessary to fully validate our hypothesis. Such a validation, however, would  
601 go well beyond the scope of the present paper.

602 In summary, the bulk (matrix + structural) permeability of an SRS fault zone is expected to be  
603 characterised by a strongly oblate permeability tensor, with the minimum permeability component  
604 ( $K_3$ ) perpendicular to the main fault plane. Instead, the direction of the maximum permeability  
605 component ( $K_1$ ) is controlled by the intersection direction of the dominant meso-scale fracture sets.  
606 Speculatively, matrix permeability and structural permeability likely vary following different trends  
607 (negative exponential and decreasing power-law, respectively) with increasing distance from the fault  
608 core(s) (cf. Mitchell and Faulkner, 2012). Consequently, structural permeability is expected to control  
609 the permeability of the whole fault zone over larger distances compared to matrix permeability related  
610 to micro-fracturing, in terms of both orientation and magnitude of the bulk  $\mathbf{K}$  principal components.

#### 611 *5.5 The fractured crystalline basement reservoir of the Rolvsnes granodiorite*

612 All fracture sets adopted in the computation of the DFN models have identical fracture apertures.  
613 Therefore, results of the DFN modelling represent the structural permeability of the fractured  
614 crystalline basement in its actual, surficial conditions. During the local geological evolution, the  
615 sequence of fracturing events, the different tectonic stresses and fluid-rock interaction processes  
616 affecting each fracture set may have led to different permeabilities, which are not captured by the  
617 DFN modelling. Indeed, previous field structural analyses have identified different fracture sets in  
618 the Rolvsnes granodiorite that are genetically related to tectonic events of different ages and  
619 characterised by different fracture apertures and mineral infillings (Scheiber et al., 2016; Scheiber  
620 and Viola, 2018). As introduced above, the Rolvsnes granodiorite is characterised by three main  
621 classes of fracture sets (Scheiber and Viola, 2018): (i) pre-Permian mineralised veins and minor  
622 faults; (ii) fault-related fractures; (iii) post-faulting fracture clusters. Sets B and C generally display  
623 orientations similar to the mineralised veins and shear fractures related to pre-Permian brittle  
624 deformation (pre-Permian veins and shear fractures; Scheiber and Viola, 2018). Their intensity is  
625 almost constant across the entire GFZ outcrop (Fig 7a, c). The orientation of Set C suggests that this  
626 set is probably related to the NE-dipping “pegmatitic greisens” identified by Scheiber and Viola  
627 (2018). Further analyses are needed to understand the origin of Set D, whose fractures are similar in

orientation to pre-Permian structures but show a variable intensity across the GFZ. Given that most of these fractures and veins are sealed by mineral infillings, the contribution of mineralised veins and shear fractures of Set B-C (and D?) to the overall current permeability of the fractured basement is likely limited (Scheiber and Viola, 2018). Set E fractures are generally oriented parallel to the main fault plane, their intensity varies as a function of the distance from the identified fault cores of the GFZ. These characteristics suggest that Set E fractures may have developed coevally with the GFZ, i.e. during the Permian-to-Early Jurassic rifting stage (Viola et al., 2016; Scheiber and Viola, 2018). Set A fractures are organized in fracture clusters composed of steeply dipping NE-SW- and N-S-trending fractures. Their orientation and the field association with alteration zone suggests that Set A fracture clusters belong to the N-S-trending structures related to the Early Cretaceous rifting stage (Viola et al., 2016; Fredin et al., 2017b). In this case, the permeability of the fractured Rolvsnes granodiorite would be mainly controlled by fault-related Set E and clustered Set A fractures (Ceccato et al., 2021). Further field analyses aimed at the characterisation of fracture aperture and mineral infilling of each fracture set are required for more detailed modelling of the permeability evolution during the deformation history of the Rolvsnes granodiorite.

The crystalline basement of Bømlo exposes a composite network of fracture clusters and fault zones (Gabrielsen and Braathen, 2014; Scheiber et al., 2015, 2016; Scheiber and Viola, 2018; Ceccato et al., 2021). In such fractured crystalline basement, major fault zones are expected to act as barriers to fluid flow in the direction normal to the fault orientation, creating “fault-bounded polyhedral domains”, where fluid flow is promoted parallel to the fault planes within fault damage zones but, at the same time, it is limited perpendicularly to the fault planes by low-permeability fault cores (Ceccato et al., 2021). Fracture clusters, cutting across pre-existing fault zones, may break the “seal” provided by low-permeability fault cores, creating viable conduits for fluid flow, increasing the connectivity of fracture networks within fractured crystalline basement units (Ogata et al., 2014; Place et al., 2016; Souque et al., 2019) and increase the basement connectivity.



## 6. Conclusions

We present an integrated VOM-DFN workflow to quantify variations of fracture intensity across a fault zone and compute changes in structural permeability changes related to SSRS fracture patterns within an SRS fault zone. The results have implications for: (i) the characterisation of SSRS fracture patterns within SRS fault zones in crystalline basement units, which are usually impossible to detect and analyse at the meso-scale by indirect geophysical methods; (ii) the quantification of the relationships between SSRS fracture patterns and the related structural permeability variations, (iii) the understanding of the spatial variation of petrophysical and structural properties of REV fault zones adopted in reservoir modelling. In detail:

- (a) The GFZ outcrop displays a complex internal architecture including two overlapping fault strands, each with a discrete core, sandwiching an Internal Damage Zone and both embedded within an asymmetric damage zone, mainly developed in the hanging wall. The  $P_{10}$ - $P_{32}$  intensity of fracture Set E, related to the main fault planes, varies more rapidly in the footwall than in the hanging wall, decreasing according to a negative power-law function moving away from the closest fault core(s).
- (b) The average structural permeability resulting from the DFN modelling of the SSRS fracture patterns within the damage zone of an SRS fault zone ranges between 0.01 and 0.14 mD, reaching local maximum values as high as 0.4 mD. The magnitude and anisotropy of the  $\mathbf{K}$  principal components depend linearly on the total fracture intensity of the fractured domain, whereas the orientation of the  $\mathbf{K}$  principal components depends on the intersection direction between the most abundant fracture sets. Thus, SSRS fracture networks represent a preferential conduit for fault-parallel fluid-flow within the damage zone of a SRS fault zone, especially along a direction parallel to the intersection of the dominant fracture sets.
- (c) The approach combining structural analysis and DFN modelling suggests that it is reasonable to expect a power-law decreasing trend for the structural permeability within the damage zone moving away from high strain zones. Thus, the structural permeability is expected to control



a fault zone bulk permeability over larger distances when compared to the likely exponentially-decreasing matrix permeability related to micro-fracturing within the damage zone (Mitchell and Faulkner, 2009, 2012).

In conclusion, the analysis of (virtual) meso-scale outcrops yields invaluable qualitative and quantitative observations that can help to understand and quantitatively upscale the role of SSRS fracture patterns in controlling the permeability structure of a major SRS fault zone. The results of stochastic DFN modelling based on inputs retrieved from VOM structural analysis can provide reliable first order estimates of the permeability in fractured crystalline basement.

## **Acknowledgments**

We acknowledge the use of the MOVE Software Suite granted by Petroleum Experts Limited through an Educational Institution Licence Agreement. We thank Golder Associates for providing the academic licences for FracMan 7.9. Our research work was funded by the still ongoing BASE 2 project (“Basement fracturing and weathering onshore and offshore Norway—Genesis, age, and landscape development” – Part 2), a research initiative launched and steered by the Geological Survey of Norway and supported by Equinor ASA, Aker BP ASA, Lundin Energy Norway AS, Spirit Energy Norway AS, Wintershall Dea Norge, and NGU. We thank all BASE colleagues for continuous discussion and constructive inputs. We thank A. Cilona and an anonymous reviewer for constructive comments and inputs.

699 **Figure Captions**

700 **Figure 1.** Geological map of the northern Bømlo Island, including the island of Goddo and the  
701 location of the Goddo Fault Zone (GFZ) outcrop (modified after, Ceccato et al., 2021; Scheiber and  
702 Viola, 2018; Viola et al., 2016; NGU geological map of Norway 1:500000).

703 **Figure 2.** (a) Simplified geological map of the Goddo Fault Zone drawn upon the orthophotos  
704 retrieved from SfM elaboration of UAV imagery and the LiDAR digital elevation model. Dashed  
705 black lines define the continuation of fracture clusters with alteration zones inferred from their  
706 topographic expression. (b) Perspective view and interpreted domains of the GFZ outcrop  
707 perpendicular to the cross-section A-A' (from CloudCompare). (c) Geological cross-section along  
708 the A-A' profile of the GFZ outcrop. (Modified after Ceccato et al., 2021). FW: Footwall; HW:  
709 Hanging wall; IDZ: Internal Damage Zone; nFC: norther Fault Core; PSS: Principal Slip Surface;  
710 sFC: southern Fault Core.

711 **Figure 3.** Main outcrops of the GFZ. (a) Outcrop of the southern Fault Core (sFC), showing the  
712 principal slip surface (PSS) and the above-lying composite fault core. (b) Outcrop of the northern  
713 Fault Core (nFC), showing the thick composite fault core characterised in detail by Viola et al. (2016)  
714 and Ceccato et al. (2021). (c) Outcrop displaying the association between a fracture cluster and the  
715 alteration zone (modified after Viola et al., 2016). (d) Stereonets of structural data collected in the  
716 field. The contoured poles stereonet includes the entire dataset of pole to fracture planes (equal area,  
717 lower hemisphere). The two stereonet on the bottom row show fracture planes associated with a  
718 lineation (slickenlines, “Slip planes”) and fracture planes associated with alteration zones (“Alteration  
719 zones”).

720 **Figure 4.** Methodological workflow adopted in this paper. See text for details regarding the steps of  
721 the procedure.

722 **Figure 5.** Virtual Outcrop Model of the Goddo Fault Zone as obtained from the SfM elaboration of  
723 the UAV-drone imagery and related structural interpretation and analyses performed in

724 CloudCompare. (a-e-i) Point cloud representing the VOM of the GFZ as visualised in CloudCompare.  
725 (b-f-j) Structural interpretation of the GFZ virtual outcrop showing the fault domains, including: the  
726 footwall (FW), hanging wall (HW), and Internal Damage Zone (IDZ), and the southern (sFC) and  
727 northern (nFC) fault cores. Fracture sets are also highlighted (Set A-E). (c-g-k) Virtual fracture planes  
728 resulting from the structural analyses and manual interpretation of fracture traces and fracture planes  
729 in CloudCompare. (d-h-l) Equal area, lower hemisphere stereonet presenting the contoured poles of  
730 virtual fracture planes interpreted in CloudCompare.

731 **Figure 6.** (a) Equal area, lower hemisphere stereonet presenting the total dataset of poles to virtual  
732 fracture planes as interpreted from VOM. (b) Equal area, lower hemisphere stereonet presenting the  
733 poles to fracture planes classified in Sets A-E and the number of planes for each set (from MOVE –  
734 Petex).

735 **Figure 7.** (a)  $P_{10}$  intensity profiles for Sets A and B, along the cross-section B-B' and C-C' of Fig.  
736 2a, respectively. The “first projected scanline” to which the X axis refers to is indicated in the  
737 Supplementary material (Supplement S1 – Set A-B). Fracture clusters are highlighted in the  $P_{10}$   
738 profile for Set A (light orange rectangles). Set B shows a rather constant  $P_{10}$  intensity. (b) Schematic  
739 cross-section of the GFZ along the A-A' profile of Fig. 2a showing the identified domains composing  
740 the GFZ on which the virtual scanlines adopted to quantify the local fracture intensity  $P_{10}$  of Sets C,  
741 D, and E are projected. (c) Diagram showing the variation of the fracture intensity  $P_{10}$  of Sets C, D,  
742 and E along the fault-perpendicular profile as reported in the schematic cross-section in (b). The  
743 locations of the modelled fault zone domains (FW\_1, FW\_2, FW\_3, sFC, IDZ, nFC, HW\_1, HW\_2,  
744 HW\_3) are also reported. See text for explanation.

745 **Figure 8.** Diagrams showing the variation of  $P_{10}$  intensity of Set D and Set E with increasing distance  
746 from fault cores and high-intensity domains. The “southernmost projected scanline” to which the X  
747 axis refers to is indicated in the Supplementary material (Supplement S1 – Set C). Two intensity  
748 profiles are plotted for Set E, representing the variation of  $P_{10}$  with increasing distance from sFC into

749 the footwall damage zone (orange dotted line – Set E footwall), and with increasing distance from  
750 nFC into the hanging wall damage zone (orange dashed line – Set E hanging wall). The distance for  
751 Set D is calculated (southward) from the point showing the maximum intensity ( $P_{10} = 5.5 \text{ m}^{-1}$ ) on the  
752 profile of Fig. 7c. (a) Linear-logarithmic plot of distance vs. intensity. A straight fitting curve would  
753 define a negative exponential trend for  $P_{10}$  intensity. (b) Logarithmic-Logarithmic plot of distance vs.  
754 intensity. A straight fitting curve would define a power-law decreasing trend for  $P_{10}$  intensity.

755 **Figure 9.** (a) Diagram showing the  $P_{32}$  intensities for each fracture Set (A-E) adopted for each DFN  
756 model (FW\_1, FW\_2, FW\_3, sFC, IDZ, nFC, HW\_1, HW\_2, HW\_3) and the total  $P_{32}$  resulting from  
757 DFN modelling. (b) Diagram showing the magnitude (vertical axis on the left) and the relative ratio  
758 ( $K_1/K_n$  with  $n=2,3$ ; vertical axis on the right) of the principal components of the permeability tensor  
759 ( $K_1 > K_2 > K_3$ ) resulting from the DFN model computations. The average permeability values (dots and  
760 squares) are reported along with their statistical variation ( $\pm 2\sigma$ ). (c) Equal area, lower hemisphere  
761 stereonets of the orientation of the principal components ( $K_1, K_2, K_3$ ) of the permeability tensor and  
762 the main orientation of the fracture planes for Sets A-E.

763 **Figure 10.** Diagram showing the linear relationship between the input  $P_{32}$  total intensity in each DFN  
764 model and the magnitude of the  $\mathbf{K}$  principal components. The permeability ratios ( $K_1/K_n$  with  $n=2,3$ )  
765 show almost constant values independent from the total fracture intensity.

766

767

768 **Tables**

769

Matrix Permeability from air-minipermeameter (mD)			
Rock type	Min	Max	Average
Granodiorite	0.030	254.887	48.429
Principal Slip Surface	0.047	58.653	43.995
Cataclasite (Strike //)	1.549	3730.449	368.762
Gouge (Strike //)	1.523	400.019	96.494

770 **Table 1.** Permeability data of fault rocks from Ceccato et al. (2021). See text for explanation.

771

Fracture set parameters													
Set	Dip	Dip dir	K Fisher	N	Uniform distribution		Length distribution parameters						
					Std Dev Trend	Std Dev Plunge	Min (m)	Max (m)	Avg. (m)	Distrib. Type	Lambda	Aperture (m)	Shape
Set A	85	286	1.34	781	11	5	0.09	5.06	0.84	Exp	-1.543	0.0001	Hexagonal
Set B	89	357	1.26	269	6	5	0.11	3.54	0.76	Exp	-1.735	0.0001	Hexagonal
Set C	46	40	48	310	-	-	0.07	3.67	0.86	Exp	-1.366	0.0001	Hexagonal
Set D	65	230	23.61	177	-	-	0.08	4.19	0.71	Exp	-1.451	0.0001	Hexagonal
Set E	60	75	36.86	269	-	-	0.07	4.67	0.83	Exp	-1.24	0.0001	Hexagonal

772

773 **Table 2.** Fracture set parameters (orientation, length distribution) as retrieved from the VOM  
774 analyses.

775

	Model	Set A	Set B	Set C	Set D	Set E	X (m)
<b>P<sub>10</sub> (m<sup>-4</sup>)</b>	FW_1	-	1.5	0.5	0.7	0.5	32.2
	FW_2	-	1.5	1.2	0.7	1	47.3
	FW_3	-	1.5	1.5	0.7	1.5	52.1
	sFC	-	1.5	2.1	2.8	5.7	54.6
	IDZ	-	1.5	1.8	2	2	60
	nFC	-	1.5	1.8	2.5	4.5	64.7
	HW_1	-	1.5	1.5	5.5	3.3	68.2
	HW_2	-	1.5	1.5	2.2	2.2	72.7
	HW_3	-	1.5	1.5	-	1.5	79.1
	Clus	7	1.5	1	-	-	85
<b>P<sub>10</sub>-P<sub>32</sub> Conversion factors</b>		1.0831	0.9655	1.4571	1.1337	1.1818	
<b>P<sub>32</sub> (m<sup>2</sup>/m<sup>3</sup>)</b>							<b>Total P<sub>32</sub></b>
	FW_1	-	1.45	0.73	0.79	0.59	3.54
	FW_2	-	1.45	1.75	0.79	0.00	5.15
	FW_3	-	0.00	0.00	0.00	0.00	6.19
	sFC	-	1.45	3.06	3.17	6.74	14.40
	IDZ	-	1.45	2.62	2.27	2.36	8.68
	nFC	-	0.00	0.00	0.00	0.00	12.20
	HW_1	-	1.45	2.19	6.24	3.90	13.74
	HW_2	-	0.00	0.00	0.00	0.00	8.70
	HW_3	-	1.45	2.19	-	1.77	5.39
	Clus	7.58	1.45	1.46	-	-	11.20
<b>Relative proportion of total fracture in DFN models (%)</b>	FW_1	-	43	18	25	14	
	FW_2	-	31	31	18	20	
	FW_3	-	26	33	15	26	
	sFC	-	11	20	26	42	
	IDZ	-	18	28	30	24	
	nFC	-	13	20	28	39	
	HW_1	-	11	14	51	24	
	HW_2	-	11	20	26	42	
	HW_3	-	31	39	-	31	
	Clus	65	16	19	-	-	

776

777 **Table 3.** DFN model set-up. Fracture set P<sub>10</sub>-P<sub>32</sub> intensities and related P<sub>10</sub>-P<sub>32</sub> conversion factors

778 adopted in the DFN model computations.

779

Model		Permeability Tensor components (mD)						
		P <sub>32</sub> (m <sup>2</sup> /m <sup>3</sup> )	P <sub>33</sub> (m <sup>3</sup> /m <sup>3</sup> )	K <sub>1</sub>	K <sub>2</sub>	K <sub>3</sub>	K <sub>1</sub> /K <sub>3</sub>	K <sub>1</sub> /K <sub>2</sub>
FW_1	Avg	3.5379	0.0004	0.031	0.027	0.013	2.43	1.14
	Std dev	0.4655	0.0001	0.008	0.007	0.003		
	Min	1.8585	0.0001	0.013	0.012	0.005		
	Max	5.5815	0.0006	0.117	0.108	0.033		
	Dir/DipDir			58/278	41/123	13/024		
FW_2	Avg	5.1480	0.0005	0.046	0.040	0.018	2.56	1.16
	Std dev	0.5620	0.0001	0.010	0.009	0.004		
	Min	3.3216	0.0003	0.022	0.019	0.008		
	Max	7.1633	0.0009	0.126	0.121	0.046		
	Dir/DipDir			46/278	35/145	25/036		
FW_3	Avg	6.1896	0.0006	0.056	0.048	0.020	2.74	1.15
	Std dev	0.6289	0.0001	0.011	0.010	0.005		
	Min	4.0665	0.0003	0.026	0.023	0.008		
	Max	8.7333	0.0010	0.137	0.126	0.050		
	Dir/DipDir			47/275	29/150	29/042		
sFC	Avg	14.3977	0.0014	0.127	0.116	0.044	2.89	1.10
	Std dev	1.0607	0.0001	0.017	0.016	0.007		
	Min	9.9835	0.0009	0.066	0.060	0.024		
	Max	18.5376	0.0020	0.239	0.222	0.089		
	Dir/DipDir			30/313	49/181	25/059		
IDZ	Avg	8.6797	0.0009	0.075	0.068	0.031	2.42	1.11
	Std dev	0.7605	0.0001	0.014	0.013	0.006		
	Min	5.7784	0.0005	0.039	0.036	0.015		
	Max	11.3742	0.0013	0.411	0.401	0.070		
	Dir/DipDir			28/304	55/170	22/047		
nFC	Avg	12.2047	0.0012	0.107	0.097	0.039	2.72	1.10
	Std dev	0.9558	0.0001	0.016	0.015	0.007		
	Min	8.4710	0.0008	0.061	0.056	0.020		
	Max	16.4494	0.0018	0.294	0.270	0.077		
	Dir/DipDir			32/310	48/176	24/057		
HW_1	Avg	13.7397	0.0014	0.121	0.104	0.050	2.44	1.16
	Std dev	1.0137	0.0001	0.016	0.014	0.007		
	Min	9.8992	0.0009	0.069	0.059	0.029		
	Max	17.7589	0.0019	0.206	0.175	0.090		
	Dir/DipDir			17/320	72/153	13/053		
HW_2	Avg	8.6993	0.0009	0.075	0.067	0.032	2.36	1.12
	Std dev	0.7618	0.0001	0.013	0.011	0.006		
	Min	5.8951	0.0005	0.041	0.037	0.015		
	Max	11.9684	0.0013	0.165	0.158	0.070		
	Dir/DipDir			30/307	55/166	19/048		



HW_3	<b>Avg</b>	5.3886	0.0005		0.052	0.041	0.015	3.52	1.26
	<b>Std dev</b>	0.5986	0.0001		0.011	0.009	0.004		
	<b>Min</b>	3.4290	0.0003		0.024	0.018	0.006		
	<b>Max</b>	7.7426	0.0009		0.161	0.153	0.034		
				<b>Dir/DipDir</b>	50/256	17/144	34/042		
Clus	<b>Avg</b>	11.1982	0.0011		0.106	0.082	0.036	2.96	1.29
	<b>Std dev</b>	0.9297	0.0001		0.016	0.014	0.008		
	<b>Min</b>	7.6337	0.0007		0.058	0.043	0.013		
	<b>Max</b>	14.93.53	0.0017		0.246	0.224	0.094		
				<b>Dir/DipDir</b>	63/190	26/018	03/286		

780

781 **Table 4.** Results of the **K** permeability tensor computations from DFN modelling.

782

783 **References**

- 784 Achtziger-Zupančič, P., Loew, S., Hiller, A., Mariethoz, G., 2016. 3D fluid flow in fault zones of  
785 crystalline basement rocks (Poehla-Tellerhaeuser Ore Field, Ore Mountains, Germany).  
786 *Geofluids* 16, 688–710. <https://doi.org/10.1111/gfl.12192>
- 787 Achtziger-Zupančič, P., Loew, S., Mariéthoz, G., 2017. A new global database to improve predictions  
788 of permeability distribution in crystalline rocks at site scale. *Journal of Geophysical Research:*  
789 *Solid Earth* 122, 3513–3539. <https://doi.org/10.1002/2017JB014106>
- 790 Antonellini, M., Cilona, A., Tondi, E., Zambrano, M., Agosta, F., 2014. Fluid flow numerical  
791 experiments of faulted porous carbonates, Northwest Sicily (Italy). *Marine and Petroleum*  
792 *Geology* 55, 186–201. <https://doi.org/10.1016/j.marpetgeo.2013.12.003>
- 793 Bell, R.E., Jackson, C.A.L., Whipp, P.S., Clements, B., 2014. Strain migration during multiphase  
794 extension: Observations from the northern North Sea. *Tectonics* 33, 1936–1963.  
795 <https://doi.org/10.1002/2014TC003551>
- 796 Bense, V.F., Gleeson, T., Loveless, S.E., Bour, O., Scibek, J., 2013. Fault zone hydrogeology. *Earth-*  
797 *Science Reviews* 127, 171–192. <https://doi.org/10.1016/j.earscirev.2013.09.008>
- 798 Biber, K., Khan, S.D., Seers, T.D., Sarmiento, S., Lakshmikantha, M.R., 2018. Quantitative  
799 characterization of a naturally fractured reservoir analog using a hybrid lidar-gigapixel imaging  
800 approach. *Geosphere* 14, 710–730. <https://doi.org/10.1130/GES01449.1>
- 801 Bisdom, K., Nick, H.M., Bertotti, G., 2017. An integrated workflow for stress and flow modelling  
802 using outcrop-derived discrete fracture networks. *Computers and Geosciences* 103, 21–35.  
803 <https://doi.org/10.1016/j.cageo.2017.02.019>
- 804 Bruhn, R.L., Parry, W.T., Yonkee, W.A., Thompson, T., 1994. Fracturing and hydrothermal  
805 alteration in normal fault zones. *Pure and Applied Geophysics PAGEOPH* 142, 609–644.  
806 <https://doi.org/10.1007/BF00876057>

807 Caine, J.S., Evans, J.P., Forster, C.B., 1996. Fault zone architecture and permeability structure.  
808 Geology 24, 1025–1028. [https://doi.org/10.1130/0091-](https://doi.org/10.1130/0091-7613(1996)024<1025:FZAAPS>2.3.CO;2)  
809 7613(1996)024<1025:FZAAPS>2.3.CO;2

810 Caine, J.S., Forster, C.B., 1999. Fault zone architecture and fluid flow: Insights from field data and  
811 numerical modeling. AGU Geophysical Monograph 113, 101–127.  
812 <https://doi.org/10.1029/gm113p0101>

813 Ceccato, A., Viola, G., Tartaglia, G., Antonellini, M., 2021. In-situ quantification of mechanical and  
814 permeability properties on outcrop analogues of offshore fractured and weathered crystalline  
815 basement: Examples from the Rolvsnes granodiorite, Bømlo, Norway. Marine and Petroleum  
816 Geology 124. <https://doi.org/10.1016/j.marpetgeo.2020.104859>

817 Childs, C., Watterson, J., Walsh, J.J., 1995. Fault overlap zones within developing normal fault  
818 systems. Journal - Geological Society (London) 152, 535–549.  
819 <https://doi.org/10.1144/gsjgs.152.3.0535>

820 Choi, J.H., Edwards, P., Ko, K., Kim, Y.S., 2016. Definition and classification of fault damage zones:  
821 A review and a new methodological approach. Earth-Science Reviews 152, 70–87.  
822 <https://doi.org/10.1016/j.earscirev.2015.11.006>

823 Damsleth, E., Sangolt, V., Aamodt, G., 1998. Sub-seismic faults can seriously affect fluid flow in the  
824 Njord field off Western Norway - A stochastic fault modeling case study. Proceedings - SPE  
825 Annual Technical Conference and Exhibition 1999-Septe, 295–304.  
826 <https://doi.org/10.2523/49024-ms>

827 Dershowitz, W.S., Herda, H.H., 1992. Interpretation of fracture spacing and intensity.

828 Dewez, T.J.B., Girardeau-Montaut, D., Allanic, C., Rohmer, J., 2016. Facets : A cloudcompare plugin  
829 to extract geological planes from unstructured 3d point clouds. International Archives of the  
830 Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives 41, 799–

831 804. <https://doi.org/10.5194/isprsarchives-XLI-B5-799-2016>

832 Evans, J.P., Forster, C.B., Goddard, J. V., 1997. Permeability of fault-related rocks, and implications  
833 for hydraulic structure of fault zones. *Journal of Structural Geology* 19, 1393–1404.  
834 [https://doi.org/10.1016/S0191-8141\(97\)00057-6](https://doi.org/10.1016/S0191-8141(97)00057-6)

835 Faulkner, D.R., 2004. A model for the variation in permeability of clay-bearing fault gouge with  
836 depth in the brittle crust. *Geophysical Research Letters* 31.  
837 <https://doi.org/10.1029/2004GL020736>

838 Faulkner, D.R., Jackson, C.A.L., Lunn, R.J., Schlische, R.W., Shipton, Z.K., Wibberley, C.A.J.,  
839 Withjack, M.O., 2010. A review of recent developments concerning the structure, mechanics  
840 and fluid flow properties of fault zones. *Journal of Structural Geology* 32, 1557–1575.  
841 <https://doi.org/10.1016/j.jsg.2010.06.009>

842 Faulkner, D.R., Mitchell, T.M., Healy, D., Heap, M.J., 2006. Slip on “weak” faults by the rotation of  
843 regional stress in the fracture damage zone. *Nature* 444, 922–925.  
844 <https://doi.org/10.1038/nature05353>

845 Faulkner, D.R., Rutter, E.H., 1998. The gas permeability of clay-bearing fault gouge at 20 degrees C.  
846 147, 147–156.

847 Fossen, H., Rotevatn, A., 2016. Fault linkage and relay structures in extensional settings-A review.  
848 *Earth-Science Reviews* 154, 14–28. <https://doi.org/10.1016/j.earscirev.2015.11.014>

849 Fredin, O., Viola, G., Zwingmann, H., Sorlie, R., Bronner, M., Lie, J.E., Grandal, E.M., Muller, A.,  
850 Margreth, A., Vogt, C., Knies, J., 2017a. Correspondence: Reply to Challenges with dating  
851 weathering products to unravel ancient landscapes. *Nature Communications* 8, 1–2.  
852 <https://doi.org/10.1038/s41467-017-01468-6>

853 Fredin, O., Viola, G., Zwingmann, H., Sørli, R., Brønner, M., Lie, J.E., Grandal, E.M., Müller, A.,  
854 Margreth, A., Vogt, C., Knies, J., 2017b. The inheritance of a mesozoic landscape in western

855 Scandinavia. *Nature Communications* 8. <https://doi.org/10.1038/ncomms14879>

856 Gabrielsen, R.H., Braathen, A., 2014. Models of fracture lineaments - Joint swarms, fracture corridors  
857 and faults in crystalline rocks, and their genetic relations. *Tectonophysics* 628, 26–44.  
858 <https://doi.org/10.1016/j.tecto.2014.04.022>

859 Gee, D.G., Fossen, H., Henriksen, N., Higgins, A.K., 2008. From the early Paleozoic platforms of  
860 Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland. *Episodes* 31,  
861 44–51. <https://doi.org/10.18814/epiiugs/2008/v31i1/007>

862 Gomila, R., Arancibia, G., Nehler, M., Bracke, R., Morata, D., Cembrano, J., 2021. Quantitative  
863 anisotropies of palaeopermeability in a strike-slip fault damage zone: Insights from micro-CT  
864 analysis and numerical simulations. *Tectonophysics* 810, 228873.  
865 <https://doi.org/10.1016/j.tecto.2021.228873>

866 Hansberry, R.L., King, R.C., Holford, S.P., Hand, M., Debenham, N., 2021. How wide is a fault  
867 damage zone? Using network topology to define the effects of large faults on natural fracture  
868 networks. *Journal of Structural Geology* 146, 104327. <https://doi.org/10.1016/j.jsg.2021.104327>

869 Hardebol, N.J., Maier, C., Nick, H., Geiger, S., Bertotti, G., Boro, H., 2015. Multiscale fracture  
870 network characterization and impact on flow: A case study on the Latemar carbonate platform.  
871 *Journal of Geophysical Research: Solid Earth* 120, 8197–8222.  
872 <https://doi.org/10.1002/2015JB011879>

873 Healy, D., Rizzo, R.E., Cornwell, D.G., Farrell, N.J.C., Watkins, H., Timms, N.E., Gomez-Rivas, E.,  
874 Smith, M., 2017. FracPaQ: A MATLAB™ toolbox for the quantification of fracture patterns.  
875 *Journal of Structural Geology* 95, 1–16. <https://doi.org/10.1016/j.jsg.2016.12.003>

876 Johri, M., Zoback, M.D., Hennings, P., 2014. A scaling law to characterize fault-damage zones at  
877 reservoir depths. *AAPG Bulletin* 98, 2057–2079. <https://doi.org/10.1306/05061413173>

878 Lei, Q., Latham, J.P., Tsang, C.F., 2017. The use of discrete fracture networks for modelling coupled

879 geomechanical and hydrological behaviour of fractured rocks. *Computers and Geotechnics* 85,  
880 151–176. <https://doi.org/10.1016/j.compgeo.2016.12.024>

881 Lüschen, E., Görne, S., von Hartmann, H., Thomas, R., Schulz, R., 2015. 3D seismic survey for  
882 geothermal exploration in crystalline rocks in Saxony, Germany. *Geophysical Prospecting* 63,  
883 975–989. <https://doi.org/10.1111/1365-2478.12249>

884 Marchesini, B., Garofalo, P.S., Menegon, L., Mattila, J., Viola, G., 2019. Fluid-mediated, brittle-  
885 ductile deformation at seismogenic depth - Part 1: Fluid record and deformation history of fault  
886 veins in a nuclear waste repository (Olkiluoto Island, Finland). *Solid Earth* 10, 809–838.  
887 <https://doi.org/10.5194/se-10-809-2019>

888 Martinelli, M., Bistacchi, A., Mittempergher, S., Bonneau, F., Balsamo, F., Caumon, G., Meda, M.,  
889 2020. Damage zone characterization combining scan-line and scan-area analysis on a km-scale  
890 Digital Outcrop Model: The Qala Fault (Gozo). *Journal of Structural Geology* 140, 104144.  
891 <https://doi.org/10.1016/j.jsg.2020.104144>

892 McCaffrey, K.J.W., Holdsworth, R.E., Pless, J., Franklin, B.S.G., Hardman, K., 2020. Basement  
893 reservoir plumbing: fracture aperture, length and topology analysis of the Lewisian Complex,  
894 NW Scotland. *Journal of the Geological Society*.  
895 <https://doi.org/https://doi.org/10.1144/jgs2019-143> This

896 Mitchell, T.M., Faulkner, D.R., 2012. Towards quantifying the matrix permeability of fault damage  
897 zones in low porosity rocks. *Earth and Planetary Science Letters* 339–340, 24–31.  
898 <https://doi.org/10.1016/j.epsl.2012.05.014>

899 Mitchell, T.M., Faulkner, D.R., 2009. The nature and origin of off-fault damage surrounding strike-  
900 slip fault zones with a wide range of displacements: A field study from the Atacama fault system,  
901 northern Chile. *Journal of Structural Geology* 31, 802–816.  
902 <https://doi.org/10.1016/j.jsg.2009.05.002>

- 903 Nelson, R.A., 2001. Geologic Analysis of naturally fractured reservoirs.
- 904 O'Hara, A.P., Jacobi, R.D., Sheets, H.D., 2017. Predicting the width and average fracture frequency  
905 of damage zones using a partial least squares statistical analysis: Implications for fault zone  
906 development. *Journal of Structural Geology* 98, 38–52.  
907 <https://doi.org/10.1016/j.jsg.2017.03.008>
- 908 Oda, M., 1988. A method for evaluating the representative elementary volume based on joint survey  
909 of rock masses. *Canadian Geotechnical Journal*. <https://doi.org/10.1139/t88-049>
- 910 Oda, M., 1985. Permeability tensor for discontinuous rock masses. *Géotechnique* 483–495.
- 911 Ogata, K., Senger, K., Braathen, A., Tveranger, J., 2014. Fracture corridors as seal-bypass systems in  
912 siliciclastic reservoir-cap rock successions: Field-based insights from the Jurassic Entrada  
913 Formation (SE Utah, USA). *Journal of Structural Geology* 66, 162–187.  
914 <https://doi.org/10.1016/j.jsg.2014.05.005>
- 915 Ostermeijer, G.A., Mitchell, T.M., Aben, F.M., Dorsey, M.T., Browning, J., Rockwell, T.K., Fletcher,  
916 J.M., Ostermeijer, F., 2020. Damage zone heterogeneity on seismogenic faults in crystalline  
917 rock; a field study of the Borrego Fault, Baja California. *Journal of Structural Geology* 137,  
918 104016. <https://doi.org/10.1016/j.jsg.2020.104016>
- 919 Peacock, D.C.P., Sanderson, D.J., 2018. Structural analyses and fracture network characterisation:  
920 Seven pillars of wisdom. *Earth-Science Reviews* 184, 13–28.  
921 <https://doi.org/10.1016/j.earscirev.2018.06.006>
- 922 Place, J., Géraud, Y., Diraison, M., Herquel, G., Edel, J.B., Bano, M., Le Garzic, E., Walter, B., 2016.  
923 Structural control of weathering processes within exhumed granitoids: Compartmentalisation of  
924 geophysical properties by faults and fractures. *Journal of Structural Geology* 84, 102–119.  
925 <https://doi.org/10.1016/j.jsg.2015.11.011>
- 926 Prando, F., Menegon, L., Anderson, M., Marchesini, B., Mattila, J., Viola, G., 2020. Fluid-mediated,

927 brittle-ductile deformation at seismogenic depth - Part 2: Stress history and fluid pressure  
 928 variations in a shear zone in a nuclear waste repository (Olkiluoto Island, Finland). *Solid Earth*  
 929 11, 489–511. <https://doi.org/10.5194/se-11-489-2020>

930 Rawling, G.C., Goodwin, L.B., Wilson, J.L., 2001. Internal architecture, permeability structure, and  
 931 hydrologic significance of contrasting fault-zone types. *Geology* 29, 43–46.  
 932 [https://doi.org/10.1130/0091-7613\(2001\)029<0043:IAPSAH>2.0.CO;2](https://doi.org/10.1130/0091-7613(2001)029<0043:IAPSAH>2.0.CO;2)

933 Rempe, M., Mitchell, T.M., Renner, J., Smith, S.A.F., Bistacchi, A., Di Toro, G., 2018. The  
 934 Relationship Between Microfracture Damage and the Physical Properties of Fault-Related  
 935 Rocks: The Gole Larghe Fault Zone, Italian Southern Alps. *Journal of Geophysical Research:*  
 936 *Solid Earth* 123, 7661–7687. <https://doi.org/10.1029/2018JB015900>

937 Rizzo, R.E., Healy, D., De Siena, L., 2017. Benefits of maximum likelihood estimators for fracture  
 938 attribute analysis: Implications for permeability and up-scaling. *Journal of Structural Geology*  
 939 95, 17–31. <https://doi.org/10.1016/j.jsg.2016.12.005>

940 Romano, V., Bigi, S., Carnevale, F., Hyman, J.D.H., Karra, S., Valocchi, A.J., Tartarello, M.C.,  
 941 Battaglia, M., 2020. Hydraulic characterization of a fault zone from fracture distribution. *Journal*  
 942 *of Structural Geology* 104036. <https://doi.org/10.1016/j.jsg.2020.104036>

943 Savage, H.M., Brodsky, E.E., 2011. Collateral damage: Evolution with displacement of fracture  
 944 distribution and secondary fault strands in fault damage zones. *Journal of Geophysical Research:*  
 945 *Solid Earth* 116, 3405. <https://doi.org/10.1029/2010JB007665>

946 Scheiber, T., Fredin, O., Viola, G., Jarna, A., Gasser, D., Łapińska-Viola, R., 2015. Manual extraction  
 947 of bedrock lineaments from high-resolution LiDAR data: methodological bias and human  
 948 perception. *Gff* 137, 362–372. <https://doi.org/10.1080/11035897.2015.1085434>

949 Scheiber, T., Viola, G., 2018. Complex Bedrock Fracture Patterns: A Multipronged Approach to  
 950 Resolve Their Evolution in Space and Time. *Tectonics* 37, 1030–1062.



951 <https://doi.org/10.1002/2017TC004763>

952 Scheiber, T., Viola, G., Wilkinson, C.M., Ganerød, M., Skår, Ø., Gasser, D., 2016. Direct<sup>40</sup>Ar/<sup>39</sup>Ar  
953 dating of Late Ordovician and Silurian brittle faulting in the southwestern Norwegian  
954 Caledonides. *Terra Nova* 28, 374–382. <https://doi.org/10.1111/ter.12230>

955 Seers, T.D., Hodgetts, D., 2014. Comparison of digital outcrop and conventional data collection  
956 approaches for the characterization of naturally fractured reservoir analogues. *Geological*  
957 *Society Special Publication* 374, 51–77. <https://doi.org/10.1144/SP374.13>

958 Slagstad, T., Davidsen, B., Stephen Daly, J., 2011. Age and composition of crystalline basement rocks  
959 on the norwegian continental margin: Offshore extension and continuity of the Caledonian-  
960 Appalachian orogenic belt. *Journal of the Geological Society* 168, 1167–1185.  
961 <https://doi.org/10.1144/0016-76492010-136>

962 Smeraglia, L., Mercuri, M., Tavani, S., Pignalosa, A., Kettermann, M., Billi, A., Carminati, E., 2021.  
963 3D Discrete Fracture Network (DFN) models of damage zone fluid corridors within a reservoir-  
964 scale normal fault in carbonates: Multiscale approach using field data and UAV imagery. *Marine*  
965 *and Petroleum Geology* 126, 104902. <https://doi.org/10.1016/j.marpetgeo.2021.104902>

966 Souque, C., Knipe, R.J., Davies, R.K., Jones, P., Welch, M.J., Lorenz, J., 2019. Fracture corridors  
967 and fault reactivation: Example from the Chalk, Isle of Thanet, Kent, England. *Journal of*  
968 *Structural Geology* 122, 11–26. <https://doi.org/10.1016/j.jsg.2018.12.004>

969 Tanner, D.C., Buness, H., Igel, J., Günther, T., Gabriel, G., Skiba, P., Plenefisch, T., Gestermann, N.,  
970 Walter, T.R., 2019. Fault detection, Understanding Faults: Detecting, Dating, and Modeling.  
971 <https://doi.org/10.1016/B978-0-12-815985-9.00003-5>

972 Tartaglia, G., Viola, G., van der Lelij, R., Scheiber, T., Ceccato, A., Schönenberger, J., 2020. “Brittle  
973 structural facies” analysis: A diagnostic method to unravel and date multiple slip events of long-  
974 lived faults. *Earth and Planetary Science Letters* 545, 116420.

975        <https://doi.org/10.1016/j.epsl.2020.116420>

976    Thiele, S.T., Grose, L., Samsu, A., Micklethwaite, S., Vollgger, S.A., Cruden, A.R., 2017. Rapid,  
977        semi-automatic fracture and contact mapping for point clouds, images and geophysical data.  
978        *Solid Earth* 8, 1241–1253. <https://doi.org/10.5194/se-8-1241-2017>

979    Torabi, A., Alaei, B., Ellingsen, T.S.S., 2018. Faults and fractures in basement rocks, their  
980        architecture, petrophysical and mechanical properties. *Journal of Structural Geology* 117, 256–  
981        263. <https://doi.org/10.1016/j.jsg.2018.07.001>

982    Torabi, A., Ellingsen, T.S.S., Johannessen, M.U., Alaei, B., Rotevatn, A., Chiarella, D., 2020. Fault  
983        zone architecture and its scaling laws: where does the damage zone start and stop? *Geological*  
984        *Society, London, Special Publications* 496, 99–124. <https://doi.org/10.1144/sp496-2018-151>

985    Viola, G., Scheiber, T., Fredin, O., Zwingmann, H., Margreth, A., Knies, J., 2016. Deconvoluting  
986        complex structural histories archived in brittle fault zones. *Nature Communications* 7, 1–10.  
987        <https://doi.org/10.1038/ncomms13448>

988    Vo Thanh, H., Sugai, Y., Nguele, R., Sasaki, K., 2019. Integrated workflow in 3D geological model  
989        construction for evaluation of CO<sub>2</sub> storage capacity of a fractured basement reservoir in Cuu  
990        Long Basin, Vietnam. *International Journal of Greenhouse Gas Control* 90, 102826.  
991        <https://doi.org/10.1016/j.ijggc.2019.102826>

992    Wilson, C.E., Aydin, A., Karimi-Fard, M., Durlofsky, L.J., Sagy, A., Brodsky, E.E., Kreylos, O.,  
993        Kellogg, L.H., 2011. From outcrop to flow simulation: Constructing discrete fracture models  
994        from a LIDAR survey. *AAPG Bulletin* 95, 1883–1906. <https://doi.org/10.1306/03241108148>

995    Wilson, J.E., Chester, J.S., Chester, F.M., 2003. Microfracture analysis of fault growth and wear  
996        processes, Punchbowl Fault, San Andreas system, California. *Journal of Structural Geology* 25,  
997        1855–1873. [https://doi.org/10.1016/S0191-8141\(03\)00036-1](https://doi.org/10.1016/S0191-8141(03)00036-1)

998    Zhang, S., Tullis, T.E., 1998. The effect of fault slip on permeability and permeability anisotropy in

999 quartz gouge. *Tectonophysics* 295, 41–52. [https://doi.org/10.1016/S0040-1951\(98\)00114-0](https://doi.org/10.1016/S0040-1951(98)00114-0)

1000