



ARCHIVIO ISTITUZIONALE DELLA RICERCA

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:

Constraints upon fault zone properties by combined structural analysis of virtual outcrop models and discrete fracture network modelling / Ceccato, Alberto; Viola, Giulio; Antonellini, Marco; Tartaglia, Giulia; Ryan, Eric J.. - In: JOURNAL OF STRUCTURAL GEOLOGY. - ISSN 0191-8141. - STAMPA. - 152:(2021), pp. 104444.1-104444.18. [10.1016/j.jsg.2021.104444]

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.

(Article begins on next page)

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

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 Ceccato¹, Giulio Viola¹, Marco Antonellini¹, Giulia Tartaglia¹, Eric J. Ryan²

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

6 ²Norwegian 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 \mathbf{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 \mathbf{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

29 **1. Introduction**

30 Metamorphic and igneous crystalline basement rocks are characterised by a very low matrix
31 permeability ($<10^{-4}$ mD), which is related to an inherent low porosity (Achtziger-Zupančič et al.,
32 2017). Their bulk permeability is thus controlled by the so-called structural permeability, i.e. the
33 secondary permeability due to fractures and fault zones (Nelson, 2001). The permeability and
34 hydraulic properties of fault zones are, in turn, controlled by the fault zone structural architecture
35 (Caine et al., 1996). The geometrical arrangement, deformation intensity and size of fault zone
36 domains and brittle structural facies (*sensu* Tartaglia et al., 2020) control whether fault zones behave
37 as conduits or barriers to fluid flow (Bruhn et al., 1994; Faulkner et al., 2010; Bense et al., 2013).
38 Fault architectural elements include (i) the fault core(s), which localises most of the deformation
39 accommodated by fault zones, and (ii) the damage zone, defined as a zone of diffuse micro- to meso-
40 scale fractures surrounding the fault core. At the micro-scale, micro-fracturing and cataclasis affect
41 the matrix properties within fault zone domains, i.e. the bulk permeability of the rock (Evans et al.,
42 1997). The matrix permeability increases proportionally to the micro-fracture intensity within the
43 fault damage zone (Mitchell and Faulkner, 2012; Rempe et al., 2018; Gomila et al., 2021). Intense
44 cataclasis and fluid-rock interaction within fault cores may form fine-grained, phyllosilicate-rich and
45 low-permeability fault rocks (Faulkner, 2004). The main factors controlling fault structural
46 permeability are, instead, fracture intensity and connectivity within the meso-scale fracture networks
47 (Hardebol et al., 2015; Peacock and Sanderson, 2018). In this paper, the term *fracture intensity* refers
48 to both linear fracture intensity P_{10} (m^{-1}), expressed as the number N of fractures intersected by a 1D
49 survey scanline of length L ($P_{10} = N/L m^{-1}$), and the volumetric fracture intensity P_{32} (m^2/m^3), which
50 quantifies the total surface area of fractures within a given volume of rock (Dershowitz and Herda,
51 1992). Fracture intensity generally varies across faults/damage zones such that a detailed
52 quantification of the spatial variability of fracture intensity is necessary to evaluate the variation of
53 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.

79 Ultimately, the focus of this combined structural and modelling approach is to understand and
80 quantify the impact on the rock bulk permeability of variable intensities of SSRS fractures associated
81 with SRS fault zones. Our results have significant implications upon the understanding of the relative
82 variation of permeability (magnitude and orientation of maximum permeability) as a function of the
83 spatially variable intensity of meso-scale fractures close to large-scale fault zones in crystalline
84 basements (e.g. Mitchell and Faulkner, 2012). This is highly relevant as fractured crystalline
85 basement blocks are increasingly becoming the focus of many applied and theoretical studies, also
86 aiming at the sustainable exploitation of georesources (oil, mineral, heat and water) (Lüschen et al.,
87 2015; Achtziger-Zupančič et al., 2016; Ceccato et al., 2021), and at their characterisation as potential
88 sites for anthropogenic waste repositories (Marchesini et al., 2019; Vo Thanh et al., 2019; Prando et
89 al., 2020). The analysis of outcrop analogues of fractured crystalline basement and the
90 analytical/numerical workflow presented here make it possible to improve our understanding of the
91 spatial variation of the permeability tensor, which, in turn, can be of great importance to the
92 development of effective exploration and production strategies for unconventional reservoirs.

93

94 **2. Geological Settings**

95 The Goddo Fault Zone (GFZ) crops out along the southeastern coast of the Goddo Island (Bømlo,
96 Hordaland, Western Norway; Fig. 1). The fault zone cuts through the Rolvsnes granodiorite, a pre-
97 Scandian granitoid pluton (466 ± 3 Ma, U/Pb on zircon; Scheiber et al., 2016) intruding the
98 metamorphic units of the Caledonian Upper Allochthon (Gee et al., 2008; Slagstad et al., 2011;
99 Scheiber et al., 2016). The Rolvsnes granodiorite is cut across by a complex network of fractures and
100 fault zones, which records the prolonged brittle deformation history that unfolded during the post-
101 Caledonian orogenic collapse and subsequent multi-stage rifting of the northern North Sea (Scheiber
102 et al., 2016; Scheiber and Viola, 2018). The tectonic history of the area is only shortly summarized
103 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:

154 (i) a polished Principal Slip Surface (PSS), dipping $50^{\circ}/071^{\circ}$ with dip-slip, normal $50^{\circ}/070^{\circ}$
155 slickenlines; (ii) a 5-10 cm thick, massive, well-sorted clay-rich gouge layer, overlain by (iii) a 40-50
156 cm thick layer of consolidated cataclasite (Fig. 3a). The northern fault core (nFC in Fig. 2; outcrop
157 S_{3B} in Ceccato et al., 2021) includes: (i) a PSS dipping $56^{\circ}/079^{\circ}$, characterised by dip-slip slickenlines
158 suggesting normal, top-to-ENE kinematics; (ii) a 5-10 cm thick layer of massive, clay-rich gouge;
159 (iii) a 10 cm thick chlorite-bearing phyllonitic gouge, characterised by S-C' microstructures; (iv) a
160 ~2 m thick layer of cohesive cataclasite (Fig. 3b). According to the general scaling relationship
161 between fault core thickness and accommodated fault throw (e.g., Torabi and Berg, 2011) and
162 considering that the fault cores are up to 2 m thick, the GFZ may have accommodated a cumulative
163 normal throw in the order of several hundreds to a thousand meters. This estimate suggests that the
164 GFZ is a good example of an SRS fault zone (Ceccato et al., 2021). The fault zone is locally crosscut
165 by NNE-SSW-striking fracture clusters usually associated with alteration of the host granodiorite
166 (Figs. 2 and 3c) (Viola et al., 2016; Fredin et al., 2017b; Scheiber and Viola, 2018).

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

176 2.2 Fault rock bulk permeability and anisotropy

177 The petrophysical and geomechanical properties of the GFZ fault rocks have been characterised
178 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 m³) volume domain composed of 8000 REV of
283 125 m³ ($5 \times 5 \times 5$ 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 m³ 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 m³ 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

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

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

325 *4.1.1 Fracture set identification*

326 The orientations of the segmented fracture surfaces and fracture traces interpreted in CloudCompare
327 were plotted on stereographic projections in MOVE (Fig. 6). The total dataset of interpreted planes
328 includes more than 2300 fractures (Fig. 6a). Clusters of fracture orientations were manually selected
329 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 λ 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 m^{-1} (1.4 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 m^{-1} in the southern
392 GFZ outcrop up to a maximum of 5.5 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 m^{-1} and 4.5 m^{-1} close to the sFC and nFC, respectively. The IDZ is
397 characterised by variable intensity ranging between 1.2 and 1.9 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 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

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

405 *4.2 Discrete Fracture Network models*

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

410 The DFN models include (Figs. 7c-9; Table 3): (i) model FW_1, representing the crystalline basement
411 affected by background fracturing alone in the footwall of the GFZ; (ii) model FW_2, representing
412 the transition from background fracturing toward the footwall damage zone (Set E $P_{10} = 1 \text{ m}^{-1}$); (iii)
413 model FW_3, representing the footwall damage zone; (iv) model sFC, representing the damage zone
414 close to the southern fault core (max Set E intensity); (v) model IDZ, representing the Internal
415 Damage Zone; (vi) model nFC, representing damage zone close to the northern fault core; (vii) model
416 HW_1, representing the hanging wall damage zone affected by the maximum observed Set D
417 intensity; (viii) model HW_2, representing the intermediate portion of hanging wall damage zone;
418 (ix) model HW_3, representing the external portion of the hanging wall damage zone without the
419 contribution of Set D. Additionally, we have created a model targeting the permeability properties of
420 the crystalline basement affected by Set A fracture clusters (model Clus in Fig. 9a). The fracture sets,
421 the related P_{10} intensities and all the fracture parameters adopted for each model computation are
422 listed in Table 2 and 3. We assumed a constant mechanical fracture aperture of $100 \mu\text{m}$ for all the
423 fracture sets in the DFN models. The proportionality coefficients relating P_{10} with P_{32} and the adopted
424 P_{32} values for each fracture set in each DFN model are listed in Table 2 and plotted in Fig. 9a
425 (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 \mathbf{K} increase linearly with the computed total
452 P_{32} fracture intensity both within the GFZ and Set A clusters (Fig. 10).

453

454 **5. Discussion**

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

457 *5.1 Geometry of the Goddo Fault Zone*

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

- 462 (i) The GFZ is characterised by two distinct fault cores probably representing two fault
463 strands with a hard overlap, which have been activated coevally, as it can be inferred from
464 the same assemblage of structural facies with the same probable age in the two fault cores
465 (Viola et al., 2016; Ceccato et al., 2021). However, the limited exposure of the studied
466 outcrop does not allow to fully characterise the large-scale geometry of the GFZ. The two
467 fault strands can either represent two en-echelon segments of a larger-scale normal fault
468 or the same fault core embedding a very large damage zone lithon (the IDZ) (Childs et al.,
469 1995; Fossen and Rotevatn, 2016).
- 470 (ii) The intensity of the ENE-dipping Set E fractures varies from $<1 \text{ m}^{-1}$ 5 m from the main
471 fault zone to $\sim 6 \text{ m}^{-1}$ adjacent to the main fault cores. If fracture intensity in the most
472 external portions of the GFZ represents the “background” fracture intensity of Set E, we
473 define c. 1 m^{-1} as the limit between the background fracture intensity and the GFZ damage
474 zone (Choi et al., 2016; Torabi et al., 2020). The transition from background intensity
475 values to values $>1 \text{ m}^{-1}$ occurs in the footwall ~ 5 m from the southern fault core. In the
476 hanging wall, the transition to intensity values $<1 \text{ m}^{-1}$ occurs at >20 m from the nFC (Fig.
477 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 ~ 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 \mathbf{K} principal components across the GFZ.

- 528 (i) The overall variation in permeability is related to an increase of total fracture intensity
529 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.
530 10). The computed increase of c. one order of magnitude in total intensity P_{32} of fractures
531 longer than 10^{-1} m leads to a relative increase of one order of magnitude of the principal
532 maximum (K_1) permeability. In all cases, the shape of \mathbf{K} tensor is strongly oblate ($K_1 \approx$
533 $K_2 \gg K_3$; Fig. 9c). The magnitude of the \mathbf{K} principal components increases linearly with
534 the computed total P_{32} , despite the different assemblage of fracture sets and related
535 intensity characterising each DFN model (Fig. 10, Table 4). Accordingly, the ratios
536 between principal components (K_1/K_2 , K_1/K_3) are almost constant despite the different
537 assemblages.
- 538 (ii) The average orientation of the K_1 principal component is generally subparallel to the
539 intersection directions of the dominant fracture sets (Fig. 9c; Table 3; Supplementary Data
540 S4). The variability of K_1 orientation (cluster vs. girdle distribution) depends on three
541 main factors: (1) the variability in orientation of each fracture set (K-fisher parameters and
542 standard deviations for uniform distributions; Table 2); (2) the similarity of the average
543 orientation of intersecting fracture sets (Table 2), and (3) the relative frequency of fracture
544 sets in each model (Table 3). A well-defined cluster distribution of K_1 orientation occurs
545 when the model is characterised by either two predominant fracture sets (e.g. Set D and E
546 in model HW_1) or fracture sets exhibiting similar orientations and relative frequencies
547 (e.g. Set B, C and E in model HW_3). Girdle distributions are, instead, promoted when
548 fracture sets characterised by dissimilar average orientations and a large statistical
549 variation have comparable relative frequency (e.g. Sets B, C, D and E in model FW_1;
550 Fig. 9c; Table 3; Supplementary Data S4).
- 551 (iii) The asymmetric development of the GFZ damage zone suggests that, even though the
552 magnitude of the \mathbf{K} components may be comparable throughout the fault zone, the

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

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

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

564 *5.4 Fault zone bulk permeability*

565 The fault zone bulk permeability results from the sum of the matrix permeability of the deformed host
566 rock within the fault zone and the superimposed structural permeability related to the meso-scale
567 fracture network. Previous investigations of the GFZ focussed on the in-situ characterisation of the
568 fault rocks matrix permeability (Ceccato et al., 2021). At odds with what would be commonly
569 expected (cf. Bruhn et al., 1994; Caine et al., 1996; Evans et al., 1997; Caine and Forster, 1999;
570 Rawling et al., 2001), the matrix permeability of fault rocks measured by air-minipermeametry (Table
571 1) is larger than the damage zone structural permeability obtained by DFN modelling (Table 4) under
572 the adopted boundary conditions. The permeability values measured by air-minipermeametry and
573 DFN modelling refer to significantly different sampled volumes ($\sim\text{cm}^3$ in air-minipermeametry, 125
574 m^3 for DFN modelling). Therefore, the comparison of permeability values retrieved from these two
575 different methods may be problematic and a straightforward correlation would require dedicated
576 analyses which go beyond the scope of the present paper. However, in terms of relative permeability
577 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

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

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

654 **6. Conclusions**

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

663 (a) The GFZ outcrop displays a complex internal architecture including two overlapping fault
664 strands, each with a discrete core, sandwiching an Internal Damage Zone and both embedded
665 within an asymmetric damage zone, mainly developed in the hanging wall. The P_{10} - P_{32}
666 intensity of fracture Set E, related to the main fault planes, varies more rapidly in the footwall
667 than in the hanging wall, decreasing according to a negative power-law function moving away
668 from the closest fault core(s).

669 (b) The average structural permeability resulting from the DFN modelling of the SSRS fracture
670 patterns within the damage zone of an SRS fault zone ranges between 0.01 and 0.14 mD,
671 reaching local maximum values as high as 0.4 mD. The magnitude and anisotropy of the \mathbf{K}
672 principal components depend linearly on the total fracture intensity of the fractured domain,
673 whereas the orientation of the \mathbf{K} principal components depends on the intersection direction
674 between the most abundant fracture sets. Thus, SSRS fracture networks represent a
675 preferential conduit for fault-parallel fluid-flow within the damage zone of a SRS fault zone,
676 especially along a direction parallel to the intersection of the dominant fracture sets.

677 (c) The approach combining structural analysis and DFN modelling suggests that it is reasonable
678 to expect a power-law decreasing trend for the structural permeability within the damage zone
679 moving away from high strain zones. Thus, the structural permeability is expected to control

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

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

688 **Acknowledgments**

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

698

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 1:50000).

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**

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

769

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						Shape
					Std Dev Trend	Std Dev Plunge	Min (m)	Max (m)	Avg. (m)	Distrib. Type	Lambda	Aperture (m)	
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)
P₁₀ (m⁻⁴)						
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
P₁₀-P₃₂ Conversion factors	1.0831	0.9655	1.4571	1.1337	1.1818	
						Total P₃₂
P₃₂ (m²/m³)						
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
Relative proportion of total fracture in DFN models (%)						
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 P₁₀-P₃₂ intensities and related P₁₀-P₃₂ conversion factors

778 adopted in the DFN model computations.

779

Model	Permeability Tensor components (mD)							
		P ₃₂ (m ² /m ³)	P ₃₃ (m ³ /m ³)	K ₁	K ₂	K ₃	K ₁ /K ₃	K ₁ /K ₂
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	Avg	5.3886	0.0005		0.052	0.041	0.015	3.52	1.26
	Std dev	0.5986	0.0001		0.011	0.009	0.004		
	Min	3.4290	0.0003		0.024	0.018	0.006		
	Max	7.7426	0.0009		0.161	0.153	0.034		
				Dir/DipDir	50/256	17/144	34/042		
Clus	Avg	11.1982	0.0011		0.106	0.082	0.036	2.96	1.29
	Std dev	0.9297	0.0001		0.016	0.014	0.008		
	Min	7.6337	0.0007		0.058	0.043	0.013		
	Max	14.9353	0.0017		0.246	0.224	0.094		
				Dir/DipDir	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 Bisdorn, 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](https://doi.org/10.1130/0091-7613(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/epiugs/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. Direct⁴⁰Ar/³⁹Ar
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., Bunes, 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 CO₂ 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