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

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Abstract

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

Keywords

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

1. Introduction

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

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

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

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

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

2. Geological Settings

The Goddo Fault Zone (GFZ) crops out along the southeastern coast of the Goddo Island (Bømlo, Hordaland, Western Norway; Fig. 1). The fault zone cuts through the Rolvsnes granodiorite, a pre-Scandian granitoid pluton (466 ± 3 Ma, U/Pb on zircon; Scheiber et al., 2016) intruding the metamorphic units of the Caledonian Upper Allochthon (Gee et al., 2008; Slagstad et al., 2011; Scheiber et al., 2016). The Rolvsnes granodiorite is cut across by a complex network of fractures and fault zones, which records the prolonged brittle deformation history that unfolded during the post-Caledonian orogenic collapse and subsequent multi-stage rifting of the northern North Sea (Scheiber et al., 2016; Scheiber and Viola, 2018). The tectonic history of the area is only shortly summarized in the following, while further details can be found in Scheiber and Viola (2018). Fractures formed during this prolonged tectonic activity can be sorted into three main sets in relation with their relative timing with the progressive development of the GFZ: (a) Pre-Permian background fractures, mineralised veins, and shear fractures; (b) GFZ-related fractures and fault zones and (c) fracture clusters spatially and genetically associated with Cretaceous alteration processes.

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

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

During the Early Cretaceous, a set of minor, N-S trending normal (top-to-E) faults and fracture zones developed in the area in response to far-field stresses related to the extensional tectonics in the northern North Sea and along the Mid-Norwegian Margin. During this latest deformation stage, N-S to NNE-SSW trending fracture clusters formed at very shallow crustal conditions (<2 km). These clusters are commonly associated with evidence of fluid-rock interaction that locally transformed the host Rolvsnes granodiorite into a sandy, non-cohesive aggregate of quartz and clay-minerals (Viola et al., 2016; Fredin et al., 2017b; Ceccato et al., 2021).

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

2.1 The Goddo Fault Zone

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

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

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

2.2 Fault rock bulk permeability and anisotropy

The petrophysical and geomechanical properties of the GFZ fault rocks have been characterised through in-situ measurements and discussed by Ceccato et al. (2021). The permeability of the fault cores (gouge, cataclasite) and host granodiorite was measured with a New England Research TinyPerm3 air-minipermeameter. Results are reported in Table 1. Details on methods and data statistics can be found in Ceccato et al. (2021). The lowest permeability was observed in the host granodiorite (48 mD on average) and in the fault core directly on PSS along a direction perpendicular to it (43 mD on average). The highest permeability was observed in the cataclasite (368 mD on average) measured parallel to the fault strike (NNW-SSE direction). The clay-rich gouge layers exhibit an intermediate permeability of 96 mD on average. Based on the discussion of literature data, Ceccato et al. (2021) suggested that the shape of the permeability tensor of gouge and cataclasite is likely strongly oblate, with the principal minimum permeability component measured perpendicular to the fault plane and on average three orders of magnitude smaller than the maximum and intermediate axes of the permeability tensor parallel to the fault plane (Faulkner and Rutter, 1998; Zhang and Tullis, 1998).

3. Workflow and methods

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

3.1 UAV imagery acquisition and Virtual Outcrop Model elaboration

Georeferenced (WGS 84 / UTM zone 31N - EPSG:32631) Virtual Outcrop Models of the GFZ outcrop were generated using UAV-drone imagery through SfM algorithms. UAV-drone image acquisition was carried out with a DJI Phantom 4 drone, equipped with a 20 MP camera (CMOS-1 sensor, 24 mm lens) using Ground Station Pro software on an iPad. Two flights were flown on the GFZ outcrop: (i) an overview survey, acquiring images at low-resolution (1 cm/pxl) and covering the entire exposed outcrop), (ii) a high-resolution (1-3 mm/pxl) survey of the central fault zone area, specifically covering the sFC and nFC. The images were taken with 80% front and 60% side overlap while the UAV was in stationary flight. Point clouds, orthophotos and digital surface models were generated through the analysis of the drone imagery by means of SfM algorithms in ContextCapture (Bentley Systems Inc.).

3.2 Virtual Outcrop Models interpretation and fracture identification

The interpretation of fractures and the structural analysis of the generated VOMs were performed in CloudCompare (https://www.danielgm.net/cc/). The VOMs were plotted in CloudCompare as point clouds. The point clouds of the two VOMs generated from the two drone flights were combined to build a single, high-resolution VOM of the GFZ (Fig. 4A). Fracture extraction from the VOMs required the segmentation of exposed fracture surfaces and the analysis of fracture traces on the outcrop surface adopting the structural analysis toolkits Facets (Dewez et al., 2016) and Compass (Thiele et al., 2017) implemented in CloudCompare (Fig. 4B). These toolkits rely on two different approaches to retrieve a geometrical representation of fracture planes. The Facets tool is designed to retrieve the planar 3D polygon that best fits the points of a manually selected portion of the point cloud. The Compass tool allows to either fit a square plane to a selected region of defined radius around a selected point of a point cloud (Plane tool), or to retrieve the plane that best fits the trace of a fracture on the outcrop surface (Trace tool). Thus, these tools are efficient in retrieving the orientation of fracture surfaces and planes when the outcrop topography is irregular and offer a three-dimensional exposure of fracture planes or traces. We have mainly adopted Facets to analyse the exposed fracture surfaces, and the Trace tool in Compass to retrieve the orientation of fracture planes and length from the fracture trace on the outcrop surface. The accuracy of both analytical tools in retrieving reliable orientation data depends on the resolution of the point cloud and the dimension of the segmented fracture plane: the smaller the fracture surface/trace, the fewer the points that can be fitted by the interpretation tools, and thus, the less accurate the retrieved plane orientation (Dewez et al., 2016; Thiele et al., 2017). Accordingly, the range of fracture length that the tools can analyse is limited at the lower bound by the resolution of the point cloud, and at the upper bound by the computational capability of the PC/workstation (Dewez et al., 2016; Thiele et al., 2017). The interpreted planar or linear trace expression of fractures ranges between 10 cm and 5 m. The structural orientation data exported from Facets and Compass tools were then analysed and plotted with Stereonet v.11.2.2. (https://www.rickallmendinger.net/stereonet). Fracture trace length distributions were analysed with an ad-hoc MATLAB script adopting the functions for distribution fitting made available by FracPaQ (Healy et al., 2017; Rizzo et al., 2017).

3.3 Analysis of fracture intensity and spatial organisation through virtual cross-sections and scanlines

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

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

3.4 Discrete Fracture Network Modelling with FracMan

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

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

Each DFN model consists of a 100x100x100 m (10^6 m^3) volume domain composed of 8000 REV of 125 m^3 (5x5x5 m) each (Fig. 4G). Each REV was populated stochastically with selected assemblages of fracture sets. The elementary block dimensions (cube side length = 5 m) are larger than the minimum dimensions suggested by Oda (1988) for the definition of a REV, which must be at least three times larger than the average length of fractures (3·0.8-1m = 2.4-3 m in our case; see Table 2). The computed volumetric grid, therefore, represents 8000 possible configurations of a 125 m^3 REV of a rock mass populated by a specific assemblage of fracture sets with specific fracture parameters. By doing so we aimed at analysing the statistical variation of the permeability tensor properties among the 8000 REV in the 10^6 m^3 modelled volume domain. The permeability computation in the DFN models follows the approach of Oda (1985). The approach of Oda allows retrieving the magnitude and orientation of the permeability tensor principal components (K_1, K_2, K_3 with $K_1>K_2>K_3$) from the "crack tensor" describing the geometrical properties of the fractures-discontinuities occurring within a REV of fractured rock mass. Comparing the magnitude and orientation of the tensor principal components computed for each of the 8000 REV within the same DFN model, we have retrieved the statistical variability of **K** components (Fig. 4H-I). The resulting permeability values and permeability tensor components only refer to the structural permeability, as the matrix permeability of the host rock is not accounted for in our models.

4. Results

4.1 Field and VOM outcrop characterization

The structural field analysis of this study was limited to the acquisition of a reliable dataset of fracture orientations and the identification of the fault zone domains (fault cores and damage zone) (Figs. 2-3). By comparing the 3D point clouds with field investigations, we could identify the three different domains composing the GFZ (Figs. 2 and 5): the footwall (FW) damage zone, the central GFZ, and the northern hanging wall (HW) damage zone.

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

4.1.1 Fracture set identification

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

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

4.1.2 Fracture trace length distribution

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

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

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

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

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

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

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

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

Spatial distribution of Sets C, D and E. To analyse the spatial distribution of P_{10} for Sets C, D and E, the variably oriented cross-sections traced for the different sets (Supplementary Data S1), as well as the related scanlines, were projected onto a cross section oriented N070°E, thus perpendicular to the strike of the main fault (Fig. 7b). On this cross-section, we assessed the spatial distribution of P_{10} intensity on a profile perpendicular to the fault dip (black line in Fig. 7b). This allowed for the relationship between P_{10} intensity of each fracture set and the distance perpendicular to the main fault planes to be determined (Fig. 7c). The intensity of Set C fractures does not display any obvious spatial trend (constant P_{10} = 1.1 m^{-1} on average; Fig. 7c). The diagram in Fig. 7c highlights two different spatial trends for fracture Sets D and E intensity. P_{10} for Set D varies from 0.5 m^{-1} in the southern GFZ outcrop up to a maximum of 5.5 m^{-1} just north of the nFC outcrop (Fig. 7c). A second peak in intensity (P_{10}= 2.9 m^{-1}) is observed next to the sFC. Set D fractures show an increasing intensity moving from SW to NE across the fault zone, which is best fitted by a power-law function (R^2 = 0.7702; Fig. 8a-b). The spatial trend of Set E fracture intensity increases next to the two main fault cores (Fig. 7c), showing 5.7 m^{-1} and 4.5 m^{-1} close to the sFC and nFC, respectively. The IDZ is characterised by variable intensity ranging between 1.2 and 1.9 m^{-1}. In the footwall, fracture intensity increases quite abruptly from <1 m^{-1} to >5 m^{-1} over less than 5 m from the southern PSS. Conversely, in the hanging wall, Set E fracture intensity decreases slowly, and P_{10} values larger than 2 m^{-1} are still observed ~15 m away from the northern PSS (Fig. 7c). The decreasing trend of Set E P_{10} intensity is best fitted by a power-law function moving away from the sFC into the FW (R^2 = 0.9809; Fig. 8a-b). The decreasing trend of Set E P_{10} intensity moving away from the nFC into the HW is instead best fitted by a negative exponential function (R^2 = 0.88; Fig. 8a), even though data fitting with a power-law function also yielded a statistically meaningful result (R^2 = 0.7293; Fig. 8b).

4.2 Discrete Fracture Network models

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

The DFN models include (Figs. 7c-9; Table 3): (i) model FW_1, representing the crystalline basement affected by background fracturing alone in the footwall of the GFZ; (ii) model FW_2, representing the transition from background fracturing toward the footwall damage zone (Set E P_{10} = 1 m^{-1}); (iii) model FW_3, representing the footwall damage zone; (iv) model sFC, representing the damage zone close to the southern fault core (max Set E intensity); (v) model IDZ, representing the Internal Damage Zone; (vi) model nFC, representing damage zone close to the northern fault core; (vii) model HW_1, representing the hanging wall damage zone affected by the maximum observed Set D intensity; (viii) model HW_2, representing the intermediate portion of hanging wall damage zone; (ix) model HW_3, representing the external portion of the hanging wall damage zone without the contribution of Set D. Additionally, we have created a model targeting the permeability properties of the crystalline basement affected by Set A fracture clusters (model Clus in Fig. 9a). The fracture sets, the related P_{10} intensities and all the fracture parameters adopted for each model computation are listed in Table 2 and 3. We assumed a constant mechanical fracture aperture of 100 μm for all the fracture sets in the DFN models. The proportionality coefficients relating P_{10} with P_{32} and the adopted P_{32} values for each fracture set in each DFN model are listed in Table 2 and plotted in Fig. 9a (Supplementary Data S2). An example of the graphical output of a DFN model computation is reported in the Supplementary Data S3. The magnitude and orientation of the permeability tensor principal components retrieved from the DFN models are reported in Table 4 and Fig. 9.

The magnitudes of the principal components of the permeability tensor show a significant variation across the GFZ (Fig. 9b). The K_1 component ranges between 0.03 mD and 0.13 mD on average, showing maximum values as high as 0.4 mD and displaying a relative increase of about one order of magnitude between the least and the most fractured zone (Table 4). The K_2 component shows a variation trend similar to K_1. The K_3 component is the least variable component, ranging between 0.01 mD and 0.05 mD. The relative magnitude of the tensor components suggests that in all cases the shape of the **K** tensor is oblate, having very similar K_1 and K_2 permeability values that are much larger than K_3 (Fig. 9b). As to the orientation of the **K** principal components (Fig. 9c), the orientation of the K_3 component is constant for all models, being almost subhorizontal and NE-striking. The orientation of K_1 varies across the GFZ: in the footwall and in the most distal portions of the GFZ hanging wall (FW_1, FW_2, FW_3, HW_3), K_1 plunges 45° eastward, laying subparallel to the intersection direction between Sets B and E or Sets B and C. In these domains, the K_2 direction is close to the intersection direction between Sets C and D (Fig. 9c, Supplementary Data S4). In the central and most fractured portions of the GFZ (sFC, IDZ, nFC, HW_1, HW_2), on the other hand, K_1 is almost subhorizontal and NW-trending, laying subparallel to the intersection direction between Sets D and E (Fig. 9c, Supplementary Data S4). In most cases, the distribution of the entire K_1 orientation dataset defines a girdle spanning almost 90° and overlapping with a similar K_2 girdle distribution (Supplementary Data S4). This girdle distribution for K_1-K_2 orientations is most pronounced in the footwall models (FW_1, FW_2, FW_3), while it becomes less pronounced in the hanging wall models (HW_1, HW_2, HW_3; Supplementary Data S4).

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

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

5. Discussion

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

5.1 Geometry of the Goddo Fault Zone

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

(i) The GFZ is characterised by two distinct fault cores probably representing two fault strands with a hard overlap, which have been activated coevally, as it can be inferred from the same assemblage of structural facies with the same probable age in the two fault cores (Viola et al., 2016; Ceccato et al., 2021). However, the limited exposure of the studied outcrop does not allow to fully characterise the large-scale geometry of the GFZ. The two fault strands can either represent two en-echelon segments of a larger-scale normal fault or the same fault core embedding a very large damage zone lithon (the IDZ) (Childs et al., 1995; Fossen and Rotevatn, 2016).

(ii) The intensity of the ENE-dipping Set E fractures varies from <1 m^{-1} 5 m from the main fault zone to ~6 m^{-1} adjacent to the main fault cores. If fracture intensity in the most external portions of the GFZ represents the "background" fracture intensity of Set E, we define c. 1 m^{-1} as the limit between the background fracture intensity and the GFZ damage zone (Choi et al., 2016; Torabi et al., 2020). The transition from background intensity values to values >1 m^{-1} occurs in the footwall ~5 m from the southern fault core. In the hanging wall, the transition to intensity values <1 m^{-1} occurs at >20 m from the nFC (Fig. 7c). The intensity profile displayed by Set E fractures within the footwall and hanging wall suggests that the fault zone is asymmetric, with the damage zone preferentially developed in the hanging wall of the fault zone.

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

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

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

5.2 Geometry of Set A fracture clusters

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

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

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

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

(i) The overall variation in permeability is related to an increase of total fracture intensity P_{32} from 3.5 m^2/m^3 (background intensity) up to 14.4 m^2/m^3 across the GFZ outcrop (Fig. 10). The computed increase of c. one order of magnitude in total intensity P_{32} of fractures longer than 10^{-1} m leads to a relative increase of one order of magnitude of the principal maximum (K_1) permeability. In all cases, the shape of **K** tensor is strongly oblate ($K_1 \approx K_2 >> K_3$; Fig. 9c). The magnitude of the **K** principal components increases linearly with the computed total P_{32}, despite the different assemblage of fracture sets and related intensity characterising each DFN model (Fig. 10, Table 4). Accordingly, the ratios between principal components (K_1/K_2, K_1/K_3) are almost constant despite the different assemblages.

(ii) The average orientation of the K_1 principal component is generally subparallel to the intersection directions of the dominant fracture sets (Fig. 9c; Table 3; Supplementary Data S4). The variability of K_1 orientation (cluster vs. girdle distribution) depends on three main factors: (1) the variability in orientation of each fracture set (K-fisher parameters and standard deviations for uniform distributions; Table 2); (2) the similarity of the average orientation of intersecting fracture sets (Table 2), and (3) the relative frequency of fracture sets in each model (Table 3). A well-defined cluster distribution of K_1 orientation occurs when the model is characterised by either two predominant fracture sets (e.g. Set D and E in model HW_1) or fracture sets exhibiting similar orientations and relative frequencies (e.g. Set B, C and E in model HW_3). Girdle distributions are, instead, promoted when fracture sets characterised by dissimilar average orientations and a large statistical variation have comparable relative frequency (e.g. Sets B, C, D and E in model FW_1; Fig. 9c; Table 3; Supplementary Data S4).

(iii) The asymmetric development of the GFZ damage zone suggests that, even though the magnitude of the **K** components may be comparable throughout the fault zone, the hanging wall damage zone could be the principal conduit for fault-parallel fluid-flow given the larger volumetric extension compared to the footwall damage zone (Fig. 7c).

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

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

5.4 Fault zone bulk permeability

The fault zone bulk permeability results from the sum of the matrix permeability of the deformed host rock within the fault zone and the superimposed structural permeability related to the meso-scale fracture network. Previous investigations of the GFZ focussed on the in-situ characterisation of the fault rocks matrix permeability (Ceccato et al., 2021). At odds with what would be commonly expected (cf. Bruhn et al., 1994; Caine et al., 1996; Evans et al., 1997; Caine and Forster, 1999; Rawling et al., 2001), the matrix permeability of fault rocks measured by air-minipermeametry (Table 1) is larger than the damage zone structural permeability obtained by DFN modelling (Table 4) under the adopted boundary conditions. The permeability values measured by air-minipermeametry and DFN modelling refer to significantly different sampled volumes (~cm^3 in air-minipermeametry, 125 m^3 for DFN modelling). Therefore, the comparison of permeability values retrieved from these two different methods may be problematic and a straightforward correlation would require dedicated analyses which go beyond the scope of the present paper. However, in terms of relative permeability changes with respect to the undeformed host rock, permeability measurements with air-minipermeametry have revealed that the gouge and cataclasite (matrix) permeability is generally four orders of magnitude larger than the host rock permeability (measured parallel to the fault plane, Table 1) (Ceccato et al., 2021). In the same way, DFN models suggest that the increase of fault-related fractures across the GFZ leads to a relative increase in (structural) permeability of one order of magnitude with respect to the area outside the GFZ damage zone.

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

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

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

5.5 The fractured crystalline basement reservoir of the Rolvsnes granodiorite

All fracture sets adopted in the computation of the DFN models have identical fracture apertures. Therefore, results of the DFN modelling represent the structural permeability of the fractured crystalline basement in its actual, surficial conditions. During the local geological evolution, the sequence of fracturing events, the different tectonic stresses and fluid-rock interaction processes affecting each fracture set may have led to different permeabilities, which are not captured by the DFN modelling. Indeed, previous field structural analyses have identified different fracture sets in the Rolvsnes granodiorite that are genetically related to tectonic events of different ages and characterised by different fracture apertures and mineral infillings (Scheiber et al., 2016; Scheiber and Viola, 2018). As introduced above, the Rolvsnes granodiorite is characterised by three main classes of fracture sets (Scheiber and Viola, 2018): (i) pre-Permian mineralised veins and minor faults; (ii) fault-related fractures; (iii) post-faulting fracture clusters. Sets B and C generally display orientations similar to the mineralised veins and shear fractures related to pre-Permian brittle deformation (pre-Permian veins and shear fractures; Scheiber and Viola, 2018). Their intensity is almost constant across the entire GFZ outcrop (Fig 7a, c). The orientation of Set C suggests that this set is probably related to the NE-dipping “pegmatitic greisens” identified by Scheiber and Viola (2018). Further analyses are needed to understand the origin of Set D, whose fractures are similar in orientation to pre-Permian structures but show a variable intensity across the GFZ. Given that most of these fractures and veins are sealed by mineral infillings, the contribution of mineralised veins and shear fractures of Set B-C (and D?) to the overall current permeability of the fractured basement is likely limited (Scheiber and Viola, 2018). Set E fractures are generally oriented parallel to the main fault plane, their intensity varies as a function of the distance from the identified fault cores of the GFZ. These characteristics suggest that Set E fractures may have developed coevally with the GFZ, i.e. during the Permian-to-Early Jurassic rifting stage (Viola et al., 2016; Scheiber and Viola, 2018). Set A fractures are organized in fracture clusters composed of steeply dipping NE-SW- and N-S-trending fractures. Their orientation and the field association with alteration zone suggests that Set A fracture clusters belong to the N-S-trending structures related to the Early Cretaceous rifting stage (Viola et al., 2016; Fredin et al., 2017b). In this case, the permeability of the fractured Rolvsnes granodiorite would be mainly controlled by fault-related Set E and clustered Set A fractures (Ceccato et al., 2021). Further field analyses aimed at the characterisation of fracture aperture and mineral infilling of each fracture set are required for more detailed modelling of the permeability evolution during the deformation history of the Rolvsnes granodiorite.

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

6. Conclusions

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

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

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

(c) The approach combining structural analysis and DFN modelling suggests that it is reasonable to expect a power-law decreasing trend for the structural permeability within the damage zone moving away from high strain zones. Thus, the structural permeability is expected to control a fault zone bulk permeability over larger distances when compared to the likely exponentially-decreasing matrix permeability related to micro-fracturing within the damage zone (Mitchell and Faulkner, 2009, 2012).

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

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Figure Captions

Figure 1. Geological map of the northern Bømlo Island, including the island of Goddo and the location of the Goddo Fault Zone (GFZ) outcrop (modified after, Ceccato et al., 2021; Scheiber and Viola, 2018; Viola et al., 2016; NGU geological map of Norway 1:50000).

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

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

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

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

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

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

Figure 7. (a) P_{10} intensity profiles for Sets A and B, along the cross-section B-B' and C-C' of Fig. 2a, respectively. The "first projected scanline" to which the X axis refers to is indicated in the Supplementary material (Supplement S1 – Set A-B). Fracture clusters are highlighted in the P_{10} profile for Set A (light orange rectangles). Set B shows a rather constant P_{10} intensity. (b) Schematic cross-section of the GFZ along the A-A' profile of Fig. 2a showing the identified domains composing the GFZ on which the virtual scanlines adopted to quantify the local fracture intensity P_{10} of Sets C, D, and E are projected. (c) Diagram showing the variation of the fracture intensity P_{10} of Sets C, D, and E along the fault-perpendicular profile as reported in the schematic cross-section in (b). The locations of the modelled fault zone domains (FW_1, FW_2, FW_3, sFC, IDZ, nFC, HW_1, HW_2, HW_3) are also reported. See text for explanation.

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

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

Figure 9. (a) Diagram showing the P_{32} intensities for each fracture Set (A-E) adopted for each DFN model (FW_1, FW_2, FW_3, sFC, IDZ, nFC, HW_1, HW_2, HW_3) and the total P_{32} resulting from DFN modelling. (b) Diagram showing the magnitude (vertical axis on the left) and the relative ratio (K_1/K_n with n=2,3; vertical axis on the right) of the principal components of the permeability tensor ($K_1>K_2>K_3$) resulting from the DFN model computations. The average permeability values (dots and squares) are reported along with their statistical variation (± 2σ). (c) Equal area, lower hemisphere stereonets of the orientation of the principal components (K_1, K_2, K_3) of the permeability tensor and the main orientation of the fracture planes for Sets A-E.

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

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

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

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

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

	Model	Set A	Set B	Set C	Set D	Set E	X (m)
P_{10} (m^{-1})	**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
P_{10}-P_{32} Conversion factors		1.0831	0.9655	1.4571	1.1337	1.1818	
							Total P_{32}
P_{32} (m^2/m^3)	**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	-	-	

Table 3. DFN model set-up. Fracture set P_{10}-P_{32} intensities and related P_{10}-P_{32} conversion factors adopted in the DFN model computations.

Model		P_{32} (m^2/m^3)	P_{33} (m^3/m^3)	Permeability Tensor components (mD)	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	14.93.53	0.0017		0.246	0.224	0.094		
				Dir/DipDir	63/190	26/018	03/286		

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

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