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In-situ quantification of mechanical and permeability properties on outcrop analogues of offshore fractured and weathered crystalline basement: Examples from the Rolvsnes granodiorite, Bømlo, Norway

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

Published Version:

Ceccato, A., Viola, G., Tartaglia, G., Antonellini, M. (2021). In-situ quantification of mechanical and permeability properties on outcrop analogues of offshore fractured and weathered crystalline basement: Examples from the Rolvsnes granodiorite, Bømlo, Norway. MARINE AND PETROLEUM GEOLOGY, 124(104859), 1-20 [10.1016/j.marpetgeo.2020.104859].

Availability:

This version is available at: https://hdl.handle.net/11585/784466 since: 2020-12-15

Published:

DOI: http://doi.org/10.1016/j.marpetgeo.2020.104859

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This is the final peer-reviewed accepted manuscript of:

Ceccato, Alberto; Viola, Giulio; Tartaglia, Giulia; Antonellini, Marco: *In–situ* quantification of mechanical and permeability properties on outcrop analogues of offshore fractured and weathered crystalline basement: Examples from the Rolvsnes granodiorite, Bømlo, Norway

MARINE AND PETROLEUM GEOLOGY VOL.124 ISSN 0264-8172

DOI: 10.1016/j.marpetgeo.2020.104859

The final published version is available online at:

https://dx.doi.org/10.1016/j.marpetgeo.2020.104859

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1	In–situ quantification of mechanical and permeability properties on outcrop analogues of
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4	
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#### 9 Abstract

8

10 Fractured and weathered crystalline basement units below erosional unconformities potentially 11 represent unconventional reservoirs for georesources (oil, mineral and water). The reservoir 12 properties and characteristics strongly depend on secondary processes connected to the local 13 structural and alteration/weathering history. Here we present the results of in-situ field quantification 14 of mechanical (uniaxial compressive strength) and petrophysical (permeability) properties of a 15 fractured and weathered crystalline basement at selected outcrops on the island of Bømlo (western 16 Norway). The Bømlo outcrops are believed to represent an onshore analogue of the unconventional 17 oil reservoir hosted in the offshore Utsira High granodioritic fractured basement (northern North Sea). 18 The off- and onshore crystalline basements have both undergone surficial weathering during the 19 Mesozoic, as shown by the occurrence of a dated, variably thick saprolitic profile on top of fresh 20 fractured basement blocks. The Bømlo crystalline basement is characterized by a complex and highly 21 permeable fracture network. Fault rocks within its fault zones are characterised by an anisotropic 22 mechanical strength and by an average permeability that is two orders of magnitude larger than that 23 of the host rock. The matrix permeability and mechanical strength are significantly affected by alteration/weathering products. Analysis of the textural and mineralogical characteristics of the 24

25 weathered outcrops allowed us to constrain the variation of permeability and mechanical strength as 26 a function of increasing alteration and to infer their distribution in the, now eroded, top-basement 27 weathering profile on Bømlo. Weathering enhances permeability and drastically decreases the mechanical strength. Nevertheless, evolved saprolitic horizons may act as low-permeability top-seal 28 29 units to the fractured and weathered crystalline basement reservoir. The obtained permeability and 30 mechanical data are finally used to better constrain the potential reservoir rocks, the fluid migration 31 pathways, and to discuss their role in the geomechanics of a conceptualised fractured and weathered 32 crystalline basement unconventional reservoir.

## 33 Keywords

34 Fractured basement reservoir; Saprolite; Utsira High; Fault rock permeability.

35

**1. Introduction** 

38 Faults, fractures, and related alteration zones control fluid transport within low-permeability 39 crystalline basement rocks at different crustal levels within all tectonic settings and geological 40 conditions (Stober and Bucher, 2015). Indeed, brittle deformation and alteration processes may 41 drastically affect the mechanical strength and permeability of inherently stiff, low-permeability 42 crystalline basement rocks through the development of secondary porosity (Brace, 1984; Bruhn et al., 43 1994; Caine et al., 1996; Stober and Bucher, 2007; Place et al., 2016; Staněk and Géraud, 2019). A 44 better understanding of how these processes affect the rock mechanical strength and the properties 45 controlling fluid flow is, therefore, of interest to geoscientific research and many applied fields. 46 Examples are the geological characterisation necessary to the construction of deep nuclear waste and 47 CO<sub>2</sub> repositories (Armitage et al., 2013), the better definition of crustal rheology and rock mechanics 48 (Caine et al., 1996; Sibson and Rowland, 2003) and the exploration and production of georesources 49 (Dewandel et al., 2006; Stober and Bucher, 2015; Kitchka et al., 2017). Specific to this last point, in 50 the recent past, economically viable unconventional oil plays have been defined in structural highs 51 within fractured and weathered crystalline basement blocks (Koning, 2003; Luthi, 2005; Kitchka et 52 al., 2017; Braathen et al., 2018; Bonter and Trice, 2019; Holdsworth et al., 2019, 2020; Trice et al., 53 2019; McCaffrey et al., 2020). There, the constituent elements of a reservoir include (Riber et al., 54 2015, 2017; Fredin et al., 2017b; Braathen et al., 2018; Lothe et al., 2018; Walter et al., 2018; 55 McCaffrey et al., 2020): (1) the host crystalline rock, characterised by primary low-56 porosity/permeability; (2) fractures, fault zones, mineral veins and open fissures characterised by 57 enhanced micro- and mesoscopic fracture porosity; (3) fluid-rock interaction zones related to either 58 alteration along structural discontinuities or to top-basement paleo-weathering profiles; (4) the 59 buffering/sealing fault zones bounding the structural highs; (5) the sedimentary cover overlying the 60 weathered crystalline basement acting as either reservoir rock, top-seal and/or source rock. The 61 reservoir rock consists of the fractured and altered/weathered crystalline basement, in which fluid 62 storage and transport are dependent mainly on the spatial arrangement, geometry and distribution of

"matrix" and "structural" permeability (Braathen et al., 2018; Trice et al., 2019). The "matrix" 63 64 permeability is directly related to the textural, compositional, and alteration characteristics of the host 65 crystalline basement (Bruhn et al., 1994; Géraud et al., 2010; Braathen et al., 2018). The "structural" 66 permeability, on the other hand, reflects and is related to the presence of structural discontinuities at 67 all scales, from microfractures to crustal-scale fracture and fault zones (Bruhn et al., 1994; Sibson 68 and Rowland, 2003; Holdsworth et al., 2020). Brittle faulting and fluid percolation within structural 69 discontinuities may either increase and/or decrease the matrix permeability of the host crystalline 70 basement (Bruhn et al., 1994; Caine et al., 1996; Holdsworth et al., 2019, 2020; McCaffrey et al., 71 2020). The geological conditions (depth, pressure, temperature) and the origin (metamorphic, 72 hydrothermal, or meteoric) of fluids may lead to different brittle fault rock development and different 73 types of alteration from textural and compositional points of view (Steefel and Mäher, 2009).

The nature, spatial arrangement, and geometry of structural and textural features at the reservoir scale are commonly defined through seismic geophysical investigations. Textural variations, fracture, and fault zones displaying sufficient seismic impedance contrast as well as fault thickness or throws > 4– 10 m are usually detected by reservoir–scale seismic investigations and are thus classified as seismic– resolution–scale (SRS) features (Tanner et al., 2019). However, the site– (well–, borehole– or tunnel– ) scale fluid transport and storage capabilities are effectively controlled by sub–seismic–resolution scale (SSRS) features (thickness/throw <4–10 m; Damsleth et al., 1998; Walsh et al., 1998).

In-situ analysis of outcrop analogues of onshore fractured and weathered basement blocks may provide the unique opportunity to characterise the details of the petrophysical and mechanical properties of SSRS features and to understand their relationships with larger, reservoir-scale SRS features (Jones et al., 2008; Howell et al., 2014; McCaffrey et al., 2020; Primaleon et al., 2020). We present here the results of the in-situ structural, geomechanical (uniaxial compressive strength, UCS), and petrophysical (permeability, k) characterisation of selected outcrops of fractured and weathered crystalline basement rocks on the island of Bømlo, western Norway (Fig. 1a-b). The crystalline

88 basement on Bømlo is being currently studied as the potential onshore analogue of fractured and weathered basement reservoirs of the Utsira High, an economically viable unconventional reservoir 89 90 located offshore western Norway in the northern North Sea (Figs. 1a-2a; Banks et al., 2019; Trice et 91 al., 2019). The crystalline basement on Bømlo consists of igneous (granodiorite, granite and gabbro) 92 and volcano-sedimentary units of Ordovician-Silurian age belonging to the Upper Allochthon of the 93 Caledonian orogen (Slagstad et al., 2011). From the Permian onward, the crystalline basement on 94 Bømlo underwent a series of brittle deformation events (Scheiber and Viola, 2018) and experienced 95 pervasive alteration/weathering in response to subaerial exposure in tropical humid climate 96 conditions during the Triassic, forming a thick weathering profile (Fredin et al., 2017b). Similarly, 97 the offshore Utsira High reservoir is characterised by a pervasively fractured crystalline basement, 98 mainly composed of felsic intrusive and gabbroic rocks of Ordovician-Silurian age (Slagstad et al., 99 2011; Riber et al., 2015), on top of which rests a paleo-weathering profile formed during the late 100 Triassic (Fredin et al., 2017b; Riber et al., 2017; Lothe et al., 2018) (Fig. 2b).

101 On Bømlo, we have worked on a few selected outcrops (Fig. 1c) that are representative of (1) 102 structural discontinuities affecting the crystalline basement "matrix" properties at different scales, 103 from SSRS fracture corridors to SRS fault zones (Fig. 2c) and (2) textural heterogeneities related to 104 the progressive development of alteration/weathering products(Fig. 2b). Our analyses aimed 105 specifically at the characterisation of the different structural and alteration products controlling the current "matrix" mechanical and permeability properties of the crystalline basement at the sub-106 107 seismic-resolution scale. The role of the different structural and alteration elements in controlling 108 fluid transport and storage, and the characterisation of potential reservoir rocks in fractured and 109 weathered crystalline basement structural highs, are then discussed to the benefit of broader, more 110 general conceptual scenarios.

111 Quantitative, high-resolution geomechanical and petrophysical datasets are quite rare, yet 112 fundamental for interpreting increasingly higher-resolution geophysical datasets, for reducing the 113 uncertainty in reservoir modelling, for better constraining fault zone mechanics and for assessing 114 borehole stability during exploration and drilling (Rutqvist and Stephansson, 2003; Wibberley et al., 115 2008; Steer et al., 2011; Jeanne et al., 2017). Our results are thus useful to help bridge the gap between field observations and large-scale geological contexts, where the lack of direct access to the 116 117 geological objects of interest and the processes determining their spatial and temporal evolution 118 commonly preclude straightforward across-scale correlations and quantifications. In addition, the 119 geological/structural contextualisation offered by the quantitative, high-resolution dataset presented 120 here may help to better read and interpret the at times overwhelming wealth of global and regional 121 geomechanical/petrophysical datasets (Lothe et al., 2018; Walter et al., 2018; Scibek, 2020).



122

Figure 1: (a) Geological map of southwestern Norway and the northern North Sea (modified after Slagstad et al., 2011; Scheiber and Viola, 2018). HFSZ: Hardangerfjord Shear Zone; NSDZ: Nordfjord–Sogn Detachment Zone. The red line X–X' represents the trace of the geological cross section presented in Fig. 1d. (b) Geological map of the northern Bømlo area, including the island of Goddo (redrawn from the NGU geological map of Norway 1:50000). (c) Simplified topographic map of Bømlo showing the locations of the studied outcrops. (d) Schematic geological cross section through the central North Sea (X–X' in (a)) (modified from Riber et al., 2015).



130

Figure 2: (a) Simplified schematic representation of the fractured and weathered basement top section 132 preserved offshore in the Utsira High beneath the Mesozoic sedimentary cover. This schematic 133 134 representation focuses on the fractured crystalline basement, which is characterised by different typologies of fractures and fault zones, the weathering profile (saprock-saprolite in grey) and the 135 136 overlying sedimentary cover (light blue). The dashed line represents the boundary between saprock 137 and saprolite within the weathering profile. (b) Simplified sketch of the top-basement weathering 138 profile showing the gradual transition from unaltered and fractured host rock at the base of the profile, 139 toward saprock and saprolite at the top. The weathering profile locally reaches greater depths where 140 in correspondence with structural discontinuities (in this case, a SSRS fracture corridor, S1 of Fig. 2a 141 and 2c). The progression of weathering is illustrated by the continuous darkening of the grey shades 142 and the increasing number in the alteration/weathering grade on the left (A1–A5). (CS: core stones). 143 (c) Simplified schematic representation of the fractured and weathered basement top section now 144 exposed onshore on the island of Goddo. The erosion of the weathering profile has led to the exposure of an "etched" basement top surface (Fredin et al., 2017). S<sub>1</sub>, S<sub>2</sub> and S<sub>3</sub> represent the three typologies 145

- 146 of deformation structures studied in this work. S<sub>1</sub>: SSRS fracture corridors; S<sub>2</sub>: SSRS fault zone; S<sub>3</sub>:
- 147 SRS fault zone.
- 148
- 149

## 2. Geological setting

151 The crystalline basement rocks exposed on the island of Bømlo in western Norway belong to the 152 Upper Allochthon units of the Caledonian orogen (Gee et al., 2008) (Fig. 1a). They mainly consist of 153 variably metamorphosed igneous, volcanic and sedimentary units derived from the Iapetus oceanic 154 domain (Roberts, 2003). The study area is located within the Rolvsnes granodiorite (RGD,  $466 \pm 3$ 155 Ma, U/Pb on zircon) (Scheiber et al., 2016), a plutonic body related to pre-Scandian magmatism that 156 intrudes the ophiolitic, gabbroic, and volcano-sedimentary orogenic units (Slagstad et al., 2011) (Fig. 157 1b). After its emplacement in the Ordovician, the RGD remained at shallow crustal levels (< 10–15 158 km depth), thus escaping pervasive ductile deformation and metamorphic re-equilibration during the 159 Scandian tectonometamorphic event (Scheiber et al., 2016; Scheiber and Viola, 2018). During the 160 post-Caledonian orogenic collapse and extension, the Upper Allochthon units in the Bømlo region 161 belonged to the hanging wall of the Hardangerfjord Shear Zone, a regional NW-dipping extensional 162 detachment reactivating earlier Caledonian thrusts and nappe contacts (Fig. 1a) (Fossen and Hurich, 2005). The RGD recorded a prolonged and multi-phased brittle deformation history, which has been 163 164 characterised in detail by means of structural and geochronological analysis of the different fracture 165 patterns exposed on Bømlo (Scheiber et al., 2016; Scheiber and Viola, 2018).

### 166 2.1 Brittle deformation and alteration history of the Bømlo basement

167 The latest stages of Caledonian compression during the Mid Ordovician-Silurian are recorded by 168 ENE-WSW-striking reverse and kinematically consistent conjugate sets of strike-slip shear fractures 169 and minor faults accompanied by the emplacement of greisens, dykes, and mineralised veins 170 (Scheiber et al., 2016). A first phase of NW-SE extension occurred during the Devonian in response 171 to Caledonian orogenic collapse, as recorded by the development of minor, NE-SW-striking normal 172 faults. Ordovician to Devonian mineralised veins, joints, shear fractures, and minor faults are 173 pervasive and widely distributed, and they are commonly filled with- and sealed by a variety of 174 minerals. In the Permian-Early Cretaceous, the area underwent renewed regional extension related

175 to the long-lived series of E-W-directed North Sea rifting events. The first main North Sea rifting 176 stage is recorded by the development of widespread NE-dipping normal faults active during Permian 177 to Triassic times (Viola et al., 2016; Scheiber and Viola, 2018). This rifting event led to the formation 178 of the most prominent structural highs and basins of the North Sea, namely the Stord Basin, Utsira High, and the Viking Graben (Bell et al., 2014; Scheiber and Viola, 2018). Rifting and crustal 179 180 stretching continued during the Late Triassic and Jurassic leading to the formation of ENE-dipping 181 normal faults associated with the deepening and development of the offshore Viking Graben 182 (Scheiber and Viola, 2018) and the progressive reactivation of the previously formed NE-dipping 183 normal faults (Viola et al., 2016). This rifting phase enhanced the rapid exhumation of the Bømlo 184 crystalline basement from 6-8 km to shallow (<2 km) depths during Permian-to-Jurassic times 185 (Scheiber and Viola, 2018). From the Late Jurassic onward, the crystalline basement has resided at 186 very shallow depth (<2 km; Fredin et al., 2017b; Scheiber and Viola, 2018). Far-field stresses related 187 to the Early Cretaceous rifting stage of the northern North Sea and the Mid-Norwegian margin 188 subsequently led to the development of N-S-trending fracture corridors in the Bømlo region (Viola 189 et al., 2016; Scheiber and Viola, 2018).

190 A distinctive characteristic of the Bømlo fractured crystalline basement is the occurrence of alteration 191 and weathering products spatially related to fracture and fault zones (Viola et al., 2016; Fredin et al., 192 2017b; Scheiber and Viola, 2018). Altered/weathered granodiorite is invariably found as lenses along 193 fractures and variably altered volumes within high-fracture density deformation zones. The dense 194 network of fractures and fault zones likely promoted fluid infiltration at depth (Place et al., 2016). K-195 Ar dating of alteration-related authigenic illite has revealed the occurrence of multiple shallow-196 crustal levels alteration/weathering events during the prolonged and multi-phased brittle deformation 197 history discussed above (Viola et al., 2016; Fredin et al., 2017b; Scheiber and Viola, 2018). A 198 significant event occurred during the Late Triassic (ca. 220-200 Ma), when the fractured crystalline 199 basement on Bømlo was exposed to sub-aerial alteration and formation of deep-weathering horizons 200 (saprock - saprolite) related to the Mesozoic tropical-humid climate of the region (Fredin et al., 201 2017b). Other alteration events likely occurred in the Permian and Jurassic–Cretaceous (A. Margreth 202 personal communication; Viola et al., 2016; Scheiber and Viola, 2018). The detailed genetic 203 processes and geological conditions under which these latter alteration events occurred are still not 204 well constrained (A. Margreth personal communication). Despite the possible diachronism and 205 superposition of different alteration/weathering events, all the observed alteration products of the 206 crystalline basement on Bømlo present similar field textural and mineralogical characteristics. 207 Progressive disaggregation of the host RGD into sandy "grus-type" aggregates (sensu Migoń and 208 Thomas, 2002) is commonly accompanied by mineral (feldspar) alteration and clay-mineral 209 authigenesis. Such characteristics are ascribable to a process of arenitisation, kaolinitisation, and/or 210 saprolitisation of the host RGD occurring at shallow crustal depths (< 6 km) up to surficial conditions 211 (Viola et al., 2016; Fredin et al., 2017b, 2017a; Scheiber and Viola, 2018). It is indeed quite well 212 known that hydrothermal kaolinitisation and saprolite formation under tropical-humid climate 213 conditions may lead to alteration products with similar textural/mineralogical/mechanical 214 characteristics (Coggan et al., 2013).

#### 215 2.2 Onshore–offshore correlation – Bømlo basement and Utsira High

216 Alteration characteristics similar to those documented onshore have been detected in offshore 217 exploratory wells from the Utsira High fractured crystalline basement at variable depth beneath the 218 sedimentary cover (Riber et al., 2015; Trice et al., 2019). Amidst the central North Sea, the Utsira 219 High represents a N-S trending basement structural high bounded by the Viking Graben to the west 220 and the Stord Basin to the east (Fig. 1a, d) (Gabrielsen et al., 2001). The basement unit in its core is 221 mainly composed of Ordovician-Silurian granitoid and gabbroid rocks (Riber et al., 2015). 222 Petrological, geochronological, and geophysical data suggest that, prior to the opening of the North 223 Sea, the crystalline basement of Bømlo and the basement units of the Utsira High likely belonged to the same unit of the Upper Allochthon (Slagstad et al., 2011; Lundmark et al., 2014; Riber et al., 224

225 2015; Fredin et al., 2017b; Lothe et al., 2018; Trice et al., 2019). The seismically imaged topbasement topography of the Utsira High shows the occurrence of widespread fracture lineaments and 226 227 fault zones, resembling the onshore joint-aligned valley morphology of the Bømlo region (Fredin et 228 al., 2017b). The pervasive and variably oriented fracture lineaments and fault zones thus suggest that, 229 similarly to the onshore margin, the Utsira High also underwent a prolonged and multi-phased brittle 230 deformation history (Fredin et al., 2017b). Brittle deformation probably started in the Permian-231 Triassic during the first rifting phase of the North Sea, and ended in the Cretaceous-Paleogene with 232 the northward migration of the rifting activity toward the Mid-Norwegian margin (Bell et al., 2014; Scheiber and Viola, 2018). Offshore exploration wells have identified the occurrence of a variably 233 234 preserved 1–10 m thick weathering profile atop of the fractured granitoid basement (Fig. 2a) (Riber 235 et al., 2015; Trice et al., 2019). The weathering profile, from top to bottom, consists of (Fig. 2b) 236 (Riber et al., 2015, 2016, 2017, 2019a): (i) clay-rich, saprolite – incoherent alteration facies A5 of 237 Riber et al., (2016); (ii) grus-type saprock, in which the granitoid magmatic texture is still preserved 238 - incoherent alteration facies A3-A4 of Riber et al., (2016); (iii) coherent, partially weathered 239 granitoid, still preserving the magmatic texture and mechanical properties of the host rock – alteration 240 facies A1-A2 of Riber et al., (2016). K-Ar dating on authigenic illite from core samples of the 241 saprolitic level in the weathering profile has shown that the Utsira High crystalline basement was 242 exposed to sub-aerial conditions and weathering during the Triassic ( $206 \pm 4$  Ma) (Fredin et al., 243 2017b).

After the Late Triassic, burial and sedimentation affected the whole passive margin (including the Utsira High and Bømlo region), causing the deposition of a several km thick Mesozoic sedimentary succession (Sclater and Christie, 1980; Gabrielsen et al., 2001; Bell et al., 2014). The buried Utsira High fractured–and–weathered basement acted as a system reservoir–trap for oil and currently, thus, represents an economically viable unconventional oil play (Trice et al., 2019). Offshore exploration wells have identified exploitable oil resources hosted in the basement–top weathering profile beneath 250 the sedimentary cover (Fig. 2a-b) (Riber et al., 2015, 2017). Pre-Cretaceous SRS faults bound 251 laterally the reservoir basement blocks, which are overlain by the Jurassic-Cretaceous sedimentary 252 cover that acted as both lateral source rock and top-seal unit for oil-migration within the structural 253 high (Trice et al., 2019). Jurassic-Cretaceous sedimentation likely affected also the Bømlo region, as 254 inferred from the occurrence of Late-Mesozoic sedimentary basins close to the present-day onshore 255 area (Fredin et al., 2017b, 2017a). Onshore, the Mesozoic sedimentary cover and the underlying 256 Triassic top-basement weathering profile have been almost completely eroded by geomorphic and 257 glaciogenic processes during the Cenozoic (Fredin et al., 2017b; Riber et al., 2017). As a consequence, only the deepest portions of the top-basement weathering profile are locally preserved, 258 259 particularly where the effects of weathering penetrated for a few tens of m into the crystalline basement along discrete structural discontinuities (i.e. fracture and fault zones; Fig. 2c) (Fredin et al., 260 261 2017b). The deepest portion of the weathering profile, preserved in these structurally-controlled 262 depressions may, therefore, have escaped from significant textural, mechanical, and mineralogical 263 modifications related to the subsequent Cenozoic erosion, weathering or alteration (Fredin et al., 264 2017b, 2017a; Lothe et al., 2018)

For these reasons, an increasing number of multidisciplinary studies in the region considers the fractured and weathered crystalline basement exposed on Bømlo as a reliable onshore analogue of the offshore crystalline basement of the Utsira High (Fredin et al., 2017b; Lothe et al., 2018; Banks et al., 2019; Trice et al., 2019).

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#### **3. Methods**

Our structural analysis focussed on the identification and characterisation of meso-scale fracture patterns and the definition of the main structural domains related to faulting. The investigation of petrophysical (permeability) and geomechanical (uniaxial compressive strength) properties has been carried out directly in the field on selected representative outcrops. In-situ permeability 275 measurements have been carried out with a New England Research TinyPerm-3 air-276 minipermeameter on both fault rocks and alteration products related to basement weathering and 277 saprolitisation. The minipermeameter is calibrated by the manufacturer with known standards. The 278 instrument allows a reliable field investigation of rock permeability within small volumes  $(1-1.5 \text{ cm}^3)$ 279 in the 10<sup>-3</sup>–10 D range, even though controlled laboratory tests have demonstrated its capability to measure permeability values as low as 10<sup>-5</sup> D (Filomena et al., 2014). In the bulk-rock permeability 280 281 mode, the instrument directly yields an estimate of the permeability based on the outgoing air flow 282 rate from the built-in compression vessel. Permeability values obtained from air-minipermeametry 283 need to be corrected and standardised in order to be comparable with permeability values obtained 284 from laboratory tests on rock plugs or image analysis (Fossen et al., 2011; Filomena et al., 2014; 285 Torabi et al., 2018). Air-minipermeameters yield either larger permeability values (by a factor of 286 1.7-1.8) when compared with results derived from image analysis quantifications (Fossen et al., 287 2011), or lower permeabilities (-37%) than those obtained from small (<10 cm) rock plugs used in 288 laboratory tests (Filomena et al., 2014). In addition, permeability estimates from permeametry tests 289 adopting a gas as permeating fluid (as in air-minipermeametry) can be significantly larger than the 290 estimates from permeability tests relying on a liquid as permeating fluid as a consequence of possible 291 slip-flow effects (Klinkenberg effect) (van Noort and Yarushina, 2019). This has to be considered 292 when using absolute gas permeability values to analyse the flow of a liquid in the same porous 293 medium.

The geomechanical characterisation has been carried out with a L–type Schmidt hammer (DRC
GeoHammer, 0.735 N·m impact energy) calibrated according to international standards (ASTM
D5873–00; EN 12 504–2; ASTM C 805–02). The reliability range of the instrument extends between
10 MPa and 300 MPa of UCS (Aydin and Basu, 2005).

We ran petrophysical and geomechanical analyses both on compositionally and texturally homogeneous volumes of the outcrops, thought to be representative of the bulk rock properties, and 300 along transects. Where rock textural anisotropies were present, we performed permeability and 301 Schmidt hammer analysis both perpendicular and parallel to the dominant planar rock fabric, aiming 302 at evaluating the potential anisotropy of petrophysical and geomechanical properties. Transects 303 allowed us to constrain the variation of the analysed properties across weathering fronts and high-304 density fracture zones. Surface spot analyses for both permeability and Schmidt hammer rebound 305 analyses have been done by probing representative outcrop surfaces with at least 10 measurements. 306 Selected measuring spots were at least 10–15 cm away from mesoscopic fractures wherever possible 307 (Aydin and Basu, 2005). Both permeability and Schmidt hammer rebound analyses were repeated 308 twice in the immediate surroundings of the selected spot along transects, for a total of three 309 measurements. The replicates were not exactly on the same point to avoid results biased by subtle 310 rock modifications (e.g., compaction and microfracturing) due to the previous measurements. Each 311 measure spot was kept at c. 5–10 cm from the nearest measuring point both along transects and within 312 selected areas, and taken to be representative of a 5 cm-radius hemispherical volume below it (ASRM standards; Aydin and Basu, 2005; Aydin, 2009; Demirdag et al., 2009). UCS values were retrieved 313 314 from the analysis of Schmidt hammer rebound values (Aydin and Basu, 2005). Schmidt hammer 315 measurements were carried out perpendicularly to clear, fresh rock surfaces (wherever possible), 316 parallel to the horizontal direction. Schmidt hammer rebound values obtained from the in-situ 317 measurement were converted into UCS by following the hammer orientation-dependent calibration 318 curves provided by the manufacturer. Horizontal rebound values were converted into UCS by the 319 following equation:

320

$$UCS = 0.0232 * R^{2.2637}$$
 (MPa)

321 Presented data are not corrected or standardised, so as to fully capture the heterogeneity and potential
322 spread of rock mechanical properties (Aydin, 2009).

At one outcrop, fracture pattern characteristics have been quantified by using circular scan windows
 along a transect previously adopted for petrophysical and geomechanical analysis (Watkins et al.,

325 2015). The results of fracture intensity (P21) quantification from circular scan windows 10-cm-326 diameter have been compared with the along-transect variation of mechanical strength (Vignaroli et 327 al., 2019). The same outcrop has been analysed also with a 1.4 m radius circular scan window to 328 capture the outcrop scale characteristics of the fracture pattern. A schematic representation of the 329 tectonic fractures of the outcrop has been obtained by line drawing on an outcrop field photo. The 330 resulting line drawing has been analysed with FracPaQ (Healy et al., 2017) in order to quantify 331 fracture intensity and 2D permeability at the outcrop scale in the direction of fluid flow (Long et al., 332 1982; Watkins et al., 2018).

333

#### **4. Results**

#### 335 4.1 Outcrop description

336 On Bømlo, we have investigated five outcrops representative of the different deformation and 337 weathering product end members, to constrain their mesoscopic structural characteristics as well as 338 their petrophysical and geomechanical properties. Some of the analysed outcrops contain both 339 structural and weathering features. For the clarity of presentation and discussion, outcrops are 340 grouped into Group S (representative of structural features, S<sub>1</sub> to S<sub>3</sub>) and Group W (weathering 341 features, W1 to W3) (Figs. 1c, 2c-d). Magmatic dykes, greisens and mineralised veins are common 342 in the RGD. The detailed characterisation of their mechanical strength and permeability properties is, 343 however, beyond the scope of this paper.

Group S includes outcrops where we measured the geomechanical and petrophysical characteristics of discrete mesoscopic deformation zones (Fig. 2c). Our field investigations focussed mainly on the analysis of fracture corridors and major (either SSRS or SRS) fault zones formed during the Permian to Cretaceous interval, which significantly contributed to the development and modification of the crystalline basement permeability (Scheiber and Viola, 2018; McCaffrey et al., 2020). The pervasive and widely distributed Ordovician to Devonian mineralised joints, shear fractures and minor faults 350 are commonly filled and sealed by different minerals (Scheiber and Viola, 2018), such that their 351 contribution to the overall current permeability of the crystalline basement is assumed to be very 352 limited (Watkins et al., 2018; McCaffrey et al., 2020). The field criteria adopted for the classification 353 of different structures include: (i) the width of the deformation zone, as indicated by the across-strike thickness of the fractured domain; (ii) the occurrence/lack of fault rocks within the deformation zone; 354 355 (iii) the width of the fault rock-bearing deformation zone (fault core). The width of the fault core may 356 help us to quantify the minimum fault throw, and thus discriminate between SSRS and SRS 357 deformation zones. The structural features included in Group S are: SSRS fracture corridors (S<sub>1</sub>), a SSRS fault zone (S<sub>2</sub>), and a SRS fault zone (S<sub>3</sub>). Group S is numbered according to the increasing 358 359 size of the studied structural features (fracture/fault zone width) as constrained by outcrop observations. The analysis of these outcrops allowed us to constrain the mechanical strength and 360 361 permeability variation related to: (1) high-intensity fracture zones within (SSRS) fracture corridors; 362 (2) fault rock development and distribution within SSRS and SRS fault cores.

363 Group W includes outcrops used to characterise the weathering features affecting the crystalline 364 basement. Each Group W outcrop has already been previously analysed and sampled for illite K-Ar 365 dating aiming at constraining the age of weathering (Viola et al., 2016; Fredin et al., 2017b; Scheiber 366 and Viola, 2018). Results from XRD analysis (Table 1) reported in the cited references are here 367 adopted to qualitatively characterise the mineral composition of weathering products. Group W 368 includes: outcrop W1 formed by partially altered RGD with incipient weathering and discolouring 369 mainly localised along fractures; outcrop W<sub>2</sub> formed by cohesionless, altered RGD, still preserving 370 the RGD magmatic structure but completely transformed into a sandy aggregate (saprock – grus); 371 outcrop W<sub>3</sub> formed by cohesionless, altered RGD with increasing clay content (saprolite). The W 372 outcrops are presented herein from W1 to W3 according to the increasing degree of weathering (from 373 incipient to evolved weathering). The degree of weathering has been qualitatively deduced directly 374 on the field comparing the mechanical/textural characteristics of the weathering products with those described by Riber et al. (2016) for the alteration facies of the Utsira High core samples. In all the
analysed outcrops, alteration/weathering products invariably postdate the formation of brittle
deformation zones.

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## 4.1.1 Group S – Fractures and fault zones within the crystalline basement

**Outcrop**  $S_1$ . This outcrop contains a deformation zone defined by a 10–15 m thick fracture corridor. 380 381 The central portion of the fracture corridor is characterised by a 2-5 m thick zone of high fracture-382 intensity (average fracture spacing = 0.05-0.1 m), composed of NNE-SSW-trending subvertical 383 open fractures (Fig. 3a). Mesoscopic fractures are usually longer than 0.5–1 m along the dip direction, 384 generally subparallel, but still locally forming a well-interconnected fracture network. Their typical 385 aperture (sensu Ortega et al., 2006) is in the order of <1 mm. This deformation zone likely 386 accommodated minor (<1m) lateral displacement, as inferred by the only local and rare development 387 of fault striae (mainly strike-slip) on fracture surfaces and the limited offset (c. 6 cm) of crosscut 388 magmatic markers (Scheiber and Viola, 2018). The outcrop is generally fresh, although fractures are 389 in some cases filled with granular material probably related to either alteration or presence of fault 390 rocks along the major fracture planes. The presence of now-eroded saprolite horizons has been 391 inferred above the outcrop (Fig. 6g-h in Scheiber and Viola, 2018). The finest grain-size fractions of 392 the alteration rock observed within the fractures are enriched in smectite-like clays of Jurassic age 393  $(187.5 \pm 16.7 \text{ Ma}; \text{ Table 1})$ , as inferred from K–Ar dating on authigenic illite (sample TSC–1 of 394 Scheiber and Viola, 2018). Alteration of the rock postdates the formation of the fracture corridor, 395 which is thus older than Jurassic in age. The only limited throw (< 1 m) and width of the fracture 396 corridor core (< 10 m) suggest that outcrop S<sub>1</sub> represents a SSRS fracture corridor.

398 **Outcrop** S<sub>2</sub>. Outcrop S<sub>2</sub> contains two subparallel, well-localised SSRS fault zones characterised by 399 a 10 cm thick cataclastic fault core (Fig. 6i-j in Scheiber and Viola, 2018). Each fault zone is 400 characterised by a polished principal slip surface (PSS) oriented 70°/140° (dip/dip direction) (Fig. 401 3b). The PSS is decorated by transtensive-kinematics slickenlines plunging 30°/070° (plunge/trend). 402 Several scattered, sub-vertical open fractures surround the fault core, defining a poorly developed 1-403 m-thick damage zone. Speculatively, the thickness of the fault core (10 cm) would be consistent with 404 a fault throw in the order of 1-10 m (Torabi and Berg, 2011). The limited fault core width and 405 estimated throw suggest that these fault zones may represent SSRS fault zones. The host RGD and 406 the cataclastic core are locally altered, as documented by the occurrence of an irregular volume of 407 sandy material (Fig. 3b). The alteration product is characterised by an increasing kaolinite content 408 over smectite (sample TSC-36 of Scheiber and Viola, 2018). K-Ar dating on authigenic clays 409 constrains alteration to the Cretaceous ( $127.4 \pm 16.5$  Ma, Table 1). Therefore, the age of faulting must 410 be older than Cretaceous in age.

411

412 Outcrop S<sub>3</sub>. The Goddo Fault Zone (GFZ) crops out along a road cut on the island of Goddo 413 (northwestern Bømlo, Figs. 1b-4). The GFZ represents a E-dipping normal fault zone formed and 414 reactivated during Permian-to-Cretaceous extensional tectonics (Viola et al., 2016; Fredin et al., 415 2017b; Scheiber and Viola, 2018). It is characterised by two separate and distinct fault cores (marked 416 as S<sub>3A</sub> and S<sub>3B</sub> in Fig. 4a-b), separated and surrounded by highly fractured damage zones (Figs. 4a-417 b, 5a-b). The two fault cores consist of several brittle structural facies (sensu Tartaglia et al., 2020), 418 i.e. different fault rocks characterised by different texture, mineralogical assemblages, and ages of 419 formation (Viola et al., 2016). Brittle structural facies observed within the fault core include: (a) a 420 polished PSS overlain by (b) a massive, well-sorted clay-rich gouge, (c) a phyllonitic gouge, and (d) 421 a cohesive cataclasite (Fig. 5a-d). The PSS of the GFZ consists of a 1-2 cm-thick fine-grained quartz-coated polished surface, dipping 50°/070° and bearing dip-slip slickenlines (50°/070°) 422

423 associated with top-to-the-east normal fault steps (Fig. 5c-d). The overlying gouge core is 20-30 424 cm thick and it is composed of two main gouge layers showing different textures and age of formation 425 (Viola et al., 2016). The clay-rich gouge consists of a 5-10 cm thick homogeneous and isotropic 426 plastic gouge (Fig. 5c-d). The phyllonitic-gouge consists of a scaly, phyllosilicate-rich gouge containing a pervasive S-C' composite fabric (Fig. 5d). K-Ar illite dating showed that the phyllonitic 427 428 gouge of the fault core  $S_{3B}$  developed during Permian extension (264.1 ± 5.4 Ma; Table 1); Triassic– 429 Early Jurassic fault reactivation led to the formation of the clay-rich gouge and reworking of the 430 phyllonitic gouge in the  $S_{3B}$  fault core (200.2 ± 4.1 Ma; Table 1) (Viola et al., 2016). The gouges are 431 overlain by a 20-40 cm thick layer of indurated cataclasite, containing internal discrete shear planes 432 decorated by purple-reddish-orange coatings of Fe-oxides (Fig. 5d). The occurrence of fault rocks is limited to the two described fault cores. The phyllonitic gouge is only observed in the S3B fault core 433 434 (Fig. 5d). No fault breccia bounding the fault core is observed.

The thickness of each fault core is in the order of 0.6-1 m (Fig. 5c-d), suggesting that each fault core 435 436 may have accommodated a cumulative normal throw of 10-100 m (Torabi and Berg, 2011), thus 437 defining a valuable example of a SRS fault zone (Viola et al., 2016). Accordingly, the damage zone 438 width would be in the order of 10 to 100 m (Wilson et al., 2003; Faulkner et al., 2006, 2010). The 439 damage zone is characterised by densely spaced (average spacing = 0.1-0.5 m) mesoscopic fractures 440 related to both the background basement fracturing and to the GFZ itself (Scheiber and Viola, 2018). 441 The GFZ damage zone is well exposed in the footwall, and between fault cores, whereas the geometry 442 and exposure of the outcrop did not allow us to quantify the exact thickness of the hanging wall 443 damage zone and the entire fault zone in the field (Fig. 4).

444

### 4.1.2 Group W – Weathered outcrops

445 **Outcrop W**<sub>1</sub>. The outcrop is in the same locality of outcrop S<sub>3</sub>–GFZ. The whole GFZ is crosscut by 446 a series of poorly exposed alteration/weathering zones (outcrops marked with  $W_{1A}$ – $W_{1B}$  in Fig. 4a; 447 Fig. 6a–b). These weathering zones are spatially related to NNE–SSW, 1–2 m thick fracture corridors 448 cutting across both the undeformed RGD host (Fig. 6a) and fault rocks (Fig. 6b) (Viola et al., 2016; 449 Scheiber and Viola, 2018). The granodiorite within the fracture corridor mostly preserves its primary 450 structure and cohesion at the hand specimen scale. Partially altered host rock lithons within the 451 fracture corridor are embedded in a cohesionless granular matrix, mainly composed of quartz and 452 clay minerals, which forms much less than 50 vol% of the altered outcrop (Fig. 6a-b). The 453 mineralogical composition of the finest fraction of this matrix is dominated by smectite, as inferred 454 from the sample BO-OFR-1 presented in Viola et al. (2016) and Fredin et al. (2017b). The 455 weathering material included therein has been dated to the Early Cretaceous ( $125.2 \pm 4.2$  Ma, Table 456 1). The mineralogical composition and textural characteristics of the weathering products suggest that 457 this outcrop is equivalent to the alteration facies A1 described by Riber et al. (2016).

458 **Outcrop W2.** Outcrop W2 is characterised by the occurrence of a pervasive NNW-SSE-trending 459 fracture set (Fig. 6c). Fractures are preferentially organised in 1-m-thick clusters, separated by 2–5 m 460 of non-fractured RGD host. Commonly, rock volumes within fracture clusters are heavily altered and 461 transformed in a variably cohesive granular material preserving the magmatic fabric. Measurements 462 were performed along a transect perpendicular to the main fracture trend, on a vertical surface and 463 crossing through an alteration zone exhibiting a variable degree of weathering (from left to right in 464 Fig. 6c). Qualitatively, the outcrop was subdivided into three main domains: (i) partially altered host 465 granodiorite with some localised mesoscopic fractures (domain d1 in Fig. 6c), (ii) granular 466 cohesionless aggregate preserving the granodiorite fabric but no mesoscopic fractures (domain d2 in 467 Fig. 6c), (iii) granular aggregate with increasing clay content (domain d3 in Fig. 6c), as inferred from 468 plastic deformation of hand samples. Unpublished K-Ar illite dating data suggest that this alteration 469 is older than Triassic and its mineralogical composition dominated by smectite (A. Margreth personal 470 communication). As reported earlier, similar weathering characteristics have been observed in 471 outcrop S<sub>2</sub>.

472	Outcrop W <sub>3</sub> . The outcrop is characterised by a 2 m thick altered rock volume within granodiorite,
473	bounded by N–S trending fractures. The altered volume consists of a cohesionless granular aggregate,
474	grading from saprock to mature, fine-grained clay-rich saprolite, enveloping variably altered "core
475	stones" (i.e., remnant blocks of granodiorite less weathered than the embedding material and resulting
476	from spheroidal weathering processes; cfr.Ryan et al., 2005; Fig. 6d) (Fredin et al., 2017b, 2017a).
477	Weathering products in outcrop W <sub>3</sub> are well represented by the samples (Bomlo2–3–4) analysed by
478	Fredin et al. (2017a,b), with a predominantly kaolinitic composition and likely developed during sub-
479	aerial exposure of the crystalline basement in the Triassic (220–200 Ma, Table 1; Fredin et al., 2017b).

		XRD Data									K-Ar Dating			
Outcrop	Sample ID	Grain Size (µm)	Quartz	Kaolin	Illite/Mica 2M1	Illite/Mica 1M	Dioctahedral smectite	Interstratified illite/smectite	Albite/Anorthite	Anatase	Lepidocro cite	Age (Ma)	Error (Ma)	Ref.
	TSC-1	0.1 - 0.4		5			95		<]			187.5	16.7	[3]
S1		0.4 - 2	<1	9			87		4			192.6	13.7	
		2 - 6	1	18			75		6			260.4	8.1	
	TSC-36	< 0.1		7			93					127.4	16.5	[3]
62		0.1 - 0.4		25			75		<1	<1		177.6	16.2	
52		0.4 - 2	<1	29	2		67		2	<1		261.7	8.4	
		2 - 6	<1	22	4		71		3	<1		324.0	9.0	
	BO-GVI-1	< 0.1		1	20			79				200.2	4.1	[1]
		0.1 - 0.4		5	21		6	68				218.9	4.4	
		0.4 - 2	3	16	28		24	29		<1		240.7	5.0	
		2 - 6	34	8	14		13	30	1			272.1	5.5	
		6 - 10	35	8	17		12	27	1			282.9	5.7	
S3														
	BO-GVI-2	<0.1	<1	12	14	4	20	49	1			264.1	5.4	[1]
		0.1 - 0.4										262.0	5.3	
		0.4 - 2										303.8	6.3	
		2 - 6	2	9	32	2	16	35	4			349.6	7.1	
		6 - 10	2	9	33	4	17	31	4			354.4	7.1	-
		< 0.1		7			93		<1			125.2	4.2	[1]
	BO-OFR-1	0.1 - 0.4		7	1		93	ĺ	<1			121.4	5.3	
W1		0.4 - 2		16	1		82	l .	2			167.7	6.5	
		2 - 6	<1	22	3		71	1	3	<1		272.1	5.8	
		6 - 10	<1	25	2		68		4	1		287.5	6.2	
		<0.1					20				11	210.0	12.1	[2]
	Bømlo 2	<u>~0.1</u>		4			79		2		16	210.0	10.6	[4]
		0.1 - 0.4	<1	7			20		2		7	290.2	28.2	
		2.6	<1	· ·	6		70		2	<1	4	406.0	20.2	
		2-0	~1	0	0		19		5	~1	-4	400.9	20.5	
W3	Bamla 2	<2	<1	76	1		23					217.3	4.8	[2]
	Bømio 3	2 - 6	<1	72	3		24							
			-1				14					222.0		102
	Bømlo 4	<2	<1	53			46		1			233.0	5.0	[2]
		2-6	<1	53	2		43		2					

482

**Table 1.** XRD data and K–Ar dates from synkinematic/authigenic illite samples of the outcrops
studied in this paper. References: [1] Viola et al. (2016); [2] Fredin et al. (2017b); [3] Scheiber and

485 Viola (2018).



Figure 3: (a) Fracture corridor at outcrop S<sub>1</sub>. (b) The fault zone of outcrop S<sub>2</sub> is characterised by a thin, well–localised, gouge– and cataclasite–rich fault core enveloped by a 1 m thick, poorly– developed damage zone. Fluids percolating through the fault core led to the alteration of cataclasite and the damage zone observed in the central portion of the image. PSS: Principal Slip Surface. Stereonets: Lower hemisphere, equal area projection of fractures and fault planes. The black arrows represent the direction of movement of the hanging wall along the fault plane.





- 496 Figure 4: (a) Schematic map of the Goddo Fault Zone (outcrop S<sub>3</sub>) overlain on a composite UAV
- 497 orthophoto and LiDAR digital elevation model image. The location of the studied outcrops along the
- 498 fault zone (S<sub>3A</sub>, S<sub>3B</sub>, W<sub>1A</sub>, W<sub>1B</sub>) is also reported. Black thick lines represent fracture lineaments
- 499 spatially related to discrete alteration zones. The black dashed lines bracket the supposed maximum
- 500 width of the damage zone. (b) Geological cross section along the A–A' profile of the Goddo Fault
- 501 Zone. FC: Fault core; DZ: Damage zone.



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**Figure 5**: Representative outcrops of the Goddo Fault Zone. (a) Fault core at outcrop S<sub>3A</sub>, showing the composite fault core. (b) Composite fault core and the reactivated slip surface of a "greisen" prefaulting fracture exposed at S<sub>3B</sub>. (c) Composite fault core at S<sub>3A</sub>, showing the juxtaposition of cataclasite, gouges, and PSS. (d) Composite fault core at S<sub>3B</sub>, showing the juxtaposition of cataclasite, gouge, and PSS. Note the alteration of the cataclasite layers. Stereonets: Lower hemisphere, equal area projection of fractures and fault planes at S<sub>3</sub>. The whole dataset of fracture and fault planes

510 collected on the field is reported as contoured distribution of poles to fracture and fault planes (in 511 red). Black great circle represent only those fracture and fault planes characterised by slip lines 512 (lineations, slickenlines). The black arrows represent the direction of movement of the hanging wall 513 along the fault plane.



515

516 Figure 6: Representative outcrops of weathered granodiorite. (a) Alteration zone W1A related to a 517 NNE-SSW-trending fracture lineament. (b) Alteration of the host granodiorite within the damage 518 zone of the GFZ at W<sub>1B</sub> (detail of Fig. 5b). (c) Outcrop W<sub>2</sub> showing an increasing alteration profile 519 along which we performed Schmidt hammer analysis and permeability measurements. (d) Outcrop W3 (saprolite) showing relatively unaltered "core stones" (enclosed by dashed white lines). The thick 520 521 white lines (A, B) represent the profile along which permeability and UCS measurements have been 522 performed. Stereonets: Lower hemisphere, equal area projection of fracture planes at outcrops W<sub>1</sub>, 523 W<sub>2</sub> and W<sub>3</sub>. Orientation of fractures within fracture clusters related to weathering zones at outcrop 524 W<sub>2</sub> are highlighted in orange in the stereoplot.

#### 526 4.2 UCS and permeability data

527 Data are presented in the following according to rock type (host rock, fault rocks and weathering 528 products) as observed from many different outcrops, to derive an average value and constrain the 529 natural variability range for each lithology. Average values of UCS and related standard deviations 530 are reported in the text and Fig. 7a. Permeability ranges are presented in the text and data distributions 531 are reported as boxplots in Fig. 7b.

#### 532 *4.2.1 Host rock*

533 The RGD on the island of Bømlo still well preserves its magmatic texture and mineralogical 534 composition. No pervasive ductile fabrics have been observed at the analysed outcrops, confirming 535 the observations of Scheiber and Viola (2018). UCS values for the RGD host as observed at three 536 different localities (outcrops S1-S2-W3). Fresh, non-altered and non-mineralised granodiorite 537 surfaces yield an average UCS value of  $169 \pm 36$  MPa. Granodiorite surfaces bounding alteration/weathering zones (measured at outcrops W2-W3) exhibit a lower range of UCS variability, 538 539 with an average value of  $107 \pm 29$  MPa ("Weathered Granodiorite surface" in Fig. 7a). Results from 540 permeability measurements on the pristine, non-fractured host granodiorite at different outcrops range between <10<sup>-4</sup> D (below the actual reliability limit of the air–minipermeameter) and 0.1 D (Fig. 541 542 7b).

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## 544

## 4.2.2 Outcrop S<sub>1</sub> – SSRS Fracture corridor

545 UCS measurements are from along a transect perpendicular to fracture strike. In order to evaluate the 546 influence of fracture intensity on the UCS, we have quantified fracture intensity with circular scan 547 windows (10 cm in diameter) centred on each measurement spot along the transect (Fig. 8a) (Watkins 548 et al., 2015). UCS values comparable to fresh and slightly altered host RGD are measured in the 549 outermost portion of the fracture corridor (Fig. 8b–c). Mechanical strength drastically decreases to 550 15–20 MPa toward the centre of the fracture corridor, where fracture intensity is higher (P<sub>21</sub> = 74 m<sup>-</sup>

<sup>1</sup>; Fig. 8b–c, e). The permeability is inferred to be related to only meso–scale fracture aperture and 551 552 interconnectivity. In order to have a relative comparison with the permeability data presented in the next sections, 2D structural permeability at the scale of the outcrop has been evaluated by analysing 553 554 the digitised fracture network obtained from line drawing on a field photo of the core zone with the software FracPaQ (Healy et al., 2017). During line drawing, only the subvertical fractures were 555 556 considered for the definition of the fracture network pattern (Fig. 8d). The subhorizontal fractures are 557 likely related to post-tectonic outcrop modifications related to either post-glacial unloading or man-558 made excavation and blasting operations, given that such fracture orientation is not observed in any other fracture set related to the brittle deformation history of the Bømlo crystalline basement 559 560 (Scheiber and Viola, 2018). The 2D permeability of the fracture pattern in the direction of flow was calculated considering a range of different values of fracture aperture, ranging from 0.01 to 1 mm and 561 562 perfect connectivity among fractures. The outcrop-scale maximum permeability is always oriented parallel to the dominant subvertical fractures, and maximum values range between 10<sup>3</sup> D to 10<sup>-3</sup> D. 563 564 for a fracture aperture of 1 mm and 0.01 mm, respectively (Fig. 8e).

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- 566

#### 4.2.3 Outcrops S<sub>2</sub>–S<sub>3</sub> –Fault rocks

UCS bulk rock data on fault rocks have been measured at the S<sub>2</sub> and S<sub>3</sub> outcrops. The PSS is 567 568 characterised by high UCS values when analysed normal to the surface  $(274 \pm 32 \text{ MPa}, \text{Fig. 7a})$ . 569 Permeability measured normal to the slip surface is in the 0.05 to 0.06 D range (Fig. 7b). UCS of the 570 clay-rich gouge layer is  $12 \pm 2$  MPa, measured parallel to fault strike. Gouge layers present a lower range of permeability, between 10<sup>-3</sup> D and 0.4 D measured parallel to fault strike (Fig. 7b). The rough 571 572 exposure surface of the phyllonitic gouge facies did not allow us to perform reliable measurements 573 (Fig. 5d). The cataclasite shows strongly anisotropic UCS, as inferred comparing the results obtained 574 from measurements performed parallel (36  $\pm$  22 MPa) and perpendicular (195  $\pm$  37 MPa) to fault strike (Fig. 7a). The cataclastic core presents a variable permeability ranging between 10<sup>-3</sup> D and 3 D 575
577

when measured parallel to fault strike (Fig. 7b). The rough exposure surface of the cataclasite did not allow us to perform reliable measurements of permeability perpendicular to fault strike.

## 578 *4.2.4 Group W*<sub>1</sub>–*W*<sub>3</sub>. Weathering along fractures and fault zones

**Outcrop W1.** UCS for altered granodiorite ranges between 30 and 90 MPa ("Weathered Granodiorite" in Fig. 7a). Values larger than 100 MPa are found in the weathered host granodiorite where the alteration is locally less developed. In the fracture corridor, altered granodiorite lithons are surrounded by a fine–grained sandy, rather non–cohesive matrix that exhibits low UCS values (<15 MPa) ("loose matrix" in Fig. 7a). The host granodiorite altered lithons exhibit a variable permeability, ranging between  $10^{-3}$  D and 0.84 D (Fig. 7b).

585 Outcrop W<sub>2</sub>. Outcrop W<sub>2</sub> displays a clear variation of mechanical strength and permeability with 586 increasing weathering grade (Figs. 6c, 9a). Incipient alteration in domain d1 exhibits variable UCS between 20 and 50 MPa and variable permeability ranging between 10<sup>-3</sup> D and 1 D. Similar values 587 588 were measured from the altered RGD observed at outcrop S<sub>2</sub>. The cohesionless alteration products in 589 domain d2, consisting of a grus-type sandy aggregate, yields UCS values <20 MPa. Permeability 590 increases (from 0.1 D up to several Darcy's) and then decreases (from >1 D down to 0.01–0.1 D) 591 moving from the left-hand side boundary to domain *d1* toward the right-hand side boundary to 592 domain d3 (Figs. 6c, 9a). Alteration domain d3 is characterised by variable UCS < 20 MPa, and low 593 permeability (from 0.01–0.1 D down to few mD).

594 **Outcrop W<sub>3</sub>.** Partially weathered "core stones" exhibit a broad range of UCS values, ranging between 595 75 MPa and 125 MPa (Fig. 7a). They have a permeability included between 0.01 D and 0.1 D (Fig. 596 7b). The clay–rich saprolite volume has been analysed along two transects (Fig. 6d). Both transects 597 yield almost constant UCS and permeability values within the clay–rich saprolite (UCS = 10–15 MPa, 598  $k = 10^{-2}-10^{-3}$  D) (Fig. 9b).



602 Figure 7: Mechanical strength and permeability box-plot diagrams. "Strike //" stands for data measured parallel to the fault plane. "Strike + " stands for data measured perpendicular to the fault 603 plane. (a) Uniaxial Compressive Strength (UCS, MPa). For each analysed lithology we report the 604 mean (orange dot), the standard deviation  $(1\sigma, black bars)$ , the number of measurements (N), the 605 606 outcrop(s) name on which the measurements were performed, and the corresponding alteration facies. (b) Permeability (m<sup>2</sup>, D). The outcrop name and the corresponding alteration facies are reported. N: 607 608 number of measurements for each lithology. Each box of the box-and-whiskers plot represents the range between the 1<sup>st</sup> and 3<sup>rd</sup> quartile of the distribution. The whole data range is represented by the 609 610 extension of the whiskers. In (b) we also plot the logarithm of the permeability ratio  $(Log_{10}(k/k_{HR}))$ 611 between the host rock and the selected lithology (Scibek, 2020). The ratio between mean values of 612 permeability (blue dots) and the ratio between the minimum reported values (red dots) for each

- 613 lithology are also reported. It is worth noting that air-minipermeametry retrieved permeability values
- 614 for saprolites are comparable to those obtained from laboratory measurements on saprolite samples
- 615 from Bømlo and the Utsira High exploration wells (Lothe et al., 2018).



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**Figure 8**: Results of the geomechanical and permeability measurements at outcrop S<sub>1</sub>. (a) Location of the measurements for the Schmidt hammer analysis, and circular scan windows for fracture intensity P<sub>21</sub> quantification; (b) Variation of mechanical strength (UCS) and fracture intensity (P<sub>21</sub>) along the analysed transect. (c) UCS against fracture intensity P<sub>21</sub>. Note the drastic decrease of mechanical strength after a threshold value of P<sub>21</sub> at about 45 m<sup>-1</sup>. (d) Line drawing of the subvertical fracture network analysed with FracPaQ (Healy et al., 2017); (e) Results of 2D permeability and fracture intensity quantification from FracPaQ..



Figure 9: Results of mechanical strength and permeability quantification along the transect at
outcrops (a) W<sub>2</sub> and (b) W<sub>3</sub>. Letters A and B in (b) refer to the two transects shown in Fig. 6d.

#### 631 5. Discussion

We have characterised the structural and weathering features controlling the matrix permeability and mechanical properties of the fractured and altered crystalline basement at a number of representative outcrops. In the following paragraphs we discuss (i) the host rock properties, (ii) the matrix permeability related to SSRS and SRS deformation zones, (iii) the mechanical strength and permeability related to weathering products, and (iv) their bearings on the definition of reservoir rock in crystalline basement structural highs.

638 The data presented in this paper represent the present-day, actual mechanical strength and 639 permeability at surficial, ambient conditions. The extrapolation of these values to depth (at deeper 640 structural levels or buried below a sedimentary cover) needs to take into consideration the effect of 641 increasing confining pressure and temperature and the compaction processes (Rutqvist and 642 Stephansson, 2003; Faulkner, 2004; Faulkner et al., 2006; Lothe et al., 2018). A further complication 643 arises from the fact that the analysed onshore outcrops may have been affected by renewed alteration 644 related to Cenozoic geomorphic and glaciogenic processes, which the fractured and weathered 645 crystalline basement buried in the North Sea by the Mesozoic cover has, instead, probably escaped. 646 The petrophysical and mechanical data presented here, however, are comparable (on average) with 647 other results in the literature from standardised laboratory tests on fresh samples from onshore 648 outcrops and offshore core samples of the same rock types analysed here (Lothe et al., 2018; Walter 649 et al., 2018; Høien et al., 2019). This suggests that possible Cenozoic geomorphic and glaciogenic 650 processes have only slightly affected the textural, mechanical and petrophysical characteristics of the 651 studied onshore outcrops.

## 652 5.1 Host rock properties

The observed host granodiorite UCS is comparable to the reference values reported in the database by SINTEF for Norwegian rock types (Høien et al., 2019). Permeability data from the RGD are quite different from available laboratory permeability measurements on intact rocks (Sibson and Rowland, 656 2003). Most of the host rock permeability values are comparable with permeability values obtained 657 from fractured crystalline and igneous rock in fault damage zones (Forster and Evans, 1991; Evans et al., 1997; Cappa and Rutqvist, 2011; Gomila et al., 2016). This discrepancy might be related to 658 659 either: (i) an analytical error during measurement (i.e. air slippage from the non-perfectly sealed 660 contact between the probe tip and the rough surface); (ii) enhanced permeability related to the 661 increased microfracture density in the proximity of fracture and fault zones (Mitchell and Faulkner, 662 2012; Belaidi et al., 2018; Torabi et al., 2018; Staněk and Géraud, 2019); (iii) enhanced permeability related to recent, very local surficial weathering processes. Therefore, further investigations are 663 664 needed to properly constrain the permeability of the host RGD.

#### 665 5.2 Group S – Mechanical strength and permeability of deformation zones

The host crystalline basement (RGD) is overprinted by several sets of fractures, including fracture
corridors and SSRS–SRS fault zones (Gabrielsen and Braathen, 2014; Scheiber and Viola, 2018).
These fracture lineaments affect differently the mechanical and permeability properties of the host
RGD and thus require a separate discussion.

670

## 5.2.1 SSRS fracture corridors

671 Fracture corridors are characterised by high-fracture-intensity deformation zones, accommodating limited (< 1m) throw, mostly barren of fault rock. The outcrop mechanical strength and bulk 672 673 permeability are mainly controlled by the spatial distribution of meso-scale fractures (Fig. 8c, e). The 674 increase in local fracture intensity leads to a drastic decrease of the host rock mechanical strength for  $P_{21} > 40-50$  m/m<sup>2</sup> (Fig. 8b-c). High fracture intensity leads to a significant increase of fracture 675 permeability up to  $1-10^3$  D (Fig. 7b). The largest 2D permeability in the direction of flow is observed 676 677 parallel to the longer, subvertical and well interconnected fractures (Fig. 8e). Such a fracture network 678 represents a preferential pathway for fluid flow (Souque et al., 2019). Thus, the permeability of 679 limited-throw SSRS fracture corridors is controlled by the mesoscopic fracture porosity. On the other 680 hand, microscopic fracture porosity may contribute to the matrix mechanical strength and

681 permeability to only a very limited extent (Faulkner et al., 2006; Mitchell and Faulkner, 2012; Rempe 682 et al., 2018). A local increase in permeability related to microscopic fracture porosity is reported by 683 Torabi et al. (2018) for fracture corridors developed within the Øygarden Gneiss Complex in the 684 Bergen area. Therefore, such SSRS, limited–throw fractures remarkably affect both the overall 685 mechanical and permeability properties of the crystalline basement.

686

## 5.2.2 SSRS and SRS fault cores

687 Strain accommodation and development of fault rocks along SSRS-SRS fault zones resulted in a 688 drastic modification of textural, mechanical and petrophysical properties of the host RGD. Fault 689 zones, either SSRS or SRS, are characterised by the development of a variably thick fault core, 690 defined by the occurrence of fault rocks, and a variably developed damage zone (Caine et al., 1996). 691 SSRS fault cores are likely to be characterised by thin, single fault cores (< 1m thickness) surrounded 692 by poorly developed damage zones (e.g., outcrop S<sub>2</sub>). SRS fault zones, instead, may be characterised 693 by the occurrence of thicker ( $\geq 1$  m), multi–strand fault cores surrounded by complex, thick and high– 694 fracture-intensity damage zones (Walsh et al., 1999; Gabrielsen and Braathen, 2014).

In both SSRS and SRS fault zones, the fault core is characterised by a composite fault plane-parallel 695 696 sequence of fault rocks including a PSS, cataclasite, and potentially (several) gouge layers. Extreme 697 strain localisation and rock comminution resulted in the formation of a thin, yet mechanically strong, 698 PSS with a low permeability (Fig. 7a,b). Cataclasite mechanical strength is strongly anisotropic (Fig. 699 7a). Cataclasites are stronger (UCS >> 100 MPa) where measured normal to the fault plane and 700 weaker (UCS <50 MPa) where measured parallel to the fault plane. Cataclasite permeability is up to 701 two orders of magnitude larger than the average permeability of the host rock (Fig. 7b). Gouge layers 702 yield a very-low mechanical strength (UCS < 20 MPa), and low permeability parallel to the fault plane (k <  $10^{-1}$  D). A strong anisotropy in permeability is expected for both cataclasite and gouge 703 704 layers (up to three orders of magnitude) (Faulkner and Rutter, 1998). The lower strength and increased 705 permeability parallel to the fault plane is probably also related to a higher density of fault-parallel

706 microfractures and micro-shear planes within cataclasite and gouge layers (Zhang and Tullis, 1998). 707 A pervasive phyllosilicate-bearing foliation characterises the phyllonitic gouge of the GFZ. Thus, 708 even though we lack direct measurements, a strong permeability and strength anisotropy should be 709 expected for the phyllonitic gouge (Shea and Kronenberg, 1993; Niemeijer and Spiers, 2005; Leclère 710 et al., 2015). Cataclasites and gouge layers are in any case two orders of magnitude more permeable 711 that the host RGD (Fig. 7b). Grain-size reduction, cataclasis and microfracturing processes likely led 712 to the increased micro-fracture-related porosity of fault rocks with respect to that of the host 713 granodiorite (Staněk and Géraud, 2019).

#### 714

## 5.2.3 Damage zones

715 The discrete and multi-strand fault cores are surrounded by variably developed fracture-dominated 716 damage zones, whose width is one order of magnitude larger than fault core thickness (Faulkner et 717 al., 2010). The mechanical strength and bulk permeability of the damage zone is strictly dependent 718 on the intensity, mechanical properties and geometry of multi-scale fractures related to both the fault 719 zone and the basement background fracturing (Bruhn et al., 1994; Faulkner et al., 2006; 720 Gudmundsson et al., 2010; Mitchell and Faulkner, 2012; Rempe et al., 2018). Local permeability 721 within the damage zone might be as large as the permeability of similarly high-fracture-intensity 722 fracture corridors (Gabrielsen and Braathen, 2014). An accurate characterisation of the fracture 723 pattern geometry is needed to properly quantify the effect of mesoscopic fractures on the evolution 724 of mechanical properties and bulk permeability in a damage zone (Healy, 2008; Gudmundsson et al., 2010). 725

In conclusion, SSRS and SRS deformation zones have distinctive structural characteristics controlling their permeability structure. Low-strain, low-displacement SSRS fracture corridors characterised by open, non-mineralised fractures greatly enhance the permeability of the crystalline basement at the sub-seismic-resolution scale. They form very localised, narrow (1–10 m in width) highly-efficient conduits for fluid flow. The largest permeability is observed parallel to the average fracture plane 731 orientation. SSRS and SRS fault zones are characterised by two domains with characteristic 732 permeability (Caine et al., 1996; Evans et al., 1997): (i) the fault core, including low-permeability 733 fault rocks; (ii) the damage zone, defined by a high-permeability multiscale fracture network. The 734 permeability of fault rocks and damage zones is in any case several orders of magnitude larger than the host rock. Therefore, despite their effective (SSRS or SRS) or relative (fault core/damage zone 735 736 width ratio) size characteristics, fault zones developed within the granodioritic crystalline basement 737 of Bømlo are likely to act invariably as preferential conduits for fluid flow. Fluid flow will be 738 promoted in any directions parallel to the fault zone, along the highly fractured damage zones. Fluid 739 flow from footwall to hanging wall of SRS fault zones, or vice versa, might be buffered/limited by 740 the occurrence of relatively low-permeability fault cores.

## 5.3 Group W outcrops and a comparison with the Utsira High weathering profile

742 Several authors described in detail the mineralogical and textural changes of the granitoid crystalline 743 basement of the Utsira High related to the development of a saprolitic weathering profile identified 744 in the core samples of offshore exploratory wells (Riber et al., 2015, 2016, 2017, 2019a; Lothe et al., 745 2018). They describe five different alteration facies accounting for the observed gradual 746 disaggregation of the igneous host rock, the alteration of feldspar, and clay mineral formation. In their 747 model, progressive downward penetration of meteoric fluids from the top-basement surface led to 748 the development of a thick weathering profile containing both saprock and more mature saprolite formed at the expense of the host granitoid (Fig. 2a-b) (Riber et al., 2015, 2019b; Walter et al., 2018; 749 750 Zauyah et al., 2018). Weathering extends from the top-basement surface (that was exposed to a sub-751 aerial tropical-humid climate) into depth in the rock column: the progressive degradation of the host 752 rock primary structure and the presence of a pervasive network of fractures and fault zones promoted 753 the penetration at depth of fluids enhancing alteration (Braathen et al., 2018; Walter et al., 2018; 754 Zauyah et al., 2018). The weathering process induces specific textural and mineralogical modification 755 of the host rock. Incipient weathering along fractures leads to discolouring and limited mineral

alteration while still preserving the igneous/metamorphic rock texture ("altered coherent facies A1–
A2" in Riber et al., 2016; Fig. 2b). The alteration of biotite and plagioclase leads to progressive grain
disaggregation and grain fracturing, clay mineral and Al–Fe oxide formation (saprock – saprolite,
"altered incoherent facies A3–A5" in Riber et al., 2016; Fig. 2b) (Goodfellow et al., 2016; Hayes et
al., 2019). Progressive weathering is also reflected in a varying mineralogy of authigenic clay
minerals, with smectite being progressively substituted by kaolinite as the degree of weathering
increases (Coggan et al., 2013; Riber et al., 2016).

763 A similar transition in mineralogical and textural characteristics of the RGD with increasing alteration 764 can be deduced by the comparison of the preserved weathering remnants at the analysed Group W 765 outcrops. Each outcrop effectively shows different textural, mineralogical (clay-mineral amounts and 766 species), and mechanical characteristics, which indicate progressive weathering and alteration. 767 Outcrops W<sub>1</sub>–S<sub>1</sub> only display partial alteration of the wall rock along fractures while preserving the 768 textural and mechanical properties of the host rock. The weathering products are represented by 769 samples BO-OFR-1 (Viola et al., 2016) and TSC-1 (Scheiber and Viola, 2018). The finest-fractions 770 of these samples are enriched in smectite-like phases, suggesting only incipient alteration (Coggan 771 et al., 2013; Riber et al., 2016). The characteristics of this outcrop, thus, resemble those of the 772 "alteration facies A1-A2" described by Riber et al. (2016). The alteration products observed at 773 outcrop  $W_2$  document, instead, a transition from a coherent host rock (domain d1 in Fig. 6c) toward 774 a cohesionless, sandy, grus-type aggregate preserving the magmatic texture but not the mechanical 775 cohesion of the host rock and increasing clay content (domain d3 in Fig. 6c). The intermediate 776 alteration domain d2 at outcrop W<sub>2</sub> presents textural and mechanical characteristics similar to the 777 alteration products observed at outcrop S<sub>2</sub>. Sample TSC-36 from outcrop S<sub>2</sub> shows increasing 778 kaolinite content over smectite (Scheiber and Viola, 2018). The clay content and the textural 779 characteristics of domain d2 at outcrop  $W_2$  and outcrop  $S_2$  are similar to those described for "alteration 780 facies A3–A4" by Riber et al. (2016). The clay–rich alteration product in outcrop W<sub>3</sub> is present in the set of samples analysed by Fredin et al. (2017b) (Bomlo2–3–4). Kaolinite is predominant over
smectite–like phases, suggesting an advanced stage of alteration (Coggan et al., 2013; Riber et al.,
2016). Outcrop W<sub>3</sub> mineralogical and textural characteristics are similar to the "alteration facies A5"
described by Riber et al. (2016).

785 Even though the alteration products analysed in the Group W outcrops may result from diachronic 786 events, they all present textural and mineralogical characteristics which are ascribable to 787 kaolinitisation and/or saprolitisation of the RGD host (Coggan et al., 2013; Riber et al., 2016; Fredin 788 et al., 2017b). Indeed, alteration processes took place at either shallow crustal levels (<6km? depth, 789 Scheiber and Viola, 2018) or surficial conditions (weathering – saprolitisation) (Fredin et al., 2017b). 790 It is worth noting that, in each of the analysed outcrops, the weathering products postdate the 791 formation of brittle structures and are not overprinted by any subsequent brittle deformation. This 792 may suggest that weathering likely developed during periods of quiescent tectonic activity, as it is 793 postulated for the development of thick saprolitic horizons (Fredin et al., 2017b)

Therefore, we speculate that the studied Group W outcrops may be adopted as representative of the different stages of progressive weathering. The partially altered outcrop  $W_1$  represents the deepest portions of the weathering profile; the outcrop  $W_2$  represents the intermediate alteration stage and the transition toward more evolved alteration products, which are well represented by outcrop  $W_3$  (Fig. 10) (Lothe et al., 2018).

Such a defined weathering profile displays a progressive degradation of mechanical strength and an overall permeability enhancement with the increasing weathering grade (from A1 to A5, Fig. 10b). Incipient alteration A1–A2 leads, on average, to a progressive decrease in mechanical strength of about 50% of the intact RGD. The permeability at this stage of weathering is increased up to 0.01-1D. The transition from coherent (A2) to incoherent alteration facies (A3–A5) is characterised by a drastic decrease in mechanical strength (UCS down to < 20 MPa, Fig. 10b). Conversely, the permeability increases up to 10 D within alteration facies A3–A4, and then progressively decreases toward  $10^{-4}$  D when approaching alteration facies A5 (Fig. 10b).

807 The observed variability of the studied properties through the weathering profile is similar to that 808 commonly reported from saprolitic profiles and alteration profiles related to granite kaolinitisation 809 (Coggan et al., 2013; Lothe et al., 2018; Walter et al., 2018). In such contexts, the variation of 810 mechanical strength and permeability are commonly related to the development and evolution of 811 micro-porosity with increasing weathering (Goodfellow et al., 2016; Lothe et al., 2018; Walter et al., 812 2018; Hayes et al., 2019). Microstructural investigations suggest that the petrophysical properties of 813 incipient alteration stages (coherent alteration facies A1-A2) are controlled by microfracture-related 814 porosity and biotite alteration (Goodfellow et al., 2016; Walter et al., 2018). The increasing alteration 815 of biotite and plagioclase into clay-minerals (alteration facies A3-A4) promotes the development of 816 vacuole-shaped porosity and triggers micro-fracturing as a consequence of positive volume changes 817 caused by the oxidation reactions in the altering rock (Goodfellow et al., 2016; Walter et al., 2018). 818 At this stage, highly interconnected pores and micro-fractures enhance the effective permeability and 819 storage capacity of the weathered rock (Walter et al., 2018). Accordingly, increased micro-porosity 820 and progressive clay-mineral formation lead to the observed drastic decrease in mechanical strength 821 between cohesive and cohesionless alteration facies, similarly to what reported by Coggan et al. 822 (2013) during progressive granite kaolinitisation. The most advanced stages of weathering (alteration facies A5) are characterised by the complete alteration of biotite and plagioclase into clay-minerals 823 824 and Fe-oxides. At this stage, mineral alteration and neoblastesis lead to obstruction of the previously 825 developed micro-porosity and to the observed reduction of permeability (Walter et al., 2018). As a result, weathering leads to immediate and drastic decrease of mechanical strength, whereas 826 827 permeability firstly increases and then decreases during weathering process progression (Fig. 10).

The characteristics of the weathering profile studied here have three main important implications for the characterization of reservoir rocks buried offshore beneath the sedimentary cover in the North Sea structural highs.

831 (i) Weathering around fracture zones, progressive matrix disaggregation, homogenization, 832 and the resulting blurring of the structural discontinuities drive the transition from 833 structurally controlled permeability of the intact host rock toward the matrix-controlled permeability of intermediate alteration facies (Fig. 10). Fracture zones are characterised 834 835 by high permeability, which is, however, spatially confined to the mesoscopic fracture 836 porosity and fracture aperture. The highly permeable alteration facies A3 is two orders of 837 magnitude less permeable than the maximum permeability inferred for fracture corridors 838 (with a fracture aperture of 1 mm). However, it involves larger volumes of the host rock, 839 and thus dramatically increases the storage capacity of the reservoir rocks.

840 (ii) The low permeability of alteration facies A5 (saprolite) suggests that the top layers of the
841 weathering profile, when preserved, may act as a partial seal to fluid flow at the base of
842 the sedimentary cover atop the basement structural highs (Dewandel et al., 2006; Walter
843 et al., 2018).

844 The analysed paleo-weathering profile developed during the Mesozoic, and was then (iii) 845 buried below the Jurassic-Cretaceous sedimentary succession of the central North Sea. 846 The observed differential mechanical strength may have led to different compaction 847 patterns and behaviours, and thus a differential modification of the permeability of 848 weathering products during the burial history of the paleo-weathering profile (Lothe et 849 al., 2018). The weaker clay–rich saprolites may have undergone to a significant change of 850 the original secondary porosity and permeability when compared to the more stiff, 851 granular saprock and incipient alteration facies (Lothe et al., 2018; Walter et al., 2018).

852



853

854 Figure 10: (a) Schematic representation of the top-basement weathering profile. The penetration of 855 weathering processes into the crystalline basement is promoted by the structural discontinuities, such 856 as SSRS fractures and fault zones. Alteration intensity decreases with depth. With increasing 857 alteration, structural permeability is progressively replaced by matrix permeability related to the 858 alteration products. (b) Mechanical strength and permeability variations through the alteration profile. 859 The continuous red and light blue curves represent the mechanical strength and permeability observed 860 at W<sub>2</sub>. The dashed red and blue curves represent the overall general trend of variation of k and UCS, 861 respectively, through the weathering profile. An initial permeability increment in the deepest portion of the alteration profile is superseded by a drastic permeability decrement toward the more evolved 862 863 weathering stages.

#### 865 *5.4 Reservoir rocks in fractured and weathered basement*

The reservoir rocks in fractured and weathered crystalline basement are made up of (Braathen et al., 2018): (1) the fractures and fault (damage) zones within the non-weathered crystalline basement, in which permeability is structurally controlled (Figs. 11, 12), and (2) the products of weathering and alteration, such as the overlying top-basement paleo-weathering profile where the permeability is dominated by the matrix properties of the weathered products (Figs. 10, 12).

871 The crystalline basement is characterised by the occurrence of a complex network of variably oriented 872 brittle deformation zones (Gabrielsen and Braathen, 2014; Scheiber and Viola, 2018). Fracture 873 corridors and damage zones related to both SSRS and SRS fault zones represent high-permeability 874 conduits for fluid flow (Fig. 11a). The volume of the fractured reservoir suited for fluid storage is 875 therefore limited to the overall deformation zone volume. However, the occurrence of fault rocks 876 within SSRS and SRS fault cores may limit the migration of fluids between highly permeable footwall 877 and hanging wall damage zones. In addition, the intersection of variably oriented fault zones may 878 limit the overall lateral fluid flow through the large-scale network of SSRS-SRS fracture lineaments. 879 This would lead to the formation of fault bounded polyhedral domains (i.e. "reservoir compartments") 880 of the fractured crystalline basement (Fig. 11b) (Watkins et al., 2018). Within each domain, fluid flow 881 is limited to the high permeability fracture corridors and footwall/hanging wall damage zone 882 connected to the domain bounding faults (Fig. 11b).

The reservoir storage volume is likely increased within the top-basement weathering profile and fracture-related alteration zones. Weathering may lead to the formation of very thick (up to 100 meter thick) profiles characterised by high porosity and permeability (Braathen et al., 2018; Walter et al., 2018) (Fig. 12). In addition, fluid percolation through fracture zones may lead to the deep penetration of weathering processes, down to even 300 m below the top-basement paleo surface (Place et al., 2016; Walter et al., 2018). Furthermore, the most altered A5 facies may represent a top-seal layer to the underlying weathered and fractured basement high, buffering the upward migration of fluids
toward the overlying sedimentary succession (Figs. 10, 12) (Walter et al., 2018).

## 891 5.5 Mechanical strength of fractured and weathered crystalline basement

892 The fractured and weathered unconventional reservoir under consideration is thus composed of 893 several structural and textural elements with strikingly different mechanical strength. The fracture 894 network and the spatial distribution of weathering/alteration products lead to a significant mechanical 895 heterogeneity/anisotropy within the crystalline basement. In turn, this mechanical heterogeneity and 896 anisotropy may in places significantly perturb the regional stress field (Gudmundsson et al., 2010). 897 This could lead to the relevant modification of the overall fracture network geometry, fracture 898 orientation and spacing within the mechanically heterogeneous rock volume during both natural 899 deformation and induced fracturing of the reservoir (Jeanne et al., 2013; Smart et al., 2014). The 900 occurrence of mechanically weak layers, such as the top-basement weathering profile, the gouge-901 bearing fault cores, and the partially altered fracture corridors within the crystalline basement may 902 control the orientation and propagation of natural or induced fractures during either tectonic 903 deformation or reservoir production (Douma et al., 2019; Forbes Inskip et al., 2020). In particular, 904 the occurrence of these low-mechanical strength layers and localised heterogeneities may arrest the 905 propagation of fractures artificially induced during the exploitation phase of unconventional 906 reservoirs to enhance the local structural permeability of the host low-permeability crystalline rocks 907 and stimulate production (Forbes Inskip et al., 2020).

908



911 Figure 11: Schematic representation of the conceptualised fractured basement reservoir. (a) Low– 912 strain fracture corridors lead to the development of a high–permeability network of fracture 913 lineaments, dominated by the structural permeability. The randomly oriented dashed arrows in the 914 coloured permeability map indicate the lack of reservoir compartmentalization. (b) The development

915 of sub-seismic-resolution scale (SSRS) and seismic-resolution scale (SRS) fault zones, and related 916 fault rocks within fault cores lead to the development of local low-permeability barriers to fluid flow. 917 The large-scale fracture network is then "compartmentalised" into polyhedral fault-bounded 918 domains, whose dimension depend on the geometry of the fault zone network. Dashed arrows 919 describe a closed path for fluid flow within each fault-bounded domain.



920

Permeability map

Figure 12. Block diagram summarising a conceptualised model of reservoir within fractured and weathered crystalline basement (not to scale). (a) The top–basement weathering profile overprints the fractured crystalline basement, exploiting the network of fractures and fault zones to penetrate to even great depth (down to to 300 m, Walter et al., 2018). (b) Schematic permeability map of the

925	conceptualised model described in (a). The reservoir is deformed by highly permeable fractures and
926	fault zones (1) and contains the deepest portion of the weathering profile (2). Fault cores (3) are
927	inherently more permeable than the unaltered host rock, thus acting as a conduit for fluid flow parallel
928	to fault strike. The potential reservoir rocks (1–2) and potential fluid conduits (1 and 3) are overlain
929	by the low permeability saprolitic horizon (4), which may act as top-seal layer. Weathering processes
930	greatly increase the fluid storage and transport potential of the reservoir close to the top-basement
931	surface, which is otherwise limited to the network of fractures and fault zones.

## 935 **6.** Conclusion

936 The matrix mechanical properties and permeability constrained by this study within the crystalline 937 basement rocks exposed on Bømlo result from the prolonged and complex interplay between tectonics 938 and lithosphere-atmosphere interactions (Fredin et al., 2017b). Brittle fracturing and weathering led 939 to the development of secondary porosity at different scales: (a) meso-scale fracture porosity; (b) 940 micro-porosity related to cataclastic processes and micro-fracturing; (c) micro-porosity related to 941 mineral alteration and reaction-induced micro-fracturing. Thus, fault rock formation and weathering 942 processes related to subaerial exposure and fluid percolation through deformation zones deeply 943 affected both the mechanical strength and the matrix permeability of the RGD.

944 The fractured and weathered crystalline basement reservoir rocks are, therefore, composed of two 945 main constituent elements: (1) the fractured crystalline basement and (2) the weathered/altered rock 946 volume. The multiscale fracture network is composed of different types of fracture zones (SSRS 947 fracture corridor, SSRS and SRS fault zones). Fault zones, either SSRS or SRS, represent zones of 948 enhanced permeability with respect to the host crystalline basement and conduits for fluid flow 949 parallel to the fault planes at all stages of evolution and at all scales (Caine et al. 1996). Meso-scale 950 fractures spatially related to low strain and limited throw fracture corridors drastically enhance the 951 overall permeability of the basement. Similarly, the formation of fault rocks, which are on average 952 two orders of magnitude more permeable than the host rock, significantly increases the crystalline 953 basement matrix permeability. They are characterised by anisotropic mechanical and permeability 954 properties. In addition, they may act as partial seal/buffer layers to fluid flow within the high 955 permeability structural network defined by fracture corridors and damage zones (Bruhn et al., 1994; 956 Caine et al., 1996).

957 The comparison of weathering characteristics between different outcrops has allowed us to quantify958 the mechanical strength and permeability as a function of the actual position within the reconstructed

959 weathering profile (Dewandel et al., 2006; Lothe et al., 2018). The weathering profile shows a 960 progressive degradation of mechanical strength coupled to an initial increase in permeability during 961 the incipient stages of weathering (up to 10 D, corresponding to its deepest portion), followed toward 962 shallower depth by a significant decrease in permeability toward the more evolved weathering stages (down to 10<sup>-3</sup> D). The matrix secondary permeability created during weathering greatly increases 963 964 fluid storage and migration in a potential reservoir, which would otherwise be limited to volumes 965 with sufficient structural permeability. Mature saprolitic horizons, on the other hand, may act as top-966 seal layer to the underlying permeable weathered products. As a consequence, weathering profiles 967 may act both as reservoir and top-seal unit in sub-unconformity unconventional reservoirs (Braathen 968 et al., 2018; Holdsworth et al., 2020; McCaffrey et al., 2020).

969 Fractured and weathered crystalline basement reservoirs are characterized by a significant mechanical 970 heterogeneity, as inferred by the strikingly different mechanical properties of deformation zones, 971 brittle fault rocks and weathering products. The mechanical heterogeneity is particularly developed 972 toward the top-basement unconformity, where brittle deformation zones may be decorated by 973 alteration products and abut the overlying weathering profile. The detailed quantification of the 974 mechanical heterogeneity and its spatial distribution is therefore fundamental to optimize the planning 975 strategies for the exploration and the operative exploitation of sub-unconformity unconventional 976 reservoirs.

977

978

# 979 Acknowledgments

980 We thank Prof. Robert Holdsworth and an anonymous reviewer for the constructive comments and 981 thorough reviews to the first version of the manuscript. Our research work was funded by the still 982 ongoing BASE 2 project ("Basement fracturing and weathering onshore and offshore Norway-983 Genesis, age, and landscape development" - Part 2), a research initiative launched and steered by the 984 Geological Survey of Norway and supported by Equinor ASA, Aker BP ASA, Lundin Energy 985 Norway AS, Spirit Energy Norway AS, Wintershall Dea Norge, and NGU. We thank all BASE 986 colleagues for continuous discussion and constructive inputs. We thank Erik James Ryan (NTNU) 987 for the UAV surveys of the Goddo Fault Zone outcrop (Fig. 4).

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