

1 **The Physical Characteristics of a CO<sub>2</sub> Seeping Fault: the implications of fracture**  
2 **permeability for carbon capture and storage integrity**

3  
4 Clare E. Bond<sup>1\*</sup>  
5 Yannick Kremer<sup>2</sup>  
6 Gareth Johnson<sup>3</sup>  
7 Nigel Hicks<sup>4</sup>  
8 Robert Lister<sup>5</sup>  
9 Dave G. Jones<sup>5</sup>  
10 Stuart Haszeldine<sup>3</sup>  
11 Ian Saunders<sup>6</sup>  
12 Stuart Gilfillan<sup>3</sup>  
13 Zoe K. Shipton<sup>2</sup>  
14 Jonathan Pearce<sup>5</sup>

15  
16 <sup>1</sup>Department of Geology and Petroleum Geology, University of Aberdeen, Meston Building,  
17 Kings College, Aberdeen, AB24 3UE, UK ([clare.bond@abdn.ac.uk](mailto:clare.bond@abdn.ac.uk))

18 <sup>2</sup>Department of Civil and Environmental Engineering, University of Strathclyde, James Weir  
19 Building, Glasgow, G1 1XJ ([yannick.kremer@strath.ac.uk](mailto:yannick.kremer@strath.ac.uk); [zoe.shipton@strath.ac.uk](mailto:zoe.shipton@strath.ac.uk))

20 <sup>3</sup>School of Geosciences, University of Edinburgh, Grant Institute, Kings Buildings, James  
21 Hutton Road, Edinburgh, EH9 3FE ([g.johnson@ed.ac.uk](mailto:g.johnson@ed.ac.uk); [stuart.gilfillan@ed.ac.uk](mailto:stuart.gilfillan@ed.ac.uk);  
22 [stuart.haszeldine@ed.ac.uk](mailto:stuart.haszeldine@ed.ac.uk))

23 <sup>4</sup>Council for Geoscience, 139 Jabu Ndlovu Street, Pietermaritzburg, KwaZulu-Natal, South  
24 Africa 3200 ([nhicks@geoscience.org.za](mailto:nhicks@geoscience.org.za))

25 <sup>5</sup>British Geological Survey, Environmental Science Centre, Nicker Hill, Keyworth, Nottingham  
26 NG12 5GG ([trl@bgs.ac.uk](mailto:trl@bgs.ac.uk); [dgj@bgs.ac.uk](mailto:dgj@bgs.ac.uk); [jmpe@bgs.ac.uk](mailto:jmpe@bgs.ac.uk))

27 <sup>6</sup>Council for Geoscience, 280 Pretoria St, Silverton, Pretoria, 0184 ([ians@geoscience.org.za](mailto:ians@geoscience.org.za))

28 \*Corresponding Author [clare.bond@abdn.ac.uk](mailto:clare.bond@abdn.ac.uk)

29  
30  
31  
32 **Highlights**

- 33  
34
- 35 • CO<sub>2</sub> migration is spatially associated with the Bongwana fault fracture corridor.
  - 36 • Cap rock permeability suggests that without fractures it would act as a flow barrier.
  - 37 • Elevated CO<sub>2</sub> concentration and flux are measured across the fracture corridor.
  - 38 • Fracture intensity and orientation variability creates permeability heterogeneity.
  - 39 • Seismically unresolvable fracture networks may impact CO<sub>2</sub> storage capability.
- 40  
41

42 **Abstract**

43 To ensure the effective long-term storage of CO<sub>2</sub> in potential geological storage sites,  
44 evaluation of leakage pathways to the surface should be undertaken. Here we use a series  
45 of natural CO<sub>2</sub> seeps along a fault in South Africa to assess the controls on CO<sub>2</sub> leakage to  
46 the surface. Geological mapping and detailed photogrammetry reveals extensive fracturing  
47 along the mapped fault trace. Measurements of gas flux and CO<sub>2</sub> concentration, across the  
48 fracture corridor, give maximum soil gas measurements of 27% CO<sub>2</sub> concentration, and a  
49 flux of 191 g m<sup>-2</sup> d<sup>-1</sup>. These measurements along with observations of gas bubbles in streams  
50 and travertine cones attest to CO<sub>2</sub> migration to the surface. Permeability measurements on  
51 the host rock units show that the tillite should act as an impermeable seal to upward CO<sub>2</sub>  
52 migration. The combined permeability and fracture mapping data indicate that fracture  
53 permeability creates the likely pathway for CO<sub>2</sub> migration through the low permeability  
54 tillite to the surface. Heterogeneity in fracture connectivity and intensity at a range of scales  
55 will create local higher permeability pathways along the fracture corridor, although these  
56 may seal with time due to fluid-rock interaction. The results have implications for the  
57 assessment and choice of geological CO<sub>2</sub> storage sites, particularly in the assessment of sub-  
58 seismic fracture networks.

59

60 **Keywords**

61 Fracture permeability, CO<sub>2</sub> storage, leakage, natural analogue

62

## 1. Introduction

Climate change is generally recognized as a global 21<sup>st</sup> century challenge (Bernstein et al., IPCC, 2007). Anthropogenic greenhouse gas emissions, primarily CO<sub>2</sub>, are extremely likely to have been the dominant driver of such change. CO<sub>2</sub> from fossil fuel combustion and industrial processes contributed 78% of the increase in GHG emissions between 1970 and 2010 (Field et al., IPCC, 2014). Carbon capture and storage (CCS) has been proposed to mitigate CO<sub>2</sub> emissions (Metz et al., IPCC, 2005). CCS is recognized as a bridging technology in energy production (e.g. Praetorius, and Schumacher, 2009), to mitigate the impact of CO<sub>2</sub> emissions, while renewable energy sources are developed. In order to expedite the deployment of CCS research is being undertaken to understand the reactivity and flow pathways of CO<sub>2</sub> in the subsurface (e.g Xu et al., 2003; Audigane et al., 2007) and to develop methods to measure, model and verify (MMV) geological CO<sub>2</sub> storage (Newell et al., 2008; Ringrose et al., 2013). Understanding the role of faults and fractures as fast fluid pathways, through overburden strata, to the surface is critical to ensure storage verification for engineered CCS sites.

Fracture controlled flow of CO<sub>2</sub> has been implicated in compromising the integrity of pilot CCS sites. For example, injection of CO<sub>2</sub> was halted at the In Salah CO<sub>2</sub> CCS pilot site due to the role of fractures in creating a conductive network through which CO<sub>2</sub> could migrate (e.g. Bond et al., 2013; Rinaldi and Rutqvist, 2013). To better understand the role of faults and associated fracture damage on controlling CO<sub>2</sub> flow pathways and flux rates, natural CO<sub>2</sub> seeps have been studied (e.g. Roberts et al., 2015). Examples of natural CO<sub>2</sub> seeps along faults include: the Paradox Basin Utah (e.g. Shipton et al., 2006); and the Apennines of Italy (e.g. Miller et al., 2004; Roberts et al., 2015). Here we describe the structural characteristics of the CO<sub>2</sub> seeping Bongwana Fault in KwaZulu-Natal, South Africa; to better constrain fracture and fault controlled CO<sub>2</sub> flow to the surface.

The Bongwana Fault is one of only two known examples of naturally seeping CO<sub>2</sub> in South Africa. The fault was identified during geological mapping between 1911-1916 by du Toit (1920), with CO<sub>2</sub> de-gassing along the fault first described by Young (1924). We present the first modern structural study of the physical characteristics of the fault, in terms of field exposure or a physical analysis of rock properties. We present new structural data from key locations where active CO<sub>2</sub> seeps occur along the fault as identified by Gevers (1941) and du Toit (1920). A hypothetical model of fracture-controlled permeability is proposed and refined by the field data. The results are discussed in the context of site selection and characterization at CCS sites where faults and fractures might play a role in permitting escape of CO<sub>2</sub> from a reservoir.

## 2. Geological Setting

The Ntlakwe-Bongwan Fault was identified during the mapping of Pondoland (Eastern Cape Province) and parts of the Alfred and Lower Umzimkulu Counties (KwaZulu-Natal) by du Toit (1920). The fault truncates sedimentary and igneous units of the Karoo Supergroup, as well as units of the Msikaba Formation in the south (Johnson et al., 2006). Within the study area, tillites and minor shales of the Dwyka Group, Karoo Supergroup, form the dominant surface lithologies. The tillite in southern KwaZulu-Natal has a thickness of ~450m (Thomas et al., 1990) and unconformably overlies coarse-grained sandstones and conglomerates of

110 the Msikaba Formation. The Msikaba Formation represents the assumed CO<sub>2</sub> reservoir,  
111 occurring as a 450m thick package in the Port Shepstone area which thickens southwards to  
112 900m north of Port St Johns (Kingsley and Marshall, 2009).

113

114 The fault crops out on the surface over a trace length of 80 km (De Decker, 1981) with its  
115 northern extension known as the Bongwan, or Bongwana Fault (De Decker, 1981; Harris et  
116 al., 1997). The fault is related to Gondwana break-up which began at 180 Ma and continues  
117 today (Watkeys and Sokoutis, 1998). The zone of faulting in southern KwaZulu-Natal is  
118 about 70 km wide and defined by arcuate fault traces that change southwards from ENE-  
119 WSW to a north-south strike (Watkeys and Sokoutis, 1998). These fault systems correlate  
120 with the early stage, arcuate, Type I fault systems defined by Von Veh and Andersen (1990)  
121 in northern KwaZulu-Natal. Passive continental margin conditions have predominated since  
122 the late Jurassic (Maud, 1961; Dingle and Scrutton, 1974) with offshore faulting evident until  
123 the Cenomanian (Singh and McLachlan, 2003). The southeastern portion of southern Africa  
124 was subject to intense periods of epiorogenic uplift resulting in a marked onshore hiatus  
125 from the late Eocene to middle Miocene times (King, 1972; Frankel, 1972; Dingle and  
126 Scrutton; 1974; Grab and Knight, 2015), as well as in the Pliocene, where ~900m of uplift is  
127 postulated by Partridge and Maud (2000). To-date no faulting related to these uplift  
128 episodes has been recorded onshore, likely due to the erosional conditions that have  
129 prevailed since the early Cretaceous. Present day seismic activity is minimal, although a  
130 survey of micro-tremors using a single-station location method undertaken as a separate  
131 part of this study indicates a possible micro-earthquake of M~0.5 in 2007, the epicentre of  
132 which locates on the northern section of the Bongwana Fault near the abandoned gas works  
133 on Lot 7 (Site A - this study; see Figure 1).

134

135 Due to the homogeneous nature and thickness of the Dwyka Group tillites, fault  
136 displacement within the study area is hard to quantify. There are no mappable stratigraphic  
137 offsets in the study area (Figure 1). However, to the south along the Londobezi River a large  
138 graben is developed between two splays of the fault in which Ecca Group and Karoo Dolerite  
139 Suite rocks are preserved. Gevers (1941) suggests vertical offset in this region of 579m  
140 (1900 feet) with all units within the graben truncated by the fault system. These truncations  
141 allow for a maximum age definition for the faulting of ~179 Ma, based upon <sup>40</sup>Ar/<sup>39</sup>Ar dating  
142 by Duncan et al., (1997) for the Karoo Dolerite Suite.

143

144 Watkeys and Sokoutis (1998) indicate that, due to intense subtropical weathering, the  
145 faulting pattern in southern KwaZulu-Natal is difficult to interpret. In areas of brecciation  
146 and silicification, the faults have a positive relief, a considerable aid to the delineation of the  
147 fault systems (Thomas, 1988). Gevers (1941) also describes the fault in many locations as a  
148 silicified feature that stands "proud of the ground", with a range in the fault (fracture zone)  
149 width of between 0.3 m - 10 m wide. Gevers (1941) describes the fracture zones as being  
150 lenticular in shape and cropping out intermittently. The fault zone is chemically altered and  
151 marked by degradation of the tillite to a white, apparently pulverized, rock. The whitening  
152 of the rock is from the extensive kaolinisation and leaching of the tillite by CO<sub>2</sub> rich water  
153 (Gevers, 1941). According to Gevers (1941), within the Bongwana region, du Toit (1920)  
154 mapped splay and minor faults on either side, and parallel or sub-parallel, to the main fault,  
155 with splays extending for up to 1.6 km in length.

156

157 Young (1924) provided the first description of CO<sub>2</sub> degassing from Bongwana fault fissures.  
158 In his recordings of the exposure on Farm Lot 7 (Site A – this study), Young (1924) described  
159 CO<sub>2</sub> gas steadily bubbling to the surface in the Umzimkulwana River close to its west bank. It  
160 was at this site that a CO<sub>2</sub> bottling plant was established around 1924 to capture the CO<sub>2</sub>  
161 exhalations for commercial use (Gevers, 1941). On the neighboring farm (Lot 10), Young  
162 (1924) identified a two feet wide vertical zone of brecciated Dwyka Group tillite from which  
163 CO<sub>2</sub> de-gassed. Significantly higher CO<sub>2</sub> flux was noted by Young (1924) along the contact of  
164 brecciated Dwyka Group tillite with non-brecciated tillite described as being altered to soft  
165 clay. Analyses of the two gas samples, collected by Young (1924), gave CO<sub>2</sub> compositions of  
166 98.3 % and 97.6 %. Gevers (1941) provides the most extensive description of the field sites  
167 seeping CO<sub>2</sub>, including analysis of the gas. Further studies of the gas chemistry, including  
168 stable isotope analyses have been completed by Harris et al. (1997), reporting the CO<sub>2</sub> to  
169 have a  $\delta^{13}\text{C}$  of -0.6 ‰ - +0.9 ‰ (PDB) and  $\delta^{18}\text{O}$  35.3-45.1 ‰ (SMOW). Gevers (1941) and  
170 Harris et al. (1997) suggest the CO<sub>2</sub> is sourced from the reaction of acidic ground water with  
171 carbonate rocks at depth. This hypothesis is plausible, as carbonate rocks of the Marble  
172 Delta Formation are seen cropping out ~30 km east of Bongwana (Figure 1), along structural  
173 basement strike, as a folded protolith enclave within Meso-proterozoic basement lithologies  
174 (Otto, 1973). Conversely with Hartnady (1985) who suggests generation of CO<sub>2</sub> by a mantle  
175 plume, with early carbonatite magma generation. Whatever the source, CO<sub>2</sub> has been  
176 seeping from the fault for some time because a series of travertine cones with CO<sub>2</sub> springs,  
177 some now dormant (Gevers, 1941; and observed in this study) attest to significant volumes  
178 of CO<sub>2</sub> over, at least, hundreds of years. Two of the localities identified by Gevers (1941)  
179 were visited, as well as a third mapped as a CO<sub>2</sub> exhalation by du Toit (1920). These  
180 locations are shown in Figure 1.

181  
182

### 183 3. Models for CO<sub>2</sub> flow to the surface

184 Significant work has been undertaken within the oil and gas sector to determine the  
185 controls on the sealing capacity of faults (Yielding et al., 1997; Manzocchi et al., 1999;  
186 Bretan et al., 2003) and overburden caprocks (Grunau, 1987; Watts, 1987) to hydrocarbon  
187 fluids. This work is being used to inform predictions of the storage capacity and viability of  
188 potential CCS sites (Li et al., 2005; Li et al., 2006; Shukla et al., 2010), although it is  
189 recognized that faults and fractures may respond differently to CO<sub>2</sub>, especially when  
190 pressurized CO<sub>2</sub> is injected (Rutquist, 2012; Verdon et al., 2015). Faults are known to act as  
191 both barriers and conduits to fluid flow (Sibson, 1995; Caine et al., 1996; Bense and Person,  
192 2006), with the permeability characteristics of the fault plane and associated damage zone  
193 combining to determine a fault's overall permeability (Caine et al., 1996; Foxford et al. 1998;  
194 Aydin and Eyal, 2002). The geometry and heterogeneity of the whole fault zone, down to  
195 the micro-scale, determine a fault's permeability. Work on understanding and predicting  
196 fault (and off-fault) damage and its implications for permeability have mainly focused on  
197 normal faults within siliciclastic reservoir sequences (Caine et al., 1996; Hesthammer et al.,  
198 2000; Shipton and Cowie, 2003; Fossen et al., 2007; Farrell et al., 2014). Understanding of  
199 fault zone characteristics in other lithologies is less well developed, especially in relation to  
200 capacity for fluid flow. Studies on fault damage and implications for permeability in other  
201 lithologies include carbonates Agosta and Kirschner, (2003), Haines et al. (2016); basalts  
202 (Walker et al., 2013); and granitic gneiss (Lawther et al., 2016). A fault zone's potential to

203 act as a conduit for fluid is dependent on a number of factors that are not easily predicted  
204 (Fossen et al., 2007; Faulkner et al., 2010; Farrell et al., 2014).

205

206 A series of hypothetical models (Figure 2) show a range of potential fault zone  
207 permeabilities that may allow CO<sub>2</sub> flow to the surface at Bongwana. The models are based  
208 on understanding of different fault-rock permeabilities, originally proposed by Caine et al.  
209 (1996); and developed by others. Faulkner et al. (2010) give a summary. Here we consider  
210 these models by collection of field data and observations along the Bongwana Fault,  
211 combined with laboratory analysis to propose a site-specific model of CO<sub>2</sub> flow to the  
212 surface for Bongwana for future testing.

213

#### 214 **4. Methodology**

215 A range of methodologies were employed to capture the structural characteristics of the  
216 Bongwana fault zone in an attempt to determine the potential role of the fault and  
217 associated fractures as pathways for CO<sub>2</sub> to the surface. Initial regional scale analysis was  
218 completed prior to field data collection using GoogleEarth™ and Aster imagery in  
219 combination with published geological maps (Gever, 1941; Thomas, 1988). In the field,  
220 these data were combined with GPS locations and structural measurements. High-  
221 resolution digital photography of fault zone outcrops were utilized for photogrammetry to  
222 create 3D virtual outcrop models. Desk-top digital analysis of the virtual outcrop models  
223 augment the in-field structural measurements. Outcrop scale maps of fault architecture  
224 were completed along with structural measurements and further detailed photography.  
225 Structural characterisation is augmented by gas (CO<sub>2</sub>) flux and concentration measurements  
226 made at a single site and porosity and permeability measurements of the assumed reservoir  
227 (Msikaba Formation sandstones) and seal (Dwyka Group tillites) rocks. Each method  
228 employed is described in turn.

229

##### 230 **4.1 Structural Data**

231 The app Fieldmove was used on an iPad Air 2 for collection of all structural data. Pre-loaded  
232 geo-tiffs of existing field maps and OpenStreet Map (mapbox.com) imagery were used in the  
233 field to aid in field site identification. In-field tracking was enhanced by Bluetooth  
234 connection of the iPad to a Garmin GLO for GPS and GLONASS location sensing. In-app  
235 functionality allows the user to define locations, take notes as in a field notebook, and take  
236 photos through access to the iPad's digital camera. Further, the app utilises the  
237 magnetometer, gyroscope and accelerometer within the iPad's hardware for use as a  
238 compass clinometer. Measurements of fracture orientation and dip were made and  
239 recorded directly on the iPad.

240

##### 241 **4.2 Virtual Outcrop Models**

242 A Nikon D3200 SLR was used with a fixed lens (35mm) to collect digital photographs of  
243 outcrops for photogrammetry. The method requires multiple photographs to be taken  
244 orthogonal to the outcrop surface, with an approximate 60 % over-lap. The photographs are  
245 georeferenced and a scale and orientation is used in each photo-set to allow for later scaling  
246 and geo-referencing of the virtual outcrop models. Each evening the photographs were  
247 downloaded and processed in Photoscan-pro software to create a 3D virtual outcrop model.  
248 The technique and its use in geology is described by various authors (e.g. Roncella et al.,  
249 2005; Bemis et al., 2014; Johnson et al., 2014; Salvini et al., 2015). Creating virtual outcrop

250 models during the fieldwork allows for checks to be made of the photogrammetric model to  
251 see if the photographs have the required overlap and coverage, so that further photos may  
252 be acquired if needed to create a full virtual outcrop model.

253

254 Oriented ortho-rectified photographs (orthophotos) were created from the virtual outcrop  
255 models; these were imported into Move software, scaled and geo-referenced, where digital  
256 interpretation of the fracture sets was undertaken. The pixel size of the imagery was kept  
257 constant at 300 dpi. The software is used to determine fracture attributes, such as  
258 orientation and length; as well as to determine if multiple fracture sets are present. The  
259 digitised fracture datasets were input into a MATLAB script to determine fracture intensity  
260 for each virtual outcrop using the circular scan-line method of Mauldon et al. (2001).

261

### 262 **4.3 Gas Flux and Composition Sampling**

263 Soil gas measurements were made using probes consisting of an 8 mm diameter (4 mm  
264 internal diameter) stainless-steel tube onto which two solid steel cylinders were welded to  
265 act as pounding surfaces when installing and removing the probes with a co-axial hammer.  
266 Prior to insertion, a sacrificial tip was fitted to the bottom of the probe to prevent blockage.  
267 The probes were inserted to a depth of 85-90 cm. In situ soil gas measurements of CO<sub>2</sub>, H<sub>2</sub>S,  
268 CH<sub>4</sub>, and O<sub>2</sub> concentrations were made using a Geotechnical Instruments GA2000 portable  
269 gas analyser. CO<sub>2</sub> flux measurements were taken using a West Systems portable flux meter  
270 with a LICOR LI-820 IR detector connected via Bluetooth to a Trimble Juno palm-top  
271 computer (PDA) with built-in GPS. Measurements took 1-3 min depending on the soil flux  
272 rate. Flux was measured before soil gas to minimise disturbance of the flux. The instruments  
273 were calibrated before and after the fieldwork using certified calibration gases.

274

### 275 **4.4 Porosity and Permeability Analysis**

276 Porosity and permeability analyses were made on samples of Msikaba Formation sandstone  
277 (3 orthogonal cores) and Dwyka Group tillite, from outside the obvious fault/fractured area  
278 (2 cores - at right angles). Porosity measurements were made on core samples using helium  
279 (He) gas, on an Edinburgh Petroleum Ltd, Mk. 2 Helium gas porosimeter. Permeability  
280 measurements were made on the core samples using a Jones permeater with nitrogen (N<sub>2</sub>)  
281 gas. A Hassler sleeve was used to pressurize the sample to 400 psi (2.76 MPa), and five  
282 repeat measurements at different fluid pressures on the high pressure gauge were  
283 measured. The results were corrected using a Klinkenburgh correction and the mean value  
284 used.

285

## 286 **5. Results and Analysis**

287

288 Within the study area the fault is expressed in a series of outcrops that are relatively sparse  
289 with respect to the fault length and which vary in character from highly fractured zones to  
290 apparently 'pulverised' rock. Nowhere is the full width of the fault obviously exposed. Small  
291 sections of fractured Dwyka Group tillite are observed. The fault zone surface expression is  
292 defined by distributed fractured rock outcrop, defining a fracture corridor, rather than a  
293 discrete single fault surface, or fault slip plane and damage zone. Three localities of CO<sub>2</sub>  
294 degassing along the fault trace informed the study (Figure 1).

295

296 Site A, occurs on Farm Lot 7 alongside the Umzimkulwana River east of Bongwana rail siding.  
297 Here CO<sub>2</sub> is observed effervescing in the Umzimkulwana River where the road bridge  
298 crosses the river; on the western bank of the river pools of water in river bank sand also  
299 show CO<sub>2</sub> bubbles. The outcrop at Site A is approximately 2.5 m x 1.5 m, sited next to the  
300 river and consists of fractured Dwyka Group tillite. The exhalations at this site have a high  
301 flux rate with Gevers (1941) indicating that exhalations identified on the neighbouring farm,  
302 Lot 10, measured 30 ft<sup>3</sup> minute<sup>-1</sup> (0.014 m<sup>3</sup>s<sup>-1</sup>) from a 5 inch (0.127 m) diameter pipe in  
303 1924.

304  
305 Site B (Figure 1), occurs 9 km south of Site A on the Manzimhlanga River, near Mjaja; here  
306 several outcrops of faulted and fractured Dwyka Group tillite crop out. CO<sub>2</sub> de-gassing is  
307 observed as bubbles in the nearby river, but the volume is minimal in comparison to Site A.  
308 Three distinct outcrops are described at Site B, which are characterized both by leaching and  
309 whitening of the rock, but with areas of iron staining and some silicification.

310  
311 Site C (Figure 1) is the southernmost of the known CO<sub>2</sub> emissions along the Bongwana Fault  
312 occurring on the northern and southern banks of the Umtamvuna River where well  
313 developed travertine cones and CO<sub>2</sub> springs are identified. Four travertine cones are  
314 developed atop large travertine mounds ~50-100m in diameter. Two cones occur on the  
315 northern bank and are by far the largest (~15m diameter). These cones are only partially  
316 active with minor CO<sub>2</sub> gas and water seeps identified. On the southern bank, two smaller  
317 cones are identified, both of which are active. Both issue CO<sub>2</sub> gas and water, with the larger  
318 "Cone Spring" represented by a steep-sided cone ~1 m in diameter and 80 cm high. The  
319 other spring occurs ~5 m east, as a flat cone termed the "Mound Spring". As well as basic  
320 mapping of the travertine cones, structural measurements were made at two key localities  
321 in the vicinity of the cones where fractured and brecciated outcrops were observed that  
322 have not previously been described.

323  
324

### 325 **5.1 Regional Trend and Structural Data**

326 The outcrops visited are linearly aligned, approximately North-South over a horizontal  
327 distance of 15 km. The outcrops fall on the line of the Bongwana fault mapped by du Toit  
328 (1920) and published by Gevers (1941) (Figure 3).

329  
330 Fracture orientations were measured at all three localities. Primary fractures identified in  
331 the field have N-S trends (Figure 3a – rose diagrams). Poles to fractures at Sites A, B and C  
332 have kappa distributions of 1.13, 2.58 and 2.5 respectively (where smaller kappa indicates a  
333 tighter clustering of fracture orientations). The fractures are sub-vertical with a mean dip  
334 between 82°-89° at the three sites. Fractures dip in both directions around a mean fracture  
335 strike for Site A of 169° and at Site C 006°. The fractures measured at Site B appear more  
336 dispersed in nature (Figure 3a) with a mean fracture strike orientation approximately NE-SW  
337 (a mean dip of 82° and a strike direction of 029°), but with significant dispersion within the  
338 NE and SW stereonet segments (Figure 3a).

339  
340 At Sites B and C multiple sub-sites form the dataset (Figure 3c and d) between 20 and  
341 several 100 m apart. Stereonet plots from individual outcrop sub-sites show more  
342 consistency in fracture strike orientation, so the dispersion in fracture orientation is created



343 from the amalgamation of the fracture data collected at the multiple sub-sites. Outcrop site  
344 *Bi* shows a fracture distribution similar to Site A with a predominant primary fracture set  
345 trend of approximately N-S, with a NW-SE oriented secondary fracture set. Sites *Bii*, *iii*, *iv* all  
346 show fractures in a NE-SW direction. At site *Bii* a NE-SW fracture strike is most prevalent.  
347 The rock here appears grey-white in colour and has the consistency of white flour when  
348 hammered. Sites *Bii* and *Biii* c. 20 m apart, are linked by almost continuous outcrop, in  
349 which the along-strike change in fracture trend can be observed. The mean fracture dip at  
350 site *Bii* is 82°, with a mean strike of 055°; at site *Biii* the mean dip is 82° with a mean strike of  
351 026°. At site *Biii* the fractures dip consistently to the east. The rock character also changes,  
352 as you move away from the apparently pulverized rock at *Bii* into the coherent rock at *Biii*  
353 where primary and secondary fracture sets can be identified. Often the secondary fractures  
354 form with horsetail geometries, splaying from primary fractures or filling the rock space  
355 between approximately N-S oriented primary fractures. These geometries are also identified  
356 in analysis of the virtual outcrop models and fault architecture mapping. The change in  
357 fracture orientation at site B corresponds to a bend in the fault line on the surface,  
358 according to the mapping of du Toit and Gevers (1941). This bend changes the fault  
359 orientation from approximately N-S 006° at Site C to an approximate NE-SW 029° at Site B,  
360 (Figure 3b).

361

362 At two sites slickensides could be measured on fracture/fault surfaces. At Site *Cii* a small  
363 fracture surface oriented with a strike of 013 and a dip of 82° had three measurable  
364 slickensides. The mean slickenside trend is 337 with a plunge of 77°. The slickensides are  
365 approximately dip-slip (vertical) (figure 3b). At Site *Biv* a larger fracture/fault surface is  
366 exposed with numerous slickensides, 14 slickenside lineation measurements were made on  
367 the surface. In figure 3b a mean fracture plane surface is plotted (great circle) with a strike  
368 of 031 and a mean dip of 82°, the slickensides are sub-parallel with a mean slickenside trend  
369 is 050 with a plunge of 72°. The slickensides at Site *Biv* are slightly oblique to dip-slip, by c.  
370 20° to the NE.

371

## 372 **5.2 Fault Architecture Mapping from Virtual Outcrop Models**

373 Virtual outcrop models were made at all three sites. Virtual outcrop models of five fractured  
374 surfaces from the three sites have been digitally interpreted on orthorectified photographs.  
375 Fracture orientations derived from the models (Figure 4a-e, stereonet), are consistent with  
376 in-field measurements (Figure 3, stereonet), with a main fracture set trending c. N-S and  
377 secondary sets either trending c. E-W, or as a conjugate set bisecting an E-W trend. Mapped  
378 fractures at Site *Bi* and *Biii* (Figure 4b and 4c), show the horsetail geometries and fracture  
379 splays.

380

381 Using a custom MATLAB script, we use the circular scanline method of Mauldon et al. (2001)  
382 to create fracture density plots (number of fractures per m<sup>2</sup>) for each digitally interpreted  
383 outcrop (Figure 4a-e). This approach defines a circular sampling window, from which the  
384 number of fracture endpoints (m) within the circle and the number of fracture intersections  
385 (n) with the circle are recorded. From these two statistics, the fracture density, intensity and  
386 mean trace length can be calculated. The script uses a moving window approach to calculate  
387 the statistics for a large number of circles at different locations, resulting in a map of  
388 fracture intensity variation. The accuracy of this method depends on the number of  
389 endpoints in the circle, and therefore on the size of the circle compared to typical fracture

390 spacing. Rohrbaugh et al. (2002) suggest that the scan-circle radius should exceed typical  
391 block size. To accurately determine the minimum scan radius required for our fracture  
392 maps, we calculate these statistics for different circle radii at several locations. Figure 5  
393 shows a plot of the three properties, density, intensity and mean trace length, against circle  
394 radius for site Ci. At this location, the statistics stabilise at a fracture radius of at least 8 cm.

395 The fracture density maps created can be used to visualise and examine the heterogeneity  
396 of the fracture network. Calculated values are artificially low near the edges of the map, as  
397 no fractures are mapped in poorly exposed areas. As such, representative values for the  
398 fracture density at this location must be taken at least one radius distance (8 cm) away from  
399 the edge of the rock outcrop. This results in typical fracture densities ranging from 1500 –  
400 3000 fractures m<sup>-2</sup> at Site Ci. For this site fracture intensity ranges from 40 to 120 fractures  
401 m<sup>-1</sup>, and mean trace lengths range from 5 to 15 cm. At the nearby site Cii, 100 m away, the  
402 fracture density is a maximum of 11 fractures m<sup>-2</sup> (Figure 4e). Fractures are mainly unfilled,  
403 e.g. Sites A and C At these site where red-brown staining around the fractures (thin halos up  
404 to 0.5cm) and coatings on fracture surfaces is interpreted as evidence for past fluid-flow. At  
405 Site B fractures appear to be cemented, as part of the pervasive (in the vicinity to fractures)  
406 chemical alteration of the rock.

407

### 408 **5.3 Gas Flux and composition measurements**

409 Gas flux and composition measurements were made at Site C along a transect perpendicular  
410 to and crossing the trend of the main fault line. The locality chosen was on the Northern  
411 bank of the Umtamvuna River between mapped active gas exhalations (Figure 6). The  
412 results of the gas flux and composition measurements are shown in map view, with circles  
413 scaled for flux (Figure 6a) and graphically (Figure 6b). Falling on the predicted fault line (zero  
414 on the x-axis of the graph) the maximum percentage of CO<sub>2</sub> in the captured gas is 27 %, with  
415 a flux of 191 g m<sup>-2</sup> d<sup>-1</sup>. Away from the predicted fault line (50-80 m) the flux and CO<sub>2</sub>  
416 composition recorded diminish to 1 % or below, and 17-26 g m<sup>-2</sup> d<sup>-1</sup>. A symmetrical pattern  
417 is seen on either side of the fault with no observed difference in the footwall or hangingwall  
418 of the structure. The results support the assertion that the fault and associated deformation  
419 structures are controlling migration of CO<sub>2</sub> to the surface.

420

### 421 **5.4 Porosity and Permeability data**

422 Porosity and permeability measurements were made on three orthogonal cores of Msikaba  
423 Formation sandstone collected in the Oribi gorge. The sandstone is quartz dominated and  
424 shows a coarsening-upward sequence within beds. The sample, of a bed approximately 20  
425 cm thick, contains quartz pebbles (2-10 mm) at its base fining up to <1 mm. The cores were  
426 taken across bedding and in two orthogonal orientations parallel to bedding.  
427 Samples of apparently undeformed and unaltered Dwyka Group tillite from Site Bii, less than  
428 1 m from highly altered tillite in the 'fault zone', were also cored in two orthogonal  
429 directions. The tillite has a fine-grained grey matrix with clasts in the samples up to 10 mm  
430 in diameter, but generally clasts are 2-3 mm in size. Samples of fractured and altered tillite  
431 disintegrated when cut or cored using water-cooled mechanisms, supporting the assertion  
432 of alteration to clays, so were not suitable for core analysis.

433

434 The results of the analyses are shown in Table 1. The unaltered Dwyka Group tillite has a  
435 high porosity (c. 20%), compared to the Msikaba Formation sandstone (c. 4-5%) but a lower  
436 effective permeability  $1 \times 10^{-2}$ . Figure 7 shows the samples plotted on a porosity-  
437 permeability plot alongside data from different types of sandstones from Lake (2007) -  
438 Society of Petroleum Engineers (SPE) (Petrowiki, accessed 2016). The Msikaba Formation  
439 sandstone falls within the range of consolidated sandstones (0.18 -0.27 mD), whilst the  
440 tillite has a permeability at the lower end of consolidated sandstone and the top end of tight  
441 sands (0.06 – 0.07 mD).

442

## 443 **6. Discussion**

444

445 The Bongwana Fault is unusual in its expression. Our observations of dip-slip slickensides on  
446 steeply dipping fracture surfaces support those of Gevers (1941) who described dip-slip  
447 slickensides on an almost vertical fault. However, no distinct fault surface is observed in the  
448 field. The fault displacement-length characteristics at the lower end of those predicted by  
449 global compilations (e.g. Walsh and Watterson, 1988; Schlische et al., 1996; Kim and  
450 Sanderson, 2005). For an 80 km long normal fault, displacement in the order of 80 m-8 km  
451 would be expected based on the range of published displacement length data, compared to  
452 the 579 m estimated throw observed by Gevers (1941). These observations suggest that the  
453 Bongwana Fault is a deep-seated basement fault, or series of amalgamated faults that may  
454 have had an earlier strike-slip history. Given the lack of observed piercing points, the  
455 amount of strike slip on the fault is not quantified.

456

457 Porosity and permeability measurements of selected rock samples attest to a potential CO<sub>2</sub>  
458 reservoir at depth and an effective cap rock seal. The Dwyka Group tillite (assumed cap-rock  
459 seal) has a high porosity but low effective permeability ( $1 \times 10^{-2}$  mD). Incontrast, the  
460 permeability of the assumed CO<sub>2</sub> reservoir, the Msikaba Formation sandstone, is  $1 \times 10^{-1}$  mD,  
461 within the range of known consolidated sandstones that form hydrocarbon reservoirs,  
462 whereas the tillite has a permeability at the high-end of tight sands (Figure 7). Tight sand  
463 reservoirs in a hydrocarbon setting are reliant on fracture permeability for effective  
464 hydrocarbon flow. The fractures identified in the field associated with the Bongwana Fault  
465 are therefore the likely conduit for CO<sub>2</sub> from the Msikaba Formation sandstone to the  
466 surface.

467

468 The dominant fracture set parallels the fault with fractures oriented c. N-S, although there is  
469 local variability in orientation. Further minor fracture sets are also seen, with significant  
470 local heterogeneity in orientation and intensity. Fractures are observed to swing in  
471 orientation towards the NE-SW at a mapped bend in the fault. Fracture connectivity and  
472 hence bulk permeability is predicted to be higher in the fault bend zone, where fracture sets  
473 with different orientations intersect. Fault bends often correspond to local high stress  
474 anomalies, and stress rotations resulting in a greater diversity in fracture orientation and an  
475 increase in fracture intensity, permeability and fluid flow (e.g. Curewitz and Karson, 1997;  
476 Kattenhorn et al., 2000; Tamagawa and Pollard, 2008). The current stress regime in the  
477 Bongwana Fault area, is extension oriented approximately NNW-SSE (Brandt, 2011). This  
478 suggests that the NE-SW oriented fault bend on the Bongwana Fault at Site B would be in  
479 net extension and some rotation of the local stress field would be expected.

480

481 In the detailed fracture intensity maps (Figure 4), shorter length 'small scale' fractures,  
482 oriented orthogonal or sub-orthogonal to the c. N-S fractures, are captured. These fractures  
483 are missing from in-field measurements at Sites A and C (Figure 3). We suggest this is the  
484 result of in-field sampling bias (e.g. Hunter and Donovan, 2005; Bond et al., 2007; Bond,  
485 2015) in which the more dominant (longer length and 'thicker') N-S fractures have been  
486 preferentially sampled. Although, often 'hairline' in width the increase in fracture  
487 connectivity afforded by an orthogonal linking fracture set can drastically increase potential  
488 fracture permeability (e.g. Watkins et al., 2015). "Linking" fractures at Site B (the fault bend)  
489 show horsetail and splay geometries, and in some outcrops these fractures dominate the  
490 fracture population e.g. Site Bii (figure 3c).

491  
492 High permeability fracture-dominated pathways controlling spatially distinct CO<sub>2</sub> leakage  
493 along a fault in Utah (Burnside et al., 2013). At the Utah site ancient travertine cones record  
494 a 400,000+ year history of CO<sub>2</sub> exhalation along the fault, concentrated along high  
495 permeability pathways controlled by areas of high fracture density (Dockrill and Shipton,  
496 2010), and with a history of sealing and fluid pathway displacement along the fault  
497 (Burnside et al., 2013). At Bongwana, there is evidence of fluid-rock interaction, notably at  
498 the bend in the fault, where Dwyka Group tillite appears to be altered to kaolinite. So  
499 although this fault-bend area is predicted as having a high fracture permeability with  
500 respect to the range in fracture orientations, it is possible that this may be reduced or sealed  
501 completely due to mineral reactions during CO<sub>2</sub> flux.

502  
503 Direct evidence for CO<sub>2</sub> surface exhalations are seen with the presence of travertine cones  
504 and gas bubbles effervescing in rivers that cross the mapped fault line. Measurements of  
505 ground gas flux and CO<sub>2</sub> concentration across the fracture corridor show a significant flux of  
506 CO<sub>2</sub> (191 g m<sup>-2</sup> d<sup>-1</sup>), with 27% CO<sub>2</sub> measured in the soil gas. The % of CO<sub>2</sub> is significantly  
507 above normal back ground levels of <1%. Within c. 50 m of the predicted fault line (on both  
508 sides) the CO<sub>2</sub> concentrations and gas flux measurements are consistent with non-elevated  
509 levels. Although, we can spatially correlate the CO<sub>2</sub> flux to the fault-line diffusion of the CO<sub>2</sub>  
510 through the soil will likely obscure any spatial heterogeneity in the flux associated with  
511 fractures.

512  
513 The CO<sub>2</sub> flux is lower than other cited examples of CO<sub>2</sub> fluxes along fault lines. Gouveia et al.  
514 (2005) and Gouveia and Friedmann (2006) measure modern exhalation of CO<sub>2</sub> flux from  
515 Crystal Geyser in Utah of 30 tonnes d<sup>-1</sup>. The flux here however is up a well that was drilled  
516 into the fault, giving a point source of CO<sub>2</sub>. Values by Roberts et al. (2015) give an average  
517 flux of between 10-100 tonnes d<sup>-1</sup> for seeps in Italy, although the area over which these  
518 values were recorded is not detailed. Annunziatellis et al. (2008) record flux values of CO<sub>2</sub> up  
519 faults in the Latera Caldera in Central Italy. The mean CO<sub>2</sub> flux value (1700 g m<sup>-2</sup> d<sup>-1</sup>) here is  
520 very high due to the maximum value of 49563 gm<sup>-2</sup> d<sup>-1</sup>, while the median value (331 gm<sup>-2</sup> d<sup>-1</sup>).  
521 Data from Beaubien et al. (2008), also from the Latera Caldera, give maximum values of  
522 over 90% CO<sub>2</sub> in soil gas and a maximum flux greater than 1600 g m<sup>-2</sup> d<sup>-1</sup>. Background values  
523 were less than 5% and the flux is generally below 10 g m<sup>-2</sup> d<sup>-1</sup>. Measurements from a  
524 traverse near the Laacher See in Germany showed max CO<sub>2</sub> concentrations exceeding 80%  
525 and maximum fluxes over 500 g m<sup>-2</sup> d<sup>-1</sup>. Away from CO<sub>2</sub> vents concentrations were below  
526 5% CO<sub>2</sub> with a flux below 50 g m<sup>-2</sup> d<sup>-1</sup> (Krueger et al 2011): these data are most comparable  
527 to Bongwana. Data from a site near Florina, Greece give max CO<sub>2</sub> concentrations also over

528 80%, with the highest fluxes exceeding  $2000 \text{ g m}^{-2} \text{ d}^{-1}$  (max over  $9000 \text{ g m}^{-2} \text{ d}^{-1}$ ). Background  
529 values here are similar to those found at Laacher See and Bongwana (Zigou et al., 2013).

530

531 Our favored model for  $\text{CO}_2$  flux to the surface at Bongwana is summarized schematically in  
532 Figure 8a. We propose that a blind fault is likely genetically linked to the surface through a  
533 connected fracture network, exposed on the surface as a fracture corridor, and through  
534 which  $\text{CO}_2$  and other fluids migrate. In Figure 8b a simplified block diagram illustrates the  
535 proposed model for a discrete fault-slip surface and associated fractures at depth connected  
536 to the surface through a fracture network. This model differs from the proposed models in  
537 Figure 2, which rely on a continuous fault and associated damage zone cropping out at the  
538 surface. A theoretical graph of permeability is shown cutting the fracture network (Figure  
539 8b). The permeability is determined by the open fracture network permeability. The  
540 jaggedness of the permeability graph represents the likely heterogeneities in fracture  
541 permeability resulting from the mapped variations in fracture intensity and connectivity  
542 mapped, and potential fracture seal due to fluid-rock interaction. Such heterogeneities  
543 captured in 2D in the graph would be mirrored along strike resulting in a 3D heterogeneity  
544 of  $\text{CO}_2$  flux to the surface.

545

546 The true heterogeneity of the fracture network's permeability in controlling  $\text{CO}_2$  flow to the  
547 surface is untested here. To better understand the genetic link between the fracture  
548 network and  $\text{CO}_2$  surface exhalation, direct measurements of  $\text{CO}_2$  flux on rock outcrops  
549 mapped for fractures is proposed as a focus for future work. This provides challenges in  
550 ensuring a seal between the rough outcrop surface and the gas capture chamber, but would  
551 provide direct evidence of the role of the fracture network permeability in controlling  $\text{CO}_2$   
552 flux. Given the observation of reaction to kaolinite in the Dwyka Group tillite, in a highly  
553 fractured zone, direct measurements of  $\text{CO}_2$  flux on fractured outcrop should be combined  
554 with detailed petrography to assess the role of fracture seal from fluid-rock interaction.  
555 Together such a study could provide not only a present day picture of fracture permeability  
556 and  $\text{CO}_2$  flux, but a history of flow and fracture seal.

557

558 The connectivity of the Bongwana Fault to the surface through a fracture network has risk  
559 implications for fault-bounded CCS sites. For CCS sites that are fault bounded at depth,  
560 fractures either associated with the initial faulting or that have formed subsequently due to  
561 fault evolution and reactivation may require re-evaluation. Work to better understand the  
562 evolution of damage resulting from fault growth and linkage (e.g. Peacock, 2002; Childs et  
563 al., 2009; Choi et al., 2016) may inform such evaluations. The observations at Bongwana  
564 suggest that rock damage associated with a propagating fault tip (e.g. McGrath and Davison,  
565 1995) at depth may create fracture permeability ahead of a discrete slip surface; as seen in  
566 hydrothermal systems (Curewitz and Karson, 1997). The bend in the fault, at Site B, could be  
567 the result of linkage of two initial fault segments, with the extra fracture damage in this area  
568 the result of fracturing ahead of the propagating fault tip prior to linkage. The fracture  
569 geometries (horsetails and splays) and orientations are consistent with such a model (Choi  
570 et al., 2016). If Site B is a fault linkage zone then we would predict higher fracture  
571 permeability at linkage zones, as described by other authors (e.g. Curewitz and Karson,  
572 1997; Rotevatn and Bastesen, 2014).

573

574 Fracture networks such as those at Bongwana will not be seismically resolvable, and fault  
575 linkage zones may be hard to distinguish in seismic imagery. Interpretation of seismic data  
576 of traps for CO<sub>2</sub> storage, may suggest an intact top seal, but could be jeopardized by an un-  
577 imaged connected fracture network. Clear understanding of fault geometries and evolution  
578 within a regional and local stress field (e.g. Kattenhorn et al., 2000; Healy, 2008) should help  
579 to predict fracture deformation patterns. Such studies are crucial to understanding how  
580 faults and associated deformation may affect storage integrity for potential fault bounded  
581 CCS sites. This understanding is particularly important for fracture networks that are below  
582 seismic image resolution.

583

## 584 **7. Conclusions**

585 Permeability measurements of Dwyka Group tillite suggest that CO<sub>2</sub> stored at depth should  
586 be sealed by the tillite. However, field observations of elevated fluid fluxes, and the  
587 presence of travertine cones on the surface purport CO<sub>2</sub> flux to the surface. The CO<sub>2</sub>  
588 exhalations are spatially correlated with a fracture corridor known as the Bongwana Fault.  
589 We propose that the CO<sub>2</sub> is exploiting the fracture network to exhale on the surface.  
590 Mapped heterogeneity in fracture orientation and intensity suggest that CO<sub>2</sub> flux to the  
591 surface will be controlled by localized zones of high permeability along the fracture corridor.  
592 Zones of high permeability are created by fracture network connectivity rather than a  
593 discrete fault zone. Fracture network connectivity is enhanced by local fault bends that  
594 result in fractures with a greater diversity in orientation, as well as local heterogeneity in  
595 fracture intensity and connectivity. Further, the spatial distribution of permeability within  
596 the fracture network is likely to vary through time as fluid rock interaction seals the  
597 fractures.

598

599 The Bongwana Fault, along with other global examples of natural CO<sub>2</sub> seeps, provides  
600 evidence that even when there is both a high permeability reservoir and low permeability  
601 caprock that localized fracture deformation can result in seal breach. Fractures are often  
602 below seismic image resolution, creating an unknown risk in the evaluation of CCS sites.  
603 Better understanding of deep-seated fault geometries and deformation around faults,  
604 particularly at faults tips and in fault linkage zones, in their regional and local stress field  
605 should aid in the prediction of areas of high fracture intensity and hence potential high-risk  
606 leakage zones in CCS sites.

607

## 608 **Acknowledgements**

609 The authors would like to acknowledge the financial support of the UK CCS Research Centre  
610 ([www.ukccsrc.ac.uk](http://www.ukccsrc.ac.uk)) in carrying out this work. Author Kremer is supported by NERC grant  
611 NE/N015908/1. The UKCCSRC is funded by the EPSRC as part of the RCUK Energy  
612 Programme. Midland Valley Exploration are thanked for an academic license for Move.  
613 Porosity and permeability analysis were undertaken in the University of Aberdeen  
614 Petrophysics laboratory with the aid of Sophie Harland. The South African National Energy  
615 Development Institute (SANEDI) Stakeholder Engagement team under the South African  
616 Centre for Carbon Capture & Storage (SACCCS) is thanked for making the scientific work  
617 possible. The National, Provincial and Local Government structures including Traditional  
618 Authorities, Municipalities, landowners and local residents are thanked for granting  
619 permission to conduct the monitoring in the areas of interest. CGS staff are thanked for

620 their assistance and support in the field. We thank two anonymous reviewers for their  
621 comments, which helped to improve the manuscript.

622

## 623 **References**

624 Agosta, F., and Kirschner, D.L., 2003. Fluid conduits in carbonate-hosted seismogenic normal  
625 faults of central Italy. *J. Geophys. Res.* 108, B4. <http://dx.doi.org/10.1029/2002JB002013>.

626

627 Audigane, P., Gaus, I., Czernichowski-Lauriol, I., Pruess, K. and Xu, T., 2007. Two-dimensional  
628 reactive transport modeling of CO<sub>2</sub> injection in a saline aquifer at the Sleipner site, North  
629 Sea. *American Journal of Science*, 307(7), pp.974-1008.

630

631 Aydin, A. and Eyal, Y., 2002. Anatomy of a normal fault with shale smear: Implications for  
632 fault seal. *AAPG bulletin*, 86(8).

633

634 Beaubien, S.E., Ciotoli, G, Coombs, P, Dictor, M. C., Krüger, M, Lombardi, S, Pearce, J.M. and  
635 West, J.M. 2008. The impact of a naturally occurring CO<sub>2</sub> gas vent on the shallow ecosystem  
636 and soil chemistry of a Mediterranean pasture (Latera, Italy). *International Journal of*  
637 *Greenhouse Gas Control*, Vol. 2, 373-387.

638

639 Bense, V.F. and Person, M.A., 2006. Faults as conduit-barrier systems to fluid flow in  
640 siliciclastic sedimentary aquifers. *Water Resources Research*, 42(5).

641

642 Bemis, S.P., Micklethwaite, S., Turner, D., James, M.R., Akciz, S., Thiele, S.T., and Bangash,  
643 H.A., Ground-based and UAV-based photogrammetry: A multi-scale, high-resolution  
644 mapping tool for structural geology and paleoseismology. 2014 *Journal of Structural*  
645 *Geology*, v. 69, p. 163–178, doi: 10.1016/j.jsg.2014.10.007

646

647 Bernstein, L., Bosch, P., Canziani, O., Chen, Z., Christ, R., Davidson, O., ... & Kundzewicz, Z.  
648 (2007). IPCC, 2007: climate change 2007: synthesis report. Contribution of working groups I.  
649 *II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate*  
650 *Change. Intergovernmental Panel on Climate Change, Geneva.* < [http://www.ipcc.](http://www.ipcc.ch/ipccreports/ar4-syr.htm)  
651 [ch/ipccreports/ar4-syr.htm](http://www.ipcc.ch/ipccreports/ar4-syr.htm).

652

653 Bond, C. E., Z. K. Shipton, R. R. Jones, R. W. H. Butler, and A. D. Gibbs. 2007. Knowledge  
654 transfer in a digital world: Field data acquisition, uncertainty, visualization, and data  
655 management. *Geosphere* 3, no. 6 (2007): 568-576.

656

657 Bond, C. E. 2015. Uncertainty in structural interpretation: Lessons to be learnt. *Journal of*  
658 *Structural Geology*, 74, 185-200.

659

660 Bond, C.E., Wightman, R. & Ringrose, PS. (2013). 'The influence of fracture anisotropy on CO  
661 2 flow'. *Geophysical Research Letters*, vol 40, no. 7, pp. 1284-1289.

662

663 Bretan, P., Yielding, G. and Jones, H., 2003. Using calibrated shale gouge ratio to estimate  
664 hydrocarbon column heights. *AAPG bulletin*, 87(3), pp.397-413.

665

666 Burnside, N.M., Shipton, Z.K., Dockrill, B. and Ellam, R.M., 2013. Man-made versus natural

667 CO2 leakage: A 400 ky history of an analogue for engineered geological storage of CO2.  
668 *Geology*, 41(4), pp.471-474.

669 Brandt, M. 2011. Seismic Hazard in South Africa Council for Geoscience Report number:  
670 2011-0061 © Copyright 2011. Council for Geoscience.

671 Caine, J.S., Evans, J.P. and Forster, C.B., 1996. Fault zone architecture and permeability  
672 structure. *Geology*, 24(11), pp.1025-1028.

673  
674 Childs, C., Manzocchi, T., Walsh, J.J., Bonson, C.G., Nicol, A. and Schöpfer, M.P., 2009. A  
675 geometric model of fault zone and fault rock thickness variations. *Journal of Structural*  
676 *Geology*, 31(2), pp.117-127.

677  
678 Choi, J.H., Edwards, P., Ko, K. and Kim, Y.S., 2016. Definition and classification of fault  
679 damage zones: A review and a new methodological approach. *Earth-Science Reviews*, 152,  
680 pp.70-87.

681  
682 Curewitz, D. and Karson, J.A., 1997. Structural settings of hydrothermal outflow: Fracture  
683 permeability maintained by fault propagation and interaction. *Journal of Volcanology and*  
684 *Geothermal Research*, 79(3), pp.149-168.

685  
686 De Decker, R.H., 1981. Geology of the Kokstad area. Explan. Sheet 3028. Dep, Miner, Energy  
687 Affairs. Pretoria.

688  
689 Dingle, R.V. and Scrutton, R.A., 1974. Continental break-up and the development of Post-  
690 Paleozoic sedimentary basins around southern Africa. Bulletin, Geological Society of  
691 America, 85, 1467-1474.

692  
693 Dockrill, B. and Shipton, Z.K., 2010. Structural controls on leakage from a natural CO 2  
694 geologic storage site: Central Utah, USA. *Journal of Structural Geology*, 32(11), pp.1768-  
695 1782.

696  
697 Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J. and Duncan, A.R., 1997. The timing and  
698 duration of the Karoo igneous event, southern Gondwana.

699  
700 du Toit, A.L., 1946. The geology of parts of Pondoland, East Griqualand. Explanation, Cape  
701 Sheet 35, Geological Survey of South Africa.

702  
703 Foxford, K.A., Walsh, J.J., Watterson, J., Garden, I.R., Guscott, S.C. and Burley, S.D., 1998.  
704 Structure and content of the Moab fault zone, Utah, USA, and its implications for fault seal  
705 prediction. *Geological Society, London, Special Publications*, 147(1), pp.87-103.

706  
707 Farrell, N.J.C., Healy, D. & Taylor, C.W. (2014). 'Anisotropy of permeability in faulted porous  
708 sandstones'. *Journal of Structural Geology*, vol 63, pp. 50-67.

709  
710 Faulkner, D., Jackson, C., Lunn, R., Schlische, R. W., Shipton, Z., Wibberley, C., & Withjack, M.  
711 O. 2010. A review of recent developments concerning the structure, mechanics and fluid



712 flow properties of fault zones. *Journal of Structural Geology*, 32(11), 1557-1575.  
713 [10.1016/j.jsg.2010.06.009](https://doi.org/10.1016/j.jsg.2010.06.009)  
714  
715 Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee,  
716 M., Ebi, K.L., Estrada, Y.O., Genova, R.C. and Girma, B., 2014. IPCC, 2014: Climate Change  
717 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects.  
718 Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental  
719 Panel on Climate Change.  
720  
721 Fossen, H., Schultz, R.A., Shipton, Z.K. and Mair, K., 2007. Deformation bands in sandstone: a  
722 review. *Journal of the Geological Society*, 164(4), pp.755-769.  
723  
724 Frankel, J.J., 1972. Distribution of Tertiary sediments in Zululand and southern Mozambique,  
725 southeast Africa. *American Association of Petroleum Geologists, Bulletin*, 56, 2415-2425.  
726  
727 Gevers, T.W., 1941. Carbon Dioxide Springs and Exhalations in Northern Pondoland and  
728 Alfred County Natal. *Transactions of the Geological Society of South Africa*. 44, 233-301  
729  
730 Gouveia, F.J., and Friedmann, S.J., 2006, Timing and prediction of CO<sub>2</sub> eruptions  
731 from Crystal Geyser, UT: Lawrence Livermore National Laboratory. UCRL-TR, v. 221731, p.  
732 16.  
733  
734 Gouveia, F.J., Johnson, M.R., Leif, R.N., and Friedmann, S.J., 2005, Aerometric  
735 measurement and modeling of the mass of CO<sub>2</sub> emissions from Crystal Geyser,  
736 Utah: Lawrence Livermore National Laboratory UCRL-TR, v. 211870, p. 59.  
737  
738 Grab, S. and Knight, J., 2015. Landscapes and landforms of South Africa – an overview. In:  
739 Grab, S. and Knight, J. (eds), *Landscapes and landforms of South Africa*. World  
740 Geomorphological Landscapes, Springer, Switzerland, 186pp.  
741  
742 Grunau, H. R. "A WORLDWIDE LOOK AT THE CAP-ROCK PROBLEM." *Journal of Petroleum*  
743 *Geology* 10, no. 3 (1987): 245-265.  
744  
745 Haines, T.J., Michie, E.A.H., Neilson, J.E. & Healy, D. (2016). 'Permeability evolution across  
746 carbonate hosted normal fault zones'. *Marine and Petroleum Geology*, vol 72, pp. 62-82.  
747  
748 Harris, C., Stock, W. D., & Lanham, J. 1997. Stable isotope constraints on the origin of CO<sub>2</sub>  
749 gas exhalations at Bongwan, Natal. *South African Journal of Geology*, 100(3), 261-266.  
750  
751 Hartnady, C. J. H. 1985. Uplift, faulting, seismicity, thermal spring and possible incipient  
752 volcanic activity in the Lesotho-Natal Region, SE Africa: The Quathlamba Hotspot  
753 Hypothesis. *Tectonics*, 4 (4), 371-377.  
754  
755 Healy, D., 2008. Damage patterns, stress rotations and pore fluid pressures in strike-slip  
756 fault zones. *Journal of Geophysical Research: Solid Earth*, 113(B12).  
757  
758 Hesthammer, J., Johansen, T.E.S. and Watts, L., 2000. Spatial relationships within fault  
759 damage zones in sandstone. *Marine and Petroleum Geology*, 17(8), pp.873-893.

760  
761 Hunter, A., & Donovan, S. 2005. Field sampling bias, museum collections and completeness  
762 of the fossil record. *Lethaia*, 38(4), 305-314.  
763  
764 Johnson, M.R., Anhaeusser, C.R. and Thomas, R.J. (Eds) 2006. The Geology of South Africa.  
765 Geological Society of South Africa, Johannesburg/Council for Geoscience, Pretoria, 691pp  
766  
767 Johnson, Kendra, Edwin Nissen, Srikanth Saripalli, J. Ramón Arrowsmith, Patrick McGarey,  
768 Katherine Scharer, Patrick Williams, and Kimberly Blisniuk. 2014. Rapid mapping of ultrafine  
769 fault zone topography with structure from motion." *Geosphere* 10, 969-986.  
770  
771 Kattenhorn, S.A., Aydin, A. and Pollard, D.D., 2000. Joints at high angles to normal fault  
772 strike: an explanation using 3-D numerical models of fault-perturbed stress fields. *Journal of*  
773 *Structural Geology*, 22(1), pp.1-23.  
774  
775 Kim, Y.S. and Sanderson, D.J., 2005. The relationship between displacement and length of  
776 faults: a review. *Earth-Science Reviews*, 68(3), pp.317-334.  
777  
778 King, L.C., 1972. The coastal plain of southern Africa: Its form, deposits and development:  
779 *Zeitschr. Geomorphologie*, N.F., Bd. 16, 239-251.  
780  
781 Kingsley, C.S. and Marshall., C.G.A., 2009. Lithostratigraphy of the Msikaba Formation (Cape  
782 Supergroup). South African Committee for Stratigraphy, Lithostratigraphic Series No. 50.  
783 Council for Geoscience, 8pp.  
784  
785 Krüger, M., Jones, D., Frerichs, J., Oppermann, B. I., West, J., Coombs, P., Green, K., Barlow,  
786 Y., Lister, R., Shaw, R., Strutt, M. and Möller, I. 2011. Effects of elevated CO<sub>2</sub> concentrations  
787 on the vegetation and microbial populations at a terrestrial CO<sub>2</sub> vent at Laacher See,  
788 Germany. *International Journal of Greenhouse Gas Control*, Vol. 5, 1093-1098.  
789  
790 Lake, L.W. (ed). 2007. Petroleum Engineering Handbook, Volumes I-VII. Society of Petroleum  
791 Engineers. Accessed via PetroWiki <http://petrowiki.org/PetroWiki>, May 2016.  
792  
793 Lawther, S.E., Dempster, T.J., Shipton, Z.K. and Boyce, A.J., 2016. Effective crustal  
794 permeability controls fault evolution: An integrated structural, mineralogical and isotopic  
795 study in granitic gneiss, Monte Rosa, northern Italy. *Tectonophysics*.  
796  
797 Li, S., M. Dong, Z. Li, S. Huang, H. Qing, and E. Nickel. 2005. Gas breakthrough pressure for  
798 hydrocarbon reservoir seal rocks: implications for the security of long-term CO<sub>2</sub> storage in  
799 the Weyburn field. *Geofluids* 5, 326-334.  
800  
801 Li, Z., Dong, M., Li, S., & Huang, S., 2006. CO<sub>2</sub> sequestration in depleted oil and gas  
802 reservoirs—caprock characterization and storage capacity. *Energy Conversion and*  
803 *Management*, 47(11), 1372-1382.  
804  
805 Manzocchi, T., Walsh, J.J., Nell, P. and Yielding, G., 1999. Fault transmissibility multipliers for  
806 flow simulation models. *Petroleum Geoscience*, 5(1), pp.53-63.

807  
808 McGrath, A.G. and Davison, I., 1995. Damage zone geometry around fault tips. *Journal of*  
809 *Structural Geology*, 17(7), pp.1011-1024.  
810  
811 Metz, B., Davidson, O., De Coninck, H. C., Loos, M., & Meyer, L. A. (2005). IPCC, 2005: IPCC  
812 special report on carbon dioxide capture and storage. Prepared by Working Group III of the  
813 Intergovernmental Panel on Climate Change. *Cambridge, United Kingdom and New York, NY,*  
814 *USA*, 442.  
815  
816 Miller, S.A., Collettini, C., Chiaraluce, L., Cocco, M., Barchi, M. and Kaus, B.J., 2004.  
817 Aftershocks driven by a high-pressure CO<sub>2</sub> source at depth. *Nature*, 427(6976), pp.724-727.  
818  
819 Maud, R.R., 1961. A preliminary review of the structure of coastal Natal: Geological Society  
820 of South Africa. *Transactions of the Geological Society of South Africa*, 64, 247-256.  
821  
822 Mauldon, M., Dunne, W.M. and Rohrbaugh, M.B., 2001. Circular scanlines and circular  
823 windows: new tools for characterizing the geometry of fracture traces. *Journal of Structural*  
824 *Geology*, 23(2), pp.247-258.  
825  
826 Newell, D.L., Kaszuba, J.P., Viswanathan, H.S., Pawar, R.J. and Carpenter, T., 2008.  
827 Significance of carbonate buffers in natural waters reacting with supercritical CO<sub>2</sub>:  
828 Implications for monitoring, measuring and verification (MMV) of geologic carbon  
829 sequestration. *Geophysical Research Letters*, 35(23).  
830  
831 Otto, J.D.T., 1973. The geology and petrology of the Marble Delta. PhD thesis, University of  
832 Stellenbosch. 174pp.  
833  
834 Partridge, T.C. and Maud, R.R. 2000. Macro-scale geomorphic evolution of southern Africa.  
835 In: T.C. Partridge and R.R. Maud (eds), *The Cenozoic of Southern Africa*. Oxford University  
836 Press, 3-18.  
837  
838 Peacock, D.C.P., 2002. Propagation, interaction and linkage in normal fault systems. *Earth-*  
839 *Science Reviews*, 58(1), pp.121-142.  
840  
841 Praetorius, B. and Schumacher, K., 2009. Greenhouse gas mitigation in a carbon constrained  
842 world: The role of carbon capture and storage. *Energy Policy*, 37(12), pp.5081-5093.  
843  
844 Rinaldi, A.P. and Rutqvist, J., 2013. Modeling of deep fracture zone opening and transient  
845 ground surface uplift at KB-502 CO<sub>2</sub> injection well, In Salah, Algeria. *International Journal of*  
846 *Greenhouse Gas Control*, 12, pp.155-167.  
847  
848 Ringrose, P.S., Mathieson, A.S., Wright, I.W., Selama, F., Hansen, O., Bissell, R., Saoula, N.  
849 and Midgley, J., 2013. The In Salah CO<sub>2</sub> storage project: lessons learned and knowledge  
850 transfer. *Energy Procedia*, 37, pp.6226-6236.  
851

852 Roberts, J.J., Wood, R.A., Wilkinson, M. and Haszeldine, S., 2015. Surface controls on the  
853 characteristics of natural CO<sub>2</sub> seeps: implications for engineered CO<sub>2</sub> stores. *Geofluids*,  
854 15(3), pp.453-463.  
855

856 Rohrbaugh Jr, M.B., Dunne, W.M. and Mauldon, M., 2002. Estimating fracture trace  
857 intensity, density, and mean length using circular scan lines and windows. *AAPG bulletin*,  
858 86(12), pp.2089-2104.  
859

860 Roncella, R., Forlani, G., & Remondino, F. 2005. Photogrammetry for geological applications:  
861 automatic retrieval of discontinuity orientation in rock slopes. In *Electronic Imaging*, p. 17-  
862 27. International Society for Optics and Photonics.  
863

864 Rotevatn, A. and Bastesen, E., 2014. Fault linkage and damage zone architecture in tight  
865 carbonate rocks in the Suez Rift (Egypt): implications for permeability structure along  
866 segmented normal faults. *Geological Society, London, Special Publications*, 374(1), pp.79-95.  
867

868 Rutqvist, J., 2012. The geomechanics of CO<sub>2</sub> storage in deep sedimentary formations.  
869 *Geotechnical and Geological Engineering*, 30(3), pp.525-551.  
870

871 Salvini, Riccardo, Silvia Riccucci, Domenico Gulli, Riccardo Giovannini, Claudio Vanneschi,  
872 and Mirko Francioni. 2015. "Geological application of UAV photogrammetry and terrestrial  
873 laser scanning in marble quarrying (Apuan Alps, Italy)." In *Engineering Geology for Society  
874 and Territory-Volume 5*, pp. 979-983. Springer International Publishing  
875

876 Schlische, R.W., Young, S.S., Ackermann, R.V. and Gupta, A., 1996. Geometry and scaling  
877 relations of a population of very small rift-related normal faults. *Geology*, 24(8), pp.683-686.  
878

879 Shipton, Z.K. and Cowie, P.A., 2003. A conceptual model for the origin of fault damage zone  
880 structures in high-porosity sandstone. *Journal of Structural Geology*, 25(3), pp.333-344.  
881

882 Shipton, Z.K., Evans, J.P., Dockrill, B., Heath, J., Williams, A., Kirchner, D. and Kolesar, P.T.,  
883 2006. Natural leaking CO<sub>2</sub>-charged systems as analogs for failed geologic storage reservoirs.  
884 *Carbon Dioxide Capture for Storage in Deep Geologic Formations—Results from the CO<sub>2</sub>  
885 Capture Project*, pp.699-712.  
886

887 Shukla, R., Ranjith, P., Haque, A., & Choi, X. 2010. A review of studies on CO<sub>2</sub> sequestration  
888 and caprock integrity. *Fuel*, 89(10), 2651-2664.  
889

890 Sibson, R.H., 1995. Selective fault reactivation during basin inversion: potential for fluid  
891 redistribution through fault-valve action. *Geological Society, London, Special Publications*,  
892 88(1), pp.3-19.  
893

894 Singh, V. and McLachlan, I. 2003. South Africa's east coast frontier offers untested mid- to  
895 deepwater potential. *Oil and Gas Journal*, 101(22), 40-45.  
896

897 Tamagawa, T. and Pollard, D.D., 2008. Fracture permeability created by perturbed stress  
898 fields around active faults in a fractured basement reservoir. *AAPG bulletin*, 92(6), pp.743-

899 764.  
900  
901 Thomas, R.J., 1988. The geology of the Port Shepstone area. Explanation of sheet 3030  
902 (1:250000). Geological Survey of South Africa, 136pp.  
903  
904 Thomas, R.J., von Brunn, V., Marshall, C.G.A., 1990. A tectono-sedimentary model for the  
905 Dwyka Group in southern Natal, South Africa. *South African Journal of Geology*, 93, 809-  
906  
907 Verdon, J.P., Stork, A.L., Bissell, R.C., Bond, C.E. and Werner, M.J., 2015. Simulation of  
908 seismic events induced by CO<sub>2</sub> injection at In Salah, Algeria. *Earth and Planetary Science  
909 Letters*, 426, pp.118-129.  
910  
911 Von Veh, M.W. and Andersen, N.J.B., 1990. Normal-slip faulting in the coastal areas of  
912 northern Natal and Zululand, South Africa. *South African Journal of Geology*, 93, 574-582.  
913  
914 Walker, R.J., Holdsworth, R.E., Imber, J., Faulkner, D.R., Armitage, P.J., 2013. Fault zone  
915 architecture and fluid flow in interlayered basaltic volcanoclastic–crystalline sequences. *J.  
916 Struct. Geol.* 51, 92–104.  
917  
918 Walsh, J. J. and Watterson J. 1988. Analysis of the relationship between displacements and  
919 dimensions of faults. *J. Struct. Geol.*, 10, 239–247  
920  
921 Watkeys, M.K. and Sokoutis, D., 1998. Transtension in southeast Africa during Gondwana  
922 break-up. In: Holdsworth, R.E., Strachan, R. and Dewey, J.F. (Eds), *Continental  
923 Transpressional and Transtensional Tectonics*. Special Publication of the Geological Society  
924 of London, 135, 203-214.  
925  
926 Watkins, H., Bond, C.E., Healy, D., Butler R.W.H., 2015. Appraisal of fracture sampling  
927 methods and a new workflow to characterise heterogeneous fracture networks at outcrop.  
928 *Journal of Structural Geology*, 72, 67-82.  
929  
930 Watts, N.L., 1987. Theoretical aspects of cap-rock and fault seals for single-and two-phase  
931 hydrocarbon columns. *Marine and Petroleum Geology*, 4(4), pp.274-307.  
932  
933 Xu, T., Apps, J.A. and Pruess, K., 2003. Reactive geochemical transport simulation to study  
934 mineral trapping for CO<sub>2</sub> disposal in deep arenaceous formations. *Journal of Geophysical  
935 Research: Solid Earth*, 108(B2).  
936  
937 Yielding, G., Freeman, B. and Needham, D.T., 1997. Quantitative fault seal prediction. *AAPG  
938 bulletin*, 81(6), pp.897-917.  
939  
940 Young R. B., 1924. Exhalations of Carbon Dioxide in Alfred County, Natal. *Transactions of the  
941 Geological Society of South Africa*. 26, 99-102.  
942  
943 Ziogou, F., Gemeni, V., Koukoulas, N., de Angelis, D., Libertini, S., Beaubien, S.E., Lombardi,  
944 S., West, J. M., Jones, D.G., Coombs, P., Barlow, T.S., Gwosdz, S. and Krüger, M. 2013.

945 Potential Environmental Impacts of CO<sub>2</sub> Leakage from the Study of Natural Analogue Sites  
946 in Europe. Energy Procedia, Vol. 37, 3521-3528.

947  
948

#### 949 **Figure Captions**

950

951 Figure 1. Location map of the field area and sites described. a) Outline of Africa, boxed area  
952 defines the location of map b. b) Outline of South Africa, grey box outlines map c. c)  
953 Geological map of the KwaZulu-Natal and Eastern Cape area of South Africa around Port  
954 Edward, after Gevers (1941), based on the mapping of du Toit (1920). d) Enlargement of the  
955 boxed area in c. showing the localities of the sites visited, and the local occurrence of CO<sub>2</sub>  
956 seeps.

957

958 Figure 2. Hypothetical models for permeability across fault zones. a) The fault core/slip-  
959 surface (red -line) is permeable and acts as a conduit for fluid. b) The fault core and the  
960 surrounding damage zone are permeable and act as a conduit for fluid. c) The fault core  
961 and/or slip surface is impermeable, but the surrounding damage zone is permeable and act  
962 as a conduit for fluid. d) permeability distribution is heterogeneous across the fault core  
963 and/or slip surface and the surrounding damage zone.

964

965 Figure 3. Structural data from the three field sites, shown in their spatial context with  
966 respect to the Bongwana Fault and CO<sub>2</sub> seeps. a) Geological map of the field area based on  
967 Gevers (1941) after the mapping of du Toit (1920), showing the spatial distribution of the  
968 three field sites, annotated with stereonet of measured fractures. b) Google Map satellite  
969 image showing the locations of images for Site B (figure part c) and Site C (figure part d), the  
970 fault trend mapped by du Toit and Gevers (1941) is shown by the white dashed line. Note  
971 the significant change in fault orientation between the sites. Stereonets show the mean  
972 fault-fracture orientation at Site Cii and Site Biv, and slickenside trend and plunge  
973 measurements (N=3 and N=14 respectively). c) Google Map satellite image of Site B,  
974 showing sub-sites i-iv and the associated fracture measurements at each sub-site. An  
975 approximate fault trend is shown by a dashed white line, star denotes site of CO<sub>2</sub> bubbles in  
976 the river. d) Google Map satellite image of Site C, showing sub-sites i-ii and the associated  
977 fracture measurements at each sub-site. Long dashed white line is the approximate fault  
978 trend, smaller dashed white lines outline travertine mounds around the Umtavuna River  
979 CO<sub>2</sub> exhalations. Present day CO<sub>2</sub> seeps are marked by white stars; the black star denotes  
980 the site of a now extinct CO<sub>2</sub> travertine cone. e) 3D photogrammetric image of the main  
981 active travertine cone, the cone is approximately 1.5m wide. All stereonet plots are equal  
982 area lower hemisphere projections (poles to fracture planes); rose plots, for the same  
983 fractures, are at 5 degree intervals.

984

985 Figure 4. Interpretations of fractures in orthorectified photographs created from virtual  
986 outcrop models. Each figure part shows the fracture interpretation and associated rose  
987 diagrams of fracture orientations, and a contour map of fracture density for each site. The  
988 sites are shown in figure 2 and are a) Site A, Fractures N=446; east fractures N=211, west  
989 fractures N=235; b) Site Bi, Fractures N=142; c) Site Biii, Fractures N=103; d) Site Ci,  
990 Fractures N=2285 and e) Site Cii, Fractures N=31.

991 Figure 5. Analysis of the effect of circle radius on fracture trace network parameters. a)  
 992 Graph of fracture density, intensity and mean trace length against radius size. b) Location of  
 993 circle centres used in the analysis on fracture trace map for site Ci.

994 Figure 6. The measured CO<sub>2</sub> ground flux at Site C. a) The aerial photograph shows the  
 995 location of the nearby CO<sub>2</sub> seeps (white stars active travertine cones, black star non-active  
 996 travertine cone). Coloured circles are measurement points scaled for gas flux and CO<sub>2</sub>  
 997 concentration % in the soil. b) Actual measurements are shown in the inset graph.  
 998

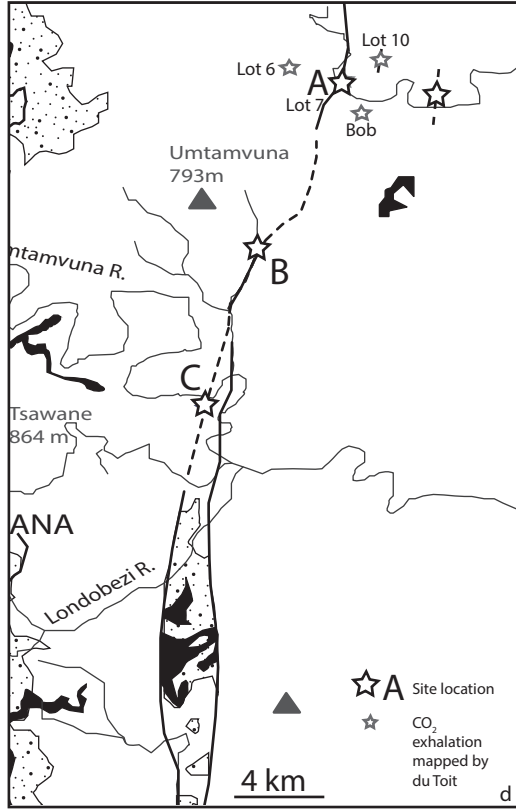
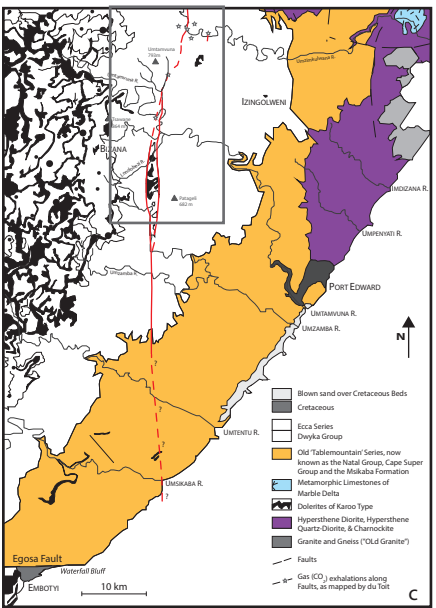
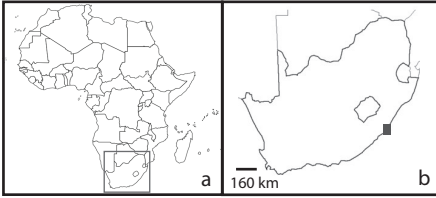
999 Figure 7. Porosity – log Permeability plot of sandstones. The plot shows the porosity-  
 1000 permeability ranges of sandstones from unconsolidated sands to tight sandstone, based on  
 1001 the Society of Petroleum Engineers, Petrowiki . The porosity and permeability values of the  
 1002 Msikaba Formation sandstone and Dwyka Group tillite are annotated.  
 1003

1004 Figure 8. Summary model for CO<sub>2</sub> flow to the surface at the Bongwana Fault. a) Proposed  
 1005 model for a deep-seated fault connected to the surface via a fracture corridor. Complexities  
 1006 in fault geometry at depth, bends and asperities, create zones of more distributed damage  
 1007 observed in the fractures at the surface. This creates a more connected fracture network  
 1008 and a higher fracture permeability due to a greater range in fracture orientation. b)  
 1009 Simplified block model of a fault at depth (thin red line) with connection to the surface via a  
 1010 high permeability fracture network (black lines). The theoretical permeability graph, shows  
 1011 a potential range in permeability created by complexities in the fracture network that may  
 1012 control the leakage pathway for CO<sub>2</sub> to the surface.  
 1013

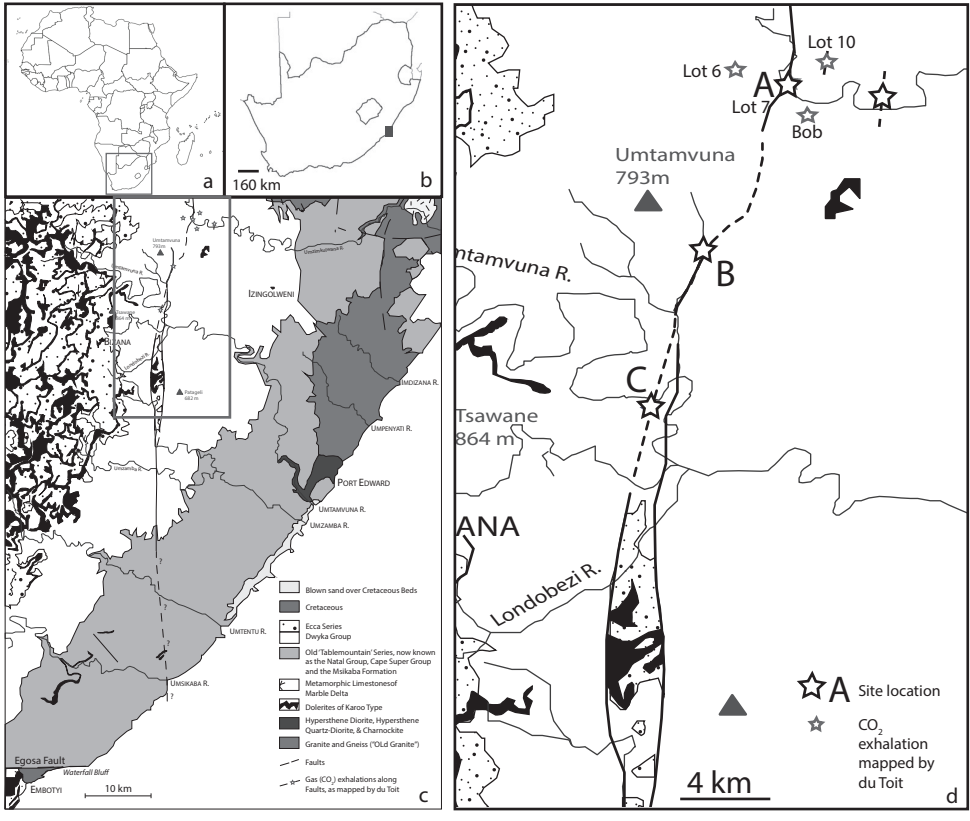
1014 **Table**

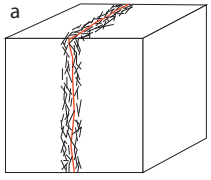
Sample	Porosity $\phi$ (He) %	Permeability - KL (N <sub>2</sub> )(mD)
<i>Msikaba Formation sandstone</i>		
20V -orthogonal to bedding	4.1	0.1865
20P - parallel to bedding	4.7	0.2762
20O - parallel to bedding orthogonal to 20P	4.4	0.2587
<i>Dwyka Group tillite</i>		
14V -vertical	22.8	0.0709
14O - orthogonal	21.2	0.0629

1016  
 1017 Table 1. Porosity and permeability measurements of the Msikaba Formation sandstone and Dwyka Group  
 1018 tillite.  
 1019

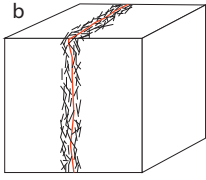
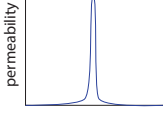




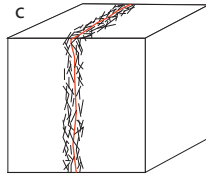
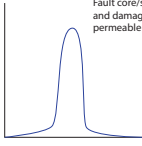




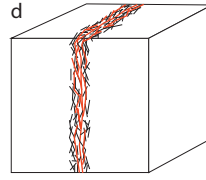
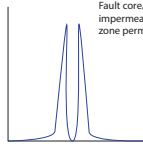
Fault core/slip surface permeable



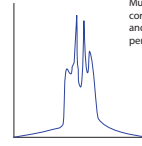
Fault core/slip surface and damage zone permeable

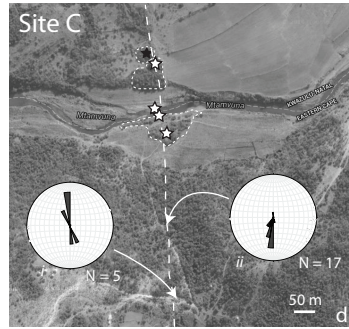
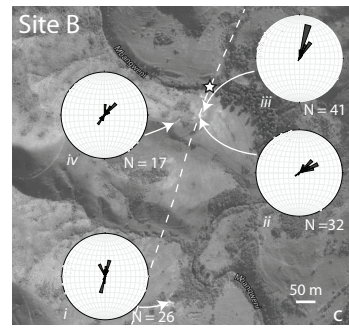
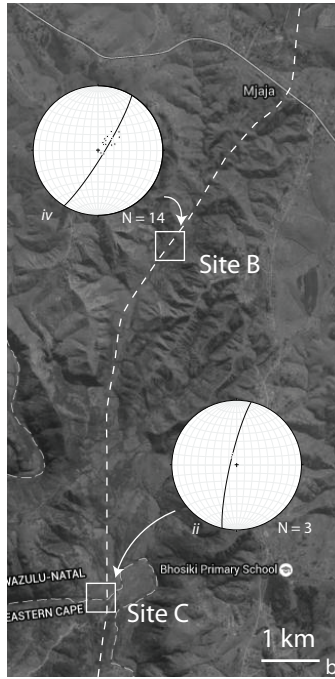
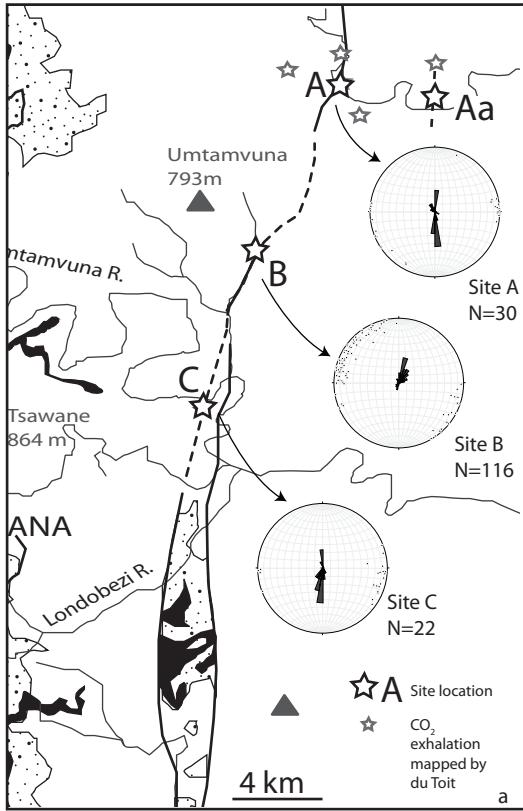


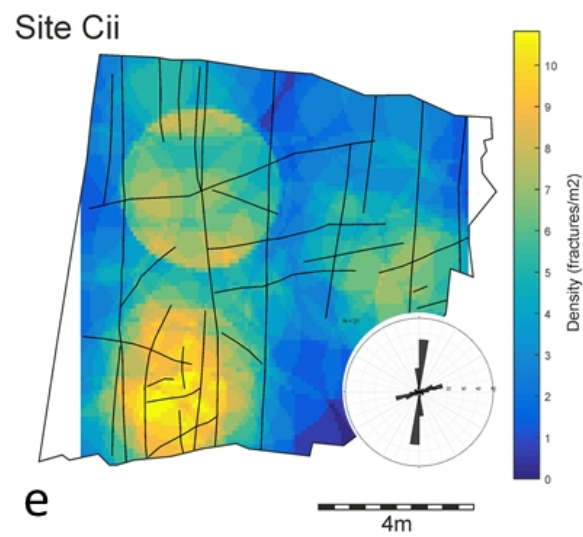
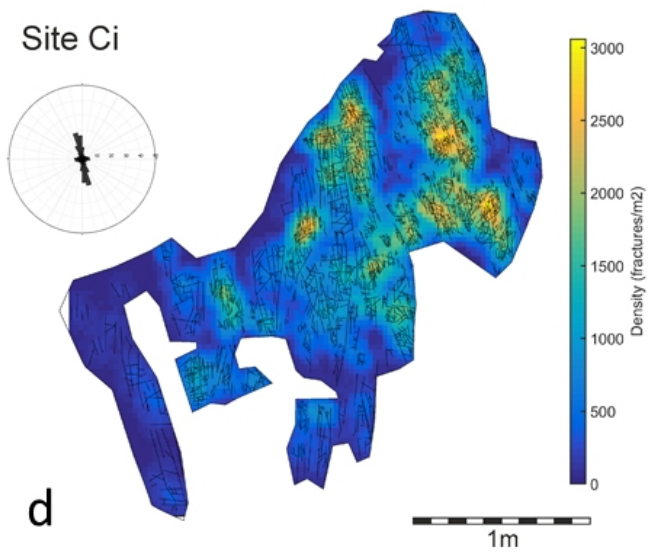
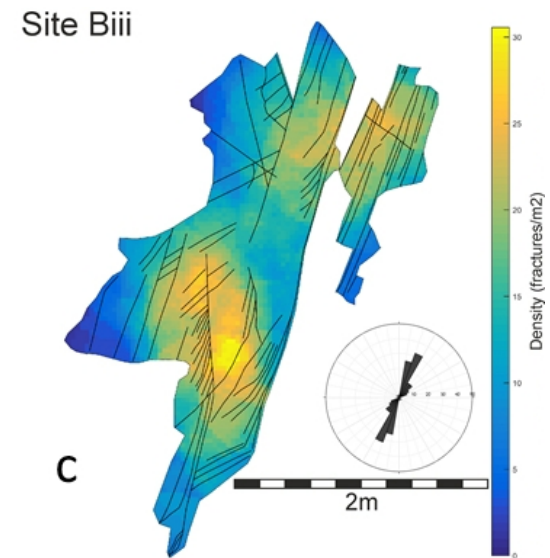
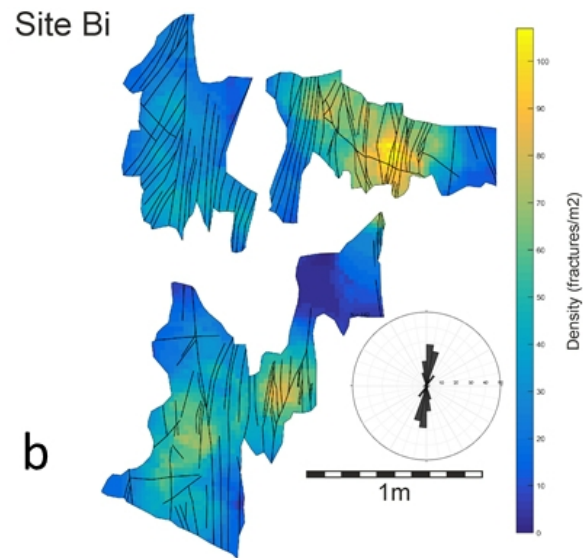
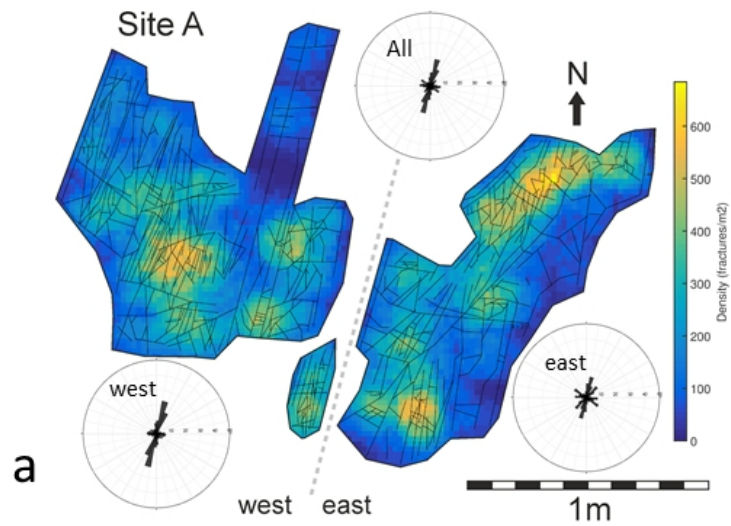
Fault core/slip surface impermeable, damage zone permeable

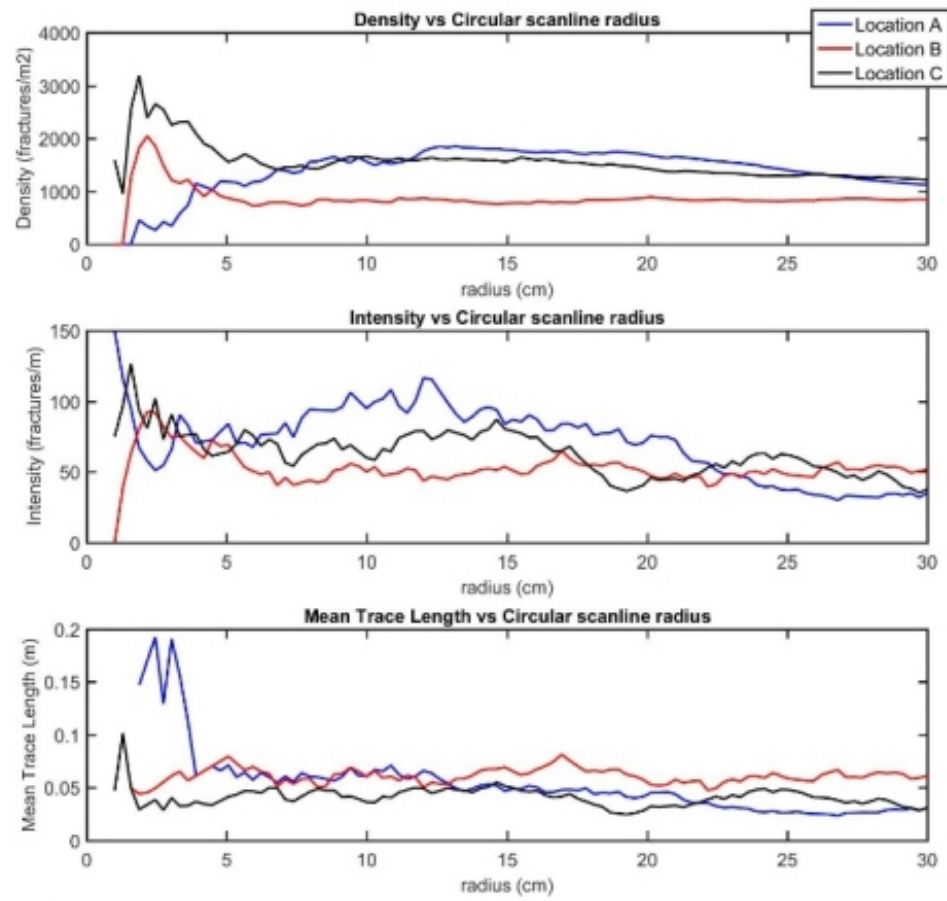


Multi-strand fault core/slip surface and damage zone permeable

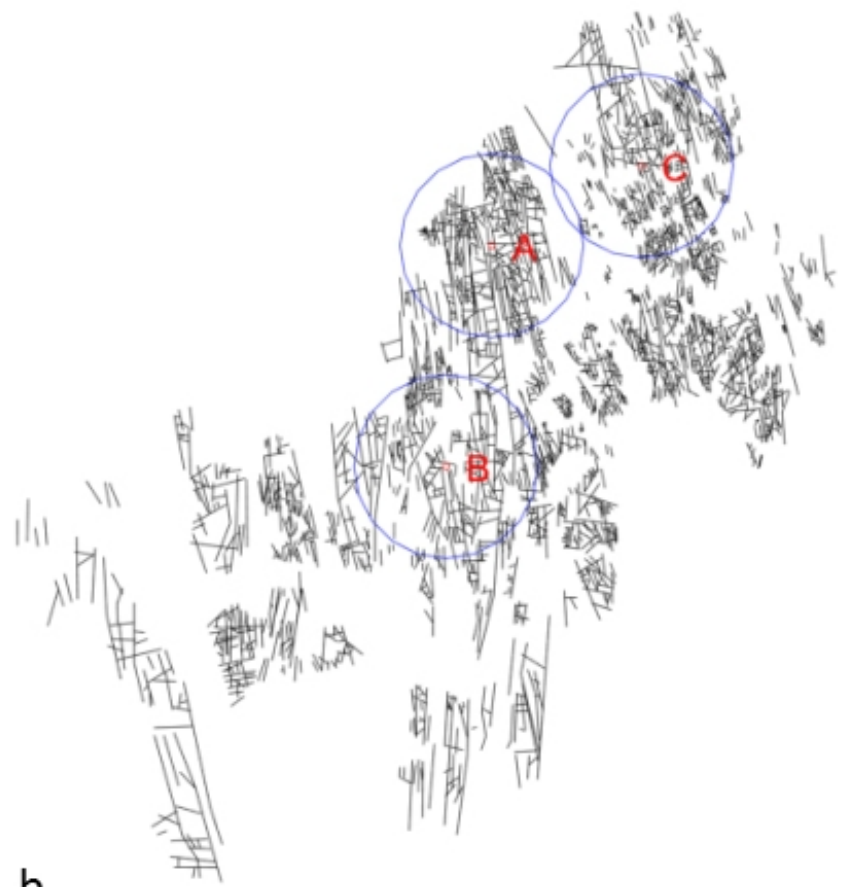






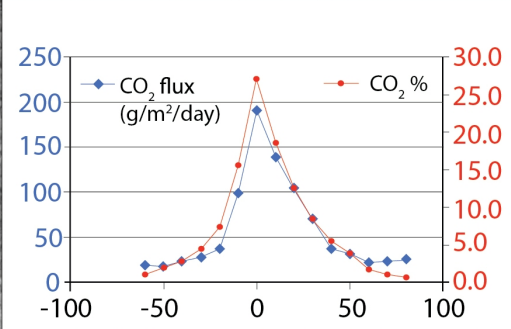
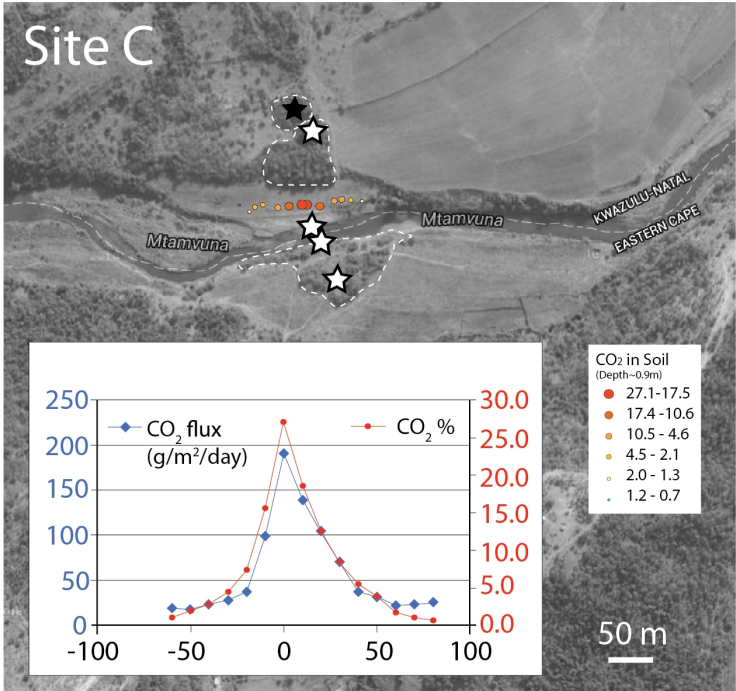


**a**

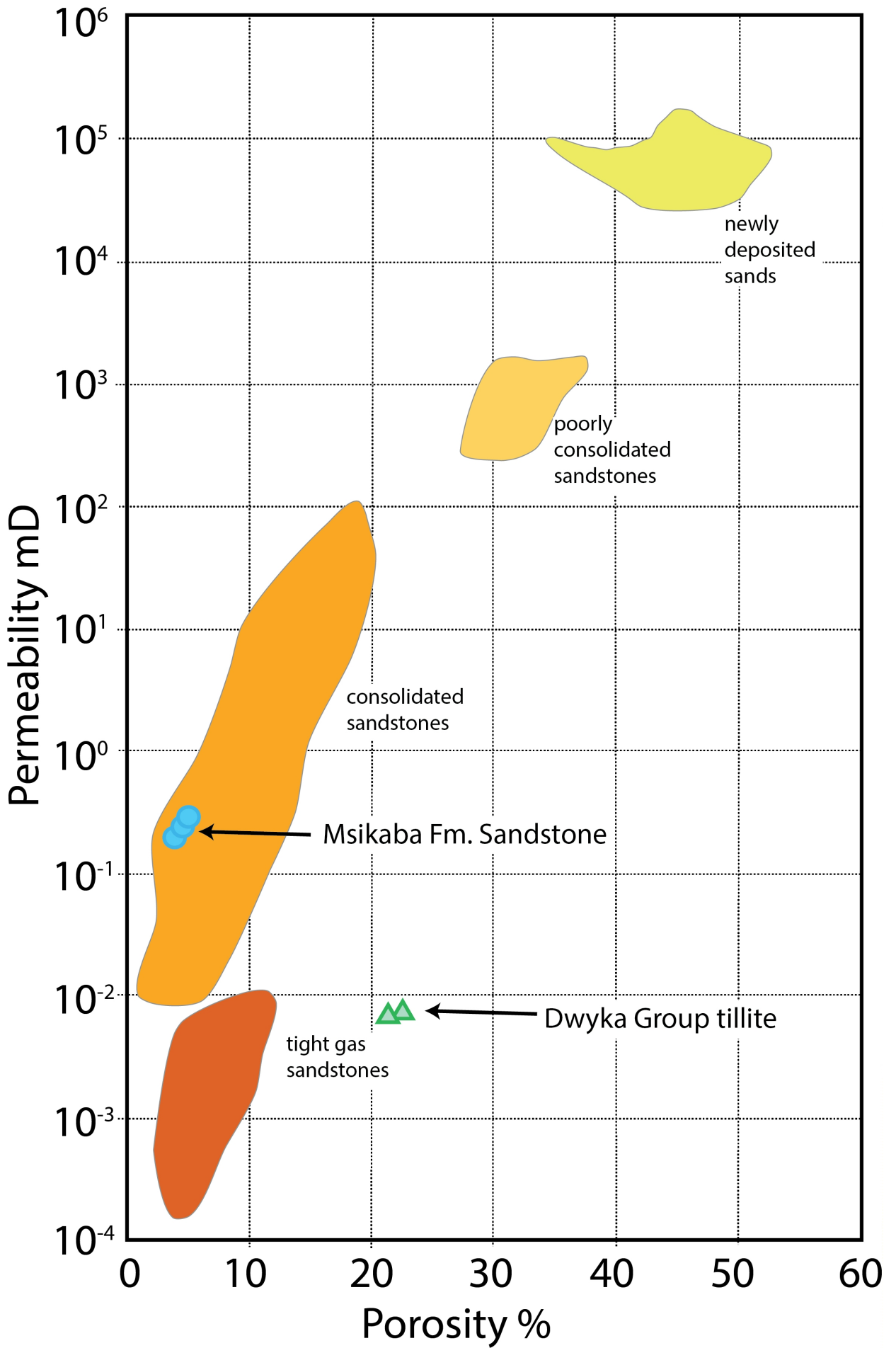


**b**

# Site C



- CO<sub>2</sub> in Soil (Depth=0.9m)
- 27.1-17.5
  - 17.4-10.6
  - 10.5-4.6
  - 4.5-2.1
  - 2.0-1.3
  - 1.2-0.7

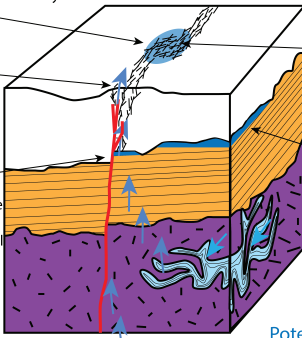


a

Multiple fracture orientations, and predicted high fracture permeability and CO<sub>2</sub> flux

CO<sub>2</sub> flow up fracture network to surface, in areas of fault complexity and splays

Juxtaposition of Dwyka Grp. tillite across the fault and high vertical fracture permeability minimises across fault CO<sub>2</sub> flow



Mantle derived CO<sub>2</sub>

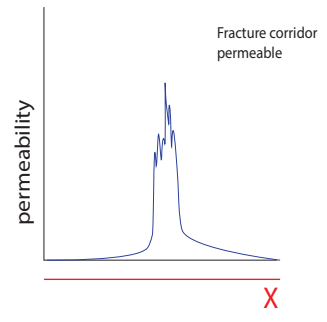
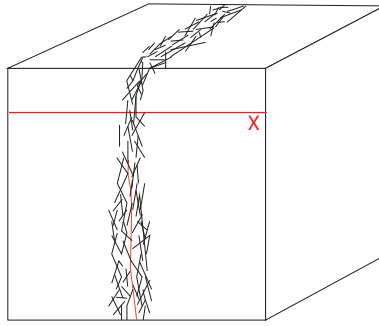
Potential CO<sub>2</sub> Sources

Bend in fault at depth - wider range in fracture orientation

CO<sub>2</sub> trapped in Msikaba Fm. Sst, unconformable base of Dwyka Grp. tillite provides a top seal away from the fault

H<sub>2</sub>O reacts with marble - degasses CO<sub>2</sub>

b





## Highlights

- CO<sub>2</sub> migration is spatially associated with the Bongwana fault fracture corridor.
- Cap rock permeability suggests that without fractures it would act as a flow barrier.
- Elevated CO<sub>2</sub> concentration and flux are measured across the fracture corridor.
- Fracture intensity and orientation variability creates permeability heterogeneity.
- Seismically unresolvable fracture networks may impact CO<sub>2</sub> storage capability.