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Fault seal analysis of a natural CO_2 reservoir in the Southern North Sea

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Abstract

A geomechanical and fault seal analysis of the fault-bound natural CO_2 reservoir of the Fizzy Field, Southern North Sea, shows that reactivation of, and leakage along the bounding fault is unlikely. Reservoirs are juxtaposed along the fault but shale-gouge ratio calculations indicate that the fault rock prohibits across-fault leakage of CO_2. This study illustrates that, even though the fault is orientated favourably for reactivation relative to present day stress and uncertainties about the geometries remain, fault seal is not the limiting factor in retention of CO_2 at the Fizzy field.

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Keywords: CO_2 storage; geomechanics; natural analouge; fault sealing; North Sea

1. Introduction

Carbon Capture and Storage (CCS) is the only industrial scale technology available to directly reduce carbon dioxide (CO_2) emissions to the atmosphere from fossil fuelled power plants and large industrial point sources [1]. To have an impact on the greenhouse gas emissions it is crucial that there is no or only a very low amount of leakage of CO_2 from the storage sites to shallow aquifers or the surface. CO_2 occurs naturally in reservoirs in the subsurface and has often been stored for millions of years without any leakage incidents [2]. However, in some cases CO_2 migrates from the reservoir to the surface. A previous study on leakage mechanisms of natural CO_2 reservoirs completed by the authors showed that the state of CO_2, pressure conditions in the reservoir and the direct overburden impact the likelihood of leakage [3]. However, at all of the studied leaking reservoirs CO_2 was migrating along fault zones, indicating that faults play a major role for fluid movement from reservoirs to the surface [3].

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The stability and sealing capacity of faults have long been identified as critical for potential CO_2 storage sites [4, 5]. There are numerous studies that evaluate the geomechanical aspects of potential or actual CO_2 storage sites, often with a focus on fault reactivation [e.g. 6, 7, 8]. The majority of these studies show that, depending on injection pressures, injecting CO_2 could lead to fault reactivation and possible CO_2 leakage. However, there are great uncertainties regarding the in-situ stress fields as well as the assumed fault properties for sealing and fluid flow. The complexity of fault zones makes the prediction of fluid flow along and through faults distinctly challenging.

Here we present a fault-seal study on a fault bound natural CO_2 reservoir, the Fizzy Field in the Southern North Sea. Previous work on the CO_2 field has shown that it is likely that the accumulation has held CO_2 safely for millions of years [9, 10]. Based on 3D seismic data Yielding et al. [11] analysed the role of stratigraphic juxtaposition for the seal integrity and across fault fluid migration and concluded that there was no risk for lateral migration. Here we build on the previous work and add more details to the stratigraphic succession to improve the fault seal analysis. Using hydrocarbon industry standard tools we calculated the sealing capacity and also studied the geomechanical properties of the bounding fault with regard to fault reactivation risks.

2. Geological setting of the Fizzy Field

The Fizzy Field is located in the UK sector of the Southern North Sea (block 50/26b, Fig. 1) in the Southern Permian Basin (SPB). The SPB is major east-west striking basin that stretches from the UK to Poland. The basin is well understood, particularly in the Southern North Sea, as it has been explored for hydrocarbons for more than four decades [12]. The main reservoir throughout the Southern North Sea is the Lower Permian Rotliegend group which, in the Fizzy area, is dominated by aeolian sandstones and has a thickness of ~100 m. The Rotliegend group is overlain by the Upper Permian Zechstein group, a cyclic carbonate-evaporite system. The thick anhydrite and salt units of up to six evaporitic cycles form the main seal for the Rotliegend. In the Fizzy area only cycles Z1 to Z3 are present and they have an average thickness of 350 m. The Zechstein group is overlain by the Lower Triassic Bacton group which comprises the Bunter Shale formation and the Bunter Sandstone formation. The Bunter shale acts as an additional seal on top of the Zechstein and has thicknesses exceeding 300 m in the Fizzy area. The reservoir hosts a gas column which comprises 50% CO_2, 9% N_2 and 41% methane [12].

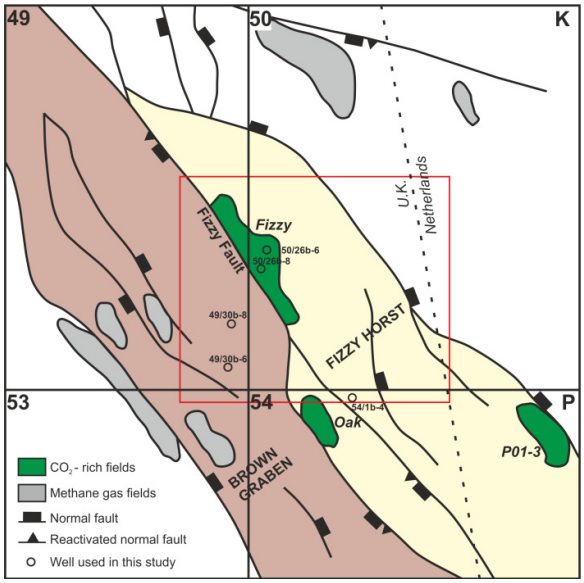

Fig. 1: Map showing the location of the Fizzy Field in the Southern North Sea. Major structural elements are illustrated as well as gas accumulations and wells used in this study. Red rectangle illustrates the extend of the 3D model, shown in figure 2. After [10].

The Fizzy field is located on the Fizzy Horst which is separated from the Brown Graben by the Fizzy Fault (Figs. 1, 2). The deep seated fault was structurally inverted in the latest Cretaceous with possible further inversion during the Cenozoic [11]. The fault acts as boundary fault for the Fizzy accumulation and has maximum offsets of up to 500 m (Fig. 2). The gas-water contact (GWC) is found at 2253.1 m (TVDSS) in well 50/26b-6 and, assuming static conditions, the outline of the GWC has been reconstructed areally (Fig. 2).

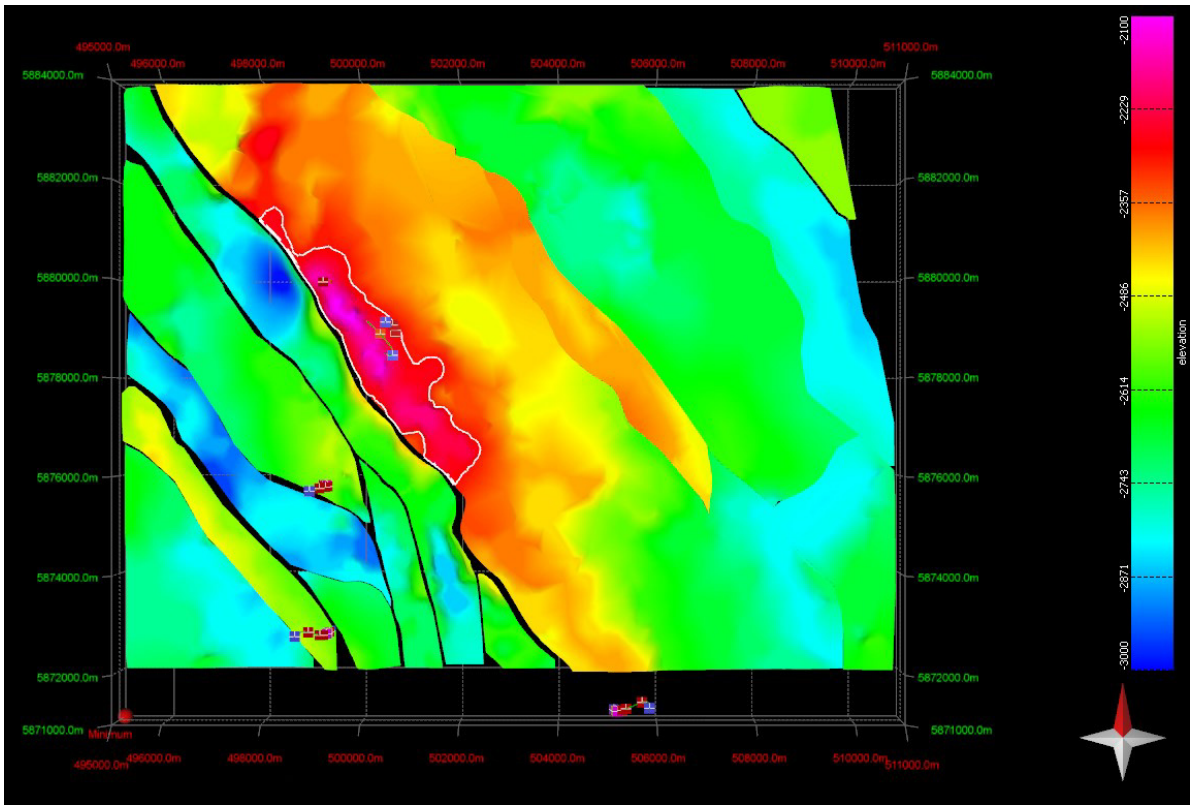

Fig. 2: Top Rotliegend surface of the Fizzy Field area (see Fig. 1 for location). GWC is illustrated by white line, the bounding fault is the Fizzy Fault. Wells used for well-tying are shown. Depths are in meters (TVDSS).

The trap is not filled to spill [11] and there are three possible explanations for this: (1) The trap was never filled to spill due to insufficient charge or (2) the trap was filled to spill and has subsequently leaked CO_2 or (3) a combination of 1 and 2. For an explanation including leakage, three leakage scenarios are possible: (i) leakage up/along the fault, (ii) leakage across the fault, and (iii) leakage through the caprock. In the following we investigate the possibilities for leakage up and across the fault.

3. Geomechanical analysis

The likelihood of fault reactivation, which can lead to leakage along the fault as an existing seal (e.g. fault gouge) is breached, can be geomechanically assessed. Common approaches are the slip tendency (Ts) which is the ratio of shear stress to normal stress and the fracture stability (Fs) which is the increase in pore-pressure needed to force the fault into failure [13, 14]. For both Ts and Fs the contemporary stress field and the fault orientation has to be constrained. The Fizzy field area is in a normal faulting stress regime ($Sv>SH_{max}>Sh_{min}$). The lithostatic pressure gradient for the UK sector of the Southern North Sea has been calculated by Noy et al. [15] from leak-off tests and is 22.5 MPa/km (Sv). They also calculated a conservative minimum horizontal stress gradient of 16.9 MPa/km

(Sh_{min}) which corresponds to 75% of the lithostatic pressure gradient. The maximum horizontal stress gradient lies between Sv and Sh_{min} and is orientated NNW-SSE in the Southern North Sea according to the World Stress Map [16].

We digitized existing structural maps based on seismic interpretation as a basis for creating digital a 3D structural model of the Fizzy field area (Fig. 2). Wells 50/26b-6, 50/26b-8, 49/30b-6, 49/30b-8 and 54/1b-4 were used for well tying and to reconstruct the overburden. The structural models were created in Move 2014™ and then transferred to TrapTester 6™ for fault seal and geomechanical analysis.

Figure 3 shows the results of the geomechanical analysis of the Fizzy fault. The fault is orientated parallel to SH_{max} (Fig. 3c) and is steeply dipping (~80°). Faults orientated parallel to SH_{max} are more likely to slip than faults that are orientated parallel to Sh_{min}. The slip tendency is low (~0.2) for the Fizzy fault because it is steeply dipping. However, the dip of the fault comes with some uncertainty as it is derived from maps of the top Rotliegend and not directly from seismic data. Assuming a dip of 60° the slip tendency of the Fizzy fault would be around 0.45 and thus much closer to the onset of slip which is generally assumed to be at ~0.6 (equal to the coefficient of static friction) [17].

Fracture stability of the Fizzy Fault was calculated for two types of fault rock: clay smear and cataclasite (Fig. 3a & 3b). Clay smear is assumed to form the lower end of a strength range of possible fault rocks for the Fizzy fault with a low coefficient of internal friction (μ=0.45) and a low cohesive strength (C= 0.5 MPa) while the cataclasite defines the upper end of fault rock strength with μ=0.75 and C=4.0 MPa. In the case of clay smear an increase in pore pressure (ΔP) of 10.5 MPa is required before the fault plane is forced into failure, for the cataclasite ΔP is 17.0 MPa.

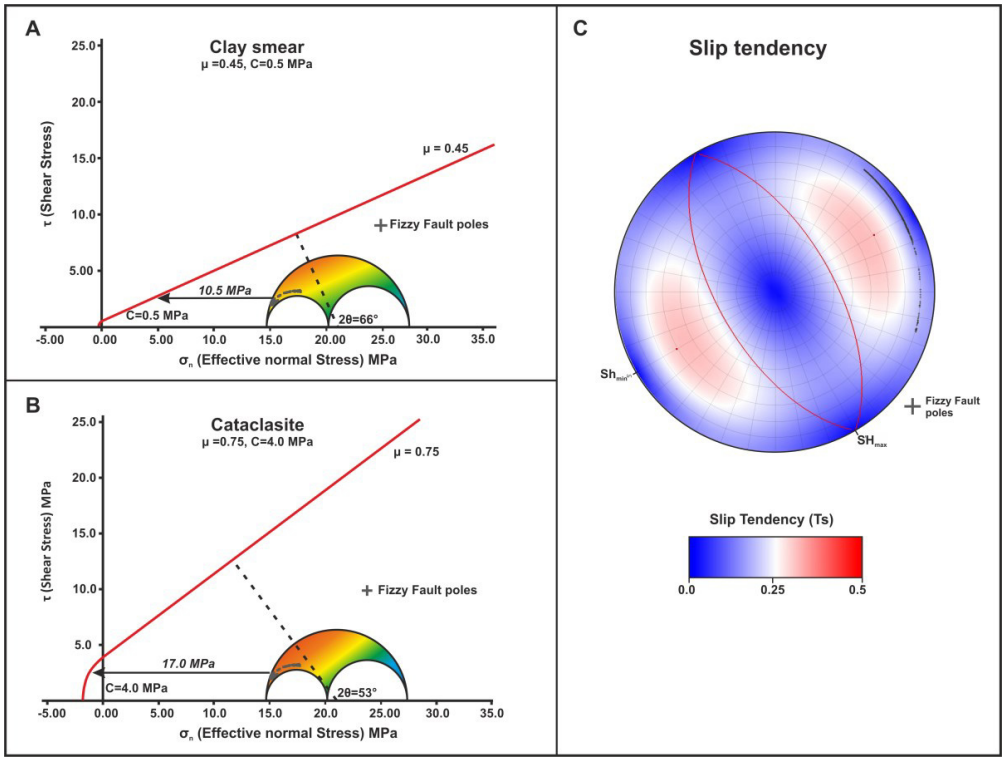

Figure 3: (a) Mohr diagram illustrating the fracture stability of the Fizzy Fault for clay smear, grey crosses are poles to the orientation of the Fizzy fault. Pore pressure could increase by 10.5 MPa before the fault would reach the failure envelope. (b) Mohr diagram illustrating the fracture stability of the Fizzy Fault for cataclasite. Pore pressure could increase by 17 MPa before the fault would reach the failure envelope. (c) Stereonet plot illustrating that the slip tendency for the Fizzy Fault is generally low. Note that if the fault dipped less steeply the tendency to slip would increase.

Based on RFT data from well 50/26b-6 pore-pressure gradients in the Rotliegend reservoir were calculated by Yielding et al. [12]. They show that the gas buoyancy pressure at the crest of the trap (against the fault) would be ~250 psi (1.72 MPa) with a gas column high of 232 m. Our results show that the Fizzy fault can withstand much higher increases in pore pressure and even if the trap would be filled to spill (gas column of ~400 m) the fault would be far away from failure. This shows that, even though the Fizzy fault is not orientated in an ideal way, reactivation of the fault is unlikely even with a greater column height and leakage along the fault under present stress conditions is very unlikely.

4. Juxtaposition and fault rock sealing

Leakage from a reservoir across a fault occurs if the reservoir is juxtaposed against a reservoir and there are no fault rocks that prevent fluid flow. Inversely this means that a fault is sealing if the reservoir is juxtaposed against a non-reservoir or fault rocks with a high capillary entry pressure/low permeability are formed during faulting. Juxtaposition seals are readily identifiable by plotting hanging wall reservoir intervals against footwall reservoir intervals [18]. Figure 4 shows such a so-called Allan diagram for the Fizzy field and illustrates the zones where across fault fluid flow may occur due to reservoir-reservoir juxtaposition. There is only one Rotliegend-Rotliegend juxtaposition and that is located south-east of the actual Fizzy trap and is thus unlikely to play a role for fluid migration out of the CO_2 reservoir. However, there are three areas where Rotliegend reservoir sandstones are juxtaposed against carbonates of the Z2 cycle, which can have average porosities of 15% and form good reservoirs [19]. As juxtaposition of reservoirs occurs, the properties of the fault rock become important for the determination of cross-fault leakage likelihood.

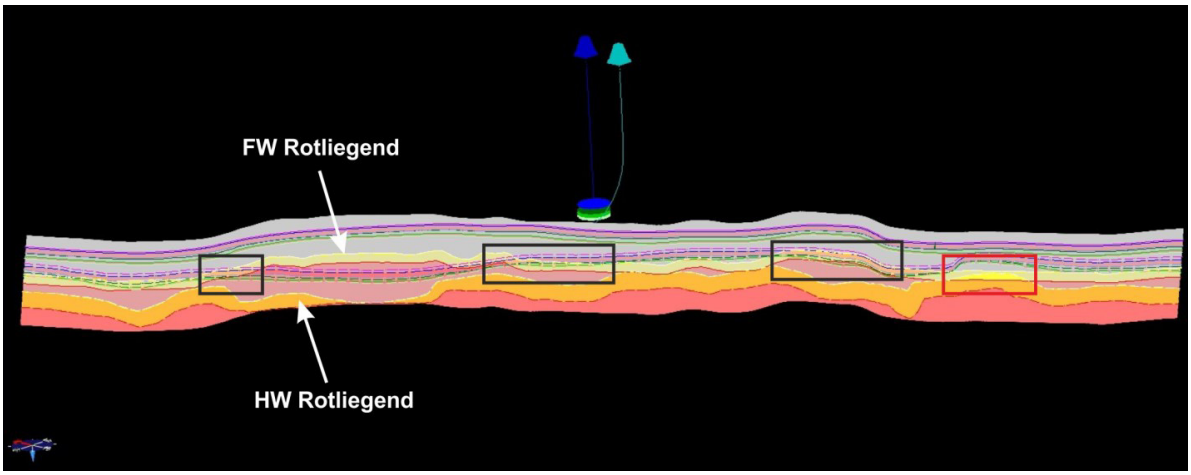

Figure 4: Allan diagram of the Fizzy fault. Yellow colours are reservoir sandstones of the Rotliegend, red colours are poor reservoir rocks of the Carboniferous and Zechstein, grey are sealing rocks. Red box indicates Rotliegend-Rotliegend juxtaposition, black boxes show Rotliegend-Zechstein Carbonates juxtaposition.Note that the red box is located outside the trap and thus migration of CO_2 at that point is unlikely.

Common algorithms for the calculation of the fault zone composition are the Shale Smear Factor (SSF) [20] and the Shale Gouge Ratio (SGR) [21]. The later has the advantage that it uses the net volume of clay (V_{clay}) which can be extrapolated from well logs of nearby wells directly onto the fault surface. We used the gamma ray logs from well 50/26b-6 to calculate V_{clay}, assuming a linear response, for reservoir and sealing layers [22]. One of the downsides is that V_{clay} cannot be used for evaporitic caprocks which comprise most of the sealing sequence in case of the Fizzy field. However, in order to calculate SGR we attributed zonal V_{clay} values for the evaporitic sequence (Fig. 5). SGR values for most of the fault are between 12 -24% and are in a critical region: Continuous clay smears generally occur above SGR values of 15-20% [23]. However, in the regions of reservoir-reservoir juxtaposition

SGR values are generally >25% and thus the likelihood of across fault fluid migration is low. This is confirmed by the fault rock permeabilities which have been calculated after Sperrevik et al. [24] from the SGR (Fig. 5). Generally permeabilities at reservoir-reservoir juxtapositions are very low (less than 0.01 mD) and may thus prohibit cross fault leakage. While the values for both SGR and permeability should be considered with caution due to the assumptions made for the evaporitic rocks in the fault zone, our results show that cross fault leakage at reservoir-reservoir juxtapositions is are not very likely.

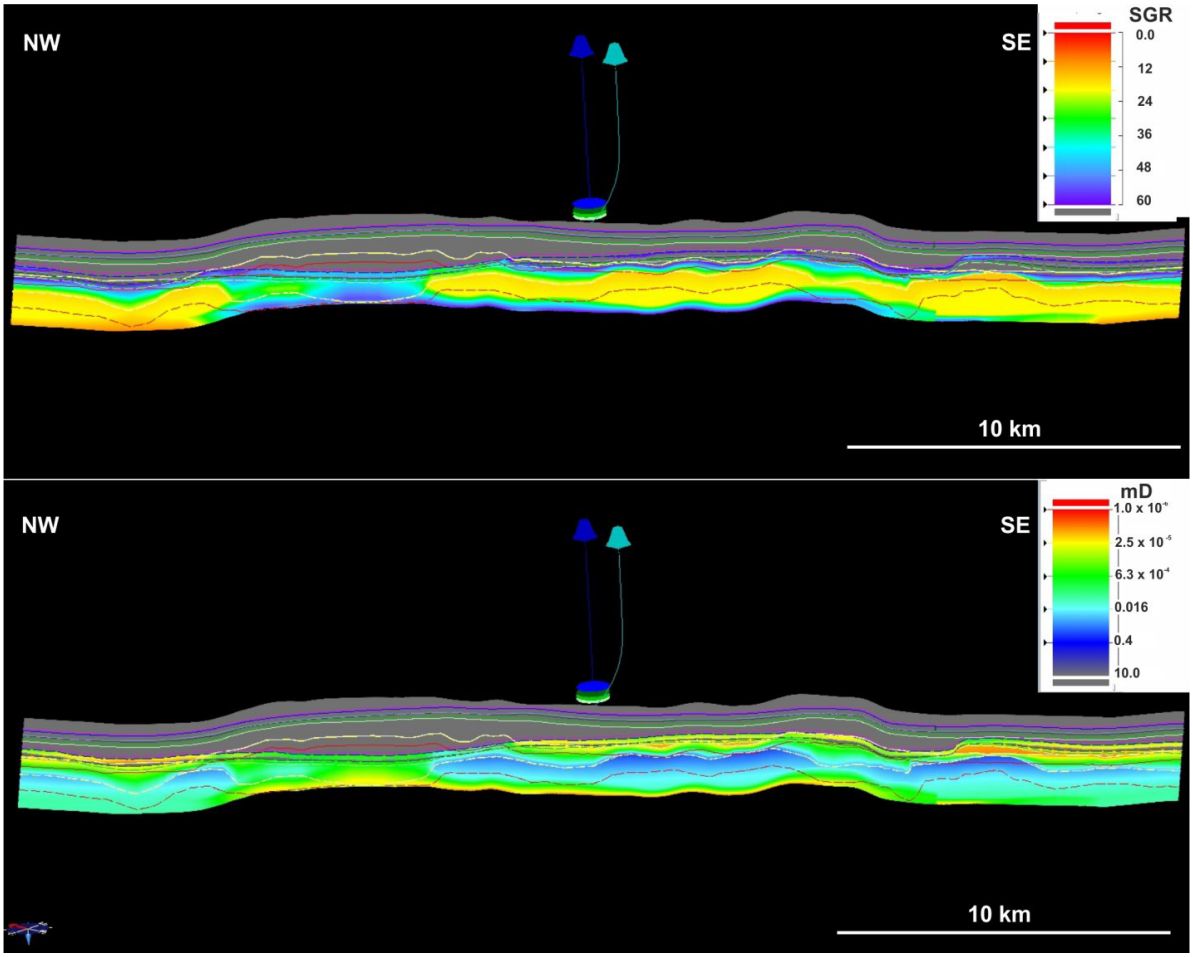

Figure 5: Shale gouge ratio (top) and permeability (bottom) of the fault rocks in the Fizzy fault. Note that the threshold for sealing SGRs is 15-20% and thus the majority of the fault has critical SGR values. See text for discussion.

5. Conclusions

We studied the natural CO_2 reservoir of the Fizzy field in the Southern North Sea with regards to possible leakage of CO_2 from the reservoir along or across the bounding Fizzy fault. Geomechanical analysis of the fault shows that it is stable under the current stress regime with a low slip tendency and that reactivation of the fault is unlikely. Fracture stability calculations indicate that a CO_2 column much greater than what could be stored in the trap before lateral leakage occurred would be needed to force the fault into failure. Fault rock properties such as the shale gouge ratio and permeability indicate that, even though there is reservoir-reservoir juxtaposition along the fault, migration of CO_2 across the fault is not likely. This is in good agreement with the current understanding of the

Fizzy field where there are no indications of CO_2 leakage either across the fault or along the fault. It is thus most likely that the trap was never filled to spill, probably due to insufficient supply from the CO_2 source.

Acknowledgments

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