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Stress field orientation controls fault leakage at a natural CO_2 reservoir

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Abstract.

Travertine deposits at the St. Johns Dome natural CO_2 reservoir in Arizona, USA, document a long (>400 ka) history of surface leakage of CO_2 from a subsurface reservoir. Travertine deposits are concentrated along surface traces of faults implying that there has been a structural control on the migration pathway of CO_2 rich fluids. Here, for the first time, we combine slip tendency and fracture stability to analyse the geomechanical stability of the reservoir-bounding Coyote Wash Fault for three different stress fields and predict areas with high leakage risks. We find that these areas coincide with the travertine deposits on the surface indicating that high permeability pathways as a result of critically stressed fracture networks exist in both fault damage zones and around a fault tip. We conclude that these structural features control leakage. Importantly, we find that even without in-situ stress field data the known leakage points can be predicted using geomechanical analyses, despite the complex tectonic setting. Thus, even though acquiring high quality stress field data for secure subsurface CO_2 or energy storage is a must, a first order assessment of leakage risks during site selection can be made with limited stress field knowledge.

1 Introduction

The successful subsurface storage of fluids in sedimentary basins is key for technologies such as Carbon Capture and Storage (CCS), cited as a cost-effective tool for climate change mitigation, or for energy storage, required to balance the intermittency of future energy systems relying on renewable sources(Alcalde et al., 2018; Matos et al., 2019; Scott et al., 2013). The integrity of such engineered subsurface storage sites is controlled by a range of geological, geochemical, and geotechnical factors. One major concern is that impermeable caprock seals may be bypassed by faults and naturally occurring, or induced, fracture networks which can form preferential fluid pathways and may lead to the rapid migration of the stored fluid (e.g. CO_2, H_2, methane) to shallow aquifers or the atmosphere (IPCC, 2005; Shipton et al., 2004; Song and Zhang, 2012). Indeed, selection criteria for subsurface storage sites commonly cite the need of minimal faulting and/or low permeability faults in the vicinity of a storage site (Chadwick et al., 2008; IEA GHG, 2009; Miocic et al., 2016). However, within sedimentary basins, which are

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key areas for geological storage of fluids, faults will occur naturally close to or within a storage complex and thus predictability of whether a fault will act as barrier to fluid flow or not is key for an accurate risk assessment.

Whether a fault zone is sealing or non-sealing is dependent on the structure and composition of the fault zone and the mechanics of the faulting (Faulkner et al., 2010). In a widely used simple conceptual model for fault zones strain is localized in the fault core which is surrounded by a damage zone of fractures; fault zones can have a single high-strain core (Chester and Logan, 1986) or contain several cores (Choi et al., 2016; Faulkner et al., 2003). The damage zone and the fault core have contrasting mechanical and hydraulic properties with the fault core being often rich in phyllosilicates which typically have low permeability while open fractures in the damage zone can have a substantially higher permeability than the host rock (Caine et al., 1996; Cappa, 2009; Faulkner and Rutter, 2001; Guglielmi et al., 2008). Lateral fluid migration across the fault zone is thus controlled by the permeability of the fault gouge within the fault core(s), which is dependent on the host rock composition and the shear strain. Contrastingly vertical fluid migration is governed by the connectivity and permeability of the fractures in the damage zone. A significant amount of research has been focused on understanding the mechanisms and parameters that control the composition, and continuity of fault gouges as well as their permeability for different fluids as they have the potential to form effective seals (Davatzes and Aydin, 2005; Lehner and Pilaar, 1997; Lindsay et al., 1993; Miocic et al., 2019b; Vrolijk et al., 2016; Yielding et al., 1997). The damage zone permeability is controlled by the permeability of the host rock and the presence and geometric composition of macro-scale fracture networks and deformation and compaction bands which decrease in frequency with increasing distance from the fault core (Mitchell and Faulkner, 2009; Shipton et al., 2002). Outcrop studies have shown flow channelling and emphasise the strong spatial and temporal heterogeneity of fault zones (Bond et al., 2017; Burnside et al., 2013; Dockrill and Shipton, 2010; Eichhubl et al., 2009; Schulz and Evans, 1998; Soden et al., 2014). If fracture networks or faults are close to failure due to tectontically induced changes in the stress conditions or changes in pore pressure vertical fluid flow is enhanced (Barton et al., 1995; Wiprut and Zoback, 2000). Geomechanical parameters such as slip tendency (Morris et al., 1996) or fracture stability can be used to assess the potential of vertical fluid flow.

The need for improved understanding of fracture networks and the potential of fracture reactivation and/or hydromechanically fracturing of caprock due to the injection of CO_2 has been highlighted by experiences at existing industrial CO_2 storage projects. At the Sleipner storage site, fractures in thin caprock layers appear to control the size and extend of the CO_2 plume (Cavanagh et al., 2015). The storage site of In Salah, Algeria, where between 2004 and 2011 around 4 million tons of CO_2 were injected into an anticlinal structure at ~1,800 m depth, has been the focus of many studies on fracture reactivation and hydraulic fracturing of caprocks as observations at the end of the injection period suggested that pressure had migrated vertically into the caprock (Bond et al., 2013; Michael et al., 2010; Rutqvist et al., 2010; Stork et al., 2015). The existing data indicate that injection pressures were too high for the low permeability reservoir rock and hydraulically fractured the reservoir and the lower caprock, potentially also reactivating pre-existing fracture networks related to small scale faults (White et al., 2014).

To study how vertical fluid flow along fault zones may be related to geomechanical parameters we examine the naturally occurring CO_2 reservoir of the St. Johns Dome, located at the border of Arizona and New Mexico. At this site migration of

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fluids from the subsurface reservoir to the surface is directly linked to faults which extend through the caprock (Gilfillan et al., 2011; Moore et al., 2005), with leakage having occurred for at least 420 ka and is still ongoing (Miocic et al., 2019a; Priewisch et al., 2014).

2 Geological setting

The St. Johns Dome (or Springerville-St. Johns Dome) natural CO_2 reservoir has more than 4.7 $x10^{10}m^3$ of recoverable CO_2 and is located on the south-eastern edge of the Little Colorado River Basin on the Colorado Plateau (Fig. 1) near to the Transition Zone to the Basin and Range and Rio Grande Rift tectonic provinces (Bashir et al., 2011; Rauzi, 1999). It is one of sixteen known naturally occurring CO_2 reservoirs on the Colorado Plateau and one of the few known naturally occurring CO_2 reservoirs world-wide where fluids are leaking to the surface (Gilfillan et al., 2008, 2009; Miocic et al., 2016). The CO_2 reservoir lies within a broad, northwest-trending asymmetrical anticline that is dissected by the steeply dipping northwest-southeast trending Coyote Wash fault (Fig. 2, Moore et al., 2005; Rauzi, 1999). This major fault seems also to form the western boundary to the productive portion of the formally commercially exploited gas field. Normal displacement across the fault ranges from less than 30 m (Salado Springs) to more than 200 m at the apex of the Cedar Mesa Anticline, 25 km SE of Salado Springs. Much of the fault displacement is thought to be of Paleogene age when Laramide compressional tectonics led to monoclinal folding of the Phanerozoic strata and the reactivation of older basement structures such as the Coyote Wash Fault on the Colorado Plateau (Marshak et al., 2000). The Permian reservoir rocks (siltstones, sandstones and limestones) discordantly overlay Precambrian granites (Fig. 3), are relatively shallow at 400-700 m depth and the CO_2 is present as gas (Gilfillan et al., 2011). Anhydrite and mudstone beds within the Permian rocks divide the reservoir into several producing zones while Triassic and Cretaceous calcareous shales and mudstones act as seals (Fig. 3). The Permian strata includes, from youngest to oldest, the San Andres Limestone Glorieta Sandstone and the Supai Formation which consist of the Corduroy Member, Fort Apache Member, Big A Butte Member and Amos Wash Member. A detailed geological description of the Permian Rocks can be found in Rauzi (1999). The current gas-water-contact is at 1425 m above sea level and the reservoir is not filled to spill. The surface rocks are mainly Triassic to Quaternary sediments, volcanic rocks and travertine deposits (Fig. 2). To the north-west the CO_2 reservoir is boarded by the Holbrook basin (Harris, 2002; Rauzi, 2000) and it is closely associated with the Plio-Pleistocene Springerville volcanic field which lies just to the south and south-west of the CO_2 reservoir (Crumpler et al., 1994; Sirrine, 1956). The volcanic field consists of more than 400 individual vents and related flows. Basaltic volcanism began around 9 Ma and the youngest flows that are about 0.3 Ma old can be found 8 km northwest of Springerville (Condit et al., 1993; Condit and Connor, 1996). As the CO_2 within the reservoir is of magmatic origin (Gilfillan et al., 2008, 2009, 2011), charging of the reservoir is thought to originate from degassing of magma underneath the volcanic field, with CO_2 migrating along fractures and faults through the basement into the reservoir (Miocic et al., 2019a).

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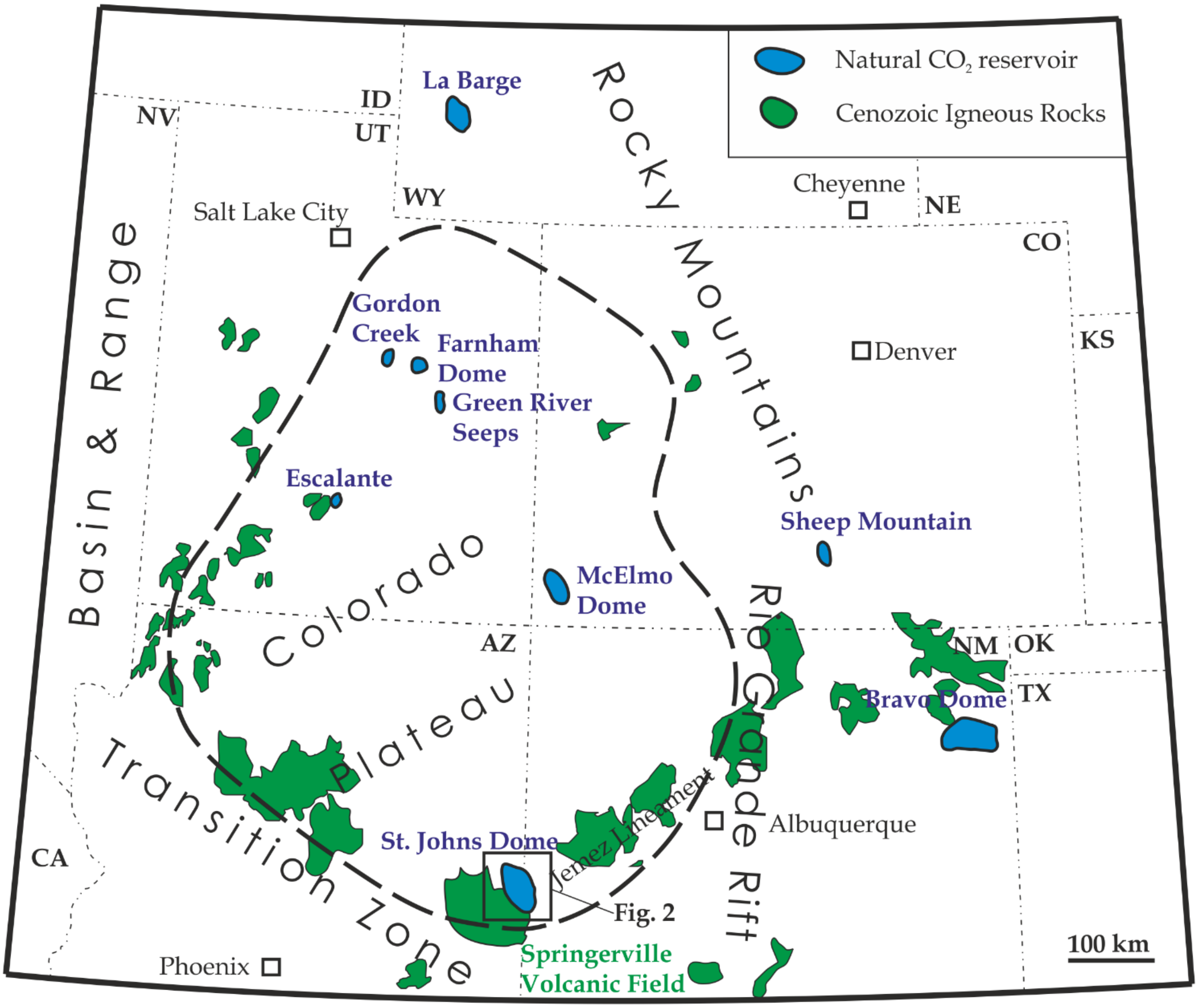
95 

Figure 1: Map showing the location of natural CO_2 reservoirs on the Colorado Plateau and adjacent areas. The St. Johns Dome reservoir is located on the southern edge of the plateau, next to the Springerville Volcanic field. After Moore et al. (2005) and Bashir et al. (2011). Black rectangle indicates outline of figure 2.

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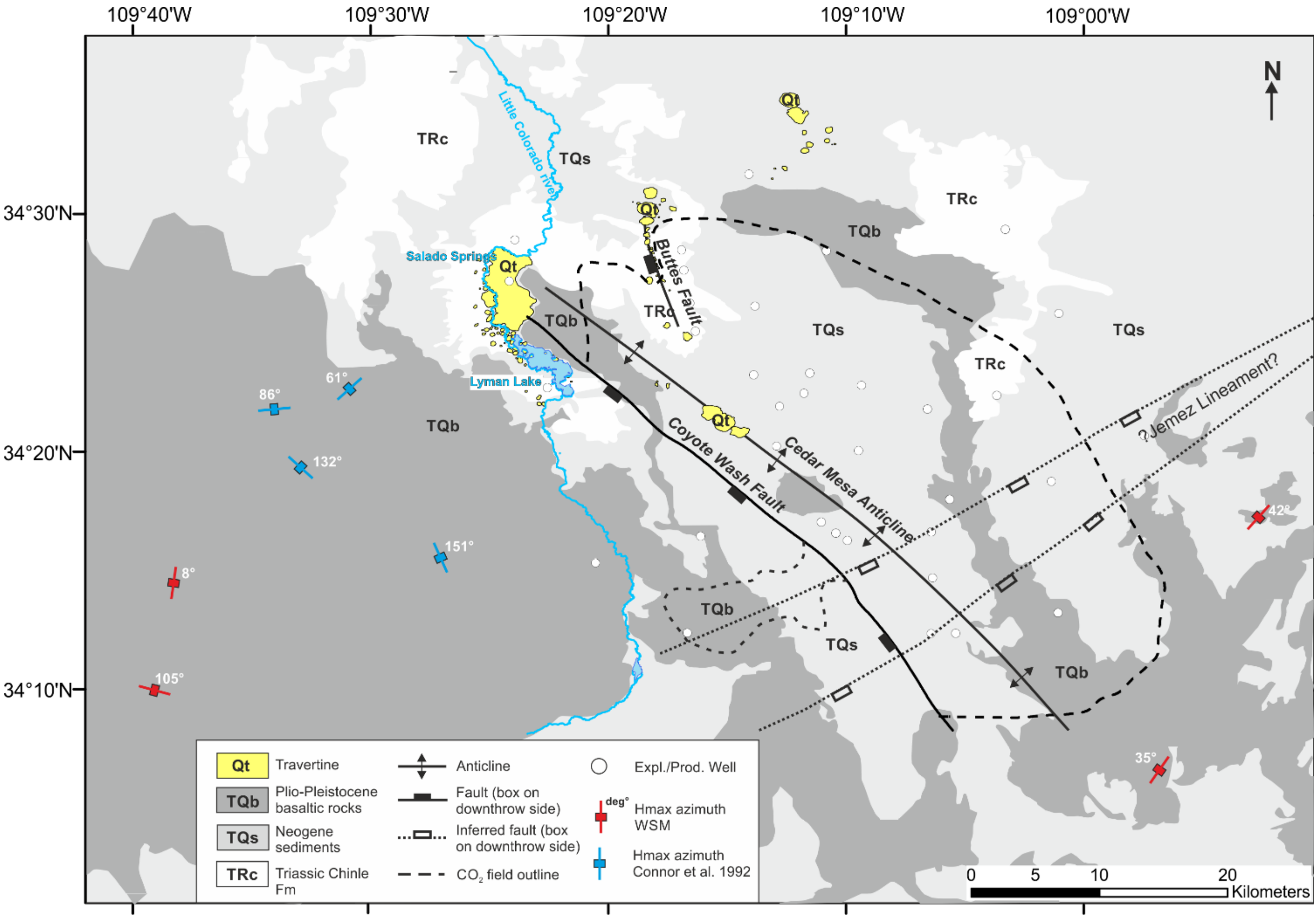

100 **Figure 2: Geological map of the St. Johns Dome natural CO_2 reservoir showing the present-day extent of the CO_2 reservoir, the location of the travertine deposits, orientation of the studied faults, and the location of exploration and production wells used to build the subsurface model. Stress field markers indicate the azimuth of maximum horizontal stress after the world stress map (Heidbach et al., 2016) in red and Connor et al. 1992 in blue.**

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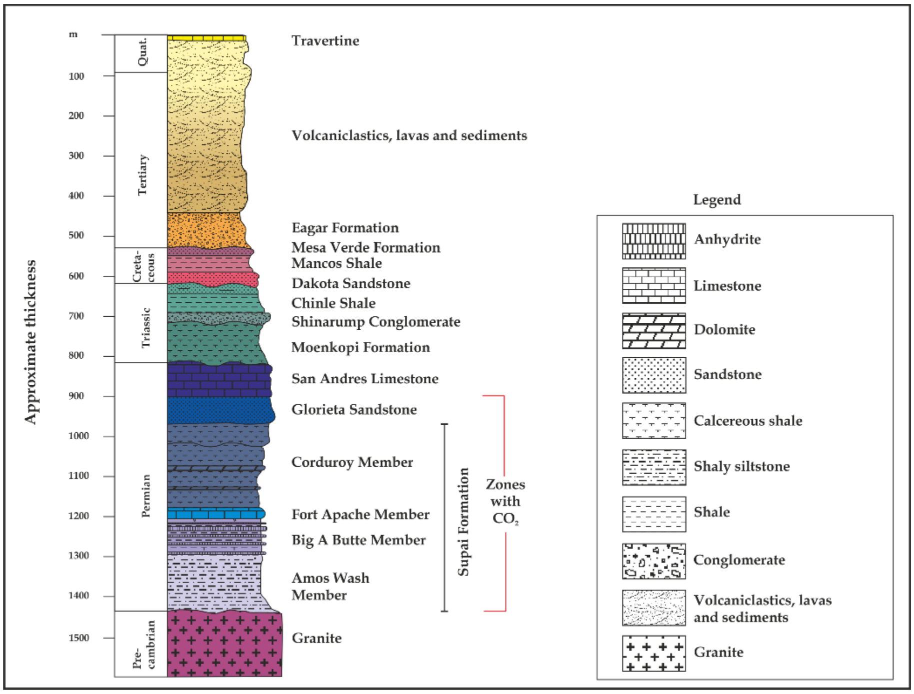

Figure 3: General stratigraphic column of the St. Johns-Springerville area. Note that Cretaceous and younger deposits are often thinner than described in this figure. CO_2 occurs in the Permian strata. After Rauzi (1999) and Embid (2009).

2.1 Expression, and timing, of fluid flow

The travertine deposits at the St. Johns Dome are an expression of CO_2-charged fluids from the subsurface to the surface as travertine formation occurs when CO_2-rich fluids outgas CO_2 as they migrate upwards to shallower depths and lower pressure, resulting in $CaCO_3$ supersaturation and carbonate precipitation. The travertine deposits cover a surface area of more than 30 km^2, spread out over more than 300 km² (Fig. 2), making them one of the greatest concentrations of travertine deposits in the U.S.. Spatially, the travertine deposits are particularly concentrated in a 10 km long zone between Salado Springs and Lyman Lake (Fig. 2, Gilfillan et al., 2011; Moore et al., 2005). This area, where present day travertine formation occurs (Priewisch et al., 2014), is bound by the Coyote Wash Fault and the distribution of the travertine deposits and active springs suggests that the local groundwater hydrology has been influenced by the Coyote Wash Fault. Analyses of surface springs, groundwater wells and CO_2 wells with respect to the CO_2 composition, water composition and noble gas concentrations have shown that samples along the Coyote Wash Fault trace and are influenced by waters from depth that have been enriched in mantle derived ^{3}He and Ca (Gilfillan et al., 2011; Moore et al., 2005). Several modelling approaches emphasise the importance of the Coyote Wash Fault for CO_2 and He migration from the Supai Formation to the surface (Allis et al., 2004; Keating et al., 2014) as in all models migration of gas to the surface occurs only if the fault forms a permeable section through the cap rocks. Soil-flux measurements indicate that there is no diffuse CO_2 leakage through the cap rocks, highlighting the role of faults for vertical fluid flow (Allis et al., 2005). In addition to the occurrences along the NW tip of the Coyote Wash Fault, travertine mounds

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are found to follow the trace of the Buttes Fault over a distance of more than 7 km (Fig. 2). Travertine mounds are also found North of the present-day extend of the CO_2 reservoir, with no clear link to structural elements. It is notable that there are no indications for fluid migration in the southern half of the reservoir.

U-series dating of the travertine mounds shows that leakage of CO_2 from the reservoir to the surface has occurred for at least 420 ka (Miocic et al., 2019a; Priewisch et al., 2014). Several of the samples analysed by Miocic et al. (2019a) fall outside the dating limitations of the U-Th method (~500 ka), which indicates that leakage may have occurred over much longer time-scales which is not surprising given the age of the Springerville volcanic field from where the magmatic CO_2 is almost certainly sourced. Individual seeps along the Buttes Fault have lifespans of up to 200 ka and the massive travertine platform between Salado Springs and Lyman lake has at least a similar lifetime. Volume calculations indicate that the subsurface reservoir is constantly recharged as several times the volume of CO_2 stored in the current reservoir has leaked in the past. However, due to the long timeframe of recorded leakage, only a very low percentage (0.1 to 0.001 %) of the reservoir volume is leaking annually and thus the site could still be seen as a suitable carbon storage site from a climate mitigation point of view (Miocic et al., 2019a).

These observations illustrate that fluid migration at the St. Johns Dome occurs along fault zones and once migration pathways have been established they are spatially stable for long periods (>100 ka). This is in contrast to other fault controlled fluid migration pathways on the Colorado Plateau for which it is suggested that these stay open only episodically for few thousands of years after rapid fault opening/movement and subsequently heal (Frery et al., 2015). Similar cyclic reopening and healing of fractures governing fault zone permeability has been recorded by travertine deposition at other active fault zones (Brogi et al., 2010). Spatially and temporally stable migration pathways are concerning for subsurface storage sites and thus the processes controlling vertical fault zone permeability at the St. Johns Dome are analysed in the following.

3 Methods

In order to investigate the mechanisms governing the vertical fluid flow at the St. Johns Dome, a geomechanical analysis of the Coyote Wash Fault was conducted using slip tendency and fracture stability approaches. Slip tendency (Ts) is a method that allows for a fast assessment of the tendency of a surface to undergo slip under the present-state effective stress field. It is the ratio of resolved shear stress to resolved normal stress on a surface (Morris et al., 1996):

$$Ts = \frac{\tau}{\sigma_n}$$

where τ is the shear stress and σ_n the effective normal stress acting on the fault plane. Slip is likely to occur on a surface if $Ts \geq \mu_s$ with μ_s being the coefficient of static friction which is generally assumed to be 0.6 (Byerlee, 1978; Moeck et al., 2009; Sibson, 2003). Fracture stability (Fs) is the increase in pore pressure that is required to reduce the effective stresses such that the fault plane is forced into failure. In contrast to slip tendency, Fs takes rock properties such as cohesion and tensile strength into account and thus fault rock composition needs to be known.

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A 3D geological model of the St. Johns Dome was built based on published geological maps, well data from 37 exploration and production wells (well logs, horizon markers) as well as previously published reservoir horizon maps. Between wells a constant stratigraphic thickness was assumed. The current gas-water-contact is at 1494 m above sea level and is assumed to be horizontal. Geomechanical analysis of the model was conducted with industry standard software (TrapTester®). For Fs analysis two different fault rocks were taken into account: claysmear (cohesion C = 0.5 MPa, coefficient of internal friction μ=0.45) and phyllosilicate (C=0,5, μ=0.6). For stress field no in-situ stress measurement was available, however in addition to world stress map data (Heidbach et al., 2016) the nearby Springerville volcanic field can be used to derive the orientation of the horizontal stresses as presented in the following.

3.1 Stress field at the St. Johns Dome

The location of the St. Johns Dome reservoir at the margin of the Colorado Plateau and just north of the Basin and Range province has significant impact on the stress field in the study area. It is clear that the regional stress field is highly variable as shown by the available stress field data in the vicinity of the St. Johns Dome (50 km radius) from the world stress map combined with a regional study on volcanic vent orientation in the Springerville volcanic field (Table 1) (Connor et al., 1992; Heidbach et al., 2016). To the south and south-east of the CO_2 field, maximum horizontal stress (SH_{max}) is oriented NE-SW while west of the reservoir SH_{max} orientation is highly variable, ranging from NW-SE to E-W (Fig. 2). While these datapoints are associated with an uncertainty of at least ±15°, the orientation of the stress field for the St. Johns Dome faults is difficult to constrain. A normal faulting regime (vertical stress (S_v) > maximum horizontal stress (SH_{max}) > minimum horizontal stress (Sh_{min})) is assumed as indicated by the world stress map and works by Kreemer et al. (2010) and Wong and Humphrey (1989) for this area of the Colorado Plateau. Integration of density logs (wells 10-29-31 and 11-16-30) gives a magnitude of S_v of 23 MPa/km. Minimal horizontal stress in normal faulting regimes is typically about 65-85% of the vertical stress (Hillis, 2003), which gives a magnitude of Sh_{min} in the range of 15 to 19.5 MPa with the magnitude of SH_{max} set between S_v and Sh_{min}.
As the reported stress field measurements seem to form three clusters (Tab 1.), three different stress fields were defined (Tab. 2): Stress field A is similar to the stress fields indicated by measurements 7 and 8, with SH_{max} having an azimuth of 140°, stress field B is similar to the stress fields indicated by measurements 2 to 4 with an SH_{max} azimuth of 50°, and stress field C is oriented similar to the stress field measurements 5 and 6. The single north-south stress field measurement (ID=1) was not considered further. For the ~NW-SE trending Coyote Wash Fault these stress fields also represent the most (A), least (B) and an intermediate (C) likely cases for fault reactivation. Geomechanical analysis was conducted under all three defined stress fields.

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Table 1: Table listing published stress field indicators around the St. Johns Dome. WSM=World stress map. They form three clusters: IDs 2-4, 5&6, 7&8.

ID	Lat.	Long.	SHmax azimuth(°)	Shmin azimuth (°)	Error	Faulting regime	Source
1	34.230	-109.630	8	98	± 25	NF	WSM, 2016
2	34.070	-108.930	35	125	± 25	NF	WSM, 2016
3	34.250	-108.870	42	132	± 25	NF	WSM, 2016
4	34.248	-109.527	61	151	± 15	NF	Connor et al., 1992
5	34.313	-109.579	86	176	± 15	NF	Connor et al., 1992
6	34.140	-109.680	105	195	± 15	NF	WSM, 2016
7	34.269	-109.557	132	222	± 15	NF	Connor et al., 1992
8	34.202	-109.449	151	241	± 15	NF	Connor et al., 1992

Table 2: Stress fields used for the geomechanical modelling.

Stress field	S_v	SH_{max}		Sh_{min}	
	MPa/km	MPa/km	Azimuth (°)	MPa/km	Azimuth (°)
A	23	20	140	16	50
B	23	22	50	16	140
C	23	20	100	16	10

4 Geomechanical controls on vertical fluid migration

The results of the geomechanical analysis of the Coyote Wash Fault highlight that the orientation of the stress field has a major impact on both the slip tendency (Fig. 4) and fracture stability (Fig. 5). Slip tendency indicates that for stress field A most parts of the fault are close to slip (Ts>0.5), for stress field C the fault is only intermediately stressed (0.3<Ts<0.5), and for stress field B the fault is far away from failure (Ts<0.2). Similarly, only slight increases of pore pressure are needed to force the fault into failure under stress fields A and C and a claysmear fault rock (0.95 MPa and 1.33 MPa, respectively). The pore pressure increase needed to force the fault into failure in case of stress field B is much higher at 6.21 MPa. Note that slip tendency in both stress fields A and C is higher at the NW tip of the fault than in the SE section of the fault (Fig. 4), indicating that failure is more likely to occur in the NW. This is also true for the spatial distribution of fracture stability which for stress fields A and B (most and least likely to fail) and a claysmear fault rock is illustrated in figure 6.

The results of the geomechanical analysis show that the bounding fault of the St. Johns Dome CO_2 reservoir is intermediately to critically stressed for two of the three modelled stress fields (A and C). For the same stress fields a weak fault rock within the Coyote Wash Fault zone results in fracture stabilities which range from less than 1 MPa to 1.33 MPa. The most critically stressed areas are located at the NW tip of the fault while the SE part of the fault is relatively stable for all studied stress fields.

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The Fs values of 0.95 MPa and 1.33 MPa translate to an additional CO_2 column of ~110 m and ~160 m, respectively. Currently the reservoir is not filled to spill and the 3D geological model indicates that the reservoir interval at the NW part of the reservoir could hold an additional ~300 m of CO_2 column. Thus, additional filling of the reservoir with a third to half more CO_2 by volume could lead to fault failure and vertical fluid migration along the fault. Evidence that the reservoir has held more CO_2 in the past is provided by older travertine deposits located outside the present day extent of the subsurface reservoir (Fig. 2, Miocic et al., 2019a) and the fact that higher paleo-reservoir pressures have been implied by a geochemical study (Moore et al., 2005). These higher reservoir pressures were likely enough to bring the NW part of the fault close to failure and we suggest that the permeability of fracture networks within the critically stressed fault damage zone was therefore increased (Barton et al., 1995; Ito and Zoback, 2000; Min et al., 2004). In order to sustain the long periods of leakage recorded by the spatially stable travertine deposition the fault must be critically stressed for similarly long periods. Indeed, volume calculations on how much CO_2 must have leaked to the surface based on the travertine deposits show that one to two orders of magnitude more CO_2 was lost from the reservoir than it can hold (Miocic et al., 2019a). It is suggested that the continuous influx of magmatic CO_2 degassing from beneath the Springerville Volcanic Field into the reservoir caused the fault to be close to being critically stressed – a reasoning also encouraged by this study.

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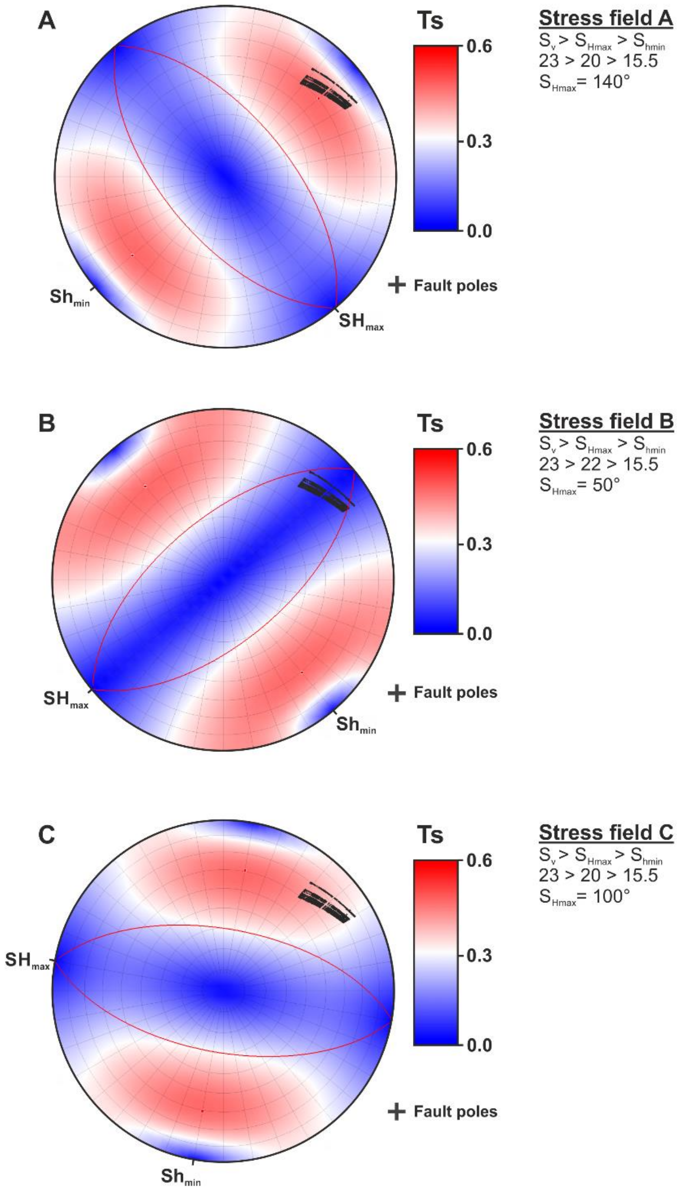

Figure 4: Stereoplots illustrating the slip tendency for the Coyote Wash Fault (black crosses) for the three different stress fields. The fault is at least partly close to failure for stress fields A and C while stress field B results in very low slip tendencies. Particularly the NW fault tip (indicated on the stereoplots) where travertine deposits are found at the surface is close to failure.

The geomechanical analysis also demonstrates that a change of the fault orientation within the stress field should not be underestimated and can lead to failure along one part of a fault while large parts of the fault are geomechanically stable. The strike direction of the Coyote Wash Fault changes from ESE-NWN in the southern part of the fault to NW-SE in the northern section and this change in strike is enough to render the northern section critically stressed (in two of the stress fields modelled; A & C) - with leakage pathways being the result (Fig. 7). Higher paleo gas columns within the reservoir likely contributed the

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forcing the fault into failure at the northern fault tip. However, some sections of the fault in the SE also have relatively low fracture stability values (Fig. 6A) which translate to only 10s of meters more supported gas column than the NW section. Yet, there are no indications for past or present leakage in the SE part of the St. Johns Dome. We argue that the stress field orientation in the SE is different from the stress field orientation in the NW area of the St. Johns Dome and that as a result the fault is far from failure. This is supported by stress field measurements in the vicinity of the southern edge of the reservoir (Fig. 2, Tab. 1) which imply a NE-SW SH_{max} orientation, similarly to stress field B in this study for which the Coyote Wash Fault is far from critically stressed.

Vertical migration of fluids through fracture networks or corridors can be classified by their location in (1) the fault damage zone, (2) at the fault tip, and (3) at the crest of a fold (e.g. Ogata et al., 2014). As evidenced by travertine deposits vertical fluid migration at the St. Johns Dome occurred at all three types of fracture networks (Fig. 2), but considerably larger volumes of fluid migrated through fracture networks linked to faults. This indicates that, at least at this site, faults are a higher risk factor for leakage than other migration pathways such as fracture networks in anticline structures or capillary leakage though a caprock. Based on travertine volumes the largest volumes of leakage occurred at the NW tip of the Coyote Wash Fault, in the area between Lyman Lake and Salado Springs (Figs. 2, 7, Miocic et al., 2019a). This indicates high permeability fracture networks within the damage zone close to the fault tip as predicted by numerical models (Backers and Moeck, 2015; Zhang et al., 2008). The lack of similar leakage pathways at the SE tip of the fault can be attributed to the different stress field orientation. For geological storage the occurrence of large-scale leakage at fault tips is also concerning as displacement at fault tips usually is low and as such fault tips are not seismically resolvable and may remain undetected. Thus seismically resolved faults should be extended beyond the normally picked extend to include the fault tips. Similarly, faults with low displacement such as the Buttes fault, for which significant fault related leakage has been recorded, are not detectable on seismic data. This highlights the need for a good structural understanding of any geological storage site to ensure that fault tips and small faults are identified and incorporated into the geological model.

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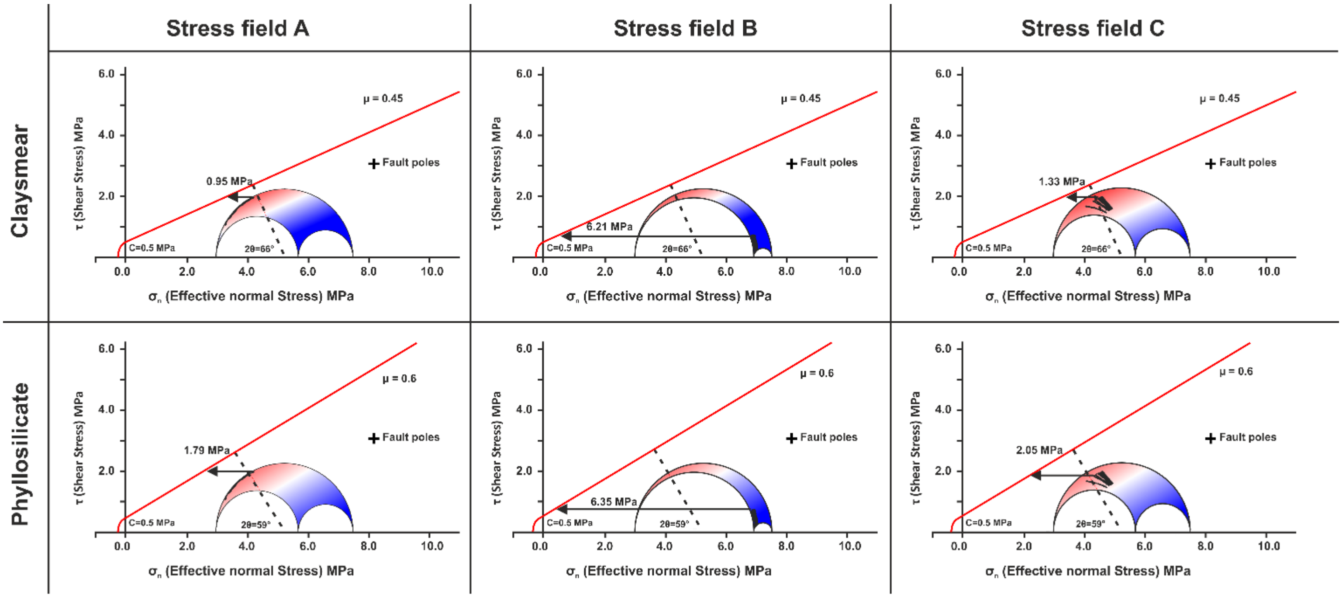

Figure 5: Mohr diagrams illustrating the fracture stability for the Coyote Wash Fault within the three stress fields for two types of fault rocks. Black arrows indicate the increase in pore-pressure needed to force the fault into failure.

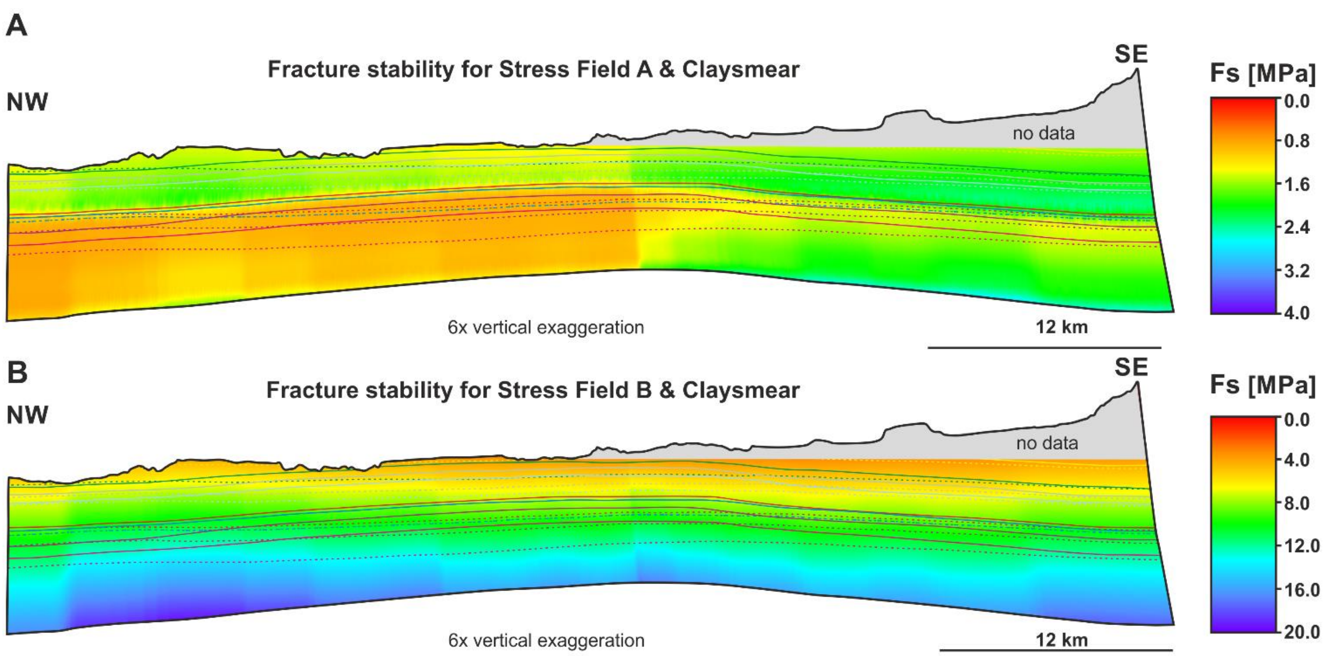

Figure 6: Fracture stability plotted onto the Coyote Wash Fault surface. (A) for stress field A and a claysmear fault rock. (B) For stress field B and a claysmear fault rock. Note the differences in the colour scale. Fs is more critical in the NW part of the fault for stress field A while Fs for stress field B is far from critical. Dashed lines represent hangingwall, straight line footwall stratigraphy.

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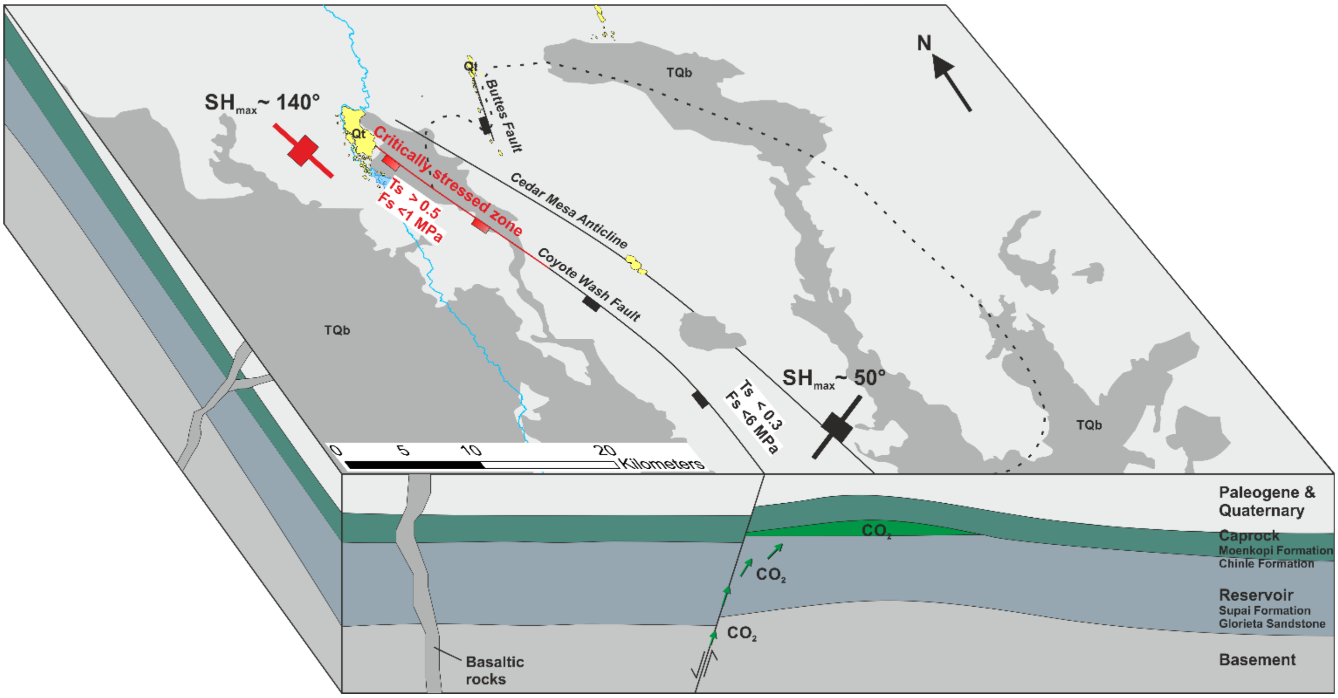

Figure 7: Block diagram illustrating the geological setting of the St. Johns Dome area. The fault-bound CO_2 reservoir is constantly filled with CO_2 from depth and leakage of CO_2 from the reservoir to the surface occurs at the NW tip of the Coyote Wash Fault. The leakage is geomechanically controlled as the stress field orientation changes along the strike of the fault as well as the strike direction of the fault. At the NW tip of the fault slip stability values of >0.5 and fracture stability of less than 1 MPa indicate a critically stressed fault. See figure 2 for a complete legend, ~10x vertical exaggeration.

While the geomechanical analysis highlights the role of critically stressed faults for fluid migration at the St. Johns Dome, it is missing in-situ stress field data from within the CO_2 reservoir. Such data is crucial for a detailed and reliable study of fracture and fault stability (e.g. Becker et al., 2019), however there are cases where such in-situ data is missing and a geomechanical analysis may be needed (Henk, 2005). In particular during the site selection and appraisal of subsurface storage sites a preliminary geomechanical analysis based on existing stress field data can identify potentially critically stressed faults. The lack of in-situ data can be compensated by studying several potential stress fields (as in this study) and including uncertainties into the geomechanical analysis. For the latter, uncertainties in the stress field orientation and magnitude and in the fault orientation should be included. Statistical approaches such as Bayesian or Markov Chain Monte Carlo modelling can be useful to identify uncertainty thresholds and to determine the precision by which the geomechanical parameters need to be known in order to have reliable fault and fracture stability predictions (Bao et al., 2013; Chiaramonte et al., 2008; McFarland et al., 2012).

For the geomechanical prediction of permeable fracture networks and thus leakage pathways at the St. Johns Dome the stress field orientation is integral. The location of the natural CO_2 reservoir at the edge of the Colorado Plateau is the likely reason for the stress field orientation change, with clear changes in crustal composition and strength in the vicinity of the St. Johns Dome (Hendricks and Plescia, 1991; Qashqai et al., 2016). The study area is located at the intersection of the NE-NNE trending

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Jemez Lineament, a tectonically active zone that is characterized by Paleogene-Quaternary extension and volcanism (Fig. 1), and the ESE tending Arizona Transition Zone (Aldrich and Laughlin, 1984; Kreemer et al., 2010). Additionally, the presence of salt deposits in the Holbrook Basin north of the study area may also impact the local stress field (Neal and Colpitts, 1997; Rauzi, 2000). The complex tectonic setting at the St. Johns Dome and the associated uncertainties for geomechanical modelling further highlight the need for good site selection criteria for engineered fluid storage sites to ensure that only reservoirs with well understood structural framework are chosen.

5 Implications for geological storage applications

Geomechanical modelling suggests that vertical fluid migration from the reservoir to the surface at the St. Johns Dome natural CO_2 reservoir is controlled by fracture networks in the damage zone and tip of close to critically stressed faults. We propose that constant filling of the reservoir with CO_2 from mantle sources increased the pore pressure within the reservoir and further reduced the stability of close to critically stressed faults, leading to the leakage of large volumes of CO_2 over the time-span of several 100 kas. While the leakage rates at the St. Johns Dome are low enough to render the faulted site an adequate CO_2 store for climate mitigation, similar leakage rates could impede geological storage of methane or hydrogen as any surface leakage of these flammable gases could be hazardous, in particularly at onshore storage sites.

For fault-bound subsurface storage sites for CO_2 or energy the history of geomechanically controlled leakage at the St. Johns Dome clearly illustrates the need for a good understanding of regional and local stress fields and faults. In particular the stress state of faults and fault related fracture networks prior to fluid injection needs to be well understood in order to reduce the risk of vertical fluid migration through fractured caprock. For subsurface storage sites it is recommended to select areas where there are no significant regional stress field changes as these complicate geomechanical predictions. Indeed, in-situ stress data from wells are key for any advanced leakage risk prognosis. As the pore pressure increase within the reservoir depends on the buoyancy of the injected fluid, site selection and appraisal needs to be fluid specific. To further understand the leakage mechanisms at the St. Johns Dome geomechanical modelling of the Buttes Fault, combined with an uncertainty assessment, is recommended. More detailed dating of the travertine deposits could reveal at which structural setting (fault tip vs fault damage zone) failure occurred first and provide insights into the time dynamics of leakage.

Author contribution

JM and SG designed the research project which was carried out by JM with help from GJ and input from SG. JM prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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