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Pressure induced deformation and flow using CO₂ field analogues, Utah

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Abstract

Exhumed reservoirs providing evidence of CO₂ accumulation and transport in geological history offer a unique possibility to supplement our knowledge on leakage processes observed along faults and fractures. A field location and drill core from Central Utah, USA has been used to characterize mechanical properties and fracture distributions in multiple reservoir-caprock couplets where bleaching pattern around fractures provides evidence of fluid flow. Analysis shows that fractures are mainly observed in low porosity units corresponding to layers with high strength and stiffness. Microstructural characterization substantiates evidence of fracture aperture separated by areas with mineral precipitation clogging aperture. Minerals observed filling fractures are calcite, gypsum and pyrite, suggestive of precipitation from reducing fluids. Fracture aperture distribution and identification of mineralogical changes along the fracture surface provides important input for improved, novel analyses of CO₂ transport properties of fractures and faults.

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1. Introduction

Geological sequestration of CO₂ is steadily maturing towards a stage where it may provide a significant means for mitigating global emissions. A key concern of the general public, potential investors, insurance companies and sequestration site operators is the risk of leakage of injected CO₂ from the reservoirs into nearby/overlying groundwater aquifers or hydrocarbon pools, or even to the surface. Existing sequestration sites are generally small and have not been operational for sufficient time to fully forecast and assess leakage scenarios of laterally extensive reservoirs on the time scales relevant for subsurface CO₂ storage. Thus the study of exhumed reservoirs showing evidence of CO₂ accumulation in geological history offer a unique possibility to supplement our knowledge on leakage processes observed along faults and fractures, and to understand the relevant spatial and temporal scales of CO₂ leakage in order to better constrain the threats of injection-induced pressure buildup.

In this paper we present the results from ongoing mapping and characterization of an exhumed reservoir and seal section in the Entrada Formation, central Utah. This site is of particular relevance to CO₂ storage studies due to natural subsurface CO₂ plumes, for instance underneath the Little Grand Wash Fault (Fig. 1). A research well drilled into the footwall damage zone of Little Grand Wash fault in 2012 retrieved a complete core of a multi-storied succession of reservoirs and caprocks [1, 2], and experimental characterization of core samples from this well is used to supplement field mapping datasets from the exhumed analogue at Humbug Flats. This site provides insight into a well exposed reservoir caprock succession of a fault and footwall anticline, where there is bleaching both along certain layers and up along faults and fractures. For the combined dataset, detailed mapping of stratigraphy and fracture distribution combined with mechanical testing and characterization of geochemical reactions and fracture flow properties, form our basis for discussion of fluid transport along fractures. This demonstrates the importance of in-depth assessment of faults and fracture corridors into seal integrity analysis, and emphasizes a demand for better understanding of controlling mechanism for fracture flow properties.

2. Study area

The study area in Central Utah (Fig. 1) is located at the northern end of the San Rafael desert, east and NE of the San Rafael Swell monocline, and above the NW termination of the Paradox Basin with its source rocks. The region offers multiple reservoirs and seal units, and has accordingly been the site for extensive hydrocarbon exploration and some production. Further, there are several reservoirs with CO₂ accumulation mainly charged from a mantle source. The local stratigraphy is described in Fig. 1d with the Jurassic eolian Navajo Sandstone and lower Entrada Formation as the two reservoirs of interest. The upper part of the Entrada Formation is a mixed (supra-) tidal to shallow marine succession where the low permeable layers of the Entrada Earthy facies, locally mottled, provide local seals to intraformational eolian sandstone reservoirs. Fluid migration and secondary trapping is controlled by faults and anticlines [e.g. 3], as seen for Little Grand Wash fault and Salt Wash graben, both truncating the Green River Anticline. These sites show ongoing CO₂-leakage with travertine, and extensive bleaching and mineralized veins in older exhumed parts. There are hydrocarbon stains documenting paleo-fluid flow [4].

In the study area, the approximately WNW-ESE trending Little Grand Wash fault has normal, down-south throw of 150-250 meters. Dated travertine documents 400,000 years of CO₂ expulsion and the Crystal Geyser is still active erupting CO₂-charged ground water [5]. Recently, a research well, CO2W55, was drilled into the footwall damage zone of the Little Grand Wash fault [1] covering a succession from the upper Entrada Formation, through Carmel Formation and into the Navajo Sandstone. Element and isotope geochemistry of fluid samples from the drilling project show a complex mixing of CO₂ saturated brine as inflow from faults and flow of CO₂ undersaturated meteoric groundwater in the Navajo Sandstone reservoir. Further, reacted CO₂-charged brines were found in the overlying fractures and reservoirs zones [1].

Humbug Flats is located to the NE side of the San Rafael Swell, the latter a regional asymmetric anticline (Fig. 1c). The study site is intersected by an E-W trending normal fault with displacement of tens to hundred meters.

Extensive structural and stratigraphic mapping of the Entrada Formation in this area show fault related fracture corridors comprising joint swarms and subordinate shear fractures with extensive bleaching within the fault tip process-zones [6].

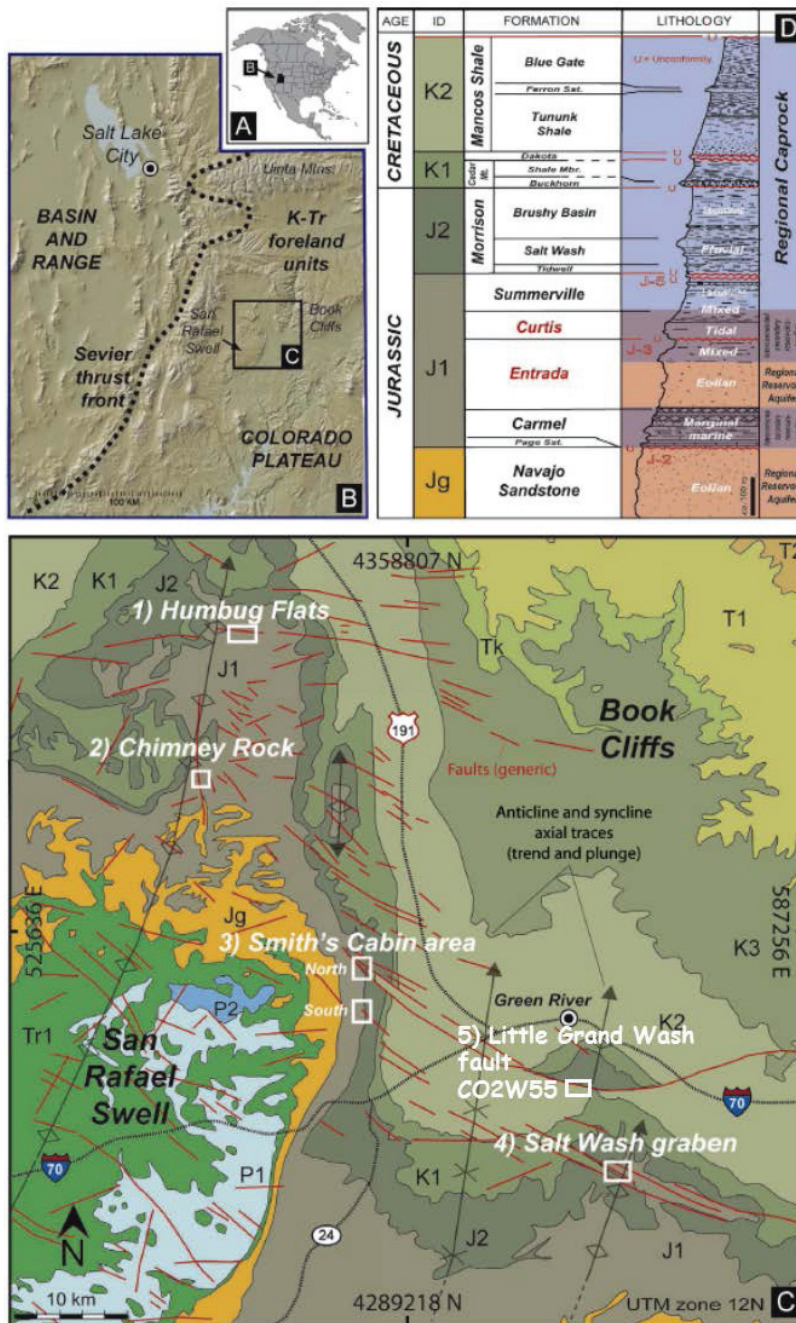


Fig. 1. Field location, Utah (A, B), geological map (C) and stratigraphy for the area (D), after Ogata et al. [6]. The locality at Humbug Flats and the well CO2W55 along the Little Grand Wash fault is marked on the geological map.

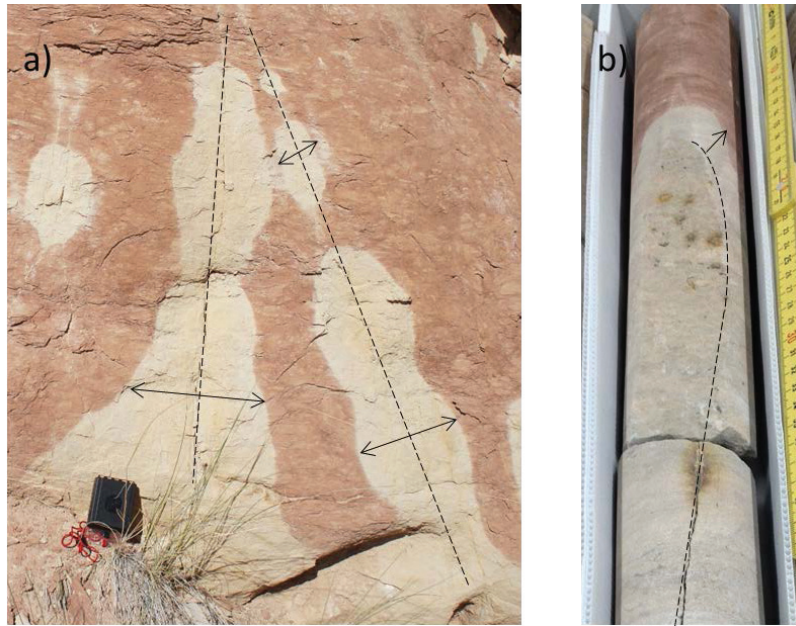


Fig. 2. Fractures (dotted lines) showing varying width of bleached, altered zone marked by arrows. Fractures observed in the Humbug Flats site (a) and in drill core from well CO2W55 (b).

3. Methods

In the field, 1d scan lines were used to collect statistical data on fracture distribution for selected sandstone layers within the upper Entrada Formation. These units vary in porosity. Fracture orientation (strike-dip), layer appearance (bed-confined or through-going) and bleaching patterns were recorded. Plugs for mechanical testing was prepared in the laboratory from blocks sampled in the field. The test program for the field samples from Humbug Flats comprised unconfined compressional strength tests (UCS) and indirect tensile strength tests (Brazil test). All tests were performed using equipment located at the Norwegian Geotechnical Institute (Oslo, Norway). Standard sized plugs of 25 mm diameter and around 55 mm height were prepared for the UCS tests. For the Brazil tests discs of 25 mm diameter and height of 12.5 mm were used. All plugs were tested in dry conditions. The porosity of the investigated layers were calculated from the plug bulk density and particle density. Since the layers all have a quartz-dominated mineralogy, the theoretical particle density of quartz, 2.65 g/cm^3 , were used in the calculations.

Natural fractures from well CO2W55 targeting Little Grand Wash fault were logged and sampled at the Shell core storage in Rijswijk, Nederland. Fractures orientation, bleaching, mineral fill, displacement and depth were recorded. Additionally the fracture roughness (joint roughness coefficient, JRC) was measured for open fractures following the method suggested by Barton and Choubey [7]. Fracture aperture was recorded using a Nikon Metrology industrial high-resolution 3-D computer tomography (CT) scanner, which images processed into three-dimensional reconstructions of the 3D aperture distribution of fractures. In addition, microstructure and mineral composition of fracture surfaces were characterized using a HITACHI SU 5000 (Field Emission) scanning electron microscope (SEM).

4. Data of Humbug Flats

4.1. Field observations

The field location at Humbug Flats shows a reservoir-caprock succession (Fig. 3a and b) of which layers with four characteristic facies, L1-L4, has been studied in detail. Work targeted layer-mechanical properties and fracture frequencies in transects toward a one m-displacement fault (Fig. 3c) with a distinct slip surface. Facies L1 and L4 is fluvial plain/overbank deposits with porosity ranging from 8-14 %, L2 is a fluvial sandstone with porosity around 20 % and L3 is a bleached eolian sandstone with 30 % porosity. The latter unit is clearly visible as a "white" layer in the succession.

The fractures were recorded in the vicinity of a fault cutting layer L1-L4. The three most competent layers, L1, L2 and L4 is dominated by bed confined fractures, although some through going fractures are observed for each layer. Fracture frequencies listed in Table 1 is from around the small fault zone. The highest fracture frequency of 5 fractures per meter is found for L1. Layer L3 differs from the three other layers by the presence of deformation bands and deformation band swarms and slightly fewer fractures. Background fracture frequencies are found to be an average of 0.7 fractures per meter. The fractures measured outline two fracture populations, respectively NNW-SSE and WNW-ESE, both with a high angle to bedding.

4.2. Geomechanical characterization

The geomechanical characterization includes a total of 11 UCS tests and 71 indirect tensile strength measurements for four characteristic facies L1-L4. The tensile strength is in the order of 0.5 to 3.5 MPa, whereas the uniaxial compressive strength (UCS) is 30-40 MPa for L4 and 60-70 MPa for L1. UCS was not measured for L2 whereas for the weak L3 facies, tensile fractures split the plug vertically and a strength of 2 MPa were measured. The results show a good correlation between tensile strength and porosity, with the highest porosity corresponding to the lower strength. The mechanical strength and elastic properties are listed in Table 1 together with porosity and fracture data from the scanlines.

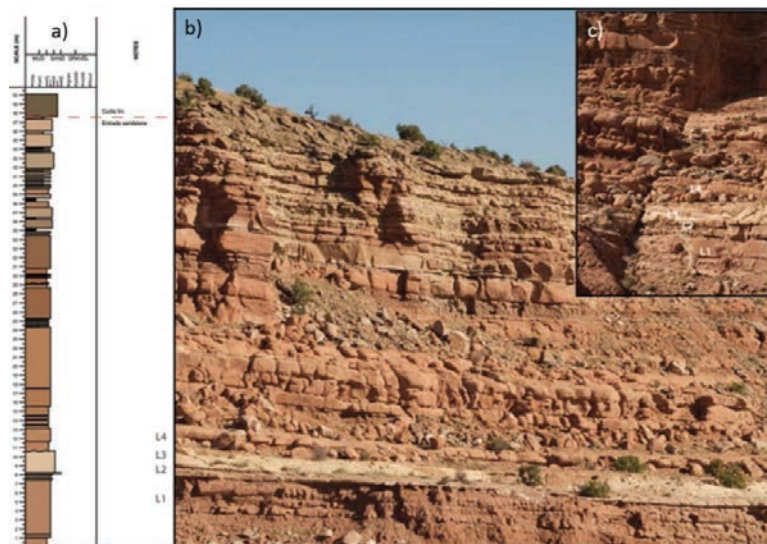


Fig. 3. Humbug Flats sedimentary log (a) outcrop photo showing the position of layer L1 to L4 in the lower part of the logged section (b) and photo of the 1 m displacement fault where scanlines for fracture frequencies are recorded (c).

Table 1. Layer description and strength measurements for location at Humbug Flats.

Humbug Flats	Description	Porosity (%)	Fracture distribution (maximum #/meter)	Young's Modulus (GPa)	UCS strength (MPa)	Indirect tensile strength (MPa)
Layer L4	Quartz dominated, some plagioclase and iron oxides	13-16	4	2-3	38	1.6
Layer L3	Quartz dominated, bleached color and extensively deformed by deformation bands	26-30	2	0.1-0.2	2	0.4
Layer L2	Quartz dominated, with carbonate crystals	16-20	4	-	-	1.2
Layer L1	Quartz dominated, some plagioclase and iron oxides	7-10	5	4-5	65 MPa	2.7

5. Data of Little Grand Wash Fault

5.1. Fracture distribution

Sedimentary log and fractures in the Entrada Formation of well CO2W55 from depth interval 20-100 m is presented in Fig. 4 and show a fracture frequency of 0-3 fractures per meter. The fractures logged are all natural sub-vertical fractures. Irregular fractures typical for degassing of CO₂ during coring is not included in the log. Deformation bands are also not included. The logged fracture are all classified as tensile (mode I) fractures with no indications of shear movement. Most fractures were found in bleached parts of the core, only four fractures were from unbleached parts. JRC was measured for all the open fractures and give an average coefficient of 8-9, with the smoothest fractures offering JRC of 6 and the roughest a JRC of 13. Comparison of the fracture log with the sedimentary log show that fractures are mostly observed within the low permeable horizons, whereas the thick reservoir sections at 35-45 m depth and 80-88 m depth is unfractured.

5.2. Fracture aperture

Preliminary results from the fracture characterization using computer tomography (CT) show that there is a distinct difference between fractures with extensive bleaching contrary to non-bleached fractures of the Entrada Formation (Fig. 5). The unbleached fracture show a small fracture aperture, with several contact points along the fracture and limited mineral growth, whereas bleached fractures have a wider fracture aperture, more complex fracture pattern and precipitation of calcite and some heavy minerals. Fracture aperture distribution was mapped using the 3D CT volume of plugs from the fractures in the core, as shown in Fig. 6. The maximum fracture aperture mapped is 1.2 mm. High aperture pathways can be interpreted as continuous zones across the plug and one high aperture zone can be correlated with an intersecting fracture. The dark blue represents areas where the fracture is completely clogged by precipitated oxides seen as high density (black) CT values.

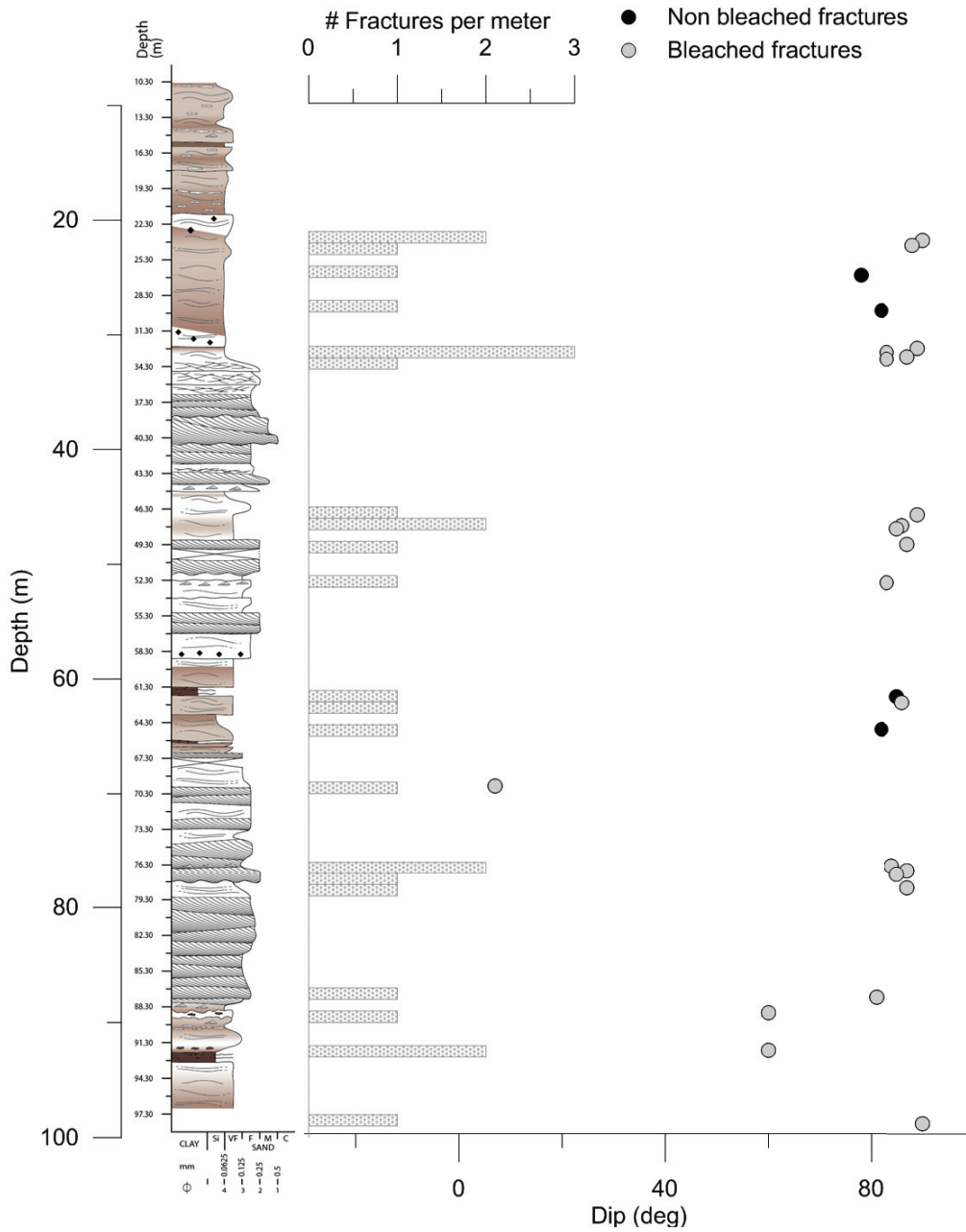


Fig. 4. Sedimentary and fracture log from well CO2W55 in the footwall damage zone of Little Grand Wash fault. Bars show natural fractures per meter of logged core (top axis). Dots show dip of fractures (lower axis) and indicate the relative amount of fractures in bleached or unbleached host rock.

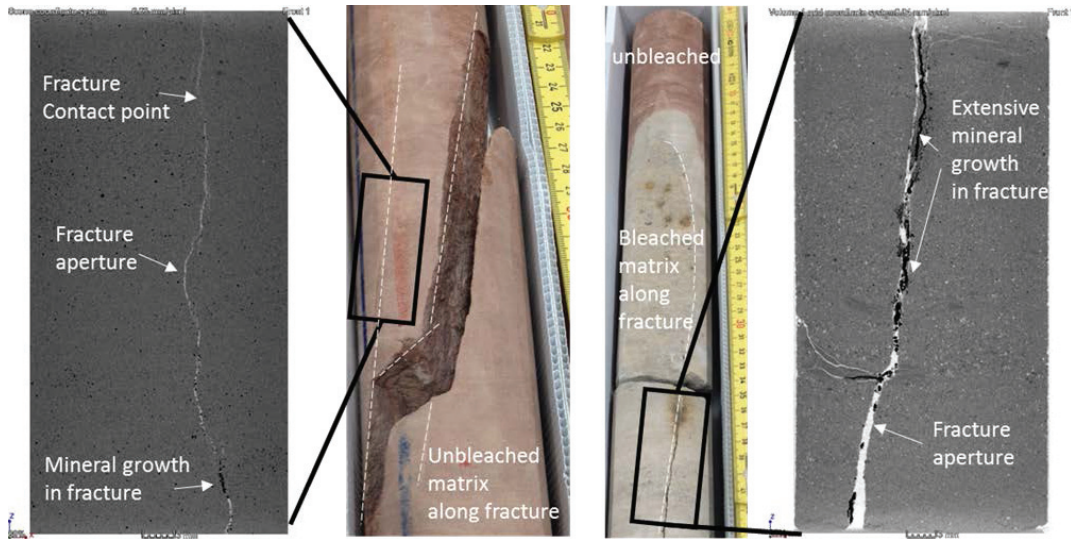


Fig. 5. Example of unbleached (sample 1) and bleached (sample 7) fractures in core from the Entrada Formation, Utah (see Fig. 4). Computer tomography (CT) images from plugs cored along the fracture show fracture aperture (white), dense minerals as fracture fill (black) and contact points along the fracture where there is no aperture.

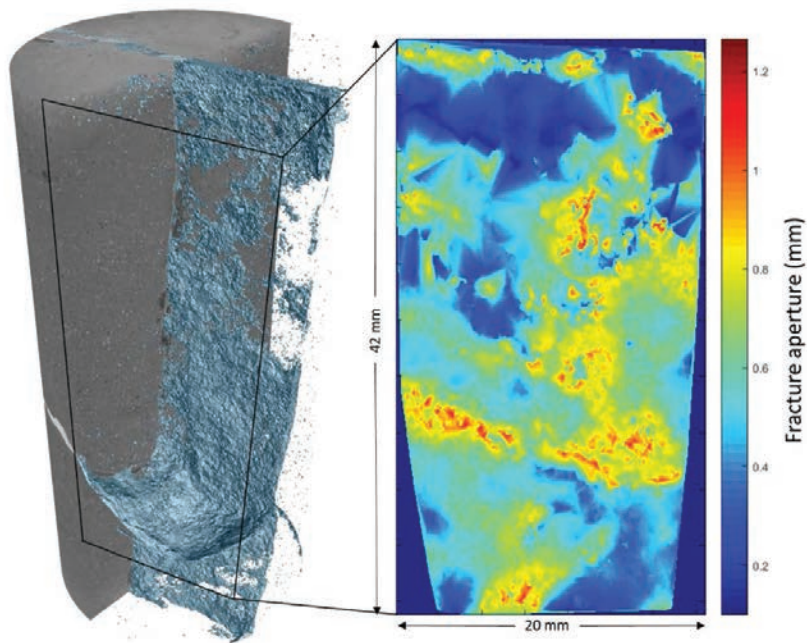


Fig. 6. Fracture aperture visualization based on the 3D CT volume of plug from bleached fracture at depth 45.75 m in well CO₂W55. A section of the main fracture surface is mapped and coloured based on aperture. Red is the highest aperture (1.2 mm), whereas dark blue is the lowest detectable aperture from the CT pixel resolution (0.1 mm) and completely clogged areas.

5.3. Fracture microstructure and geochemical characterization

Fractures from the core were sampled from bleached and unbleached Entrada Formation. From each sampling interval one fractured and one intact/unfractured plug were sampled. Table 2 show the preliminary results from the fracture and matrix characterization. On the fracture plane of sample 1, representing red coloured diagenetic facies of Entrada Sandstone, large, euhedral calcite crystals are observed. Barite crystals are relatively abundant as well. These may have precipitated from saline pore-fluids, but may also be a sample pollutant sourced from drilling mud (barite appears to postdate calcite). The calcites are interpreted as precipitated in situ from a carbonate saturated solution. Grains making up a quartz-rich sandstone matrix are coated with illite. The red color characteristic for aeolian deposits is commonly found to stem from hematite (often mixed with illite) coating [8]. The fracture surface of sample 4, representing a bleached zone, is rougher compared to sample 1. Dark, scattered mineral growth (sparse) in light grey sandstone matrix is pyrite, interpreted to have precipitated from reducing fluids. Fe-reduction with resultant bleaching, with associated sulphate (aqueous) reduction may form pyrite [8]. Clay coatings are not observed, however pore filling clays (illitic) are present. K-feldspars appear leached. Sample 7 matrix comprises porous, light coloured quartz rich sandstone with evident overgrowths. Dark patches on the fracture surface are made up of gypsum with abundant pyrite. Gypsum appears as fibrous crystals in rosettes, with scattered euhedral, cubic pyrite crystals. Their coexistence is indicative of varying redox-conditions, consistent with Ca and S in gypsum that is sourced from carbonate weathering and pyrite oxidation [9, 10].

Table 2. Description for selected fractured intervals within the core from the drill hole CO₂W55, Little Grand Wash fault.

Core depth (m)	Sample (#)	Description	Host rock porosity (%)
24.71 - .77	1-3	Unbleached zone with sub-vertical fracture. The matrix is quartz-rich with illite as grain coating. Calcite and barite crystals are observed on the fracture surface.	5-6
32.02 - .37	4-6	Bleached zone with sub-vertical fracture. Quartz rich matrix with pore filling clays. Pyrite scattered on the fracture surface.	8-9
45.75 - .94	7-10	Bleached zone with sub-vertical fracture. Quartz rich sandstone. Fracture surface show patches of gypsum and pyrite.	8-10

6. Discussion and conclusions

The mapped fracture distribution of Humbug Flats and the core from well CO₂W55 show that fractures are mainly found within the low porosity Earthy facies sections of the Entrada Formation. The current strength data available for Entrada Formation at Humbug Flats suggests a relationship between mechanical strength and porosity, where the layer L1 is found to have the highest fracture frequency and the lowest porosity together with the highest stiffness and strength. The fractured samples from the core logging in well CO₂W55 is from intervals with similar matrix porosity as layer L1, suggesting a similar strength and stiffness for these layers. Overall, the dominant failure mode observed within the core is mode I joints. Our interpretation is that the logged section of Entrada Formation can be described as the damage zone of Little Grand Wash fault and that the sub-vertical fractures define a fracture corridor seal bypass system as described by Ogata et al. [6].

Microstructural and geochemical observations from the fracture surfaces sampled indicate transport of reducing fluids along the fractures. The fluid is most likely a reacted CO₂ charged brine as described by Kampman et al. [1] resulting from the complex mixing of CO₂ saturated brine and groundwater within the Navajo reservoir sandstone and migrating upwards and along the fracture corridors. The CT imaging of the fractures and following aperture mapping indicate that the fracture is a mixture of open fracture providing distinct pathways for flow (Fig. 6) and

contact points where the fracture has been clogged by a dense mineral phase identified as pyrite precipitated from the in-situ fluid within the fracture.

The fracture mapping and characterization provided in this study provide important background data needed for the design and interpretation of planned fracture flow tests. Controlling parameters for fracture flow is the fracture aperture, whereas the sensitivity of a fracture to open or close due to changes in normal stress or shear stress is controlled by the fracture stiffness. The fracture stiffness can be related to the distribution of contact areas versus aperture and further visualization and quantification of the fracture aperture and contact points will be important aspect together with measurements of fracture flow properties under varying stress conditions.

Acknowledgements

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