The effect of CO₂ on the mechanical properties of the Captain Sandstone: Geological storage of CO₂ at the Goldeneye field (UK)

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ABSTRACT

Geological storage of CO₂ in clastic reservoirs is expected to have a variety of coupled chemical–mechanical effects, which may damage the overlying caprock and/or the near-wellbore area. We performed conventional triaxial creep experiments, combined with fluid flow-through experiments (brine and CO₂-rich brine) on samples of poorly consolidated, carbonate- and quartz-cemented Captain Sandstone from the Goldeneye field. The main goal was to study the effect of carbonate cement dissolution on mechanical and ultrasonic properties, as well as on the failure strength of the material. Our experiments were performed under in situ reservoir conditions, mimicking reservoir depletion and injection. Although total dissolution of calcite was observed, and confirmed by microstructural and fluid chemistry analyses, it did not affect the rock mechanical properties, nor was any measurable rock strength reduction observed. This is most likely because grain-to-grain contacts were sufficiently quartz-cemented and quartz is not affected by CO₂-rich brine. Failure data for the Captain Sandstone showed that the stress conditions under which CO₂ injection will take place remain far away from the failure envelope. Therefore, CO₂ injection is not expected to lead to shear failure of the reservoir. However, longer-term chemical reactions, involving minerals such as feldspar, clays or micas, still require more research.

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1. Introduction

For industrialised countries with a major hydrocarbon infrastructure, such as the United States, United Kingdom or the Middle East, carbon capture and storage (CCS) in depleted oil and gas reservoirs forms a particularly attractive option to reduce anthropogenic CO₂ emissions (Bachu, 2000; Orr, 2004). Carbon dioxide injection into clastic hydrocarbon reservoirs may lead to mechanical, chemical and/or hydrological effects on the host and seal formations, both in the short- and long-term (Johnson et al., 2004). In response to CO₂ injection, and the concomitant change in pore pressure, there will be a direct poroelastic response (Wang, 2000). Furthermore, CO₂/brine/rock chemical interactions may potentially lead to changes in porosity and permeability, via chemically-coupled mechanical effects. Such effects include creep due to dissolution reactions (Le Guen et al., 2007; Madland et al., 2006; Vialle and Vanorio, 2011), CO₂-enhanced microcracking (Atkinson, 1979; Chester et al., 2007; Hangx et al., 2010; Liteanu et al., 2012) and diffusive mass transfer processes like pressure solution (Croizé et al., 2010; Dewers and Hajash, 1995; Renard et al., 1999; Schutjens,

1991), leading to time-dependent reservoir deformation. Chemical reactions between host rock and fluids include relatively rapid dissolution of fast-reacting minerals such as carbonates, either present as framework grains or as intergranular cement (Liteanu et al., 2012; Pokrovsky et al., 2009), as well as slow, long-term CO₂ mineralisation through reaction with Ca-, Mg-, or Fe-rich framework minerals such as feldspars, clays, micas and Fe-oxides (e.g. see Agaard et al., 2004; Carroll and Knauss, 2005; Hangx and Spiers, 2009; Palandri et al., 2005).

Depending on their rates, CO₂-induced creep processes can have important effects on storage integrity, both during the injection phase, as well as after abandonment. Creep can potentially cause reservoir compaction, leading to damage to wellbores, the overlying caprock and any fault/seal systems. However, it is difficult to evaluate the effect of such processes as little data exists on the rates of the creep processes relevant for subsurface reservoirs (e.g. see Grgic, 2012; Hangx et al., 2010; Le Guen et al., 2007; Liteanu et al., 2012) and no constitutive laws to predict the chemical–mechanical response to CO₂ injection have been developed. Therefore, for each individual site considered for CCS, it is currently necessary to evaluate the effect of CO₂/brine/rock chemical interactions on rock properties, under in situ conditions, in order to provide long-term numerical simulation models with appropriate input parameters.

The Goldeneye depleted gas condensate field, located offshore in the UK North Sea, is a candidate for the storage of at least 10 million tons of CO₂ into the weakly consolidated Captain Sandstone.

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Injection will commence in the Captain D unit, at a depth of ~2600 m and a temperature of ~80 °C. The reservoir rock mainly consists of quartz (~80%) and feldspar (~10%), with small amounts of authigenic clays and intergranular cement. The main grain-cementing phases consist of quartz, kaolinite and calcite. It is possible that rapid dissolution of calcite cement at grain contacts may weaken the rock on short timescales (weeks, months) after CO₂ injection has commenced, i.e. during the injection phase. If this were to occur it could lead to pore collapse, reduced injectivity, and reservoir or near-wellbore failure, potentially damaging the overlying caprock and/or the near-wellbore area.

No significant effect of carbonate dissolution upon the rock properties was expected for the Captain D Sandstone, as it contains additional quartz and kaolinite cement to strengthen the grain-to-grain contacts. However, the effect of CO₂ injection on carbonate-bearing sandstones has not been extensively studied to date, especially not its effect on mechanical properties. Therefore, it was prudent to (experimentally) investigate the effects of carbonate dissolution on the behaviour of the material. To this end, we performed conventional triaxial creep (constant stress) deformation experiments on Captain D Sandstone, combined with fluid flow-through (synthetic reservoir brine with or without high-pressure CO₂) for two of the experiments. Our aim was to study the mechanical properties (thermal expansion coefficient α , Young's modulus E , Poisson's ratio ν , bulk modulus K_b , compressional wave velocity V_p , shear wave velocity V_s) of Captain Sandstone and to assess the effect of rapid CO₂/brine/rock interactions, i.e. the dissolution of carbonate cement, both on the mechanical properties and on the failure strength of this material. The experiments were performed at temperatures of 20 or 60 °C, effective confining pressures P_c^{eff} of 15.0–22.8 MPa, effective axial stresses $\sigma_{\text{ax}}^{\text{eff}}$ of 27.6–28.5 MPa, and pore pressures P_p of 3.7–14.0 MPa. Since flow-through conditions with CO₂-rich brine are extreme conditions, only representative for a small part of the storage reservoir, it should be noted that our experiments represent a worst-case scenario for the entire field. If in these experiments no significant changes in rock-mechanical properties are observed due to flushing of acidified CO₂-rich brine, no effects are expected in the field with respect to calcite cement dissolution. Other, much slower (in the order of 10s to 1000s of years) chemical reactions, such as interaction with feldspar and clay minerals, were not assessed in these experiments, but have been assessed in a separate study using the geochemical modelling tool PHREEQC (Parkhurst and Appelo, 1999).

2. Experimental method

Two types of triaxial deformation experiments were carried out:

1. Mechanical tests with brine. This set aimed to determine the key mechanical properties of brine-saturated sandstone.
2. Mechanical and failure tests with brine, with or without injection of CO₂. These experiments were carried out in the presence of brine, with and without high-pressure CO₂, to assess the effect of calcite dissolution on the rock mechanical properties and failure strength.

All experiments were conducted at 20 or 60 °C. The experimental conditions are shown in Tables 1 and 2. The mechanical tests consisted of up to three stages, with key mechanical properties determined during each stage: (1) a set of two cycles simulating reservoir depletion and injection for brine-saturated samples (GE- and PS-series), (2) continuous flow-through of synthetic reservoir brine (PS-series), and (3) continuous flow-through of CO₂-saturated brine (PS-series). The depletion/injection cycles

were carried out at a constant axial stress of 41.6 MPa, a constant confining pressure of 36.8 MPa, and a pore pressure varying from 3.7 MPa (reached at the end of the depletion) to 14.0 MPa (reached at the end of the injection). The flow-through experiments were performed at a constant axial stress of 42.5 MPa, a constant confining pressure of 29.0 MPa, and pore pressures of 14.0 MPa. Failure tests were conducted at the end of the three-stage mechanical tests (PS-series), by slowly bringing the CO₂-exposed samples to failure. These experiments were performed to investigate the effect of carbonate dissolution on the rock strength. It should be noted that the stress conditions employed during the different test stages yielded the same effective stresses as the in situ stress-path of the Goldeneye field, during the fluid depletion and injection phases.

2.1. Starting material and pore fluid preparation

The sandstone used in this study was obtained from two cores retrieved from wells 14/29a-3 and 14/29a-5, Goldeneye field, Moray Firth, UK North Sea. Sample material was taken from the Captain D Sandstone unit, which is the main reservoir of the Goldeneye field. In total, six cylindrical samples (GE01, GE02, GE03, PS6, PS9, PS17) measuring 37.5 mm in diameter and 76 mm in length were drilled from the available core material. Their ends were ground square to ensure uniform load distribution. The samples were drilled dry, with compressed air for lubrication, to avoid crumbling of the material due to its friable nature. Retrieval depths of the material varied from 2968.5 to 3014.6 m TVD for well 14/29a-3, and from 2602.0 to 2602.6 m TVD for well 14/29a-5.

Full-core CT scans along radial and axial planes of the starting material were performed (Fig. 2a). The samples did not appear to contain any pre-existing cracks. Based on scanning electron microscopy (SEM) and optical thin section analysis, the Captain D Sandstone is classified as a poorly consolidated sub-lithic to subfeldspathic arenite (Fig. 2b). X-ray diffraction (XRD) analysis indicated an average mineralogy consisting of quartz (78.1 wt%), feldspar (5.7 wt% K-feldspar; 5.6 wt% plagioclase), and clays (7.6 wt%; mainly kaolinite), with ~0.3% calcite. From thin section analysis, average grain size was shown to be ~200 μm with a coarse- to fine-grained distribution. Larger grains are often very well-rounded and up to 1000 μm in size, while smaller grains are more angular. Locally re-precipitated (diagenetic) quartz is observed in the form of irregular ('dog tooth-like') grain coatings on detrital grains (Fig. 2c). Many detrital quartz grains show long grain boundaries and numerous concavo-convex grain-to-grain boundaries, as clearly seen in the BSEM images (Fig. 2d and e). Authigenic minerals consisted of quartz overgrowths, forming partial to complete, rarely interlocking, thin rims (10–30 μm), kaolinite booklets and grain-coating/pore-lining mixed and Fe-rich clays, as shown by secondary electron (SE) microscopy. Local occurrences of kaolinite or other clays indicated replacement of feldspars. Minor amounts of ferroan dolomite and calcite were found as a patchily distributed, pore-filling cement phase (Fig. 2d and e). Large areas containing calcite were not encountered in the pre-experiment samples, although patches of poly-crystalline siderite (iron-rich carbonate) were observed (Fig. 2e).

Sample porosity was determined by weighing the samples, measuring the grain volume by submerging the samples in chloroform, and determining the bulk volume by carefully measuring the dimensions of the samples. The porosities thus obtained ranged from 26.4 to 29.2%, while the measured permeability ranged from 6.5 to 21.0 $\times 10^{-13} \text{ m}^2$, as obtained using nitrogen permeametry.

Synthetic brine was prepared by adding various salts (NaCl, Mg₂Cl, KCl, CaCl₂, CaCO₃) to distilled water to create a fluid with a salinity of 53,936 ppm, which corresponds to a total dissolved solids content of 56,147 mg/l, in accordance with the composition of the formation fluid at the Goldeneye field. For CO₂-saturated

Table 1

Mechanical parameters and ultrasonic velocity data determined for the pore pressure depletion/injection cycles.

Sample name	GE01	GE02	GE03	PS6 ^a	PS9	PS17
ϕ_i [%]	29.2	27.6	26.6	n.d.	26.4	n.d.
To in situ conditions ($\sigma_{ax} = 41.9$ MPa, $P_c = 36.8$ MPa, $P_p = 14.0$ MPa)						
E [GPa]	6.8	8.3	7.8	6.2	10.0	8.4
ν [–]	0.05	0.10	0.07	0.05	0.08	0.05
K_b [GPa]	2.5	3.4	3.0	2.3	4.2	5.2
α_{axial} [10^{-6} K ⁻¹]		10.4		14.4		
α_{radial} [10^{-6} K ⁻¹]		17.9		10.4	10.8	
T [°C]	21	62	21	62	62	62
1st pore pressure depletion cycle ($\sigma_{ax} = 41.9$ MPa, $P_c = 28.1$ MPa, $P_p = 3.7$ MPa)						
E [GPa]	8.4	10.0	9.6	6.9	12.3	9.6
ν [–]	0.17	0.16	0.16	0.16	0.14	0.19
K_b [GPa]	4.2	4.9	4.7	3.4	5.7	5.2
V_p [m/s]	3533	3580		3251	3504	3415
S_{vp} [GPa ⁻¹]	0.8	0.6		0.3	0.7	0.4
R_{vp} [–]	13.2	6.1		1.9	8.8	4.3
V_s [m/s]		2022			1821	1691
S_{vs} [GPa ⁻¹]		1.7			1.4	1.0
R_{vs} [–]		17.7			18.0	10.8
1st pore pressure injection cycle ($\sigma_{ax} = 41.9$ MPa, $P_c = 36.8$ MPa, $P_p = 14.0$ MPa)						
E [GPa]	16.2	15.5	17.3	14.0	19.8	13.7
ν [–]	0.25	0.24	0.29	0.27	0.21	0.28
K_b [GPa]	10.6	9.8	13.6	10.3	11.5	10.2
V_p [m/s]	3509	3556			3485	3388
S_{vp} [GPa ⁻¹]	0.9	0.9			0.8	0.8
R_{vp} [–]	15.5	14.3			17.6	12.3
V_s [m/s]		1999			1803	1672
S_{vs} [GPa ⁻¹]		1.7			1.4	1.3
R_{vs} [–]		27.8			29.7	18.8
2nd pore pressure depletion cycle ($\sigma_{ax} = 41.9$ MPa, $P_c = 28.1$ MPa, $P_p = 3.7$ MPa)						
E [GPa]	15.2	14.6	16.7		17.6	12.0
ν [–]	0.23	0.20	0.26		0.21	0.26
K_b [GPa]	9.3	8.2	11.4		10.0	8.3
V_p [m/s]	3536	3584			3512	3416
S_{vp} [GPa ⁻¹]	0.9	0.8			0.9	0.8
R_{vp} [–]	14.7	12.0			19.2	10.3
V_s [m/s]		2030			1843	1690
S_{vs} [GPa ⁻¹]		1.4			1.3	1.0
R_{vs} [–]		20.9			27.9	12.8
2nd pore pressure injection cycle ($\sigma_{ax} = 41.9$ MPa, $P_c = 36.8$ MPa, $P_p = 14.0$ MPa)						
E [GPa]	15.8	15.1	17.2		19.0	12.6
ν [–]	0.27	0.22	0.32		0.21	0.27
K_b [GPa]	11.6	9.0	15.5		11.0	9.2
V_p [m/s]	3502	3552			3478	3387
S_{vp} [GPa ⁻¹]	1.0	1.0			0.9	1.0
R_{vp} [–]	16.0	15.7			17.2	13.0
V_s [m/s]		2000			1801	1668
S_{vs} [GPa ⁻¹]		1.8			1.4	1.4
R_{vs} [–]		28.2			26.0	18.3

Symbols: ϕ_i is initial porosity, E is the Young's modulus, ν is Poisson's ratio, K_b is the bulk modulus, α_{axial} is the axial, or linear, thermal expansion coefficient, α_{radial} is the radial thermal expansion coefficient, T is the experimental temperature, V_p is the compressional wave velocity, V_s is the shear wave velocity, S is the stress sensitivity of the ultrasonic velocity, and R is the strain sensitivity of the ultrasonic velocity.

^a Note that sample PS6 failed during the first pore pressure depletion/injection cycle.

brine flow-through experiments (PS-series), the synthetic brine was saturated with supercritical (SC, $P_{crit} > 7$ MPa, $T_{crit} > 31$ °C (Span and Wagner, 1996)) CO₂ in a 300 ml autoclave, employing a 1:5 (initial stages PS9) or 1:2 (final stages PS and all PS17) CO₂:brine volume ratio. The pressure and temperature conditions of the autoclave ($T \sim 35$ – 40 °C, $P_{CO_2} = 7.2$ MPa) were selected such that we obtained fully saturated CO₂-rich brine. As the experiments were performed at a temperature of 60 °C, instead of the in situ reservoir temperature ($T = 80$ °C), theoretically this gives rise to a slightly higher CO₂ solubility under the experimental conditions, compared with the mixing conditions (e.g. see Duan and Sun, 2003; Wiebe and Gaddy, 1939, 1940). This procedure of pressurisation and heating was followed to avoid significant exsolution of CO₂ from the brine as it is being transferred from the autoclave to the sample.

2.2. Experimental set-up

We performed the deformation experiments in axi-symmetric compression under constant stress conditions. To this end, we used an externally heated triaxial compression apparatus, with Therminia B heat transfer oil as the confining medium. Additionally, this apparatus was equipped with a specially designed flow loop to allow for flushing of the samples with high-pressure fluid at a constant flow rate. Confining pressure is applied to the pressure vessel by pressurising the confining oil using a servo-controlled volumetric pump. Axial load can be applied by advancing a loading piston into the vessel, while keeping the confining pressure nominally constant. A schematic diagram of the apparatus is shown in Fig. 1.

Table 2

Mechanical parameters and ultrasonic velocity data determined for the experiments flushed with brine and CO₂-saturated brine. During both flow-through stages, stress conditions are set to: $\sigma_{ax} = 42.9$ MPa, $P_c = 29.0$ MPa, $P_p = 14.0$ MPa. The experiments were performed at $\sim 60^\circ\text{C}$.

Cum. ml of fluid flow	E [GPa]	ν [-]	K_b [GPa]	V_p [m/s]	S_{Vp} [GPa ⁻¹]	R_{Vp} [-]	V_s [m/s]	S_{Vs} [GPa ⁻¹]	R_{Vs} [-]
PS9									
Brine flow									
160	21.7	0.24	13.6	3442	1.1	30.3	1764	1.0	26.8
CO ₂ -saturated brine flow									
260	21.5	0.25	14.4	3435	1.1	29.8	1755	0.9	22.8
540	21.4	0.27	15.3	3434	1.1	29.9	1758	0.7	18.8
1230	21.3	0.24	14.0	3404	1.1	31.1	1758	1.0	27.4
1780	21.9	0.25	14.6	3416	1.3	32.1	1754	1.1	27.2
PS17									
Brine flow									
300	14.2	0.18	7.4	3341	1.5	27.7	1625	1.2	22.6
550	15.4	0.20	8.5	3342	1.6	27.4	1625	1.3	21.2
CO ₂ -saturated brine flow									
840	16.0	0.19	8.8	3335	1.6	28.4	1614	1.3	22.8
1010	16.2	0.19	8.6	3333	1.7	31.4	1616	1.3	25.0
1130	16.5	0.19	8.8	3331	1.7	31.3	1618	1.5	26.8
1220	16.2	0.21	9.5	3325	1.6	28.8	1612	1.5	27.3

Symbols: E is the Young's modulus, ν is Poisson's ratio, K_b is the bulk modulus, V_p is the compressional wave velocity, V_s is the shear wave velocity, S is the stress sensitivity of the ultrasonic velocity, and R is the strain sensitivity of the ultrasonic velocity.

Axial sample deformation is measured using two internal linear variable displacement transducers (LVDT; with a range of 50 mm and a resolution of $\pm 25 \mu\text{m}$). Radial deformation of the samples is measured using strain gauges (2 mm range, resolution $\pm 0.5 \mu\text{m}$). Both confining pressure and applied axial load are controlled by two separate custom analogue servo-controllers and are measured using pressure gauges (100 MPa range, resolution ± 0.1 MPa). Sample temperature is measured using two type-K (chromel/alumel) thermocouples, located near the sample sleeve and in the oil, far from the sample. The triaxial apparatus is located inside an oven, for which temperature is controlled using a PID (proportional/integral/derivative) controller (150°C range, resolution $\pm 0.4^\circ\text{C}$). The end-pistons are equipped with transducers, consisting of piezo-electric crystals, able to measure ultrasonic (0.8–0.9 MHz),

axial P- and S-wave velocities, using the pulse transmission technique (Birch, 1960).

During the pore pressure depletion/injection tests (GE-series), the pore fluid is introduced through the end-pistons. The pore pressure is controlled by a servo-controlled volumetric pump (ISCO® 100DM, 68.95 MPa (10,000 psi) range, resolution ± 0.3 MPa) and monitored at both ends of the sample with two pressure gauges (100 MPa range, resolution ± 0.1 MPa). During the tests employing brine and CO₂-saturated brine flow-through (PS-series), pore pressure is applied using two, serial servo-controlled Quizix® volumetric pumps, with one pump being used to apply a constant flow rate (0.83 ml/s range, resolution $\pm 0.1\%$ of set flow rate) through the sample, while the second pump is used to maintain a constant pore fluid pressure (41.3 MPa (6000 psi) range, resolution ± 0.1 MPa).

2.3. Sample assembly

The samples were frozen prior to assembly, to ensure that the friable material remained intact during assembly. All samples were covered by a FEP (fluorinated ethylene propylene) inner sleeve, of the same size as the sample. Two small holes were cut into the inner sleeve to accommodate for the placement of the radial displacement transducers in direct contact with the sample. A 2.5 mm thick HNBR (hydrogenated nitrile butadiene rubber) outer sleeve, enclosing the two end-pistons, was placed over the FEP-coated sample. The FEP inner sleeve was necessary to reduce CO₂ diffusion through the HNBR outer sleeve during the experiments employing CO₂-saturated brine. The end-pistons contained a bore hole to allow for pore fluid access. Note that the bore holes were offset, to avoid interference with the acoustic measurement path.

After assembly, the sample is placed into the pressure vessel and an isostatic load of 2.0 MPa was applied to the sample ($\sigma_{ax} = P_c = 2.0$ MPa). The sample was left to thaw for ~ 70 h and subsequently the sample was vacuum-saturated with synthetic reservoir brine. The sample was carefully brought to the initial in situ stress conditions ($\sigma_{ax} = 41.9$ MPa, $P_c = 36.8$ MPa, $P_p = 14.0$ MPa), while measuring the key elastic parameters (K_b , E , ν). Once the appropriate in situ stress conditions were obtained, the sample was brought to the required temperature ($\sim 60^\circ\text{C}$) and the thermal expansion coefficient α was determined, while maintaining the pre-established stress conditions. After heating, the sample was left to consolidate for at least 24 h.

Fig. 1. Schematic diagram of the triaxial compression apparatus, which consists of a main pressure vessel, containing the sample, and a hydraulically-driven axial loading piston.

Fig. 2. X-ray tomography and SEM images showing the microstructure of sample PS9 at different scales, before (a–e) and after CO₂ exposure (f–j). (a) Sectional CT image displaying bright, oval-shaped fossil. (b) Low magnification SE image displaying the poorly consolidated nature of the sandstone. (c) Higher magnification SE image of the dog tooth-like precipitate on the quartz grains. (d and e) Low magnification BSEM image of the material, showing the quartz framework with concave-convex grain boundaries and minor carbonate cement. (f) CT image of the same section as shown in (a). Note the disappearance of the fossil and other minor calcite aggregates, and the failure plane at the top of the sample section. (g) Low magnification BSEM image of a hole resulting from the dissolution of calcite. Note that the sandstone has not collapsed around the hole. (h) Low magnification SEM image of the failure plane. (i and j) BSEM images of the failure plane, showing significant grain size reduction and the angular nature of the grains in the shear plane.

2.4. Experimental procedure

The GE-series consisted only of two pore pressure depletion/injection cycles, which were performed under uniaxial strain conditions. In the depletion steps, applied axial stress was kept constant at 41.9 MPa while confining pressure and pore pressure were reduced from 36.8 MPa to 28.1 MPa and from 14.0 MPa to 3.7 MPa respectively, mimicking reservoir depletion, only to be brought up again to the initial values during the injection

cycle. Each step was followed by a consolidation period of at least 12 h to allow for creep. During the pore pressure depletion/injection cycles, elastic (E , ν and K_b) and ultrasonic (V_p and V_s) parameters were measured by means of small axial stress cycles ($\sigma_{ax} \pm 10$ MPa).

The PS-series consisted of two additional flow stages, a brine flow stage and a CO₂-saturated brine flow stage, following the pore pressure depletion/injection cycles. After the second pore pressure depletion/injection cycle, stress conditions were changed to simulate the in situ stress state at the start of CO₂ injection ($\sigma_{ax} = 42.9$ MPa, $P_c = 29.0$ MPa, $P_p = 14.0$ MPa). This was again followed by a 12-h consolidation period. Rock mechanical parameters (E , ν , K_b , V_p , V_s) were determined prior to the start of each of the flow stages. During the brine flow stage, synthetic reservoir brine was flowed through the sample at a rate of 0.06 ml/min, up to the point where no significant creep was observed. For experiment PS9, this meant a total brine-flow of 160 ml (7 pore volumes); while for PS17 a total of 550 ml (24 pore volumes) of brine was flowed through. After creep had ceased, key mechanical parameters were determined again. Subsequently, the synthetic brine was saturated with supercritical CO₂ (see Section 2.1). This CO₂-saturated brine was flowed through the sample at a constant rate (0.025 or 0.06 ml/min) and rock mechanical parameters were measured several times during this stage. A total of 1780 ml (77 pore volumes) and 1220 ml (53 pore volumes) of CO₂-saturated brine were flowed through samples PS9 and PS17, respectively. After each 10 ml of fluid flow, the effluent was collected. The total amount of effluent collected within one day was combined.

After CO₂-saturated brine flow was stopped, the axial load on the sample was increased at a constant rate of 10 MPa/h until failure occurred. During the failure test, P_c and P_p were kept constant at 29.0 MPa and 14.0 MPa, respectively. After failure, the axial displacement was stopped. The experiments were terminated by carefully removing the pore pressure, axial stress and confining pressure, hereby fully unloading the sample. Samples, with their FEP inner sleeve intact to avoid disaggregation of the samples, were left to dry prior to (partial) impregnation with epoxy resin to allow for thin section preparation for SEM analysis, and CT scanning.

2.5. Data acquisition and processing

Throughout the experiments, axial load, confining pressure, axial and radial displacement and velocity data were recorded continuously. Data acquisition and experiment sequence control were done by custom software operating on a PC computer. The raw data were processed to yield differential stress ($\sigma_1 - \sigma_3$), axial strain (ϵ) and volumetric strain (ϵ_{vol}). The raw data (axial and radial displacement) were corrected for apparatus distortion and temperature changes. From the resulting stress-strain curves, peak strength is defined as the maximum differential stress $(\sigma_1 - \sigma_3)_{max}$ supported by a given sample and failure as the loss of strength of the material beyond the peak. The apparent Young's modulus (E), bulk modulus (K_b) and Poisson's ratio (ν) of individual samples were determined from the linear portion of the stress-strain curves (Jaeger et al., 2007), for each loading/unloading step and averaged over the loading/unloading time, not including the creep phase.

Furthermore, for each loading/unloading step, the strain-sensitivity factor, R [–], and the stress-sensitivity factor, S [GPa^{–1}], were determined from the average slopes of the velocity vs. strain and velocity vs. effective stress curves, respectively. Note that velocities obtained for the depletion stages were taken at maximum effective stress (i.e. maximum pore pressure depletion), while the velocities stated for the injection stages were taken at minimum effective stress (i.e. maximum pore pressure injection). The R and S

factors are determined for both axial V_p and axial V_s waves and are defined as follows:

$$\text{Strain sensitivity factor : } R = \frac{\Delta V_i / V_i}{\Delta e} \quad (1)$$

$$\text{Stress sensitivity factor : } S = \frac{\Delta V_i / V_i}{\Delta(\sigma_{ax} - P_p)} \quad (2)$$

where V_i are compressional V_p [m/s] or shear V_s [m/s] wave velocity, e is axial strain [–], σ_{ax} is applied axial stress [MPa] and P_p is pore pressure [MPa].

2.6. Microstructural and analytical analyses

Computer tomography (CT) scans of the core samples were made before and after the experiments. In addition, scanning electron microscopy (SEM) on polished thin sections and unprepared material, and X-ray diffraction (XRD) analyses of the pre- and post-experiment material were performed. CT analyses of the whole samples and back-scattered electron microscopy (BSEM) of polished thin sections show grey scale variations representing the various types of minerals, with heavy minerals (e.g. pyrite, calcite) being lighter in colour than light minerals (e.g. quartz). During SE microscopic analysis, energy dispersive X-ray (EDAX) analysis was performed for mineral identification. In addition, the daily cumulative effluent obtained during both experiments was analysed for elemental composition by inductive coupled plasma (ICP) analysis.

3. Results

In this study, we take compressive stresses, compressive axial strains and compacting volumetric strains (compaction) positive. The principal compressive stresses are denoted σ_i , with $\sigma_1 > \sigma_2 = \sigma_3 = P_c$, where P_c is the confining pressure. Principal effective stresses are accordingly denoted σ_i^{eff} , and are defined as $\sigma_i^{\text{eff}} = \sigma_i - P_p$, where P_p is the applied pore pressure (MPa).

3.1. Mechanical parameters and ultrasonic velocities of unexposed material

From the heating stage of experiments GE02 and PS9, we obtained axial thermal expansion coefficients of 10.4×10^{-6} and $14.4 \times 10^{-6} \text{ K}^{-1}$ and radial thermal expansion coefficient of 17.9×10^{-6} and $10.4 \times 10^{-6} \text{ K}^{-1}$ for samples GE02 and PS9, respectively (Table 1). In Fig. 3, the effective axial stress is plotted as a function of axial strain for all depletion/injection cycles. Note that there is a strong variation among the samples regarding the amount of axial strain induced by bringing the sample to the initial in situ stress conditions ($e_{\text{initial}} = 3.4\text{--}7.6\%$), as well as the amount of irreversible (non-elastic) strain accumulated during the consolidation period following the first depletion stage ($e = 0.13\text{--}0.38\%$). Both show a positive correlation with sample porosity, indicating that the differences in behaviour are mainly caused by the differences in initial porosity of the sample material.

After the first depletion phase, all samples showed a linear and reversible effective stress vs. axial strain relationship (Fig. 3) and no further compaction was observed during the second depletion/injection cycle. Average values (and standard deviations) for Young's modulus E , Poisson's ratio ν and bulk modulus K_b obtained up to the first depletion cycle were $8.7 \pm 1.7 \text{ GPa}$, 0.12 ± 0.03 , $4.1 \pm 1.1 \text{ GPa}$, respectively (see Fig. 4). In contrast, for the injection phase of the first cycle and the second depletion/injection cycle $E = 15.8 \pm 2.2 \text{ GPa}$, $\nu = 0.25 \pm 0.03$ and $K_b = 10.6 \pm 1.9 \text{ GPa}$. This shows that values obtained during loading and the first depletion cycle are approximately 30–70% lower than the values obtained after the first depletion cycle. Note that the measured parameters show

Fig. 3. Effective axial stress vs. axial strain curves for the two pore pressure depletion/injection cycles performed on our samples. The stress conditions used were: $\sigma_{ax} = 41.9 \text{ MPa}$, $P_c = 36.8 \text{ MPa}$ and $P_p = 14.0 \text{ MPa}$ during loading to initial in situ conditions and the pore pressure injection phases. During pore pressure depletion, axial stress remained constant, while P_c and P_p were decreased to 28.1 and 3.7 MPa, respectively. Note that all experiments were performed at 60°C , with the exception of experiments GE01 and GE03, which were performed at room temperature.

some sample variability, which can be correlated to sample porosity (see Fig. 4). Comparing the results from experiments GE01 and GE03, which were performed at room temperature, with the other experiments, performed at 60°C , shows that temperature did not significantly affect our measurements.

With increasing stress or strain, axial P- and S-wave velocities increased slightly, with generally values in the range of 3387–3584 m/s for V_p ($R = 12.7 \pm 5$; $S = 0.8 \pm 0.2 \text{ GPa}^{-1}$) and 1690–2030 m/s for V_s ($R = 21.4 \pm 6$; $S = 1.4 \pm 0.3 \text{ GPa}^{-1}$). An overview of the elastic data for the pore pressure depletion/injection cycles is given in Table 1.

3.2. Elastic parameters, ultrasonic velocities and rock strength after exposure (brine $\pm \text{CO}_2$)

For the two flow-through experiments (PS9 and PS17), very little deformation, i.e. less than $<0.01\%$, is observed in either the axial or radial direction during the brine flow stages, as can be seen in Fig. 5. Note that no enhanced deformation is observed during the CO_2 -saturated brine flow, compared to the brine flow stage, though sample PS17 showed some fluctuations in radial strain (Fig. 5). Throughout both flow phases, Young's modulus, Poisson's ratio and bulk modulus show no significant change, as can be seen in Fig. 4, with $E = 18.4 \pm 3.1 \text{ GPa}$, $\nu = 0.22 \pm 0.03$ and $K_b = 11.2 \pm 3.1 \text{ GPa}$. For the P-wave and S-wave velocities little variation between the different measurements in each stage is seen, with V_p ranging from 3325 to 3442 m/s ($R = 30.0 \pm 1.9$; $S = 1.4 \pm 0.3 \text{ GPa}^{-1}$) and V_s ranging from 1612 to 1764 m/s ($R = 24.1 \pm 2.7$; $S = 1.2 \pm 0.3 \text{ GPa}^{-1}$). All elastic rock properties obtained during the flow-through experiments are summarised in Table 2.

After continuous flushing with CO_2 -saturated brine, we measured the failure strength of the samples. Brittle shear failure occurred at an applied axial stress σ_{ax} of 80.2 MPa for sample PS9 and 74.9 MPa for sample PS17, as indicated by a sharp drop in axial stress.

3.3. Microscopic and chemical analyses

3.3.1. CO_2 -exposed material – XRD, CT and SEM analysis

XRD analysis of the exposed material did not show any indication of calcite, though the starting material already contained little calcite, and small variations in initial calcite content between

Fig. 4. (a) Young's modulus, (b) Poisson's ratio and (c) bulk modulus values measured for each of our experiments. Under static brine conditions (solid symbols), the parameters were determined after initial loading and for each loading/unloading step and averaged over the loading/unloading time, not including creep phases. Under brine and CO₂-saturated brine flow-through conditions (open symbols), elastic properties were determined prior to start of flow, during and at the end of flow. Note that all experiments were performed at 60 °C, with the exception of experiments GE01 and GE03, which were performed at room temperature.

the sample volumes needed for analysis could equally explain the observed difference. Therefore, solely based on the basis of XRD analysis, calcite dissolution cannot be confirmed. However, from CT imaging it is evident that the initial calcite has disappeared (Fig. 2f). Note that even large structures, such as fossils, have completely dissolved during the flushing with CO₂-saturated brine. These observations are confirmed by SEM analysis, which shows the formation of holes in the post-experiment samples, suggesting dissolution of calcite (Fig. 2g). The material did not collapse around these cavities, due to the angular, dog tooth-shaped secondary quartz covering the detrital grains, as well as the concavo-convex grain-to-grain contacts, prevented shifting and rotation of the grains.

At the end of the experiment, shear failure was induced (Fig. 2f). The grain size of the (quartz) grains in the failure plane was dramatically reduced to very small and highly angular grains (grain size

generally less than 20 μm) – see Fig. 2h. The fine grains result from the fracturing of larger grains during failure, as well as from shearing along the failure plane. Therefore, there are still some remnant large well-rounded grains within the fault gouge – see Fig. 2i and j (failure plane oriented perpendicular to the plane of view).

3.3.2. Effluent composition

We will proceed to present the results for the Ca²⁺ concentration measurements, as [Ca²⁺] can be used as an indicator for calcite dissolution (Grgic, 2012; Pokrovsky et al., 2009). As can be seen in Fig. 6, the initial Ca²⁺ concentration in the brine is ~1000 ppm (25 mmol/l). Both experiments show similar behaviour in [Ca²⁺], displaying a rapid increase up to ~1600 ppm (40 mmol/l) shortly after CO₂ exposure started. After ~250 ml (11 pore volumes) of CO₂-saturated brine flow, the calcium concentration decreased again to values close to the initial calcium concentration of the brine.

Fig. 5. Axial and radial strain vs. cumulative fluid flow during the brine and CO₂-saturated brine flow stages. There is very little strain measured during either stage. Note that some fluctuations are seen in the radial strain for sample PS17, which may be an effect of pump control.

Using the effluent data obtained during the CO₂-stage and assuming all Ca²⁺ comes from calcite dissolution according to the reaction $\text{CaCO}_3 + \text{CO}_2 + \text{H}_2\text{O} \rightarrow \text{Ca}^{2+} + 2\text{HCO}_3^-$ (Grgic, 2012; Pokrovsky et al., 2009), mass balance calculations can be made to determine the amount of calcite that has been dissolved. For both experiments, it amounts to ~0.3 wt% of calcite, which is in accordance with the amount predicted by the XRD measurement on the starting material.

It should be noted that [Ca²⁺] already shows a short-lived peak-increase during brine flow. Studying the trends of the other elements present in the effluent indicated concentrations of cations not present in the initial brine. This suggests that there are impurities present in the sample, e.g. from the drilling mud used to drill the core, which are flushed out during brine flow and slightly distort the results of the first few effluent samples. No such artefacts were found in the effluent samples taken after this peak nor during CO₂-saturated brine flow, indicating that the measured excess calcium concentration is indeed a measure for calcite dissolution.

Fig. 6. Calcium concentration vs. cumulative fluid flow for the effluents obtained in experiments PS9 (■) and PS17 (◆). Brine flow stages are indicated by dashed lines and CO₂-saturated brine flow stages are indicated by solid lines.

4. Discussion

4.1. Effect of CO₂/brine/rock interactions on mechanical properties

Studies on the effect of CO₂-saturated fluids on mechanical and transport properties of carbonate rocks and aggregates (Grgic, 2012; Le Guen et al., 2007; Liteanu et al., 2012; Madland et al., 2006; Vialle and Vanorio, 2011) show dissolution of the carbonate phases, leading to the creation of flow channels (Le Guen et al., 2007; Madland et al., 2006) and a significant increase in porosity and permeability (Le Guen et al., 2007; Vanorio et al., 2011; Vialle and Vanorio, 2011). As a result, compaction and compaction rates increase (Grgic, 2012; Le Guen et al., 2007; Liteanu et al., 2012; Vanorio et al., 2011), while a decrease in elastic properties (Madland et al., 2006; Vialle and Vanorio, 2011) and rock strength (Madland et al., 2006) is observed.

However, the effect of CO₂-rich brine injection on the mechanical properties of carbonate-bearing sandstones is less clear-cut. It is known that the introduction of water weakens sandstone as a result of the activation of fluid-enhanced microcracking mechanisms (e.g. see Baud et al., 2000). In contrast, CO₂ injection into water-saturated sand aggregates significantly reduces microcracking (Hangx et al., 2010), limiting fluid-enhanced compaction and decreasing creep rates. Several studies (Le Guen et al., 2007; Oikawa et al., 2008; Ross et al., 1982) showed that injection of CO₂-saturated brine into carbonate-cemented sandstones leads to dissolution of the carbonate phases (Le Guen et al., 2007; Ross et al., 1982), occasionally resulting in collapse of the rock matrix (Ross et al., 1982). Le Guen et al. (2007) observed an increase in creep rate in response to flow-through of CO₂-rich fluids, compared to dry conditions, though the effect was smaller than that observed for limestones. In contrast, creep tests on competent Berea sandstone (~5 vol% carbonate, 20% porosity (Zhang et al., 1990)) in the presence of static CO₂-saturated water showed longer creep life times, i.e. time until failure, compared to water, and a positive correlation between time until failure and time of CO₂ exposure prior to creep loading, suggesting a decrease in creep rate in response to the presence of CO₂ (Oikawa et al., 2008). This is in accordance with our experiments as no significant compaction was observed during the brine- or CO₂-dominated creep stages, despite the friable nature of the Captain Sandstone. Furthermore, Oikawa et al. (2008) observed variable, though small, effects on the elastic properties after one to four days of CO₂/water/rock interaction. This is also in accordance with our results, which show <10% variation in Young's Modulus and Poisson's ratio, without a clear dependence on fluid type, which is also reflected in the ultrasonic velocity data. It is therefore suggested that this could be an effect of sample variability, particularly in carbonate content.

It should be noted that P-wave velocity was found to be sensitive to pore fluid type, as is evident from comparing the ultrasonic results obtained in experiment PS9, which had a slightly different procedure for preparation of the CO₂-saturated brine midway the experiment (cf. Section 2.1). Measurements showed that the amplitude of the P-waveform acquired during the brine flow is similar to the amplitude obtained during the initial stage of the CO₂-saturated brine flow (CO₂:brine = 1:5), as can be seen in Fig. 7. After changing the CO₂-brine ratio to 1:2, a reduction of the ultrasonic P-wave amplitude of approximately 45% was observed. In addition, a small drop in P-wave velocity from ~3440 m/s to ~3420 m/s was noted, as well as a shift in zero-crossing, indicative for a change in wave travel time.

When employing a 1:5 mixing ratio, a pressure drop occurred in the autoclave (down to $P = 5$ MPa) as brine was being extracted, lowering the CO₂ concentration in solution in the autoclave (Duan and Sun, 2003). This resulted in a slightly CO₂-undersaturated

Fig. 7. P-wave amplitude vs. travel time for several P-waves obtained during experiment PS9. Note the significant drop in amplitude and the increase in travel time, as a result of the change in CO₂:brine volume ratio from 1:5 to 1:2.

solution (Duan and Sun, 2003), but maintaining a single-phase fluid system, under the experimental conditions. Decreasing the mixing ratio to 1:2 maintained the pressure within the autoclave, but also resulted in a slightly oversaturated solution after introduction into the sample (Duan and Sun, 2003). The concomitant exsolution of CO₂ lead to a two-phase system (SC CO₂ plus CO₂-saturated brine) being present within the sample. Therefore, P-wave velocity is a good indicator for CO₂ coming out of solution, as the bulk modulus of SC CO₂ is about one order of magnitude lower than of (CO₂-saturated) brine (Espinosa et al., 2011; Rubino et al., 2011). It should be noted that V_s did not change significantly ($V_s = 1759 \pm 4.9$ m/s) during both flow phases, as shear waves are less affected by changes in pore fluid properties (Geertsma, 1961).

4.2. Chemo-mechanical effect of CO₂ on rock strength

For partially wet Captain C and D sandstone (Shell International Exploration and Production, unpublished data), failure data obtained at room temperature and confining pressures of 0.5–20 MPa showed cohesion $S_0 \approx 3.0$ MPa with a friction angle ψ of 34°. For confining pressures of 15–20 MPa, the average apparent Young's modulus obtained during the loading stage was ~ 6 GPa, while Poisson's ratio was < 0.1 . We compared the failure strength data obtained in this study after CO₂/brine/rock chemical interaction to the failure behaviour of the unexposed material. The elastic parameters in our experiments, determined during the loading to in situ stress conditions phase and the first depletion phase, show comparable values to the unexposed material deformed at 15–20 MPa. In contrast, values for E and ν obtained after the first depletion stage are shown to be significantly higher (cf. Fig. 4).

We have plotted the previous data together with the failure data obtained in this study in Mohr–Coulomb stress space, with $\sigma_{\text{mean}} = \frac{1}{2}(\sigma_{\text{ax}} + P_c) - P_p$ and $\tau_{\text{max}} = \frac{1}{2}(\sigma_{\text{ax}} - P_c)$ (Fig. 8). Note that the unexposed samples were tested at room temperature, while the exposed samples were heated to 60 °C. Temperature may play a role in rock strength, though our experiments have shown that there is little variation between the room temperature and the 60 °C experiments, when it comes to the elastic parameters (cf. Fig. 4). This may then also be (partly) true for the rock failure strength. As can be seen, the failure strength obtained in our CO₂-exposure experiments falls in line with the previously obtained (unexposed) material strength. Therefore, it can be concluded that the continuous flushing of the material with CO₂-saturated brine, and the concomitant removal of calcite, does not affect material strength or elastic properties.

Fig. 8. Mohr–Coulomb failure envelope showing maximum shear stress τ_{max} vs. mean normal stress σ_{mean} for unexposed Captain D Sandstone (◇, unpublished data), as well as after exposure to CO₂-saturated brine (◆, this study). The changing in situ state of stress of the Goldeneye field has been indicated as well. It is clear that failure of the reservoir will not occur during fluid depletion or CO₂ injection.

It is likely that removal of calcite cement may only have significantly affected rock properties and strength if the cement would have contributed considerably to the overall rock strength. Analyses have already shown that the small amount of calcite present in the Captain D Sandstone is dispersed very finely throughout the rock, and is most likely not significantly contributing to rock strength, as suggested by the very low cohesion ($S_0 = 3$ MPa). Therefore, removal of calcite cement did not lead to further loss of cohesion, i.e. did not lead to any significant weakening of the reservoir rock. Furthermore, matrix collapse around holes generated by the dissolution of fossil remains (Fig. 2g) may have been inhibited by rough grain-coatings on and the concavo-convex grain-to-grain contacts of the quartz grains (cf. Section 3.3.1), preventing shifting and rotation of the grains during compaction.

4.3. Implications

On the time-scale of our experiments (several weeks), the results showed dissolution of carbonate present within the sandstone material. However, due to sufficient quartz-cementation at the grain-to-grain contacts and the convex-concave nature of the contacts, calcite dissolution at grain contacts did not significantly affect the mechanical properties of the reservoir rock of the Goldeneye CCS candidate field: the Captain D Sandstone. It should be noted though that other candidate fields situated at shallower depths will have experienced less quartz cementation and diagenesis, and may be at an increased risk for calcite-dissolution-induced weakening. Therefore it remains important to investigate the short-term effect of CO₂ injection of such formations containing no or less quartz-cementation.

The effect of long-term reactions, such as the dissolution of feldspars, has not been investigated experimentally in this study. Under the stated in situ reservoir conditions ($T \approx 80$ °C, $\text{pH} = 3\text{--}5$, $d = 200$ μm), such mineral reactions will take $> 100\text{--}1000$ years (e.g. see Oelkers and Schott, 1995; Oxburgh et al., 1994). Their slow reaction kinetics makes it difficult to study the effect of such reactions via experiments, even under elevated conditions (e.g. Hangx

and Spiers, 2009; Kaszuba et al., 2003). If the load-supporting framework of the reservoir is sufficiently strong, dissolution of the ~10 vol.% of feldspars present in the Captain D Sandstone, and the precipitation of the product phases on the unstressed pore walls (Moore et al., 2005), instead of in the stressed grain-to-grain contacts (Baines and Worden, 2000; Zerai et al., 2006), would result in very minor poroelastic compaction of the reservoir (Hangx et al., 2010). A decrease in porosity and permeability, as a result of precipitation of secondary phases such as carbonates and clays, may be expected.

In the case of shear failure occurring within the reservoir rock, analysis of the shear plane showed a significant reduction of grain size by one order of magnitude (down to 20 μm). If shear failure occurs in the vicinity of a well bore, such fine particles may pose an issue during well shut-in. When injection is temporarily ceased, fluids may flow back into the well bore, taking along the produced fines. This may lead to well plugging and significant loss of injectivity. We plotted the stress conditions prior to depletion, after depletion and at the end of CO_2 injection onto our Captain D Sandstone Mohr–Coulomb failure envelope. As can be seen, under the conditions at which CO_2 injection will take place (i.e. going from $\circ$ to $\times$ in Fig. 8) it is unlikely that failure of the reservoir, as a result of carbonate dissolution, will occur. However, the long-term effect of aluminosilicate reactions on mechanical properties and rock strength still requires further research.

5. Conclusions

In this paper, we aimed to investigate the effect of carbonate cement dissolution on the elastic and ultrasonic properties, and failure strength of the Captain D Sandstone. This formation forms the main storage reservoir for the Goldeneye CCS candidate project and consists of poorly consolidated, carbonate- and quartz-cemented sandstone. Therefore, we performed conventional triaxial compression experiments on brine-saturated samples, under constant in situ stress conditions simulating reservoir depletion and CO_2 injection ($T = 20$ or 60°C , $\sigma_{\text{ax}}^{\text{eff}} = 27.6\text{--}28.5$ MPa, $P_c = 15.0\text{--}22.8$ MPa, $P_p = 3.7\text{--}14.0$ MPa), to study the rock mechanical properties (α , E , ν , K_b , V_p and V_s) of the material. Furthermore, we proceeded to perform flow-through experiments on two samples, aiming to study the effect of brine with and without the injection of CO_2 at high pressure on mechanical properties and failure strength. In summary, our main findings are:

1. Under brine-saturated, in situ stress conditions, prior to fluid flow, the average values (and standard deviations) for the mechanical parameters, obtained from the injection phase of the first cycle and the second depletion/injection cycle, were $E = 15.8 \pm 2.2$ GPa, $\nu = 0.25 \pm 0.03$ and $K_b = 10.6 \pm 1.9$ GPa. Variation in the measurements between the samples could be explained by variation in initial sample porosity. We obtained values of 3387–3584 m/s for V_p ($R = 12.7 \pm 5$; $S = 0.8 \pm 0.2$ GPa $^{-1}$) and 1690–2030 m/s for V_s ($R = 21.4 \pm 6$; $S = 1.4 \pm 0.3$ GPa $^{-1}$). We measured linear expansion coefficients of 10.4×10^{-6} and 14.4×10^{-6} K $^{-1}$ in the range 20–60 $^\circ\text{C}$.
2. After flow-through with brine and CO_2 -saturated brine, the mechanical parameters did not differ significantly from those prior to flow: $E = 18.4 \pm 3.1$ GPa, $\nu = 0.22 \pm 0.03$ and $K_b = 11.2 \pm 3.1$ GPa. Compressional wave velocity V_p ranged from 3325 to 3442 m/s ($R = 30.0 \pm 1.9$; $S = 1.4 \pm 0.3$ GPa $^{-1}$) and shear wave velocity V_s from 1612 to 1764 m/s ($R = 24.1 \pm 2.7$; $S = 1.2 \pm 0.3$ GPa $^{-1}$).
3. The small amount of carbonate present in the starting material was completely dissolved after several weeks of flow-through with CO_2 -saturated brine. This was confirmed by comparing

XRD, CT-scan imaging and SEM analysis of the pre- and post-experiment samples, and by mass balances using chemical analyses of the effluent during the experiments.

4. Our CO_2 -saturated brine flow experiments showed that P-wave velocity and amplitude are good indicators for assessing the exsolution of supercritical CO_2 , while S-wave velocity was not sensitive to pore-fluid changes.
5. Though calcite dissolution was observed for the Captain D Sandstone, grain-to-grain contacts appeared to be sufficiently quartz-cemented to prevent significant weakening of the material. Hence, no shear failure of the reservoir is expected for the conditions under which CO_2 injection will take place, and production of fines during well shut-in should not be an issue. However, for other potential sequestration sites with shallower, less quartz-cemented sandstones there may be an increased risk for calcite-dissolution-induced weakening. Therefore, it is important that the short-term effect of CO_2 injection on mechanical properties is investigated for such formations.

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