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Mechanisms for CO_2 leakage prevention – a global dataset of natural analogues

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Abstract

Natural CO_2 reservoirs have similar geological trapping mechanisms as required for CO_2 storage sites and often have held CO_2 for a geological period of time without any indication of leakage. Yet, migration of CO_2 from reservoirs to the surface is also common. 49 natural CO_2 reservoirs have been analysed to provide an overview of factors that are important for (1) retention of CO_2 in the subsurface and (2) leakage of CO_2 from the reservoir. Results indicate that overpressure of the overburden and the state of CO_2 in the reservoir influence the likelihood of migration and hence the performance of reservoirs.

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Keywords: CCS; CO_2 Storage; Leakage; Natural Analogues; Overpressure

1. Introduction

Carbon Capture and Storage (CCS) is the only industrial scale technology currently planned to directly reduce CO_2 emissions from fossil fuelled power plants and large industrial point sources to the atmosphere [1]. CO_2 is captured at the source and transported to subsurface storage sites, such as depleted oil and gas fields or saline aquifers [2]. In order to have a reduction of emissions it is crucial that the amount of CO_2 leaking from storage sites to shallow aquifers or the surface remains very low (<0.1% per year, over 10.000 years) [3].

Therefore the long-term behaviour of CO_2 in the subsurface, including possible CO_2 migration pathways and CO_2-brine-rock interactions, needs to be critically assessed for each storage site. This is ideally done with several methods: (1) geometric, structural and geochemical appraisal of the storage site; (2) planned monitoring strategies; (3) laboratory experiments on both reservoir and cap rocks; (4) geochemical and coupled modelling of CO_2 behaviour and (5) the study of natural CO_2 fields as analogues for storage sites [4]. Laboratory experiments help to understand how CO_2 may modify the reservoir and cap rocks during the first months to years after injection but fail to give insights into the long-term behaviour (100's to 1000's of years). Modelling approaches often use parameters obtained from laboratory experiments and/or simplify the complex subsurface. Additionally, the up-scaling of pore-scale processes to reservoir size needs significant computing power and new softwares. Natural CO_2 reservoirs have the advantage that CO_2 has

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interacted with the reservoir and cap rocks for a long period of time (up to 10s of millions of years). Leaking reservoirs offer the opportunity to study the mechanisms that lead to the migration of CO_2. However, natural reservoirs are complex systems and detailed information on the subsurface is often rare. Here we present the results of a global study of natural CO_2 reservoirs with a focus on identifying possible leakage mechanisms.

2. Natural CO_2 reservoirs

Natural CO_2 reservoirs are widespread in sedimentary basins world-wide and have geological elements similar to hydrocarbon reservoirs. The CO_2 can originate from a number of sources such as mantle degassing, carbonate rock metamorphism or the degradation of organic matter [5]. The reservoirs are sometimes encountered during hydrocarbon exploration activities and regularly abandoned as they are not as profitable as hydrocarbon accumulations. However, because of the demand of CO_2 for enhanced oil recovery, several reservoirs are commercially exploited (e.g. on the Colorado Plateau, US).

Many natural CO_2 fields have been studied, often with focus on the origin of the CO_2 in order to avoid hydrocarbon exploration in areas where such reservoirs could occur [e.g. 6] and naturally do not focus on trapping mechanisms and possible leakage pathways. Other authors have focused on the impact the long-term residence of CO_2 has had on the mineralogy and geochemistry of reservoirs [e.g. 7, 8]. Detailed geological information including production data is only available for few reservoirs [e.g. 9]. Reviews and comparisons of natural CO_2 reservoirs exist on a regional scale, usually as analogue studies for carbon storage sites [10, 11]. Roberts [12] has completed a comparison of leaking and non-leaking reservoirs in Italy, but to date no global comparison of leaking and non-leaking reservoirs exists.

3. Creating a global dataset

We compiled a global dataset of 49 well described natural CO_2 reservoirs (Fig. 1; Appendix A). Well logs were analysed for additional information such as pressure gradients and temperature gradients. The quality of reports differs and only literature that had a certain scientific standard (peer-reviewed or well documented methodology and sources) was included. If in doubt about the reliability of a source, only reservoirs with several independent sources were incorporated.

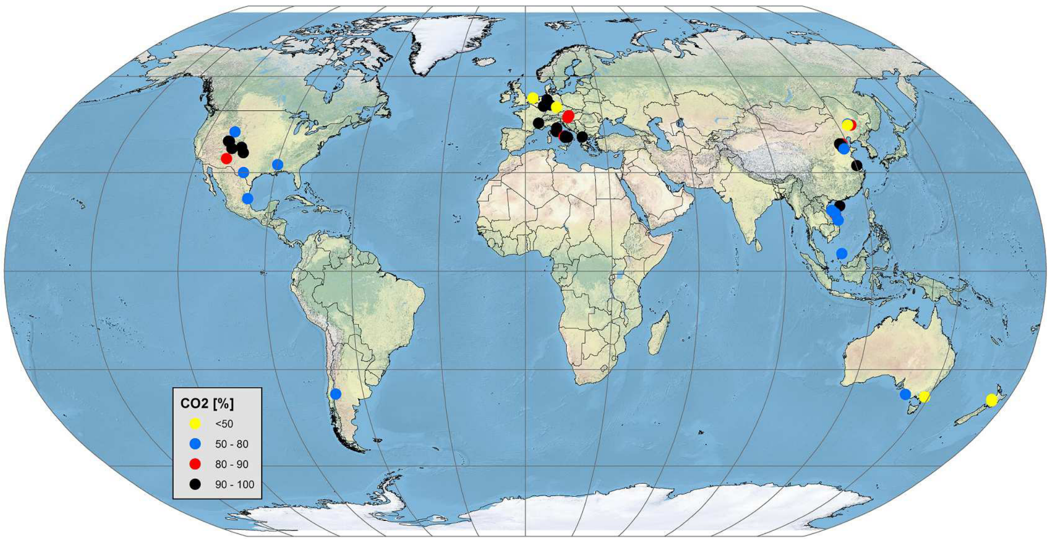

Fig. 1. Locations and CO_2 content of natural CO_2 reservoirs included in this study.

The goal was to identify possible leakage mechanisms, consequently it was crucial to correctly differentiate between leaking and non-leaking reservoirs. The following criteria were used to identify leaking reservoirs:

- CO_2 showing at the surface spatially close to the reservoir. This includes CO_2 rich springs and diffusive degassing and indicates a present day leakage.

- Formation of carbonate rocks (travertines) at the surface spatially close to the reservoir. Even if there is no current precipitation, carbonates may indicate historical leakage.
- Gas chimneys identified on seismic data.
- Occurrence of CO_2 in an aquifer above the reservoir in lower concentration than in the actual reservoir.

While the first two points can be readily analysed by studying the relevant literature and maps, the latter two points can be harder identify. In addition, there is also a small chance that CO_2 is leaking from a reservoir into a shallower aquifer without being detected.

The dataset includes depth, temperature, pressure and CO_2 content for all reservoirs. For reservoirs for which in situ pressure and temperature data was not available missing pressure data has been calculated assuming a hydrostatic pressure gradient of 9.8 kPa/m. Missing temperature data was calculated using measured regional temperature gradients [13]. CO_2 state and density for each reservoir was calculated using the equation of state from Huang et al. [14]. Possible leakage pathways like faults were identified on structural cross-sections where available. Vertical pressure profiles for several analogues were created by using well- and mudlog data.

4. Results

4.1. Pressure controls on leakage

Natural CO_2 reservoirs follow in general “normal” depth-pressure trends, i.e. reservoir pressure is between hydrostatic and lithostatic pressure. Shallow reservoirs (<1200 m) are often underpressured with regards to hydrostatic pressure while deep reservoirs (>2000 m) tend to be overpressured. Leaking reservoirs are either shallow or near or above a fracture gradient for reservoir sandstone (Fig. 2).

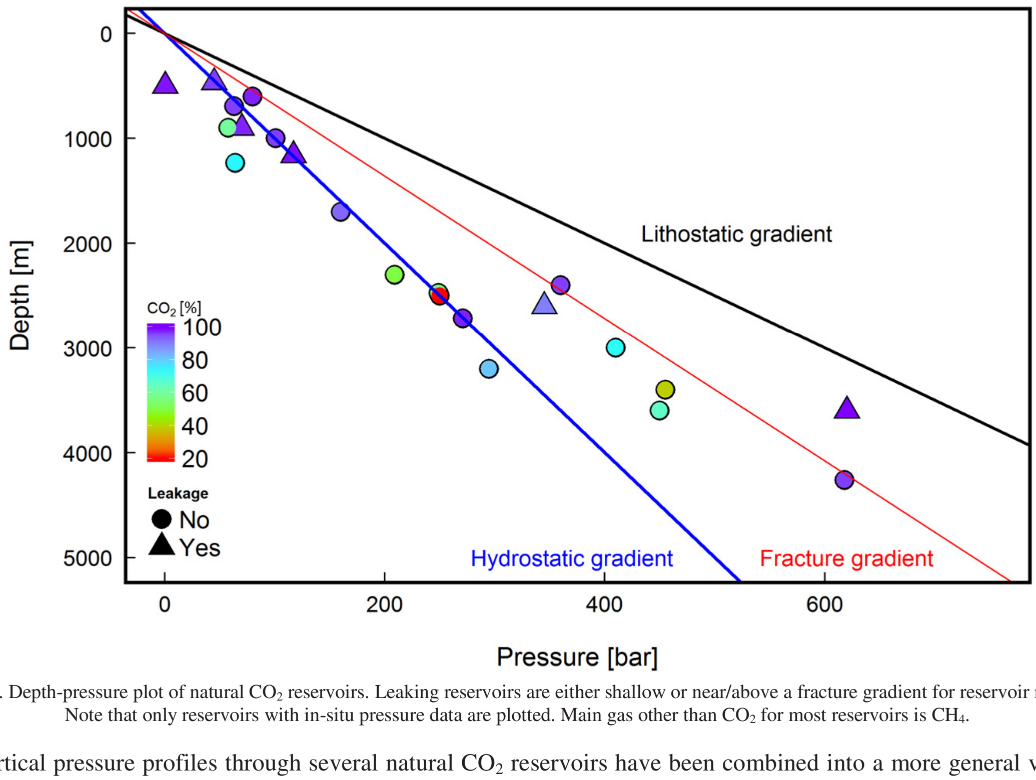

Fig. 2. Depth-pressure plot of natural CO_2 reservoirs. Leaking reservoirs are either shallow or near/above a fracture gradient for reservoir rocks. Note that only reservoirs with in-situ pressure data are plotted. Main gas other than CO_2 for most reservoirs is CH_4.

Vertical pressure profiles through several natural CO_2 reservoirs have been combined into a more general vertical profile (Fig. 3). Reservoirs that are underpressured with regards to the overburden are less likely to leak than reservoirs that are overpressured with regards to the overburden.

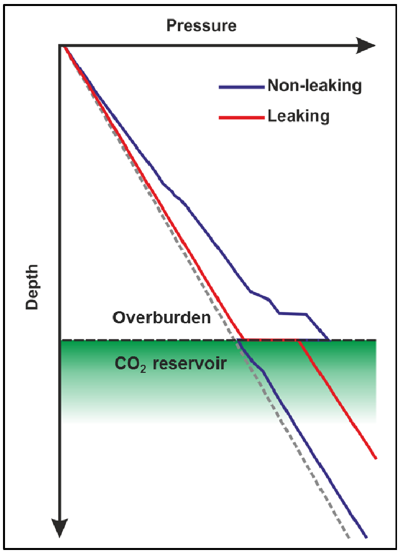

Fig. 3. Correlation between leakage from natural CO_2 reservoirs and vertical pressure profiles through the reservoirs and overburden (after [12]). Blue line represents a non-leaking natural analogue for which the pressure in the reservoir is lower than the pressure in the overburden. For leaking reservoirs the pressure in the overburden is lower than the pressure in the reservoir (red line). Thus leakage is less likely if the overburden is overpressured with regard to the reservoir.

4.2. CO_2 state

The CO_2 state for all reservoirs has been calculated based on pressure and temperature data (fig. 4). Results show that reservoirs with gaseous CO_2 have a high likelihood of leakage (6 out of 9, 66%). Reservoirs with supercritical CO_2 have only a moderate to low chance of leaking (4 out of 40, 10%).

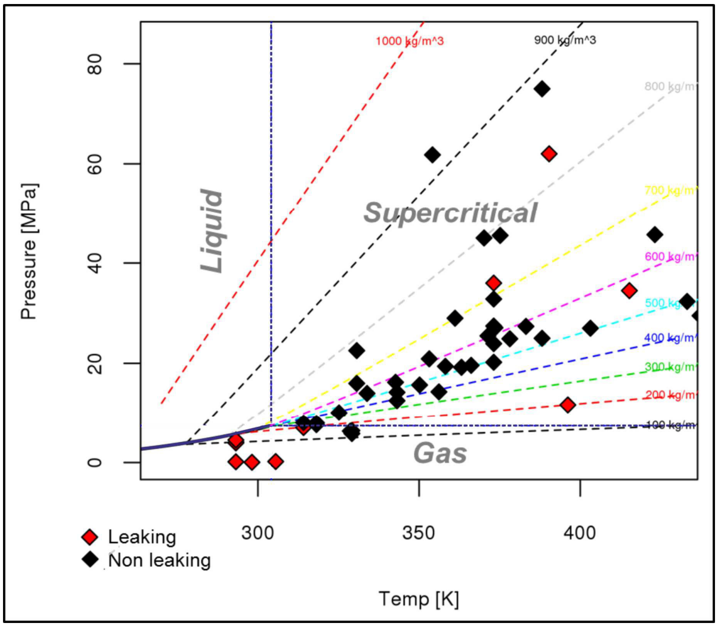

Fig. 4. CO_2 state diagram showing the temperatures and pressures in the natural CO_2 reservoirs. Blue lines (solid and dotted) indicate phase boundaries. Dashed lines are lines of equal density.

5. Discussion

5.1. Pressure controls on leakage

Vertical pressure profiles through the overburden and the reservoir are available for several fields. Comparison of those profiles from leaking and non-leaking reservoirs showed that reservoirs which are underpressured in regards to the overburden are less likely to leak CO_2 than reservoirs which are overpressured in regards to the overburden.

Overpressured reservoirs near or above fracture gradients have an increased probability of leakage as fractures in the reservoir rocks can propagate into the overburden and create fluid pathways through the sealing rock [15]. Additionally, elevated pore pressures due to the presence of natural gases such as CO_2 can lead to the reactivation of existing faults [16]. The depth dependency of leakage reflects the change of CO_2 state with rising pressures and temperatures (see section 4.2).

A positive pressure gradient from the reservoir to the overburden hampers the flow of fluids into the overburden and thus vertical leakage of CO_2. This is illustrated by the fact that leakage seems less likely if the overburden is overpressured with regards to the reservoir. Other authors have suggested that this could be used to artificially overpressure the overburden to prevent CO_2 leakage [17].

5.2. CO_2 state controls on leakage

Gaseous CO_2 reservoirs are in shallow depths (generally <1000 m, depending on the local temperature and pressure gradients) while dense state CO_2 occurs in reservoirs with a depth greater than 1000 m. The fact that reservoirs with gaseous CO_2 are more likely to leak than reservoirs with dense state CO_2 can be partially attributed to the higher buoyancy of gaseous CO_2 compared to the buoyancy of supercritical CO_2 and thus higher stress on the overburden. Furthermore, recent laboratory experiments indicate that the flow of dense CO_2 through fractures in mudrock seals is impeded compared to the flow of gaseous CO_2 [18].

6. Conclusions

The analysis of a global dataset of 49 natural CO_2 reservoirs of which 10 are known to leak has helped to identify mechanisms that promote leakage of CO_2 from reservoirs: (1) shallow depth, (2) CO_2 in gas phase and (3) hydrostatic overburden pressure. Based on the results of this study sites for engineered containment of CO_2 are best where CO_2 is in the dense state, overburden is geopressured and the reservoir pressure is less than 50% of lithostatic pressure.

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Appendix A. List of fields and literature used in this study

No.	Name of field	Leakage	Source
1	Jackson Dome	No	[10], [19]
2	St. Johns Dome	Yes	[8], [20], [21]
3	Moxa Arch	No	[9], [22], [23]
4	Sheep Mountain	No	[23], [24], [25], [26]

5	Farnham Dome	Yes	[23], [27], [28]
6	Gordon Creek	No	[23], [29]
7	McElmo Dome	No	[23], [30]
8	Bravo Dome	No	[23], [31], [32], [33]
9	JM- Brown Bassett Field	No	[34], [35]
10	El Trapial Field	No	[36]
11	Quebrache Field	No	[37], [38]
12	Montmiral	Yes	[11], [39]
13	Messokampos	Yes	[39]
14	Fizzy Field	No	[7], [41], [42]
15	Vorderrhön	Yes	[42]
16	Cheb Basin	Yes	[43]
17	Latera Caldera	Yes	[44]
18	Benevento Field	No	[12]
19	Monte Taburno Reservoir	Yes	[12]
20	Muscillo Reservoir	No	[12]
21	Acerno Reservoir	No	[12]
22	Pieve Santo Stefano	Yes	[12]
23	Frigento Field	Yes	[12]
24	Wiehengebirgsvorland	No	[45]
25	Budafa Field	No	[46],
26	Mihalyi-Repcelak	No	[42]
27	Zaizhuangzi Field	No	[6], [47]
28	You' aicun Field	No	[47], [48]
29	Dazhongwang WG1	No	[6], [47], [48]
30	Gaoquing Field	NA	[47], [49], [50]
31	Ping Fang Wang Field	No	[47], [48], [50]
32	Yang 25 Field	No	[47], [48], [50]
33	Balipo Field	No	[47], [48]
34	Pingnan	No	[47], [48], [50]
35	Hua 17 Field	No	[47], [48], [50]
36	Huangquiao Field	No	[49]
37	Huanchang 3-4 Field	No	[51]
38	Wanjinta Field	No	[47], [49]
39	Qian'an	No	[47]
40	Nong'ancun Field	No	[47], [49]
41	Changling Field	No	[52]
42	DF1-1 Field	No	[53]
43	LD28-1 Field	No	[53]
44	LD15-1 Field	No	[53]
45	Natuna D-Alpha Block	No	[54]
46	Ladbroke Grove Field	No	[55], [56]
47	Tuna Field	No	[57]
48	Kapuni Field	No	[58], [59]

49	New Plymouth Area	Yes	[58], [60]