Caprock integrity and public perception studies of carbon storage in depleted hydrocarbon reservoirs

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Abstract

Capture and subsurface storage of CO_2 is widely viewed as being a necessary component of any strategy to minimise and control the continued increase in average global temperatures. Existing oil and gas reservoirs can be re-used for carbon storage, providing a substantial fraction of the vast amounts of subsurface storage space that will be required for the implementation of carbon storage at an industrial scale. Carbon capture and storage (CCS) in depleted reservoirs aims to ensure subsurface containment, both to satisfy safety considerations, and to provide confidence that the containment will continue over the necessary timescales. Other technical issues that need to be addressed include the risk of unintended subsurface events, such as induced seismicity. Minimisation of these risks is key to building confidence in CCS technology, both in relation to financing/liability, and the development and maintenance of public acceptance. These factors may be of particular importance with regard to CCS projects involving depleted hydrocarbon reservoirs, where the mechanical effects of production activities must also be considered. Given the importance of caprock behaviour in this context, several previously published geomechanical caprock studies of depleted hydrocarbon reservoirs are identified and reviewed, comprising experimental and numerical studies of fourteen CCS pilot sites in depleted hydrocarbon reservoirs, in seven countries (Algeria, Australia, Finland, France, Germany, Netherlands, Norway, UK). Particular emphasis is placed on the amount and types of data collected, the mathematical methods and codes used to conduct geomechanical analysis, and the relationship between geomechanical aspects and public perception. Sound geomechanical assessment, acting to help minimise operational and financial/liability risks, and the careful recognition of the impact of public perception are two key factors that can contribute to the development of a successful CCS project in a depleted hydrocarbon reservoir.

Keywords: carbon capture, fluid injection, geomechanics, depleted reservoirs, caprock integrity, leakage

1. Introduction

Despite attempts in Europe, the United States, and elsewhere to phase out the use of carbon-based energy sources, a 2% global rise in CO_2 emissions was projected for 2018 (Le Quéré et al., 2018), as most countries still vent the vast majority of industrial CO_2 waste that they produce into the atmosphere (Figueres et al., 2018). Because of the long residence time of carbon dioxide in the atmosphere, carbon capture and storage (CCS) is viewed by many experts as "a necessity, not an option, for reaching net-zero greenhouse gas emissions" (Stark and Thompson, 2019). CCS pertains not only to hydrocarbon energy consumption, but also to industries such as cement and iron/steel production, which generate 8% (Lena et al., 2019) and 6-7% (SETIS, 2019) of global anthropogenic emissions, respectively. CCS is also important in the context of increasing sources of emission such as geothermal power production (Armannsson, 2017),

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and the mining of metals and minerals (Vidal et al., 2013). This latter category includes the mining and recycling of "green minerals" and rare earth elements, such as neodynium, copper, cobalt, and lithium, to meet the accelerated increasing demand of materials for renewable technologies (Vandepaer et al., 2017). In addition, the implementation of hydrogen as a low-carbon fuel for heat in buildings and industrial processes relies on decarbonisation instrumented by CCS (Joffe et al., 2018).

The challenge of limiting or lowering the amount of CO_2 in the atmosphere has prompted new strategies that involve emission reduction, including capturing carbon at the industrial source emitters, as well as CO_2 utilisation (CCU), CO_2 utilisation and storage (CCUS), and greenhouse gas removal (GGR). These strategies are complementary, and aim to offset both local and remote emissions of CO_2. While CCU is a promising technology, and is favourably perceived (Markewitz et al., 2012; Arning et al., 2019), it targets considerably smaller volumes of greenhouse gases than would be required in order to meet emission targets. CCUS includes subsurface technologies that use CO_2 in injection operations, and thereby trap some of the carbon used into the treated formations (Tapia et al., 2018). GGR provides a portfolio of removal strategies, including land-based strategies such as soil carbon storage, subsurface mineral carbonation, and direct air capture and carbon storage (DACCS), which rely on geological storage to accommodate large volumes of gas to be removed from the atmosphere (Rockström et al., 2017). As energy usage continues to increase, emission of CO_2 into the atmosphere is unlikely to decline unless a combination of approaches are employed. An example is geothermal energy, which is expected to save around 1000 million tons/year of CO_2 emissions. Geothermal power plants, which emit both CO_2 and hydrogen sulfide (H_2S) of magmatic origin, will probably need to rely on CCS in future scenarios as the geothermal sector increases in volume and expands into producing systems with relatively high CO_2 concentrations (Fridriksson et al., 2011; Bonafin et al., 2019), in some cases with greenhouse gas emission rates even higher than those of coal-fired power plants (Kaya and Zarrouk, 2017).

Captured CO_2 can potentially be stored in the deep ocean, injected into reactive rock formations, or injected into depleted reservoirs and saline aquifers (Bickle, 2009); under the right economical conditions, CO_2 can also be stored in depleted shale gas reservoirs that have been drained of hydrocarbons (Myshakin et al., 2018). To make a significant impact, the large volumes of CO_2 to be captured and stored require a long term, cost-effective, industrial-scale storage solution, which points to the possibility of storing carbon in the very same porous rocks that contained it in the first place. Once injected underground, the mobility of CO_2 is reduced by a combination of physical and chemical processes, including trapping by (1) structural and stratigraphic, (2) physical hydrodynamic, (3) and geochemical processes including dissolution and mineral precipitation, leading over time to immobilisation (IPCC Special Report on Carbon Dioxide Capture and Storage, 2005). The importance of these mechanisms varies over time. For the first 100 years the dominant trapping mechanism is structural/stratigraphic - that means on the short term, geomechanics is key to ensuring containment and remains important even on the order of 1000's of years. Geomechanical studies of CO_2 injection and storage seek to de-risk CCS and DACCS, and support GGR, by quantifying leakage and induced seismicity risk (Rutqvist, 2012). The latter two points are common concerns when it comes to public perception and acceptance of geological storage of CO_2 (Oltra et al., 2010; Seigo et al., 2014a; Xenias and Whitmarsh, 2018). Therefore, fundamental geomechanics research is a necessary first step to help address such concerns.

Carbon capture pilot studies in depleted sites are instrumental in this pursuit, as they aim to identify storage effectiveness and operational constraints, which are considered among the most important feasibility concerns for industrial operators (Vercelli et al., 2017). In addition, depleted pilot sites for storage can validate numerical models that predict subsurface conditions during and after injection, as often caprock and reservoir flow properties have already been characterised to some extent. An important relationship therefore emerges between depleted pilot sites, public perceptions, and geomechanical studies, as they enable and interfere with one another's ability to bring CCS technology to fruition. Just as geoscience is important to ensure the technological feasibility of CO_2 storage, public perception is also important to ensure acceptance of a project in the local implementation area, affecting both short and long term viability of a storage site. On one hand, perceived risks are likely to be reduced by pilot sites and appropriate technical assessment, including geomechanical risk assessments. On the other hand, factors impacting the potential for a site to be successful are complex and go beyond perception of risk either from the public, regulators or financiers. Although fundamental geomechanics research does not directly address risk perceptions, it does provide the necessary evidence base for social scientists and science communicators to help address concerns and public acceptance.

This paper explores complex geomechanical factors in fourteen depleted hydrocarbon CO_2 storage sites, and the broader context of public perceptions of and concerns about CCS, by considering both scientific and societal aspects of geomechanical effects of storage in depleted sites. In the remainder of this section, the wider context is first considered in relation to: (i) depleted reservoirs of relevance, (ii) caprock integrity, CO_2 migration and leakage, and (iii) public perception studies. This is followed by consideration of the three geomechanical aspects of interest. Firstly, the characterisation and understanding of Earth materials involved in carbon storage and its success. Secondly, the numerical simulation of scenarios of interest and their impact on our understanding of the process of storage. Thirdly, the public perception of geomechanical aspects of storage, both in the broader context and specific to several of these pilot studies. The three geomechanical perspectives have a strong impact on the ability to de-risk storage, and are intertwined in the way that they impact society, influencing experts, operators, regulators, and the general public. Given that geological storage can generate fear in some members of the public (e.g. Sharp et al., 2009), geoscientists, social scientists and science communicators have often worked to address the underlying causes of such fears, with various approaches dating back at least three decades (see (e.g. Slovic et al., 1991), on geological storage of nuclear waste). As with nuclear storage research where the public is not intimately familiar with nuclear technology, detailed knowledge of CO2 technologies, or geologies, is not necessary to affect public perceptions. Fundamental as well as applied research is then needed, to address perceptions and misconceptions. However, the amount and granularity of available geological information and methods varies with each storage project, and this is an important shortcoming that this paper aims to address.

1.1. Carbon storage in depleted reservoirs

Depleted hydrocarbon reservoirs have a number of advantages for carbon storage. In addition to local trapping mechanisms, storage is supported by a system of impermeable caprocks that once sealed hydrocarbons into place over million-year time scales. Depleted reservoirs provide the volume necessary for storage, have already been geologically characterised, and are, to some extent, equipped with the infrastructure and industrial setup required for fluid injection. Field data are usually available, as the reservoir has been previously studied and monitored (Orlic, 2016). In addition, depleted reservoirs are “brown sites” that have the advantage of having proved to already have stored liquids and gases over long periods of geological time without appreciable leakage.

The study of CO_2 storage has developed from a concept technology, to a tested field technique with multiple successful pilot test sites worldwide. Table 1 summarises the characteristics of fourteen depleted reservoir pilot sites developed throughout the world. Prior to 2013, only four large-scale CCS projects had demonstrated the technology, storing approximately 50 $MtCO_2$ (CCS Technology Roadmap 2013 edition, IEA). Since then, nine further projects, which together have the potential to capture and store 13 $MtCO_2$ per year, should have been operational by 2016. Many of the larger proposed projects have been placed on hold, while others have been cancelled. In many CO_2 storage pilot studies, geomechanical-related concerns including induced seismicity, leakage into the groundwater or marine environment, and long-term well integrity, have been cited as major influences on value-cost considerations, safety, and public concerns (Wallquist et al., 2010; Tapia et al., 2018; Gough et al., 2018; Lee et al., 2018). Specifically the fear of leaks, tied to the hydrogeomechanical behaviour of the site, appears to be a common factor of concern across several countries (Ashworth et al., 2013; Whitmarsh et al., 2019). This is despite experience from European projects that has shown that there are “no significant concerns regarding technology, and technology implementation is not considered a major reason for [CO_2 storage] project progress delays” (Kapetaki et al., 2017). This does, however, highlight the importance of risk (both technical and financial) on barriers to deployment such as liability and social acceptance (Poumadère et al., 2011).

1.2. Caprock integrity, CO_2 migration, and leakage

A primary aspect of all geological storage options is the requirement of at least one suitable sealing layer above the injection interval (Pires et al., 2011). Long-term integrity of this seal and associated overburden seals is of paramount importance to demonstrating short-term containment, and of secondary importance on long timescales, though still necessary. The interaction between CO_2 and sealing lithologies can be complex. For example, mud-rich interbeds can act as a series of baffles to the upward migration of CO_2 (Chadwick et al., 2009). Increased certainty around such behaviour is beneficial for constraining expected storage site evolution. In the case of depleted reservoirs, the intended seal is usually the caprock that previously trapped hydrocarbons prior to anthropogenic extraction. In these, the sealing capacity of the caprock has been previously demonstrated, though this does not account for changes to properties and structure resulting from hydrocarbon production activities, or the differing properties of CO_2.

Site Name	Host Country	Operator	CO_2 Source	CO_2 Fate	Capture	Volume	Status
Snøhvit	Norway	Equinor	LNG Proc.	Depl. Gas	Post	0.7 Mt/yr	2007-
Heletz	Israel	EWRE	Various	Depl. Oil	Pre	<0.5 Mt/yr	2016-
K12-B	Netherlands	GDF Suez	Gas Proc.	Depl. Gas	- - -	0.2 Mt/yr	2004-2006
Schwarze Pumpe	Germany	Vattenfall	Coal	Depl. Gas	Oxy	13.45 kt/yr	2008-2014
Lacq	France	Total/Alstom	Oil/Gas	Depl. Gas	Oxy	12.75 kt/yr	2010-2013
In Salah	Algeria	BP	Gas Proc.	Depl. Gas	- - -	1.2 Mt/yr	2004-2011
Otway	Australia	CO2CRC	Gas	Depl. Gas	Natural	0.065 Mt/yr	2008-2011
ROAD	Netherlands	E.ON	Coal	Depl. Oil/Gas	Post	1.1 Mt/yr	On Hold
Magnum	Netherlands	Nuon/Vattenfall	Various	Depl. Oil/Gas	Pre	8.64 Mt/yr$^{\gamma}$	On Hold
Peterhead	UK	Shell and SSE	Gas	Depl. Gas	Post	1 Mt/yr	Canc. 2015
Teesside LC	UK	Progressive	Coal	Depl. Oil/Gas	Pre	2.5 Mt/yr	2013-Hold
Hunterston	UK	Ayrshire Power	Coal	Depl. Gas	Post	11.5 Mt/yr$^{\beta}$	Canc. 2010
Barendrecht	Netherlands	Shell	Oil Refinery	Depl. Gas	Post	0.4 Mt/yr	Canc. 2010
FINNCAP	Finland	Fortnum	Coal	Depl. Gas	Post	1.25 Mt/yr	Canc. 2012

Table 1: Sites storing CO_2 in depleted oil or gas reservoirs, worldwide. The fate of the CO_2 refers to the type of reservoir identified for storage; "Depl. Oil" and "Depl. Gas" are depleted oil and gas fields respectively. The capture data indicates the method of retrieval of the CO_2 from the fuel source. Post combustion capture removes CO_2 from the flue gases using chemical scrubbers such as amines; these would be retrofitted to existing infrastructure. Pre combustion capture removes the CO_2 from the fuel via chemical reaction before the combustion has taken place. Pre combustion capture takes place in stages; initially a syngas is created by partially oxidising the fuel in a gasifier. The syngas is reacted with steam to produce H_2 and CO_2; the CO_2 can be captured, whilst the H_2 can then be used as a fuel. Oxy-fuel combustion requires the fuel to be burned in oxygen rather than air and the resulting flue gas is almost entirely CO_2 and water vapour. Sources of this table include: Carbon Capture and Sequestration Technologies at MIT (2016), Bouzalakos and Mercedes (2010), Gal et al. (2019). $^{\beta}$Calculated using 1600MW electricity generation capacity × 90% capture × 8000 tonnes CO_2 per year per MW electricity generation capacity, following the method of Rai et al. (2008). $^{\gamma}$ Calculated following the method of Rai et al. (2008) using 1200MW electricity generation capacity.

A leak can be defined as a migration event that entails the movement of fluids all the way to the surface. Migration through a fault into the overburden, has the potential to result in at least some CO_2 fully progressing to the surface and being released into sea water or the atmosphere. Whilst terrestrial leakage is a possibility for some proposed CCS schemes, for those involving the use of a depleted reservoir, the primary consideration is the impact to leakage into the marine environment. This relates to any potential interaction with the biosphere, including the shallow subsurface and surface ecosystems (Turley et al., 2006). Should migrating CO_2 reach the surface, any subsequent leakage is likely to be localised, potentially emerging from discrete point-sources, such as abandoned wells (Boothroyd et al., 2016) or specific faults (Shipton et al., 2004). In a recent study of natural gas reservoirs in Italy (Roberts et al., 2017), only two of nine reservoirs, taken as analogues of CO_2 storage sites, were found to leak at the surface. The study found that the leaking reservoirs were located <10 km away from modern extensional faults, and the sealing reservoirs were all found to have elevated overburden pressures (Roberts et al., 2017). This study also measured the leakage rates primarily through faults and fractures.

Public support is crucial for onshore (Kapetaki et al., 2017) and offshore projects alike. Leaks from an offshore storage site might affect local ecosystems, and the economy of local fisheries, by altering pH with accompanying physiological effects (Turley et al., 2006). Relevant timescales are substantially longer than those required for many other environmental assessments and involve, not just the injection period, but also post-closure over hundreds of years (Krüger et al., 2011; Rastelli et al., 2016). Nevertheless, recent work has suggested that concerns such as acidification, changes in biological diversity and species composition (Rodríguez-Romero et al., 2016), may only become relevant at unlikely high CO_2 concentrations, and may result in only short-term impacts on local fauna (Amaro et al., 2018).

Geomechanical studies can aid the assessment of caprock integrity and can facillitate in the monitoring or mitagation of CO_2 migration above the caprock. Geomechanical studies include the characterisation of mechanical properties of sealing rocks (discussed in Section 3), and the numerical modelling of damage and fracture growth leading to changes in permeability of the caprock, fault displacement leading to seismicity, and thermal stresses (discussed in Section 4). Geomechanical studies are primarily focussed on constraining the mechanical deformation of the caprock and other potential migration pathways, such as pre-existing faults, shrinkage fractures, and pre-existing sealed boreholes. Mechanical behaviour can then be used to constrain subsurface observations of migration and loss of integrity. Fluids migrating through a storage reservoir can potentially trigger shallow microseismic events that can be monitored from the ground surface (Mitchell and Green, 2017). Detection of the microseismic signals and mechanical deformation of the reservoir can help to build a picture of subsurface processes (Boreham et al., 2011), and the migration of injected fluids in the reservoir can be modelled (e.g. Estublier and Lackner, 2009). The geomechanical response of a reservoir can be continuously modelled prior to and during injection (Salimzadeh et al., 2018a) to understand how the injected CO_2 remains trapped in the subsurface. An important factor that influences mechanical failure of a shale rock is the relative quantity of "soft" components, such as clay and kerogen, and "stiff" components, such as quartz, feldspar, pyrite and carbonates, in the shale caprock (Sone and Zoback, 2013a,b). This has been shown for caprocks, where either fracture growth is promoted or, in some cases, crack healing is induced (Kim and Kemeny, 2009). And in the case of low permeability mudrocks, key influencing factors on the permeability of the caprock include initial stress conditions, stress path gradient and caprock strength heterogeneity (Harrington et al., 2018). Fracture growth can, under brittle conditions, also increase the permeability of the caprock, depending on the mechanical properties of the rock and the *in situ* stresses, as well as the fracture density and spacing (Lang et al., 2014, 2018). Therefore, for assessing the probability of fracture growth on the caprock seal, it is necessary to incorporate accurate fracture growth predictions into a numerical model (Salimzadeh et al., 2018a).

1.3. Public perception studies

Potential CO_2 leakage also features among public concerns (Wallquist et al., 2010; Seigo et al., 2014b; Gough et al., 2018). A review of the CCS perception literature found that, consistent with other new technologies, benefit perceptions (personal and societal) were the strongest predictor of CCS acceptance (Seigo et al., 2014b; Wallquist et al., 2012; Howell et al., 2014; Krause et al., 2013; Schumann et al., 2014; Warren et al., 2014; Braun et al., 2018). While CCS offers environmental and economic benefits, it can be controversial across cultures in terms of both risk perception and benefit perception, influenced to some extent by cultural dimensions, such as uncertainty avoidance and society's long- vs. short-term orientation (Karimi and Toikka, 2018). It has met high-profile public opposition to particular CCS developments (Oltra et al., 2012), and strong regulatory frameworks currently control its development. The latter could also be regarded as an indirect expression of public concern about carbon storage. An example of regulatory mechanisms controlling CCS is the European Directive on the geological storage of CO_2 (2009/31/EC), which calls for the operator to demonstrate that CO_2 will be "completely and permanently contained". The directive also outlines three criteria that must be met to demonstrate this: "(i) the conformity of the actual behaviour of the injected CO_2 with the modelled behaviour, (ii) the absence of any detectable leakage, and (iii) that the storage site is evolving towards a situation of long-term stability". Such risk-averse regulation at the highest level might reflect political will to alleviate public concern to a new technology (Burgess and Chilvers, 2006).

Demonstration of effective storage is tied to the ability to monitor the environment, and predict the flow and mechanical behaviour of the reservoir during and after injection. From a geomechanical point of view, effective CCS is largely dependent on the caprock's mechanical stability (Karimnezhad et al., 2014), and on the ability to correctly model and predict subsurface deformation and CO_2 migration using numerical and analytical models, both at short and long time scales. Pilot sites in depleted reservoirs play an important role in providing insights into the technology, as well as valuable data to validate predictive models, used for subsurface planning and industrial de-risking of the technology. These pilot sites also expose regulatory and societal expectations of the technology (Kapetaki et al., 2017), serving to shape the type of test and quantifications that are developed to understand requirements for its successful deployment.

Success of a CCS project is also linked to public perception of its capability to become a potential instrument to decrease carbon emissions at an industrial scale (IPCC and Climate Change, 2014; IEA, 2013). Alongside economic and regulatory criteria, public acceptance of CCS is an important precondition for its implementation (RCUK, 2010; Wennersten et al., 2015; van Alphen et al., 2007). Public concerns about CCS do not usually discriminate between types of geological CO_2 storage, yet it is important to understand and address successfully the concerns at an early stage at each specific site. It is crucial to provide evidence to the public that CCS can be an effective instrument that can form part of a wider strategy for achieving significant cuts in CO_2 emissions. Further public acceptance may be gained by viewing CCS as a transition technology while renewable energy technology and increased energy efficiency measures are being developed as well as serving as a solution for industries, such as steel and cement, that are difficult to power from clean sources (Shackley et al., 2004; van Alphen et al., 2007; Duetschke et al., 2016; Upham and Roberts, 2011a).

Recognising climate change as a problem, and trust in the ability of industry to develop CCS projects, as well as demographic factors -age, gender, education, and political values- are crucial factors driving acceptance (Poumadère et al., 2011; de Best-Waldhober et al., 2011; Terwel et al., 2011, 2012; Carley et al., 2012; Ashworth et al., 2014, 2015; Gough et al., 2014; Lofstedt, 2015). Seigo et al. (2014b) conclude that trust plays a particularly important role for benefit perception in the case of CCS, and benefit perception is the best predictor of acceptance of CCS. Academics, followed by government and then industry, are most trusted in the UK (Roberts and Mander, 2011), and environmental NGOs are also more trusted than industry (Terwel et al., 2011). Trust can be engendered better through face-to-face contact with experts and developers; this can be done better through citizens panels than via printed/online materials (Poumadère et al., 2011; Chrysostomidis et al., 2013), as well as through substantively involving communities in decision-making (Terwel et al., 2011), as the engagement process can profoundly influence community perceptions of CCS (Oltra et al., 2012; Duetschke, 2011; Buhr and Wibeck, 2014; Brunsting et al., 2015). In addition to benefits perception, trust is also critical to how information on CCS is perceived; in turn, this is related to the perceived competence and integrity of the source (Vercelli et al., 2013).

Another factor linked to the perception of storage site integrity is long-term liability, which is of particular concern to operators and investors. Liability in this context is related to both the perception of and expected magnitude of risk associated with long-term containment. Specifically, liability includes any damages that can be related back to the leakage, the cost to stop and mitigate any leaks, and any associated international or local sanctions that may have been, or will be, legislated at present or at a future time (Zapantis et al., 2019). This directly influences pilot sites and the development of CO_2 as a technology, as it strongly influences finance and insurance structures required for the success of these projects (Gomersall et al., 2018; Zapantis et al., 2019). Governments can incentivise CO_2 storage by minimising operator/investor concerns around liability. A range of mechanisms have been adopted or are under consideration, including capping financial risk, or liability transfer to government in the long-term, recognising that the risk of leakage decreases after injection, and continues to decrease with time (Gomersall et al., 2018; Zapantis et al., 2019). Nevertheless, confidence in storage integrity is key to minimising the real and perceived risks associated with any remaining liability. According to the review conducted by Seigo et al. (2014b) the most important risks people perceive regarding CCS are that it may displace investment in renewable energy, and that CCS may lead to leakage or overpressurisation of the CO_2 storage formation. The latter is directly related to the "geomechanical perspective" of storage, and can be addressed by careful assessment of geomechanical integrity at proposed sites. This includes site-specific rock characterisation as well as numerical and analytical studies examining the potential for CO_2 migration, combined with careful monitoring during injection to confirm conformity to expected behaviour and a move towards system equilibration and stability. Lessons and understanding derived from pilot sites are invaluable for informing such work.

2. Pilot sites of CO_2 storage in depleted reservoirs

The majority of CCS pilot projects worldwide are for enhanced oil recovery (EOR) and enhanced gas recovery (EGR), or have utilised saline aquifers as the destination for the injected CO_2 (Herzog, 2016). However, there have been at least fourteen pilot studies to inject CO_2 into a depleted hydrocarbon reservoir (Table 1). Four hosted by the Netherlands (Barendrecht, K12-B, ROAD and Magnum), three by the UK (Hunterston, Peterhead, and Teesside Low Carbon), and the remaining projects hosted by Finland (FINNCAP), Germany (Schwarze Pumpe), France (Lacq), Norway (Snøhvit), Israel (Heletz), Algeria (In Salah) and Australia (Otway). Most of these projects are not currently operating, and are no longer receiving CO_2, except for Snøhvit and Heletz, either because their operational lifespan has completed (K12-B, Schwarze Pumpe, Lacq, In Salah, and Otway), or they are on hold (Teesside Low Carbon, ROAD, Magnum and Peterhead), or they have been definitively cancelled (Barendrecht, FINNCAP and Hunterston). Table 1, which summarises the presented depleted reservoir pilot sites, highlights that while many of the pilot sites were cancelled or placed on hold, others successfully completed operational periods, and two are still ongoing.

2.1. Active Projects

Snøhvit. In this Norwegian project, the natural gas produced from three offshore hydrocarbon reservoirs (Snøhvit, Askeladden and Albatross) is stripped of the CO_2 at an LNG plant, which is subsequently re-injected into a saline aquifer at the edge of the Snøhvit gas reservoir at a depth of 2.7 km, part of the same formation (Estublier and Lackner, 2009). The 45-75 m thick Tubaen formation predominantly comprises two sandstone units on either side of a shale-rich interval (Gao, 2013); coals are also present. The permeability and porosity of the Tubaen formation are 10-16% and 1.28-8.68 $\times 10^{-13}$ m^2, respectively (Maldal and Tappel, 2003). The site can store up to 0.7 Mt per year, and as of June 2017, more than 4 million tonnes of CO_2 have been stored at Snøhvit since the start of the injection in 2008. Geomechanical studies include understanding fault reactivation (Chiaramonte et al., 2011), geomechanically-driven changes to permeability during injection (Hansen et al., 2013), and the study of *in situ* 3D fracture network properties and their influence on fault permeability (Wennberg et al., 2008).

Heletz. The Heletz pilot CO_2 injection site has been developed in the framework of several EU projects (MUSTANG, PANACEA, TRUST). This site is part of the Heletz oil field, discovered in 1955, and is located in the Southern Mediterranean Coastal Plain of Israel (Niemi et al., 2016). This is a scientifically motivated site with the objective of gaining understanding of the various CO_2 transport and trapping processes and their quantification and monitoring, rather than a site intended for actual CO_2 storage. The geomorphological characteristics of Heletz, namely, that it has saline edges where no oil was discovered, along with the relatively thin caprock and fault locations, make it ideal for testing injection scenarios. The reservoir is located at a depth of around 1.6 km, and comprises a limestone and three lower-Cretaceous high permeability sand layers, with a total thickness of 10 m. It is sealed by a low permeability shale and marl caprock layer of 40 m thickness, and is intersected by two pre-existing sub-vertical normal faults (Niemi et al., 2016). The injection experiments carried out have focussed on quantifying capillary/residual trapping. The project met no public opposition, and was supported by the regulating authorities, including the Israel Water Authority, Ministry of Science, Ministry for the Protection of the Environment, and Ministry of Energy.

2.2. Completed Projects

K12-B. This North Sea project, which operated between 2004 and 2006, was designed to remove CO_2 from a CO_2-rich natural gas at the extraction location, and return it to the same reservoir from which it came, simultaneously studying CO_2 storage and migration pathways in the reservoir (der Meer et al., 2005). The storage reservoir is the Rotliegend sandstone, located 3.8 km below the North Sea. The project was motivated by a need to remove the CO_2 from natural gas before transporting it back to the Netherlands, because CO_2 concentrations were above the acceptable limit for the pipeline. Re-injecting at the same site removed the need for transportation of the removed CO_2. The project comprised three stages: an initial feasibility study (Phase 1), a pilot study (2004-2005) with two periods of CO_2 injection into the reservoir to trace the migration pathways and investigate the potential for EGR (Phase 2), and an upscaling to industrial-scale CO_2 storage (Phase 3). Phase 3 of the project, which focused on upscaling, has yet to take place.

Schwarze Pumpe. This project was supported by Vattenfall and Gaz de France, and was designed to test both oxyfuel combustion and post-combustion capture processes, with the captured CO_2 being stored in a depleted gas field. The Altmark depleted gas field was originally identified as the storage location for the liquefied CO_2 produced at Schwarze Pumpe (Strömberg et al., 2009). However, a combination of the shortcomings of federal CO_2 storage legislation and public protesting contributed to the cancellation of storage at Altmark (Zero Emission Resource Organisation, 2016). This led to the identification of pilot site Ketzin for the CO_2 storage. CO_2 injection at Ketzin was operated by GeoForschung Zentrum Potsdam between June 2008 and August 2013, with more than 67 kt CO_2 stored (Ouellet et al., 2011). In 2014, Vattenfall announced a decrease in their research and development budget, with all research into CCS to be discontinued. The Vattenfall CCS project was abandoned partly due to "popular opposition based on environmental fears" as it was tied to the continued production of increasingly cheap coal, citing lack of political will as one of the main obstacles for CCS development in Germany (Reuters, 2011).

Lacq. This pilot project was the first CCS chain in Europe, covering all steps from capture to storage, operated between 2011 and 2013, and was designed as a research experiment. The project combined oxyfuel combustion of gas to obtain a flue gas stream of only steam and CO_2. This CO_2 was then transported 27 km to the Rousse depleted gas field, and sequestered at 4.5 km depth (Pourtoy et al., 2013). A finite amount of CO_2 was injected (51 kilotonnes); this CO_2 was then monitored for a period of five years to ascertain that the gas would be successfully trapped in the subsurface. A number of geomechanical studies were supported by this project, including seal integrity (Pourtoy et al., 2013), microseismic monitoring (Lescanne et al., 2011), as well as wellbore effects and long term CO_2 migration

(Thibeau et al., 2013). The project had a favourable economic and social context (Ha-Duong et al., 2011), and was successful, validating oxy-combustion for carbon capture, and demonstrating that CO_2 could be stored in an onshore depleted gas reservoir. Soil analysis at Lacq measuring CO_2 concentration levels during and after injection at the site yield no indication of leakage up to date (Gal et al., 2019).

In Salah. This Algerian project involved stripping CO_2 from natural gas being produced from seven proven gas reservoirs in the 20 m thick Krechba carboniferous sandstone reservoir, located 1.9 km under the southern part of the Sahara desert; CO_2 was then re-injected into the water-leg of the reservoir at a rate of up to 50 mmscf/day (Verdon et al., 2015). The reservoir has an anticline structure, with a porosity and average permeability of 13-20% (Verdon et al., 2015) and 10 mD (Mathieson et al., 2011), respectively. The storage reservoir is sealed by a sequence of carboniferous mudstones nearly 1 km thick (Wright, 2007). Injection at In Salah stopped because of the identification of increased levels of risk relating to the vertical leakage of CO_2 into the caprock (Ringrose et al., 2013). Quantified risk assessments were regularly conducted based on new seismic and satellite data, as well as geomechanical modelling (Ringrose et al., 2013). In 2010, seismic data from 2009 allowed the identification of linear features which, alongside analysis of InSAR data, suggested the possibility that the caprock was being inadvertently hydrofractured (Ringrose et al., 2013). This led to the reduction of the CO_2 injection pressure, and injection was suspended in 2011.

Otway. The Otway Project initiated in 2008, after four years of searching for a suitable geological site (Jenkins et al., 2012a). It became Australia's first geological CO_2 storage project (Steeper, 2013), with the aim of undertaking CO_2 storage research at the same time as executing a CO_2 storage trial (Tenthorey et al., 2014). In Stage 1 of the project (2008-2009), 65,000 tonnes of CO_2 were injected into the structural trap of the depleted gas field (the Waare-C Formation reservoir) (Paterson et al., 2013) at a depth of approximately 2 km, demonstrating successful storage of CO_2 and *in situ* monitoring (Hortle et al., 2011). The porosity and average permeability of the Waare C formation are 10-28% (Dance, 2013) and 2700 mD (Mehin and Constantine, 1999), respectively. The formation caprock is the 25–30 m thick Belfast Mudstone, which has a porosity of 15% and permeability of less than 1 mD (Dance, 2013). The second stage of the Otway project (2011 onwards) involved the injection of CO_2 at 1.3 km depth into the tilted saline Paaratte formation (Tenthorey et al., 2014). This lithologically heterogeneous formation has no apparent structural trap (Paterson et al., 2013). The trapping mechanism relates to the carbonate cement layers within the reservoir that block the pore space and decrease the permeability. The goal of Stage 2 of the Otway Project was to improve the understanding of migration and trapping mechanisms in saline formations (Watson et al., 2012).

2.3. On-Hold Projects

The following four projects have all been placed on hold at different stages in their planning, before CO_2 capture and storage could begin. On-hold projects include two sites in the Netherlands, and two in the United Kingdom.

ROAD. The Rotterdam Capture and Storage Demonstration project, Rotterdam Opslag en Afvang Demonstratieproject (ROAD), was designed to operate retrofitted post-combustion capture of CO_2 from a new coal fired power plant. It aimed to use an existing onshore to offshore pipeline, and store the sequestered CO_2 in a depleted North Sea gas reservoir (Read et al., 2014). In 2009, 180 million euros was granted by the EU, within the Government Economic Energy Programme for Recovery, supplemented in 2010 by 150 million euros from the Government of the Netherlands (Kapetaki et al., 2017). The project has contended with a number of obstacles including permitting, commercial negotiations, and funding. Capture and storage permits are now in place and are definitive and irrevocable (Kapetaki et al., 2017). A further five million euros were committed by the Global Carbon Capture and Storage Institute (GCCSI). ROAD was planned to start in 2015, but has since been placed on hold due to lack of funding (Arts et al., 2012). A recent public perception study of ROAD and other pilot sites found that technical, legal, financial, and social barriers are largely interdependent, and that financial barriers are much more important than the others (Sara et al., 2015). Financial barriers depend, in turn, on geomechanical studies, as these feed into the quantification of leakage risk and long-term damage liability of the sites.

Magnum. The Nuon Magnum capture and storage project was designed to use a multi-fuel pre-combustion technology (coal, gas and biomass) with CO_2 storage in offshore North Sea oil and gas fields. The Magnum project built on the successful Buggenum IGCC pilot plant test (with Shell), and Shell's Coal Gasification Process was to be implemented for the pre-combustion capture (van Dijk et al., 2014). Nuon also appointed Mitsubishi Heavy Industries to deliver the gas-fired part of the power plant. In 2011, the project was put on hold, and the coal gasification technology was postponed to 2020 due to both rising coal prices and opposition from environmental campaigners (Damen et al., 2014). Additional problems with storage location as a result of the Dutch law banning onshore CO_2 storage have contributed to the project's uncertainty. The Magnum gas plant is now destined to be converted into a hydrogen-powered plant, extracting hydrogen from natural gas, aiming to capture and store CO_2 by 2020 (Barrett, 2017).

Peterhead (Goldeneye). The Peterhead project was a joint venture between Scottish and Southern Energy (SSE) and Shell participating in the UK government's Department of Energy and Climate Change (DECC) £1bn CCS commercialisation competition (Spence et al., 2014). The DECC competition's aim was to develop and fund a full-scale CCS pilot project before 2020; the competition was conceived in 2007 and launched five years later with £1bn available in capital funding (MacNeil et al., 2016) and Contracts for Difference (CfDs) then offered as a source of further support. The Peterhead project involved retrofitting post-combustion CO_2 capture to an existing Combined Cycle Gas Turbine (CCGT) power station. The planned offshore storage location was the Goldeneye Gas Field in the North Sea, for which existing onshore to offshore pipeline infrastructure was available. The UK's first licence for geological CO_2 storage was provided in 2012, and a lease was signed by the crown estate. In 2013, the Peterhead project was chosen as one of two preferred bidders in the CCS competition (Spence et al., 2014) alongside the White Rose Project in North Yorkshire (Capture Power). The preferred projects were given financial backing to conduct Front End Engineering Design (FEED) studies. These studies represented a significant step towards developing major infrastructure projects. In 2014, the UK secretary of state made an agreement with Shell to implement the FEED phase and ensure that the design was fully refined, cost certainty was optimised and technical risks fully reduced ahead of any final investment decisions. In 2015, shortly before the award of the £1bn CCS competition was finalised, the UK government announced that the competition would be cancelled and the funding withdrawn (MacNeil et al., 2016).

Teesside Low Carbon. The Teesside Low Carbon Project was a pre-combustion coal gasification project devised by a consortium of industry partners led by Progressive Energy competing in the UK government's DECC £1bn CCS competition. The project involved the advanced separation of coal into CO_2 and hydrogen-rich synthesis gas (syngas) before the CO_2 could be transported through the North East CCS Transport Network, part of a new National Grid Carbon pipeline. The storage location was identified as a Central North Sea depleted oil field (Lipponen et al., 2017), specifically the Captain and the Bunter Aquifers (Teesside Collective UK, 2015), which were also investigated geomechanically in the context of the Goldeneye field and the Peterhead project. In 2013, the Teesside Low Carbon Project was not selected as one of the two finalists of the UK government's DECC CCS competition, and was instead placed on a reserve list. The community of the Teesside area is largely accepting of CCS technology, which is perceived as a local opportunity for growth (Gough et al., 2018). Teesside, while currently on hold, is an excellent potential pilot site for a CO_2 Central North Sea storage hub (Brownsort et al., 2016).

2.4. *Cancelled Projects*

Three of the projects using depleted reservoirs have been cancelled altogether. Two of these, Barendrecht and Hunterston, experienced strong opposing sentiment from local populations, whereas the other experienced financial issues that ultimately prevented it from progressing.

Hunterston. Ayrshire Power's Hunterston project was planned to include a carbon capture facility at a new coal-fired Hunterston power station, and to store CO_2 in depleted gas reservoirs in the East Irish Sea (Coulthurst et al., 2011). The Hunterston project was a contender for the UK's CCS commercialisation competition, with backers from both Denmark (the power company Dong Energy - now Ørsted) and the UK (the property firm Peel Holdings). Hunterston faced some local opposition based on factors involving siting and efficiency, and the fact that the project would 'enable' and 'lock-in' coal production in the local area (Mabon et al., 2014). This did not translate into a rejection of CCS as a carbon-storage technology, instead it was interpreted as a rejection of this specific project. As a consequence of the timing of the economic slowdown, in June 2012 Ayrshire Power withdrew the planning application, citing funding uncertainties as the cause of the decision.

Barendrecht. The Barendrecht project was devised for CO_2 injection into depleted gas reservoirs beneath Barendrecht near the port of Rotterdam (Brunsting et al., 2011; Terwel et al., 2012). The initial injection phase was due to begin in 2013, with three years of CO_2 injection at 1700 m depth, followed by twenty-five years of injection at a greater depth of 2700 m (Herzog, 2016). The aim was to store CO_2 from the Pernis Oil Refinery in close proximity to the storage site (Feenstra et al., 2010; Kuijper, 2011). The intended storage location was located beneath a densely populated area, and it was recognised early on that public perception would be important to the success of the project (Kuijper, 2011). Barendrecht would have been the first onshore CO_2 storage project in the Netherlands (van Eijs et al., 2011). However, poor communication of the proposed plans to the local population, combined with a resentment towards government pushing industrial projects onto rural areas, caused strong public opposition which ultimately derailed the project.

FINNCAP. The FINNCAP-Meri Pori CCS Project was a proposal by the Finnish power generation companies Fortum and Teollisuuden Voima (TVO) to jointly develop a carbon capture and storage solution for the Meri-Pori power plant by 2015 (Iso-Tryykäri et al., 2011). The project, which had planned to capture and store more than 1.2 million tonnes of CO_2 per year in the Danish North Sea, had hoped to be one of the European Commission's twelve large-scale CCS demonstration projects up and running by 2015. Fortum had been testing CO_2 capture at its Värtan CHP power plant in Stockholm, Sweden since 2007. The joint venture planned to retrofit post-combustion technology supplied by Siemens Energy, to treat 50% of the plant's flue gases at full capacity, with a target capture rate exceeding 90%. Unfortunately, in October 2010 Fortum announced that the project had been abandoned due to company strategy and the outcome of 'various studies'. TVO had already withdrawn from the project earlier that year.

3. Characterisation of rocks at depleted sites

Analytical and numerical methods quantify the likelihood of CO_2 migration from storage sites by evaluating the mechanical and transport behaviour of caprocks. These studies rely on awareness of physical properties at depth (Li and Laloui, 2017), as well as the environmental conditions *in situ*. To perform numerical studies of the thermo-hydro-mechanical behaviour of the caprock during injection, fluid and mechanical properties of both reservoir and caprock must be characterised. While reservoir flow data tend to be highly characterised at pilot sites in depleted reservoirs (Rutqvist et al., 2010; Saeedi et al., 2011; Shell, 2011; Saeedi and Rezaee, 2012; Norden and Frykman, 2013), rock mechanical properties at the same sites (e.g. Marbler et al., 2013; Klapperer et al., 2013a) are less readily available. In particular, transport and mechanical properties of caprock materials are even less commonly reported. Tables 2 and 3 report most reservoir and caprock properties available in the literature for the studied pilot sites, and highlight this disparity. In addition to the lack of geomechanical measurements of caprock properties, some of these reported values are not directly measured from core samples, and in some cases the source of the data is unclear. In addition, some of the measurements (applicable to both mechanics and fluid data) may have not been made under true reservoir conditions, and may not capture natural *in situ* variability of properties. This highlights the need to improve the characterisation of caprocks, but also to conduct numerical simulations that explore the effect of caprock mechanical properties, and their spatial variation, on predictions of leackage and induced seismicity. Field data is not only instrumental in informing and calibrating models, it also drives process understanding and numerical modelling as a unifying approach to redress uncertainty and thus help to build public confidence.

Experimental techniques measuring reservoir and caprock properties in the laboratory allow the prediction of *in situ* behaviour. A range of methodologies allow the assessment of (i) mechanical behaviour/properties, including uniaxial/triaxial compressive strength, volumetric strain evolution, elastic moduli and Poisson's ratio; and (ii) transport behaviour/properties as a function of effective stress, including void ratio/porosity and intrinsic hydraulic permeability. These properties can vary widely. For example, hydraulic permeability can range between 10×10^{-12} m^2 and 10×10^{-23} m^2 for porous sandstones and tight caprocks, respectively (Neuzil, 1994; Wang, 2000; Tanikawa and Shimamoto, 2009; Armitage et al., 2016; Harrington et al., 2018). These values in clays, shales, and unconsolidated sands are also highly sensitive to the stress state (Nguyen et al., 2014; Ewy, 2019). Laboratory-scale testing provides a useful tool for examining the hydromechanical response of storage site materials to the stress changes that result from depletion, and the subsequent reinflation that occurs during storage. Testing at laboratory scale cannot capture the full field scale and *in situ* variability of properties. Therefore, careful projection of laboratory values to the reservoir scale is required as part of the characterisation process.

Project name	Storage site	Age	rock type	Formation name	thickness (m)	capacity (Mt)	depth (m)	ϕ(%)	K (m^2)	E (GPa)	ν	UCS (MPa)	
Snøhvit	Snøhvit Field	Mid Jurassic	Fluvial Sandstone	Tubaen Fm.	45-75	31-40	2700	7-20, 14-17	$0.1\text{-}8\times10^{-13}$	9.6	0.3	-	-
Heletz	Heletz	Lower Cretaceous	sandstone regressive – transgressive deposition	Heletz sand	21	$\approx 10-20$	1200-1400	18-22	$1\text{-}7\times10^{-13}$	4.8-5	0.2	-	-
K12-B	Leman Gas Field	Late Carboniferous-Permian	Aeolian Sandstone	Rotliegend Sandstone	<275	-	2000	12-23	3.5×10^{-10}	15-20	0.25	34.1	-
Schwarze Pumpe	Ketzin	Upper Triassic	Sandstone	Stuttgart Fm.	40-70	-	630-650	5-35	$0.002\text{-}5\times10^{-12}$	-	-	8.1-177	-
Lacq	Rousse Gas Field	Jurassic	Carbonate	Mano Dolomite Fm.	-	0.12	4500	2-4	$<1\times10^{-15}$	1-2	0.15-0.33	-	-
In Salah	Krechba Gas Field	Carboniferous	Sandstone	Tournasian Sandstone	20	17	1850-1900		1.3×10^{-14}	6	0.2	-	-
Otway	Naylor Field	Late Cretaceous (91-89.5Ma)	Coarse-grained, beach-barrier sandstone	Waarre Fm. Unit C	25-40	-	1980-2180	23	$1\text{-}4.93\times10^{-12}$	12	0.22-0.33	21,210	
ROAD	P18-4 depleted reservoir	Triassic	Lower Germanic Triassic Grp., Main Buntsandstein Subgrp.	Hardegsen, Upper Detfurth, Lower Detfurth, and Volpriehausen	30-100	35	3500	5,9-12,23-28	3.5×10^{-13},(100-200, 0.2-1)$\times10^{-7}$	20-25	0.2	-	36.1
Peterhead	Goldeneye Field	Cretaceous	Sandstone	Captain Sandstone	<100, >200	10-15	2600	28-35	1×10^{-11}-6×10^{-13}	6.2-10	0.05-0.1	-	-
Barendrecht	Barendrecht (Ziedewij)	Triassic	Bunter Sandstone	Rot Fm., Solling Fm., Main Buntsandstein Subgrp.	-	9.5	1700 (2700)	21-27	1×10^{-6}-1×10^{-9}	6.4	-	11-48	4-60
Hunterston	East Irish Sea Hamilton Oil/Gas	Triassic	Aeolian/ fluvial sandstones	Sherwood Sandstone Grp. Ormskirk Sandstone	<450	-	690-1200	12-20	1×10^{-8}-5×10^{-13}	-	0.3	-	-

Table 2: Reservoir properties. The geological features of carbon dioxide sequestration sites worldwide storing CO_2 in depleted oil or gas reservoirs. The UCS column is divided into unsaturated and saturated measurements. ROAD: Orlic (2016); Marbler et al. (2013); Peters et al. (2013), Snohvit: Shi et al. (2013); Hansen et al. (2013); Estublier and Lackner (2009); Chiaramonte et al. (2011), Otway:Aruffo et al. (2014); Dance et al. (2009); Berard et al. (2008); Vidal-Gilbert et al. (2010), K12-B:Marbler et al. (2013); Orlic et al. (2011b). Heletz: Edlmann et al. (2016); Elhami et al. (2016); Niemi et al. (2016).

Project name	Storage site	Age	Caprock type	thickness (m)	ϕ(%)	K (m^2)	E (GPa)	ν	UCS (MPa)
Snøhvit	Snøhvit Field	Mid Jurassic	Nordmela Fm.	60-105, 62-200	13	1-23$\times10^{-15}$	-	-	-
Heletz	Heletz-Kokhav	Lower Cretaceous	Rewaha shale	23-54	6-10	1$\times10^{-18}$	0.8-3	0.4	-
K12-B	Leman Gas Field	Late Carboniferous-Permian	Upper Permian Zechstein anhydrite, halite evaporites	550	-	-	-	-	-
Schwarze Pumpe	Ketzin	Upper Triassic	Claystone	165	-	-	-	-	-
Lacq	Rousse Gas Field	Jurassic	Flysch Sequence (clay and marl)	>2000	-	-	-	-	-
In Salah	Krechba Gas Field	Carboniferous	Carboniferous Visean mudstone	900-950	1	1$\times10^{-14}$	-	-	-
Otway	Naylor Field	Late Cretaceous (91-89.5Ma)	Belfast Mudstone (89-82Ma)	280	<15	<1$\times10^{-15}$	8-16	0.3	9970-14830
ROAD	P18-4 depleted reservoir	Triassic	Solingen, Rot, Muschelkalk and Keuper Fm., Upper Germanic Trias Grp.	200	-	-	26	0.3	-
Peterhead	Goldeneye Field	Cretaceous	Carrack Fm.	40-100	6	1$\times10^{-20}$	20	0.15	-
Barendrecht	Barendrecht	Triassic	Claystone	90	-	-	-	-	-
Hunterston	East Irish Sea Hamilton	Triassic	Sandy mudstones and halite, Mercia Mudstone Grp. Leyland Fm.	<594	20-40	-	-	-	-

Table 3: Caprock properties. The geological features of carbon dioxide sequestration sites worldwide storing CO_2 in depleted oil or gas reservoirs. Sources for this table include: Barendrecht: Feenstra et al. (2010); Bisschop (2011); Breunese and Remmelts (2009); Yaliz and Taylor (2003); Dyke and Dobereiner (1991); Bell (2016); Marbler et al. (2013), Barendrecht (Ziedewij): Koenen et al. (2013, 2014), Hunterston: Yaliz and Taylor (2003); Yaliz (1997); Olden et al. (2012), Peterhead: Johnson et al. (2005); McDermott et al. (2016); Johnson et al. (2005); Wilkinson (2006); Hangx et al. (2013); McDermott et al. (2016), K12-B: Sullivan et al. (1990); Glennie et al. (1978), Otway: Boreham et al. (2011); Siggins (2006); Buffin (1989); Dance (2013); Aruffo et al. (2014); Berard et al. (2008), Lacq: Prinet et al. (2013); Miersemann et al. (2010); Gapillou et al. (2009), Snohvit: Estublier and Lackner (2009), ROAD: Kopp et al. (2013); Arts et al. (2012); Orlic (2016), In Salah: Rutqvist et al. (2010), Schwarze Pumpe: Norden and Frykman (2013); Norden et al. (2008); Klapperer et al. (2013b), Heletz: (Edlmann et al., 2016).

Laboratory techniques. Several laboratory techniques are available for assessing transport properties of caprock materials, including steady-state, transient pulse-decay, and pore oscillation permeametry techniques. Recent efforts have compared these approaches and considered standardisation in detailed reviews (Busch and Mueller, 2011; Gensterblum et al., 2015; Sander et al., 2017). Concern relates to the trade-off between test accuracy and duration. Understanding the impact of the experimental approach is also of importance when parameterising numerical simulations. Clay-rich materials differ from reservoir rocks in that there is a significant coupling between chemical and mechanical state, and between hydraulic and mechanical state (Ewy, 2015; Lyu et al., 2018). Reduced salinity induces swelling that impacts porosity, permeability, and strength. Therefore, testing using a solution comparable to *in situ* pore fluid composition is desirable. Similarly, initial hydration of test samples must be conducted at *in situ* effective stress conditions to avoid sample swelling and consolidation (Ewy, 2015). Good sample preservation state is also key, as argillaceous materials are damaged by drying, resulting in erroneous data (Desbois et al., 2014). Several recent reviews have also considered a range of analytical methodologies for assessing pore-scale properties, which are often used to estimate transport behaviour (Bertier et al., 2016; Busch et al., 2017). As with flow testing, the influence of pore fluid and effective stress must be considered when transferring this data, as well as the potential for sample damage resulting from desiccation during analysis (Ewy, 2015). Caprock permeability data is not necessarily openly available for depleted storage sites, in part as a result of the scarcity of well-preserved core taken from offshore fields. However, there are studies examining hydraulic and gaseous flow behaviour for caprocks at Lacq (Tonnet et al., 2011) and Sleipner (Harrington et al., 2009), as well as for caprock that relates to prospective depleted sites in the East Irish Basin and Southern North Sea (Armitage et al., 2016; Harrington et al., 2018).

Shale caprocks. Direct assessment of geomechanical properties of shales is also often hampered by the shortage of well-preserved core and values are often estimated, without any calibration to laboratory data, using empirically-derived correlations. However, recent evidence involving the collation of widely ranging laboratory mechanical datasets on shales has demonstrated a number of limitations to this approach in relation to the use of seismic velocity, porosity, and clay content data (Dewhurst et al., 2015). Where laboratory testing is performed, the choice of loading arrangement is key. In uniaxial deformation ($\sigma_1 >> \sigma_2 = \sigma_3 = 0$), a cylindrical test sample is loaded axially under unconfined conditions, until failure. This is a simple and common mechanical test, allowing a rough comparison of strength between rocks. However, material behaviour may differ significantly in the presence of lithostatic pressure, particularly at higher effective stresses. This is considered in 'conventional' triaxial testing ($\sigma_1 > \sigma_2 = \sigma_3$), where samples are loaded under a constant radial (or confining) stress, whilst axial load is increased. In both cases, samples are instrumented to quantify the evolution of deformation with time. More recently, a number of laboratories have developed 'true' triaxial cells ($\sigma_1 > \sigma_2 > \sigma_3$), which allow deformation of cubic samples to be investigated in response to loading by three independently controlled stresses (Mortazavi and Atapour, 2018). For example, a recent study by Mortazavi and Atapour (2018) examined the evolution of minimum and maximum horizontal stresses in response to depletion and observed a sensitivity to the initial vertical stress applied.

Deformation of reservoir rocks. Deformation testing across a range of effective pressures allows the construction of yield and failure envelopes (e.g., Mohr-Coulomb, Mogi-Coulomb, Critical State) for a given rock, which can be used to predict material response under a chosen stress path. For example, the size and shape of the critical state yield envelope has been experimentally delineated for a wide range of sandstones (Cuss et al., 2003; Sheldon et al., 2006; Nguyen et al., 2014; Louis et al., 2017; Dobbs et al., 2018). In particular, sandstones compacted under deviatoric load (shear strain) have been found to have peak stress values approximately three times higher than samples with similar porosity compacted hydrostatically (volumetric strain) (Bedford et al., 2019). Fitting of models to this data allows the prediction of reservoir response for a given stress path scenario (Sheldon et al., 2006; Schutjens et al., 2004). This approach has been used in recent years to assess reservoir behaviour in response to depletion (Hol et al., 2018; Rathnaweera et al., 2018) and/or reinflation at several proposed CCS sites situated in depleted reservoirs (Orlic et al., 2011b; Hangx et al., 2013; Dobbs et al., 2018). Hangx et al. (2013) also investigated the effects of mineralogical reaction with CO_2 upon the mechanical strength, for the Captain sandstone, in the context of reutilising the Goldeneye field. They demonstrated that the stress changes expected as a result of both depletion and reinflation were not sufficient to approach failure conditions for the reservoir. A similar approach was taken by Dobbs et al. (2018), who assessed the triaxial deformation behaviour of unreacted samples of Sherwood Sandstone, within the context of CCS storage in depleted UK Triassic reservoirs. Their findings also indicated that reservoir rock would not reach yield during drawdown or CO_2, and also not during CO_2 injection.

Deformation of caprocks. In contrast, similar studies are scarce for caprock materials, and data delineating the form of the yield surface are substantially lacking (Graham et al., 2019). For the Peterhead project, mechanical testing of caprock samples was not conducted due to core degradation (Shell, 2011). Instead, the friction angle was estimated based on a correlation with surface area measurements taken on shale cuttings (Shell, 2011). Similarly, cohesion values were estimated using a proprietary correlation with sonic log data. Mutschler et al. (2009) performed triaxial loading on claystone samples recovered from the injection well at the Ketzin pilot test. They focussed primarily on the impact of sample scale on viscosity index, which was found to be negligible at the sizes tested and also observed the transition from brittle to ductile deformation at higher effective pressures. Hangx et al. (2010a) conducted comprehensive deformation testing of dry and saturated anhydrite samples and delineated both failure and dilation envelopes for the material. They found no evidence that the presence of CO_2 and pore fluid affected mechanical properties, on short timescales. Using the mechanical data derived, the authors considered depletion and injection scenarios for a hypothetical caprock, and found that integrity was not likely to be influenced by mechanical damage. Recent work has been conducted to examine the critical state envelope in several caprocks (Graham et al., 2019), considering both plastic and indurated samples with different compositions and diagenetic histories. Harrington et al. (2018) used mechanical data obtained from Mercia Mudstone Group samples to consider the impact of depletion- and reinflation-related stress changes and demonstrated the potential for yield in some, but not most, scenarios. Such an approach allows assessment of the type of yield behaviour, and they found that this was usually more likely to be compactive, and, hence, less likely to affect seal performance. Nevertheless, the impact of this deformation on faults and wellbores in the vicinity requires investigation by modelling on a larger scale (see Section 4).

Drained vs. undrained testing. As with transport testing, use of appropriate pore fluid composition and initial effective stress on hydration are key to ensure that no alteration occurs before geomechanical testing (Ewy, 2015; Lyu et al., 2018). A number of uncertainties must also be considered when parameterising numerical simulations with geomechanical test data for caprocks. In particular, the drainage condition used is particularly significant in low permeability materials (Islam and Skalle, 2013). In drained testing the pore pressure within the sample is maintained constant, whilst in undrained testing the pore fluid is isolated and pore pressures will tend to change during loading. The former approach is commonly used during testing of high permeability materials, but is experimentally more challenging in low permeability materials. The drainage condition can significantly impact the measured strength of the material and test findings should only be utilised under comparable conditions in numerical simulations.

Yield. An additional complication is uncertainty in determining the onset of yield. This is particularly important for shales, where inelastic deformation may begin substantially in advance of peak stress, resulting in only a brief elastic phase. A number of criteria may be used to assess the initiation of damage (Cuss et al., 2003; Nicksiar and Martin, 2012), including: (i) the deviation of the stress-strain curve from a linear trend, (ii) change in ultrasonic velocity, (iii) change in pore fluid volume, or (iv) onset of acoustic emissions (post-crack-closure). Nevertheless, these latter two methods are limited in their usefulness for shales, as (i) the necessity for quick testing means undrained conditions are often chosen (meaning pore fluid volume cannot be monitored) and (ii) the acoustic and mechanical properties of shale are such as to limit the effectiveness of acoustic emission detection. Recent work on samples including the Whitby Shale has indicated that analysis of ultrasonic attenuation may provide a useful indicator of the transition from elasticity to inelasticity (Barnhoorn et al., 2018). Understanding the criteria for the assessment of yield is important when utilising experimental data for numerical simulation. It is also important to discriminate between 'yield' envelopes, versus those constructed from peak stress data, since permeability may be enhanced before total caprock failure occurs. Nevertheless, with the exception of testing in anhydrite (Hangx et al., 2010b, 2011), there is minimal evidence that can quantify permeability enhancement in advance of failure, as a function of stress state in caprock materials.

Sample variability. Variability in rock samples impacts uncertainty in experimentally-determined mechanical properties. Sample variability can be the result of natural variability within the rock, and may also be the result of sample selection bias favouring the testing of more competent materials or bias caused by core recovery, likely to be higher in more competent sections of the borehole. Well-preserved caprock material is scarce and laboratory assessment of the impacts of lithological variability (e.g., from diagenesis) is rarely quantified, despite its influence on yield strength (Harrington et al., 2018). Handling of the (often substantial) anisotropy of caprocks is also vital (Ambrose and Zimmerman, 2015; Cheng et al., 2017), though it was historically less commonly quantified. Renewed interest in shale materials has resulted in a number of recent experimental studies examining the mechanical impact of this variation (Gao et al., 2015; Islam and Skalle, 2013; Rybacki et al., 2015; Bonnelye et al., 2017; Douma et al., 2019a,b).

Geomechanical characterisation aids in the selection of caprocks with properties that are favourable towards geomechanical stability and sealing during depletion and reinflation. It also provides the necessary parameterisation for reservoir modelling of sites with a significant stress history and small-scale validation of numerical approaches. Nevertheless, there are still limited quantitative data demonstrating the relationship between yield strength in shales and the influence of key controls (e.g., clay content, porosity, degree of cementation), as a function of stress state.

4. Caprock integrity modelling studies of the depleted pilot sites

Numerical models of CO_2 injection, and its impact on reservoir and caprock properties, can be divided into three categories that balance computational cost with modelling accuracy: flow-only, iteratively-coupled, and fully-coupled models. Flow-based simulators include single-phase and multiphase flow with or without heat transfer, and solve the governing equations without taking into account mechanical coupling (Doughty and Pruess, 2004; Gasda et al., 2013). In iteratively coupled models, an independent geomechanical solver is linked to a flow simulator and the thermal, hydraulic, and mechanical problems are solved sequentially, feeding information into each other in a one-way or two-way manner (Rutqvist et al., 2010; Pan et al., 2014). In fully-coupled models, the set of coupled equations governing the flow in and deformation of reservoirs are formulated in a monolithic manner, and the problem is solved accounting for the physical processes simultaneously (Salimzadeh et al., 2018b). Computational and developmental time may be saved by using uncoupled or weakly coupled schemes at the cost of loss of accuracy; however, modelling monolithically coupled processes accurately is instrumental to modelling caprock failure, in particular if poroelastic or viscoelastic effects are considered. Table 4 summarises coupled computer codes that model thermo-hydro-mechanical processes with or without fractures and other discontinuities. These computer codes model a varied combination of deformation modes and mechanical models, including compressive *in situ* stress modelling, coupled elastic, elastoplastic and fracture mechanics, as well as coupled thermal and poroelastic effects. Reservoir modelling studies that focus on the discussed CO_2 storage pilot sites (see Table 5), using various computer codes that implement geomechanics analysis (see Table 4), are discussed below. The listed studies are specific to depleted storage reservoirs, and simulations are specific to caprock integrity analysis in these scenarios. Approaches are validated independently against analytical and field data, highlighting the lack of a consistent set of validation benchmarks for coupled geomechanical simulations. In contrast to fluid-flow and fluid-flow in fractured media studies (Flemisch et al., 2018; Berre et al., 2019), benchmarks are lacking for fracture and fault propagation during thermo-hydro-mechanical deformation of subsurface reservoirs.

Overpressure and Fracture growth. Existing studies focus on fluid flow and caprock integrity by comparing overpressure with a limiting fracture pressure in addition to evaluating potential leakage pathways (e.g. Geel et al., 2006; der Meer et al., 2006; Shell, 2008; Eigestad et al., 2009; Estublier and Lackner, 2009; Hortle et al., 2009; Gapillou et al., 2009; Oldenburg et al., 2011; Pham et al., 2011; Jenkins et al., 2012b; MUSTANG, 2014a,b; Buscheck et al., 2016; Marshall et al., 2017). Implicit fracturing in the context of caprock integrity was investigated for the In Salah site (Gor et al., 2013a; Gor and Prevost, 2013; Gor et al., 2013b; Preisig and Prévost, 2011; Vilarrasa et al., 2015), for the Goldeneye field (Peterhead) (Akhurst et al., 2017; McDermott et al., 2016; Davison et al., 2012), for the Lacq project (Pourtoy et al., 2013), and for a generic depleted Dutch field (Orlic et al., 2011a). Explicit fracture growth for caprock integrity analysis was investigated for the Captain reservoir (Peterhead and Teesside Low Carbon) (Salimzadeh et al., 2018a) and the Heletz site (Paluszny et al., 2017). In particular, caprock integrity of the In Salah site has been studied extensively, and variations within the site models include using different numerical methods (finite differences vs. finite elements), different stress regimes (hypothetical normal fault regime vs. actual strike-slip stress conditions), different boundary conditions (with or without the underburden), different geometry scale, different temperature contrast (45 vs. 60 degrees), different injection duration and amount (570 tons/day for three years vs. 300 tons/day for thirty years), and different locations of the wells (middle vs at the base) (Vilarrasa et al., 2015; Preisig and Prévost, 2011).

Code	Reference	Numerical Method	Coupling	Discontinuity	Dimension
TOUGH2/EGS	Xiong et al. (2013)	IFD	THM (fully coupled)/ THC (iterative)	Fractured rock with empirical correlation to fracture aperture and fractured rock properties.	2D
TOUGH2/FLAC	Rutqvist (2011)	IFD, FDM	Iterative, Jacobian (explicit) THM	Fractured rock with empirical correlation to fracture aperture.	3D
TOUGH2/RDCA	Pan et al. (2014)	IFD, FEM	Iterative THM	Pre-existing fracture/Faults	2D
COMSOL	Selvadurai et al. (2015)	FEM	Iterative THM	Fracture/Faults	2/3D
CODE_BRIGHT	Zareidarmiyan et al. (2018)	FDM (temporal), FEM (spatial)	Fully coupled THM	Fractures/Faults	3D
DYNAFLOW	Prevost (1981); Preisig and Prevost (2011)	FEM	Fully coupled THM	-	2/3D
GPRS-PyLith	Jha and Juanes (2014)	Finite volume, FE	Iterative HM	Faults	3D
T2STR (modified TOUGH2)	Gosavi et al. (2005)	FDM, FEM	Fully coupled THM	-	2D
ICGT/CSMP	Salimzadeh et al. (2018a,b)	FDM (temporal), FEM (spatial)	Fully coupled THM	Faults/Fracture growth	2/3D
DIANA	Buijze et al. (2017)	FEM	Sequentially coupled to reservoir simulators	Faults/Fractures	2/3D

Table 4: Numerical codes available in literature for THM modelling and fracture growth integration. IFD: Integral Finite Difference Method (Narasimhan and Witherspoon, 1976), FEM: Finite Element Method, FDM: Finite Difference Method, DEM: Discrete Element Method, THM: Thermo-Hydro-Mechanical, THC:Thermo-Hydro-Chemical, TOUGH2 (Pruess et.al., 1999).

Project name	Reference	2/3D	Constitutive Model	Scale (km)	Tool	Time (yr)	Fractures, Faults	Findings
Snøhvit	Chiaramonte et al. (2011)	3D	one phase fully coupled HM, MC failure criterion	9×6×2.1	Geocentric (FE) with embedded discontinuities	30	faults	Maximum horizontal stress orientation, friction coefficient of faults and poroelastic effects important for fault reactivation. Hydrofracturing may occur before major fault reactivation
Heletz	Paluszny et al. (2017)	3D	LE, disk-shaped interaction integral to compute the three stress intensity factors, THM fully coupled, Augmented Lagrangian method for fracture wall friction	0.5×0.4×0.5	ICGT, CSMP++ (FEM)	1	explicit fracture growth, SIFs, faults	Fracture propagation in the reservoir mostly downwards due to cold plume, caprock integrity not affected
Lacq	Pourtoy et al. (2013) & Total (2015)	1/3D	One way HM / LE / poroelasticity / MC failure criterion	4×4×5	1D MEM, 3D FEM	41+5	Fault reactivation, implicit fracture propagation	CO_2 injection minimal impact on caprock integrity
In Salah	Gor et al. (2013a)	2D	brine - CO_2 mixture, fully coupled THM / MC nonlinear (shear)	5×1.82	DynaFlow FE code	12	implicit fracture initiation and propagation	Initial stresses important, rock thermal expansion can lead to large changes in stresses due to pore pressure build up, resulting in tensile stress regimes in the caprock but also shear failure
In Salah	Preisig and Prévost (2011)	2D	brine-CO_2 mixture, fully-coupled two-phase THM / MC nonlinear (shear)	5×1.82	DynaFlow FE code	3	implicit fracture initiation	Increased pore fluid pressure due to poromechanical effects unlikely to affect caprock integrity, whereas with thermomechanics tensile stresses can develop in the caprock, inducing growth or leakage
In Salah	Vilarrasa et al. (2015)	2D	THM two-phase flow / MC nonlinear (shear) caprock	4×10	CODE BRIGHT	30	faults	Capillary functions negligible effect on overpressure, cooling thermal stresses reduce caprock stability
Otway	Aruffo and Henk (2014)	3D	one way HM / MC failure criterion / linear and non-linear	4×4×2.8	FEM stress / ECLIPSE flow / VISAGE	-	fault reactivation / faults	Faults not likely to reactivate
Otway	Aruffo et al. (2014)	3D	one way HM / Byerlee (1978)-type fault friction / MC failure criterion	12×12×4.5	ECLIPSE flow / VISAGE	8	fault reactivation	Numerical models yield lower critical pore fluid pressure for reactivation than analytical models
ROAD	Peters et al. (2013)	2/3D	multi-phase	r=0.7 (2D) / r=6, z=2.5(3D)	TOUGH2, ECO2M, DIANA	5	fracture growth	At the actual depth no thermal fracturing was induced
ROAD	Orlic et al. (2011b) & Orlic et al. (2011a)	2D	MC(res/cap), no cohesion for faults, μ_f=0.6	10×6	DIANA / PFC2D	50,000	fault re-activation	Top seal leass affected by poromechanical effects. No faults fail
Peterhead Goldeneye	Salimzadeh et al. (2018a)	3D	LE / THM	10×6×4	ICGT, CSMP++ (FEM)	10+160	fracture growth, SIF's, 4 faults included for re-activation	Mode I growth not observed, partial mode II fracture growth at interface of reservoir/caprock
Peterhead	Akhurst et al. (2017)	2/3D	Fully coupled THM multi-physics, LE	163×84×5	Open Geosys	35	tensile failure / rock fracturing / reactivation of faults	Interaction due to pressure, not due to temperature contrast
Peterhead	McDermott et al. (2016)	2/3D	Fully coupled THM, LE homogeneous isotropic materials	130×20×4	Open Geosys	30	tensile failure/rock fracturing/reactivation of faults	Stress bridging can increase horizontal stress and lead to enhanced stability of the caprock
Barendrecht & K12-B	Orlic et al. (2011a,b)	2D	MC (reservoir/caprock), no cohesion for faults, μ_f=0.6	10×6	DIANA, PFC2D	50,000	fault re-activation	Top seal less affected by poromechanical effects. No faults fail

Table 5: Numerical simulations of geomechanical deformation of carbon injection into depleted reservoirs. For all models, the scale is of several kilometers, and analyses the behaviour of the entire reservoir (MEM: Mechanical Earth Model, SIMED: differential equation solver - integrates using several methods / information exchanged between ABAQUS (FEM) and COORES allowing iterative or explicit coupling to update the pore volume, non-isothermal unsaturated flow and transport (NUFT)).

Orlic et al. (2011a) showed the importance of site characterisation and numerical modelling to predict the maximum allowable overpressures to ensure caprock integrity. Mechanical stability studies of the caprock for Goldeneye (Shell, 2011) and Lacq-Rousse (Pourtoy et al., 2013), showed that injection pressures do not exceed the minimum total principal stress, nor are they expected to exceed initial gas pressure before depletion. McDermott et al. (2016) found a much smaller extent of the thermal CO_2 plume compared to the injection-induced fluid overpressure in the long-term. They found that reservoir rock contraction due to cold CO_2 injection results in a stabilising arching effect of the horizontal stresses in the caprock. Akhurst et al. (2017) studied interaction effects of consecutive injections of CO_2, and found no interaction due to temperature contrast. Conversely, interaction due to overpressure was noted, despite the distance between the sites being on the order of tens of kilometres. This agrees with the findings of McDermott et al. (2016).

Gor et al. (2013a) and Gor and Prevost (2013) estimated fracture propagation analytically based on numerically computed results. They found that thermally-induced stresses can lead to tensile regimes developing in the caprock, which may lead to fracturing, while shear failure of both the reservoir and caprock rocks can also be aided by a large temperature difference. Gor and Prevost (2013), who accounted only for poromechanical effects (HM) in their simulations, analytically predicted rapid fracture propagation during injection. Conversely, Preisig and Prévost (2011) found that the injection-induced fluid overpressure alone would not be sufficient to affect the caprock mechanical stability in terms of tensile failure. When accounting for thermal effects, though, tensile stresses in the caprock were found to develop, and fracture flow could potentially extend the fracture growth outside the thermally affected zone (Preisig and Prévost, 2011). No shear failure was predicted for the caprock. Vilarrasa et al. (2015) also showed that thermal effects due to cold CO_2 injection can be significant in a zone of a few tens of metres close to the interface with the storage rock; however, due to the caprock thickness (900 m) in In Salah, this should not influence the overall sealing performance. Tensile failure was predicted when the minimum horizontal stress was based on White et al. (2014), highlighting the importance of accurate representation of the initial stress regime. Davison et al. (2012) accounted for THM effects, and found the caprock integrity not to be at risk.

Studies that model fracture growth explicitly are far fewer, as compared to implicit and analytical studies. Paluszny et al. (2017) studied the Heletz field using a finite element numerical model that combines THM full coupling with fracture growth, by computing the three modes of stress intensity factors (i.e. mode I: tensile, mode II: sliding and mode III: tearing). Results showed that fracture growth takes place in a downward direction, not largely influencing the caprock. Salimzadeh et al. (2018a), using the same numerical model, predicted minimal mode II fracture growth at the interface of the reservoir and caprock rocks when modelling Goldeneye with the implication that caprock breach is unlikely. Conversely, Peters et al. (2013), in the ROAD project, used iterative coupling between TOUGH2 and DIANA to calculate the size of the fractures to model the increased permeability, and found no thermal fracturing when the reservoir was modelled at its actual depth, agreeing with the results of Vandeweijer et al. (2011).

With regard to shear failure of the caprock, Orlic (2016) carried out geomechanical analyses for the ROAD project (the P18-2 depleted reservoir was modelled rather than the P18-4), and showed that stress changes were larger at the end of depletion than during injection, but no shear failure of the caprock was predicted at the end of depletion. He also showed that the area mostly affected during depletion and injection is more limited, compared to injection in saline aquifers.

Fracture Permeability. Tensile fracturing of the caprock does not necessarily imply a pathway to flow (Paluszny and Matthäi, 2010). Thus, predicted growth does not necessarily translate to containment loss, as only when the effective permeability is enhanced is CO_2 leakage likely to take place. Numerical models that can explicitly account for fracturing can replicate this process, using variable permeability models (based on geomechanically-computed apertures as opposed to uniform fracture apertures) as a function of fracture growth and *in situ* stresses (Lang et al., 2018). Additionally, as aforementioned, different studies employ different forms of thermo-hydro-mechanical coupling (i.e. full, one-way or iterative). Preisig and Prévost (2011) have shown that the type of coupling used is of utmost importance to the accuracy of the predictions. The time-integration scheme when transient conditions are considered (e.g. consolidation), and the size of the time step chosen, are also of fundamental importance for the accuracy of the numerical solution (Potts and Zdravković, 1999). Iding and Ringrose (2010) accounted for fractures to calculate effective permeabilities for In Salah, however, their analyses focussed only on fluid flow calculations. The dimensionality of the problem is important in accounting for geometry effects, as 3D predictions can substantially depart from 2D predictions of growth and permeability (Lang et al., 2014). Geomechanical studies of 2D and 3D fracture growth found that the predicted permeability of a geomechanical system may be lower if mechanically realistic apertures are considered (Paluszny and Matthäi, 2010; Thomas, 2019). In fact, in interacting fractures, apertures may be suppressed by the shadow zone of nearby fractures, further reducing the permeability of the system (Salimzadeh et al., 2017; Thomas et al., 2017).

Fault reactivation and induced seismicity. Fault reactivation and its impact on sealing performance has been studied for In Salah (Vilarrasa et al., 2015), Snøhvit (Chiaramonte et al., 2011), for generic depleted Dutch fields (Orlic et al., 2011b), for Otway (Aruffo and Henk, 2014; Aruffo et al., 2014; Krawczyk et al., 2015), for North Sea reservoirs relevant to Peterhead and Hunterston (Chadwick et al., 2015; Akhurst et al., 2017; McDermott et al., 2016; Shell, 2011), and for Lacq Rousse (Pourtoy et al., 2013; Total, 2015). Vilarrasa et al. (2015) and Orlic et al. (2011b) found the fault shear failure to be more critical than the tensile failure of the caprock, while Chiaramonte et al. (2011) computed the maximum injection-induced overpressure for fault shear slip for different stress regimes at Snøvit. Vilarrasa et al. (2015) suggested that during cold injection in a normal fault stress regime, stress redistribution was unlikely to induce fault shear slip, as the thermal strains have the effect of tightening the caprock and preventing leakage. Akhurst et al. (2017) and McDermott et al. (2016) also accounted for fault reactivation to compute the maximum injection overpressure. Aruffo et al. (2014) showed that the numerically computed maximum overpressure for shear slip is substantially smaller than that computed analytically, while the studies of Krawczyk et al. (2015) showed that faults are likely leakage paths. Aruffo and Henk (2014) predicted no fault reactivation for the conditions modelled, similar to the predictions of Chadwick et al. (2015) for Peterhead and Pourtoy et al. (2013) and Total (2015) for Lacq as long as the post-injection pressure remains below the initial gas pressure.

Inversion modelling and ground surface displacement. Inverse modelling to match the observed ground surface displacement magnitudes and patterns has also been conducted to understand the opening of fractured zones and faults at depth. Examples of these are (Shi et al., 2013; Rinaldi and Rutqvist, 2017; Bissell et al., 2011; Gemmer et al., 2012; Fokker et al., 2011; Morris et al., 2011; Rutqvist, 2011), and Vasco et al. (2010), who focussed on In Salah. Modelling of a fractured zone, often extending through the caprock, was required to match the observed surface deformation. Li and Laloui (2016) carried out a "blind prediction" of the surface uplift observed next to the injection well KB501 at In Salah during the 4.5 years of cold CO_2 injection. The results of a 2D thermo-hydro-mechanical analysis with full coupling and multiphase fluid flow predicted a high potential for shear failure of both the reservoir and cap rocks. This was found to be a result of an increased deviatoric stress from the initial anisotropic stress state, due to a decrease in the *in situ* effective stress from the combined effect of pressure increase and temperature drop.

Thermal stresses. Thermal stresses can develop tensile regimes in the caprock (e.g. Gor et al., 2013a; Preisig and Prévost, 2011), which may lead to fracture growth and damage conducive to an increase in permeability. Thermal stresses depend on the temperature difference, as well as the bulk modulus and the coefficient of volumetric thermal expansion of the rock matrix (Zimmerman, 2000). Variability in the values of these factors can, therefore, play a major role in these non-converging results. Different sites will obviously have different mechanical (both stiffness and strength), hydraulic and thermal parameters of the various rocks, explaining, at least partly, the difference in the results. The geometry and thicknesses of the various strata can also play a key role, as explained by Vilarrasa et al. (2015) for In Salah. Peters et al. (2013) and Vilarrasa et al. (2015) highlighted the importance of the *in situ* stresses, as a smaller overburden (i.e., shallower depth) and lower minimum horizontal stress can enhance the temperature contrast effect.

Vilarrasa et al. (2015) also emphasise the importance of the orientation of the injection well for caprock integrity, as well as the significance of thermal stresses when CO_2 is injected at a much lower temperature than the *in situ* temperature. Despite this, several studies only account for poro-mechanical effects (e.g. Gor et al., 2013b; Orlic et al., 2011b), although injection of liquid CO_2, which is commonly at a lower temperature than that in the reservoir, has become more common (Vilarrasa et al., 2013; Vilarrasa and Laloui, 2015).

5. Geomechanical studies and public perception of the depleted pilot sites

Public perception studies specific to the considered pilot sites are scarce, more so in the context of the actual geomechanics of these sites. Pilot studies and their findings serve to inform experts and policy makers who may have an impact on regulatory frameworks, and can inform public acceptance through successful public engagement at project site level (Xenias and Whitmarsh, 2018). While public support for CCS is generally lower than expert stakeholder acceptance (Huijts et al., 2007; Shackley et al., 2007; Oltra et al., 2010), both groups consider CCS to be a partial solution to climate change. In general, storage of CO_2 in depleted reservoirs engages with local communities that have experience with other subsurface industries (Sacuta et al., 2017), and can directly benefit from continued usage of these sites.

There are a number of studies related to the Barendrecht site in the Netherlands, a case in which social perceptions in the form of protests stalled and halted development (Xenias and Whitmarsh, 2018). Public responses to CO_2 storage in this and other European sites have cited concerns about the potential impact of carbon storage on "health, the environment and the local community in general", referring to the potential effects of local leakage of CO_2 into an urban area (Oltra et al., 2012). In Barendrecht, in addition to lack of support from politicians (Brunsting et al., 2011), the main concerns of local residents related to the potential negative impacts of CO_2 leakage on public health and safety (Oltra et al., 2012), and consequences for the value of their properties (Terwel et al., 2012). In Finland, CCS suffered from poor and negative attention from the media after 2009 (Kojo and Innola, 2017), and was categorised as an alternative to renewables (Teir et al., 2011), as opposed to being considered as a complementary carbon-offsetting technology. In Hunterston, concerns from the public that eventually led to cancellation of the project, included fear of uncontrolled leakage and long-term migration, and the possible effect on marine ecosystems, as well as induced seismicity (Mabon et al., 2014, 2015). These factors are strongly related to the assessment of the caprock integrity of the site, which for the Hunterston site was scarcely reported in the literature.

In contrast, a number of geomechanical studies that investigate caprock integrity scenarios have been conducted for the on-hold projects Peterhead (Akhurst et al., 2017; McDermott et al., 2016; Salimzadeh et al., 2018a) and ROAD (Peters et al., 2013; Orlic et al., 2011b), as well as for concluded projects, including Otway, In Salah, Lacq, Schwarze Pumpe, and K12-B. The latter have a number of accompanying geomechanical studies focused on caprock integrity (Preisig and Prévost, 2011; Chiaramonte et al., 2011; Gor et al., 2013a; Pourtoy et al., 2013; Aruffo and Henk, 2014; Aruffo et al., 2014; Vilarrasa et al., 2015). For Snøhvit, geomechanical studies included understanding fault reactivation (Chiaramonte et al., 2011), geomechanically-driven changes to permeability during injection (Hansen et al., 2013), and the study of *in situ* 3D fracture network properties and their influence on fault permeability (Wennberg et al., 2008). The ongoing Heletz pilot CO_2 injection site in Israel was supported by a number of large EU-funded projects (PANACEA, TRUST, and MUSTANG) which financed numerical injection experiments focussed primarily on quantifying capillary/residual trapping (Niemi et al., 2016), but also on mechanical studies that examined caprock stability during cold injection (Paluszny et al., 2017). In this case, no public opposition was apparent and the project was supported by local regulating authorities.

Most of these sites considered leakage and seismicity, and in many cases, operations relied on extensive surface and subsurface-based monitoring to minimise these risks. Providing information about CCS does not always allay fears or change attitudes (Upham and Roberts, 2011a,b; Wallquist et al., 2011; Brunsting et al., 2013a; Braun et al., 2018). However, it is notable that both the way in which CCS information is framed (van Knippenberg and Daamen, 1996; Whitmarsh et al., 2019) and audience characteristics (e.g., knowledge, values, cultural world views) influence public views on the technology (Yang et al., 2016; Brunsting et al., 2013b; Hope and Jones, 2014; Howell et al., 2014; Krause et al., 2013; Warren et al., 2014; Karimi et al., 2016) It is the case, however, for most of the completed projects that geomechanical studies contributed to the quantification of caprock integrity during storage, and in many cases were instrumental in providing interpretations during monitoring. Such studies could provide a useful tool for building confidence in CCS technology and as a public engagement tool.

In the general study of social perception of CCS, there is a disparity in public perception according to whether attitudes are studied at the level of the general public, or specific communities that are likely to be affected by CCS (Midden and Huijts, 2009; Huijts et al., 2007). The strength of this disparity may well differ for depleted storage sites, where previous interaction with the hydrocarbon industry is often present, although there is limited research assessing this. As with other energy developments (e.g., nuclear, wind, geothermal, wave), different public and communities will respond differently to CCS in general, as opposed to specific proposed sites; "public acceptance of CCS in the global sphere does not necessarily translate to local support for a CCS storage site" (Poumadère et al., 2011; Krause et al., 2013; Braun, 2017). For the general public, factors such as values, beliefs, trust, and education are likely to predict CCS support, while for proposed/actual communities affected, familiarity with the industry, operator trust, place identity, and perceived costs and benefits are likely to be more important (Desbarats et al., 2010). These are only some of the factors that may influence public perceptions, and wider, more integrated social and technical research is needed to address public acceptance (Mabon et al., 2013). For communities close to depleted sites it is likely that several of these latter factors are likely to differ significantly to those in regions less familiar with offshore industry. Nevertheless, public response at both Barendrecht and Hunterston demonstrate the potential for concerns around storage integrity at depleted sites. More generally, CCS faces sustainability concerns and geological concerns, including the perceived increased risk of induced seismicity and leakage (Seigo et al., 2014b), both of which can be tied to the geomechanical performance of the seal that traps the carbon in place. Understanding the geomechanics of the seal traps is a necessary step, which if translated and communicated appropriately will address some of the concerns associated with geological storage.

6. Final Remarks

Advantages of carrying out CCS at depleted reservoirs include a history of previous containment, often substantial geological and geophysical characterisation, and the potential to incorporate pre-existing infrastructure into new schemes. They differ from previously unused sites due to previous anthropogenic involvement, which may include factors such as a history of geomechanical perturbation and the presence of multiple boreholes. Studies that relate to depleted pilot sites for CCS have been collated and examined in relation to three key aspects associated with assessment and perception of containment at these sites:

1. Characterisation of storage site materials provides the fundamental data and understanding necessary to constrain performance assessment and parameterise predictive simulations.
    - Geomechanical data used for parameterising numerical simulations is substantially less common for caprock materials.
    - Care needs to be taken when selecting parameters from the experimental and analytical literature and transferring to appropriate conditions.
    - Heterogeneity remains a topic for further work, particularly for caprock materials, where a lack of test material limits testing for calibration and/or verification of values from proprietary relationships.
    - These factors will contribute to the overall degree of certainty in performance assessment through simulation.
2. Caprock integrity modelling studies are instrumental to understanding the effects of storage site materials, geological structure, and injection protocols on the long term storage of CO_2.
    - Numerical studies of the depleted sites consider overpressure, fracture growth, fault reactivation, ground surface displacement, and the effect of thermal stresses. These have been developed with a number of independently validated simulators capable of capturing mechanical, flow, thermal, and geochemical processes that ensue during injection into depleted reservoirs.
    - The numerical studies of the sites are primarily focused on understanding the conditions leading to the potential onset of leakage and induced seismicity, rather that on the quantification of leakage rates or seismicity development over longer periods of time. These two factors feed into some financial liability models that monetise the risk of caprock integrity breach associated with CCS sites.
    - Numerical studies study a variation of rock materials, and *in situ* and injection conditions, often assuming that rock layers are homogeneous and in many cases geometrically simplified.
    - Findings suggest a series of geomechanical benchmarks quantifying leakage rates for specific scenarios is necessary. These benchmarks should be tied to field-based validations, and to critical societal and operator concerns such as potential leakage rates over short and long periods of time.
    - These numerical models improve our understanding of mechanical changes that occur during injection and storage both in general, and for specific reservoirs, and contribute to building confidence in the capacity to store carbon while seeking to minimise both leakage and seismicity.
3. Public concern over leakage risks has been a contributing factor in the cancellation of some projects.

- Providing information about CCS does not always allay fears or change attitudes.
- CCS faces sustainability and geological concerns, including perceived increased risk of induced seismicity and leakage
- These factors can be tied to the geomechanical performance of the storage seal and this should be considered by experts and regulators during the development of a public engagement strategy.

Examining studies from these three perspectives, it is clear that geomechanical effects, relating to both leakage and induced seismicity, are strongly linked to both the real and perceived risks of CCS at depleted storage sites. The geomechanics literature tends to emphasise the evaluation of induced seismicity, thermal stresses, and injection pressure constraints. Examining perception and risk analyses alongside pilot site-specific studies suggests the need for the geomechanics community not only to perform binary caprock integrity studies (e.g. will a given site leak or not leak), but to perform long-term quantifications of leakage, estimating leakage rates, and analysing potential 'domino' effects of leaks. Careful quantification and assessment of aspects such as the role of heterogeneity, localisation of flow, and the permeability evolution of faults and fractures/damage, will improve certainty around storage site evolution and containment. When combined with careful monitoring to confirm behaviour, such an approach will contribute to reduced technical and financial risks, contribute to a sound public engagement approach, and facilitate the successful development of CCS projects in depleted hydrocarbon reservoirs.

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