The state of the art in monitoring and verification - ten years on

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Abstract

In the ten years since publication of the IPCC Special Report on CCS, there has been considerable progress in monitoring and verification (M&V). Numerous injection projects, ranging from small injection pilots to much larger longer-term commercial operations, have been successfully monitored to the satisfaction of regulatory agencies, and technologies have been adapted and implemented to demonstrate containment, conformance, and no environmental impact. In this review we consider M&V chiefly from the perspective of its ability to satisfy stakeholders that these three key requirements are being met. From selected project examples, we show how this was done, and reflect particularly on the nature of the verification process. It is clear that deep-focussed monitoring will deliver the primary requirement to demonstrate conformance and containment and to provide early warning of any deviations from predicted storage behaviour. Progress in seismic imaging, especially offshore, and the remarkable results with InSAR from In Salah are highlights of the past decade. A wide range of shallow monitoring techniques has been tested at many sites, focussing especially on the monitoring of soil gas and groundwater. Quantification of any detected emissions would be required in some jurisdictions to satisfy carbon mitigation targets in the event of leakage to surface: however, given the likely high security of foreseeable storage sites, we suggest that shallow monitoring should focus mainly on assuring against environmental impacts. This reflects the low risk profile of well selected and well operated storage sites and recognizes the over-arching need for monitoring to be directed to specific, measureable risks. In particular, regulatory compliance might usefully involve clearer articulation of leakage scenarios, with this specificity making it possible to demonstrate "no leakage" in a more objective way than is currently the case. We also consider the monitoring issues for CO_2-EOR, and argue that there are few technical problems in providing assurance that EOR sites are successfully sequestering CO_2; the issues lie largely in linking existing oil and gas regulations to new greenhouse gas policy. We foresee that, overall, monitoring technologies will continue to benefit from synergies with oil and gas operations, but that the distinctive regulatory and certification environments for CCS may pose new questions. Overall, while there is clearly scope for technical improvements, more clearly posed requirements, and better communication of monitoring results, we reiterate that this has been a decade of significant achievement that leaves monitoring and verification well placed to serve the wider CCS enterprise.

1 Introduction

This article reviews progress in the monitoring and verification (M&V) of CO_2 storage over the decade since the publication of the IPCC Special Report on CCS (IPCC, 2005). Our emphasis will be on "progress" rather than "review" – an enormous amount of work has been done on M&V since the Special Report, and a thorough literature review would be a large task indeed. Out of this large volume of work, we have elected to emphasize the aspects where we believe there has been important strategic progress towards the goal of widespread deployment of CCS. While morale and confidence ebbs and flows, seen from a ten-year perspective the subject has moved forward in many of the areas that were identified in the original Special Report as needing development.

In our view, a key aspect is the development of storage regulation and the growing clarity about how M&V should align with it. This review is therefore not a critique of monitoring methods *per se*, but more an account of how they have come to be used in enabling storage projects which, over the period of review, have operated in an evolving regulatory context. We will attempt to distil out of these experiences the essential features of regulation and M&V that have emerged, and show how they are coming into alignment. Much of our review emphasises this aspect, because it is central to deployment of CCS in the short to medium term. There is, of course, much longer-term research that aims, for example, at the development of radical and new monitoring methods. Such research is extremely important but, in the interests of focus and brevity, except where we see near-term benefits we will not cover these topics. Site characterization has connections to M&V, through both defining the rock framework and fluid distribution in which monitoring will occur and by providing pre-injection baseline data against which change during injection can be assessed, however, we avoid detailed assessment of this project stage, covered elsewhere in this volume.

Since our objective is to chart the gains over the past ten years, we will begin by outlining some of the main features of the M&V chapter of the Special Report. These paint an interesting picture of the state of the subject at the time.

Probably the most striking feature of the Special Report's chapter is that it could not refer to a wide range of geological storage monitoring experience; only Sleipner (Baklid, 1996) and Weyburn (White et al., 2004; Wilson and Monea, 2004) were available to inform discussion. Since then monitoring datasets from Sleipner and Weyburn have continued to evolve and provide the opportunity for increasingly sophisticated analysis. In addition, numerous new projects – both commercial and research – have added greatly to our understanding of storage in general and M&V in particular. The relevance of CO_2-EOR has also become more widely recognized, with information from the long history of this activity becoming more widely accessible. Examples of storage projects developed during this decade for which detailed and publically accessible M&V results are available include K12-B (van der Meer et al., 2009; van der Meer et al., 2005), Ketzin (Martens et al., 2013; Würdemann et al., 2010), Lacq (Aimard et al., 2007; Prinet et al., 2013) and Snøhvit (Hansen et al., 2013) from Europe, In Salah (Eiken et al., 2011; Mathieson et al., 2010; Ringrose et al., 2013) from Africa, Nagaoka (Kikuta et al., 2005) from Japan, Otway (Cook, 2014b; Jenkins et al., 2012) from

Australia and a number of US projects: Frio Test (Hovorka et al., 2006), Mountaineer, Cranfield (Hovorka et al., 2013c), Illinois Basin, Decatur (Finley, 2014b), Bell Creek, Michigan pinnacle reefs and other R&D projects under the US Regional Carbon Sequestration Regional Partnership program. In Canada, Aquistore has just begun operations (Worth et al., 2014). In addition projects recently permitted or currently in planning provide information on how M&V experience garnered over the decade is coming into play at larger scales. Examples include Gorgon (Flett et al., 2009) from Australia, Peterhead, ROAD and White Rose from Europe, Quest (Bourne et al., 2014) from Canada, Tomakomi from Japan and Decatur Phase II, Hastings, Kevin Dome and West Ranch from the US. Summaries of outcomes of many of these projects can be found in Cook (2014a); NETL (2009); and at online data bases maintained by the Massachusetts Institute of Technology Energy Institute (MITei, 2010) and the Global CCS Institute (GCCSI, 2014b).

The other very striking feature of the Special Report chapter was the lack of regulatory and certification frameworks at that time. Sleipner operated and continues to operate under Norwegian petroleum regulations, and Weyburn, being an EOR project, also operated under Canadian petroleum regulations. The chapter raised the issue that there were no standard protocols for verification, and commented that "…at the very least, verification will require measurement of the amount of CO_2 stored" and that demonstrating containment is "…likely to require some combination of models and monitoring." The questions of who would do the monitoring for long-term stewardship, and how it would be done, were also raised. Today, in a number of jurisdictions, one can refer to detailed regulatory documents for answers to these questions; and while these may not be as clear as one would like, the rules of the game are now known in a way that was not the case ten years ago. However, despite the many developments in CCS, it is striking that most geologically stored CO_2 has been cycled through an EOR project in the USA (Kruuskra and Wallace, 2014). Regulation, accounting and monitoring of CO_2-EOR from the CCS perspective continues to be developed and will therefore be discussed in some detail in this review.

Technologies for monitoring were evaluated in the Special Report, and while there was limited direct experience of these for CCS, it is notable that few have been added to the portfolio that was identified. For monitoring the storage reservoir, fluid sampling, tracers, and 4D seismic were highlighted. With considerable foresight, the authors suggested that with seismic a "resolution (*sic*) of 2500 – 10000 tonnes free phase CO_2" would be achievable, and that shallow gas should be very easily seen; this has only recently been demonstrated at Sleipner, as we will describe later. Other standard oilfield techniques of electromagnetic or gravity measurements were mentioned, but at the time little was known about their applicability for CCS, with just one seabed gravity survey having been carried out at Sleipner. Interestingly, in the light of later events, it was stated that "tilt meters or remote methods …… for measuring ground distortion" might be productive, and likewise passive microseismic monitoring. While the use of annular pressure was mentioned as an indicator of wellbore integrity, the more general use of pressure measurement for assurance of maintenance of mechanical integrity, model validation in the reservoir or above-zone monitoring of aquifers was not.

In the area of shallow monitoring, most current methods were also foreshadowed, but interestingly under the heading of "environmental effects" rather than leakage. This important distinction continues to cause confusion in some quarters. Topics mentioned included groundwater monitoring,

CO_2 atmospheric concentration and fluxes, hyperspectral imaging and soil gas. Natural and introduced tracers for groundwater were considered, but the specific use of noble gas tracers to detect leakage from depth was not.

Since the Special Report was written, risk assessment for CCS, and its integration with M&V and mitigation, has become a field of study in itself with the development of varied methodologies and the accumulation of much experience in actual projects. Extensive on-line databases are available, including “Features, Events and Processes” and tools for selecting monitoring techniques in the light of risks. All of this points to the greatly increased maturity of the context for M&V now, compared with only a decade ago.

Risk assessment and environmental impacts have partly risen to prominence as a result of public opposition to CCS, specifically onshore, and our view of M&V is now conditioned to some degree by this issue. To some extent the problem is a European one, with the cancellation of storage projects at Altmark and Jänschwalde in Germany and Barendrecht in the Netherlands. However social licence is important everywhere and an understanding has developed that monitoring might be required to deal with concerns felt by the public, whether these be technically justified or not. The “Kerr affair” at the Weyburn CO2-EOR project was certainly widely discussed in the CCS community at the time (GCCSI, 2014b), and the rising incidence of induced seismicity from subsurface injections (but not from CCS so far) has far-reaching implications (Ellsworth, 2013), not least for M&V as a risk management tool.

2 The Nature of Verification

The nexus between M&V and regulation is in the word “verification” – the way in which monitoring results demonstrate to regulators and other stakeholders that their requirements are being met. Proponents have learned a good deal about this concept over the decade, although regulation in some cases seems to have crystallized ideas surrounding verification before they were properly developed.

We discuss the nature of verification early in this review so that our readers are alerted to the underlying issues as we work through the specifics of projects and techniques. The concept is not simple, and is often made opaque by being phrased as if it were possible to prove a negative proposition, for instance, “monitoring proves that there is no leakage”. Whether conformance, containment, or environmental impact is being discussed, the most that can be done with monitoring data is to show consistency, on some agreed basis, between observation and expectation or observation and requirement. Consider, as an example, the seismic imaging of a plume of CO_2. The image will certainly not look exactly like the prediction of the dynamic flow model, and there will also be parts of the plume that are below the limit of detection. By adjusting parts of the model – which are otherwise perhaps not known very well – a better fit may be obtained, but will this prove conformance, in a regulatory setting? Are the discrepancies between model and data statistically significant, and crucially, are they important in terms of future outcomes? In some scenarios quite large deviations might not signify any prospect of loss of containment; whereas in others some small discrepancy might signal a problem in the making.

Part of the idea of verification must involve a sensitivity analysis – investigating the range of models that can be satisfactorily fitted to the data and checking their implications. The idea of a range of models is important and proper site characterisation is necessary to assess the scope of this. The European regulations, which are particularly well developed, lay stress on the notion of thresholds in monitoring data as triggers for action. How would such thresholds be set? Clearly by consideration of alternative models and the significance, in terms of outcomes, of their differences. In the case of containment modelling, for example, a base-case “no leakage” model would be of no use in setting a threshold for pressure, say, to indicate a breach of containment. Specific (and probably a range of) “leakage” models would be needed to do this. Verifying containment would then consist of showing that pressure data sit well away from these thresholds, taking account of measurement and modelling error as much as possible. The conclusion encapsulates a good deal of judgement, the selection of “reasonable” cases to consider, and is necessarily a statement phrased in terms of probability. Application of this methodology to shallow monitoring is particularly challenging, because any hypothetical leakage routes to surface would, by definition, be poorly-understood and so “leakage” models are hard to construct.

Where verification thresholds are placed has implications for both sensitivity (how large a leak can we reliably detect?) and the false alarm rate (how often will the threshold be exceeded because of natural variability or measurement error?). Adequate characterization is important to understand these issues. The CCP Certification Framework (Oldenburg et al., 2009) is unusual amongst the multiplicity of M&V guidelines in dealing quantitatively with specific leakage models; others are more qualitative and flexible, but a logical gap then remains in setting actual numerical thresholds for monitored quantities. The measurement units of a threshold demonstrate the point; if a threshold is quoted, say, in units of concentration of bicarbonate in groundwater, there are clearly extra logical steps before it becomes a threshold in terms of leakage units, say tonnes per year.

Monitoring for environmental impact is an area where we have learned that clear thinking is vital. A leakage of stored CO_2 to surface may, or may not, have an environmental impact. However, groundwater, soil, atmosphere, seabed and seawater-column are all part of open systems that are perturbed by many more things than containment failure, and whether monitoring these systems can tell us very much about leaks needs to be carefully examined on a site-specific basis. For example, if environmental impacts are used as leak detectors, the false alarm rate might be very high and this poses obvious issues for social licence. Nevertheless, some methods which principally monitor for environmental impact may have utility in monitoring for well-defined risks of leakage to the near-surface.

None of this is to say that monitoring for environmental impact is not important – it clearly is, and is mandated by many regulations. However the “rules of the game” are different to those for monitoring for containment and conformance. In particular, establishing thresholds for action is better done by referring to environmental standards and norms, for example water quality standards, or possibly to specifically designed ‘control’ sites, rather than by attempting to frame the issue in terms of modelling the effects of hypothetical leakage. On the other hand, if there is a leakage risk that can be addressed by an environmental monitoring method, then reference to containment and conformance criteria does become relevant.

3 Regulation and Monitoring

Over the past decade, regulation has developed in two ways. In a number of cases, *ad hoc* regulatory agreements, including M&V requirements, have been negotiated in the absence of legislation specific to CCS, such as Gorgon in Western Australia, Quest in Alberta, or Frio in Texas. On the other hand, regulatory regimes with requirements for M&V have been, or are being, developed in a number of jurisdictions, although these have not yet been extensively tested. These include the 2009 European Storage Directive (European Commission, 2011), the US Environmental Protection Agency (EPA), recent injection well requirements (Class VI) and greenhouse gas reporting rules(Environmental Protection Agency, 2012), and recent legislation in Australia, Canada and Japan.

NW Europe hosts two of the world’s currently operational large-scale storage projects and it is here, guided by this project experience, that the regulatory framework for storage as part of a greenhouse gas programme is most developed, in the form of the European Storage Directive. This regulates the permanent storage of CO_2 in amounts exceeding 100 kilotonnes and emphasises monitoring for the purposes of assessing whether injected CO_2 is behaving as predicted, whether unexpected migration or leakage is occurring, and if this is damaging the environment or human health. If there is clear evidence of leakage, quantification is required. Storage offshore must additionally comply with the 2007 amendments to the 1996 London Protocol on offshore dumping and with the 2007 OSPAR Convention which applies to the NE Atlantic (key aspects are summarised in Dixon et al. (2009), and in Dixon et al. (this volume)). The Sleipner (Norwegian North Sea) and Snøhvit (Norwegian Barents Sea) storage projects predate the current legislation, but Norway has now adopted the Storage Directive voluntarily and consultation is under way for the possible incorporation of Sleipner and Snøhvit within the storage regulatory framework. The planned Peterhead (UK North Sea), White Rose (UK North Sea) and ROAD (Netherlands North Sea) projects will all be subject to European storage regulation.

The new federal regulations in the USA pertaining to CCS are additions to the Clean Air Act (Environmental Protection Agency, 2010a) and to the Safe Drinking Water Act (Underground Injection Control (UIC) (Environmental Protection Agency, 2010b), both under the jurisdiction of the US EPA . The relevant part of the Clean Air Act requires quantification of sources of emissions. Regulation of emissions under the Act is currently under consideration. The Act includes a requirement for a monitoring, reporting, and verification (MRV) plan and for the use of this plan to estimate the amount of CO_2 that is “missing from storage”, somewhat different to the requirements for “quantification” under European Union rules. In the US, all underground injection is regulated by the Underground Injection Control program of the Safe Drinking Water Act to protect underground sources of drinking water. A new class of well, UIC Class VI (Environmental Protection Agency, 2012), was defined for CO_2 injection (except EOR), including provision for a monitoring and testing plan. Besides detailed surveillance of the performance of the injection well, this plan must describe how monitoring will track the extent of the carbon dioxide plume and elevated pressure, using direct or indirect measurements and periodic monitoring of chemistry and water quality above the injection zone. Groundwater monitoring is implicit and soil gas or air monitoring may be required.

CO_2 injection for EOR in the US has long been permitted under oil and gas laws and is included in the Class II category in the UIC programme, with individual states granted primacy (Environmental Protection Agency, 2010b). Class II monitoring is focused on assuring isolation of fluids in the injection zone from drinking water and require activities to evaluate and report on the highest risk pathways; including proper construction and maintenance of the injection well and management and remediation of existing wells within a 1/4 mile of the injection well. Historically EOR operations have had a good record of retaining CO_2 and work is underway to provide mechanisms for certification of the storage of the CO_2 that was injected for EOR.

In Alberta, the Quest project was permitted within existing legislation, mainly pertaining to sour gas, after negotiations between Shell and the regulators, and has a strong M&V programme (Bourne et al., 2014). Somewhat in parallel, the Government of Alberta initiated a regulatory framework assessment process (RFA) for CCS in March 2011. This concluded with publication of a comprehensive summary report containing a set of recommendations and actions to be taken forward (Alberta Energy, 2012). The philosophy is similar to that of the European legislation and emphasises monitoring for demonstrating conformance and containment of sequestered CO_2 and affected fluids within the sequestration complex and also for demonstrating no significant adverse effects on the environment or other resources. The RFA, and the precedents set by QUEST, will gradually take effect in terms of affecting regulations. In Saskatchewan, the storage element of the Boundary Dam project is regulated under oil and gas legislation. Criteria for the application of environmental legislation were deemed not to apply by a Ministerial determination, so in effect this project is proceeding with no CO_2-specific legislation.

In Japan the Industrial Science and Technology Policy and Environment Bureau of the Ministry of Economy, Trade and Industry (METI) has issued a report providing a standard "For Safe Operation of a CCS Demonstration Project" (METI, August 2009). The stated monitoring aims are to monitor the behaviour of the injected CO_2 to confirm that it is injected and stored securely and stably as originally planned; to improve the accuracy of predictive models through comparison of the acquired data with the detailed model simulations and to detect abnormalities, such as CO_2 leakage, if any such should occur.

Many CCS and CCUS projects are being developed in China (for example Guangdong, involving capture from the Haifeng power plant;   Yanchun experiments at Saanxi). Several are underway (Jiling EOR and the Shenhua group's experiments with saline injection). Regulations and monitoring expectations are not yet well defined.

It is clear from the above that, worldwide, a wide range of regulatory requirements, at various levels of detail and in a range of contexts, has been devised for the regulation of storage. Nevertheless a number of relatively consistent monitoring-related objectives have emerged: to show that a storage site is performing effectively and safely by secure containment of injected CO_2; to demonstrate a robust understanding of current storage processes; and to provide information supporting reliable prediction of future performance. These fall within two main categories, containment assurance and conformance assurance. Contingency monitoring may be required in the event that containment and/or conformance requirements are not met. In some jurisdictions this may entail quantification of the leakage or emissions.

In addition, many jurisdictions require some form of environmental impact assessment, which may not be specific to CCS regulations. Monitoring for possible environmental impacts may therefore be also required.

3.1 CONTAINMENT

The principal element of proving storage performance is to show that the stored CO_2 is securely retained within the storage site, so that it is isolated from the atmosphere and presents no hazard to health or the environment. Containment monitoring has two elements. Deep-focussed surveillance aims to identify unexpected migration of CO_2 out of the primary storage reservoir, subsequent migration into the overburden, into possible secondary reservoirs and ultimately, towards the surface. Shallow-focussed monitoring (for example soil gas, atmospheric or water-column monitoring) is less useful for verifying containment except in cases where there is a clear risk associated with a specific potential pathway to the near-surface, for example via possibly defective wellbores.

3.2 CONFORMANCE

Conformance is the measure of agreement between simulations of the behaviour of stored CO_2 and its observed behaviour. This should be close enough to demonstrate that storage processes at a site are sufficiently well understood so that no important or material deviation from the predicted storage behaviour is expected. Conformance monitoring is therefore primarily deep-focussed, and aims to test and calibrate models of current site behaviour. These models in turn can be used to set the basis for prediction of future site behaviour, long-term secure storage and satisfactory site closure. Technologies should have sufficient resolution, sensitivity and quantitative capability to test and calibrate simulation models thoroughly.

Non-conformance occurs when observed site behaviour deviates from that predicted to a significant degree, for example, by falling outside predicted uncertainty ranges or other performance thresholds. Some non-conformance may be material, deviating in important ways from the planned performance and putting achievement of the site objectives at risk; other non-conformance may be inconsequential. An example of material non-conformance is if injection pressure exceeds the fracture opening threshold and the mechanical integrity of the storage system is threatened.

3.3 CONTINGENCY MONITORING

Material non-conformance might require additional contingency monitoring to track the deviation and assess possible consequences, to design corrective measures if necessary, and, should these be deployed, to confirm that they have been effective. In the EU, should leakage be established, quantification of any emissions to atmosphere is required, because of the linkage into the European Emissions Trading Scheme (European Commission, 2011). In the US, a storage project reporting under the greenhouse gas rules must use an approved MRV plan to estimate the mass of any CO_2 that is missing because of leakage to the atmosphere. In addition, contingency monitoring might be required to determine if leakage has led to contamination of drinking water. In Australian legislation there is a particular concern with unintended migration into hydrocarbon-bearing pore space, and contingency monitoring might be needed if that were suspected or alleged.

Should leakage occur, quantification is important as climate mitigation is the sole driver for CCS, and the IPCC has provided guidelines for CCS as part of its framework for emissions accounting (National Greenhouse Gas Inventories Programme, 2006). In this review we will not discuss quantification in detail, as no injection project has been obliged to quantify leakage in the decade under review, although some have had limited plans to do so. We will refer to these cases in our project reviews (Section 4 and 8). Some controlled release projects have endeavoured to test quantitative monitoring tools: at Svelvik (Jones et al. (2014)), at Ginniderra (Feitz et al., 2014) and Feitz, personal communication), also offshore in the QICS project (Blackford et al., 2014; Taylor et al., 2014).

3.4 ENVIRONMENTAL IMPACT MONITORING

A large category of monitoring focused on near surface environments is more motivated by societal concerns, or by the requirement to check for possible environmental impacts. This type of monitoring has been emphasised in small-scale pilot projects with a research focus, although it might also form a minor component of the monitoring suite in larger commercial projects. An advance since the Special Report has been the development of controlled release projects (Blackford et al., 2014; Cohen et al., 2013; Feitz et al., 2014; Jones et al., 2014; Lewicki et al., 2007; Spangler et al., 2010; Taylor et al., 2014), which assess the response of environments to introduction of CO_2 (simulating leakage) and the efficacy with which these responses might be monitored. Testing leakage detection in field settings has been an important contribution of the controlled release projects.

4 Examples of storage projects and their monitoring programmes

A major achievement of the past decade has been the successful execution of more than forty geological storage projects that have safely stored many millions of tonnes of both natural and anthropogenic CO_2. They vary considerably in size (from ~1000 tonnes to ~1 million tonnes of CO_2 stored per year), and include commercial, research and demonstration activities. Reviews of many of these projects have been compiled by IEA (Cook et al., 2013), NETL, (NETL, 2009), MIT (Massachusetts Institute of Technology Energy Institute, 2015) and GCCSI (GCCSI, 2014b). A detailed analysis of the contributions of each project is beyond the scope of this paper, but as a group they have contributed considerably to progress in CCS monitoring. The availability of data and results in the peer-reviewed literature does not fully represent the state of learning as much material is unpublished, albeit commonly in the public domain.

Before moving on to specific examples, we highlight some strategic achievements of this activity.

A wide portfolio of monitoring tools has been tested under diverse conditions. Prior to their application in CCS, many of the tools were in commercial use, typically in oil or gas production. The outcomes of testing in the CCS context have been more widely disseminated than is typical for most commercial hydrocarbon projects, and detailed outcomes have been distributed for analysis, evaluation and review (Arts and Winthaegen, 2005; Benson, 2005; Chadwick, 2010; Hovorka et al., 2014; IEAGHG, 2014; NETL, 2012; Pearce et al., 2007; Pearce et al., 2005).

Importantly, the portfolio of new projects has built on and extended existing oilfield experience. Pilot-scale tests have allowed rigorous validation of multiphase fluid flow and rock-water-CO_2 reaction modelling against measured data, with tool testing in settings significantly simpler than in the EOR projects that provided previous results. Most of the pilot projects injected CO_2 into a rock-brine pore system where both measurement and modelling is significantly simpler than a system containing uncertain amounts of depleted hydrocarbons. Similarly, many pilot tests were conducted with a single active well rather than in an injection/withdrawal pattern where interference among wells adds to complexity. Finally, conditions at project start were near pressure and geochemical equilibrium, much simpler than EOR sites where CO_2 injection follows decades of water flooding, leaving a legacy of complex conditions. Examples of these intensely monitored pilot projects are Nagaoka (Kikuta et al., 2005), Frio Brine (Hovorka et al., 2006), Otway (Cook, 2014b; Jenkins et al., 2012), Ketzin (Martens et al., 2013; Würdemann et al., 2010), Cranfield (Hovorka et al., 2013b) and Decatur (Finley, 2014a).

Strategic benefits from the past decade of testing include a considerable increase in the number, geographical and discipline diversity of engineers and researchers with experience in monitoring CO_2 storage. Prior to these pilot projects most of the expertise was held by employees of oil companies engaged in CO_2-EOR. In addition a wide group of stakeholders have had their first exposure to M&V. These include governments at various levels, regulators, policy-makers, CO_2 producers, liability-holders, oil and gas operators and oil field service companies (NETL, 2009).

Here we choose a small number of exemplar projects, covering a range of geological and operational settings, to illustrate how the main requirements of storage regulation can be met by suitable monitoring programmes (Table 2.1). The selected projects had a wide range of objectives in diverse regulatory and societal environments, but we will show how monitoring did largely address the key issues we have distilled from the regulations: notably in showing containment, conformance, and the absence of environmental impact. In this section we examine two large-scale commercial storage operations (Sleipner and Snøhvit), a demonstration project (Decatur), and one pilot-scale research project (Otway). In the next section we examine two large CO_2-EOR projects that have associated research monitoring programmes (Weyburn and Cranfield).

These examples are just one possible selection from the large portfolio of projects; all of which have contributed to the pool of knowledge we will draw upon in commenting upon our examples. Our focus is on the contribution of M&V to how projects are permitted and operated in a safe and effective manner under a regulatory regime. We will not attempt to describe advances in monitoring research project by project, nor will we attempt to describe every monitoring tool. The available tools are catalogued, with some indication of their capabilities, in various large compilations: the IEAGHG on-line M&V Toolbox (IEAGHG, 2014), the NETL Best Practice Manual (National Energy Technology Laboratory, 2012), the WRI CCS Guidelines (World Resources Institute, 2008), the CO2QUALSTORE guidelines (Aarnes et al., 2010; Carpenter et al., 2011b) and the IEAGHG reviews of quantification and of marine monitoring. We will discuss in a later section the advances in monitoring technology which we think are of longer-term importance to the goal of regulatory compliance.

Monitoring technique		**Sleipner**	**Snøhvit**	**Decatur**	**Weyburn**	**Cranfield**	**Otway**
		storage	**storage**	**storage**	**CO2-EOR**	**CO2-EOR**	**research**
Deep-focussed							
3D time-lapse surface seismic		🟥	🟥	🟦	🟦	🟦	🟦
3D multi-component seismic				🟦	🟦		
2D surface seismic		🟦					
Vertical seismic profiling				🟦	🟦	🟦	🟦
Cross-hole seismic				🟦	🟦	🟦	🟦
Cross-hole ERT						🟦	
Microseismics				🟦	🟦	🟦	
Seabed gravimetry		🟦	🟦				
CSEM		🟦					
Downhole gravimetry						🟦	
Downhole EM						🟦	
Downhole pressure			🟥	🟦	🟦	🟦	🟦
Downhole temperature			🟥	🟦	🟦	🟦	🟦
Downhole geophysical logging					🟦	🟦	🟥
Downhole fluid sampling					🟦	🟦	🟥
Tracers					🟦		🟥
Shallow-focussed (offshore)							
High resolution 3D seismic			🟦				
Seabed and water-column acoustic imaging		🟦	🟦				
Sediment sampling		🟦	🟦				
Water column physics			🟦				
Water column chemistry		🟦	🟦				
Shallow-focussed (onshore)							
Shallow aquifer geochemistry				🟦	🟦	🟦	🟥

	Soil CO_2 concentration				🟦	🟦	🟦	🟥
	Surface CO_2 flux				🟦	🟦	🟦	🟥
	Mobile infra-red laser				🟦	🟦		🟥
	Atmospheric CO_2 concentrations and fluxes				🟦	🟦		🟥
	Airborne EM						🟦	
	red = compliance monitoring							
	blue = research monitoring							

Table 1 Monitoring tools deployed at the selected CO_2 storage and CO_2 - EOR projects. Compliance monitoring is required to satisfy regulators; research monitoring is concerned with the development of monitoring but the results are not used for regulatory purposes. This illustrates the rather small suite of tools that is needed, and in fact only a subset of these is likely to be required for regulatory compliance and satisfactory operation. In some projects, such as Decatur, the boundary between research and compliance monitoring evolved over time.

4.1 SLEIPNER

The CO_2 injection operation at Sleipner in the Norwegian sector of the North Sea is the world's longest-running industrial-scale storage project, commencing in 1996 in response to environmental legislation (Baklid, 1996; Korbol and Kaddour, 1995). CO_2 in the natural gas produced from the Sleipner Vest field is separated out on the platform and injected into the Utsira Sand, a regional-scale saline aquifer. Injection is via a deviated well at a depth of 1012 m below sea level (Figure 1). The average injection rate is just below one million tonnes (Mt) per year, with over 15 Mt of CO_2 stored by 2014.

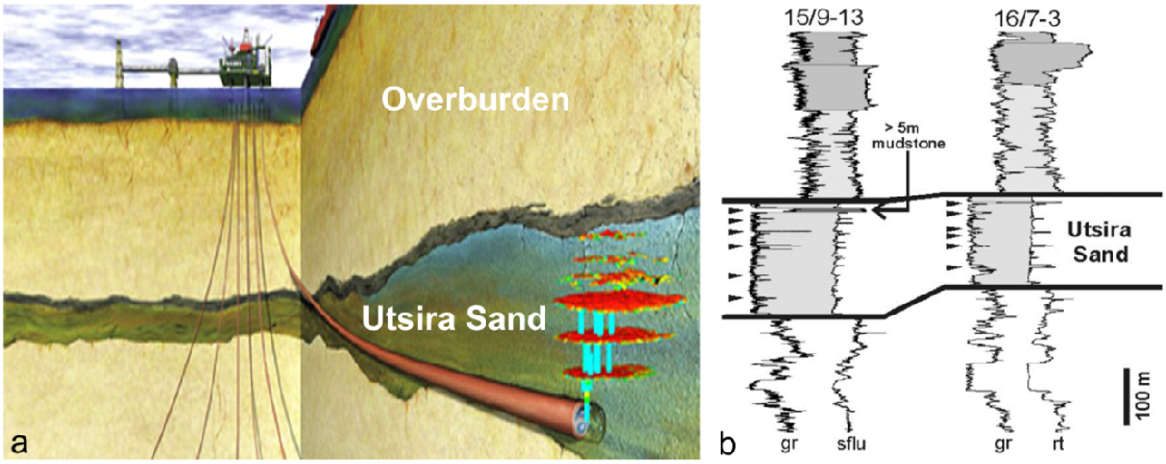

Figure 1 a) Schematic diagram of the Sleipner injection infrastructure and the CO_2 plume b) Sample geophysical logs through the Utsira Sand from two wells in the Sleipner area. Note the low gamma-ray (gr) signature of the Utsira Sand, with peaks denoting the intra-reservoir mudstones. (Sleipner schematic diagram courtesy of Statoil ASA).

Sleipner currently operates under Norwegian offshore petroleum regulations. Its operational monitoring programme nevertheless can be seen to address the main high level objectives of containment and conformance, although these concepts were not explicit at the time of design. The main processes that might affect containment are migration of CO_2 out of the Utsira Sand reservoir, either laterally into adjacent licence areas or vertically through the overburden, via geological pathways or wellbores. Monitoring is thus based around tracking CO_2 migration in the storage reservoir to understand current behaviour and help to predict future migration, and to detect changes in the overburden to provide early warning of any out-of-reservoir migration.

Operational monitoring emphasis is on surveillance of the reservoir via a single tool: time-lapse 3D seismics. Although no dedicated baseline data were acquired, a legacy dataset from 1994 being used instead, the 3D time-lapse surveys acquired at Sleipner do give the current definitive picture of 3D time-lapse survey capability for CCS, in terms of plume imaging and the provision of other seismic attributes suitable for addressing conformance and containment. The roughly biennial frequency for the surface seismics (repeats in 1999, 2001, 2002, 2004, 2006, 2008 and 2010) is a consequence of associated research projects utilising datasets that were primarily acquired for monitoring the deeper gas reservoir. It is evident from the rather uniform progression of plume development that much sparser temporal sampling would suffice to show satisfactory containment and compliance.

The CO_2 plume at Sleipner is imaged as a tiered feature comprising a number of bright sub-horizontal reflections within the reservoir, growing with time (Figure 2). The plume is roughly 200 m high and elliptical in plan, with a major axis approaching 5 km by 2010. The plume is underlain by a prominent velocity pushdown and an attenuation shadow which introduces significant time-shifts and amplitude reductions to the Base Utsira reflection and deeper events.

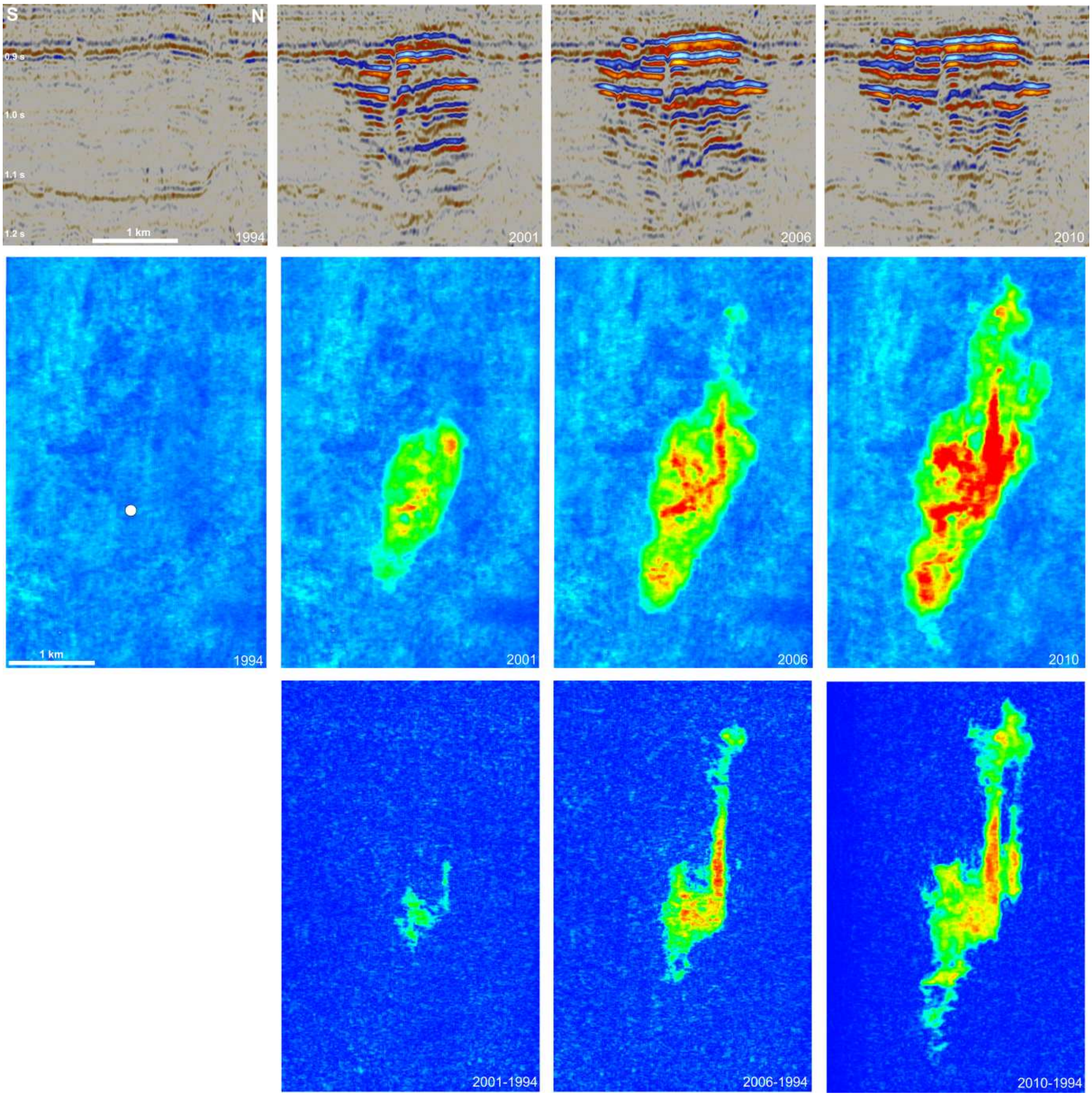

Figure 2 A selection of time-lapse seismic images of the Sleipner CO_2 plume showing its evolution from 1994 (baseline) to 2010. Top panels show the development of reflectivity on a north-south vertical section (inline). Middle panels show in map view the development of reflectivity of the whole plume. Bottom panels show development of the

topmost CO_2 layer as reflectivity difference maps. (Seismic data courtesy of Statoil ASA).

Early interpretations of the Sleipner plume reflectivity (Arts et al., 2004; Chadwick et al., 2004) identified nine separate reflective levels in the reservoir which trap CO_2. These individual and interpretatively distinct reflections have remained consistently identifiable from the first time-lapse survey in 1999 to the latest in 2010 and are interpreted as arising from thin layers of CO_2 (mostly < 8 m thick in the earlier years) trapped beneath the intra-reservoir mudstones and the reservoir top seal. The detectability limit at the outer edge of the layers is estimated to be 1 m thick or less. Patterns of reflectivity and time-shifts within the time-lapse data have been used for a wide range of interpretive and analytical studies related to demonstrating containment and conformance (Chadwick et al., 2010). A significant technical advance came in 2010 when Statoil deployed a streamer with dual-sensor technology that allows the source to be towed at a shallower depth with significant gains in frequency bandwidth and improved resolution (Furre and Eiken, 2014).

4.1.1 Containment

Time-lapse 3D seismics provides a very powerful leakage monitoring tool because of its ability to detect small changes in fluid content of the overburden rock volume above the storage reservoir. Accumulations of CO_2 in the overburden might occur either as sub-vertical columns (‘chimneys’) of vertically migrating CO_2, or as thin sub-horizontal layers of ponded CO_2 which grow laterally. In both cases, changes in the time-lapse seismic signature are extremely sensitive to even very small amounts of CO_2 and are manifest as either reflectivity changes, or time-shifts in reflectivity (the latter are discussed further in Section 5).

The ability of time-lapse data to detect small time-dependent changes depends on the accuracy with which successive datasets can be repeated (the level of repeatability noise), the geometry of the CO_2 accumulation and the reflectivity and properties of the CO_2 itself. Difference datasets at Sleipner show that repeatability noise varies both laterally and vertically (Figure 3).

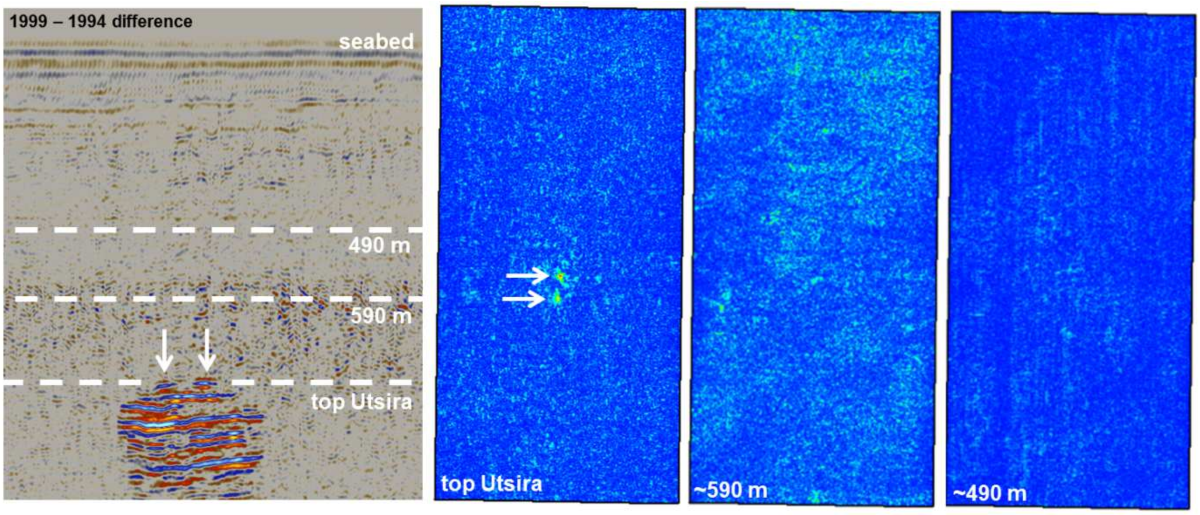

Figure 3 Time-lapse 3D data from Sleipner showing time-lapse difference data between 1999 and the 1994 baseline survey. North-south Inline (left) and horizontal slices (middle, right) showing reflectivity changes at top reservoir and at two levels in the overburden, with different levels of repeatability noise. Two small accumulations of CO_2 (arrowed) are visible on the Inline section and on the top Utsira slice.

A spatial-spectral methodology has been developed (Chadwick et al., 2014) to determine the actual detection limits of seismic datasets which takes these factors into account. Preliminary analysis indicates that, at the top of the Utsira reservoir, CO_2 accumulations with pore volumes greater than about 3000 m^3 should be robustly detectable for layer thicknesses greater than one metre (Figure 4), which will generally be the case. At full CO_2 saturation, this corresponds to a CO_2 mass detection threshold of around 2100 tonnes (lower saturations would convert to lower mass detection thresholds). Within the overburden CO_2 becomes progressively more reflective, less dense, and correspondingly more detectable at shallower depths, as it passes from the dense phase into a gaseous state. The detection threshold thus falls to less than 500 tonnes at some levels in the shallow overburden where repeatability noise is particularly low.

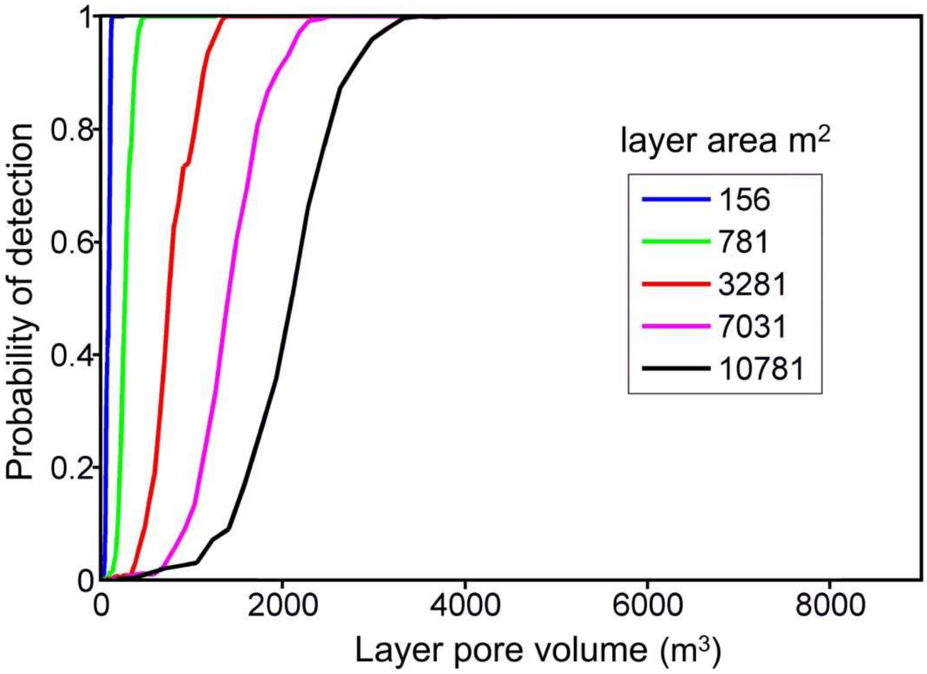

Figure 4 Probability of detecting CO_2 accumulating in a thin layer at the top of the Utsira Sand reservoir (from Chadwick et al. 2014).

4.1.2 Conformance

At Sleipner a number of predictive flow simulations have been carried out over the years aiming to match the known CO_2 injection history with the observed evolution of the plume. These were reasonably successful e.g. (Lindeberg et al., 2001; Van der Meer et al., 2001), but differing interpretations of the geometry and flow properties of the intra-reservoir mudstones illustrated a significant degree of non-uniqueness in model solutions. Moreover, history-matching of more recent time-lapse results is hampered by the progressive reduction with time of image clarity in the deeper plume (Figure 2).

Attention has recently switched to the topmost layer of CO_2 that is trapped directly beneath the reservoir top seal. Because of this it is very clearly imaged and its geometry can be constructed more accurately than for the deeper layers. With time most of the injected CO_2 will end up trapped at the reservoir top, so the topmost layer is a powerful predictor of medium to longer-term plume evolution. A number of studies (Cavanagh, 2013; Chadwick and Noy, 2010; Zhu et al., 2015) have obtained satisfactory geometric matches (Figure 5) of the observed monitoring data with numerical flow models - it is quite clear that the CO_2 is migrating beneath topographic features in the reservoir top seal via a buoyancy-driven fill-and-spill process. However uncertainties do remain, particularly regarding the rate at which the CO_2 attains its buoyancy-stable configuration, and there is continuing discussion over the key controls on CO_2 mobility: CO_2 composition (roughly 2% of the injected stream is methane which might be distributed preferentially towards the reservoir top), CO_2 temperature, reservoir properties and whether flow follows Darcy's Law or is dominated by capillary forces (Cavanagh, 2013).

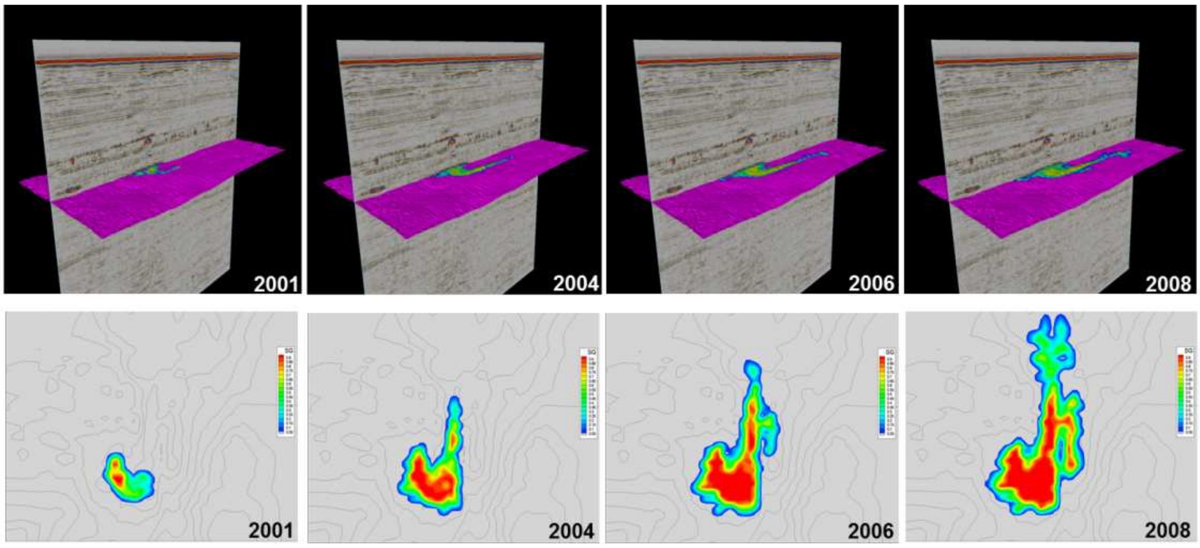

Figure 5 History-matching the topmost layer of CO2 in the Sleipner plume. Observed spreading (top), TOUGH2 models (bottom).

There is no downhole pressure monitoring at Sleipner; due to the large spatial extent, thickness and high permeability of the Utsira Sand, pressure is not thought to be an important conformance issue. However (Ehlig-Economides and Economides, 2010) suggested that pressure increase was significantly impeding plume spreading. Chadwick et al. (2012) carried out a detailed assessment of travel-time changes (time-shifts) through the Utsira Sand, to see if any pressure induced velocity decrease could be detected seismically. The analysis focussed on measuring small time-shifts between the baseline data and 2006, on thousands of seismic traces in the brine-filled part of the reservoir, outside the spatial footprint of the CO_2 plume. Measured time-shifts are of a few milliseconds, positive and negative, and show a Gaussian distribution about a small positive value (Figure 6). This corresponds to only a very small velocity decrease, consistent with a pressure increase of less than 0.1 MPa, which matches the modelled pressure increase in a hydraulically connected (uncompartmentalised) reservoir (more detail in Chadwick et al. (2012)).

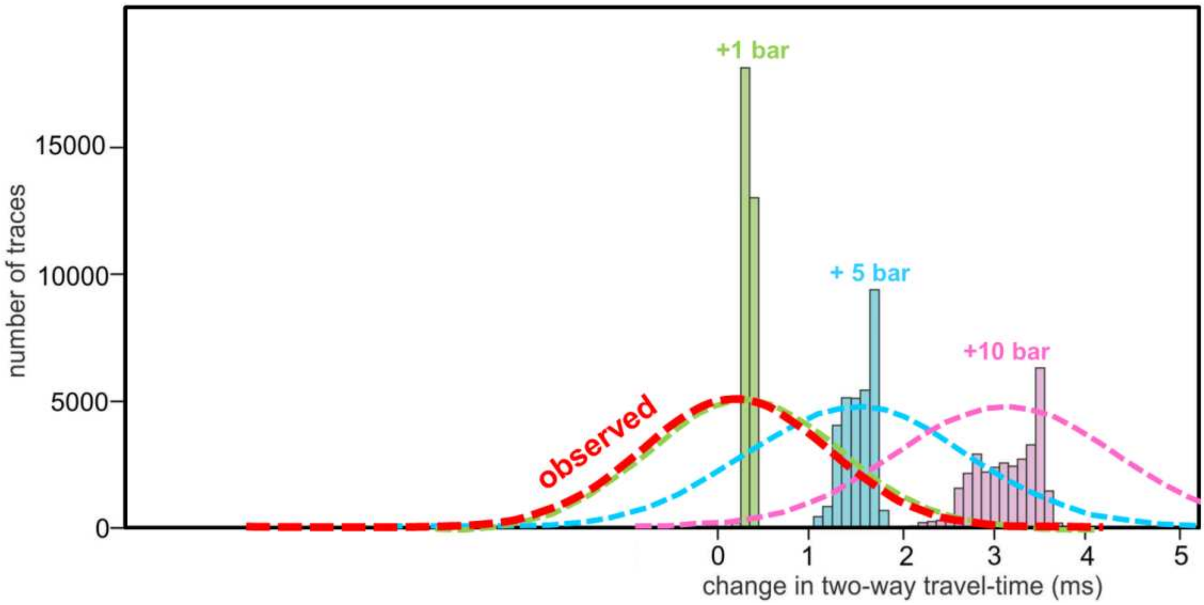

Figure 6 Time-shifts between 1994 and 2006. Bars show theoretical 'noise-free' pressure response distributions from the Utsira reservoir for 1, 5 and 10 bars. Corresponding dashed lines show the theoretical responses convolved with time-lapse repeatability noise. Red dashed line shows observed time-shifts distribution (Chadwick et al., in preparation).

Taking a broader view of conformance, Chadwick and Noy (2015) examined how accurately the large-scale development of the CO_2 plume could be modelled and predicted with time as more monitoring datasets became available. A number of key performance measures were assessed such as plume footprint, lateral migration distance of CO_2 from the injection point**,** and volume of CO_2 trapped at top reservoir. These give various insights into plume mobility and storage efficiency in the reservoir. The study reconstructed predictive modelling scenarios for 1996 (prior to the start of injection when only baseline and characterisation datasets were available), 2001 (when two repeat time-lapse surveys were available) and 2006 with five repeat datasets plus additional reservoir temperature data. The study showed a dramatic improvement in predictive accuracy as more monitoring data became available. Some uncertainties do remain in terms of reservoir properties and flow processes but the study concluded that these are very unlikely to lead to unexpected or adverse outcomes in the future.

4.1.3 Environmental impact monitoring

A number of shallow monitoring techniques have been trialled at Sleipner including side-scan sonar, pinger, single/multibeam echosounding and, as part of the ECO2 project (www.eco2-project.eu), an AUV equipped with synthetic aperture sonar to measure the acoustic back-scatter intensity of the seafloor. Video footage was taken from the gravity survey ROV in 2002, 2005, 2009 and 2011. Normal seabed conditions were encountered throughout. In the period 2001 to 2009 there was a programme to monitor total hydrocarbons and certain trace metals (Pb, Ba, Cu, Cr, Zn, Cd) in the sediments and seabed sediment pore-waters. No increase in any of the analytes has been detected.

This research work was unrelated to any regulatory requirements at the site, but was intended to develop methods that might later be used for environmental impact monitoring elsewhere.

There have been few public assurance issues with Sleipner. One potential example was an ill-informed claim of induced seismicity. In September 2009 the magazine New Scientist published an article claiming that the Sleipner injection operation had triggered a Magnitude 4 earthquake in 2008. Although not part of the operator's monitoring plan, external seismic monitoring proved effective in countering this story. The British Geological Survey global seismicity database (www.earthquakes.bgs.ac.uk/) showed that no such event had occurred and the New Scientist article was quickly retracted.

4.2 SNØHVIT

The Snøhvit storage project (Hansen et al., 2013) lies offshore of northern Norway in the Barents Sea. Natural gas from Snøhvit is transported 160 km by pipeline onshore to the Melkøya LNG plant near Hammerfest. After separation the excess CO_2 is piped back offshore for injection via a single injector well. Injection of CO_2 started in 2008 at a rate of about 0.8 Mt per year, with some 23 Mt of CO_2 planned for storage over the projected thirty year project lifetime. The Tubåen Formation formed the initial CO_2 storage reservoir with CO_2 being injected beneath the main gas accumulations at a depth of about 2600 m.

As at Sleipner, operations at Snøhvit preceded the European Storage Directive and are licensed under Norwegian offshore petroleum regulation. The operational monitoring aims at Snøhvit are twofold: firstly to maintain mechanical integrity of the reservoir and its caprock by ensuring that injection pressures do not exceed the fracture threshold, and secondly to monitor where the CO_2 plume is moving and whether it is migrating to shallower depths, which might risk impinging on the overlying gas reservoirs. The storage reservoir is at considerable depth with a great thickness of sealing overburden strata, so migration into the shallow section and leakage to seabed are not considered to be realistic risks. The primary monitoring objective is therefore to verify conformance.

Two deep-focussed monitoring technologies have been deployed at Snøhvit: downhole pressure (and temperature) monitoring and time-lapse 3D surface seismics. Although the Tubåen storage reservoir is much deeper and thinner than at Sleipner with significantly less CO_2 injected (Eiken et al., 2011) the 3D seismic clearly shows reflectivity changes and time-shifts, both close to the injection point and also farther afield within the reservoir (Figure 7).

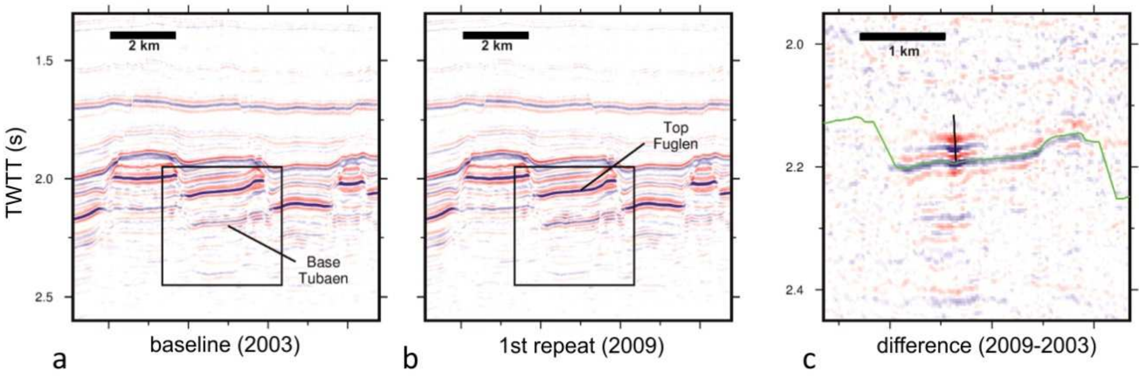

Figure 7 Seismic sections through the Snøhvit injection point. a) 2003 baseline survey showing the reservoir cut by normal faults b) 2009 repeat survey c) time-lapse difference (2009 – 2003) showing significant difference response around the injector well (black line) and also more widely within the local fault-block. (Seismic data courtesy of Statoil ASA).

4.2.1 Containment

The current Snøhvit monitoring datasets show no evidence of CO_2 migration out of the Tubåen storage reservoir. Preliminary analysis of the time-lapse seismics indicates superior repeatability compared with the Sleipner data, most likely due to the newer baseline. If this is the case then leakage detectability thresholds in the shallow section might be even smaller than at Sleipner.

4.2.2 Conformance

Pressure measurement is a key conformance tool at Snøhvit, demonstrating reservoir permeability, storage capacity and geomechanical stability. Downhole pressure/temperature sensors are positioned at a depth of 1782 m. This is several hundred metres above the injection perforations but because the CO_2 column is in the dense phase its properties are sufficiently well known for steady-state reservoir pressures to be reliably calculated from the depth difference (Figure 8). An early anomalous pressure increase in 2008 was related to near wellbore salt precipitation and was successfully remediated. Longer term pressure measurement became crucial in establishing non-conformance (Hansen et al., 2013). Pressure increase was at the upper limit of the predicted range and eventually threatened the geomechanical stability of the store as fluid pressures approached the estimated fracture threshold in late 2010. In addition, modelling of the pressure decay (or fall-off) curves, which had followed earlier cessations in injection, indicated that the capacity of the storage reservoir was smaller than anticipated, probably due to both horizontal and vertical flow barriers. Taking into account these observations and interpretations, the operation was deemed to be in non-conformance and injection into the Tubåen was suspended in early 2011.

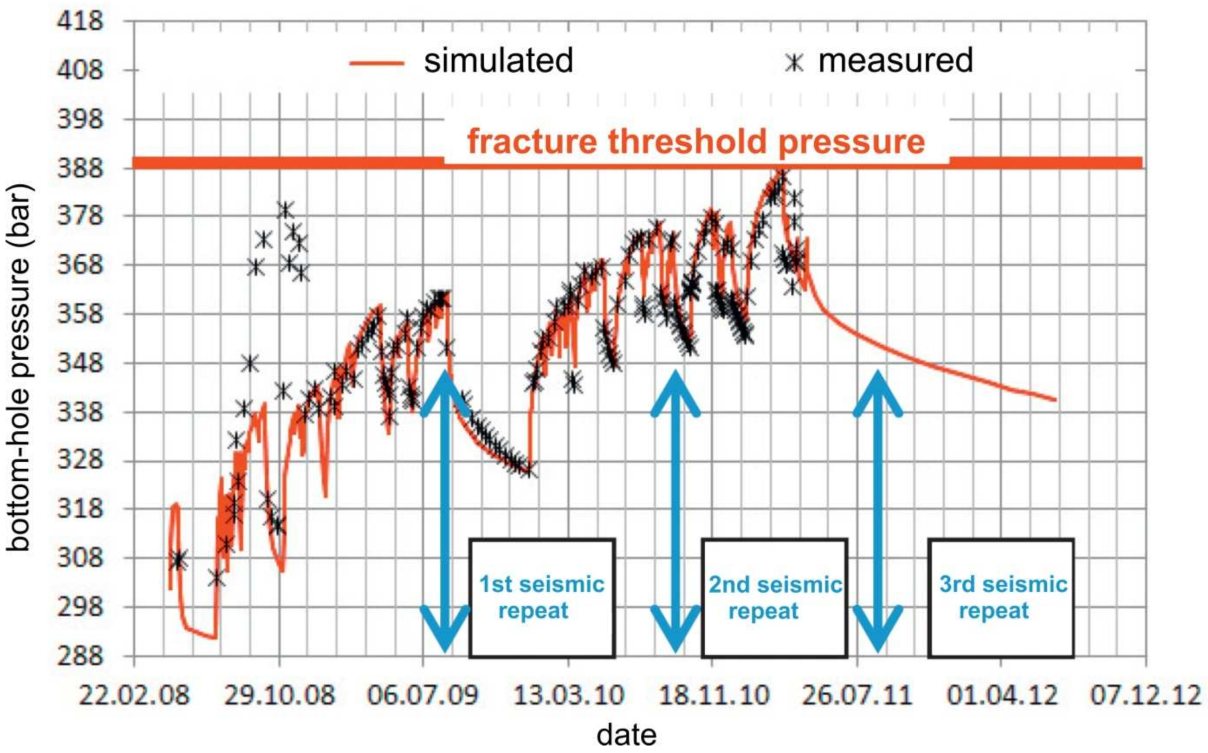

Figure 8 Downhole pressure measurement and history matching at Snohvit, 2008 to 2012. The timing of time-lapse 3D seismic surveys is also shown. (Image modified from Hansen et al. (2013)).

Subsequent to the non-conformance, Statoil set in train their previously planned remediation strategy which involved re-perforating the tubing at a shallower reservoir unit and continuing CO_2 injection in the Stø Formation. Pressure and seismic monitoring of the new reservoir have shown that the operation is now in conformance.

It is notable that although the pressure monitoring at Snøhvit ultimately led to the decision to cease injection into the Tubåen unit, by itself it was not sufficient to provide detailed understanding of fluid and pressure distributions within the reservoir. This was provided by the time-lapse seismics (Figure 9). The largest changes in reflectivity and time-shifts occur close to the injection point, but more diffuse effects extend laterally into the reservoir, before being terminated at faults. The former are interpreted as corresponding to the CO_2 plume itself, whereas the latter have been interpreted as signifying pressure changes within the surrounding water-filled reservoir (Hansen et al., 2013). The seismic data therefore show that stratigraphical complexity around the injection point was preventing free spreading of the injection plume and, in addition, faults were acting as barriers to wider fluid flow within the reservoir (Figure 9).

More detailed analysis of the time-lapse seismics (Figure 9) has demonstrated the possibility of discriminating objectively between fluid saturation changes (the CO_2 plume) and pressure changes in the wider aquifer. AVO analysis (Grude et al., 2013) and work on spectral attributes (White et al., 2015) both suggest that the seismic response at Snøhvit might be used to discriminate between pressure and fluid substitution effects. This is a potentially powerful finding, enabling surface seismic and downhole pressure measurements to be used in a strongly complementary fashion.

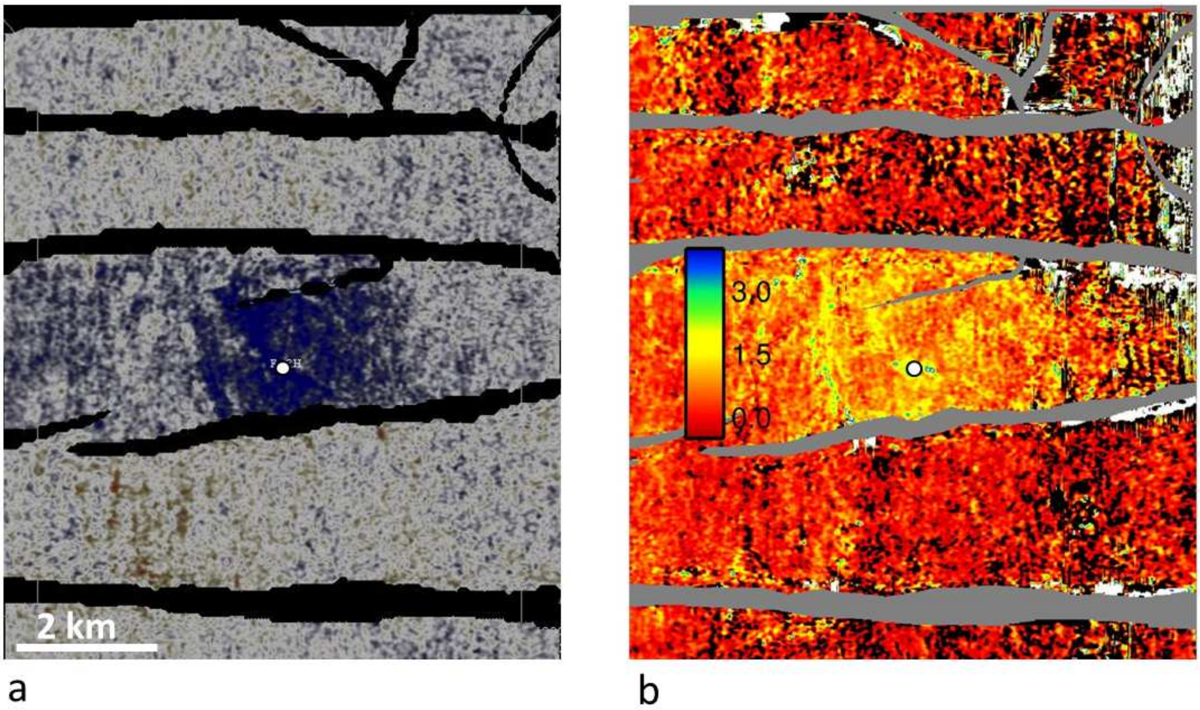

Figure 9 Maps of time-lapse changes at Snøhvit a) Reflectivity changes in reservoir b) Time-shifts at base reservoir (in milliseconds). Note how the more extensive changes terminate at the faults (black/grey lines). White disc denotes position of injection point. (Seismic data courtesy of Statoil ASA).

It is clear that at Snøhvit the most complete understanding of reservoir performance therefore came from a combination of the accurate, integrative pressure measurements and the positional imaging ability of the time-lapse seismics.

A number of shallow-focused monitoring systems have been also deployed at Snøhvit as research tools and, as is the case at Sleipner, normal seabed conditions have been encountered.

4.3 ILLINOIS BASIN DECATUR PROJECT (IBDP)

The US Department of Energy (DOE) Regional Carbon Sequestration Partnerships (RCSP) were set up with the goal of conducting pilot and full scale (>1 million tons injected) field tests during a 15 year programme across the US. The permitting environment for the injections evolved during the development of the program. Initially projects were considered to be permitted under flexible class V experimental programs; later EPA required use of Class I and Class II permits under non-hazardous waste injection and EOR permits, and the last RCSP project will be permitted under the newly promulgated Class VI rules specific to CCS.

Pure CO_2 emitted from Archer Daniel Midland's (ADM) ethanol plant in Decatur, Illinois is used for the Midwest Geological Sequestration Consortium large scale project, known as the Illinois Basin Decatur Project (IBDP), and the geological setting and monitoring program conducted at this site is reviewed here. IBDP is being scaled up to an industrial project which has received the first Class VI CO_2 sequestration permits in the US.

The IBDP injected a fraction of the ADM plant's CO_2 emissions, injecting just less than 1 million metric tons over three years (in order to not exceed the permit). The storage formation is the regionally extensive and thick basal Cambrian Mount Simon Sandstone at depths of about 2000 m in an area belonging to ADM adjacent to the plant (Finley, 2014a). The Mount Simon Formation is more than 500 m thick and is composed of sand-rich coarse grained braided plain and alluvial deposits with interbedded low permeability flood plain, aeolian, and playa deposits. The confining system is composed of the Eau Claire shale, overlain by the permeable St. Peter Sandstone. The shallower Maquoketa and New Albany shales are described as back-up seals.

The monitoring program includes conformance (described by the project as injectivity and capacity), containment (described as security), and environmental monitoring elements. Tools used include well-bore integrity logging, cased-hole logging, time-lapse VSP and surface seismic, groundwater surveillance, eddy covariance, and satellite interferometry. Elements of the monitoring programme that yielded novel results include a Westbay system (see below) in a dedicated monitoring well and a dedicated 1,061 m-deep uncased well with 31 geophones hung on tubing and cemented in place.

4.3.1 Containment

The Westbay sampler(Koch and Pearson, 2007; Schlumberger, 2015), is a system of ports and packers installed in a dedicated well that is designed to allow pressure measurements and fluid sampling from multiple zones without disturbing the system. The IBDP design used seven ports in the thick Mt Simon and two ports in the St. Peter Sandstone, which thus functions as an above-zone monitoring interval (AZMI). The propagation of pressure showed that the pressure increase in response to injection in the lower parts of the Mt Simon was 9.9 bars; above an internal low permeability baffle pressure increase was only 1.5 bar (Finley, 2014a). Repeated pulsed neutron saturation logs showed that during the 3 year injection period, the CO_2 was also confined to the lower part of the formation beneath the baffle. This is in contrast to the performance observed at Sleipner, where CO_2 passed through baffles to accumulate and spread laterally beneath the top seal. Monitoring will continue at this site to determine if this is a longer-term outcome.

4.3.2 Conformance

The pressure, fluid composition, and logging results in the injection zone, documenting an observed response similar to that predicted, are an important element of demonstrating conformance. Also, microseismicity associated with injection was measured at the IBDP starting after injection (Bauer et al., 2014; Finley, 2014b); and is interpreted as linked to an increasing area of elevated pressure. The microseismicity is located vertically in the basement and pre-Mt Simon units and laterally with lineal features associated with basement topography. Events were not located in sediments above the injection zone.

4.3.3 Environmental monitoring

Various types of trends and variation were observed in groundwater compositional data that was collected both for regulatory compliance and research (Iranmanesh et al., 2014, 2014b). Both a multi-year pre-injection analysis and a multivariate analysis were needed to demonstrate that variability was not linked to injection but was part of rock-water reaction variably related to weather and recharge.

4.4 OTWAY

The Otway Project (Stage 1) was a small-scale demonstration project in SW Victoria, Australia, located in a rural, dairy-farming area that has seen significant oil and gas activity over many decades. Over 18 months, 65000 tonnes of mixed CO_2/CH_4 were injected at a depth of 2008 m into a small depleted gas field, fault-bounded on three sides. The reservoir sand (the Waarre-C Unit C) consists of poorly sorted very fine to coarse quartz sands and occasional gravels, separated by minor mudstones. Overlying the Waarre Formation is the Flaxmans Formation, consisting of interbedded siltstone and fine grained sandstone, fining upwards to highly bioturbated mudstone, and the Belfast Mudstone, black, pyritic, offshore mudstone. The Belfast Mudstone provides the primary seal to the gas bearing Waarre Formation. Immediately overlying the Belfast Mudstone is the Skull Creek Mudstone, a secondary seal. The Stage 1 injection is fully described in Cook (2014b); Jenkins et al. (2012).

The project preceded CCS legislation in Victoria and was permitted via a mixture of regulations and some ministerial discretion. Different aspects of the site operations are covered by the State Environmental Protection Agency, by various agencies with responsibility for groundwater, and by oil and gas regulators (because of residual methane in the depleted reservoir). Reporting specific to CO_2 storage is with respect to a number of Key Performance Indicators (KPIs) administered by the EPA (Sharma et al., 2011). It has been accepted by the regulators that these have all now been met but environmental monitoring at the site is being continued to maintain a baseline for other experiments that are planned.

4.4.1 Containment

It was known before injection started that it would be difficult to image the CO_2 plume at reservoir depth by seismic methods, because of the residual methane. The KPIs focus specifically on the requirement for there to be no detected injected CO_2 in the atmosphere near the injection well, or in the head-space of a number of deep (800 m) water wells nearby. Tracers (especially SF_6) were added to the injection stream to make these measurements technically feasible. No tracers were detected above ambient levels in the designated areas. The other containment indicator required by the KPIs was that wireline logs should show no sign of CO_2 above the secondary seals and this was achieved by measurements taken after injection ceased (Dance and Datey, 2015).

The KPIs did not of course make reference to what were seen as technically challenging measurements. In the event, the 3D time-lapse seismic was able to place quite tight limits on possible out-of-reservoir migration above the regional seal, with modelling showing that amounts of about 5 kt should have been detectable in the overlying aquifer (Jenkins et al., 2012).

4.4.2 Conformance

Consistency with downhole pressure methods had been expected to be a primary indicator of conformance, as the injection is into a simple aquifer-bounded depleted container. However the pressure gauges failed on deployment into the monitoring well. The KPIs required that migration should be within the bounds of predictions, but did not specify how this should be demonstrated. Fortunately, the U-tube system in the monitoring well remained intact and fluid samples showed good agreement with the predictive models (Figure 10).

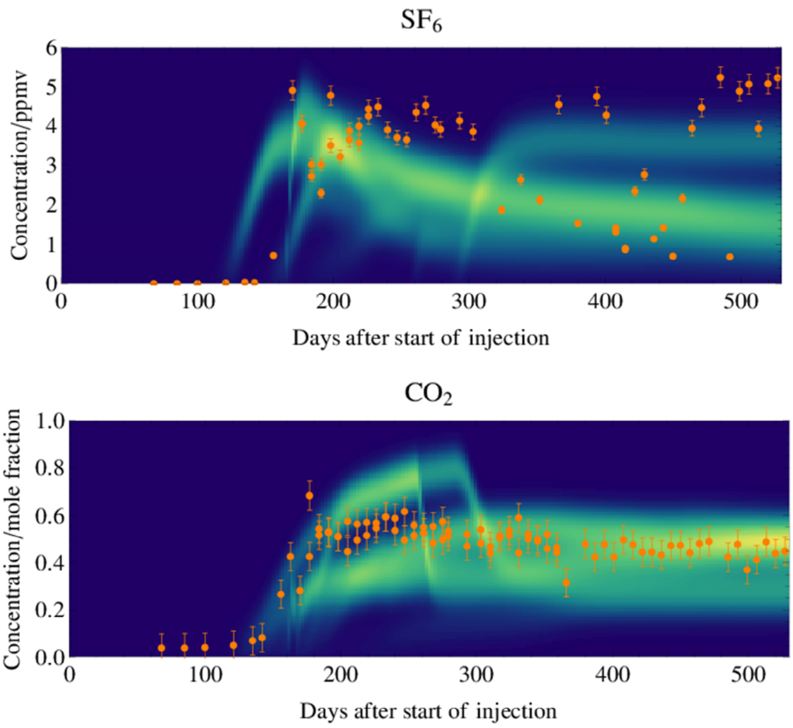

Figure 10 Fluid sampling data from the monitoring well (Naylor-1) at Otway. The orange points show the measured concentrations of CO_2 and the tracer SF_6, measured with samples taken at reservoir level with the U-tube system. A number of predictions was made based on several geostatistical realizations of the geology of the reservoir, and these are shown as the background colour scale; the lighter regions correspond to the most probable (most common) predictions at each time interval. From Jenkins et al. (2012).

4.4.3 Environmental monitoring

The KPIs made general reference to the need for environmental impact to be within legislated bounds. The specific consequence for monitoring was the need to monitor water quality in both deep and shallow pre-existing wells; these measurements were made twice a year, reducing latterly to yearly (de Caritat et al., 2013; Hortle et al., 2011). A wide range of properties was measured, but the reporting to water protection agencies focussed on pH, conductivity, and bicarbonate, comparing pre- and post-injection distributions of these quantities. These results showed variations from year to year, but post-injection results remained within the bounds that were established prior to injection.

Other environmental monitoring was carried out, partly for public assurance, partly to supplement submissions to regulators, and partly for research purposes. These somewhat vague aims typically made reporting a challenge, as it was not clear what would constitute a success in any of these domains. Monitoring in this category included an extensive annual soil gas survey (Schacht and Jenkins, 2014), and continuous passive seismic and atmospheric monitoring (Etheridge et al., 2011). The soil gas results showed considerable year-to-year variation in CO_2 concentration, both before and after injection. The largest anomalies however showed no coherent spatial patterns, and no correlation with ^{13}C anomalies (the injected CO_2, being of magmatic origin, had a very different isotopic composition to that typically resulting from microbial and plant metabolism). The atmospheric monitoring in fact succeeded in setting useful bounds on wellbore leakage to surface. The monitoring set-up could have detected spatially small areas of leakage near the well bore at a level of about 2 kt yr^{-1} (Jenkins et al., 2012; Leuning et al., 2008) and might be also included in the Containment category.

5 CCUS projects and monitoring

CO_2 enhanced oil recovery (CO_2-EOR) involving large scale injection of CO_2 from both anthropogenic and natural sources has been conducted commercially since 1972 and has increased over the decades to more than a hundred locations (Kruuskra and Wallace, 2014) predominantly in North America. The size of CO_2-EOR projects is variable, with the largest volumes stored (>80 million tonnes) at the SACROC field in Texas (Koottungal, 2014). CO_2-EOR projects are operated to maximize oil recovery, a purpose with no intrinsic conflicts, and a number of substantive overlaps, with the objectives of geological storage in terms of CO_2 containment and conformance. The preferential success and increasing numbers of projects linking anthropogenic sources of CO_2 to EOR is demonstrated by the fact that CCS projects using EOR for offtake have increased relative to saline storage counterparts (GCCSI, 2014a).

However, in North America EOR regulation, reporting and conventional business operation does not release sufficient information to provide transparent assurance that secure storage is occurring. Providing sufficient information to confirm that containment and conformance are being achieved can be done by an appropriate monitoring programme. Although the reporting or certification regime is undeveloped for long-term geological storage by CCUS, there seems to be no technical problem in devising monitoring strategies that will adequately demonstrate conformance and containment. We will review the experience from a number of CCUS projects to support this assertion, but first we make some general observations about the issues.

To show that there is benefit to the climate, a monitoring programme to document CO_2-EOR containment will be needed to support emissions accounting. It is possible that certification of secure storage might be provided by governmental or non-government third parties. There are already examples of aspects of CCS projects being certified in this way during project development. For example, the Texas Railroad Commission (which regulates oil and gas and associated activities) has enacted a process of certification of storage incremental to EOR, which requires monitoring activities but does not require any additional permitting (TAC 5.301, 2011). Similar accreditation models have been developed, but not yet applied, to US Tax Credits associated with CCS projects, including EOR ("Section 45Q") (IRS, 2009). The requirements for the necessary monitoring programmes are unclear and at the time of this review are being discussed in several North American jurisdictions. Part of this discussion is the standard that may be required of a monitoring program to document satisfactorily the containment at a CO_2 EOR project. However, several guiding principles can be derived from the last decade of experience.

The scope of the monitoring programme for EOR, as for saline storage, should be risk-based. Some elements of risk are systematically reduced at EOR sites compared to equivalent sites operated for saline storage, some risks are similar at the two types of sites, and some risks are larger at EOR sites. Duplicating monitoring activities designed for a saline site might not only fail to meet the different risk profiles, but could be ineffective because of conditions at the EOR site (Wolaver et al., 2013). For example engineered pressure gradients must be considered, as they can enhance or damage ability to detect leakage, prevent leakage, or if removed allow post injection migration.

The monitoring programme for EOR must be closely tied to the operational programme, as this already potentially provides much of the needed data, for example high-frequency accounting of the composition and volumes extracted and injected and the pressure response of the reservoir. However, typical operational monitoring and modelling programmes at EOR sites are probably insufficient to provide robust evidence of containment and conformance, and monitoring programmes will need to be tailored to these sites. An important example is the characterization, remediation, and surveillance of performance of the many wells in a typical EOR system. Reporting of these data to regulatory authorities is typically inadequate to support a monitoring programme (Gan and Frohlich, 2013; Porse et al., 2014). It is important to implement a protocol to make data from the operator's confidential records available for the monitoring programme. However it is possible that not all data need be fully publicly disclosed in order to provide assurance of storage. To increase the sensitivity of the monitoring programme it might also be necessary to collect higher frequency data than is typical at present, extending data coverage in the reservoir, and collect pressure or compositional data from shallower zones. Finally, full modelling of the response of all the well patterns to all of the changes of injection and withdrawal might be burdensome and not very sensitive to out-of-pattern migration or vertical leakage. Models designed to identify the potential uncertainties and optimize detection of material deviations in the reservoir response that could lead to leakage are needed.

5.1 CONTAINMENT IN CCUS

In considering monitoring for CCUS, it is important to review current practices and the current level of risk. The accumulation of hydrocarbon over geological time in an oil reservoir reduces one of the largest uncertainties in aquifer storage; the existence and continuity of a top-seal capable of retarding vertical migration. The lack of large areas of pressure increase during injection will also tend to reduce containment risk. Conversely, penetration of the top seal by numerous wells may increase leakage risk. EOR operators have numerous strategies in place to assure the proper function of wells in containment. In the USA under the UIC class II program operators are required to determine, and then maintain, the integrity of all wells within a specified radius (typically ¼ mile) of injectors (Environmental Protection Agency, 1980). Operators are also financially motivated to conserve CO_2 for recycling, and to avoid the failure of well control that would entail loss of revenue during times injection was stopped for well repair. The cost of repairing wells and cleaning up spills that include oil and brine also motivates operators to monitor their performance. Evaluation of existing well management programmes is hampered by poor record keeping, but suggests that well failure during injection is uncommon and that CO_2-EOR does not elevate risk compared to other types of injection such as water flood (Porse et al., 2014). Loss of large amounts of fluid from the intended injection zone to shallower horizons ("subsurface blowouts") are avoided by EOR operators both because of the cost of lost CO_2 and pressure and because of the potential loss of CO_2 to surface. At least two examples of CO_2 migrating to intermediate zones followed by escape to the surface have been reported, at Salt Creek Field Wyoming (U.S. Department of the Interior, 2006) and at Delhi Field, Louisiana (Denbury, 2013). However, we know of no technical reports detailing the volumes lost or impacts on environment or resources, probably because all incidents have had low consequences.

Another containment risk that is more probable with EOR than in saline settings is unexpected lateral migration of CO_2 to an unprepared well. The fastest escape path is via a producing well that is not on recycle; either via a well of the unit in operation or a by well belonging to another operator. We know of no published reports evaluating this history, but anecdotes are known amongst EOR operators. Containment of CO_2 within well patterns is typically managed by a combination of production, creating strong pressure sinks, and by water injection "water curtains" creating high pressure barriers. So far as we are aware, evaluations of the effectiveness of these practices are not in the public domain. However commercial management and mitigation for CO_2-EOR is well established, with numerous techniques available for diagnosing and remediating damaged or questionable wells (Skinner, 2002). Plugging damaged wells and drilling new or side-tracked new sections is probably the most common remediation, as is pressure management via water curtains and production wells.

It is important to note that so far we have been unable to document unacceptable outcomes resulting from the current EOR operations, where conformance, containment and mitigation are motivated by a combination of regulations concerning well integrity as well as economic drivers. It is difficult to prove a negative, however substantive programs designed to identify CO_2 leakage from EOR operations at three fields (Weyburn, SACROC and Cranfield), failed to identify evidence of leakage (Beaubien et al., 2013; Romanak et al., 2012b; Yang et al., 2012). A study of soil gas emissions at Rangley Field Colorado identified microseepage of methane as well as CO_2 derived from methane oxidation, however the identification of CO_2 derived from the EOR operation is undetermined (Klusman, 2003). An attempt to broaden the database by searching for litigation resulting from escape of CO_2 did not identify any cases in Texas, where there is much CO_2-EOR; trespass by CO_2 has been either uncommon, settled out of court, or (anecdotally) been beneficial to the impacted wells in terms of increased production.

5.2 CONFORMANCE IN CCUS

Production history is a major source of data that can be used to greatly improve confidence in how the reservoir will respond to CO_2 injection as compared to a previously unused saline site. Production history provides a multi-decade calibration period to predict how the reservoir will respond to injection and is the starting point for planning and designing a CO_2-EOR project (Hosseini et al., 2013). A well-documented production history can provide both input and validation periods to create a calibrated multiphase pressure and mass-balance constrained fluid flow model before CO_2 injection starts, greatly reducing the burden on conformance monitoring. It should be noted that introduction of CO_2 in an EOR setting will expose the same types of uncertainties as it does in a saline injection, for example in terms of fluid interaction with reservoir heterogeneity.

CO_2-EOR projects require patterns of producers to capture oil and CO_2 flowing away from injectors. Production wells form the essential element of EOR and are used for engineered active management of the area occupied by CO_2 as well as active pressure management. Typically the operator tracks the volume of CO_2 injected, wellhead pressure at all wells, and the volumes of CO_2, brine, and oil extracted from the field and from each well daily, however accurate quantification of fluids of mixed composition is difficult, and high quality quantification is typically spatially and temporally focused. Other monitoring data are collected on an as-needed basis and may include injection and production logs showing where fluids are leaving or entering well perforations, bottom hole pressures under flowing or shut-in conditions, wireline saturation, 3-D or 4-D seismic or gravity surveys to assess fluid distribution, microseismic surveys to assess fluid migration and many other types of standard oilfield survey - for examples see CO2 Capture Project Team (2009). Operators use these data in modelling the flood performance using both analytical and numerical models.

The operator's voluntary surveillance activities comprise most elements of a CCS conformance programme, but they are typically not released into the public domain. Also, monitoring is focused on optimization of production and is not necessarily concerned with conformance, as understood in CCS. For example, the operator may invest heavily in models of well patterns to optimize injection and withdrawal locations and rates but these models might not conceptualize unintended out-of-pattern migration. If the risk is not conceptualized in a model, the monitoring strategy to detect conformance may be misdirected.

5.3 EXAMPLES OF MONITORED CO_2-EOR SITES

5.3.1 Weyburn

The longest running and most comprehensively documented monitoring programme at an EOR operation is at the Weyburn and Midale fields in Saskatchewan, Canada (Hitchon, 2012). The operation is principally CO_2-EOR, with CO_2 injection starting in late 2000 at rates of between one and two million tonnes per year and more than 22 Mt of CO_2 currently stored. The storage reservoir comprises the thin, calcite-dolomite Midale reservoir at a depth of about 1500 m. A thick variable overburden containing both aquitards and aquifers extends to the surface.

It is important to note that injection was part of a normal EOR project under provincial injection permits and no monitoring or reporting of retention was required as part of the injection permitting or from the supplier of anthropogenic CO_2 at the Dakota gasifier. Monitoring therefore has been primarily research oriented within a two-phase R&D programme (Hitchon, 2012; Wilson and Monea, 2004).

Deep-focussed monitoring at Weyburn (White et al., 2014a) has included downhole pressure measurements and downhole fluid sampling (Johnson and Rostron, 2012) together with a comprehensive time-lapse 3D seismic monitoring programme (including some multi-component measurements), down-hole active seismics (VSP and cross-hole) and downhole passive seismics. The strong downhole monitoring component reflects the large number of wellbores, of varying geometry, which transect the storage site (**Error! Reference source not found.**).

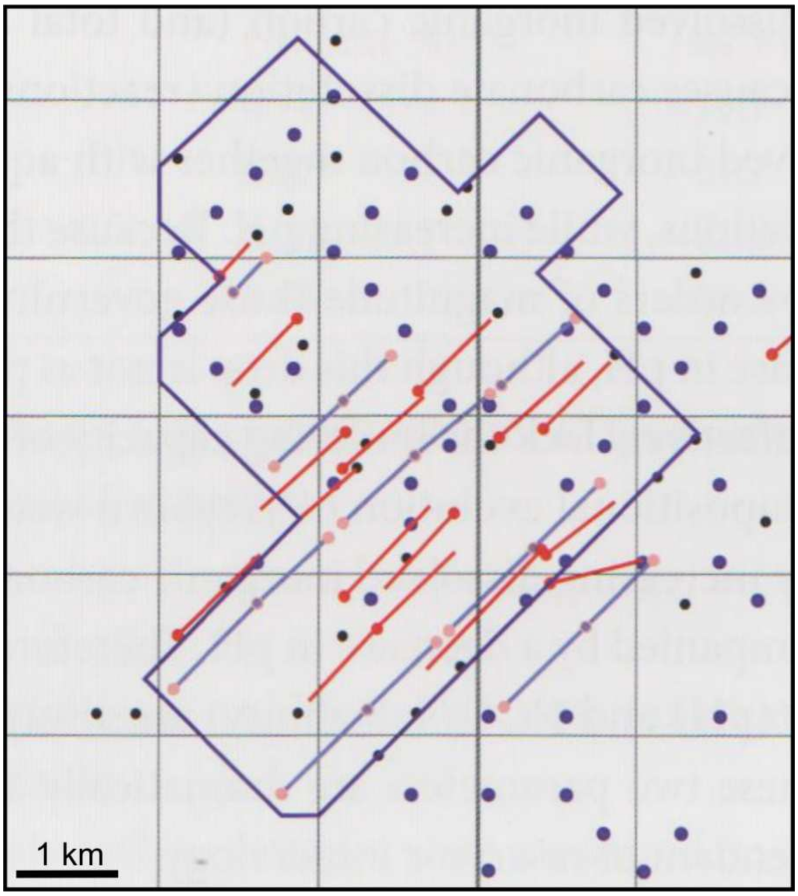

Figure 11 Map showing the Weyburn wells. Horizontal and vertical production wells denoted by red lines and black dots respectively. Horizontal and vertical CO_2 injection wells shown as blue lines and blue dots respectively (Johnson and Rostron, 2012).

5.3.1.1 CONTAINMENT

The time-lapse 3D seismic programme included a three-component baseline survey and repeats in 2001, 2002, 2004 and 2007. These provide robust spatial coverage of the overburden and mapping of small time-shifts has been used to place upper bounds on out-of-reservoir migration of CO_2. Interval travel time changes were mapped from the time-lapse seismics (White, 2013a) for four stratigraphical intervals: shallower and deeper overburden (Os and Od), reservoir top seal (T) and reservoir plus underburden (R). The reservoir interval shows time-shifts of up to 2 ms clustered around the CO_2 injection wells (Figure 12). The Watrous top seal also shows smaller but significant time-shifts, some associated with pressure effects around water-injection wells. By contrast the two overburden intervals show few if any significant time-shifts (Figure 12).

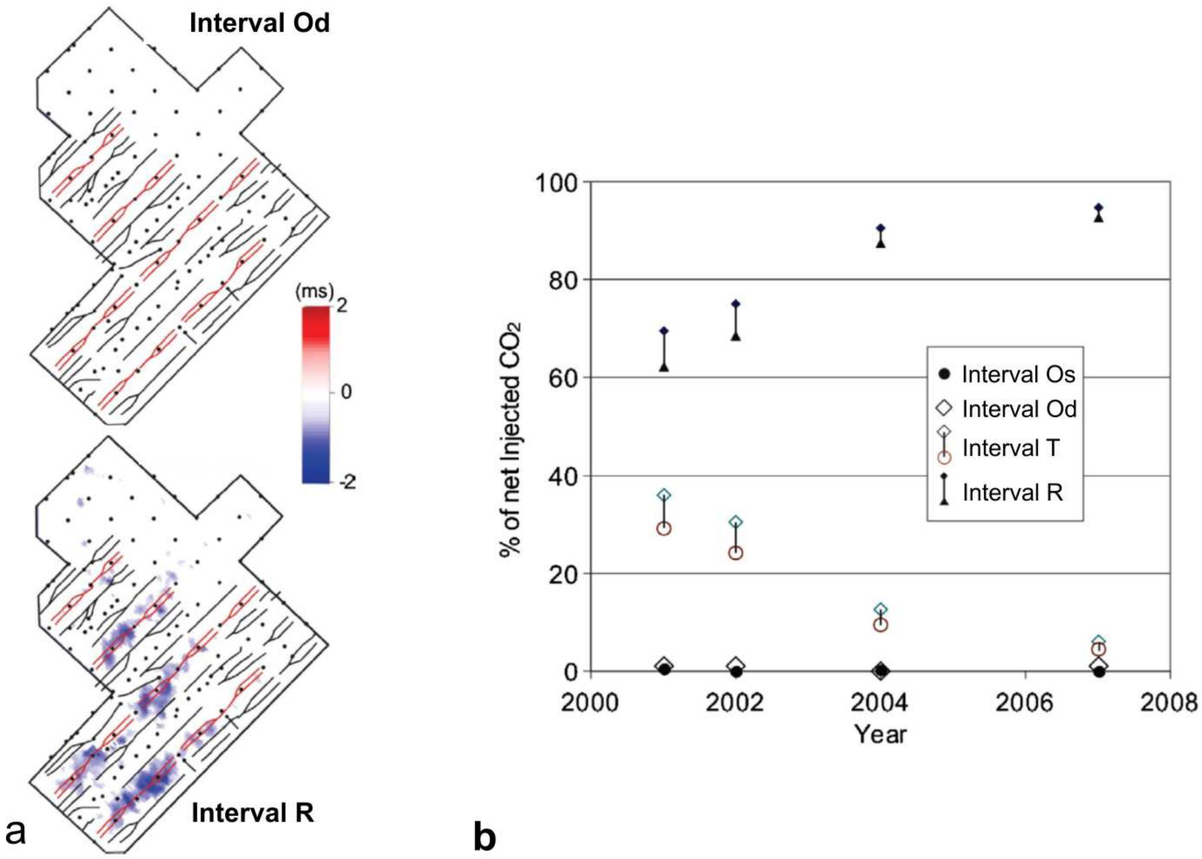

Figure 12 (a) Map of travel-time differences for the deeper overburden interval (Od) and the reservoir interval (R) b) Seismic based relative mass estimates by stratigraphical interval. Red and black lines denote horizontal injection and production wells respectively (modified from White (2013b)).

Application of appropriate rock physics enables time-shifts to be converted into CO_2 thicknesses, which mapped spatially, translate into CO_2 volumes. From these, upper limits on the amounts of CO_2 in the four intervals can be estimated (Figure 12). It is clear that the upper bound on possible CO_2 in the two overburden layers is extremely small, less than 1% of the injected amount for Od and effectively zero for Os. A portion of CO_2 might reside in the immediate top seal to the reservoir, but this is likely to be 5% or less after 7 years and may well be falsely inflated by pressure effects. The vast bulk of the CO_2 resides in the storage reservoir, the minimum amount rising to approximately 94% after 7 years. If current trends continue, this will increase further as the total amount of stored CO_2 rises with time but the time-shift signals of the analysed intervals remain relatively constant.

5.3.1.2 CONFORMANCE

The deep-focussed monitoring datasets at Weyburn were used for performance verification by history-matching the data to reservoir simulation and reactive transport flow models (Johnson and White, 2012). The key performance verification criteria were CO_2 distributions from the 3D time-lapse seismics and water compositions and isotopic data from the reservoir fluids sampling campaign (Johnson and Rostron, 2012).

Systematic time-lapse changes in seismic amplitude and time-shifts have been observed in the reservoir around the horizontal CO_2 injection wells and can be explained by a combination of CO_2 saturation and pressure increase (Figure 13).

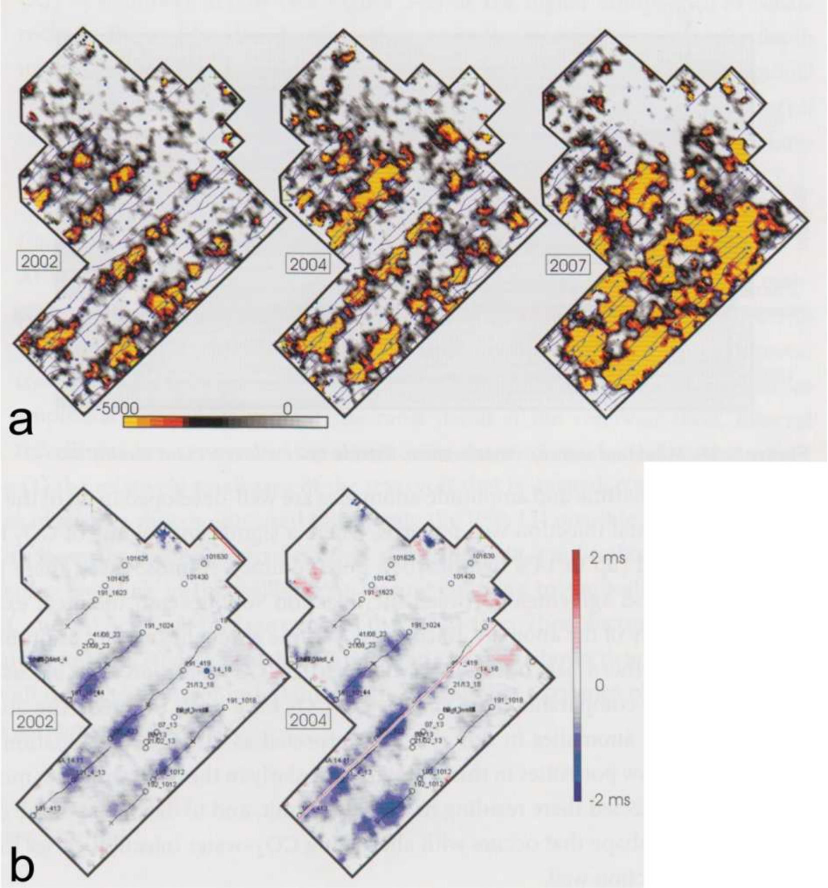

Figure 13 3D time-lapse seismics at Midale reservoir level showing maps of time-lapse changes concentrated around the NE-SW trending horizontal injector wells. Top panels show seismic amplitude changes between the baseline data and subsequent repeats in 2002, 2004 and 2007. Bottom panels show corresponding increases in travel-time beneath the reservoir (modified from White (2012)).

A number of analytical methods have been tested on the seismic data to try and discriminate between the effects of CO_2 saturation change and pressure. These include analysis of p- to s-converted seismic waves, and amplitude-versus-angle (AVA or AVO) analysis. The converted wave analysis was unsuccessful due to poor quality P-S arrivals from the reservoir. Trace-by-trace AVA analysis also showed limited efficacy due to high noise levels on the pre-stack data. However AVA analysis using partial offset stacks combined with an impedance inversion scheme was able to identify systematic changes in p- and s- impedance which enabled estimates of pressure and saturation changes to be made (Figure 14). Results suggest pressure increases up to around 8 MPa and CO_2 saturations approaching 1.0.

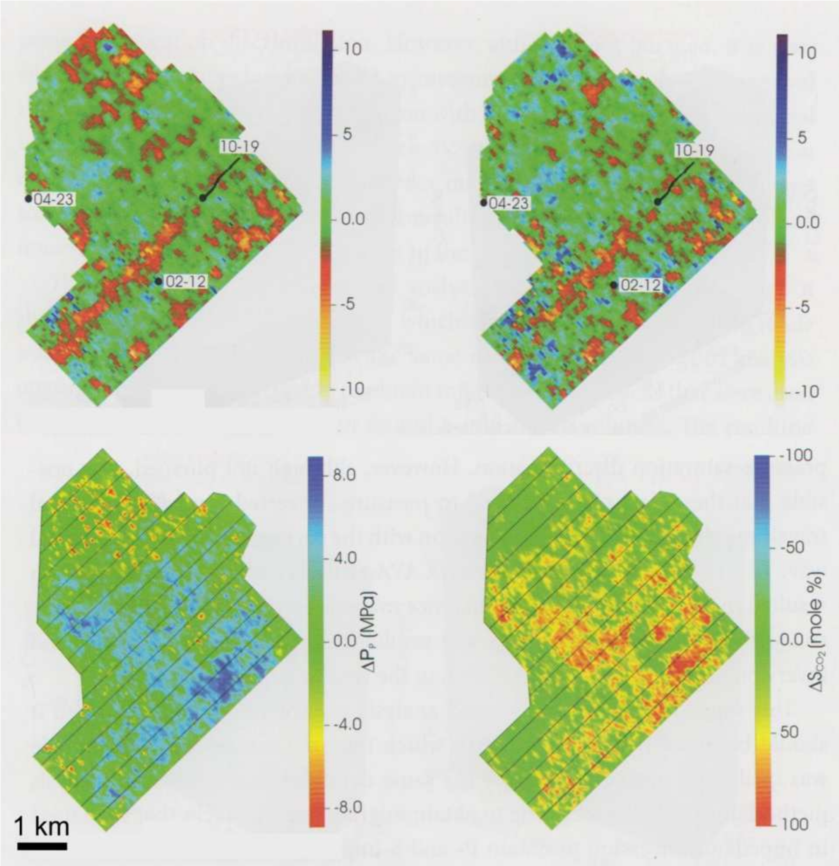

Figure 14 Time- slices changes at Midale reservoir level between 1999 and 2002. P-impedance change (top left) and s-impedance change (top right) compared with inverted pressure change (bottom left) and CO2 saturation change (bottom right) (modified from White (2012)).

Passive seismic monitoring comprised a geophone array located about 200m above the reservoir. Low intensity microseismicity (magnitudes typically between -3 and -1) was evident (White and Weyburn Geophysics Monitoring Team, 2011) with around 200 events recorded between 2003 and 2010. Events are located within, above and beneath the reservoir and show some correlation with specific operational activities in the field. There is some spatial correlation with some of the 3D time-lapse seismic amplitude anomalies indicating CO_2 or pressure changes, but this is not consistent. Overall the programme has been beneficial for public assurance notably with respect to demonstrating a lack of induced earthquakes.

Tracking the geochemical evolution of the storage reservoir is of particular importance in carbonate-dominated lithologies such as are found in the Midale reservoir, where dissolution of the host rock might induce severe changes in permeability. A number of chemical parameters can be measured in order to calibrate and verify geochemical and reactive transport models to understand and characterise the CO_2 – induced reactions in the reservoir. The initial process of CO_2 dissolution in formation water lowers pH, raises total alkalinity and increases dissolved inorganic carbon (DIC). The lowered pH then causes carbonate dissolution reactions which also increase dissolved inorganic carbon but tend to raise pH. Fluid chemical measurements and sampling at Weyburn comprised baseline data gathering in 2001 followed by 16 repeat surveys up to 2010 (Johnson and Rostron, 2012). Measured properties included alkalinity, pH, calcium and DIC stable isotopes (Figure 15).

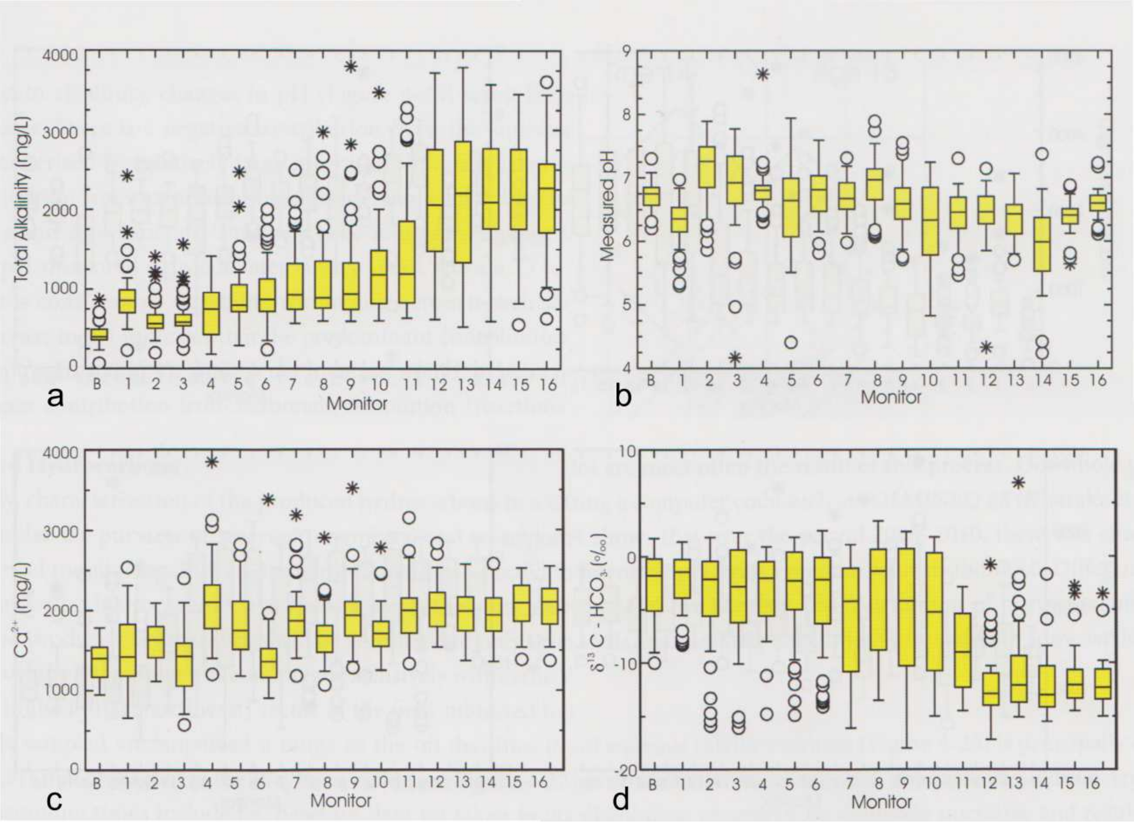

Figure 15 Reservoir fluid sampling results from Weyburn a) total alkalinity b) pH c) Calcium ion d) change in $\delta^{13}C$ of Dissolved Inorganic Carbon (Johnson and Rostron, 2012).

These are all consistent with the effects of early CO_2 dissolution in the formation waters, followed by the gradual dissolution of carbonate. The direct effects of CO_2 dissolution (e.g. lower pH) are generally dominant but the slower rate effects of carbonate dissolution become increasingly evident with time, increasing calcium ion content (Figure 15) indicative of calcite dissolution. Similar increases in magnesium content indicate progressive dissolution of dolomite. There is significant spatial variation with effects tending to be greatest in the southeast of the area where most of the CO_2 has been injected.

In addition to the deployed techniques a number of feasibility studies were carried out for other monitoring tools, including InSAR, electrical resistance tomography and microgravimetry. The latter two techniques were considered insufficiently sensitive for use at Weyburn but InSAR was thought to have potential application. Due to the seasonal vegetation cover its use would require the installation of a network of permanent scatterers, in addition, due to possibility of seasonal ground movements, a year or more of pre-injection monitoring would be probably be required.

5.3.1.3 ENVIRONMENTAL MONITORING

In collaboration with the operators, but not forming part of their regulatory obligations, a variety of shallow monitoring techniques has been tested at the Weyburn site. This included soil gas, soil gas flux, groundwater composition, including noble gas isotopes and atmospheric concentrations. (Jones and Beaubien, 2005; Riding and Rochelle, 2005; Strutt et al., 2003). These techniques had a limited spatial footprint and were not intended to test containment or conformance.

As is well known, an allegation was made by landholders during 2011 that leakage of CO_2 had occurred to their property. The so-called “Kerr Affair” led to an intensive analysis of existing background data, as well as campaigns to obtain new data. Although existing datasets were extensive, they did not include the area where leakage was alleged; however it was possible to show that the claimed CO_2 and $\delta^{13}CO_2$ anomalies were within the expected ranges from other, nearby sites (Beaubien et al., 2013). Noble gas data likewise showed no evidence of a deep origin of gases reaching the near-surface (Gilfillan, 2013). These conclusions were strongly reinforced by the baseline-independent process-based method of analysis, which was able to draw conclusions without extrapolations from elsewhere (Romanak et al., 2013; Romanak et al., 2014b). While it proved possible to demonstrate that measurements from the Kerr Farm were similar to those obtained elsewhere, both during previous campaigns and at the time, the episode illustrated the very large amount of effort that might be required to deal with allegations of leakage. Since there was no definite leakage mechanism proposed, it was also impossible to interpret the available data to set any definite limits on leakage.

5.3.2 SECARB Cranfield Early test

The Southeast Regional Sequestration Partnership (SECARB) was developed as part of the RCSP by the Southern States Energy Board (SSEB) with a focus on supporting the geologic storage component related to Southern Company’s ambitious plans to conduct large scale CO_2 capture. As part of this, construction has been completed at the 582 MW Kemper County Energy lignite gasifier at Plant Ratcliff, Mississippi, with start-up scheduled for 2016 (Mississippi Power, 2015). CO_2 from this plant (~3.5 Mt / year) will be sold commercially into the regional pipeline network and used for EOR, with no monitoring beyond current commercial practices.

However, in 2006 toward the early stages of the SECARB project the project partners decided that because of uncertainty in how fast the capture projects could develop, it would be advantageous to conduct an early test with a focus on monitoring large volume injection. The site selected for the early test was at Cranfield, operated by Denbury Onshore LLC, an EOR project using natural CO_2 injected at rates of about 1 million metric tons per year. During the first stage, monitoring was focused on documenting containment in a complex EOR setting. A second phase focused in the down-dip water leg addressed issues of conformance by measuring observed plume evolution using many tools and matching the observations to models.

The middle Cretaceous Tuscaloosa Formation at Cranfield forms a relatively simple domal structure, with the top at 3km above a salt pillow at greater depth. The field originally had a large gas cap and an underlying oil rim, and was produced from 1942-1966, including a long period where gas was extracted, congas condensate stripped and methane re-injected. A graben at the top of the structure creates two faults which are sealing over much of their length that segment the field. The lower Tuscaloosa Formation is composed of gravelly sandstones deposited in a complex incised fluvial system so that the 20-30 m thick unit is in good pressure communication and has highly heterogeneous permeability which is enhanced by variable cementation (Kordi, 2013).

Cranfield provided a number of advantages not found in other fields in terms of testing conceptual and numerical models. Unlike most EOR operations (e.g. Weyburn), the field did not undergo a water flood prior to CO_2 injection. The field was abandoned in 1966 and so underwent four decades of pressure recovery and fluid re-equilibration, which is a simpler starting point for modelling. The production history is documented in detail, summarised in (Mississippi Oil and Gas Board, 1966). During the period July 2008-February 2015 when the project was monitored by SECARB, 5.3 Mt of CO_2 from a natural CO_2 source at Jackson Dome were injected. About an equal amount of CO_2 was produced, separated from oil and re-injected as part of the EOR project recycle.

5.3.2.1 CONTAINMENT

The containment monitoring programme at Cranfield deployed for the first time in CCS a well-known gas storage monitoring technique: measuring pressure in a permeable zone overlying the injection zone (Katz and Tek, 1981). The pressure increase in the injection zone at 3000 m depth is as much as 8 MPa over hydrostatic pressure. AZMI (Above Zone Monitoring Interval) pressure monitoring in a thin sandstone about 100 m above the injection zone has detected 7 bar increases in pressure that have been history matched either to geomechanical pressure propagation (Kim and Hosseini, 2014) or attributed to hydrologic response at a leakage point away from the observation well (Tao et al., 2013). Time-lapse 3-D seismic monitoring has detected no velocity change above the injection zone, although repeatability noise to some extent might weaken this finding (Carter, 2014; Ditkof et al., 2013). If the results of the seismic survey are accepted as evidence that no large amount of CO_2 has migrated to the AZMI, the pressure signal can be attributed to brine migration. Single AZMI installations were designed to obtain proof of concept; to bound leakage rates quantitatively would require multiple AZMI installations in each horizontally isolated fault block (Sun and Nicot, 2012; Sun et al., 2013a). Possible flow paths include failed well completions that allow hydrologic connection between the injection zone and the AZMI or vertical flow up fracture systems near a laterally sealing fault.

5.3.2.2 CONFORMANCE

The RCSP programme requires an evaluation of storage capacity, which plays a similar role to conformance. The approach taken to conformance monitoring at Cranfield was not comprehensive, but was fitted to the projects' role as an intermediate step to test a large number of tools and approaches.

A detailed study area (DAS) was developed as a test bed, down-dip of the oil production area in the saline aquifer. Two observation wells were placed 70 and 100 meters down-dip of the DAS injection well to analyze flow at a closer spacing than usual and to assess in detail a typical unit volume of the flow system. The performance of multiple tools used to assess the evolution of the CO_2 plume were compared both for fundamental and operational limits (Hovorka et al., 2013b). Time-lapse pulsed neutron, sonic , and resistivity logging was conducted in an interval with non-conductive casing (Butsch et al., 2013). Pre-injection cross-well seismic was repeated after one and 5 ½ years of injection. Electrical resistance tomography (ERT) was conducted daily over a year, and changes in the response can be related to the evolution of the plume; (Carrigan et al., 2013; Doetsch et al., 2013). Natural tracers (isotopically distinctive CO_2) and dissolved methane in reservoir brine and emplaced pulses of SF_6, PFT, and noble gas tracers provided data on fluid flow not available from imaging (Lu et al., 2012a). A well-bore gravity tool was deployed and was able to detect changes due to substitution of CO_2 in relatively thin intervals (Dodds et al., 2013). In addition, a baseline 3-D seismic survey was conducted over the field with a repeat survey after injection of the first 1 million metric tons. A complementary sonic logging and 3-D VSP programme was also executed.

Outcomes from the work at Cranfield can be extrapolated to other projects. Forward modelling of the ability of tools to detect substitution of CO_2 for brine proved to be accurate in application. The observed response of ERT was especially significant, as it appeared to show increasing saturation over time, a favourable conformance outcome. However, comparison among multiple tools analyzing the same signal in the reservoir showed that the effect of assumptions made during processing, noise and non-repeatability were larger than anticipated. Large non-repeatability arose from deployment issues, which could potentially be avoided in future projects. Other factors, as described below, leading to imprecision and non-repeatability in monitoring measurements probably cannot systematically be improved but should be considered as uncertainties to be expected during project planning.

Examples of techniques that can be improved include instrument relocation in gravity surveys, the deployment of electrical resistance tomography (ERT) electrodes and cabling to increase the probability of success of the installation and reduce noise, the incompatibility of resistivity logs and ERT electrodes because of excessive interference and the durability of gauges and geophones at the depths and temperatures at this site. Examples of difficult-to-reduce uncertainty include non-unique inversions of the data collected and low signal-to-noise ratios. For example the ERT analysis of Doetsch et al. (2013) can be compared to Carrigan et al. (2013) to illustrate the impact of various types of assumptions during inversion of ERT data. Similar outcomes were observed in the different processing of the time-lapse cross-well and time lapse surface 3-D seismic Ajo-Franklin et al. (2013) compared to Butsch et al. (2013). In different inversions, the same trends can be observed, however a significant uncertainty bar needs to be applied to the outcomes of the measurements made.

A related source of uncertainty is modelling dense measurements of the fluid flow system. The complex facies architecture cannot be adequately constrained even using relatively closely-spaced wireline-log and seismic data. The interpretation of the tracer arrivals at the observation wells indicates a channel flow system that by-passes the closest observation well as the plume develops. This matches well with the ERT images which show separate “blobs” of CO_2 that can be interpreted as channels crossing the plane imaged in the inversion (Hovorka et al., 2013a). Standard stochastic approaches can be used to generate geometries that fit this interpretation (Hosseini et al., 2013) but even with 100 realizations as a starting point, no case matches available data in detail. This experiment may be useful to develop methods to determine how good a match between modelled and observed reservoir response is required in a regulatory environment.

A third limitation exposed by the SECARB study at Cranfield is the extent to which seismic data might be expected to provide a desired level of assurance. The time-lapse 3-D seismic was successful in imaging CO_2 and analyses were completed in a number of studies (Carter, 2014; Carter and Spikes, 2013; Ditkof, 2013; Zhang et al., 2013). However, the ability of these inversions to map the plume is limited because 1) no change was observed in some areas where injection and withdrawal document the presence of CO_2, and 2) signal-to-noise ratio at the edges of the plume are too low to create a reproducible CO_2 extents map. Complexities such as noise and other repeatability errors, reduction in fold of cover toward the edges, thin areas of CO_2 and possible presence of residual methane might account for some of the limitations, and additional survey or improvements in processing could be proposed. However, realistically this tool at this site under these circumstances is of only modest value for demonstrating conformance.

5.3.2.3 ENVIRONMENTAL MONITORING

A controlled CO_2 release experiment conducted in shallow (120 m) groundwater has defined the signal that would be expected should CO_2 reach freshwater aquifers, and emphasized the importance of collection of dissolved inorganic carbon (DIC) and dissolved CO_2 (Yang et al., 2013). Quarterly groundwater sampling at an array of groundwater monitoring wells (one at each injector) has detected little change in groundwater and no signal or trend indicative of leakage of CO_2 or brine (Yang, in preparation). Soil gas has been shown to be dominated by atmospheric signal. One soil gas monitoring point with displaced methane and CO_2, initially thought to be related to potential leakage along a historic well has been shown by $\delta^{14}C$ composition to be of modern composition, and so cannot be indicative of leakage from the deep subsurface (Romanak, personal communication).

5.3.3 Other sites

A study conducted over the longest running (and largest volume injected) CO_2-EOR project at the SACROC field found no indicators of CO_2 leakage from the injection zone at >2000 m depth to the freshwater Dockum or Ogallala groundwater system. Selecting the correct geochemical parameters (e.g DIC, or dissolved CO_2) shows that this groundwater is very sensitive to CO_2 (Romanak et al., 2012b; Yang et al., 2014c).

Other R&D oriented monitoring programs at EOR projects conducted by Plains CO_2 Reduction (PCOR) partnership at Bell Creek Field, Montana, by Midwest Regional Carbon Sequestration partnership (MRCSP) at several pinnacle reef fields in Michigan and by Southwest Partnership (SWP) at Farnsworth field are reviewed in a NETL best practices report (NETL, 2012). Only preliminary results from these programs are currently publicly available.

6 Shallow-focussed monitoring

Over the decade there has been significant development of what we will label “shallow focussed monitoring”. This term includes monitoring of groundwater, soil gas and soil flux, atmospheric concentrations, shallow geophysics such as resistivity, flora (types, abundance and health of plants) and soil microbial populations, seabed features, bubbles and water-column chemistry. Sometimes these activities are called “assurance monitoring”, sometimes “environmental monitoring” and sometimes they are part of the study of possible “environmental impact”. If there is a specific and well-defined risk of CO_2 reaching the near surface, shallow monitoring might have a role in verifying containment; and if it does reach the surface, quantification will be needed in some jurisdictions. Within the general area of shallow monitoring there are clearly a variety of motivations and possible applications.

Supporting each of these areas is a very large amount of research. Groundwater monitoring is described by, amongst others, de Caritat et al. (2013); Hortle et al. (2011); Iranmanesh et al. (2014, 2014b). The use of soil gas in monitoring various projects is described in Beaubien et al. (2013); Romanak et al. (2013); Romanak et al. (2012a); Romanak et al. (2014b); Schacht and Jenkins (2014); Schloemer et al. (2013). A very useful review of near-surface gas-based methods is in Klusman (2011).

Atmospheric methods, including soil flux measurements, were reviewed in general by Leuning et al. (2008) and later concentration techniques were tested, and then applied at the Otway project in Etheridge et al. (2011); Loh et al. (2009); Luhar et al. (2014); Wilson et al. (2014). At ZERT, the focus was on eddy covariance methods, described in Lewicki and Hilley (2009, 2012); Lewicki et al. (2009a, b); Lewicki et al. (2005); Lewicki et al. (2007). Mobile measurements of concentration were demonstrated at In Salah (Jones et al., 2011) and at the natural seeps at the Laacher See and Latera (Jones et al., 2009; Krueger et al., 2011).

Seabed and water column measurements are reviewed by Blackford et al. (2015); Blackford et al. (2014), with much detailed work in the associated special issue on the QICS experiment. Isotopic analysis is very useful in interpreting shallow data, with possibilities including $\delta^{13}C$ (Beaubien et al., 2013; Moni and Rasse, 2014), $\delta^{14}C$ (Donders et al., 2013; Turnbull et al., 2014) tracers (Myers et al., 2012) and noble gases (Gilfillan, 2013). More citations on techniques are given in the project-specific sections of this review, and later in this section.

Additional significant research has been undertaken at controlled release sites: ZERT (Spangler et al., 2010), Ginninderra (Feitz et al., 2014), Svelvik (Jones et al., 2014), and the CO_2-Vadose project (Cohen et al., 2013). The QICS experiment is an important off-shore controlled release experiment (Blackford et al., 2014; Taylor et al., 2014). Controlled releases have also been used to test geochemical effects of CO_2 on groundwater (Newell et al., 2014; Rillard et al., 2014; Trautz et al., 2013).

Shallow monitoring involves considerations of environmental impact (see below), reviewed in detail by Jones et al. in this Special Issue. Hyperspectral imaging has been investigated because of the effect of high CO_2 in soil gas on plant health (Keith et al., 2009; Male et al., 2010) and there have also been studies of the effect of "gassing" plants with CO_2 (Smith et al., 2013) as well as studies of the effect of natural releases of CO_2 (Lombardi et al., 2008; Ziogou et al., 2013). Soil microbial populations are also affected by high CO_2 and may be indicators of environmental impact (Frerichs et al., 2013; Krueger et al., 2009; Noble et al., 2012; West et al., 2011). Environmental impact has been studied in detail by a European consortium and results, both for offshore and onshore environments, are reported in Pearce et al. (2014). In what follows we make some comments about aspects of onshore shallow monitoring, and then turn to the off-shore case.

6.1 IMPLEMENTATION

Most shallow surface monitoring techniques are adaptations of methods well-developed in environmental applications. Many are essentially point measurements in space and time, and the issue then arises of the probability of a monitoring method intersecting a CO_2 surface expression, as sketched in Figure 16 and discussed in Oldenburg et al. (2003). This is a difficult problem as both controlled releases, and natural analogues, indicate that leakage sites might be small and dispersed and so the probability of finding these sites might be very low. Implementing a soil gas survey, for example, may also involve complex negotiations with landowners and be costly and labour-intensive; for this reason, automation has been considered (Schloemer et al., 2013). Atmospheric sensing methods can survey wider areas, although of course signals decline with distance from a source. Airborne imaging covers the widest areas, but the quality of the information is correspondingly poorer in this application, with high false alarm rates. Groundwater monitoring is limited by the slow rate of transport of dissolved CO_2. Only a small area around a leakage point is impacted above detection thresholds, with correspondingly limited areal coverage (Yang et al., in prep).

6.2 INTERPRETATION

Shallow monitoring techniques investigate dynamic, open systems in which the quantity of interest, CO_2 is respired in large quantities by ecosystem activity and is very variable. Groundwater might be strongly affected by external factors such as droughts and extraction rates. A standard approach to reduce this environmental noise is to compare pre- and post-injection monitoring results, but it is unclear how long baselines need to be for this method to be effective and it is highly site-specific. Methods that rely on a process understanding of the method to hand, for example the fixed gases technique for soil gases have advantages here (Romanak et al., 2013; Romanak et al., 2012a; Romanak et al., 2014a).

There are however three distinct applications of shallow monitoring, and environmental noise is probably not too serious an issue for two of them. In the case of environmental impact monitoring, it is often sufficient to show that monitoring results have not changed, in a statistically significant sense, once injection commences. If there are changes, in some cases there are well-defined regulatory guidelines (air or water quality, for instance) which make interpretation and reporting of results straightforward. The issue of locating leakage (Figure 16) may not be an issue in this case if regulators are satisfied that a reasonable sample of environmental assets has been monitored, for instance, the set of groundwater extraction wells that are actually being used.

In the important case of quantification of leakage, the leakage sites would already be identified and the issues summarized in Figure 16 would not arise. Since the nature of the surface expression of the leakage would be clear, environmental noise could be reduced by tailored reduction in the area measured, and the duration of measurements. Obvious candidates for quantification would be soil flux and atmospheric measurements, although experience with these in quantification is so far limited to the controlled releases.

Attempting to use shallow measurements for containment assurance is a research challenge. The risk of CO_2 reaching the surface is judged to be very low in all current projects, and because no plausible leakage pathways have been identified (with the exception of defective wellbores) it is not known exactly what a shallow monitoring programme should look for. The problem for site operators is how to report the null results that are a feature of shallow monitoring. Without a quantitative underlying model of leakage, it is not possible to surmise what kind of leak might have occurred and yet remained undetected (Jenkins, 2013). This continues to be an area where further research is required to arrive at cost-effective solutions.

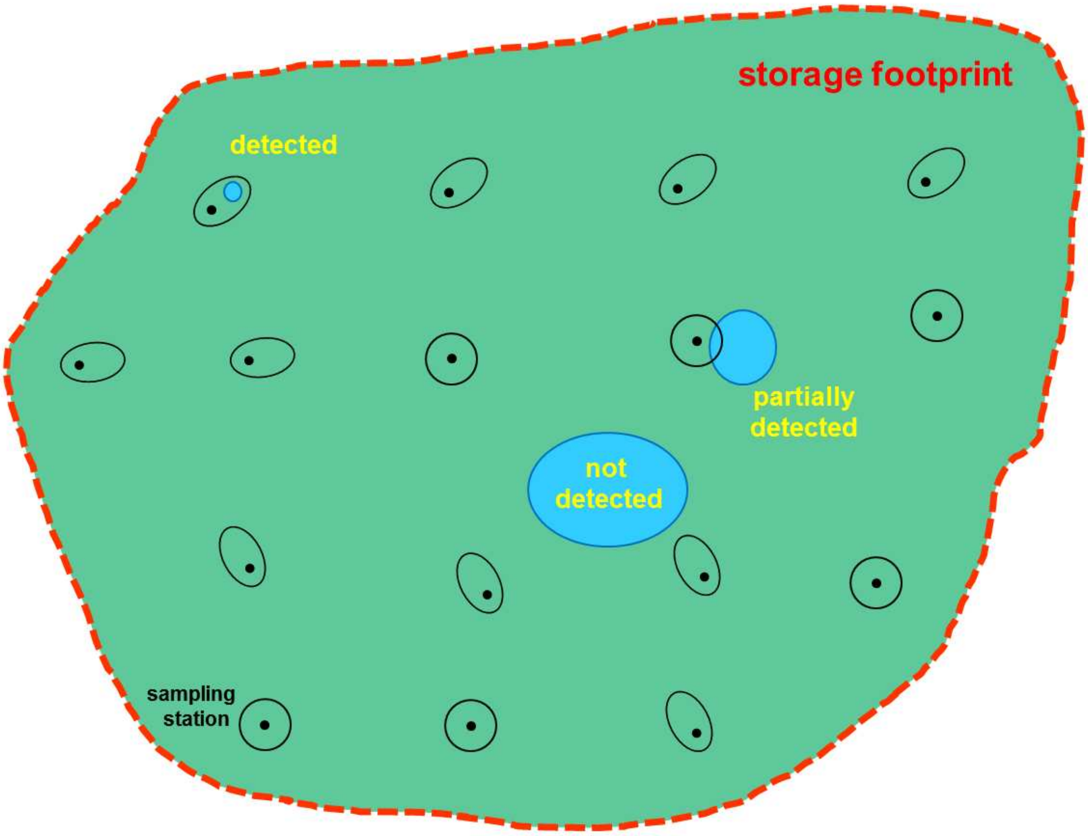

Figure 16 Schematic map of a storage site illustrating the spatial sampling problem with point-wise monitoring. Blue ellipses denote CO_2 emissions. Black spots denote sample stations with surrounding ellipses indicating the extent of detection capability.

6.3 REGULATIONS

Regulatory compliance, at present, has not mandated much by way of shallow monitoring. Excepting research projects, examples are quite limited. Groundwater chemistry monitoring is usual (for example at Cranfield (Yang, in preparation), Otway (de Caritat et al., 2013; Hortle et al., 2011) Decatur (Iranmanesh et al., 2014, 2014b), and proposed for Quest (Bourne et al., 2014). Limited soil gas monitoring is done at Decatur (Finley, 2014b), but not planned for Quest. There was a long-running campaign of soil gas measurements at Weyburn e.g. (Beaubien et al., 2013), Cranfield (Hovorka et al., 2011; Romanak et al., in review) and Ketzin (Martens et al., 2013), but this was undertaken for research, not regulatory purposes. At Otway the soil gas results supported a general argument to the regulator that no environmental impact had been detected. Decatur has a groundwater monitoring programme and the SECARB project at Citronelle had a soil gas programme required by the regulator. US Class VI regulations mandate measurements in the deepest drinking water aquifer above the storage site, aimed at detecting changes in pressure due to possible brine or CO_2 intrusion; an example of such a programme is described in Section 8.4.3 in connection with FutureGen. QUEST is considering airborne hyperspectral surveys to monitor plant health (Bourne et al., 2014).

In a regulatory context, the decade of research has shown that the impacts of leakage are probably small (either onshore or offshore) and they are unlikely. It follows that risks (= probability x consequence) are very small and this is presumably why neither regulators nor operators are making much use of shallow monitoring methods. An exception to this is the risk posed by wellbore leakage – here there is a clear potential pathway to the surface and a relatively straightforward monitoring strategy suffices, as exemplified in the Quest, ROAD and Peterhead proposals, or the Otway atmospheric monitoring.

6.4 ENVIRONMENTAL IMPACT

A second aspect of shallow monitoring pertains to testing for environmental impact, discussed by Jones et al. in this volume. In most jurisdictions regulations will require an environmental impact assessment to be performed and approved before an injection permit is granted; many examples have been given in this review. Such assessments will usually cover routine matters like noise and traffic, as well as issues more specific to CO_2. They might therefore include groundwater, soil gas and atmospheric monitoring. Detailed work, particularly in Europe, has examined the possible consequences of a leakage of CO_2 (Pearce et al., 2014). This has used both controlled and natural releases of CO_2 to give substantive guidance on the environmental impact assessments that may be needed for a storage site. This work has shown that impacts are likely to be minimal. Even large leakages are rapidly dispersed in the ocean or atmosphere, and damage to ecosystems seems likely to be small and recoverable.

Research into environmental impacts has naturally involved the use and development of monitoring tools, and has posed questions about how to find impacts, which may be spatially small, in large areas over large spans of time. However, as noted, there is not much evidence that this is required for projects to proceed. Monitoring for environmental impact is also not the same as monitoring for leakage, and many (perhaps most) methods for monitoring for environmental impact are unsuitable for monitoring for containment. For example, (Carroll et al., 2014) have shown that ingress of stored CO_2 into a model aquifer is extremely difficult to detect from water chemistry alone, because it is unlikely to affect the water quality in a particular well. Thus a CCS project might show a “pass” in its environmental monitoring, even though containment was known to have failed (for example from deep geophysics). This example also illustrates that a very large modelling effort may be needed to interpret environmental impact data in terms of leakage, only to arrive at an unsatisfactory result. The underlying problem is that most shallow monitoring methods have low statistical power for leakage, but high false alarm rates (Jenkins, 2013).

Monitoring for environmental impact is also not as difficult as sometimes supposed because regulators can appeal to straightforward standards, for example for air or water quality. If, however, these standards have to be shown to apply across wide spans of space or time, rather than referring to current or foreseeable uses, the monitoring and interpretation burden may become large or insuperable.

6.5 SOCIAL LICENCE

Social licence is clearly important for the success of CCS, and one aspect of obtaining it is for a convincing monitoring programme to be in place that satisfies societal (rather than purely technical) concerns. Typically these concerns are about near-surface assets and so shallow monitoring may be needed to allay them. Open communication of monitoring results seemed to be an important contributor to social licence at the Otway Project (Cook, 2014b) but other research shows that trust in the administering organizations and people is at least as important as the monitoring that they may do (Huijts et al., 2007; Upham and Roberts, 2011) . Monitoring is thus a necessary, but not sufficient, part of a complex of factors needed to secure social licence.

When all stakeholders are engaged in a genuinely open process of risk assessment about a CCS project, the range of perceived risks can be very broad (Bowden et al., 2013). Monitoring a risk that has low probability (from a technical point of view) but high consequence (from a stakeholder point of view) is sometimes referred to as “assurance” monitoring. The diversity of impacts that are of possible concern poses challenges for monitoring programmes, both to sharpen up concerns to the point where there are well-defined monitoring targets, and to control false alarm rates in systems which are subject to many external influences.

Bowden et al. (2013) comment that “One of the highest consequences potentially arising in relation to the project was public perception of issues associated with the Weyburn-Midale Project arising as a result of unrelated changes to groundwater chemistry, and samples being taken of surface and groundwater”. The lesson has been widely drawn that establishing and maintaining environmental baselines will be a necessary feature of CCS projects, in case of allegations based on third party measurements of environmental variables. This might be called “defensive monitoring”. An operator will make this decision on a (probability x consequence) basis that is likely to be highly site dependent. Since allegations of leakage need only be distantly related to real possibilities, the number of types of baselines that might be needed could be quite large. It would in any case be better to have understanding of processes – for example, the reasons why groundwater chemistry varies seasonally – than purely empirical data. Devising monitoring methods to deal with this issue in a cost-effective way is another challenge..

From a governance point of view, it seems that an operator will reach agreement with a regulator on what quantities need to be monitored at a storage site. If allegations are made by third parties on the basis on different types of data, investigation of these might be argued to be the responsibility of the regulator, not the operator. Otherwise the operator faces a discouraging type of risk, in which the regulator – or public pressure - can decide after the fact what constitutes evidence.

Overall, the design and execution of monitoring programmes that are intended to secure social licence is a challenging task. Avoiding excessive cost and also undertaking meaningful measurements, while forestalling unfounded allegations, will have to be balanced with transparency in governance and respect for a wide range of stakeholder views.

6.6 OFFSHORE MONITORING

A number of shallow monitoring issues are unique to the offshore and these are outlined below. Little or no shallow-focussed monitoring has been yet been deployed offshore as a regulatory requirement, but this will change as new projects (e.g. ROAD, Peterhead) come on stream (Section 8). Extensive research deployments of shallow monitoring systems have taken place at both Sleipner and Snøhvit, and in both cases normal seabed conditions have been encountered throughout e.g. (Bünz and ECO2, 2013). In addition, a number of monitoring tools have been tested at both natural and artificial CO_2 emission sites (Blackford et al., 2015; Blackford et al., 2014; Lombardi et al., 2008). In this section we will review some of the issues and options for shallow monitoring off-shore.

A number of natural and man-made issues can affect the efficacy and practicality of offshore shallow-focussed methods. Water depth, temperature and salinity will impact the logistics of deploying survey equipment and also the nature of CO_2 emissions in the water column (e.g. bubble sizes and rate of dissolution). Water movement will determine the rate at which localised emissions of CO_2 or other fluids are dissipated into the wider marine environment, dictating the required sensitivity of instrumentation and/or its spatial coverage. The nature of the seabed will affect how upwardly migrating fluids escape to the water column, fine-grained sediments having the greater tendency to produce emission-induced pockmarks. Seabed permanence will determine the reliability of repeat time-lapse sea-bottom surveys (for example pockmarks or algal growths may be short-lived). This might influence aspects of monitoring survey design such as spatial sampling strategy or repeat survey frequency for example. Trawling activity can have severe effects on the seabed, sufficient to modify or destroy subtle changes of the seabed that might be indicative of emissions. It will also destroy all but heavily protected in situ monitoring equipment. Wind-farms are an increasing component of offshore seabed infrastructure. The extent to which wind-farm development and CO_2 storage will ever be co-incident is uncertain, but the turbine installation and foundations might well compromise the logistics, coverage and quality of seabed monitoring surveys.

Compared to onshore, the offshore is logistically remote and relatively difficult of access which means that operations can be very expensive, particularly if ship time is involved. Although public acceptance and communication issues are much less significant than onshore, health and safety is paramount and only proven and approved operational procedures can be undertaken (for example HSE protocols for offshore platforms). A number of issues determine the types of monitoring technologies that can be utilised and these will impact upon the design, implementation and overall efficacy of integrated shallow-focussed systems.

Shallow-focussed tools fall into three categories: geophysical, chemical and biological. The former essentially comprise acoustic methods (variants of sonar/echosounding) and aim either to detect time-lapse changes of seabed morphology and/or reflectivity or to directly detect bubble-streams in the water column. Chemical sampling methods aim to detect and characterise changes in the shallow sediments or seawater column due to emitted CO_2 or precursor fluids from the subsurface. Biological methods of emission detection are still in their infancy, and reliable practical methods have yet to be developed. Deployment of all these technologies can be via ship, remotely-operated vehicle (ROV) or automatic underwater vehicle (AUV). The latter offers the potential for low-cost long-term monitoring deployments but battery life and data collection and transmission constraints are still significant.

The issue of obtaining robust spatial coverage is particularly pertinent offshore where logistical aspects can cause costs to spiral. Currently we have little or no information on how an emission might be expressed at the seabed, but based on natural analogues it might well be of limited spatially extent. Monitoring systems therefore may need to be able to both cover large areas in a reasonable length of time and also detect small discrete features (Figure 16). To achieve this would require continuous mobile spatial detection monitoring for wide area coverage combined with pointwise static sampling for measurement and characterisation. The former is likely to use either active or passive acoustics which respectively 'image' or 'listen' for bubbles, or chemical detection of changes in pH, pCO_2 etc. Point-wise sampling will likely utilise mostly chemical techniques and can be deployed for lengthier periods to assess time variance. Whether any of these technologies are needed or justified will depend fundamentally on whether stored CO_2 is thought at all likely to reach the seabed. As on land, the likeliest conduits are probably wellbores and these can be monitored more easily than large, ill-defined areas.

Promising shallow monitoring technologies include active and passive acoustics, and chemical sensors (reviewed in an IEAGHG report, currently in press). The detection limit for active acoustics is typically in the range of hundreds of metres; lower frequency systems have increased range but lower resolution and vice versa. Dissolution of the bubble-stream will occur rapidly and dispersion of dissolved CO_2 from an emission point will take place via physical mixing by tidal action, waves and currents. For any type of chemical sensor the primary determinant will be current speed and direction, which determine rates of dilution and dispersion. Down-current of an emission point an Eh sensor may detect a release over hundreds of metres, and a pH sensor on the order of tens of metres. Because of these effects, sensor detection capability might well not be symmetrical about the tool.

An active area of research is the characterisation and quantification of bubble fluxes in the sea-water column utilising either active or passive ('listening') acoustics. Bubble-streams can be detected by the degree of acoustic scattering of high frequency active sonar but estimating the gas content of the bubble-stream is not straightforward because the wavelength of commercially available sonar systems is often larger than the bubble sizes (Ainslie and Leighton, 2011) and the acoustic inversion method assumes an infinite body of water (Leighton and White, 2012). Further research is needed therefore to improve inversion accuracy.

An alternative approach is to use passive acoustics to characterise the sound that bubbles produce, whose pitch relates to bubble size. Spectral approaches have recently been developed to enable quantification of gas flux from seeps of a significant size (Leighton and White, 2012; Leighton et al., 1998). These were tested in the QICS marine leakage experiment (Blackford et al., 2015). Three acoustic recorders were placed near the leak site to collect the sounds emitted from the bubble-streams. The recorders were moved around within the site to collect data from various locations through the duration of the release. By analysing the acoustic energy accompanying the bubble formation it is possible to estimate the initial size of the bubbles as they leave the sediment, and from that the flux rate. Uncertainties relate principally to the amount of energy that is imparted to each bubble as it is released, a proportion of which is then radiated as acoustic energy. Flux rates determined from the acoustic emissions were compared with values obtained by divers collecting gas from individual bubble-streams and it was found that the collected values fell within the range predicted by the acoustic techniques.

A benefit of passive acoustic techniques is their ability to monitor continuously for extended periods allowing flux rates to be estimated over time. A drawback is susceptibility to background noise which can be significant with both natural (storms, waves, natural gas seeps) and man-made components (marine traffic, oil/gas platforms etc).

7 TECHNICAL DEVELOPMENTS

The suite of possible monitoring tools has expanded considerably over the decade; we will focus in this short section on what we see as important developments, that is, those with a foreseeable application to major monitoring goals of containment, conformance, and demonstrating no environmental impact. Research-scale sites have had the ability to pick interesting or promising techniques from these lists, or indeed to add new ones. The larger-scale projects have tended to select much smaller sets of monitoring tools, selected in a rigorous way to reduce risk as economically as possible. In what follows we pick examples from both types of project.

7.1 3D SEISMICS

Time-lapse 3D seismics is a well-established oil industry tool and so developments for CCS to some extent track oil industry practice. As illustrated at both Sleipner and Weyburn in different applications, simple time-shift or travel-time analysis is emerging as a particularly useful time-lapse monitoring tool, with sub-sample rate picking accuracy enhanced by the statistical power of multi-trace 3D coverage. Time-shifts are a complementary seismic property to reflectivity and are in some ways more robust, integrating the time delay effects of CO_2 columns rather than relying on the development of discrete reflective interfaces. As such they show potential for establishing statistically and spatially robust constraints on key storage performance measures: fluid saturation changes and pressure changes in large 3D volumes.

In addition to the analyses described in Section 4, a number of sophisticated seismic methods have been deployed at storage sites, with the Sleipner datasets providing perhaps the greatest scope so far. A number of advanced techniques have been tested here and some are summarised in Chadwick et al. (2010). These include, *inter alia,* pre- and post-stack inversion (Clochard et al., 2010; Ghosh et al., 2015); full waveform inversion (Queisser and Singh, 2013) ; spectral inversion (Rubino et al., 2011b); spectral attenuation (Rubino et al., 2011a); spectral decomposition (Williams and Chadwick, 2012); amplitude-versus-angle analysis (Rabben and Ursin, 2011) and travel-time / attenuation tomography (Rossi et al., 2012). The varied approaches have all helped to understand better the complexity of the CO_2 plume at a range of scales and have added to a progressive reduction in uncertainty of some key parameters. No single technique has proved to be a 'game-changer' in providing uniquely diagnostic new insights. The complex interplay of highly reflective thin layers, tuning effects, variable fluid saturation and mixing patterns, various modes of signal attenuation still renders full understanding of the plume highly challenging.

So far, most surface seismic for storage monitoring has deployed non-permanent receiver arrays for data acquisition, notably in the use of towed streamers offshore. There is a developing trend however towards deployment of fixed receivers which removes time-lapse placement errors and, in the offshore case, adds the ability to record multi-component data. At Ketzin a permanent buried array of three-component geophones was used to obtain wide-angle data from active sources and also to record long-term ambient seismicity (Paap et al., 2014). The Aquistore storage project in Saskatchewan (White et al., 2014a) is deploying a permanent array of buried geophones augmented by three-component seismometers, to provide both active time-lapse 3D seismics and also continuous passive recording of natural and induced seismicity. In the offshore context, Shell is considering a seabottom recording array for Peterhead, although not for permanent deployment in the current plan. In fact permanent seabottom sensors are very vulnerable to trawling damage at Goldeneye, so 4D VSPs using acoustic optic-fibre technology (DAS) in four long deviated monitoring wells are being considered as an alternative. These types of permanently installed systems have the potential to provide improved data quality and information content, at lower long-term cost, than stand-alone repeat surveys. By integrating focussed active seismics with much longer-term natural and induced signal recording, they also open the door to a range of imaging and characterisation tools, including 3D velocity and attenuation mapping, azimuthal anisotropy analysis and more novel techniques such as seismic interferometry.

At Aquistore, surface acquisition is integrated with downhole seismic recording, the latter utilising an optic-fibre cable configured for seismic (DAS). This can further extend the potential for high fidelity characterisation of fluid and geomechanical changes in reservoir and overburden.

7.2 GRAVIMETRY

Potential field techniques can offer complementary information to the seismic methods and seabed gravimetry has been tested at Sleipner (Alnes et al., 2011; Alnes et al., 2008). For aquifer storage dense-phase CO_2 is significantly less dense than typical reservoir brine, so an injected CO_2 plume will produce a gravitational response proportional to the mass deficit of the plume compared with an equal volume of formation water. The response is of the order of microGals, so to achieve the necessary accuracy, the gravimeter has to be deployed on the seabed, rather than on-ship. An initial survey was acquired at Sleipner in 2002 with 5.19 Mt of CO_2 in the reservoir. Repeat surveys were then acquired in 2005 (7.74 Mt of CO_2) and in 2009 (11.05 Mt of CO_2). Permanent concrete benchmarks on the seafloor served as reference locations for the gravity measurements with relative gravity and water pressure readings being taken at each benchmark by a gravity and pressure measurement module mounted on a remotely operated vehicle (ROV). Each survey station was visited at least three times to better constrain instrument drift and other errors. After correcting for benchmark elevation changes, water-depth / tidal variations and the time-dependent gravimetric response from the Sleipner East field (the deeper gas reservoir currently in production), the resulting time-lapse detection threshold is estimated at around 5 µGal.

Gravity modelling initially focussed on constraining the *in situ* density of CO_2, which constituted a significant uncertainty at a time when reservoir temperatures remained uncertain (Alnes et al., 2008; Nooner et al., 2007). More recently, Alnes et al. (2011) armed with much improved reservoir temperature information, obtained a best-fit CO_2 density of 720 ± 80 kgm^{-3} and compared this with a theoretical average CO_2 density in the plume of 675 ± 20 kgm^{-3}, based on a thermal model. The density (mass deficit) discrepancy is interpreted as significant, and perhaps indicative of CO_2 dissolution within the plume. Taking uncertainties into account it was concluded that the upper bound on total dissolution is 18%, with a most likely figure significantly lower. Flow simulations of the plume development suggest dissolution values up to around 10% , so the gravimetry seems to be in good accordance with this. As future gravimetry surveys are carried out with more CO_2 injected, uncertainties will progressively decrease further. In fact, had a baseline gravity survey been acquired, uncertainties would be significantly reduced at all time steps.

It is clear that in the Sleipner case gravimetry can potentially provide valuable complementary information to the 4D seismics – notably in providing an estimate of dissolved CO_2 which is a key stabilisation process. The obvious application would be post-injection to demonstrate the onset of plume stabilisation. It should be emphasised however that Sleipner is an ideal case for gravimetric monitoring, with its shallow reservoir (~900 m depth) and tall CO_2 plume (~200 m high); both factors maximising the amplitude of the CO_2 gravity signal. Other storage situations are likely to be less optimal, but in general terms large stored amounts of CO_2 (> 50Mt) should be suitable for gravimetric characterisation in many scenarios. It should also be noted that offshore seabed gravimetry as deployed at Sleipner is very expensive compared to land gravimetry. Well-based gravity was tested at Cranfield and was successful in obtaining signal from injected CO_2 (Dodds et al., 2013) and is in testing at several EOR fields.

7.3 INTERFEROMETRIC SYNTHETIC APERTURE RADAR (InSAR)

InSAR is able to detect subtle ground movements by comparing phase differences from successive passes of an orbiting satellite. There are several sophisticated signal processing methodologies which provide the means to compare multiple satellite passes to enhance ground displacements and suppress the multiple noise sources due to atmospheric effects. These provide an accuracy of around 5 mm/year and down to 1 mm/year for a longer term average.

The rate and pattern of surface displacement can be evaluated to provide an understanding of pressure changes at depth arising from the injection of CO_2, the basic premise being that the surface displacements reflect pressure propagation in and around the reservoir.

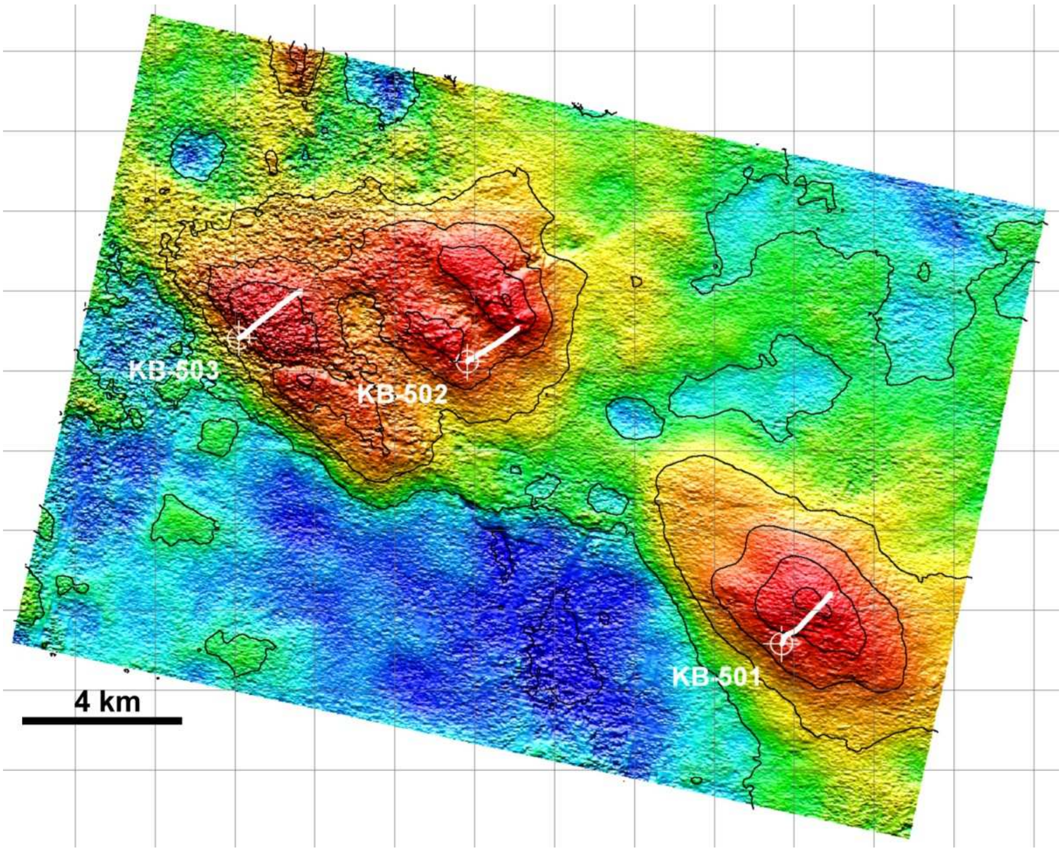

Figure 17. InSAR image showing cumulative surface displacements at In Salah up to June 2010. Relative uplift observed above the three CO_2 injectors, with subsidence above the producing gas field to the south and west of the injectors. Scale from – 9mm (blue) to + 20 mm (red).

A very significant application of InSAR was at the In Salah gas development project in Algeria. This is an industrial-scale CO_2 storage operation that commenced in 2004. CO_2 separated from the natural gas is injected into the aquifer leg of the gas reservoir, at depths of about 1900 m. By 2011 nearly 4 million tons of CO_2 had been injected, principally via three injection wells Kb-501, Kb-502 and Kb-503.

The ground surface at In Salah is rocky desert, which has a high and stable coherence suitable for InSAR. Analysis of interferometric data through time shows growth of spatially delineated uplifts overlying the injection wells at rates of up to 5 mm/year e.g. (Onuma and Ohkawa, 2009; Tamburini et al., 2010) with cumulative uplifts in excess of 20 mm (Figure 17). Considerable research effort has gone into combining the InSAR results with data from other monitoring technologies to produce coherent geomechanical models and inversions to explain the observed uplift patterns and the injected CO_2 plume development, summarised in Ringrose et al. (2013); White et al. (2014b). A key insight from the InSAR was associated with the unusual double-lobe pattern of uplift above well Kb-502 (Figure 17). This has been interpreted as uniquely diagnostic of pressure-induced or hydro-fracturing (most probably of pre-existing features) in and around the reservoir (Vasco et al., 2010). Independent analysis and modelling of reservoir pressure data (Bissell et al., 2011) supports this hypothesis. In this respect the InSAR data is performing the same role as the time-lapse seismics at

Snøhvit, in providing additional geometric information to complement and help explain the reservoir pressure measurements.

InSAR is inexpensive and can provide important insights into reservoir geomechanical stability. Its use is essentially restricted to suitable onshore areas, but high atmospheric humidity, abundant vegetation, and noise from pressure fluctuations in zones above the reservoir, for example groundwater use will limit the sensitivity compared to the ideal situation at In Salah. The method is used for monitoring of domestic gas storage, e.g. Teatini et al. (2011) in urban areas and shows promise for extension to rural areas (Goel and Adam, 2012) that are more relevant to CCS.

Similar methods involving sea bed displacement measurements were considered for Peterhead and deployment of a single platform-mounted differential GPS is planned. Onshore a three-station GPS array was tested at the beginning of a large scale EOR project at Hastings Field, Texas (Dixon et al, in review). A signal of increasing pressure was successfully separated from nearer surface groundwater effects by using a fairly dense regional GPS network.

7.4 GEOCHEMICAL METHODS

Geochemical tools can be used both for conformance and containment monitoring. CO_2 is abundant and highly variable in space and time in the geosphere, so its direct detection may need to be augmented by other methods. Geochemical tools can be applied to fluids in the reservoir, above the reservoir, in the groundwater, soil, seabed, water-column and atmosphere. The suite of tools is so extensive as to defy review, but we will highlight some significant developments in the last decade.

Geochemical tools can be by far the most sensitive in the portfolio, able to detect before any other tool the first indication of CO_2 arrival or leakage and then measure changes over the entire spectrum. On the other hand measurements are typically made on a small sample which must be collected *in situ*. The extent to which this sample is representative of the volume to be assessed must be considered with care. For example, samples of a two-phase flow system will be strongly biased by the sampling method. Samples can also miss a focused flow path.

Free-phase CO_2 arrival at monitoring wells, known as breakthrough, can be an important calibration point for models as it is sensitive to the plume thickness and anisotropy. Breakthrough is highly responsive to reservoir heterogeneity however, with much better matching to models being achieved in less heterogeneous reservoirs (Otway) than in more complex settings (Ketzin, Cranfield). Fluid sampling provides the most sensitive detection of this change if the sampling apparatus is designed to accommodate supercritical or gas phase CO_2. Traditional oilfield fluid sampling methods include flowing, pumping or lifting fluids to surface or sampling near the perforations using a triggered downhole sampler deployed on wireline. A novel method of lifting fluids to the surface was designed to rapidly sample mixed phases without contamination is the U-tube (Freifeld et al., 2005). Other options include extraction of gases by diffusion from a port at depth, as developed for the Ketzin project (Myrttinen et al., 2010).

In depleted gas reservoirs geochemical methods may be required to assess reservoir performance where wireline or surface geophysical methods are less able to detect the subtle fluid substitution of CO_2 for gas already in the reservoir. Breakthrough was identified by fluid sampling where CO_2 was injected into depleted methane reservoirs at K12-B (van der Meer et al., 2009) and at the first Otway experiment (Boreham et al., 2011; Stalker et al., 2009).

Most native and introduced tracer studies also require fluid sampling. Tracer studies may not be part of commercial monitoring, however they have been of high value in research for validating models of CO_2 –reservoir fluid interactions (Hosseini et al., 2012; Lu et al., 2012b; Stalker et al., 2009; Underschultz et al., 2011).

CO_2-soluble tracers have been deployed in several projects (Freifeld et al., 2005; Jenkins et al., 2012; Lu et al., 2013; Paterson et al., 2010), for multiple purposes. Tracers can be important as a methods of uniquely identifying the injected CO_2, especially in the containment context because CO_2 is ubiquitous in the environment, but tracers are not. The Peterhead and Quest projects propose to use tracers for this purpose. Tracers make both the detection and the attribution step of monitoring much easier (Myers et al., 2012). Measurements of soil gas, groundwater and atmosphere at Otway were checked for the presence of SF_6, which while present in the environment at low concentrations, is much less variable than CO_2. In a conformance context, engineered tracers used to tag the injected CO_2 can be used to calculate flow rate during plume evolution and interactions among constituents such as dissolution of CO_2 into brine and exsolution of methane into the CO_2 . Non-reactive tracers can give insight into details of pore-scale flow, since they may be less or more soluble than CO_2 in the pore fluids. At Otway, experiments with noble gas tracers were used to make direct measurements of residual trapping in a deep injection (LaForce et al., 2014; Paterson et al., 2010).   Tracer use must be managed with strict protocols to limit cross-contamination, and to reserve tracers for different uses so that they do not interfere or overlap.

At the West Pearl Queen field, New Mexico, a 2003 study conducted under EOR conditions, 2100 tonnes of CO_2 tagged with perfluorocarbon tracer (PFT) was injected to an active oil reservoir depths of 900 m and allowed to “soak” prior to being extracted (Pawar et al., 2006). PFT was detected using passive sorbent packs installed into the soil at shallow depths, and because of preferential orientation away from the injection well, was attributed to flow from near surface fractures in caliche (Wells et al., 2007). The monitoring conducted was not adequate to identify a method of transport from depth; transport along the injection well (formerly a production well) was suspected because of the geometry of detections and the rapid response.

There has been a recent concern that leakage of CO_2 into drinking water aquifers could mobilize heavy metals and US EPA class VI regulations require in-reservoir fluid sampling. The extent of the risk depends on the minerals present; several controlled releases have been done without highlighting any major concerns (Yang et al., 2014b; Yang et al., 2014c). Measurements assessing CO_2 – rock - water interactions have been extensively explored in geochemical models (Bachu et al., 1994; Emberley et al., 2005), through batch reactions (Yang et al., 2014a), and through field-based sampling projects (e.g. Weyburn, Frio, Nagaoka, Otway). Natural analogues have also been informative, suggesting that the associated transport of deep brines upward is of more significance to risk to groundwater than the movement of CO_2 itself into shallow aquifers (Keating et al., 2010; Viswanathan et al., 2008).

The decade of observations has documented some limitations in the value of fluid sampling from the reservoir for conformance purposes. Predicted breakthrough timings in particular are very sensitive to local reservoir heterogeneity. Detection of free phase CO_2 arrival in aqueous systems can be detected more quantitatively and at lower cost by pressure and well logging methods.

7.5 PRESSURE AND TEMPERATURE

Pressure is a key parameter for conformance verification and containment assurance and is the only parameter specified as mandatory for monitoring under EU storage regulation. In the past decades cost has decreased and reliability increased for various types of installed pressure gauges (Unneland et al., 1998). The reduced cost of digital recorders and improved satellite, cellular telephone, and other types of data linkages have increased the potential for collection of high frequency (seconds to daily) and real-time data. Pressure data collection is relatively simple, involving perforation of a section of well so that fluids inside the well are in direct contact with pore fluids of the interval to be interrogated. Selecting and effectively isolating the correct interval is of high importance. Measurements both at the injection well and at distant monitoring points are valuable for model validation.

Examples of projects using pressure gauges temporarily or permanently placed at or a short distance above the perforations either in an injection well or at an observation well include Frio, Nagaoka, Gaylord Michigan, SnøHvit, Ketzin, Otway, Cranfield, Citronelle; similar deployments are also planned for Quest, FutureGen, and ROAD. At ROAD for example it is the key tool for demonstrating conformance.

Rich pressure data sets allow not only traditional calibration of model time steps (Doughty and Freifeld, 2012; Hosseini and Nicot, 2012) but also analysis of high frequency variability such as pressure falloff (Kelley et al., 2014), cross-well isolation communication (Meckel et al., 2013), earth tides, and other types of innovative measurements. For example, Hosseini et al. (in review) have developed a method for time lapse harmonic pressure testing to assess changes in fluid compressibility that would allow discrimination between ambient brine and introduced CO_2 in the area probed. Reservoir pressure data are also needed for compliance with regulations related to geomechanically determined maximum allowable injection pressures. Anomalies in any of these areas would immediately be informative about conformance and containment, as for example as described earlier for Snøhvit.

Temperature is typically collected with pressure in an integrated instrument package but has different applications in the monitoring program. The fluid properties of $CO_{2,}$ including density, viscosity, and capillary entry pressure, have strong pressure and temperature dependence. The large density changes with temperature and pressure create a significant difficulty in well-based pressure measurement because the density of a column of CO_2 can be strongly dependent on injection temperature and geothermal gradient. In wellbores with a complex mixture of fluids, or fluid phases, temperature measurements can enable the fluid properties to be determined and, from this, pressure in the reservoir. At Ketzin, a fibre-optic temperature sensor system (DTS) attached to the tubing was able to obtain accurate real-time continuous temperature profiles down the wellbore (Wiese, 2014). Combining the pressure measurement with other tools in a modular system can reduce deployment costs and add value (Freifeld et al., 2014).

Where the well is filled with fluid of stable density it is possible to make measurements of the pressure at reservoir depths near the top of the fluid column, as is commonly done in groundwater wells. This low-cost technique may be useful in cases where the well is filled with water, because pressure and temperature density changes are small. Change in wellhead pressure as CO_2 replaces water standing in the wellbore provides a large and distinctive signal indicating arrival (breakthrough) of free phase CO_2 to the well (Verma et al., 2013).

Above-zone pressure measurement has been used above gas storage reservoirs to provide assurance of no out-of-reservoir leakage (Katz and Tek, 1981) - this technology has been adapted for the same purpose in CO_2 storage. Hydraulically connected zones, for example two permeable horizontal beds connected through a flaw in the confining system will show a systematic and analysable response to pressure changes (Strandli et al., 2014; Sun and Nicot, 2012; Sun et al., 2013a; Zeidouni, 2012; Zeidouni and Pooladi-Darvish, 2012), and also Section 5.3.2.1. If pressure is monitored in one part of a laterally continuous transmissive above zone monitoring interval (AZMI), the presence or absence of leakage into the AZMI at a threshold rate can be detected. The pressure response is sensitive to the volume and rate of fluid leakage, therefore the response to migrating CO_2 becomes stronger as the fluid migrates to shallower zones. Above-zone pressure is potentially a powerful monitoring technique for containment. The magnitude of the pressure increase in the AZMI depends on the hydrologic properties of the system, including the characteristics of the connective leakage path, the thickness, porosity, permeability and boundary conditions of the AZMI, the distance between the leakage path and the measuring point, the response of the injection zone pressure and relative permeability to the leakage (Sun and Nicot, 2012; Sun et al., 2013a; Sun et al., 2013b). Complicating factors include zonal isolation, geomechanical and tidal effects, and possibly pressure signals from other activities by other operators at hydrologically connected sites. Gauge noise and drift are also important limitations. Modelling is needed to determine the spacing of wells needed to detect the leakage rate and volume to which the system will respond above its overall noise level.

Regulatory expectations for AZMI monitoring include US EPA class VI monitoring and Texas Railroad Commission certification for storage incidental to CO_2 EOR. AZMI monitoring is underway as part of conformance demonstration at Hastings Field, a US DOE-funded industrial storage project at an EOR site, and planned at West Ranch, where CO_2 from a large scale capture project at NRG's J.W. Parrish plant will be stored via EOR. Above-zone monitoring is planned as a major conformance technique at the Shell Quest saline monitoring site (Bourne et al., 2014).

7.6 WELL INTEGRITY MONITORING

Loss of well integrity is widely recognized as one of the most important risks to containment. For example, all the provisions of the US EPA underground injection control (UIC) program under which all US injection wells have been permitted since the 1970s requires episodic or in some cases continuous well integrity monitoring. Pressure surveillance is the principal tool. Under US UIC regulations, all the wells in the area where pressure is elevated to a relevant risk threshold during injection must be considered. In the EU, well integrity monitoring is an important element of the proposed M&V plan for ROAD.

A variety of methods is available for monitoring well integrity. Episodic surveillance can take the form of Mechanical Integrity Testing (MIT) which requires pressurizing components of the well to show that they are isolated. Wells can be instrumented to check that pressure is stable in different compartments of the well (surface casing, long string) during injection. A wide portfolio of wellbore-focused geophysical tools is available, including active seismic (for example cement bond logs), passive seismic (noise logs, temperature logs), and measurement of natural and introduced tracers (for example radioactive tracers, oxygen logs).

During the last decade, significant advances have been made in conceptualizing and modelling well failure (Barlet-Gouedard et al., 2009; Carpenter et al., 2011a; IEAGHG R&D Programme, 2012; Liteanu and Spiers, 2011; Raoof et al., 2012; Zhang and Bachu, 2011). Essentially all geological storage projects have expended significant effort in establishing that the injection well as well as other wells in the site have integrity using well-established methods. However the progress in field monitoring of well failure has been limited because the few wells that have failed have not been at sites with research programs, and information in the public domain is sparse (Porse et al., 2014; Ringrose et al., 2013)

7.7 NEAR-WELL GEOPHYSICAL MEASUREMENTS

Measurements made with tools deployed on wireline are common in hydrocarbon reservoir management (Bateman, 2014). The range of tools deployed on wireline is large, but uptake over the past decade is variable, from not being used at all to comprising a key monitoring tool (Frio, Bell Creek, Nagaoka, Otway). The strength of logging technologies, providing quantitative high-resolution measurements of changes in fluids over small rock volumes, is also a limitation in that uncertainty is introduced by extrapolation of measurements over large rock volumes between wells. Wireline logs can provide detailed information to support extrapolation of saturation measurements made with seismic or electrical methods over larger areas.

Near-well geophysical measurements have been shown to be valuable in the zone of injection to measure saturation changes (CO_2 substitution for brine) for model validation (Hovorka et al., 2006; Sakurai et al., 2005; Sato et al., 2011). Logs are used for conformance monitoring to assess quantitatively the first arrival of CO_2 as the plume expands, and the thickness and saturation as the plume matures that then feeds back into the model to assess if the model assumptions are reasonable. In commercial petroleum field management, a spatial array of logs may be collected, however CCS projects typically have a limited number of penetrations.

Wireline logging can also be used above the injection zone for confirmation of containment. For example, in the Michigan Basin test conducted by MRCSP (part of the US RCSP), where a total of 35,000 metric tons of CO_2 were injected into carbonates of the Bass Island dolomite, a near-well bore change in saturation was noted during both time-lapse 3D seismics and time-lapse VSP (Gerst, 2009; Gerst et al., 2009). Attribution of the source of the fluid, whether CO_2 or methane, would however require chemical sampling. Logs may also be a critical tool in assessing stabilization (Hovorka et al., 2006; Mito and Xue, 2011). The high resolution saturation measurements allow assessment of whether the CO_2 is migrating laterally or vertically or migration has stopped. At Nagaoka the combination of non-conductive fibreglass casings, high-frequency repetition logging over 10 years and low salinity brine in the injection formation has resulted in the collection of an excellent record of changes in fluids during and after injection, including both substitution of free phase CO_2 for brine and dissolution of CO_2 into brine with associated changes in conductivity. Log-based post closure monitoring continues at the site, providing a unique contribution to understanding plume dissolution and stabilization after the end of injection.

Pulsed-neutron tools have been shown to be especially favourable to geologic storage research projects because they can be collected through both steel casing and tubing, allowing use of the monitoring well for multiple purposes (Braunberger et al., 2014; Butsch et al., 2013; Dance and Datey, 2015; Morris et al., 2005; Sakurai et al., 2005). Time-lapse sonic logs have been effectively used in cased wells but may be of greatest value in cased and non-perforated dedicated monitoring boreholes.

Wireline-based multi-component sonic and pulsed-neutron logs provided the foundation for interpretation and quantification of plume migration and history matching at Frio (Sakurai et al., 2005) and at Cranfield (Butsch et al., 2013). Electrical logging was not successful at these sites, because of interference from casing and other metallic elements in the completions. When injection was stopped at Frio, the CO_2 saturation at the monitoring wells peaked, declined, and stabilized, documenting the attainment of residual saturation (Hovorka et al., 2006).

7.8 SHALLOW MONITORING

Shallow focussed monitoring over the decade has not involved much expansion of the suite of tools, but there have been considerable advances in understanding of their use in CCS. Here we comment on three areas that have seen significant development, and may become more important in future.

Measurements of soil gas are very common, either in current sites or in proposed monitoring. Large campaigns have been undertaken, and instrumentation and understanding has been refined (Beaubien et al., 2013; Bernardo and de Vries, 2011; Klusman, 2003; Risk et al., 2013; Romanak et al., 2013; Romanak et al., 2014a; Schacht and Jenkins, 2014; Schloemer et al., 2013; Strazisar et al., 2009). Soil gas measurements were important during the “Kerr Affair” at Weyburn. The key issues with soil gas as an M&V tool, as recognized by practitioners as well as modellers (Lewicki et al., 2005), is that measurements are often sparse in space and time, as a matter of practicality and cost, and have to deal with very wide levels of natural variability in CO_2 , likewise in space and time. Soil gas sampling instrumentation has been refined to deal with some of these issues, but is hampered by mundane matters such as seasonal flooding by groundwater, or cost of sensors (Bernardo and de Vries, 2011; Schloemer et al., 2013). The wide levels of variability can to some extent be calibrated out by baseline observations that are used to calibrate models of production of CO_2 in the vadose zone (Risk et al., 2013), but these are once again labour-intensive in field application.

An important development in this area has been the advocacy by Romanak and collaborators of “process based” soil gas monitoring, which relies on the simple stoichiometric ratios of various gases (most obviously, CO_2 and O_2 compared to N_2, a less active gas in the soil system) if the CO_2 in the soil is produced by metabolic activity (Romanak et al., 2012a). This is a powerful and baseline-independent method for identifying concentrations of CO_2 that are unlikely to arise from metabolic activity in the soil. As such, it is well suited for environmental impact monitoring, because it is the concentrations of CO_2 that affect soil health. Since concentrations are related indirectly to fluxes by transport parameters, the applicability to leakage monitoring would require further, probably labour intensive calibration of soil permeabilities and would be vulnerable to the apparent spatially-limited surface expression of leakage (Feitz et al., 2014; Lewicki et al., 2007; Lombardi et al., 2008; Ziogou et al., 2013). However as we have suggested elsewhere in this review, shallow monitoring is in general better suited to checking for environmental impact, rather than testing containment. The phrase “process based” is also a useful reminder that even baselines should preferably be understood in terms of processes based in scientific understanding, rather than purely empirical collections of possibly relevant data.

A tool with some promise for wide-area monitoring of environmental impact is aerial hyperspectral imaging (Bateson et al., 2008; Bellante et al., 2013; Feitz et al., 2014; Male et al., 2010). The effect on vegetation of high CO_2 concentrations in the root zone is readily apparent in such imagery; however the false alarm rate as high as there are many other factors that affect plant health. Despite much research in the area, there do not seem to be any unique spectral signatures of damage from high CO_2 specifically (Lakkaraju et al., 2010) although a combination with distinctive spatial patterns may be helpful (Govindan et al., 2011; Noomen et al., 2012). However, large areas can be regularly and economically surveyed. If experience can be accumulated at a particular site, the method may be useful as a supplementary method of monitoring for environmental impact. Because of the visual nature of the data it may also be helpful for public assurance.

Atmospheric monitoring has not been used for regulatory compliance except at Otway, where it was linked to Key Performance Indicators (Cook, 2014b; Sharma et al., 2011). There is a misapprehension that human activities may make a local CO_2 atmospheric baseline impossibly complex, but in fact even in a rural area ecosystem activity makes the baseline very variable. At Otway, excursions of over 100 ppm in a day are normal and analysis has been developed to deal with this (Cook, 2014b; Etheridge et al., 2011; Jenkins et al., 2012). While the environmental impact aspect of atmospheric monitoring is clear, it may also be relevant to containment monitoring. Leakage to surface might not result in hazardous concentrations but nonetheless violate limits on the tolerable leakage into the atmosphere to meet climate abatement goals (Enting et al., 2008; Haugan and Joos, 2004; Shaffer, 2010; Stone et al., 2009).

Atmospheric measurements of CO2 concentration, possibly at distributed locations around an injection site, can place limits on direct leakage into the atmosphere. Because of rapid dilution in the atmosphere, the areas of leakage would need to be spatially small, as in fact observed at natural analogues and controlled release sites. If access by operators is possible, episodic surveys can be made by modified vehicles (Jones et al., 2009; Jones et al., 2011; Krueger et al., 2011). Automated, continuous atmospheric techniques have been successfully tested both at ZERT (Lewicki and Hilley, 2009, 2012; Lewicki et al., 2009a, b) and at Otway and associated test sites (Etheridge et al., 2011; Humphries et al., 2012; Jenkins et al., 2012; Loh et al., 2009; Luhar et al., 2014), and show promise as routine methods of locating leakages if their location is suspected within relatively small areas (~ km2). The limiting sensitivity for this work at Otway, over km2 scales, was around 2 t day -1. The sensitivity of the methods can be greatly increased if tracers are used; for example, at Otway a mixed gas was used at the CRC-2 injection well during a controlled release and the methane in this mixture proved to be a very effective tracer (Luhar et al., 2014). A network of inexpensive, autonomous CO2 sensors has been more recently tested at Otway (Figure 18) and was successful in locating the same controlled release (Jenkins et al, submitted to IJGGC). In this case the detection limit was around 1 t day^{-1}.

Figure 18. The left panel shows the disposition of atmospheric monitoring stations around the controlled release at the injection well CRC-2 at the Otway site, and at right are the inferred contours enclosing 50% and 90% of the probability of the source location. This measurement of the release was based on a Bayesian inversion of data from the monitoring stations. In this panel the pink disc is at the wellhead and the white disc at the release site.

8 The way ahead: MMV technology for future large-scale storage

New CO_2 storage projects will operate under dedicated storage regulation. Here we choose four examples, onshore and offshore, to illustrate the type of monitoring programmes likely to be deployed for future large-scale operations (Table 3.1). The Canadian QUEST project will operate within the recently enhanced Alberta regulatory regime and, should they proceed, the Peterhead and ROAD projects will be operated under OSPAR and the European Storage Directive. FutureGen, while very recently cancelled, is a good example of a monitoring plan within US regulation (and was cancelled for non-technical reasons). A summary table of monitoring tools for these projects is in Table 2.

Monitoring technique		Quest	Peterhead	ROAD	FutureGen
Deep-focussed					
3D time-lapse surface seismic		🟥	🟥	🟥	
Vertical seismic profiling		🟥	🟥		🟥
Microseismics		🟥		🟥	🟥
Downhole pressure		🟥	🟥	🟥	🟥
Downhole temperature		🟥	🟥	🟥	🟥
Downhole geophysical logging		🟥	🟥	🟥	🟥
Downhole fluid sampling		🟥	🟥		🟥
Tracers		🟥	🟥		🟥
Surface deformation (INSAR)		🟥			🟥
Shallow-focussed (offshore)					
High resolution 3D seismic			🟥		
Seabed and water-column acoustic imaging			🟥	🟥	
Sediment sampling			🟥	🟥	
Water column physics			🟥		
Water column chemistry			🟥		
Shallow-focussed (onshore)		🟥			
Shallow aquifer geochemistry		🟥			Baseline only
Soil CO_2 concentration		🟥			Baseline only
Hyperspectral imaging		🟥			Baseline only
Atmospheric concentrations and fluxes		🟥			Baseline only
Ecosystem studies		🟥			
🟥 red = compliance monitoring					
🟦 blue = research monitoring					

Table 2 Monitoring tools deployed at planned CO_2 storage projects operating under dedicated CCS regulatory regimes. All of these are indicative as monitoring programmes have not been finalized with regulators.

8.1 Quest

The Quest project in Alberta, Canada, is scheduled to become operational in late 2015. It will capture and store CO_2 from the Scotford heavy oil upgrader at a rate of more than 1 $Mtyr^{-1}$, with a target of 25 years of operation. The storage reservoir is formed by the Basal Cambrian Sands, at a depth of 2000 m. The project is regulated under adaptations of existing legislation (mostly for oil and gas).

This M&V plan was developed from a comprehensive risk assessment, based on the bow-tie method which links threats to consequences via a range of preventative and corrective measures. The terms containment and conformance are used explicitly. Monitoring techniques emerge from the analysis because they are needed to either detect the threats that might cause a problem, or control the responses to mitigate it. The selection methodology is structured and methodical, based on comprehensive databases of monitoring techniques with quantitative rankings of options against the tasks that have to be performed. Although heavily dependent on expert input at this stage of CCS, the approach puts the development of a monitoring plan within a familiar framework of engineering and project management. In addition, uncertainties are recognized: the effectiveness of M&V methods is evaluated using three-valued logic, for example, and a more standard probabilistic framework is used to assign thresholds for measured quantities, balancing false alarms with sensitivity.

8.1.1 Containment

The monitoring programme for containment is comprehensive. The most important techniques that are proposed are probably conventional 4D seismic, and pressure monitoring, both in the reservoir and above-zone. The seismic surveys set limits on the amounts of CO_2 above the ultimate seal, much as described for Otway and Sleipner. The estimated limits on CO_2 detectability at depth are however quite large, around 100000 tonnes. Pressure measurements are proposed to be made in the first permeable zone above the primary seal, and are estimated to be very sensitive to fluid leakage into those zones (tens to hundreds of tonnes).

The site has a number of legacy wells that reach the storage formation: these may be logged for cement integrity. In addition, groundwater monitoring in shallow wells near legacy wells will be performed. A programme of wellbore monitoring is proposed for the injection and observation wells. This includes, in addition to standard oilfield logging techniques, optic-fibre distributed temperature and acoustic sensing. Other, less quantitative monitoring that will be deployed to check containment includes microseismic monitoring and monthly InSAR. Injection pressures and rates will be monitored continuously, to check for induced fracturing.

8.1.2 Conformance

The main methods proposed for conformance monitoring are standard 4D seismic and continuous pressure in an observation well drilled into the reservoir interval. These data will be supplemented by monthly InSAR measurements.

8.1.3 Environmental monitoring

The main concern is the integrity of legacy wells, especially any possible effect of leakage on groundwater. To address this there is a programme of monitoring from shallow wells drilled near the legacy wells, as well as from landowner wells. Addition of tracers to the injected CO_2 is an important element in this strategy. Atmospheric CO_2 levels will be monitored using a line-of-sight infrared laser methodology from the injection well pads. In addition there are proposals to use remote sensing by radar to detect changes in near-surface salinity, and remote sensing hyperspectral imagery to monitor vegetation health. The project recognizes that these methods are somewhat immature and may have a high false alarm rate.

While the methodology is rigorous and the plan comprehensive, there are two aspects where experience may help to further it. The first concerns sensitivity, meaning the size of event that would cause a signal above the thresholds stipulated in the M&V plan. The Quest methodology does not appear to model specific leakage events in a quantitative way, and so the sensitivity to leakage implied by the thresholds is not known yet. The false alarm rate, as implied by the adopted thresholds, is well-defined since it by definition refers to the well-studied case where there is no leakage event.

The other aspect is related. Quest, like many projects, has elements of its monitoring plan that involve measurements near the surface, such as properties of vegetation or shallow groundwater. The units of the thresholds for these quantities, such as species per square meter or pH, make it evident that these measurements are really about environmental impact. However the Quest plan treats them as an aspect of containment. Thresholds are much more meaningfully set by conceptualizing this type of data as being about environmental impact rather than leakage, since they are typically poor leak detectors with a high rate of false alarms being possible. As the public and regulators become more familiar with CCS, this distinction will become much easier to make and the scope of environmental monitoring should narrow to well-defined risks.

8.2 PETERHEAD

The Peterhead full-chain CCS project proposes to capture CO_2 from an existing gas-fired power-station at Peterhead and store this at a depth of around 2600 m beneath the outer Moray Firth offshore of eastern Scotland. The plan is to store 10 to 20 million tonnes (Mt) of CO_2 commencing in 2019. Storage will utilise the depleted Goldeneye gas condensate field with the Captain Sandstone as the primary storage reservoir. The monitoring programme has been designed to meet the requirements of the storage permit under the European Storage Directive and covers all operational phases from defining the pre-injection baseline through to transfer of responsibility.

The programme was developed from a comprehensive risk assessment, based on the bow-tie method which links threats to consequences via a range of preventative and corrective measures. Potential risks include short and long-term releases of CO_2 to seabed, sub-sea and platform blowouts, lateral migration to adjacent fields and wellbores, and lateral migration of dissolved CO_2.

The monitoring programme is designed to meet European offshore storage requirements and has comprehensive plans both for deep-focussed and shallow-focussed monitoring activity (Table 3.1), covering baselines, operational and post-closure phases. The main deep-focussed element provides surveillance of the reservoir and overburden and utilises a limited number of proven technologies: time-lapse 3D seismics, down-hole pressure and temperature, geophysical logging and fluid sampling. A shallow environmental monitoring programme is also planned, including seabed imaging, and seabed and seawater sampling.

8.2.1 Containment

Containment monitoring is addressed by time-lapse 3D seismics, and possible 4D VSPs (utilising downhole acoustic optic-fibre technology), to image the reservoir and overburden. It is expected that imaging the plume within the footprint of the original gas-water contact might prove problematical due to residual gas, but the seismic will cover possible lateral egression of CO_2 outside of the original gas-water contact and also any migration of CO_2 into the overburden. The seismics will be acquired with a combination of streamer and sea-bottom nodes to allow coverage beneath the platform. Currently planned surveys include a baseline, mid-project repeat, end-injection repeat and a final survey immediately prior to transfer of responsibility.

8.2.2 Conformance

The main conformance monitoring tool will be downhole pressure measured in a number of injection wells and also in a dedicated monitoring well, plus fluid sampling and downhole geophysical (fluid saturation) logging. 3D seismics will provide additional constraints on lateral plume migration.

Pulsed neutron capture (PNC) logging is planned over the reservoir in the injection and monitoring wells to measure CO_2 saturation. Good baseline data is necessary to distinguish CO_2 from existing methane and baseline logging is planned during the well recompletions. Logging is only envisaged for the reservoir interval, because processing will be more challenging in the overburden as a result of the changing borehole and tubing sizes. Downhole sampling of the reservoir fluids at periodic intervals throughout injection has also been proposed for conformance monitoring. Wireline sampling is preferred over a permanent installation (e.g. u-tube) which is considered too expensive to install and has well integrity and safety concerns. Simulations suggest annual repeat logging between years 5 and 10 would be most appropriate, with two samples taken from the interpreted hydrocarbon column and one from the water leg.

Pressure changes associated with the CO_2 injection are predicted to cause seabed uplift in excess of 30 mm and this will be monitored with a high resolution GPS mounted on the platform.

8.2.3 Contingency

Contingency monitoring is also addressed, in the event of non-conformance or the threat of containment loss. For example a 3D high resolution seismic survey such as p-cable is an option to help image and understand shallow migration in the event of leakage being detected at the top of the storage complex. Contingency multi-beam echosounding and contingency sediment sampling might also be deployed if unexpected lateral migration of CO_2 out of the site or migration in shallower formations were to be detected.

In the event that emissions measurement were to be required, based on the experience from QICS (Blackford, Bull, Cevatoglu et al. 2015), the Peterhead project will investigate the use of quantitative acoustic techniques to estimate bubble-stream fluxes.

8.2.4 Environmental monitoring

Detection of the impacts of possible shallow migration and leakage to seabed is addressed by a comprehensive surface monitoring programme. A multi-beam echo-sounding (MBES) baseline survey, deployed from ship or ROV, is planned over the whole storage complex to image the seabed and identify any active pockmarks or other possible fluid expulsion conduits. Side-scan sonar is included to aid MBES interpretation. MBES will also be acquired around the abandoned wellbores within the storage site area about five years after injection start-up. Subsequent seabed surveys will be collected one year after cessation of injection over the entire storage complex (as for the pre-injection baseline). A Conductivity, Temperature, Depth (CTD) seawater sampling probe is proposed to monitor conductivity, temperature, pressure, pH, redox, salinity and potentially, partial pressure of CO_2 (pCO_2). This would be permanently connected to the platform for power and real-time data transfer and optimally positioned on the seabed as early as practicable to gain a suitable baseline.

Tracers are being considered to distinguish between natural CO_2 and CO_2 injected from Peterhead or possible additional sites. The different $\delta^{13}C$ and $\delta^{18}O$ isotopic fingerprints of the fluids and gases present in the Peterhead injectant stream have been assessed to see if they could act as a natural tracer. Noble gases have also been considered. Currently a continuous tracer stream of PFCs in very low concentration is envisaged, added either onshore at the St Fergus terminal or at the platform.

Sediment sampling is planned to collect benthic macrofaunal, physiochemical and pore gas/water samples to assess possible impacts of leakage to seabed. The planned baseline survey includes the area of the storage complex, plus wellbores and any active pockmarks revealed by the seabed imaging. Reference conditions will be provided by three sampling stations outside of the Storage Complex, perpendicular to predicted plume migration direction. During injection, sediment sampling (and seabed imaging) will be undertaken around the abandoned wellbores within the storage site area, around five years after injection start-up. Subsequent samples will be acquired one year after cessation of injection over the entire Storage Complex (as for the pre-injection baseline), to serve as post-injection/closure baseline.

8.3 ROAD

The ROAD full-chain CCS project aims to store CO_2 in the depleted reservoir of the P18-4 gas field, twenty km NW of Rotterdam, in the Netherlands Southern North Sea. In July 2013, the project was granted a permit to store up to 8.1 Mt CO_2 at a maximum rate of 1.5 Mt/year starting in 2015 (latest Jan 2018), subject to conditions (see below). The P18-4 reservoir lies at a depth of about 3500 m within Triassic sandstones of the Buntsandstein (Arts et al., 2012).

Although ROAD has been granted the first storage permit in Europe, the monitoring programme is subject to updates and the inclusion of more detail, as set out in the conditions of the storage permit. It is largely risk-based with surveillance of leakage via wellbores being the primary focus. The key objectives are to ensure the safety and the integrity of the storage and to provide the necessary information to allow transfer of responsibility. An additional objective is to monitor the effectiveness of any corrective measures that may be required. The operational monitoring plan aims to deploy a limited number of tools focussed on the identified risks (Table 3.1).

8.3.1 Containment

Leakage detection will be addressed through 3D time-lapse seismic surveying of the overburden above the evaporite seals, combined with well integrity measurements to assess the potential for the boreholes to act as leakage pathways. Wellbore leakage is the main identified risk and the well integrity monitoring plan includes cement bond logging (CBL), borehole imaging via downhole video, multi-fingered caliper and electromagnetic casing integrity tools. In addition ultrasonic imaging for casing and cement thickness and quality and well annular flow detection are also proposed.

8.3.2 Conformance

This monitoring requirement will be met by downhole pressure, temperature and passive seismic monitoring to assess any geomechanical responses to injection and to monitor the injection progress. Because of the thick evaporite caprock, imaging of the CO_2 plume within the reservoir is thought to be impractical. Conformance assurance will be provided principally by history-matching numerical simulations of reservoir pressure and temperature with downhole measurements.

8.3.3 Contingency and environmental monitoring

Shallow-focussed surveys will include seabed imaging and acoustic bubble detection. Acoustic bubble detection will be deployed as a baseline survey and then for contingency deployment (if a significant irregularity occurs and sea bed leakage is a possibility). Sediment sampling (gas samples using vibrocore and laboratory analysis) is also planned although the deployment phase and timescale is not stated. No contingency monitoring for emissions quantification is currently included in published plans, although this would be required.

8.4 FUTUREGEN2

The FutureGen2 full-chain CCS project was designed to capture CO_2 from repowering the existing coal-fired Meridosia power plant with oxy-combustion and carbon capture technology and ship the CO_2 via pipeline to a storage site in a rural area of Morgan County, Illinois (FutureGen Alliance, 2013). The project was cancelled in early 2015 because it was progressing more slowly than planned in the funding mechanism. However it is included in this review because the permit was the first granted under the US EPA's Class VI program specific to CO_2 storage, the technical work is well presented in the public domain, so that the precedent set by this project will be valuable to future projects.

The project plan was to inject 1.1 Mt of CO_2 per year over 20 years to a depth of 1300 m below ground surface into the Mount Simon Sandstone. The Mount Simon has been extensively studied, but no penetrations existed in the site area, and the permit application was based on a stratigraphic test well drilled for the project (Panno et al., 2013; Person et al., 2010). Because permeable zones in the Mount Simon are relatively thin in this area, an array of four wells accessing the formation in the centre of the project, but fanning out to make a clover-form plume are planned. The primary confining zone is the Eau Clair Formation and a secondary zone, the Franconia Formation is also identified.

In contrast to the EU approach, the EPA class VI application does not require a risk assessment from the project developer. The EPA UIC programme has decades of injection experience from which they have derived a generic set of concerns about risk to groundwater. The permit application guidance requests information about specific issues as well as monitoring and mitigation plans, followed by a dialog with the site developer to determine if the risks identified are managed or mitigated by the proposed operation and corrective actions.

Groundwater in the area is extracted from shallow (<50m below ground surface) surficial sediments, however the sampled salinity of the St. Peter sandstone at 600 m depth is 3700 ppm TDS, qualifying it as a protected underground source of drinking water. An area of review, defined by the modelled volume which contained 99% of the CO_2 was mapped to determine that no wells penetrate the injection zone in this area.

A detailed plan including the frequency and duration of the testing and sampling is available in the public domain (FutureGen Alliance, 2013, 2014), but final decision on the deployment of many technologies is designed to be adaptive as additional experience and analysis is gained at the site.

8.4.1 Containment

No faults or existing well penetrations have been identified, so that no localized features of geological concern have been identified. As is standard in the UIC programme, much of the monitoring and detail provided in the plan is focused on assuring correct isolation is maintained at the project wells, and includes oxygen activation and cement –bond logging, radioactive tracers, temperature logging, fall-off pressure testing, and corrosion monitoring.

Containment monitoring is based on a deep early-detection monitoring well placed near the centre of the project and completed above the primary confining zone in the permeable Ironton Sandstone This would provide the first indication of any unanticipated containment loss. Predictive flow modelling shows that the pressure response to a leakage of 1% of the 22 Mt injected mass over 20 years would be rapidly detectable near the leak point (Williams et al., 2014). Slower leakage however is modelled as requiring gauges sensitive to < 0.014 bar. Chemical leakage indicators considered include separate liquid and gas phase CO_2, hypersaline water, and other chemical changes (Amonette et al., 2014). Introduced PFTs as well as an array of natural tracers are also under consideration. The same well may be designed to host a microseismic array or VSP geophones, if this equipment does not interfere with other operations. The project accepted the possibility of maintaining a monitoring program, if needed, for 50 years after closure.

8.4.2 Conformance

The major conformance monitoring tools for the Morgan County site will be three in-zone wells that will provide information for modelling validation in the form of pressure response and CO_2 distributions within the reservoir, in compliance with expectations of the Class VI rule for tracking the plume and matching the model predictions. One well completed in multiple zones (Westbay, Schlumberger (2015) or other multilevel piezometer) is placed within the predicted plume footprint at year 2, and within the predicted plume foot-print at year 22, and one is outside of the modelled plume area. At the time of preparation of the testing and monitoring plan for the permit, the selection of indirect monitoring methods was left open so that additional screening could be applied. An array of tools is under consideration to augment the in-zone monitoring provided by the wells, based on a model and baseline noise-based sensitivity analysis that may serve as a prototype for other projects (Strickland et al., 2014). An initial 2D seismic survey yielded poor quality data, so that the value of additional seismic methods for plume tracking was still pending additional processing. Sensitivity analysis based on a Gassmann-type fluid substitution model also showed that signal in this thin zone in relatively stiff rocks was near the limits of detection. Modelling using a sequentially coupled fluid-flow and geomechanical simulation suggested that surface deformation might be up to around 2 cm, mostly in the first year. An orbital InSAR and GPS survey were therefore planned. Modelling of gravity response at the surface showed it to be near the detection threshold, however surface gravity in combination with the GPS survey is low cost and was selected. Electrical methods were rejected following a formal analysis of signal-to-noise levels and after consideration of interference with other higher ranked technologies.

8.4.3 Environmental monitoring

The Class VI rule requires an emergency and remedial response plan, which provides pragmatic and engineering details for many contingencies (Futuregen Alliance, 2014). Direct monitoring of the lowest protected groundwater is required by the Class VI rules. A single well near the project centre is planned in the St Peter Sandstone, because of the definition required by the rules. In addition, baseline monitoring of the shallow groundwater that is in use for domestic water supply and soil gas, atmospheric and hyperspectral ecological monitoring are planned. The need for these types of monitoring activities will be evaluated and they may not be repeated during the injection phase of the project, relying instead on deeper systems.

9 Discussion and Conclusions

Over the past decade or so, the state-of the art in CO_2 storage monitoring has moved from a rather limited experience of a suite of proven methodologies, together with desk-top studies of more novel tools or prototypes, to a much more mature situation where a wide range of monitoring technology has been tested in the field over a variety of storage scenarios. Completion of a portfolio of diverse projects (large/small injection volumes, long/short injection duration, carbonate/clastic rocks, deep/shallow reservoirs, offshore/onshore settings), testing many of the possible monitoring approaches is a major technical accomplishment.

It is becoming clear that stored CO_2 behaves in a manner that is consistent with theoretical expectations. These are built on decades of experience, particularly in the oil and gas industry, but it is reassuring that there have been few real surprises. Progress in verifying predicted behaviour has been widespread in a range of geological settings, increasing confidence that surveillance of the injected CO_2 and associated fluid pressure changes is effective, and that unexpected changes outside of the planned storage volume can be detected.

Distinctive aspects of CO_2 storage have been studied at pilot-scale projects, in addition to testing a wide range of detailed monitoring methods. A focus on downhole deployments in closely-spaced wellbores at sites such as Ketzin, Frio, Nagaoka, and Cranfield has shown that tools can detect and image CO_2 and fluid pressure changes to high sensitivity in the deep subsurface. These results have confirmed and improved our understanding of the details of fluid flow in heterogeneous reservoirs. Moreover, post-injection well logging at Nagaoka has shown the onset of CO_2 dissolution, which can be important as a longer-term stabilisation process. Intensively-monitored small scale injections at Otway have demonstrated residual trapping on a field scale, another important mechanism for stabilization. Datasets such as these provide essential analogues to underpin the longer-term predictive models at large-scale storage sites.

At the larger projects such as Sleipner, monitoring has continued to provide assurance that storage sites are behaving as predicted, and are likely to continue to do so in the future. Where performance issues have arisen, such as at Snøhvit and In Salah, monitoring has proved successful both in providing early warning of a developing non-conformance and also in characterising the causal processes. At Weyburn, a CO2-EOR operation, deep-focussed research monitoring has shown that conformance can be demonstrated in the storage reservoir and has constrained maximum possible out-of-reservoir migration amounts, albeit over the limited area of the research project.

In terms of technology development, advances in deep-focussed monitoring have been progressive; arising partly from research at pilot-scale projects but largely from the requirements of the oil exploration and production industry. So for example the latest time-lapse seismics at Sleipner have major improvements in resolution and repeatability compared with the old baseline data, motivated by the commercial need to improve time-lapse monitoring of producing fields. In contrast shallow –focussed developments have been driven almost exclusively by the storage research community, with significant advances in monitoring methodologies both onshore and offshore. In terms of novel monitoring methods, a small number have made their mark in the past decade. At the In Salah storage site, InSAR has proved spectacularly cost-effective for elucidating the geomechanical state of the reservoir, albeit in rather specifically suitable surface environment. Fibre-optic downhole technologies are also gaining a foothold for continuous downhole surveillance, with fibre-optic seismic cables giving the possibility of wider subsurface coverage. Gravimetry is a technique that is fully complementary to seismic (by explicitly measuring mass change) and is proving promising for estimating amounts of CO_2 dissolution at Sleipner.

Monitoring practice at the currently active larger storage sites indicates that a limited number of proven tools is likely to be the norm. Systematic methodologies have been developed to focus on those techniques whose inclusion materially reduces storage risk. Nevertheless, the first generation of large-scale projects designed to meet GHG regulatory requirements such as Quest, Gorgon, Peterhead, FutureGen, Decatur and ROAD will provide further substantive information and opportunities to optimize M&V approaches. It is clear however that site logistics vary widely and will affect the types of monitoring portfolios selected. Offshore, wellbores are widely-spaced and commonly not accessible, so non-invasive, wide area surveillance is taking precedence. Conversely onshore, wellbore monitoring might well take a higher profile, with surface seismic methods being perhaps less prominent. Public acceptance issues are much more acute onshore than offshore and modified or enhanced shallow monitoring might be required, particularly for early projects. Many shallow monitoring methods are now available to meet this perceived need, although larger projects have converged on a small subset – typically soil gas and groundwater monitoring.

It is clear that the interpretation of shallow monitoring data continues to be a challenge, specifically because it is typically not gathered to check for a well-defined risk, but rather to meet vague concerns and unease. We have argued that a clear separation between the concepts of “environmental impact” and “leakage” might be helpful in clarifying objectives. This issue is important because comprehensive shallow monitoring is potentially very expensive, and the accumulation of hard-to-interpret data is a potential liability in itself. Acquiring baseline characterization of environmentally-relevant variables can be useful. For example, shallow monitoring data at Weyburn was helpful in refuting widely publicised claims of surface leakage. Similarly, press claims of an induced Magnitude 4 earthquake at Sleipner were easily refuted by reference to long-term regional seismicity records. The power of baseline datasets to reduce the occurrence of ‘false positives’ and to refute mischievous claims of storage problems, should not be underestimated. However an operator cannot reasonably be expected to accumulate “defensive” baselines in every possible variable over conceivably a very wide range of spatial and temporal scales, and clarity is needed on what type of near-surface anomalies an operator is responsible for investigating. Reference monitoring sites acting as controls which can be compared with active storage operations might overcome some of these challenges (Pearce et al., 2014).

Enhanced oil recovery projects, mostly in the US, have injected large volumes of CO_2 in the subsurface over four decades. At the small number of EOR sites where geologically-focused monitoring programmes similar to those used for aquifer storage have been conducted (e.g. Weyburn, Cranfield, Bell Creek, Michigan pinnacle reefs), the results have supported the viability of storage at these sites. However, for the value of EOR to be widely recognized as a greenhouse gas mitigation option, additional reporting of outcomes will be required. Much of the data on containment and conformance is in the field operators' records and currently not accessible to review; but it could be used to provide strong evidence of conformance and to certify storage. Some additional modelling and data collection might also be needed to provide assurance that CO_2 is not migrating laterally or vertically into uncontrolled areas, and to show long term storage will be effective.

Pragmatically, commercial EOR offtake is beneficial to the start of CCS by supporting the early needs of capture facilities. Demonstrating that CO_2-EOR can serve as a greenhouse gas mitigation method is primarily administrative, rather than technical, in that an existing regulatory regime must be melded with a new objective. It is important both for geotechnical and business reasons that certification of EOR storage be tuned to the specific needs of this type of project. Current evidence does not provide any cause for concern, so whilst some small adjustments might be appropriate no wholesale modifications to the system are needed. Modest and incremental analysis and data collection to fill gaps in current processes should be considered to improve assurance that storage is effective.

Storage regulation has evolved differently across the world. In some jurisdictions we have seen the emergence of systematic legislative frameworks which set out in some detail regulatory requirements and how monitoring should be used to achieve them (for example the EU Storage Directive). On the other hand, in the US, forty years' experience of managing all injection under the UIC program underpins existing as well as new regulatory arrangements.

A key element of any regulatory philosophy is the linkage between monitoring and verification; conformance and containment providing the main elements. So far, large-scale projects such as Sleipner and Snøhvit have largely met conformance and containment monitoring goals with simple 'operational' monitoring plans. This contrasts with many of the research projects where the focus was on tool testing and development and process demonstration, for example by showing the extent to which a monitoring technology can provide an estimate of volume stored or a simulation can be calibrated to create a satisfactory approximation of the fluid flow observed.

Mature verification, that fully and rigorously provides the assurance desired by stakeholders, does remain challenging however. There are technical issues - for example, can the quality of the confining system be demonstrated over the ultimate area of plume migration? Can vertical leakage though wells or other features be shown to be sufficiently small over long time-frames? There are also matters of wider principle. We have frequently in this review alluded to consistency between models and data, or referred to the absence of material deviations from conformance, but there is no doubt that these notions, while sufficient at the moment, are also imprecise. As more storage projects are implemented, and issues or controversies arise, we expect that more clarity will emerge.

Of particular interest to M&V is the extent to which a quantitative statement of monitorable project goals can reduce cost and improve stakeholder confidence. Such goals might quantify acceptable and unacceptable outcomes from injection, including storage footprint, the time-frames to be considered, relevant mass changes and other occurrences – mass / distance migrated, geomechanical stress changes, pressure increases, or induced seismicity magnitudes. The quantification of these goals is likely to be based on multiple predictive model scenarios and might take the form of an absolute value range, or a probabilistic function. The extent to which quantitative performance objectives might become the norm is uncertain. At the present state of development a qualitative approach to showing that the monitoring results match the expected response of the system is typical, but as experience accumulates more quantitative methods will become more robust.

Explicit consideration of significant adverse events would be helpful in designing monitoring strategies and clarifying requirements. Such adverse events are evaluated in the process of risk assessment, but need routinely to be linked to clearly monitorable outcomes. Also, it needs to be clear that the list of possible events to monitor is exhaustive; otherwise any monitoring strategy could be accused of having failed to identify some hitherto-unspecified failure mode. *A priori* assessment of the monitoring system would include forward modelling the signal of the hypothetical adverse event, and demonstrating that the monitoring system can detect the event at the threshold desired, considering variables such as environmental noise and measurement inaccuracy. Contingency planning for when an adverse event does occur is relatively in its infancy, although the example of Snøhvit shows that such preparation can be highly effective. As more experience is gained in detecting and remediating adverse events confidence in M&V will grow further.

To sum up, M&V experience from the wide range of projects we have considered is demonstrating that containment, conformance and environmental impact can be monitored with a degree of certainty and level of detail that is appropriate for the storage projects of the next decade. Challenges remain, but the largest of these concern the extent to which regulatory requirements might be interpreted in ways that are impractical and limit CCS. Ultimately, while there are risks that monitoring may miss significant adverse events, the evidence from the decade is that these risks are small, certainly smaller than the risks from climate change that CCS is designed to reduce.

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