Review of monitoring issues and technologies associated with the long-term underground storage of carbon dioxide

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Abstract

Large-scale underground storage of CO_2 has the potential to play a key role in reducing global greenhouse gas emissions. Typical underground storage reservoirs would lie at depths of 1000m or more and contain tens or even hundreds of millions of tonnes of CO_2. A likely regulatory requirement is that storage sites would have to be monitored both to prove their efficacy in emissions reduction and to ensure site safety. A diverse portfolio of potential monitoring tools is available, some tried and tested in the oil industry, others as yet unproven. Shallow-focussed techniques are likely to be deployed to demonstrate short-term site performance and, in the longer term, to ensure early warning of potential surface leakage. Deeper focussed methods, notably time-lapse seismic, will be used to track CO_2 migration in the subsurface, to assess reservoir performance and to calibrate/validate site performance simulation models. The duration of a monitoring programme is likely to be highly site specific, but conformance between predicted and observed site performance may form an acceptable basis for site closure.

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To combat global warming and ocean acidification, effective control of greenhouse gas emissions is likely to prove one of the most important scientific and technological challenges of the 21st Century. The Royal Commission on Environmental Pollution (2000) considered that atmospheric CO_2 levels should not rise above 550 parts per million (ppm), but more recent work (Schellnhuber 2006) suggest that levels above 400 ppm will have dangerous impacts. An equitable international agreement to keep CO_2 levels in the atmosphere below even 550 ppm, based on emissions contraction and convergence by 2050, could require a reduction of UK annual carbon dioxide emissions of 60% by 2050 and possibly 80% by 2100. These would be massive reductions (Metz *et al*. 2005). A promising technology to achieve these aims involves injecting industrial quantities of CO_2 into underground storage reservoirs. Large-scale geological storage is currently being systematically monitored at three sites: Sleipner (North Sea), Weyburn (Canada) and In Salah (Algeria). It is clear that geological storage could make a significant impact on greenhouse gas emissions, perhaps acting as a bridging technology to ease the transition from current fossil fuel based energy systems to a future low- or zero-carbon energy system.

For CO_2 storage to contribute to significant emissions reduction, it will have to be carried out on a very large scale. Total annual UK emissions for 2002 were estimated at 536 Mt CO_2, of which the twenty largest power plants produced 119 Mt. A typical underground storage reservoir will need, therefore, to be capable of holding hundreds of millions of tonnes of CO_2.

If underground CO_2 storage is to become widely accepted, it has to be demonstrably effective from an emissions reduction standpoint and also to be demonstrably safe. Storage sites will, therefore, need to be monitored both to establish the current performance of the site and to constrain and calibrate predictions about its future behaviour (Benson *et al.* 2004, DTI 2005). This paper reviews some of the current technologies available for storage site monitoring, and some of the issues associated with tool deployment, such as complementarity. Examples from two ongoing CO_2 storage operations are presented; emphasis is on the offshore storage site at Sleipner site, with additional onshore issues illustrated by reference to Weyburn. Costs, both relative and absolute, will clearly be an important driver in the selection of an overall monitoring strategy, but they are highly site-dependent, and not discussed in detail.

Principles of Underground Storage

CO_2 can be injected into the pore spaces of an underground reservoir rock via one or more wells (Fig. 1), permeating the rock, and displacing some of the fluid (commonly saline water) that originally occupied the pore spaces. In basins around the UK, given likely injection depths in the range 1000 to 2000 m, CO_2 would typically be in a supercritical fluid phase, with a density of between 300 and 800 kgm^{-3} (depending on geothermal gradient). The injected CO_2 would, therefore, be buoyant, with a strong tendency to move upwards through the storage reservoir until it reaches a sealing barrier that prevents its further vertical migration. Horizontal or vertical permeability barriers, such as shale layers or faults, will impede movement within the reservoir and favour intra-reservoir trapping; lateral fluid pressure gradients will also play a part. Migration out of the reservoir would be facilitated by transmissive faults, caprock permeability or degraded wellbores (Fig.1).

For the purposes of describing the movement of CO_2 in and around the primary storage reservoir it is convenient to define two distinct terms. ***Migration*** is here defined as movement of CO_2 within the storage reservoir and the surrounding subsurface. ***Leakage*** is defined as transfer of CO_2 from the geosphere either to the atmosphere at the land surface, or to seawater or to potable shallow aquifers.

The amount of CO_2 that can be injected into a particular reservoir will be limited by adverse processes, which can occur both in the short term, and also over much longer timescales, as the result of migration of the injected CO_2. These include: an unacceptable rise in reservoir pressure, pollution of potable water by displacement of the saline/fresh groundwater interface, pollution of potable water by CO_2 or toxic substances mobilised by CO_2, escape of CO_2 to the outcrop of a reservoir rock and escape of CO_2 via a migration pathway through the caprock.

In the long term, the interaction of five principal mechanisms will determine the fate of CO_2 in the reservoir: immobilisation in structural traps, immobilisation as a residual CO_2 saturation, dissolution into the formation water, geochemical reaction with the formation water or rock-forming minerals and, if the seal is not perfect, migration out of the primary storage reservoir (e.g. Metz *et al*. 2005).

To design a monitoring programme to address migration and potential leakage over both the short term (the injection period) and long term, risk assessment is needed to determine a conceptual envelope of possible migration and leakage scenarios. Leaks may not necessarily occur directly above the storage site but will be strongly influenced by the local geological structure. For example, in the case of migration up gently dipping permeable strata, leaks may appear many kilometres from the storage site and the area needing to be covered by a monitoring programme may be much larger than the intended footprint of storage within the primary reservoir itself (Fig. 1). Leaks may also not occur for hundreds of years if the leakage path is long, but thereafter could be highly significant. In this respect, realistic long-term simulations of future site behaviour would be a pre-requisite for satisfactory site operation, monitoring and closure.

A comprehensive portfolio of tools is available for potential utilisation in storage site characterisation and monitoring (Fig. 2). Broadly speaking these can be categorised as deep-focussed tools for reservoir and overburden characterisation and monitoring CO_2 migration, and shallow-focussed methods for overburden and surface characterisation, and the detection and measurement of surface leaks. A selection of the most promising tools is outlined below.

Monitoring CO_2 migration in the subsurface

At the current time, monitoring CO_2 migration in the subsurface relies on geophysical and well-based methods that have been developed over many years in the oil industry. In particular, geophysical time-lapse techniques, whereby repeated datasets are acquired over a period of time, have proved a powerful means of identifying and mapping subsurface changes, such as fluid movement. A brief account of some key geophysical tools is given below.

Seismic methods

Seismic techniques have a high imaging potential, most notably demonstrated at Sleipner (Fig. 3), but their performance varies significantly depending on reservoir depth, properties and pressure-temperature conditions (McKenna *et al*. 2003). As a general rule, reservoirs with good injection and storage characteristics (relatively unconsolidated with high porosity and permeability) will also tend to have suitable seismic properties for CO_2 monitoring. Conversely, it will be more difficult to image CO_2 stored within low porosity, low permeability reservoirs.

Surface 3D seismic data are ideally acquired over the full volume of the reservoir and overburden, and offer the potential to quantify total amounts of CO_2 in the reservoir and also to identify migration from the storage reservoir into and through the overburden. Direct quantification of CO_2 volumes in the reservoir can, at least in principle, be achieved through the analysis of reflection amplitudes and the amount and distribution of velocity 'pushdown' (the acoustic 'shadow' cast by the plume on underlying reflections). Quantitative analysis however is a challenging problem due to a number of significant uncertainties, well illustrated by the Sleipner case (see below). Migration of CO_2 upwards through the overburden, particularly in the gas phase, can be detectable on seismic data via the generation of 'bright spots'; distinct high amplitude reflections of localised extent caused by the sharp decrease in acoustic impedance within rocks saturated by CO_2.

Detection of CO_2 in the overburden, as 'bright spots', can potentially be used to estimate migration fluxes. To be detectable a CO_2 accumulation must have lateral and vertical dimensions sufficient to produce a discernible seismic response. A study by Myer *et al*. (2002) based on theoretical resolution considerations, has suggested that CO_2 accumulations as small as 10000 to 20000 tonnes should be detectable under favourable conditions. Results from the Sleipner time-lapse surveys (see below) indicate that these figures may be somewhat conservative. Repeatability noise (which depends on the accuracy with which successive surveys can be matched), rather than resolution, may be the key parameter controlling detection thresholds.

Wellbore seismic methods, such as VSP and cross-hole seismics, provide higher resolution of the near-borehole environment with direct measurement of velocity and signal attenuation (both key indicators of fluid saturation) providing finer-scale information complementary to the surface methods. VSPs provide specific detail around the wellbore such as the early detection of CO_2 migration outside the casing. Cross-hole seismic requires at least two wells through or close to the storage reservoir. Changes in travel-time and signal amplitude between the wells can be used to map velocity and attenuation variations in the section between the wells that relate to CO_2 saturations and/or pressure changes. Recent practical experience from the Nagaoka CO_2 injection experiment (Kikuta *et al*. 2005) indicates that amounts of CO_2 as small as hundreds of tonnes can be detectable using the crosshole method.

Multicomponent (MC) seismic methods record both the compressional (P-wave) and shear (S-wave) components of ground motion. The latter are more sensitive than the former to fractures or microfractures, but much less sensitive to the fluid content. By analysing combined P- and S-wave signals, it is possible to obtain a more complete picture of fluid behaviour, including improved discrimination of fluid pressure and saturation changes and better imaging beneath gas accumulations. In particular, changes may be observable in low permeability overburden sequences where the lack of discrete CO_2 accumulations may render conventional seismic ineffective. Notable examples of the successful deployment of MC seismic include the CO_2-Enhanced oil recovery (EOR) operation at the Vacuum Field in Texas (Angerer *et al*. 2001) and more recently, at Weyburn (Wilson & Monea 2004). MC seismic is, however, considerably more expensive than conventional seismic and shear-wave data collection presents additional difficulties offshore.

Gravimetric methods

Gravimetry measures the gravitational acceleration due to mass distributions within the earth to detect variations in subsurface rock or fluid density. The possibility of monitoring injected CO_2 with repeated gravity measurements is strongly dependent on CO_2 density and subsurface distribution. In general terms the size of the gravity change gives information on subsurface volumes and densities, while the spatial variation in gravity gives information on lateral CO_2 distribution. The weakest aspect of the gravity data is in resolving absolute depth information on the CO_2 accumulation.

Although of much lower spatial resolution than the seismic methods, gravimetry offers some important complementary adjuncts to time-lapse seismic monitoring. Firstly, it can provide independent verification of the change in subsurface mass during injection via Gauss's Theorem. This may enable estimates to be made of the amount of CO_2 going into solution, an important uncertainty in efforts to quantify free CO_2 in the reservoir (dissolved CO_2 is effectively invisible on seismic data). Dissolution, moreover, is an important long-term trapping process, difficult to quantify accurately through flow simulations. Secondly, deployed periodically, gravimetry could be used as an 'early warning system' to detect the accumulation of migrating CO_2 in shallow overburden traps where it is likely to be in the low density gaseous phase with a correspondingly strong gravity signature.

The detection limits of gravimetry are highly site specific and depend on very high resolution levelling. Low CO_2 density and a spatially confined CO_2 bubble will give the largest gravity change for a given mass, shallow depths and high temperatures favouring lower densities. Recent work at Sleipner (see below) suggests that measurement accuracy for repeat surveys offshore may be as low as 3 to 5 μGal. Land gravimetry is likely to have a similar accuracy. At these repeatability levels, under favourable conditions, accumulations of CO_2 in the gaseous state of less than 1 Mt may be detectable at depths around 500 m (Fig. 4). Such a figure seems quite large, but in the context of a possible future large-scale storage site, would be less than 1% of the total amount stored. For general mass verifications within a reasonably shallow storage reservoir, injected CO_2 masses of more than about 2 Mt would be expected to produce a detectable response.

Electromagnetic methods

In a similar way to gravimetry, electromagnetic (EM) methods offer the potential for low resolution, low-cost, site monitoring. EM techniques deploy time-variant source electrical fields to induce secondary electrical and magnetic fields that carry information about subsurface electrical structure. CO_2 is resistive, so EM methods are likely to be suitable for monitoring storage in saline formations where CO_2 is displacing more conductive formation waters.

Recent developments of offshore controlled source EM systems (so-called seabed-logging) can detect thin resistive anomalies at depths up to several kilometres. Recent surveys have successfully determined the presence and absence of hydrocarbons within reservoirs (Johansen *et al.* 2005). Direct detection of resistive CO_2 zones within more conductive water-filled strata should, therefore, also be possible. So far, seabed logging has been restricted to quite deep waters (>300m) as airwave interference made getting satisfactory results in shallow water difficult. Recent developments indicate that these technical difficulties are being overcome.

Cross-hole EM is comparable to cross-hole seismics in that transmitters and receivers are placed in adjacent boreholes and tomography is used to map the conductivity structure of the section between the wells. The technique is particularly useful when used in conjunction with seismic methods, providing complementary information to reduce uncertainty. Cross-hole EM imaging experiments in the United States were successful in monitoring CO_2 migration in an enhanced oil recovery (EOR) flood (Hoversten *et al*. 2002). It is fair to say, however, that the electrical properties of CO_2 distributed in subsurface reservoirs are not fully understood. Significant further research is required before the efficacy of the electrical methods can be fully assessed.

Monitoring CO_2 leakage

Monitoring for CO_2 leakage involves the detection or measurement of CO_2 in the overburden above the caprock and either in the soil or in the air, or, offshore, in the seabed or the water column. Unlike the deep-focussed technologies, shallow monitoring for leakage would not be expected to actually detect leaking CO_2 at a well-designed storage site in the foreseeable future. Current research emphasis therefore is on methodologies for establishing secure baseline conditions, developing tools and strategies for the robust detection and measurements of leaks should they occur in the future, and testing tools at naturally-ocurring CO_2 seep sites..

A key aspect of leakage monitoring is the ability to obtain robust measurements of leakage flux over wide areas. There is something of a conflict here, in that methods which can readily be deployed over large areas tend to provide only qualitative information on CO_2 fluxes, whereas tools capable of accurate measurement tend to be only applicable to very restricted sites. A comprehensive leakage monitoring programme therefore, will have to deploy complementary methods in combination.

Technologies for the direct measurement of CO_2 leakage offshore are very much in their infancy. Seabed sampling systems are under development, a key requirement being that fluid within the sample chamber is maintained at seafloor pressure, allowing fluid subsamples to be withdrawn for a number of analytical techniques without degassing the remaining fluid. Onshore, there is a wide range of established techniques for the detection and measurement of CO_2 and other gases in spring and well waters, and in the soil. These can be used to establish pre-storage baseline conditions and also, by detecting naturally-occurring seepages, to indicate potential migration and leakage pathways.

Acoustic imaging and sonar bathymetry

Indirect methods can provide important shallow monitoring information over large areas above storage sites. Offshore, acoustic imaging can provide very high resolution images of the seafloor and the shallow sub-seafloor, perhaps resolving features more than an order of magnitude smaller than conventional seismic reflection data. They offer the capability of imaging gas escape structures at the seabed such as pockmarks (Fig. 5a) and even free gas in the water column itself (Fig. 5b). Naturally occurring pockmarks and shallow gas chimneys (due to methane escape) may act as preferential pathways for future CO_2 seepage and may therefore be used to optimise the deployment of dedicated gas measurement equipment.

Soil gas methods

Ambient levels of CO_2 in soils are many times greater than concentrations in the air. Welles *et al*. (2001) quote typical soil gas CO_2 concentrations of 2000-10000 ppm, The equipment needed for soil gas surveying ranges from fixed accumulation chambers to small portable systems comprising sampling and analysis equipment. In the latter case, probes or accumulation chambers are placed in a grid configuration over the expected leakage ‘footprint’, in or on the soil, and samples analysed periodically to determine soil gas composition and fluxes. A key issue in soil gas surveying is to establish accurate baseline conditions by identifying and removing the effect of seasonal variations. A clear requirement therefore is to have a robust understanding of climate and seasonal changes in soil use and processes for the site. This is exemplified by the Weyburn soil gas monitoring programme (see below).

Atmospheric measurement

Most techniques for the measurement of atmospheric CO_2 rely on the absorption of infrared radiation, and range from large, ground-based instruments, to small and portable tools that can be mounted on a vehicle or in an aircraft. There are two basic types: non-dispersive infrared gas analyzers and infrared diode laser instruments. The former use a broad-spectrum source in a small closed chamber containing the sample to be analyzed - a ‘short closed-path’ technique. Infrared diode laser instruments can be used in closed-path mode, but also for ‘open-path’ techniques where the free atmosphere is analyzed. They can be deployed over either a short (less than 2 m) or long path length (hundreds of metres), with results averaging the concentrations over these distances. The eddy covariance (or correlation) micrometeorological method (Miles *et al.* 2004) essentially consists of an infrared gas analyzer mounted on a tower alongside a sensitive sonic anemometer to measure wind speed and direction. The detector is basically very similar to those described above, and is able to detect CO_2 from an area (‘footprint’) upwind. The size and the shape of the footprint is derived mathematically from the wind speed and direction. By combining CO_2 concentration data with meteorological information, eddy covariance can produce CO_2 flux data, expressed as the amount of CO_2 released per unit area per unit time and is particularly appropriate in more open terrain. A weakness of the eddy covariance technique is its propensity to detect other anthropogenic sources of CO_2 (vehicles, industrial plant etc), as well as natural variations (diurnal, seasonal etc). These have to be carefully characterised so their effects can be removed.

Remote sensing

Remote sensing (airborne and satellite) methods are mainly suitable for detecting changes in floral cover due to the effects of CO_2. The use of airborne hyperspectral imaging for mapping floral habitats is well established, for example surveys over the Rangely CO_2-EOR field have suggested that surface seepages are minimal (Pickles & Cover 2004). A more innovative approach is to use the method for direct detection of CO_2 by utilizing absorption features that fall within the wavelength range of airborne hyperspectral scanners (e.g. Goff *et al*. 2001 and Mori *et al*. 2001). Imaging of leaks from natural gas storage facilities (REFERENCE) has proved the efficacy of the method, which could be potentially extended to CO_2 detection. Methodological testing and calibration is required to establish if the smaller concentrations likely to be associated with leaks from CO_2 storage facilities could be detected against the more complex and variable backdrop of the natural environment.

Airborne EM techniques have been used to detect conductivity anomalies associated with hydrogeochemical changes in ground water, which are caused by pollution plumes derived from overlying mineral spoil heaps. The method could potentially detect changes in shallow (< 100 m depth) groundwater resistivity due to the presence of dissolved CO_2.

Example of monitoring CO_2 migration in the subsurface - Sleipner

The CO_2 injection operation at the Sleipner gas field in the North Sea (Baklid *et al*. 1996), operated by Statoil and partners, is the world's first industrial-scale CO_2 injection project aimed at greenhouse gas mitigation (specifically to avoid Norwegian carbon tax). CO_2 separated from natural gas produced at Sleipner is currently being injected at a depth of just over 1000 m into the Utsira Sand, a major saline aquifer. Injection started in 1996 and is planned to continue for about twenty years, at a rate of about one million tonnes per year. The CO_2 plume is currently being monitored by time-lapse seismic and gravimetric methods.

Imaging CO_2 migration

Time-lapse 3D seismic data were acquired in 1994, prior to injection, and again in 1999, 2001 and 2002, with respectively 2.35, 4.26 and 4.97 Mt of CO_2 in the reservoir. Full details of current interpretive work on the seismic datasets are given in Arts *et al*. (2004a, b) and Chadwick *et al*. (2004, 2005). Suffice to say here that the CO_2 plume is imaged as a number of bright sub-horizontal reflections within the reservoir, growing with time (Fig. 6a). The reflections are interpreted as arising from thin (< 8 m thick) layers of CO_2 trapped beneath thin intra-reservoir mudstones and the reservoir caprock. The plume is roughly 200 m high and elliptical in plan, with a major axis increasing from about 1500 m in 1999 to about 2000 m in 2001 (Fig. 6b).

The plume is underlain by a prominent velocity pushdown, a downward relative displacement of reflectors (Fig. 7), caused by the seismic waves travelling much more slowly through CO_2-saturated rock than through the virgin aquifer.

History-matching and quantification

History-matched reservoir flow simulations of plume development at Sleipner produce a reasonable fit to the observed data. For example, individual CO_2 layers observed on the seismic can be reproduced in the flow simulations (Lindeberg *et al*. 2001) and synthetic seismic models based on the flow simulations show reasonable agreement with the observed data (Fig. 8; Arts *et al.* 2005). Significant uncertainty remains however, regarding the detailed geometry of plume layering and, in particular, the nature of CO_2 - water mixing at low saturations (see below), which precludes accurate simulation of velocity pushdown.

Inverse modelling based upon quantifying amounts of CO_2 from layer reflectivity and velocity pushdown has been used in an attempt to verify the *in situ* injected mass of CO_2. Modelling assumed that plume reflectivity largely comprises tuned responses from thin layers containing high levels of CO_2 whose thickness varies directly with reflection amplitude. Calculated models comprise thin layers containing high saturation CO_2, mapped according to an amplitude-thickness tuning relationship. Between the layers, a lesser component of much lower saturation CO_2 is required to match the observed pushdown.

A key uncertainty at Sleipner is formation temperature. A poorly constrained measurement of 36°C is available for the Utsira reservoir, but regional temperature patterns suggest that the reservoir may be several degrees warmer. At the higher temperatures, CO_2 would have markedly different physical properties, with a significantly lower density and bulk modulus. The principal effect of lowering density would be a correspondingly larger *in situ* volume of CO_2; a secondary, but still important, effect of higher reservoir temperatures would be to give significantly lower seismic velocities. Both effects would impact crucially on any quantitative analysis of the seismic data.

Inverse models of CO_2 distribution in the 1999 plume have been generated, based on both the measured, and a possible higher, temperature scenario. The distribution of CO_2 in both models is consistent with the known injected mass (allowing for parameter uncertainty) and both models can replicate the observed plume reflectivity and the observed velocity pushdown (Fig. 9). However, the higher temperature model requires that the dispersed (low-saturation) component of CO_2 has significantly higher seismic velocities than is required for the lower temperature model. This implies that the dispersed CO_2 has a somewhat patchy distribution, with heterogeneous mixing of the CO_2 and water phases (Sengupta & Mavko 2003). This highlights a key uncertainty in verification estimates, the velocity behaviour of the CO_2-water–rock system, which is heavily dependent on the (poorly-constrained) nature of small-scale mixing processes between the fluid phases (Mavko & Mukerji 1998). Because of these uncertainties, a modelling solution that uniquely verifies the injected volume has not yet been obtained.

Migration detection

The potential capability of the Sleipner seismic data to detect the migration of small quantities of CO_2 can be illustrated by examining the topmost part of the 1999 plume, which is marked by two small CO_2 accumulations trapped directly beneath the caprock (Fig. 10). From the reflection amplitudes the net volumes of the two accumulations can be estimated at 9000 and 11500 m^3 respectively. Other seismic features on the timeslice can be attributed to repeatability noise, arising from intrinsic minor mismatches of the 1999 and 1994 (baseline) surveys. It is clear that the level of repeatability noise plays a key role in determining the detectability threshold. Thus for a patch of CO_2 to be identified on the data it should be possible to discriminate unequivocally between it and the largest noise peaks. Preliminary analysis suggests that accumulations larger than about 4000 m^3 should fulfil this criterion. Assuming high saturations, this would correspond to about 1600 tonnes of CO_2 at the top of the reservoir where CO_2 has a density of about 400 kg m^{-3}, but less than 600 tonnes at 500 m depth, where the density is considerably lower (detectable mass would be further lowered for CO_2 at lower saturations). Actual detection capability however depends crucially on the nature of the CO_2 accumulation. Small thick accumulations in porous strata would tend to be readily detectable, whereas distributed leakage through low permeability strata may be difficult to detect with conventional seismic techniques. Similarly, leakage along a fault within low permeability rocks would be difficult to detect. It could be argued however that faults within low permeability strata are, in any case, unlikely to provide effective fluid pathways.

Gravimetry

A seabed gravity survey was acquired at Sleipner in 2002 (Nooner *et al*. 2006), with 4.97 Mt of CO_2 injected, and a repeat survey in 2005 with 7.75 Mt of CO_2 injected (an additional 2.78 Mt). The surveys were based around pre-positioned concrete benchmarks on the seafloor that served as reference locations for the (repeated) gravity measurements. Relative gravity and water pressure readings were taken at each benchmark by a customised gravimetry and pressure measurement module mounted on a Remotely Operated Vehicle (Fig. 11a). Thirty concrete benchmarked survey stations were deployed in two perpendicular lines, spanning an area of about 7 km east-west and 3 km north-south and overlapping the subsurface footprint of the CO_2 plume (Fig. 11b). Each survey station was visited at least three times to better constrain instrument drift and other errors, resulting in a single station repeatability of about 4 μGal. For time-lapse measurements an additional uncertainty of 1–2 μGal is associated with the reference null level. The final detection threshold for Sleipner therefore is estimated at about 5 μGal.

The time-lapse gravimetric response due to CO_2 was obtained by removing the modelled gravimetric time-lapse response from the Sleipner East field (the deeper gas reservoir currently in production) from the measured gravity changes between 2002 and 2005.

Forward modelling was then performed (Nooner *et al*. 2006) to investigate whether the gravity changes between 2002 and 2005 could provide an indication of the *in situ*

CO_2 density. This was done via plume models constrained both by time-lapse seismic data (using generalised plume distributions based on the 2001 3D survey) and also by reservoir flow models. The best fit was obtained for the higher temperature seismically-constrained model. Statistical analysis indicates that the average CO_2 density in the plume is around 530 kgm^{-3}. This is consistent with reservoir temperatures towards the high end of the uncertainty range.

It is clear from this example that the gravimetry survey has provided valuable independent information capable of reducing uncertainty in the seismic analysis. The use of complementary methodologies in this way can be very effective in an integrated monitoring programme.

Example of monitoring for surface leakage - Weyburn

The Weyburn operation in Saskatchewan, Canada (Wilson & Monea 2004), is principally an EOR project, but with the secondary aim of ultimately storing 20 Mt of anthropogenic CO_2. Injection started in late 2000, using CO_2 captured from a coal gasification plant in North Dakota and transported to the site via a 320 km pipeline. CO_2 is injected at rates of between one and two million tonnes per year, into a thin, carbonate reservoir at a depth of about 1500 m. Weyburn differs from Sleipner in having a large number of wells, both active and abandoned, which penetrate the storage reservoir.

The shallow monitoring programme at Weyburn provides a field example of a generic monitoring methodology that could be applied at future onshore storage sites or around onshore transport infrastructure. A full account of the Weyburn shallow monitoring work is given in Riding & Rochelle (this volume), here we shall just summarise those key findings pertinent to this paper.

Baseline surveys were acquired in 2001 to evaluate natural variation (principally seasonal effects), in soil gas concentration and to identify sites of higher gas flux that may be indicative of deep gas escape (*e.g.* Strutt *et al*. 2003). Measurements included gas concentrations in the shallow unsaturated soil horizon (soil gas); mass transfer rates of CO_2 across the soil-atmosphere interface (gas flux) and long-term monitoring of radon flow rates, as a proxy for CO_2, using probes buried for up to a year at 2 m depths.

Soil gas monitoring of CH_4, CO_2, CO_2 flux, O_2, ^{222}Rn and thoron (via ^{220}Rn) was carried out on a 360 point grid at 200 m spacing, with points extending to the southwest of the initial injection area. Soil gas samples were also analysed in the laboratory for He, light hydrocarbons, N_2, O_2 and S. Follow-up surveys in the autumn of 2002 traversed anomalies seen on the earlier grid survey. Selected CO_2 and radon anomalies on these profiles were investigated in more detail for signs of natural pathways for deep gas escape, using He, CH_4 and Rn as proxies for potential future CO_2 escape. Continuous radon monitoring probes were installed at sites where He and radon data, in particular, indicated the potential for deep gas migration. Surveys of the sampling grid, and most of the more detailed profiles, were repeated in the autumns of 2002 and 2003. The radon monitoring probes were in operation virtually continuously from the autumn of 2001 through to 2004.

Marked changes were seen in CO_2 concentration and surface flux levels between each of the three datasets (Riding & Richelle Fig. 21, this volume). Higher values marked the growing season of July 2001, with lower levels in autumn 2002 and further reduction in autumn 2003, when conditions were cooler and the growing season almost over. These results illustrate the importance of shallow biological reactions that produce CO_2 as a metabolic by-product. In contrast, the radon and thoron data were found to be similar for the three years, implying that both these gases have a shallow *in-situ* origin. Some of the CO_2 anomalies, based on initial air-photo interpretation, may represent the surface expression of deep faults, but soil gas data indicated that the elevated values in these areas are more likely due to shallow biological reactions in the moist, organic-rich soil. Stable isotopic analyses may help identify the sources of CO_2, potentially distinguishing near-surface biogenic CO_2 from deeper injected CO_2, if isotopic values were sufficiently distinct. There was no clear correspondence between soil gas CO_2 anomalies and the location of the CO_2 injection wells.

The temporal variation of CH_4 was significantly different from the CO_2 with only a very slight increase over the same period. This trend may be due to the seasonal drying of the soil and subsequent increase in soil permeability to air, resulting in the greater downward diffusion of air with its constant methane concentration of about 2.5 ppm. The correlation between soil gas CO_2 and CH_4 is low because they are produced via different metabolic pathways.

The distribution of radon and thoron anomalies lacked any clear linear trends that might indicate the presence of a gas-permeable fault or fracture system. Continuous profiling by gamma spectrometry did not indicate any marked anomalies in uranium or thoron series radionuclides that might be linked to radon escape through a fault or fracture system.

An inverse linear relationship was observed between concentrations of CO_2 and O_2, whereas N_2 remained essentially constant (Riding & Rochelle this volume), providing further strong evidence of a biogenic origin for the CO_2 via reactions in which O_2 is consumed. If significant migration of CO_2 from depth were occurring, both O_2 and N_2 would be diluted as CO_2 levels increased, similar to areas of natural deep CO_2 escape, such as Cava dei Selci in Italy (Riding & Rochelle this volume). The isotopic values of three soil gas samples collected in summer 2001, all indicated that the soil gas CO_2 was produced by microbial or root metabolism of organic matter from local plants. However, it is difficult to draw firm conclusions from this small number of samples.

Borehole integrity was investigated by measuring soil gas around two decommissioned oil wells, one abandoned and the other suspended due to failed casing. The well with failed casing had weakly anomalous CO_2 at two sites but this was not the case for other gases. The abandoned well had normal background CO_2 values. Statistical populations of CO_2 and radon were generally higher for the suspended well while those for CH_4 and C_2H_6 were higher for the abandoned well, compared to background values, although all individual values lay well within the range observed across the site. There was one He anomaly at the abandoned well site, but the lack of correspondence between anomalies of different gases suggests that current leakage from depth in the well is insignificant.

Electronic radon sensors were installed up to 1.9 m deep at six sites selected from the detailed soil gas profiles located across radon and CO_2 anomalies. Hourly measurements of radon concentration, temperature and atmospheric pressure showed seasonal variations in radon concentration, which were modelled against atmospheric parameters, indicating the importance of pressure, rainfall and temperature on gas migration. In addition, CO_2 fluxes deeper in the soil were calculated and compared to surface rates. Ultimately, the probes may detect the first precursors of any possible CO_2 escape to the surface. Data from the probes showed seasonal variations in the gas flow regime and in soil permeability. Maximum gas velocities were in the range 5-15 cm h^{-1}, values typical of faults, while background values reflected diffusive gas transport. Carbon dioxide fluxes at 2 m depth were calculated to be 10-20 times lower than those at surface. This is consistent with declining biogenic CO_2 production with depth and suggests it may be better to monitor flux at this depth where biogenic influences are muted.

Site performance and monitoring detection capability

The principal requirements of a site monitoring programme are to establish current storage site performance and to assist in the prediction of future performance, with the ultimate aim of enabling site closure (Pearce *et al.* 2006). It is clear that site performance in terms of safety is not necessarily synonymous with performance in terms of emissions reduction. Thus, a site leaking low fluxes of CO_2 over a wide area may fail a total emissions mitigation criterion, but could well be perfectly safe. Conversely, a site may have a single localised small leak that is well beneath an approved total emissions threshold, but which gives rise to a locally hazardous leakage flux at the surface.

In fact, the basic aspiration for geological storage is zero leakage. In other words, a properly characterised storage site would be expected to store CO_2 indefinitely with no loss to atmosphere or seawater. Nevertheless, it is possible that a proportion of sites may leak in due course, with leakage perhaps of a localised and/or erratic nature. Other sites will employ multiple reservoir and/or multiple barrier storage concepts where significant subsurface migration of CO_2 is part of the storage plan.

Monitoring-based verification of site containment performance could, therefore, follow a number of approaches: direct tracking and/or quantification of CO_2 in the reservoir; reliable detection and quantification of subsurface migration out of the primary reservoir (including via engineered components such as wells) and robust measurement of fluxes at the surface.

The utility of setting site performance thresholds is currently an issue of much debate in regulatory circles. Setting aside for the time being issues of local health and safety (see below), a logical way of establishing satisfactory containment performance in terms of emissions reduction could be to estimate how well a nominal storage site should perform in order to fulfil its basic emissions reduction function. Lindeberg (2003) showed how different storage retention times were related to future stabilised atmospheric concentrations – sites retaining CO_2 for several thousand years (or longer) can be considered as providing effective mitigation. In a simpler treatment, Hepple & Benson (2003) have calculated global site leakage rates consistent with atmospheric stabilisation targets of 350, 450, 550, 650 and 750 ppm (Table 1). This was done by calculating the difference between six possible future CO_2 emissions scenarios as proposed by the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic & Swart 2000) and the emissions consistent with meeting a range of long-term atmospheric CO_2 stabilization targets (Wigley *et al*. 1996). By assuming that the amount of leakage is proportional to the amount of CO_2 stored at any given time, acceptable annual site leakage rates can be calculated. Although simplistic, this approach forms a credible basis for a preliminary treatment of the problem. Thus, according to Hepple & Benson, stabilization at any atmospheric CO_2 level less than 550 ppm would require annual leakage rates to be less than 0.01% for all IPCC emission scenarios.

The question arises therefore as to what extent could a monitoring programme be able to demonstrate that a storage site emissions are below a given threshold.

Subsurface monitoring

Deep monitoring technologies do not measure surface leakage explicitly, so cannot provide a direct indication of site emissions performance. However the ability to reliably detect small fluxes of CO_2 migrating out of the primary storage reservoir can place a useful upper bound on any consequent surface leakage, and, perhaps more importantly, can provide powerful insights into current and future containment processes.

At Sleipner, the seismic data is yielding a nominal detection limit of around 1600 tonnes of CO_2 at the top of the reservoir (see above). No migration from the primary reservoir has so far been detected on any of the time-lapse datasets up to and including the 2002 survey. Following Hepple & Benson (2003), whereby supposed migration fluxes would be proportional to the amount of CO_2 stored, the absence of detectable migration at Sleipner by 2002 is consistent with a migration rate of less than 0.02 % per annum. Clearly, the longer that migration out of the reservoir remains demonstrably undetectable, the tighter the rates that can be constrained. This approach however does not take into account the possibility that several undetected smaller amounts of CO_2 may be migrating from more than one point in the reservoir. On the plus side, as intimated above, detection of migration from the primary reservoir is an inherently conservative performance measure, as this will generally significantly exceed any subsequent leakage, due to other trapping processes that operate on CO_2 as it migrates to the surface.

In principle therefore, seismic monitoring can provide the type of information required for performance verification. Considerable caution must be exercised in applying this principle however. As expanded above, the fact that a seismic detection limit can be determined does not necessarily mean that migration can be reliably quantified. If migrated CO_2 does not accumulate in a suitable trap it may remain undetectable as a seismic reflection (although velocity pushdown may well produce a detectable time-lapse signal depending on the reflectivity of the geology). In this case, other monitoring techniques with different detection requirements may help in leakage assessment (*e.g.* downhole pressure in either the target reservoir or overlying aquifers). Irrespective of what particular tools are deployed, the detection and quantification of small CO_2 fluxes in the subsurface remains technically very challenging and ultimate monitoring capabilities in this regard are likely to be highly site specific.

Surface monitoring

In principle, surface monitoring can provide a direct measurement of site leakage. However, robust surface monitoring is likely to be practicable at onshore sites only. Offshore, acoustic seabed imaging and local sediment or seawater sampling may be utilised but reliable quantification of shallow fluxes over extended areas is unlikely to be a practical proposition in the near future. A further consideration is that a properly selected storage site is unlikely to result in leakage to surface in the near future, so measurable fluxes are unlikely to occur. So, whilst surface monitoring datasets can verify current site performance, more generally they will have to be used in a predictive manner to indicate the possibility of future surface leakage, for example through identification of potential leakage pathways and their impacts. Surface monitoring will also require very well defined baselines, against which future CO_2 concentrations and fluxes can be compared. This, in itself, poses challenges, especially considering the likely decadal timescales of projects and variable nature of ecosystems, which control baseline conditions over these timeframes. Once baseline surface monitoring has been completed, subsequent monitoring at the surface may only be required if deep monitoring indicates leakage may occur

Turning to health and safety issues, surface CO_2 flux measurements are currently available for a number of sites, mostly naturally-occurring, where CO_2 is leaking to the surface at the present day (Table 2). These provide valuable insights into the circumstances surrounding the buildup of potentially hazardous accumulations, and the likelihood of these actually occurring.

Natural CO_2 emissions are found in large provinces such as the French carbo-gaseous province (Czernichowski-Lauriol personal communication), the Paradox Basin (Shipton *et al*. 2005) or the Yellowstone hydrothermal area (Werner & Brantley 2003). In these areas CO_2 generally emerges through a number of small, discrete emission points - in sedimentary basins these are commonly carbonated springs or mofettes (dry CO_2 emission sites) but in hydrothermal areas they also include geysers and fumaroles. Individual flux measurements need to be treated with caution. Clearly the flux per unit area per unit time is not only dependent on the area over which the flux is averaged, but also it is not necessarily a good indicator of the risk to man; this is dependent on whether potentially harmful levels of CO_2 can build up in the ambient air. Typical surface fluxes vary widely from <5 to localised values of >17000 t km^{-2} day^{-1}. In all of these cases, human activity is more-or-less unaffected. The potential impact to ecosystems is currently being investigated at a number of sites.

The Rangely CO_2 – EOR operation provides a good example of surface monitoring at a man-made CO_2 injection site. Here, surface fluxes of deep-sourced CO_2 are comparable with the lower limits of naturally occurring leaks, with no detectable environmental effects. However, it is likely that some, if not all, of this CO_2 is microbially-oxidised methane rather than injected CO_2 leaking from the reservoir

(Klusman 2003). No leakage has currently been detected at the Weyburn CO2-EOR project (Wilson & Monea 2004).

A putative future storage site with 500 Mt of CO_2 stored may, depending on subsurface structure, have a storage footprint in the region of 100 km^2. An annual leakage rate of 0.01% (the Hepple & Benson 550 ppm performance criterion) would give rise to surface fluxes peaking at 50 kt per year or ~137 tonnes per day. If leakage were distributed uniformly over the storage footprint, surface fluxes would be between 1 and 2 tonnes km^{-2} day^{-1}, much lower than many non-hazardous natural leaks. On the other hand, if leakage were concentrated along a fault, say 5 km long with a permeable damage zone 20 m wide, then the surface flux might approach 1400 tonnes km^{-2} day^{-1}. This is similar to fluxes found in naturally-occurring leakage sites and is a more typical leakage scenario. Evidence from natural CO_2 mofettes suggest that gases leaking from depth rarely have a large uniform distribution, since once breakthrough is achieved in a small area this becomes the effective pathway for migration.

Furthermore, the degree to which a given leakage flux will be hazardous depends on a large number of factors, including surface topography and infrastructure, weather conditions, population density and the nature of surface terrestrial or marine ecosystems (West *et al*. 2005). In general the risk depends more on how effectively the emitted CO_2 is dispersed than on the quantity released (Hepple 2005).

The key issue in shallow monitoring both for hazardous leakage and also for emissions performance is how to monitor a large potential leakage area robustly. One approach would be to identify the most likely leakage zones (from other information such as the presence of faults, old wells etc) and concentrate monitoring around them. This depends on reliable prediction however. Another approach would be to concentrate monitoring on those areas where leakage would have the greatest potential impact (e.g. built-up areas in structural depressions). A third approach would be to carry out systematic stochastic atmospheric monitoring of the whole potential leakage area, integrated with more detailed localised monitoring focussed on detected atmospheric anomalies, though the risks for false positive anomalies in built-up or industrial areas could be high. Clearly the strategy for leakage monitoring is likely to be highly site specific, and will depend on the type and reliability of site information, information from deep monitoring, overall risk assessments, and potential impacts.

Towards a pragmatic monitoring programme for long term assurance

As stated above, a properly selected site should have a secure geological seal or seals which, providing performance goes according to plan, should store CO_2 indefinitely (far in excess of the atmospheric requirements). Within these seals specific containment risks may be identified, such as wellbores or faults. Estimating potential leakage through such containment risks depends on assessing the probability of their failure and also on some kind of flux estimation based on flow simulation. Both of these parameters are exceedingly poorly-constrained however, and to all intents and purposes it is not currently possible to reliably predict, in a quantitative way, future site leakage performance for geological storage.

An effective site monitoring programme therefore needs to address aspects of site performance in a pragmatic rather than a prescriptive way (see also Pearce *et al*. 2006). The main objectives of monitoring might be as listed below:

- To demonstrate that the site is currently performing effectively (perhaps with respect to a stated emissions criterion) and safely.
- To track storage performance with respect to the containment risks and enable suitable remediation if necessary.
- To calibrate and verify predictive models of future storage site behaviour to permit satisfactory site closure.
- To provide warning of any future hazardous surface leakage.
- To identify and measure surface leakage should it occur.

These will probably require deep geophysical and/or well monitoring systems focussed on the primary storage reservoir and caprock, and also shallow subsurface, surface and atmospheric detection systems and baseline datasets. The above high-level objectives translate to a number of specific technical aims, these include:

- Direct imaging (and, if possible, quantification) of CO_2 in the storage reservoir.
- Measurement of pressure changes in and around the reservoir.
- Detection of migration of CO_2 from the primary reservoir.
- Detection of migration of CO_2 through the overburden to shallower depths.
- Detection and/or measurement of CO_2 at the surface or in the atmosphere or water-column.

In addition to the overall aims and objectives, monitoring tool selection depends on a number of site specific factors including surface conditions (onshore/offshore, rural, urban, flat mountainous etc), site geology (reservoir depth, type etc). The International Energy Authority Greenhouse Gas Programme website hosts an interactive tool for the design of CO_2 monitoring programmes (IEA 2007). This allows the user to input basic storage site parameters (location / land-use, reservoir depth, reservoir type, injection quantity), and up to ten monitoring aims. It then calculates applicability scores for specific monitoring technologies according to the selected aims. These are based on the expected technical capability of the various tools for the given site, but cost considerations will inevitably have a part to play too. Thus it may be cost-effective to deploy a number of complementary monitoring tools rather than adhere strictly to a technically optimal monitoring programme. An example of this would be an onshore storage case where the repeat interval for time-lapse seismic monitoring may be relaxed by deploying intermediate gravimetry surveys at much lower expense. Such strategies will be very site-specific. Thus, for offshore storage, gravimetry is comparably expensive to 3D seismic, so would not generally constitute an effective cost-saving option except perhaps where it provided important complementary data, such as at Sleipner (see above).

Ultimately the selected monitoring programme depends on the monitoring aims, which are highly site-specific. It is for the site operator and the regulator to agree on these, and on a cost-effective suite of tools to achieve them. In general terms, for a site performing according to expectations, the repeat frequency of monitoring surveys would decrease with time, as confidence in predictive in models grows – particularly during the post-injection phase.

Conclusions

Site monitoring will play a key role in future large-scale CO_2 storage operations. Deep-focussed methods will be used to prove short-term site compliance with regulatory requirements, to remediate non-compliances should they occur, and to constrain and steer simulations of longer-term site performance. At present, uncertainty in geophysical parameters and fine-scale fluid flow processes preclude accurate quantification of CO_2 in the subsurface. Nevertheless, by adopting a multi-strand approach, utilising complementary tools, and coupling results to flow simulations, uncertainties continue to be reduced. With shallow-focussed methods the aims are to establish pre-injection baseline conditions and to develop effective methods of detecting and monitoring surface leaks if and when they occur.

Assessment of site performance depends on the parameter under consideration. Safety performance is highly site specific, depending on subsurface migration paths, surface leakage fluxes and how these interact with surface infrastructure and biota. Emissions performance can be more easily generalised. A simple published criterion for emissions performance can be tested at current storage sites. Results so far analysed suggest that Sleipner is meeting or exceeding this criterion.

Specific monitoring programmes will clearly vary from site to site, depending firstly on geology but also on surface conditions – whether the site is offshore or onshore, beneath an urban or rural situation etc. As more monitoring data becomes available from large-scale storage sites, both onshore and offshore, it will become clearer how optimal site monitoring strategies can be developed. Although not discussed in detail here, it is clearly desirable that site monitoring activities are cost-effective, such that the total monitoring costs comprise just a small fraction of the total capture and storage budget. To achieve these aims it is likely that a range of different tools will be deployed, which may change as the project develops, utilised in a complementary manner to maximise information content whilst at the same time, minimising overall costs.

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Stabilization target (ppm)	Steady-state allowable emissions ($GtCO_2$ yr^{-1})	Allowable leakage (% yr^{-1})
350	3.3	0.01
450	7.0	0.01
550	9.9	0.01
650	12.8	0.1
750	15.8	0.1

Table 1: Allowable steady state emissions, from Hepple and Benson (2003)

	Area (km^2)	Flux (tonnes km^{-2} day^{-1})
Tyrrhenian Basin	15	~ 5
Matraderecske		~ 300
Matraderecske faults		~ 17000
Alban hills		~ 2570
Yellowstone	4500	~ 10
Rangeley EOR	78	~ 0.3

Table 2: Estimated leakage from natural CO_2 occurrences and deep-sourced CO_2 fluxes from the Rangeley CO2-EOR site

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Figure captions

Fig. 1 Schematic diagram of an underground CO_2 storage site showing possible migration and leakage pathways and monitoring options. N.B storage topseal need not necessarily be salt.

Fig. 2 Potential tools for monitoring CO_2 storage

Fig. 3 Part of the 1999 3D seismic dataset from Sleipner. The front left-hand corner of the cube intersects the CO_2 plume, imaged as a number of bright, sub-horizontal seismic reflections.

Fig. 4 Gravity models to illustrate changes in gravimetric signature caused by migration of 5Mt of CO_2 from the primary storage reservoir to shallower depth

Fig. 5 a) Multibeam sonar image of the seabed showing pockmarks and other features associated with natural gas leakage at the seabed b) High resolution acoustic profile showing (methane) gas plumes in the water column (courtesy of B. Schroot).

Fig. 6. Time-lapse seismic images of the CO_2 plume a) N-S inline through the 1994 dataset prior to injection and through the 1999, 2001 and 2002 datasets. Enhanced amplitude display with red/yellow denoting a negative reflection coefficient. b) Maps of integrated absolute reflection amplitudes calculated in a two-way travel-time (twtt) window from 0.8 to 1.08s, for 1994, 1999 and 2001. Blue - low reflectivity; red - high reflectivity. Black disc denotes injection point.

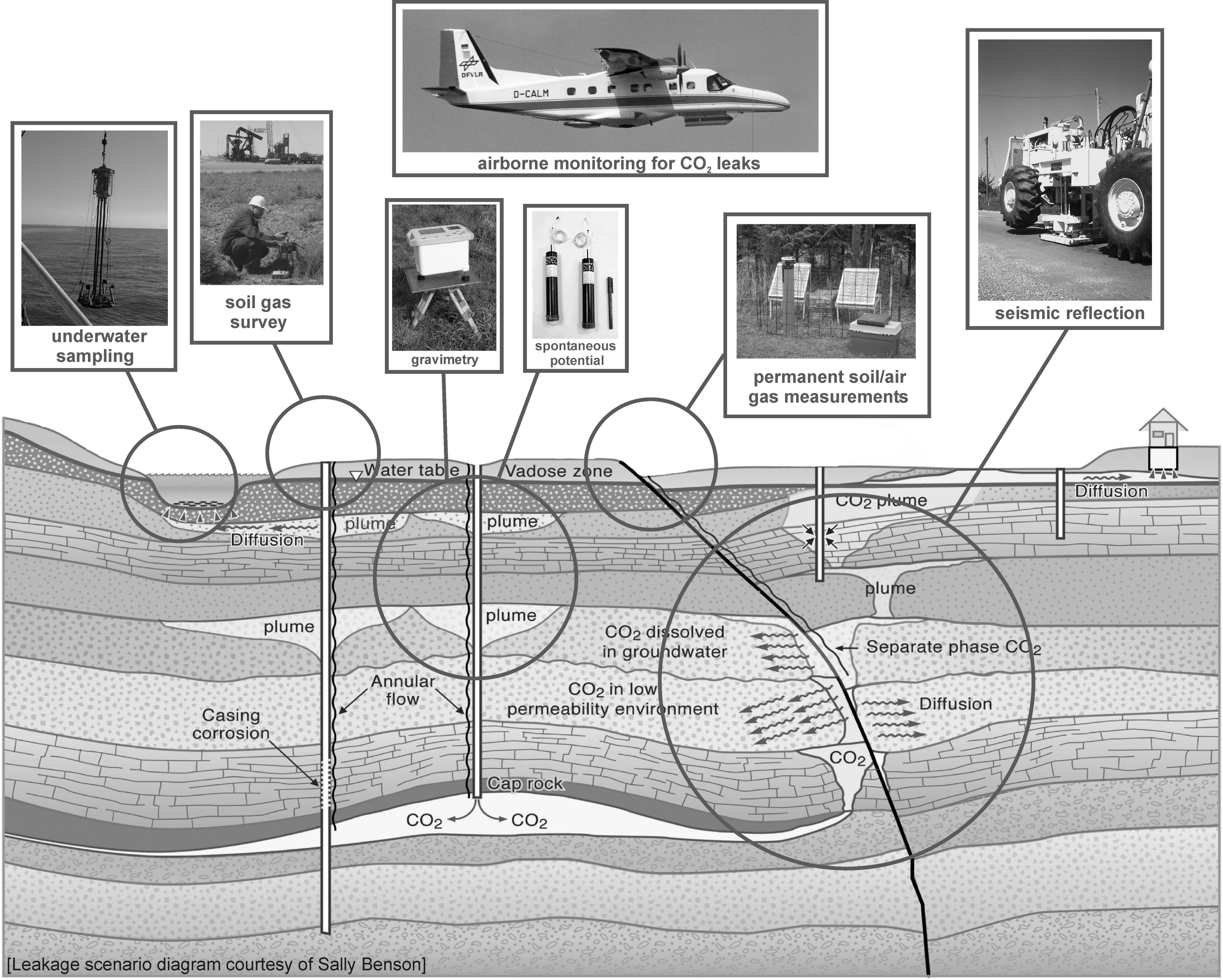
Fig. 7. Velocity pushdown. a) Inline through the storage reservoir in 1994 and 1999 showing pushdown of the Base Utsira Sand (the reservoir) beneath the plume. b) Cross-correlogram of a reflection window beneath the central part of the 2001 plume. Yellow line follows the correlation peak and defines the pushdown. c) Pushdown maps in 1999 and 2001. Black disc denotes injection point.

Fig. 8 3D seismic modelling of the Sleipner CO_2 plume: Acoustic impedance model based on reservoir flow simulation (left) and synthetic seismic volume (right).

Fig. 9 2D inverse modelling of the 1999 plume. Observed data (centre) compared with synthetic seismograms based on inverse models for two plume scenarios: Injection point at 36°C with fine-scale mixing throughout (left); Injection Point at 45°C with patchy mixing in the intra-layer dispersed component of CO_2 (right).

Fig. 10 Estimating the detection limits for small amounts of CO_2. a) Map of the 1999-94 difference data showing integrated reflection amplitude in a 20 ms window centred on the top Utsira Sand. Note high amplitudes corresponding to two small CO_2 accumulations at the top of the reservoir. Note also scattered amplitudes due to repeatability noise. b) Seismic line showing the topmost part of the plume and the two topmost accumulations.

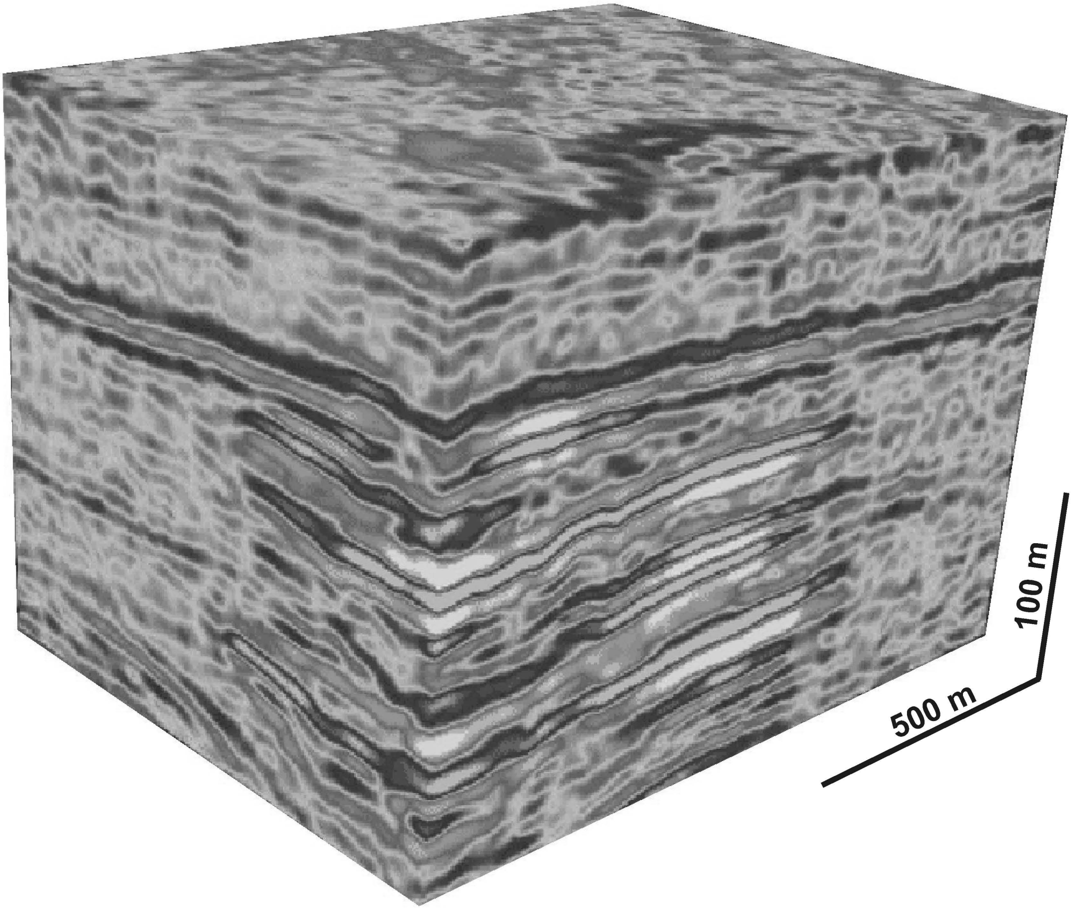
Fig. 11 Sleipner gravity survey a) ROV with gravimeter at left b) map of gravity station coverage

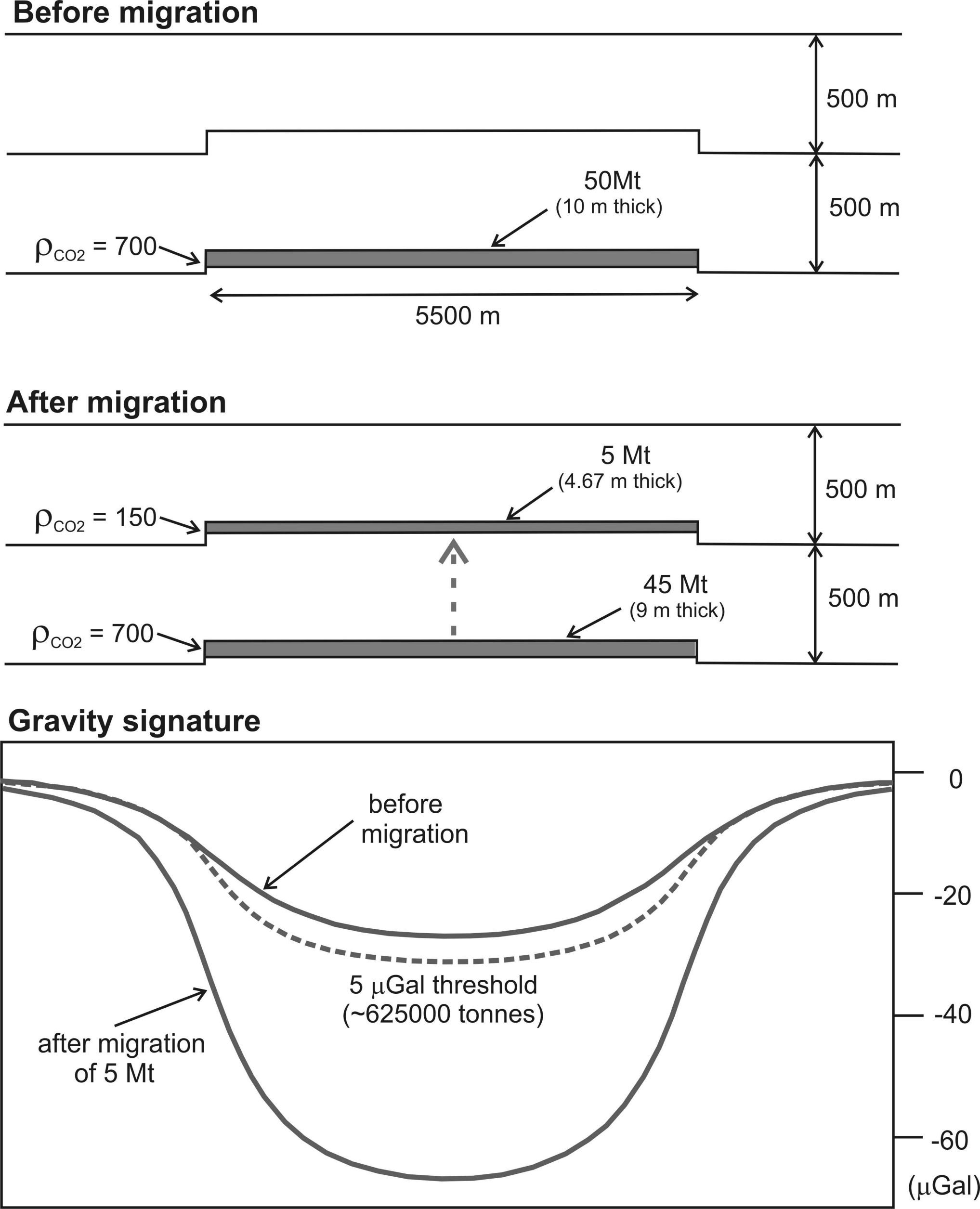


underwater sampling
soil gas survey
airborne monitoring for CO_2 leaks
gravimetry
spontaneous potential
permanent soil/air gas measurements
seismic reflection
Water table
Vadose zone
plume
Diffusion
CO_2 plume
CO_2 dissolved in groundwater
Separate phase CO_2
CO_2 in low permeability environment
Annular flow
Casing corrosion
Cap rock
CO_2
[Leakage scenario diagram courtesy of Sally Benson]

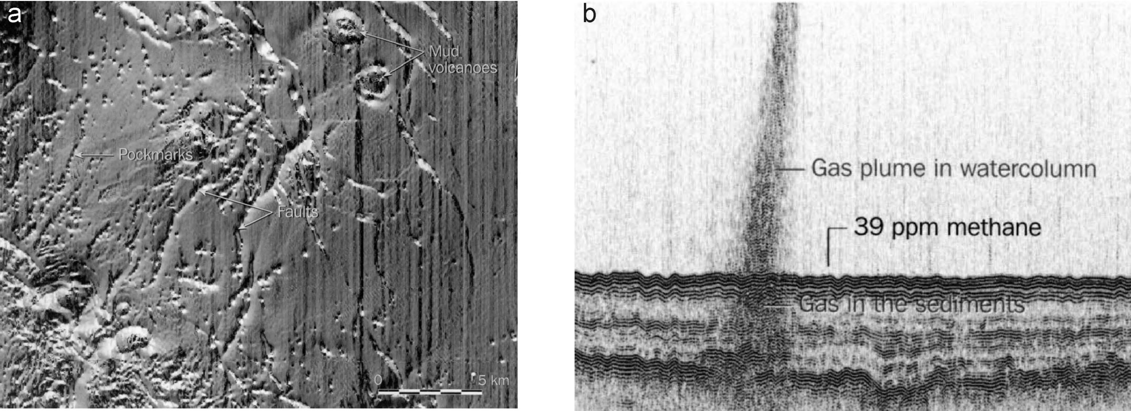
(white)	Onshore only
(light grey)	Offshore only
(dark grey)	Onshore & Offshore

Seismic			3D/3C surface seismic	Onshore & Offshore
			2D surface seismic	Onshore & Offshore
			Boomer / Sparker	Offshore only
			High resolution acoustic imaging	Offshore only
			Microseismic monitoring	Onshore & Offshore
			cross-hole seismic	Onshore & Offshore
			VSP	Onshore & Offshore
Sonar Bathymetry			Sidescan sonar	Offshore only
			Multi beam echo sounding	Offshore only
Gravimetry			Time lapse surface gravimetry	Onshore & Offshore
			Time lapse well gravimetry	Onshore & Offshore
Electric / Electro - magnetic			Surface EM	Onshore only
			Seabottom EM	Offshore only
			Cross-hole EM	Onshore & Offshore
			Permanent borehole EM	Onshore & Offshore
			Cross-hole ERT	Onshore & Offshore
			ESP	Onshore & Offshore
Geochemical	Fluids	downhole /onshore	Downhole fluid chemistry	Onshore & Offshore
			PH measurements	Onshore & Offshore
			Tracers	Onshore & Offshore
		marine	Seawater chemistry	Offshore only
	Gases		Bubble stream chemistry	Onshore & Offshore
		atmosphere /water	Non dispersive IR gas analysers	Onshore only
			IR diode lasers	Onshore only
			Mobile gas cells	Onshore & Offshore
			Eddy covariance	Onshore only
		soil gas	Gas flux	Onshore only
			Gas concentrations	Onshore only
Ecosystems			Ecosystems studies	Onshore & Offshore
Remote sensing			Airborne hyperspectral imaging	Onshore only
			Satellite interferometry	Onshore only
			Airborne EM	Onshore only
			Airborne spectroscopy	Onshore only
Others			Geophysical logs	Onshore & Offshore
			Pressure / temperature	Onshore & Offshore
			Tiltmeters	Onshore & Offshore

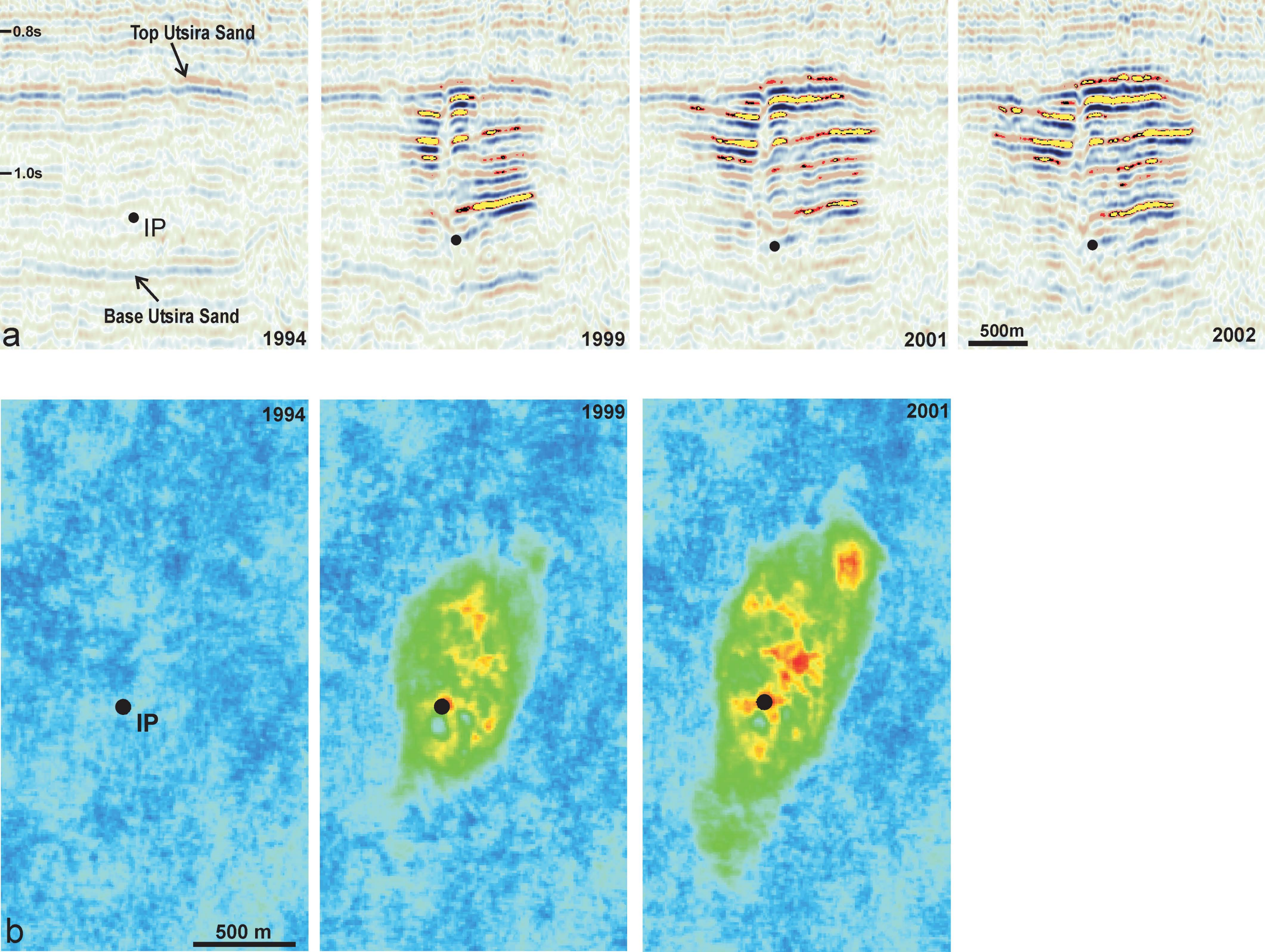

100 m
500 m



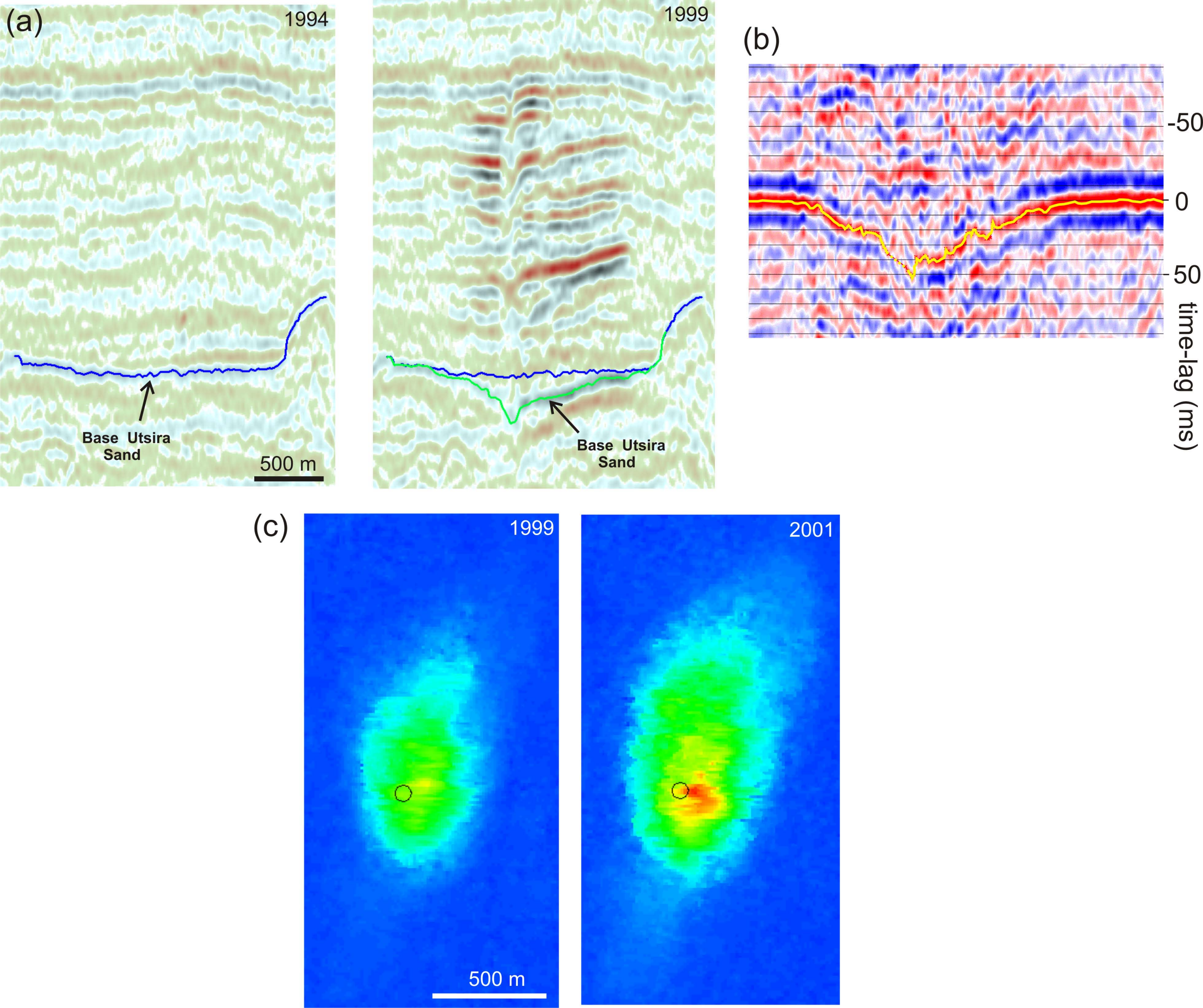
Before migration
500 m
50Mt
(10 m thick)
500 m
ρCO2 = 700
5500 m
After migration
5 Mt
(4.67 m thick)
500 m
ρCO2 = 150
45 Mt
(9 m thick)
500 m
ρCO2 = 700
Gravity signature
before
migration
0
-20
5 μGal threshold
(~625000 tonnes)
-40
after migration
of 5 Mt
-60
(μGal)



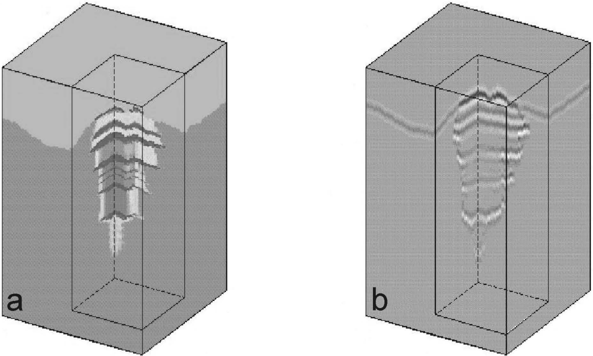
a
Mud volcanoes
Pockmarks
Faults
0
5 km
b
Gas plume in watercolumn
39 ppm methane
Gas in the sediments

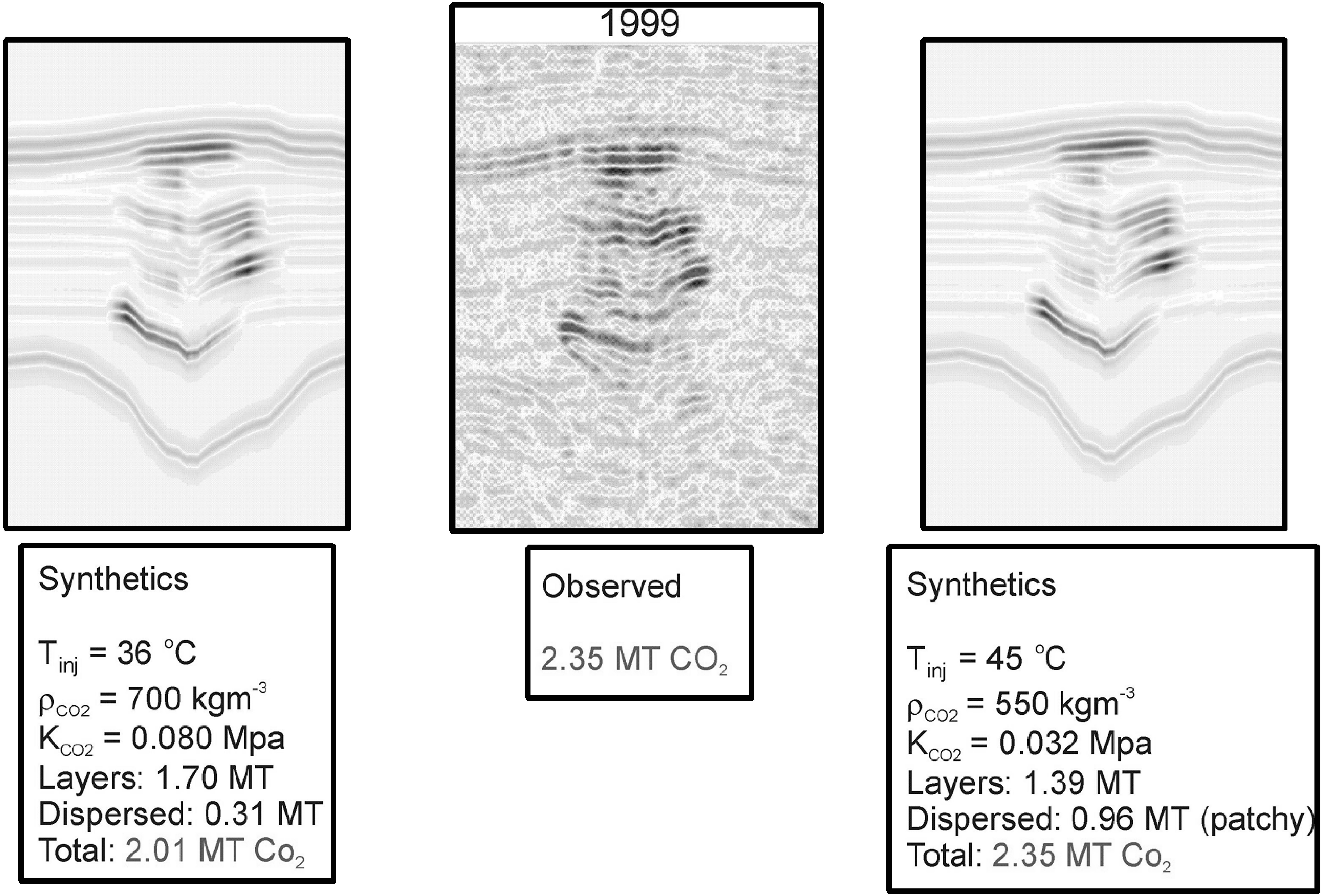


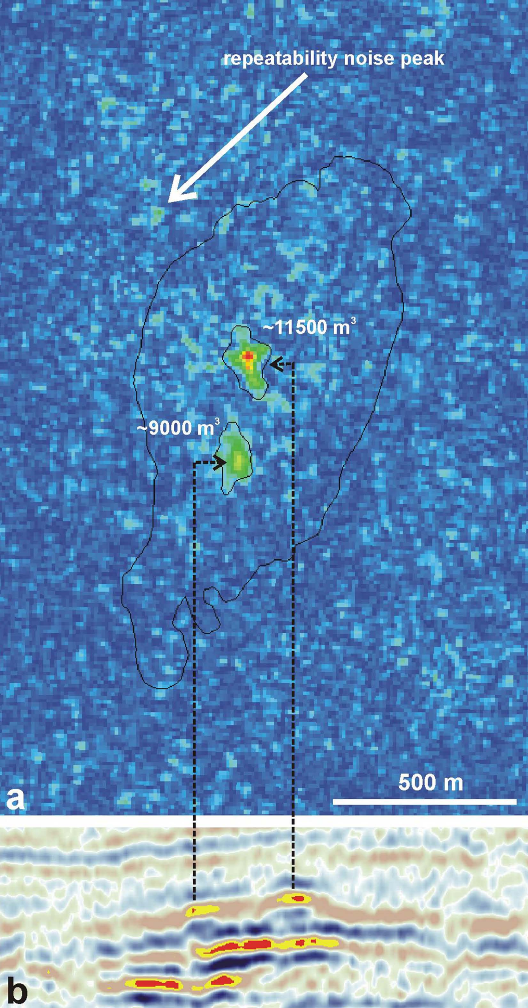
0.8s
Top Utsira Sand
1.0s
IP
Base Utsira Sand
a
1994
1999
2001
500m
2002
b
1994
IP
500 m
1999
2001

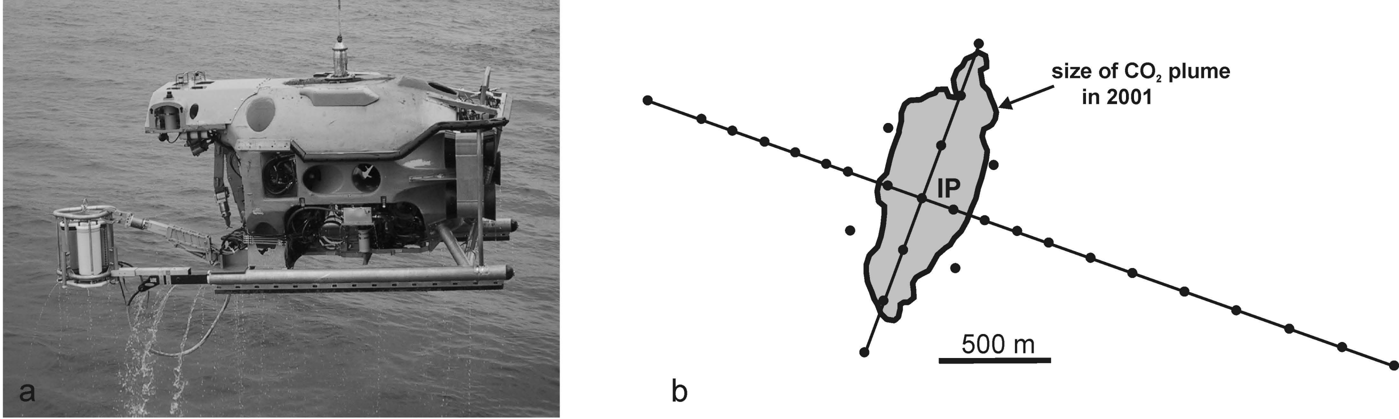


(a)
1994
Base Utsira Sand
500 m
1999
Base Utsira Sand
(b)
-50
0
50
time-lag (ms)
(c)
1999
500 m
2001


a
b


1999
Synthetics
T_{inj} = 36 °C
ρ_{CO2} = 700 kgm^{-3}
K_{CO2} = 0.080 Mpa
Layers: 1.70 MT
Dispersed: 0.31 MT
Total: 2.01 MT Co_2
Observed
2.35 MT CO_2
Synthetics
T_{inj} = 45 °C
ρ_{CO2} = 550 kgm^{-3}
K_{CO2} = 0.032 Mpa
Layers: 1.39 MT
Dispersed: 0.96 MT (patchy)
Total: 2.35 MT Co_2


repeatability noise peak
~11500 m³
~9000 m³
500 m
a
b


a
size of CO_2 plume
in 2001
IP
500 m
b