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A (not so) shallow controlled CO_2 release experiment in a fault zone

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Abstract

The CSIRO In-Situ Laboratory Project (ISL) is located in Western Australia and has two main objectives related to monitoring leaks from a CO_2 storage complex by controlled-release experiments: 1) improving the monitorability of gaseous CO_2 accumulations at intermediate depth, and 2) assessing the impact of faults on CO_2 migration. A first test at the In-situ Lab has evaluated the ability to monitor and detect unwanted leakage of CO_2 from a storage complex in a major fault zone. The ISL consists of three instrumented wells up to 400 m deep: 1) Harvey-2 used primarily for gaseous CO_2 injection, 2) ISL OB-1, a fibreglass geophysical monitoring well with behind-casing instrumentation, and 3) a shallow (27 m) groundwater well for fluid sampling. A controlled-release test injected 38 tonnes of CO_2 between 336-342 m depth in February 2019, and the gas was monitored by a wide range of downhole and surface monitoring technologies. CO_2 reached the ISL OB-1 monitoring well (7 m away) after approximately 1.5 days and an injection volume of 5 tonnes. Evidence of arrival was determined by distributed temperature sensing and the CO_2 plume was detected also by borehole seismic after injection of as little as 7 tonnes. Observations suggest that the fault zone did not alter the CO_2 migration along bedding at the scale and depth of the experiment. No vertical CO_2 migration was detected beyond the perforated injection interval; no notable changes were observed in groundwater quality or soil gas chemistry during and post injection.

The early detection of significantly less than 38 tonnes of CO_2 injected into the shallow subsurface demonstrates rapid and sensitive monitorability of potential leaks in the overburden of a commercial-scale storage project, prior to reaching shallow groundwater, soil zones or the atmosphere. The ISL is a unique and enduring research facility at which monitoring technologies will be further developed and tested for increasing public and regulator confidence in the ability to detect potential CO_2 leakage at shallow to intermediate depth.

Keywords: CO_2 controlled-release; Western Australia, CO_2 geological storage; fault zone; CO_2 monitoring

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1. Introduction

Although due diligence with respect to site selection and characterisation of a CO_2 storage project will make leakage of CO_2 to the shallow environment unlikely, storage project operators may need to provide adequate monitoring systems for assuring regulators and the public that leakage could be confidently detected, managed and remediated. To achieve this, previous field tests have focussed on shallow-release experiments performed at less than 25m depth [1,2] or CO_2 storage pilot and demonstration experiments at more than 600m depth [3,4]. Few of these projects put emphasis on detecting CO_2 leakage on its migration path between the storage complex and groundwater resources or the atmosphere. Only a few recent projects in Canada [5] and eastern Australia [6], have been investigating the migration behaviour and detectability of gaseous CO_2 between 25m to 600m depth. Furthermore, the identification and characterisation of potential leakage processes and pathways are important for developing properly targeted monitoring schemes [7,8]. In this context, fault zones have been identified as a potential leakage pathway that may concentrate or focus CO_2 migration upward to the shallow subsurface, potentially accumulating in groundwater aquifers or continuing to migrate to the atmosphere [9,10,11]. However, the study of CO_2 migration along faults has largely been limited to characterising leakage from natural CO_2 accumulations [12,13,14] and is not well constrained for geological storage of industrial CO_2.

The In-Situ Laboratory (ISL) in Western Australia (Fig. 1) was established to address the two above-mentioned challenges of CO_2 leakage from a reservoir and more details are provided by Michael et al. [15]:

1. Test and develop monitoring technologies that are cost effective and have adequate depth, temporal and spatial coverage for the timely identification of leakage by detecting small volumes of CO_2, ideally before reaching groundwater resources or the atmosphere.
2. Identify and characterise potential CO_2 leakage pathways in the shallow subsurface and assess two-phase flow processes in a fault zone.

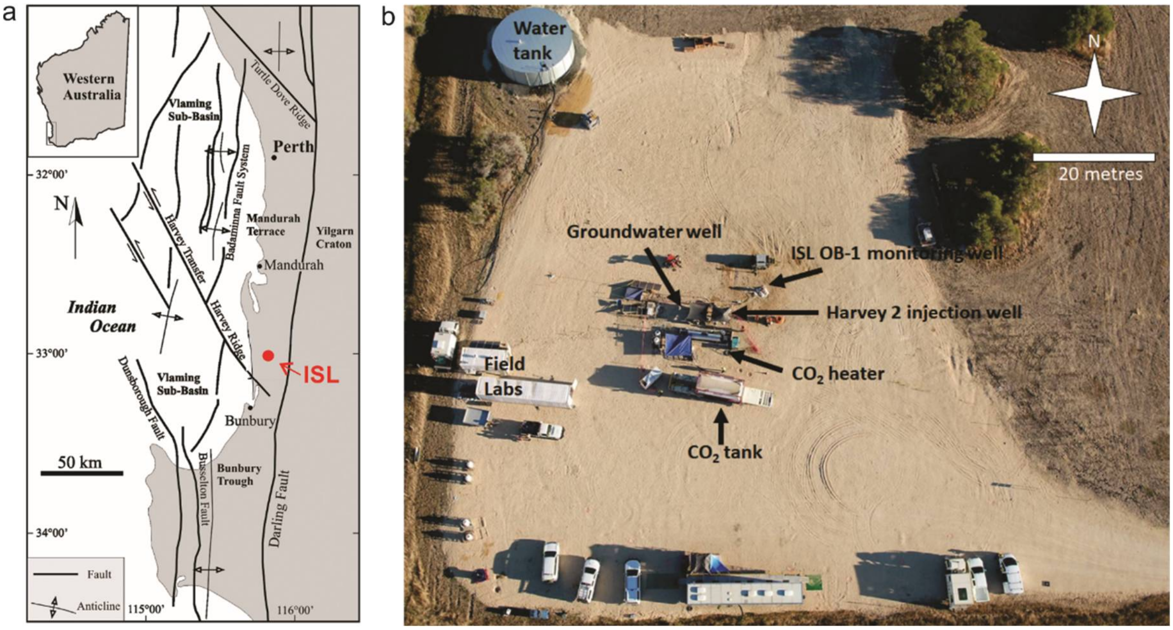

Fig. 1. (a) Location of the ISL field site in Western Australia; (b) Aerial photo of field site during CO_2 controlled-release experiment.

1.1. Geological and structural settings

The ISL is centred around Harvey-2 which was previously drilled for the South West Hub Project and was recompleted as an injection well. It is situated on a north-west trending broad basement high within the Southern Perth Basin (Fig. 1). Faulting is attributed to normal and strike-slip deformation of the Phanerozoic sedimentary cover [16].

The Mesozoic sequence at the ISL site comprises Triassic and Jurassic sediments below a significant Early Cretaceous unconformity, overlain by later Cretaceous to recent deposits. The Eneabba Formation, the injection target (Fig. 2a), is interpreted to be a Jurassic continuation of the predominantly fluvial-alluvial to perhaps fluvio-deltaic environment of the Late Triassic Yalgorup Member [17]. The Yalgorup Member is highly heterogeneous and consists of an interlayered system of low- to high-permeability sandstones and low-permeability siltstones and paleosols. The Yalgorup Member and the Eneabba Formation contain lithology with highly variable porosity and permeability with notably high average porosity (28 %) and mean permeability (5 D) values.

Above the Early Cretaceous unconformity at ~200m below surface, the Leederville Formation contains up to 100m of horizontally bedded, Late Valanginian to Aptian, poorly consolidated, clastics, shales and lignite seams [18]. The Pleistocene Guildford Formation lies below surficial sediments and disconformably on Leederville Formation strata comprising alluvial sand and clay with shallow-marine and estuarine lenses, with a basal conglomerate [19].

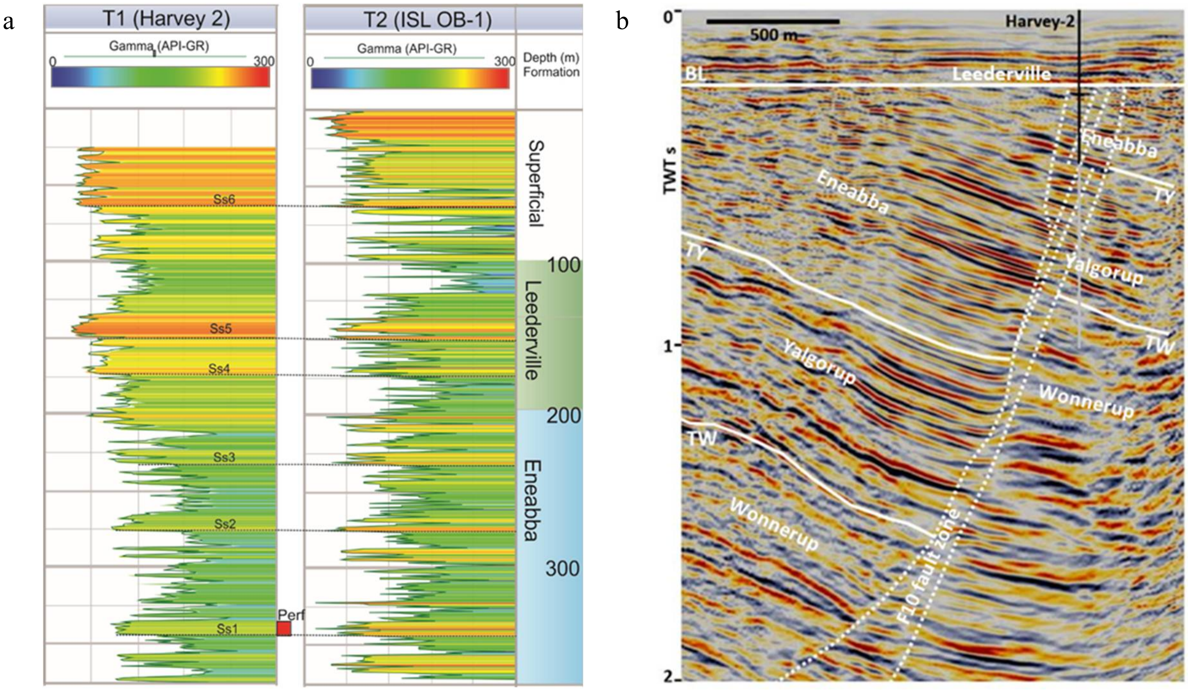

Fig. 2. (a) Natural radioactivity (GR) log data from Harvey-2 and ISL OB-1. Correlations between the base of selected sandstone units (Ss1-Ss6) are depicted by dashed lines between T1 and T2. The location of the perforation interval in Harvey-2 is denoted by the red box and coincides with Ss1. (b) W-E seismic cross-section through Harvey-2 and across the F10 fault (vertical scale in two-way-time).

The main structural feature in the project area is the F10 fault zone. It divides two structural blocks with Harvey-2 penetrating through F10 into the footwall block (Fig. 2b). The faults in the Mesozoic sedimentary succession are truncated by the Early Cretaceous unconformity. The main F10 fault displacement is 1600m at the top Sabina Sandstone, 1000m at the top Wonnerup Member and 750m at the top of the Yalgorup Member. The faults have typical normal fault dips of around 60° to 70°. Approximately 225m of disaggregation have been interpreted in the ~650m F10 fault zone intersection in Harvey-2. Disaggregation occurs between lenses of less deformed lithology, including intersections of apparently undeformed sediments. The disaggregated units tend to be sandstones; adjacent oxidised hardpans, silty paleosols and silts are more competent at the time of deformation. Once reconstructed, the true thickness of the fault zone in F10 is 200–300 m. Within the reconstructed fault zone there is approximately 70–100m thickness of disaggregated fault rock, constituting a quarter to a third of the fault zone thickness.

The in-situ stress regime at shallow depth in Harvey-2 is a strike-slip fault regime with the major horizontal stress slightly above or equal to the vertical stress. King et al. [20] determined the vertical, minimum and maximum horizontal stress gradients in the Northern Perth Basin at 400m depth to be 21.6 kPa/m, 18.5 kPa/m and 21.7 kPa/m, respectively. Given the orientation of the principal stress (105°) in the strike-slip regime and the dominantly N–S orientation of the faults, none of the faults in the area are predicted to be close to reactivation (Langhi et al., 2013). Rock mechanical tests were conducted on several core plugs obtained from the injection zone in Harvey-2. The core materials were extremely weak, and the test plugs had to be frozen during the sample preparation and experimental set up. The stress-strain curves for the two triaxial tests show a highly ductile/strain hardening plastic deformation behaviour. As such, no distinctive peak strength could be identified from the stress-strain curves.

1.2. Test design

The ISL project commenced in May 2018 with the concept of developing an enduring test site for controlled CO_2 release experiments to mimic a CO_2 accumulation in a shallow fault zone by the end of May 2019. The ISL consists of 1) Harvey-2, re-completed primarily for CO_2 injection; 2) ISL OB-1, a newly drilled fibreglass geophysical monitoring well with behind-casing instrumentation, and 3) a groundwater well for sampling of the Surficial aquifer (Fig. 3).

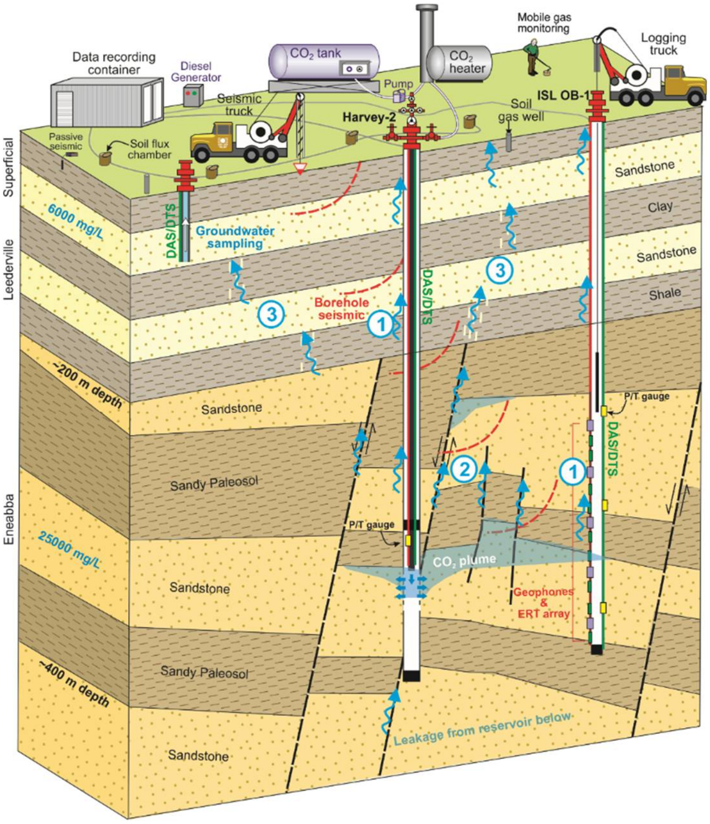

Fig. 3. Concept of In-Situ Laboratory for monitoring CO_2 leakage processes. Injection of CO_2 mimics a secondary CO_2 accumulation due to leakage from a deep reservoir. Potential leakage processes to the ground surface include: 1) leakage along well due to inadequate cementing, 2) leakage along faults and 3) leakage through zones of weakness in sealing units.

The project planned to inject up to 40 tonnes of CO_2 over 4 days based on operational considerations, including the cost and transport of CO_2 to the site, the time available for drilling and completion of the wells, as well as for conducting the injection experiment and performing associated monitoring activities. From core observations, an 11m thick sandstone layer in the Eneabba Formation, overlain by a 3m paleosol, was selected as injection interval in Harvey-2 and was perforated in the upper 6m between 336 and 342m depth.

1.3. Injection system

The surface injection system consisted of an ISO tank to supply liquid CO_2, a pump to maintain the CO_2 in the liquid phase and provide sufficient pressure for injection; followed by a heater to vaporise the pressurised CO_2 prior to entering the well. The ISO tank contained food-grade gas with a nominal pressure between 2000 and 2400 kPa. At 2400 kPa the vapour/liquid equilibrium temperature is approximately −13 °C. The tank was refilled twice by tanker truck. An air-compressor powered AGD-7 gas pump which can handle both liquid and vapour CO_2 was initially chosen based on piston volume and pressure rating. This pump ended up not achieving the required pump rates and, after first combining it with an ASF-B10 liquid pump, was later replaced by a larger ATV-8 liquid pump. As the initial reservoir conditions (T =31 °C and p=3300 kPa) were subcritical with CO_2 existing within the gas phase, a propane-fired atmospheric water bath heater exchange with a rating of 750,000 Btu/hr was used for vaporization.

1.4. Monitoring scheme

Monitoring activities during the controlled-release experiment included: 1. Pressure and temperature monitoring for real-time management of the injection operation; 2. Borehole geophysics, fibre optic sensing and logging for detection and spatial delineation of the CO_2 plume; and 3. Near surface assurance monitoring, including passive seismic, atmospheric, soil gas concentration and flux measurements, as well as groundwater sampling to detect any impacts from the operational activities or any anomalous CO_2 from the injection experiment at the surface.

2. CO_2 controlled release experiment

2.1. Injection operations

A total volume of 38 tonnes were injected over 101 hours, corresponding to an average injection rate of approximately 0.4 tonnes per hour. The anticipated injection pressures for the experiment were modelled to be below 4000 kPa at the injection interval and an injection rate of up to 1 t/hour. After an initial pressure increase associated with the flushing of the water present in the well, the bottomhole pressure (BHP) stabilised at around 4000 kPa, which was higher than predicted, and resulting a lower than desired injection rate (approximately 0.1 tonnes/hour). After replacing the pump, the injection rate increased to up to 0.4 tonnes/hour with a corresponding BHP of 5000–5500 kPa. Further modifications to the injection system resulted in a maximum injection rate of 1 t/hour and a BHP of approximately 6600 kPa.

Temperatures at the wellhead ranged widely between 85 °C at low injection rates and 20 °C at high injection rates. Bottom hole temperature remained relatively constant during injection between 27.5 and 30 °C, slightly lower than the initial reservoir temperature of 31 °C. For these temperatures and most of the observed pressures the CO_2 exists as a vapour. However, at bottomhole pressures above 6000 kPa, CO_2 is injected close to the liquid-vapour line and observed temperature decreasing to as low as 24 °C indicates occasional two-phase conditions for short time towards the end of injection.

At 94 hours, ISL OB-1 was observed to be flowing water, BHP had exceeded 6200 kPa at that point in time. While monitoring of pressure, DTS and DAS continued, injection was stopped at 101 h in response to an eruptive release of formation water and CO_2. All unnecessary personnel were removed from site and the well was allowed to depressurise naturally by a total of seven eruptive releases in form of geysering that occurred over a period of 12 hours. Once the periodicity of the expulsions had been ascertained, the well was closed with a high-pressure cap 115 hours after start of injection. The well has since been remediated and cemented back above the leakage point to a depth of 280 m.

2.2. Monitoring results

This section presents a summary of the more interesting monitoring results from DTS and cross-well seismic. Please refer to Michael et al. [15] for a more comprehensive description of the monitoring activities at the ISL and detailed results of specific monitoring technologies are provided in separate publications [21,22,23]

Continuously recorded DTS data in ISL OB-1 allowed the identification of CO_2 arrival as well as the characterization of the geysering events in both time and space (Fig. 4) At 30 hours after start of injection, the first increase in temperature occurred at 335 m (immediately below the sealing paleosol) indicating the first arrival of CO_2 after approximately 5 tonnes of injection. injection rates after replacing the pump. Joule-Thomson heating due to the increase in pressure in the injection interval could explain why CO_2 arriving at ISL OB-1 is warmer than at the point of injection. No temperature changes were observed above the paleosol at 331 m, indicating a lack of vertical CO_2 migration beyond the injection interval at that time. After 54 hours, increased temperatures can be seen at 341m and 356 m and the rate of temperature began to increase between 335 and 341 m, which is interpreted as an up to 5 m thick accumulation of warm CO_2 below the paleosol. A sharp temperature increase can be observed at 88 hours at 331 m depth, corresponding to a slight drop in temperature at 341 and a decline in temperature from 356, while the temperature at 335 continued to rise steadily. This event is interpreted to coincide with CO_2 and formation water entering the well through the damaged fibreglass casing. Cooling at the top of the well is probably due to opening of the wellhead and water flowing from the well. The 7 expulsion events of formation water and CO_2 are reflected by cyclic temperature changes (from 100 – 115 hours) at all depths at and above the injection interval.

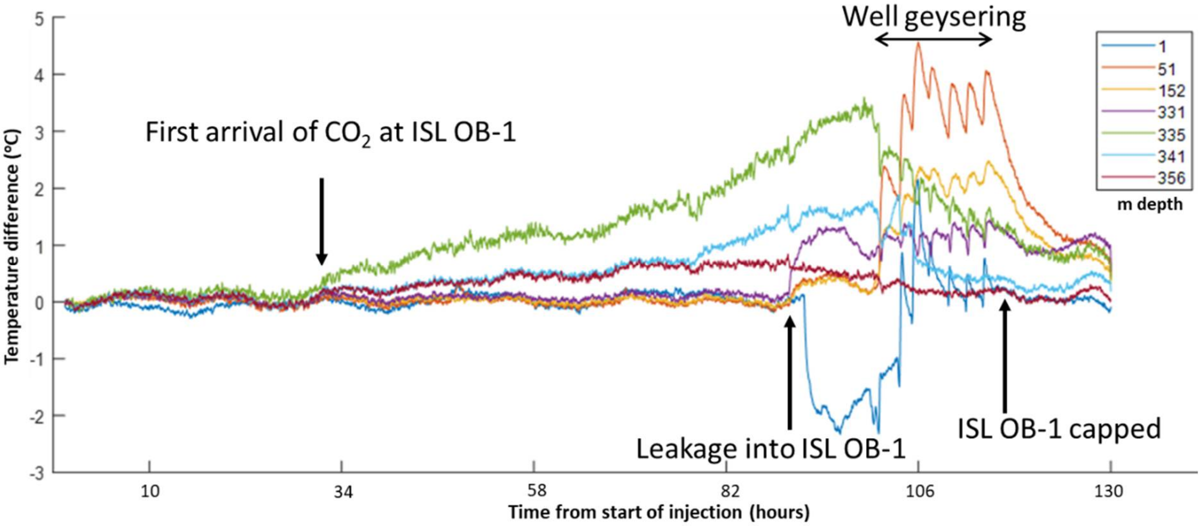

Fig. 4. Temperature difference at selected depths in ISL OB-1 during and post injection. The 1 m, 51 m and 152 m data are chosen to show the general temperature range downhole at 50 m intervals. The data gathered at 335 m is just below the paleosol interval and near the top of the perforated interval. Data for 341 m are within the perforated interval and 356 m is 14 m below the base of the perforated interval.

The offset vertical seismic profiling (VSP) monitoring acquisitions were set up as a series of lines extended from around the ISL OB-1 well within the north-eastern quadrant (due to the permitted land access) and spaced every ten degrees. A low power light seismic source (a 45 kg accelerated weight drop) was used for the surveys. In total, nine surveys were acquired including the initial baseline dataset. Eight excitations per shot point were performed to increase the signal to noise ratio. The recording parameters for the DAS acquisition were a pulse repetition frequency of 50 kHz, 2 seconds record length, and a channel step of 0.5 m.

Offset VSP data are of good quality and a high level of repeatability was achieved that enabled the detection of a small amount of the injected CO_2, even in anticipation of a relatively low signal. The signal to noise ratio was significantly improved by stacking the shot points located around the monitoring well at the constant nearest offset (40 m) to produce an effective zero-offset VSP geometry in a single ensemble. The normalised root mean square (NRMS) estimate between the baseline and the eighth monitor dataset (after injecting 38 tonnes of CO_2) in Fig. 5 are attributed to the high repeatability rate reached, even considering relatively low power seismic source used for the survey. The wavelet for deconvolution was estimated for each shot location and vintage separately. Fig. 5 (a-c) shows deconvolved gathers of the baseline data, data from the eighth monitor vintage) and their difference. Data is normalised over all three sections for display purposes, and the remains of the direct on the difference section are visible but very insignificant with respect to initial amplitudes. A clear manifestation of the time-lapse signal is observed on the difference section at the target depth (highlighted by the red arrow). Slight differences in the images to baseline can be seen as early as the fourth monitor vintage at which point 7 tonnes of CO_2 had been injected after 44 hours.

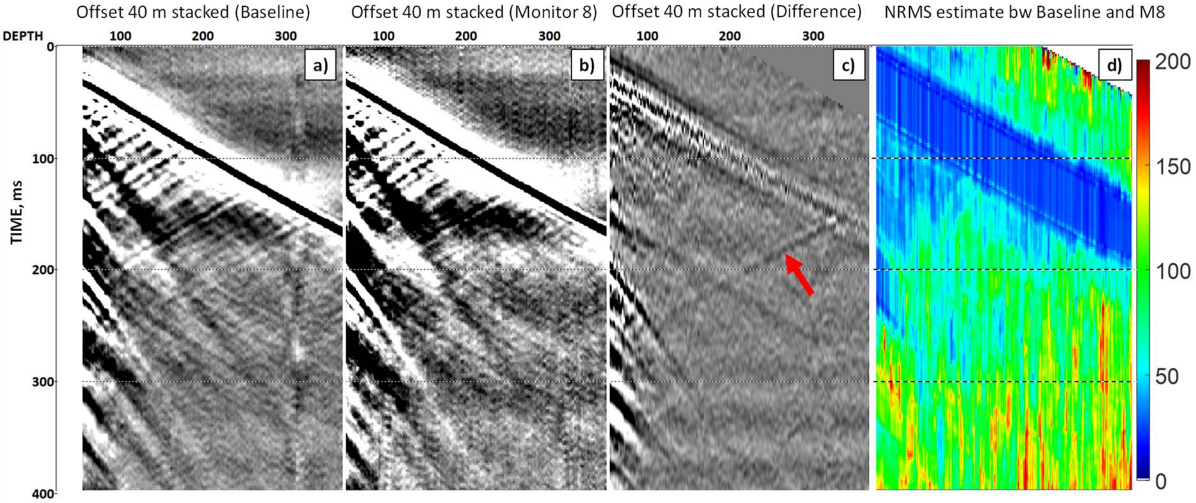

Fig. 5. Time-lapse images of the CO_2 plume on VSP sections. a) baseline seismogram; b) monitor 8 seismogram; c) differences of the baseline and monitor data; d) NRMS estimate between baseline and monitor 8 datasets. Red arrow indicates clear response from the injected gas.

Due to issues related to faulty connections during the installation of the hybrid cable, the cemented geophones were not active for every survey, and as such data analysis was primarily focused on DAS data. It would be desirable to increase signal to noise ratio of the active seismic data to elevate the level of detectability that could be achieved by introduction of a more powerful source. In the future, continuous recording with the behind-casing sensors would provide significant advantages for observation of various aspects of the experiment as well as microseismic monitoring. Alternative approaches of reverse VSP for similar shallow rapidly developing processes should be discussed as it allows extremely fast acquisition of a single vintage and use of high frequency downhole sources.

2.3. Assurance monitoring

Apart from the elevated CO_2 levels which were observed for a very short period in the soil surface around the ISL OB-1 monitoring well due to the well geysering, no anomalous CO_2 has been detected up to two months post injection [24]. The measured CO_2 soil flux and concentration four weeks post injection are within the range of baseline levels observed prior to injection. Parts of the surface monitoring program (i.e., Li-COR, West Systems, soil-gas sampling) will continue for a significant period after injection.

Based on the groundwater monitoring results, groundwater in the Superficial aquifer within the study has a salinity above 5000 mg/l and is suitable for irrigation and livestock purposes only. In contrast, formation water salinity in the CO_2 injection interval, the Eneabba Formation, is on the order of 25,000 mg/L and too high to be suitable for any use. No significant changes in the water chemistry in the In-Situ Lab groundwater well were observed during the monitoring period suggesting that injection of CO_2 into the Eneabba Formation had no impact on the Superficial aquifer.

3. Conclusions

The objectives of the In-situ Lab CO_2 controlled-release test were to assess the monitorability of shallow, gaseous CO_2 accumulations, and to investigate two-phase flow processes in a fault zone.

3.1. Monitorability of shallow gas accumulations

The controlled-release test at the ISL has demonstrated that DTS and downhole seismic were able to detect a plume of less than 38 tonnes of gaseous CO_2 at approximately 336m depth. The detectability of the plume has been largely successful by casing-conveyed instrumentation, while wireline time lapse logging and ERT could not be adequately assessed due to limited access to or insufficient vertical resolution across the interval of interest during the test. The detectability of such a small amount compared to a commercial-scale injection (i.e., 800,000 t/year over 30 years has been deemed feasible for the SW Hub; [25]) is a promising achievement regarding the monitorability of potential leaks in the shallow subsurface before detection at the ground surface. However, the controlled release experiment was focussed on a relatively small area and an engineered location. More research needs to be done on improving detectability but also monitoring instrumentation for detecting more dispersed leakage, both laterally and vertically.

No anomalous CO_2 has been detected in the groundwater or the soil up to two months after the injection test. DTS data in the three wells and pulsed neutron logging in ISL OB-1 have not detected any CO_2 above the injection interval, suggesting that the injected CO_2 has not migrated vertically from the injection zone in the vicinity of the wells.

3.2. Impacts of fault zone geology

The geological data and the simulations predicted the injected CO_2 to migrate vertically through the paleosol due to the fault-related disturbed nature of the sediments. However, the paleosol at the top of the injection interval proved less permeable than expected from core testing and, in contrast to the modelling predictions, the injected CO_2 did not migrate vertically. While existing seismic and observations from Harvey-2 core show that the main fault displacement lies between approximately 400-600 m depth at the location of the controlled-release experiment, the location and configuration of smaller faults in the wider fault zone remains uncertain. Higher-resolution seismic would provide a more detailed model of the fault zone structure.

Lower than expected injectivity and lack of vertical hydraulic communication resulted in higher than expected injection pressures, temporarily rising to within the fracture pressure range. However, no fracturing events have been recorded by the deployed monitoring techniques.

3.3. Well leakage

The high injection pressures, laterally focussed migration of the injected CO_2 along the base of the paleosol, and likely weakening of the fibreglass integrity during in-well cement drilling, resulted in a casing leak at 336 m depth in ISL OB-1. Although the leak in the fibreglass casing was accidental, there were no adverse environmental impacts. The resulting geysering of the well provides important information with respect to the risks of CO_2 accumulations in the shallow subsurface environment (approximately 50 times volume increase of CO_2 between 400 m depth and the ground surface) and contains valuable insights into quantifying the volumes of CO_2 and water that may be produced in such an event.

3.4. Concluding remarks

The In-Situ Lab forms an enduring and unique research facility for further research into the monitoring and characterisation of CO_2 migration in fault zones and from the shallow groundwater environment to the ground surface. Near-term improvements to the site include well remediation activities to improve injectivity and new, high-resolution seismic for better characterisation of the fault zone geometry. Demonstration of successful monitoring technologies in such setting is important for increasing public and regulator confidence in the ability to confirm the safety of CO_2 geological storage.

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