National Geosequestration Laboratory

Feasibility and design of robust passive seismic monitoring arrays for CO_2 geosequestration

Project Results @ 6 months

ANLEC Project 7-0212-0203

May 2014

David Lumley, Jeff Shragge, Nader Issa, Rie Kamei, Toby Potter, Taka Miyoshi;

University of Western Australia (UWA)

Roman Pevzner, Andrej Bona, Konstantin Tertyshnikov;

Curtin University

Laurent Langhi, Joel Sarout;

CSIRO

Primary contact: *david.lumley@uwa.edu.au*

© 2014

Australian Government Department of Education | CSIRO | The University of Western Australia Achieve International Excellence | Curtin University | wa:era western australian energy research alliance

The National Geosequestration Laboratory is supported by the Australian Government through the Education Investment Fund.

EXECUTIVE SUMMARY

- Passive seismic monitoring is the science of recording and analysing natural or induced seismicity with surface or borehole sensor arrays, without the need for active (man-made) seismic energy sources.

- Passive seismic monitoring can be useful in CO_2 geosequestration projects to:
  - image/monitor the injected CO_2 plume, the injection pressure front, and any potential rock (micro)fracturing, CO_2 non-containment or fault displacement activity;
  - estimate the in-situ stress conditions in the subsurface to help constrain model-based predictions of fault seal and any potential for CO_2 non-containment,
  - serve as an early-warning system to detect low-level (unfelt) seismicity before, during and after CO_2 injection, in order to mitigate any possibility of larger seismic energy releases; and
  - determine whether any measured/felt seismicity in the project area is natural, or may be related to CO_2 injection.

- Early key results from this ANLEC research project include the following:

  1. The permeability of the four Harvey-1 core plugs we cut in the main Wonnerup facies targeted for CO_2 injection were found to be unexpectedly low (1-32 mD). The cores also exhibit strong permeability anisotropy; the deeper Wonnerup cores at 2508m exhibit a 5:1 k_h:k_v permeability ratio, and the shallower Wonnerup cores at 1924m exhibit a 2:1 k_h:k_v permeability ratio. The low permeability values suggest that it may be challenging to inject CO_2 into some portions of the best Wonnerup reservoir rock facies type, and the strong permeability anisotropy suggests it may be challenging to sweep the full CO_2 storage volume with just a sparse set of injectors and perforation intervals. To more fully assess these results, we recommend that more core samples be obtained and measured at new SW Hub drilling locations to provide a statistically significant spatial sampling, and be measured for permeability by multiple methods including both coreflood lab experiments, and field trial tests of water and/or CO_2 injection.

  2. We have converged to specific hardware requirements and deployment designs for optimal passive seismic monitoring arrays. We expect to commence procurement of the passive seismic hardware in May/2014. Land access discussions with DMP are underway, and we hope to install the passive seismic test array at the SW Hub in the Q4/2014 or Q1/2015 timeframe.

  3. We have created a new 3D geological velocity model for the SW Hub site, and populated the model with realistic seismic velocity (Vp, Vs) and density values based on the Harvey-1 well log data. The resulting 3D velocity model is 32km x 22km x 5km, with cell sizes of 10 x 10 x 5m, and will be used to simulate full 3D wavefield seismic data for the passive seismic and VSP deliverables of this ANLEC project.

  4. We have completed the High Performance Computing (HPC) feasibility analysis portion of the ANLEC project, and have confirmed that we can simulate 3D elastic wavefields for the SW Hub 3D velocity model size of interest (32km x 22km x 5km), and through scaling analysis confirmed that we have access to adequate HPC hardware resources and modelling software to allow us to complete the required 3D elastic wavefield simulations for the ANLEC project.

SUMMARY OF PROPOSED RESEARCH OBJECTIVES

Measurement, Monitoring, and Verification (MMV) is an important aspect of any CO_2 Geosequestration project. A key component of any MMV program includes ***passive seismic monitoring***. Passive seismic monitoring is the science of recording and analysing natural or induced subsurface seismicity with surface or borehole sensor arrays, without the need for active (man-made) seismic energy sources. Passive seismic monitoring can be useful in CO_2 geosequestration projects to: (1) image/monitor the injected CO_2 plume, the injection pressure front, and any potential CO_2 non-containment or fault displacement activity; (2) estimate the in-situ stress conditions in the subsurface to help constrain model predictions of fault seal and any potential for non-containment, and (3) serve as an early-warning system to detect low-level (unfelt) seismicity before, during and after CO_2 injection in order to mitigate any possibility of larger seismic energy releases. Passive seismic monitoring can also provide the ability to determine whether any measured/felt seismicity in the project area is natural, or may be related to CO_2 injection.

The design of a high-quality passive seismic monitoring array is site specific; the optimal design depends on site-dependent signal and noise conditions. Current state of the art passive seismic design uses technology similar to that which the earthquake community has been using the past 100 years. We propose to innovate a step-change in passive seismic systems to optimise site-specific array design and data analysis/imaging in order to help achieve the MMV goals stated above.

There are four main research objectives to our proposal:

1. Estimate and predict the likely microseismic energy at the SW Hub site by making geomechanical lab measurements on cores taken from wells at the site;
2. Measure and characterise the natural seismic signal and noise conditions at the SW Hub site with a small field test array of passive seismic sensors in shallow boreholes;
3. Simulate realistic 3D microseismic wavefields using supercomputing algorithms, develop and test innovative 3D/4D seismic wave-equation and VSP imaging methods to improve images of the subsurface with passive seismic array data.
4. Develop methods to optimize the sensor array design, in order to maximize the ability to detect/image microseismic events at CCS Geosequestration sites.

PROJECT RESULTS TO DATE (at 6 months)

1. Geomechanical lab experiments

We examined all available Harvey-1 cores at the DMP-GSWA core facility at Carlisle in Feb/2014. We selected 4 core plugs (2 vertical and 2 horizontal) to be cut in the main reservoir facies (***Aii***) near the top (1924m) and base (2508m) of the Wonnerup formation, in the expected primary flow zone for injected CO_2. DMP cut the core plugs, and CSIRO prepared the cores for geomechanical testing. All 4 cores were measured by CSIRO with nitrogen gas porosimeter/permeameter at various confining pressures up to 5000psi (with pore pressure = 200psi). The experimental protocol for the geomechanical core tests has been drafted and is being finalised. The next step is the triaxial stress loading and fault reactivation experiments in the tri-axial rig.

A key early result is the observation that the permeabilities of the core samples taken in the main Wonnerup target zone for CO_2 injection are unexpectedly low (Table 1). This is partly consistent with the comprehensive CSIRO Report EP133710 by Delle Piane et al. (2013). The four cores range in porosity from 9-12% which is reasonable for reservoir rock, but only range in permeability from 1-32 mD, which is very low. A second observation is that the cores exhibit strong permeability anisotropy; the deeper Wonnerup cores at 2508m exhibit a 5:1 horizontal:vertical k_h:k_v permeability ratio, and the shallower Wonnerup cores at 1924m exhibit a 2:1 k_h:k_v permeability ratio. The low permeability values suggest that it may be challenging to inject CO_2 into some portions of the best Wonnerup reservoir rock facies type, and the strong permeability anisotropy suggests it may be challenging to sweep the full CO_2 storage volume with just a sparse set of injectors and perforation intervals.

To more fully assess these results, we recommend that more core samples be obtained and measured at new SW Hub drilling locations to provide a statistically significant spatial sampling, and be measured for permeability by multiple methods including both coreflood lab experiments, and field trial tests of water and/or CO_2 injection.

Sample	CSRO-1	CSRO-2	CSRO-3	CSRO-4
Formation	*Wonnerup*	*Wonnerup*	*Wonnerup*	*Wonnerup*
Depth	*2508.05*	*2508.17*	*1924.05*	*1924.15*
Facies	*Aii*	*Aii*	*Aii*	*Aii*
Orientation	*Vertical*	*Horizontal*	*Vertical*	*Horizontal*
Diameter [mm]	*38*	*38.1*	*38*	*38.2*
Length [mm]	*79.3*	*66.6*	*99.3*	*63.3*
Mass [g]	*206.12*	*173.36*	*253.91*	*161.8*
Porosity [%]*	*9.9 – 10.5*	*9.2 – 9.5*	*9.8 – 10.2*	*11.7 – 12.1*
Permeability [mD]*	*0.8 – 1.4*	*4.2 – 5.4*	*16.5 – 17.4*	*28.4 – 32.6*

Table 1. Measurements on the four Wonnerup reservoir core plugs sampled for geomechanical testing. * *Porosity and permeability ranges are given for a confining pressure ranging from 500 to 5000 psi, at a pore pressure of 200 psi.*

2. Passive seismic test arrays

The design analysis for passive seismic test arrays has been performed and is being finalised. Literature search and field data analysis is underway and well ahead of schedule regarding passive seismic test data sets from other CCS test sites (Otway, Ketzin etc). We have held collaborative visits from TNO researchers to UWA, and from UWA researchers to Otway, TNO, France. We have held several working conference calls with LBNL (Tom Daley et al.), CGG and others re test array design and equipment selection.

Our planning for the deployment of the passive seismic monitoring test array at SW Hub is currently underway. Recent discussions have been held with several colleagues regarding the definition and optimization of the hardware and deployment requirements of the array. Considerations have included sensors, layout, borehole depths, borehole completion, data recorders, power, telemetry and housing. These discussions have included Tom Daley (Lawrence Berkeley National Laboratory), the SeisMovie team (CGG), Christophe Maisons (Magnitude), and Christian Dupuis (Université Laval). Through these discussions, we are converging to specific hardware and deployment requirements from a wide range of alternatives. We expect to finalize the experimental design and commence procurement of the passive seismic equipment in May/2014. Land access discussions with DMP are underway, and we hope to install the passive seismic test array in the Q4/2014 or Q1/2015 timeframe.

A number of key passive seismic test array findings are highlighted here:

1. The established practices of passive seismic monitoring for mine site operations have significantly different objectives to CCS reservoir monitoring. While hardware systems engineered for mine monitoring purposes have a high level of development maturity, these systems are not typically adequate for the objectives of CCS monitoring.

2. The provision and reliability of continuously recorded data from the array is one such key requirement. Such data is highly valued for the purposes of passive imaging and inversion, regional earthquake or hazard monitoring and detection of weak events not necessarily detected in individual seismic traces.

3. The noise reduction benefits of burying geophones rather than surface deployment is widely accepted. However, an 'optimal' depth for deployment is currently an active field of investigation. While the noise spectrum is expected to be highly site dependent, it is also found to be dependent on depth. On the other hand, signal strength is also depth dependent, being stronger at depths closer to potential sources in the reservoir or on faults, but also stronger near the surface due to amplification by low seismic velocities in the near surface. At some sites it has been found that most noise attenuation is achieved in the first 1-2m of depth, while other sites show continued noise reduction down to 100-200m depth.

4. Through our continuous search of commercially available sensors, digitizers, power systems and telemetry we have identified a sub-array 'module' which provides highly flexible deployment either in a borehole array or linear near-surface array. This module is comprised of 8x 3-component sensors and single digitizer unit within a solar powered housing. The module will be used for the shallow borehole stations described below.

5. We have identified that permanent deployment by grouting/cementing geophones into the boreholes is likely to give the best signal-to-noise quality. By attaching the geophones to the outside of tubing and grouting between the tubing and casing we maintain access to the borehole (inside the tubing) for any future monitoring and testing activities. Such a borehole completion may result in the detection of unwanted tube waves, however a variety of techniques have been identified to suppress these effects.

6. Figures 1 and 2 show our currently favoured hardware deployment and array design for the SW Hub. Broadband seismometers are suitable for the detection and location of M>0 microseismic events within a few km's of the array and regional M>2 earthquakes distant 10's of km's from the array. Shallow borehole arrays are suitable for signal-to-noise characterization and monitoring of microseismic events M>-2 (natural or induced) nearby within 1km of the array. The shallow boreholes are to be strategically located with respect to the CO_2 injectors and/or significant faults for monitoring, in consultation with the key SWH stakeholders.

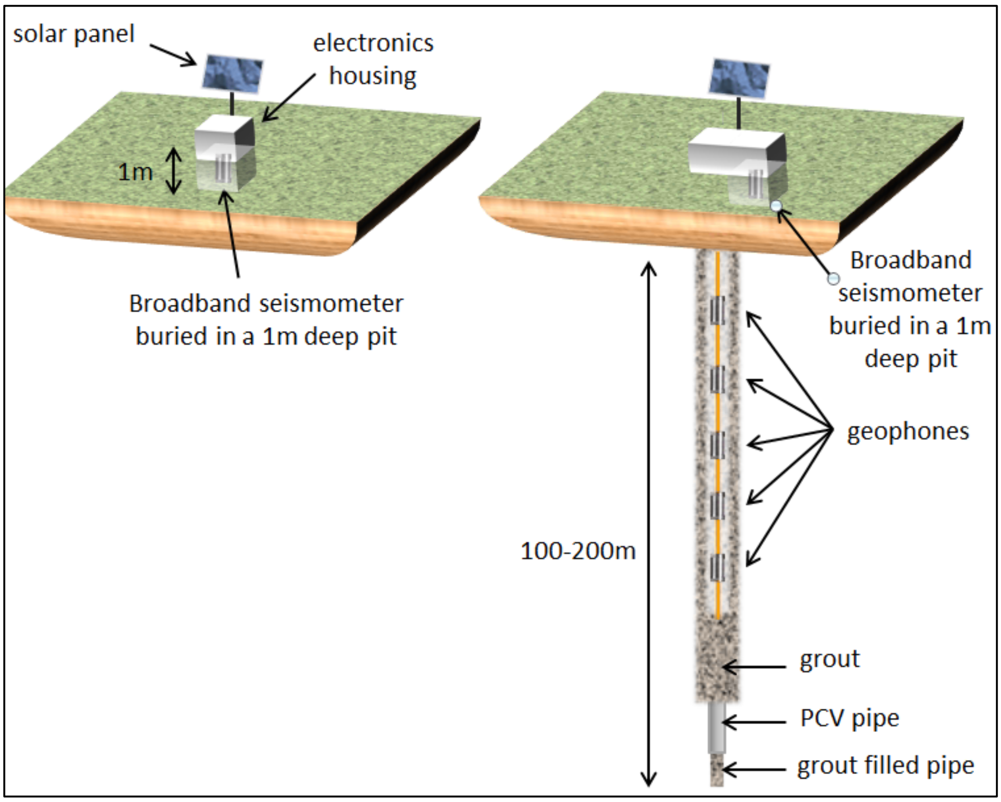

Figure 1. (Left) Schematic of a broadband seismometer station. **(Right)** Schematic of a shallow borehole station. (UWA)

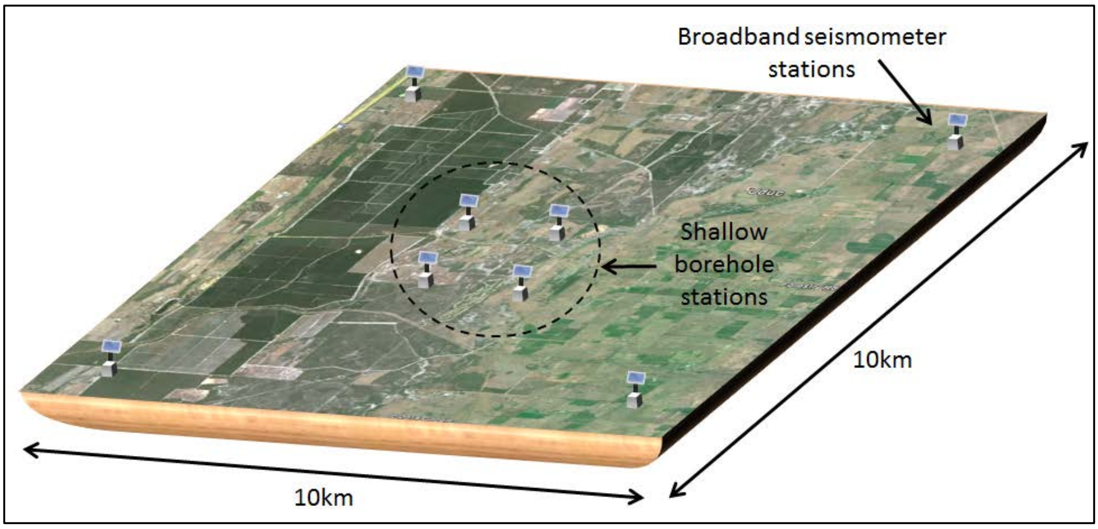

Figure 2. Example of a possible layout design for a passive monitoring array. (UWA)

3. Passive seismic modelling and simulation

3.1 –Building a 3D geologic velocity model for the SW Hub site

We have created a new 3D geological velocity model for the SW Hub site (Figure 3), and populated the model with realistic seismic velocity (Vp, Vs) and density values based on the Harvey-1 well log data. The resulting 3D velocity model is 32km x 22km x 5km, with cell sizes of 10 x 10 x 5m, and will be used to simulate full wavefield seismic data for the passive seismic and VSP deliverables of this ANLEC project.

The first-pass 3D velocity and density models were created from the SW Hub structural model (ANLEC report, Langhi et al. 2013), gridded to 50m x 50m x 20m cells. Fine-scale Vp, Vs and density logs from the Harvey-1 well were upscaled to this coarser model cell size and interpolated along the stratigraphy interpreted from the 2011 2D seismic data. This procedure results in missing values in the upper Eneabba Formation due to the regional structural dip to the east. A pseudo well intersecting the missing values was created using data from the lower Eneabba Formation, and Vp, Vs and density were re-interpolated using Harvey-1 and the pseudo well and an interpolation z-radius of 250m such that all missing cells become populated.

The geological model was next imported into GoCAD and gridded to a 35 x 35 x 4.7m regular Cartesian grid using the nearest-neighbour cell values for Vp, Vs and density. The following steps were performed to obtain the final 10 x 10 x 5m grid and to ensure the model is physically self-consistent and avoids bad H-1 log values, especially in the Yalgorup. For cells with Vp/Vs < 1.73, Vs was adjusted to Vp/1.73. For the empty cells at the bottom part of the model (basement) where we have no log velocity data, Vp was set to 4.7 km/s, Vs to 2.71 km/s, density to 2.57 g/cm3 via the Gardner equation. Empty cells at the top of the model (air above the land surface) were filled with the values from the first cell below the surface. The model was then re-gridded to 10 x 10 x 5m using, first, frequency domain interpolation along the depth axis, then, bi-linear interpolation in horizontal plane.

This new 3D velocity and density model for the SW Hub is now available for seismic modelling purposes.

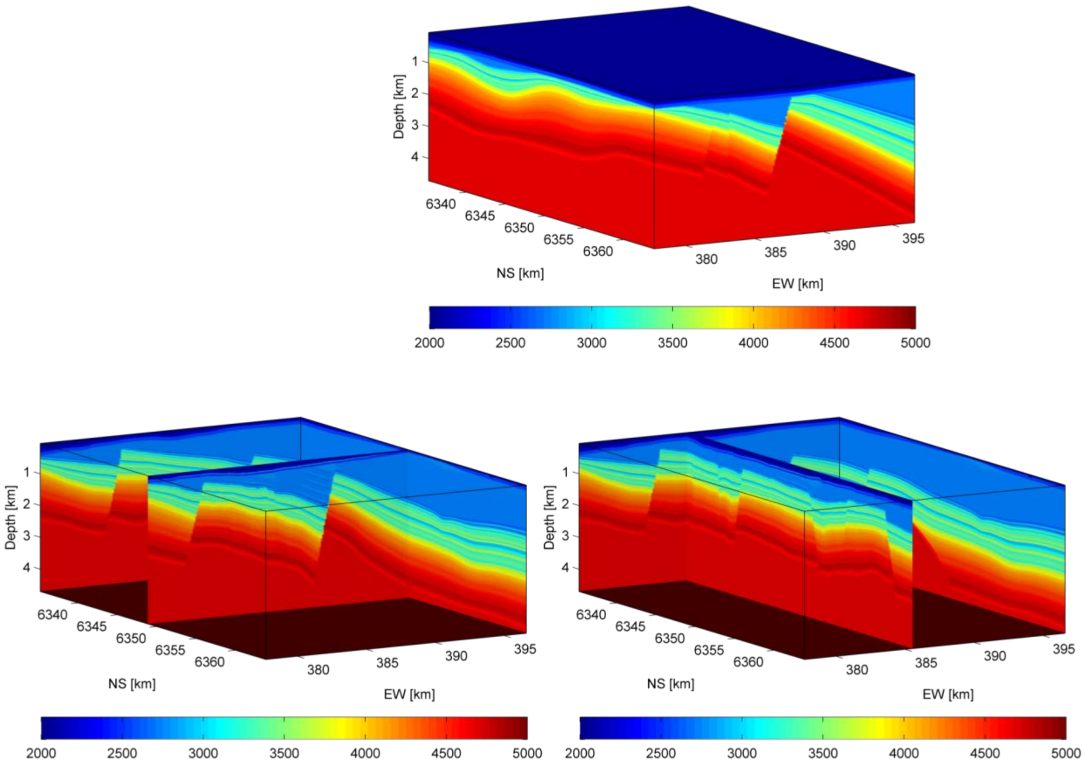

Figure 3 – P-wave velocity model. (Top) 3D volume, (bottom-left) east-west slices, and (bottom-right) north-south slices. Units of colour bars are velocity in m/s.

3.2 – High Performance Computational (HPC) 3D seismic modelling

We have completed the computational feasibility analysis portion of the ANLEC project, and have confirmed that we can simulate 3D elastic wavefields for the SW Hub 3D velocity model size of interest, and through scaling analysis confirmed that we have access to adequate hardware resources and software that will allow us to complete the required 3D elastic and acoustic wavefield simulations for the ANLEC project. A potential source of uncertainty is obtaining sufficient compute allocations and run time to complete wavefield simulations runs on our available iVEC Fornax and Magnus supercomputing resources. Although we have applied for and received a sufficient iVEC allocation to complete this ANLEC project, the timeline required to complete the wavefield simulations is dependent upon iVEC HPC resources being available as expected.

A key computational modelling aspect of the ANLEC project is the ability to complete simulations of 3D elastic wavefields arising from proposed micro-seismic events through the full 3D elastic model of the South West Hub (SWH). Because the size of the SWH model dimensions are expected to be of the order $N^3=1600^3$ grid points, this presents a computational challenge that requires the use of high-performance computing clusters with a sufficient number of CPU cores and available memory.

To demonstrate capability, we have evaluated a number of UWA 3D elastic modelling codes on IVEC's Magnus cluster on model domains that cover the range of wavefield simulation experiments that will be completed the second half of this project. Figure 4 presents a (vertical-displacement) 3D wavefield snapshot from a simulated point-source-like seismic source on the SWH "F10 Fault" 1.8s after source excitation. The wavefield has been superimposed over a 2D cross-section from the 3D ANLEC P-wave velocity model. As expected the compressional P-wave is expanded out the farthest and elastic scattering from layers is visible just behind the initial wavefront. The shear S-wave is also observed lagging behind the P-wave, due to a slower propagation velocity. Figures 5 and 6 show 2D FD elastic modelling examples of a propagating 2D wavefield snapshot and its corresponding shot gather for a surface source (Figure 5), and the corresponding 2D VSP shot gathers at several deep borehole array locations (Figure 6).

We have conducted 3D modelling tests similar to that visualised in Figure 4, in order to analyse the computational requirements of 3D elastic full-wavefield simulation. Table 2 summarises the results for three canonical models, the sizes of which span the dimensions of models we expect to use when performing upcoming 3D modelling and imaging experiments.

Based on this analysis, we have confirmed that we have the 3D elastic full-wavefield modelling codes and access to sufficient computational hardware (through IVEC) to simulate the 3D elastic wavefields that are required for to complete this component of the ANLEC project.

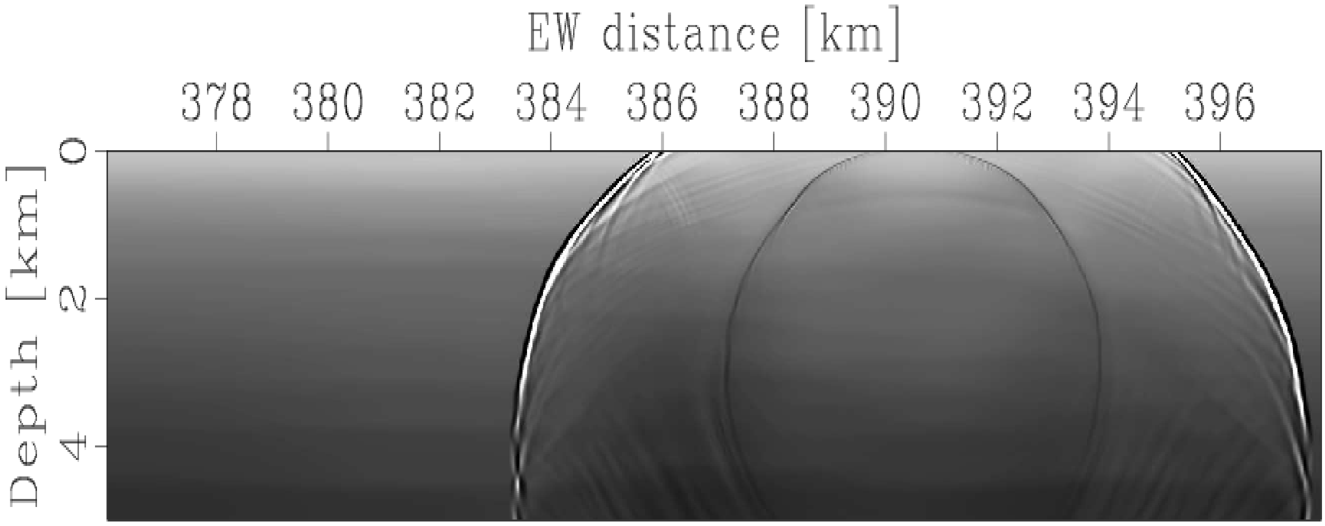

Figure 4. A 2D wavefield snapshot of vertical displacement from a point-source seismic source 1.8s after excitation. The wavefield is superimposed over a 2D cross-section of the P-wave velocity field from a version of the ANLEC 3D elastic model.

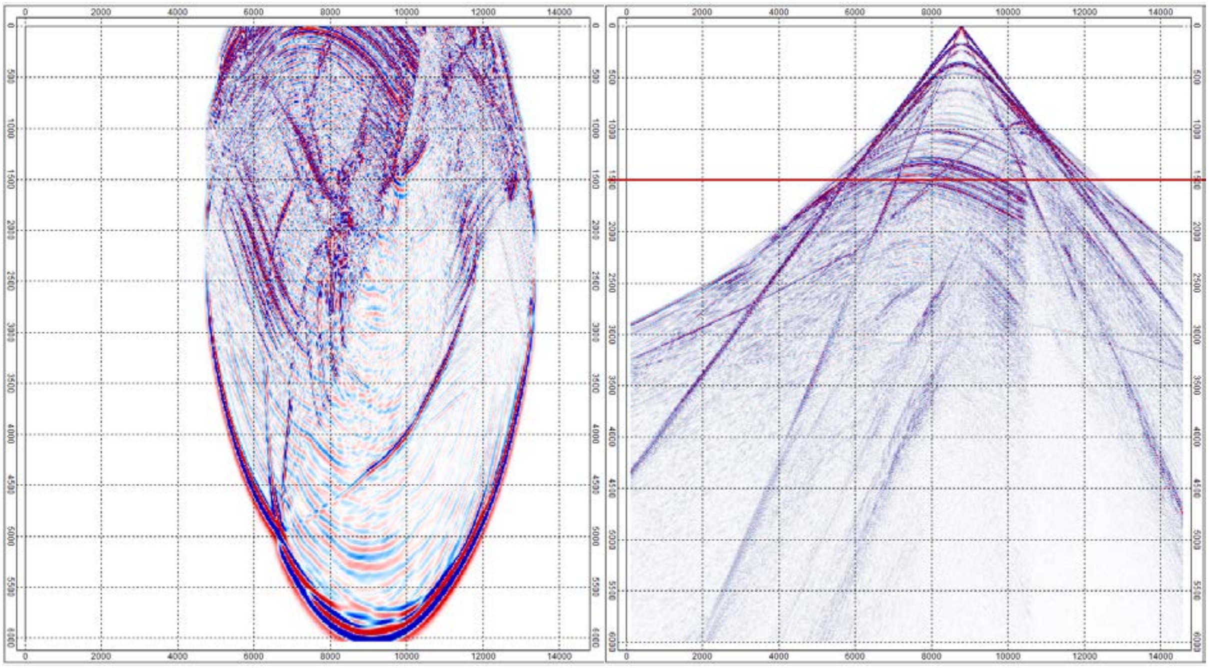

Figure 5. a) Snapshot at 1.5 s of the 2D FD wavefield propagating from a surface shot point; b) Corresponding shot-gather.

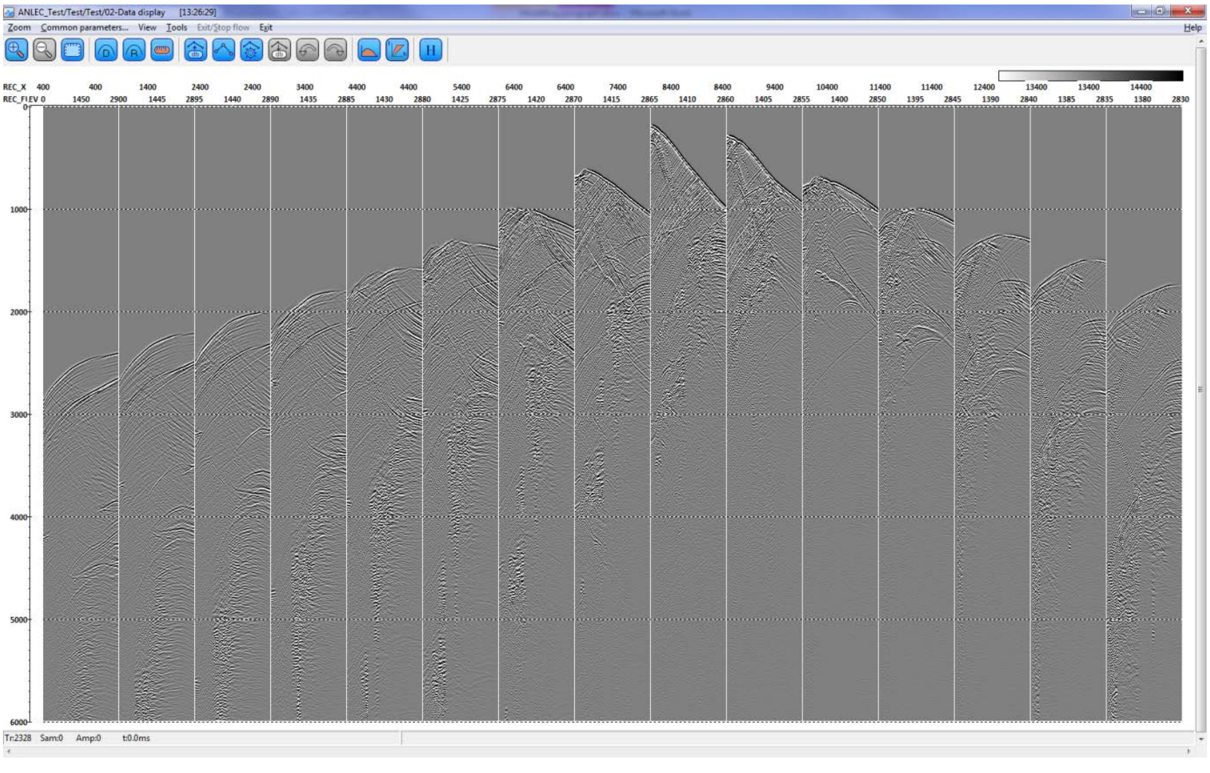

Figure 6. 2D FD common-source gathers for VSP borehole arrays in 15 separate 3km-deep well locations.

Model Name	Small	Medium	Full
Size [km^3]	5x5x2	10x10x5	25x25x5
Grid points	824^3	967^3	1730^3
Grid spacing [m]	5	9	9
Time steps	18,000	20,000	25,000
Duration [sec]	3.0	6.0	7.5
Required memory size [GB]	47	70	340
Computation Nodes	**32**	**32**	**64**
Computation time [hours]	1.9	2.8	7.0

Table 2: ANLEC model and runtime metrics for CPU-based modelling codes running on iVEC Magnus compute nodes.

CONCLUSION

This project is well underway and has already identified several early key results that may be of interest to the CCS stakeholder community, as summarised in the leading Executive Summary.

ACKNOWLEDGMENT

The authors would like to acknowledge contributions to the South-West Hub Flagship project by the Western Australian Department of Mines and Petroleum (including the Geological Survey of Western Australia), the Western Australian Royalty for Regions Program and the Commonwealth Department of Resources, Energy and Tourism. The authors wish to also acknowledge financial assistance provided through Australian National Low Emissions Coal Research and Development (ANLEC R&D). ANLEC R&D is supported by Australian Coal Association Low Emissions Technology Limited and the Australian Government through the Clean Energy Initiative.

GLOSSARY of terms

FD – Finite Difference. A computational method used to solve the wave equation and model seismic waves.

HPC – High Performance Computing (supercomputing).

iVEC – our local network of supercomputing resources, including the Magnus and Fornax computer systems.

Passive seismic – seismic energy that is created by fracturing of rock, and/or displacement of rock along fracture surfaces, at both micro and macro scales. Usually caused by significant stress/pressure changes within porous rock, especially if fluids are forced into low permeability, low injectivity rock. Can be natural (eg. via tectonic forces), or induced by man-made processes.

Vp – propagation velocity of seismic P-waves (compressional waves).

Vs – propagation velocity of seismic S-waves (shear waves).

VSP – Vertical Seismic Profile. Arrays of seismic sensors (geophones or hydrophones) are placed in a vertical borehole, and record seismic data generated by seismic sources located at/near the surface.