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CO_2 storage site characterisation using combined regional and detailed seismic data: Harvey, Western Australia

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Abstract

Some 115 km^2 of regional 3D seismic data were acquired in the first quarter of 2014 near Harvey, Western Australia, for the needs of the South West CO2 Hub project. The survey proved to be of great importance for a regional characterisation of the reservoir, identification of the large structures and key geological interfaces. However, small to medium size structures of interest for the development of the static and dynamic models were poorly imaged in this survey as the recording geometry was adjusted for the greater depths, which was between 2 km and 3 km. To improve the imaging of the shallow structures, a high-resolution (nested) 3D survey centered at Harvey 4 well was undertaken in 2015 (Urosevic et al., 2015). This survey utilised a single geophone and single, 24 s long, broadband (6–150 Hz) sweep combined with high data density to improve signal to noise ratio that was initially lowered by not employing high-power sources and geophone arrays. The results of this high-resolution 3D survey demonstrate that high-density surveys are important even at the characterisation stage and are crucial for development of a detailed static model. For that purpose, both post and pre-stack inversions of these data were utilised to model distribution of paleosols, lenses of high clay content, which are assumed to serve as baffles for CO_2 upward migration. A good correlation was established between very low impedance values and increased percentage of paleosols and on the other end of the scale very high impedance values and low porosity sandstones. A pre-stack migrated high-resolution cube and the attribute derived from it, such as coherency and impedance, enabled improved structural and stratigraphic analysis around Harvey 4 well. The results shown were of a crucial importance for the containment studies, development of the dynamic model and establishment of the injection intervals.

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1. Introduction

In 2013, a first-order assessment of the CO_2 containment for the South West Hub (SWH) suggested possible migration pathways across faults with potential for improving reservoir connectivity but also bypassing the primary and secondary seals (Langhi et al., 2013). The assessment was based on a geological model built upon sparse 2D seismic data with locally high uncertainties specifically regarding the structural architecture. The next stage of the site characterisation involved integration of the regional 3D seismic dataset acquired in 2014 with the available Harvey-2 and Harvey-4 wells data. This vastly improved the initial assessment of the CO_2 containment. Regional 3D seismic shed new light onto the structural architecture of the SWH site and provided an initial assessment of the potential for lateral and vertical circulation of CO_2 through the Wonnerup and Yalgorup Members (Pevzner et al., 2015). The relationship between the modelled faults and the present-day stress field is investigated to analyse the stress field changes on fault kinematic behaviour and to define which critically stressed fault segments are most likely to be forced into failure with pore-pressure build-up. Areas of fault reactivation are associated with an increase in structural permeability and therefore with the potential for the fault flow (Morris et al., 1999, Mildren et al., 2005, Bretan et al., 2011).

The regional Harvey 3D seismic survey provided good information of the large-scale subsurface structures and main stratigraphic units. The survey is officially known as DMPWA 2013 Harvey-Waroona 3D seismic survey. For simplicity, in this paper we refer to it as the regional Harvey 3D seismic survey or simply Harvey 3DR. This survey, as it is typical for most of regional land 3D surveys, suffers from low data density, which limits the imaging. Hence, the spatial distribution and orientation of shallow fractures and faults remained unresolved. These geological features were targeted by an additional high-resolution 3D survey, acquired in December 2014. It was hoped that this nested high-resolution 3D survey, would produce a crisp image of the structures surrounding the Harvey-4 well, define fault tips and the termination points in the shallow and provide sufficiently high data quality that could be utilised for quantitative interpretation.

The primary objective of the nested 3D survey at the Harvey-4 well was to obtain a better image of the shallow fault zones and to assess the risk for the CO2 storage complex. The opportunity to use the latest state-of-the-art seismic data acquisition equipment enabled us to design a high-density, high-resolution 3D survey. The application of powerful 3D processing technologies was expected to produce:

- A high-definition seismic image of the shallow subsurface geology around Harvey-4 well.
- Detailed characterisation of the near-surface structures around Harvey-4 well.
- Information on the location of the new shallow wells through the identification of additional, smaller scale faults associated to the larger faults observed in the regional 3D survey. Possible presence of a more complex fault system was suggested by (Lenghi et al., 2012, 2013).
- Validation of the “infill approach” where conventional and high-resolution seismic methods are combined to produce high-quality images for all depths. The high data density utilised in the nested 3D survey provides geological information of the shallow structures that are not recorded with sparse regional 3D seismic survey geometry. This approach is rarely utilised in the seismic exploration practice. In the case of SWH investigations at Harvey, the “high-resolution infill approach” is of a particular interest due to difficulties associated with obtaining the permission for seismic survey execution.
- Validation of the effectiveness of high-resolution data acquisition and processing techniques.
- Investigation into the potential use of converted shear waves for an improved fault characterisation workflow.

The integration of the processed seismic datasets and well data, allows us to interpret the data in terms of subsurface distribution of petrophysical properties. This information can be used to constrain static and dynamic models, which form a core value for feasibility studies of CO_2 sequestration at the SWH area.

2. Regional and nested 3D seismic designs

A Harvey 3DR seismic reflection survey was acquired by the Department of Mines and Petroleum, Western Australia in February−April 2014 (Figure 1a). The seismic survey was carried out by Geokinetics (Australasia) Pty. Ltd. in the Shires of Harvey and Wroona, 140 km South from Perth. It covered 114.81 km^2 of land in total (Pevzner et al., 2015).

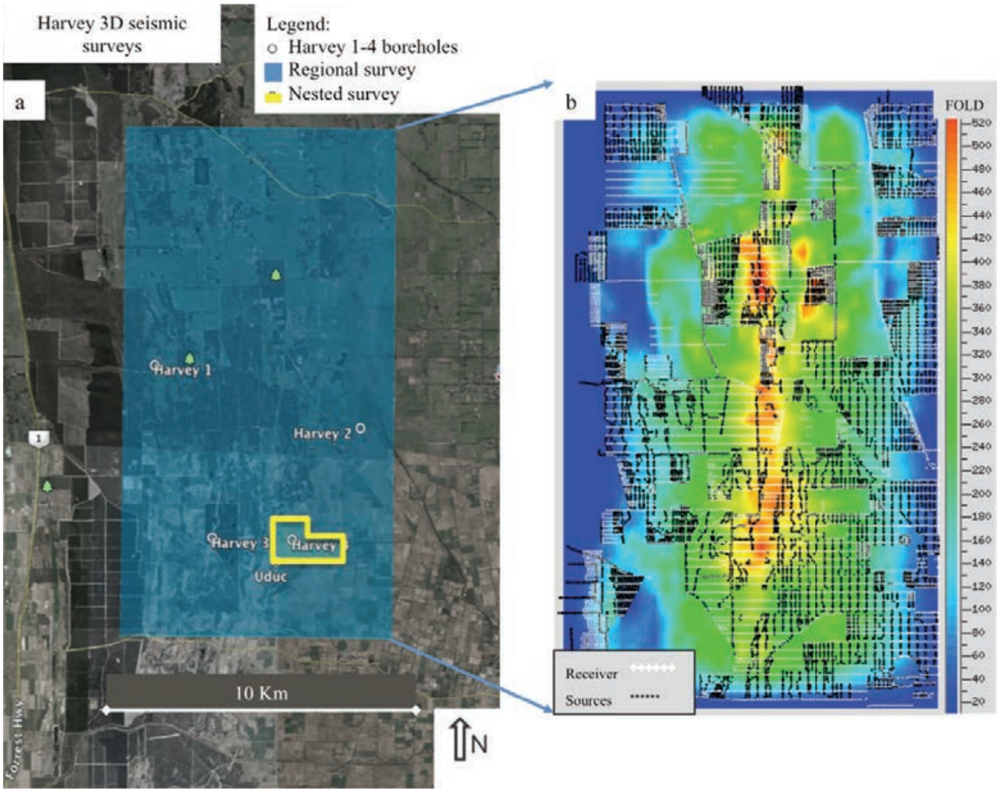

Fig. 1. (a) Harvey 3D seismic surveys location. Apart from Harvey-1, other three boreholes were drilled after 3D survey took place. The area of the high-resolution nested 3D survey is shown in yellow; (b) Harvey 3DR survey layout and fold coverage.

The survey covered many small farms, which are often owned/operated by the multiple individual landowners. The permission across a number of farms was not granted in time. This resulted in long total duration of the survey, patchy data coverage and uneven fold of the survey (Figure 1b). The uneven fold distribution in the regional seismic survey made the processing and particularly imaging difficult. Also data was not suitable for the quantitative analysis. Following the acquisition of the Harvey 3DR data, several wells were drilled (Harvey-2, 3 and 4). Subsequently, a new study was approved. In 2015, a small (2.12 km^2) high-resolution 3D seismic survey was designed and acquired by the National Geosequestration Laboratory (NGL) and Curtin University crew (Urosevic et al., 2015). Location of the nested 3D surveys is shown in Figure 1a.

The principal difference between two surveys was in the data density, that is the number of vibrating points (VP) and live receivers per km^2. Details of the data acquisition parameters for both regional and nested 3D survey are provided in Table 1. The high data density of nested 3D provided a much higher fold, particularly in the shallow and hence much improved the signal to noise ratio (SNR). Since SNR is proportional to square root of fold, the resultant nested data images proved to be superior. Moreover, the high data density and broad band sweep resulted in much improved vertical and horizontal resolving power.

Table 1. Regional and nested Harvey 3D seismic survey parameters.

Design parameters	Regional Harvey 3D	Nested Harvey 3D
Receiver spacing	50 m	15 m
Source spacing	50 m	15 m
Receiver line interval	200 m	50 m
Source line interval	200 m	90 m
Bin size	25 m x 25 m	7.5 m x 7.5 m
Maximum fold	~440	~150
Survey area	130 km^2	2.12 km^2
Near offset	25 m	8 m
Far offset	8218 m	2340 m
Sweep parameters	12 s 5–100 Hz linear upsweep with 350 ms tapers; 2 sweeps per VP	24 s 6–150 Hz linear upsweep with 500 ms tapers; 1 sweeps per VP

The advantage of the nested 3D design for imaging of shallow targets can be illustrated by choosing 550 ms of two-way-travel time (TWT), which can be recorded by maximum 1100 m offset, assuming that events are sub-horizontal and the mute is 40% stretch (Figure 2). Fold coverage limited by 1100 m offset of regional survey drops to only 20, while in nested survey it is at 100. This is the reason why noise suppression in a nested survey is expected to be more successful.

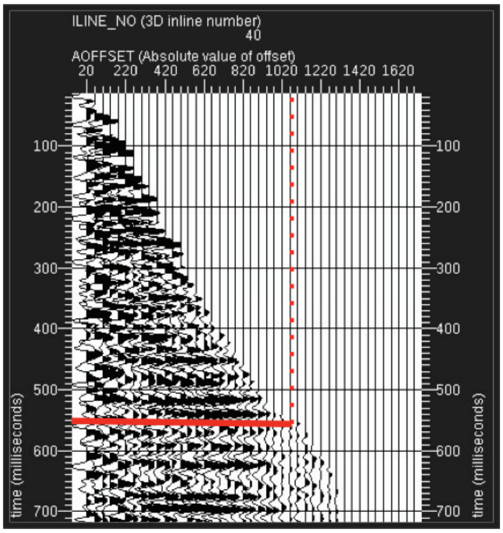

Fig. 2. Image gathers showing useable offsets to record event of 550 ms TWT.

It worth noting that, if a location for shallow release of gas is identified, then the initial results indicated that a set of high-density electrical resistivity profiles should be able to map, in detail, the continuity and distribution of shallow clays. The resistivity is surprisingly heterogeneous over the site, suggesting that the shallow geology is complex. The continuity and distribution of the shallow clays may be of considerable importance. If for example, a shallow release of CO_2 into faulted sediments is to be completed, final migration pathways may be strongly influenced by distribution of shallow clays.

Clearly, the nested 3D survey design was built to improve the lateral resolution. The receiver/source density is an order of magnitude higher that Harvey 3DR, while bin size of the nested survey is reduced to 7.5 m, approximately by a factor of 3 (Table 1). It was also hoped that broadband sweep (6–150 Hz) would inject high frequencies at shallow depths, which would improve the vertical resolution as well. The new broadband seismic vibrating source also proved to be quite powerful. It generates enough energy to clearly record events from depths of at least 1500 m, as verified in the nested survey data. The equipment and the approach used in this project provide a low footprint, low impact option for acquiring seismic data in areas that have public concern regarding the surface environmental disturbance, yet still have the capacity to obtain high-resolution images to reservoir depth. A small crew size of only eight people, operating some 3000 channels completed shooting this survey in less than five days. Such surveys may get a wider acceptance for CO_2 monitoring programs and also public approval in Harvey area.

3. Seismic data processing and imaging

For both the regional and nested survey, the processing was structured around two flows. The first flow utilised robust scaling, 3D dip moveout (DMO) and post-stack migration. The second flow utilised an amplitude preservation approach and pre-stack time migration (PSTM). The aim of the first flow was just to produce a “baseline” image against which further processing improvements are measured. It became apparent that a conventional DMO correction followed by post-stack migration was insufficient to handle the lateral changes in velocity field. Therefore, pre-stack time migration based on Kirchhoff integral solution was attempted to aid in handling the complex velocity field. The goal of pre-stack time migration was to derive a velocity model appropriate for the geologic setting, to place events at the proper position, to avoid introduction of a false structure and to flatten the image gathers.

The processing flow for the final imaging is shown in Table 2 and 3.

Table 2. Processing parameters.

Processing procedure	Parameters
Data conversion	SEG-D data Input and conversion to Seispace internal format
Geometry and binning	Nested 7.5 m x 7.5 m, Regional 25 m x 25 m
Gain recovery	Surface consistent amplitude recovery and spherical divergence correction
Static correction	Application of elevation and residual statics
Deconvolution	Minimum phase predictive
Band-pass filter	Sweep frequencies inclusive
Surface wave noise attenuation	Velocity 1200 m/s, frequencies 4–40 Hz
Automatic gain control (display purposes)	500 ms

Table 3. Imaging algorithm.

Imaging procedure	Parameters
Data input	Pre-processed dataset
PSTM Iteration I	PSTM velocity field I
Velocity analysis	Compute PSTM velocity field II
PSTM Iteration II	PSTM velocity field II
60% stretch mute	Post-NMO top mute
3D stack	Normalisation scalar 0.5
FXY deconvolution	Window 200/800 ms
SEGY output	Standard SEG Rev1

4. Regional and nested 3D surveys

The main objective of the nested 3D survey was to produce high-resolution images of the shallow structures (0–1000 m). One way of verifying that the objective was achieved is through a direct comparison of migrated nested 3D imagines with those of the Harvey 3DR survey. Initial comparison was made using a chair display. One such example is shown in Figure 3. A brief inspection of images shown clearly demonstrates that the objectives were achieved and that the nested 3D survey contains new geological details, not observable in the previous regional survey. Further investigation and comparison utilised 2D images planes, which are easier to comprehend and observe in detail. One of the objectives was compare fault expression in the two data sets. For that purpose we first enhanced the faults through the computation of a so-called minimum similarity cube.

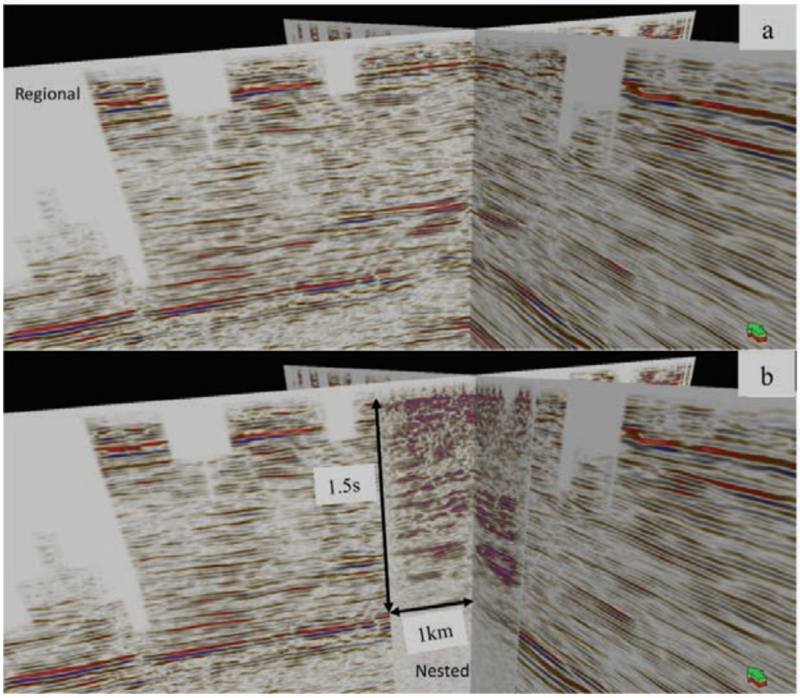

Fig. 3. (a) Regional Harvey 3D survey (b) regional survey with nested survey inserted. Nested 3D survey demonstrated higher resolution and better overall expression of shallow geology. Vertical scale is in time.

Firstly, time slices showing clear fault expression were selected. Then the in-line and cross-line passing through the fault trace were used for comparison. This is demonstrated in Figure 4. It is clear that the nested high-resolution 3D has provided new information about the shallow structures, not seen in the regional data. It is also clear that the dense survey grid has provided more fidelity of fault traces down to an approximately 1.5 km depth and possibly deeper.

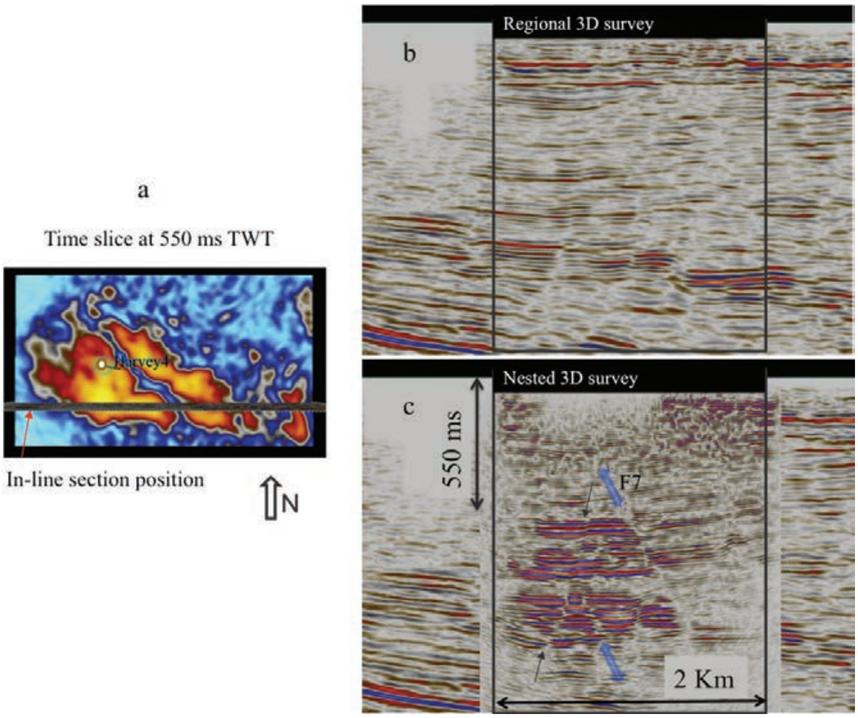

Fig. 4. (a) Time slice through similarity section with the location of the in-line section under investigation and Harvey 4 borehole shown as a green circle, (b) regional Harvey 3D and (c) nested 3D PSTM stacked section inserted into the rectangular area. The blue transparent double arrow is used to denote fault images that are clearer in nested 3D volume, such as Fault 7. The black arrow denotes where fault is expressed with much better clarity in the nested 3D. Vertical scale is in time.

A number of fault expressions were analysed in time slice domain. Additional information and improved fault trace identification was achieved with so-called similarity cube. Such an example is shown in Figure 5 where horizontal intersections through amplitude and similarity cubes area compared. Faults of different scales or orders can be seen in these two displays. Both displays should be used concurrently as some faults are better expressed in one domain rather than the other.

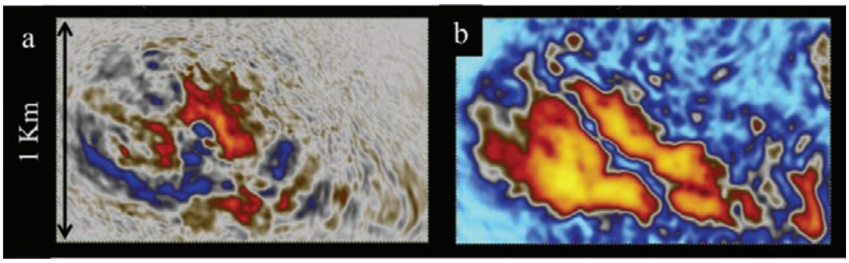

Fig. 5. (a) Time slice from the amplitude cube; (b) time slice from similarity cube. Main faults can be seen tracking from top left to bottom right as a blue linear trend with the orange area of the similarity time slice.

5. Seismic quantitative interpretation

Having the processed seismic datasets along with analysed well data, we can start 3D quantitative interpretation to integrate these pieces of information into 3D reservoir models. The aim is to interpret the data in terms of subsurface distribution of petrophysical properties, relevant for the CO_2 sequestration modeling: porosity, permeability etc. Derived petrophysical cubes are then used to constrain static and dynamic models.

To tie well data to the seismic, one needs to compute a synthetic seismic trace using a logs-based 1D model of elastic impedance:

$$EI = V_P^{\left(1+\tan^2\theta\right)} V_S^{\left(-8K\sin^2\theta\right)} \rho^{\left(1-4K\sin^2\theta\right)} \tag{1}$$

where $K=(V_S/V_P)^2$; θ - angle of wave incidence at the boundary. At the normal incidence EI reduces to the acoustic impedance [$Z_P=\rho V_P$]. Well tie requires log data conditioning, but other challenges surrounding each well in the area (Figure 6). Some are listed below:

- Harvey-1 corresponds to the area of reliable seismic amplitudes, but almost vanishes in the Wonnerup member; moreover the logs were acquired only at the bottom of the Yalgorup member;
- Harvey-2 penetrates Fault 10 which causes intense scattering of the seismic energy, thus a complex wavefield is present close to the borehole;
- Harvey-3 is surrounded by the forest, prohibiting deployment of receivers and shot points; this results in a blank vertical zone in the seismic image along the borehole;
- Harvey-4 trajectory is intersected by the oblique Fault 7 and possibly another fault going in parallel to the Fault 7, which are not clearly visible in the commercial seismic but obvious in the nested seismic (Figure 4). As a result, intensity of the seismic varies significantly above and below the faults.

The features listed above limit significantly the reliability of the amplitude-based inversion of both 3D seismic surveys. It also affects correlation of the logs interpretation to the seismic. Even improved processing of the large seismic did not lead to a significant improvement of the correlation to the wells. However we were able to obtain meaningful elastic impedance cube from the nested 3D seismic data after correlation to Harvey-4 well. The main objective of inversion was to utilise inverted impedance data for characterisation of the Yalgorup member. Of particular interest was to define paleosols, as they are potential barrier to upward migration of CO_2. Their limited lateral extent and small thickness makes them difficult target for analysis, particularly from seismic amplitudes. Preserved relative amplitude seismic data and edited logs were used in correlation process. First, we extracted seismic wavelet from the data based on the highest log-derived synthetic to seismic correlation of 75%. Subsequent stages included acoustic and elastic inversion.

We established that the highest SNR corresponds to the mid-offset range of seismic data that correspond to 15^o–25^o angle stack. After series of cross-plots it was determined that the intervals of low values of $EI(20^o)$ and negative deviation from this trend correlate with paleosol facies derived form well data (Figure 7). At the right part of the figure we see the comparison of the detected paleosol bodies against the paleosol effective thickness interpreted from the well logs (micro-imagers, gamma-ray and density logs). The agreement is rather good.

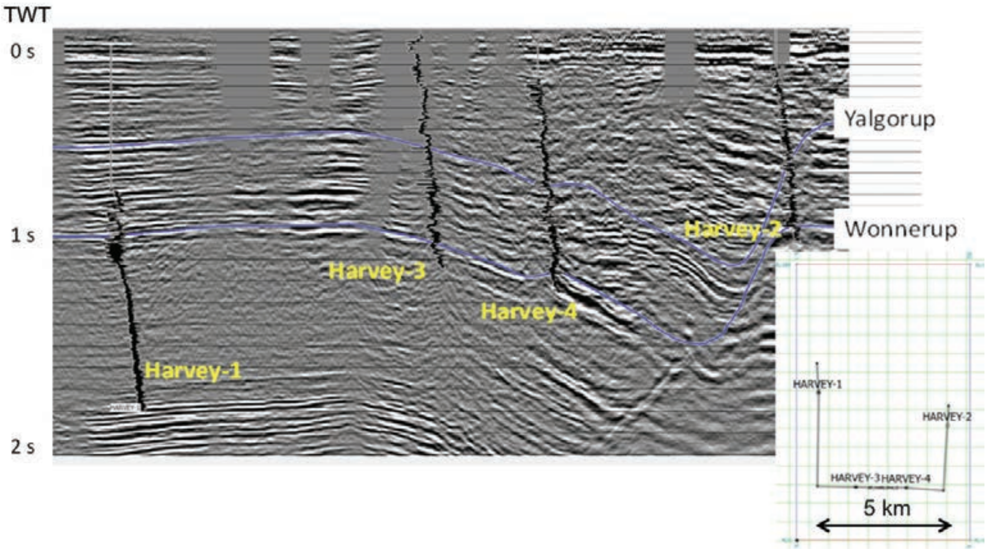

Fig.6. Arbitrary line (shown in the inset) extracted from the large commercial seismic overlaid by V_P from logs.

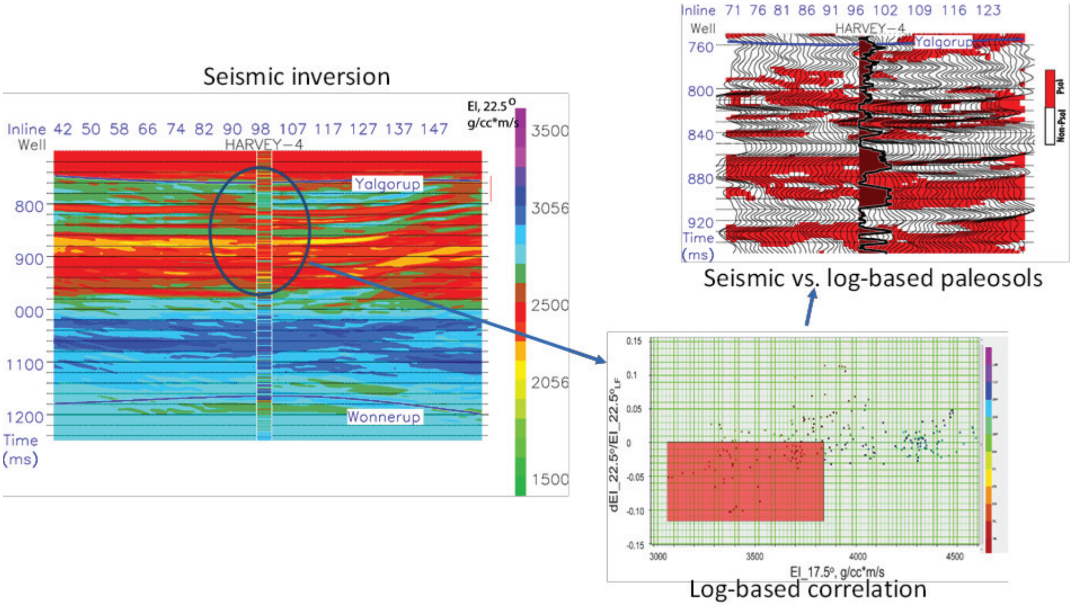

Fig.7. Elastic impedance inversion flow aimed at the paleosol mapping: Impedance section after well tie (left), cross-plot of the elastic impedance and selection of low values that are expected to be characteristic for paleosols (lower right) and mapping low EI values onto the seismic data (upper right) and comparing it to the log-derived paleosol intervals.

6. Conclusion

The high-resolution Harvey nested 3D seismic data has been acquired with the NGL using a state-of-the-art hybrid recording system. Two light NGL vibrator trucks (UNIVIB) with extra-wide tires were deployed in a "flip-flop" shooting pattern. No footprint was left in the ground by this seismic source vehicle. A small seismic crew comprised of eight people managed the deployment of 2,300 channels with ease and fired close to 1600 shots in 4.5 days. A single long-duration sweep and a single sensor, combined with the achievements of a high fold produced very good quality data of envious SNR. Preserved amplitude processing and pre-stack imaging proved to be a very effective processing approach for both structural and stratigraphic analysis. Very good quality images enabled qualitative studies involving acoustic and elastic inversions.

By inserting the nested 3D data cube into the regional 3D data we show that:

- Several new faults, not seen in the regional data, were identified in nested 3D data;
- All discontinuities (large and small) are much better imaged in nested 3D survey;
- The extent of some fault tips close to the surface was mapped from the nested data;
- Faulting in the area has a high complexity than previously thought;
- The Harvey 4 well was drilled through a fault of a large throw (several tens of metes).

The fault density and their complexity cannot be fully realised with the low-resolution seismic data even at greater depths. Low-resolution data are also not appropriate for the implementation of seismic stratigraphy and quantitative interpretation. The new nested high-resolution seismic data after appropriate processing and imaging were of sufficient quality to produce good correlation with well data and permit the process of seismic inversion. After low values of the elastic impedance were related to paleosols it was the matter of mapping these intervals onto seismic section. Very good agreement achieved stimulates further work along this path.

Considering all the additional structural and stratigraphic information obtained from the nested 3D seismic it is that such surveys can be very valuable for site characterisation. Moreover, such data can be also used to optimise well position through better fault location prediction. The cost of the nested survey conducted is only a fraction of the drilling cost but the impact can be significant in terms of borehole relocation, fault correlation, derivation of static model and subsequent dynamic simulations.

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