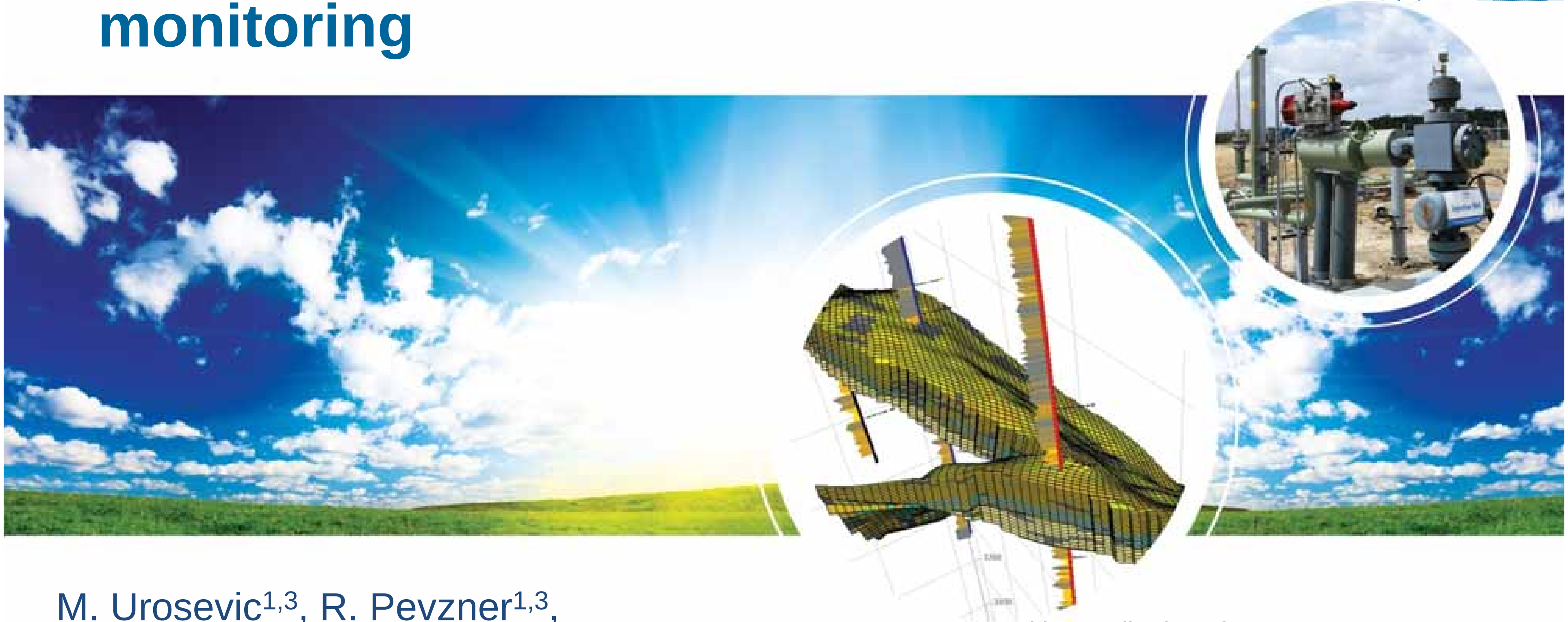
Otway Basin Project Stage I: results of seismic monitoring



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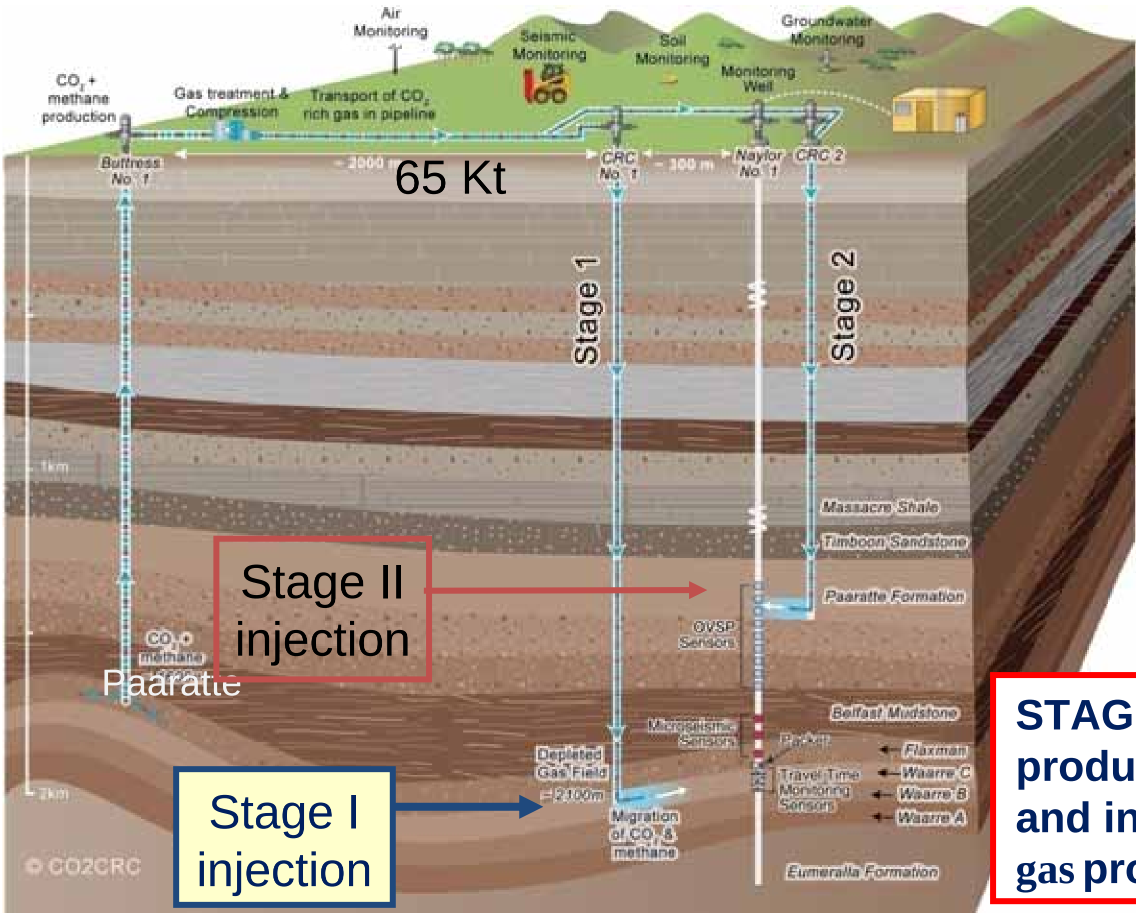
Curtin University CSIRO CO2CRC

Outline

- Stage I study: CO_2 injection into a depleted gas reservoir

- Numerical simulations and pre base line tests
- Seismic monitoring program
- Data acquisition
- Results
- Final modelling
- Conclusions

CO2CRC Otway Project (Victoria, Australia)



STAGE I: An 80/20 % of CO_2/CH_4 stream produced from Buttress, transported and injected into CRC-1 well (previous gas production well)

STAGE II: CO_2/CH_4 stream injected into CRC-2 well(huff-and-puff) – up to 10 Kt.

Naylor field, Otway

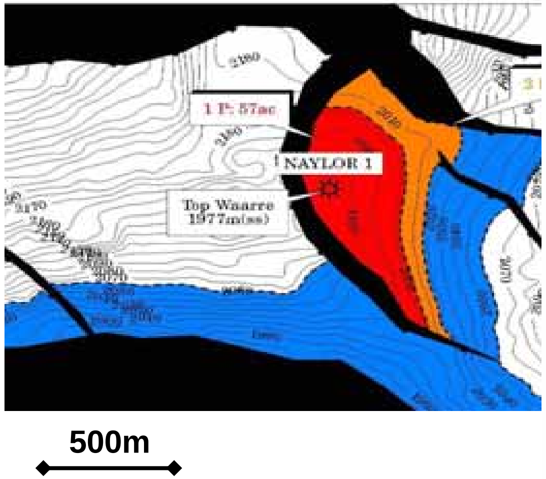
- Unique test site (relevant for EHR)
- Infrastructure in place, natural CO_2 accumulations
- Opportunity to develop M&V strategies for several different reservoirs
- Current (phase I) CO_2 storage involves deeper, depleted gas field (Naylor), highly porous and permeable formation
- Opportunity to devise appropriate methodology that can be applied to CO_2 storage in depleted gas reservoirs

The reservoir

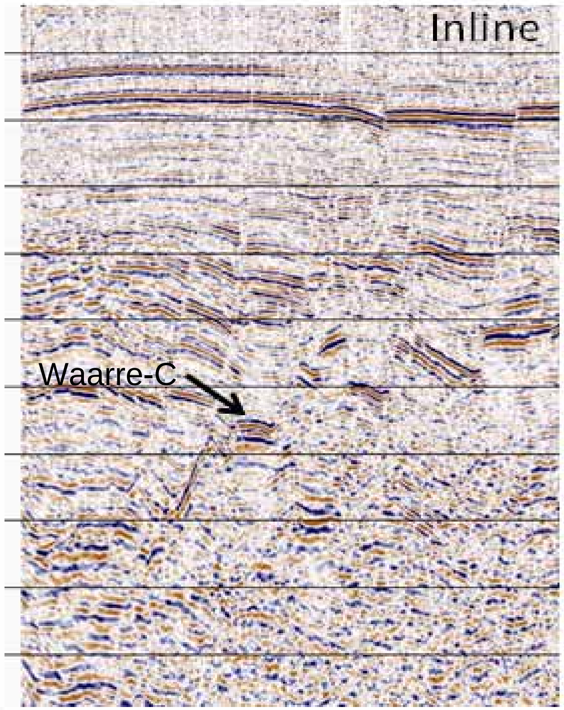
Small, thin, heterogeneous and deep depleted gas reservoir, surrounded by complex faulting,

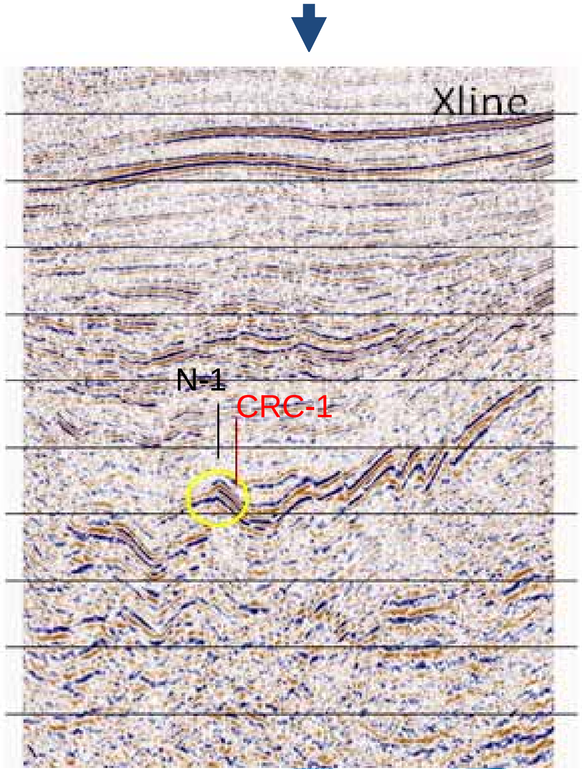
CO_2/CH_4 – mix injected and monitored with the most sensitive seismic techniques

Naylor gas field



Pre-production 3D seismic data recorded in 2000





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Geophysical monitoring

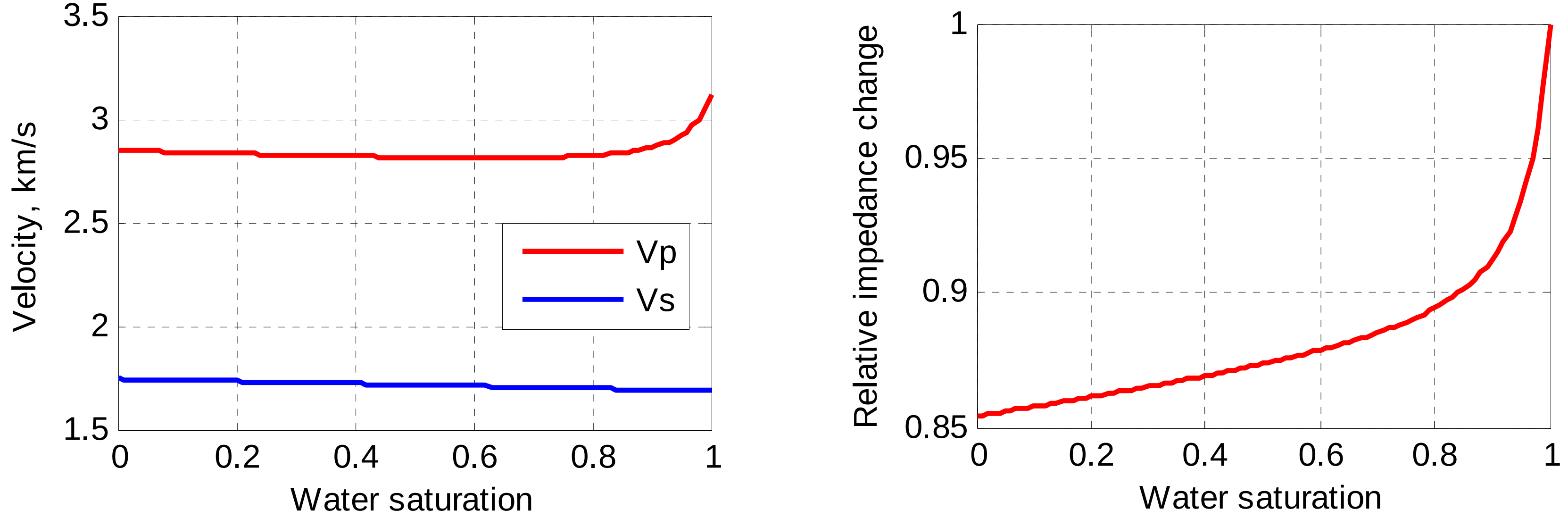
Only time lapse (TL) seismic methods – great penetration, resolution

Issues:

Expect small changes of the elastic properties of the reservoir due to CO_2/CH_4 mix injection – saturation changes mainly (subtle TL signal)

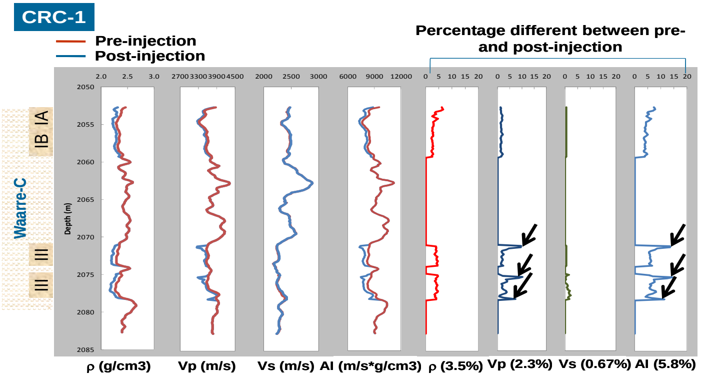
Traditionally poor repeatability of land seismic surveys + accessibility, environmental restrictions, cost, etc…

Changes of rock properties due to fluid substitution – homogeneous model

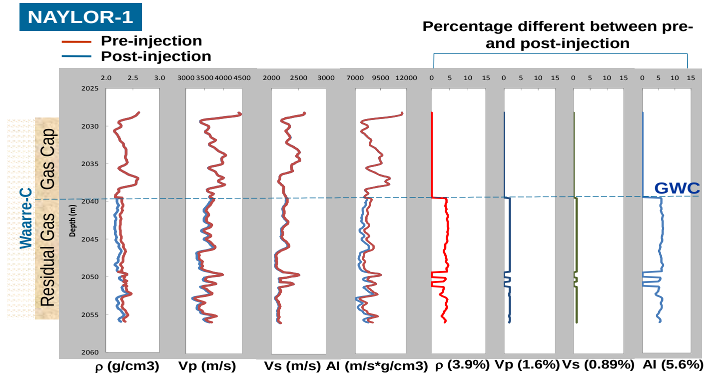


Injection of CO_2 in supercritical form into saline aquifer with 25% porosity

Modelling/predicting TL seismic effect due to CO_2/CH_4 mix injection into Waarre-C



ΔAI ~3-6%



Computed changes in elastic properties including acoustic impedance for two wells. In both cases impedance changes up to 6%; density dominated; very small change

For Δ AI~6% Max, ΔR up to 15%. If NMRS < 20%...

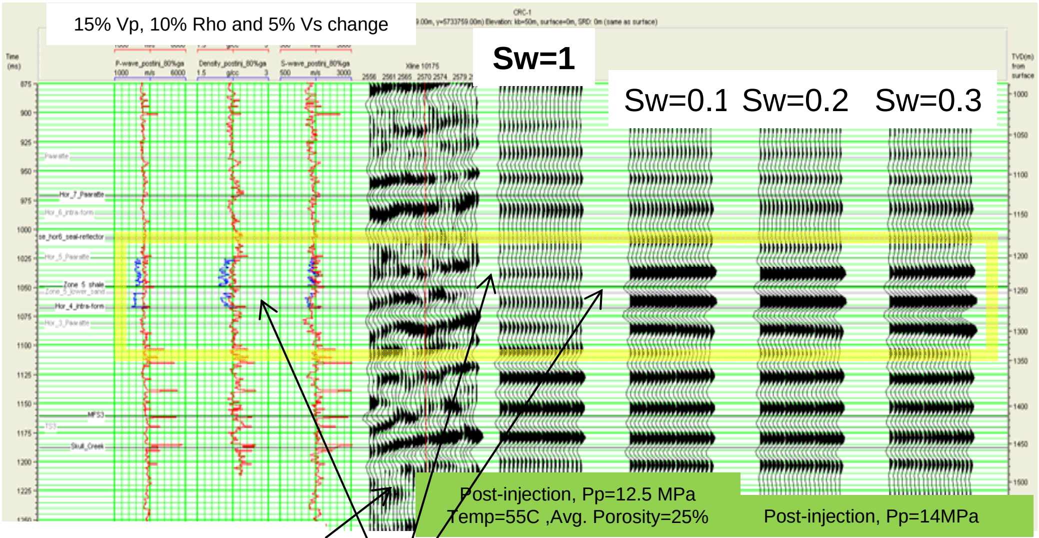
Challenging...

1D Modelling of CO_2 "leak" scenario

Upward migration of CO_2 into overlain strata (Paaratte saline aquifer 500 m above Naylor)

Assurance monitoring

Depth
~ 1100 m



Pre-production seismic

Paaratte saline formation

Very strong TL effect due to CO_2 accumulation in Paaratte!

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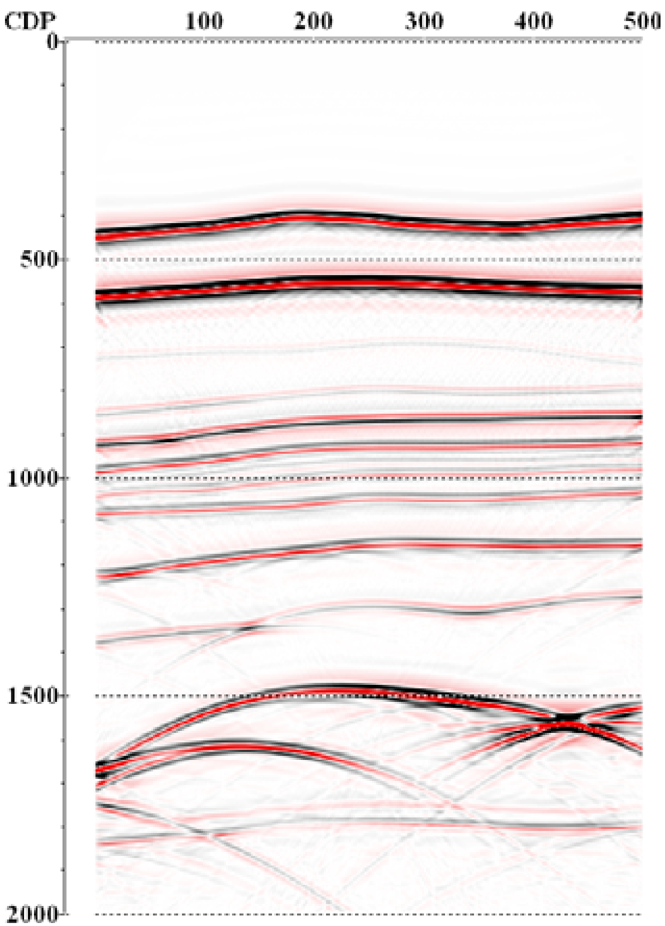
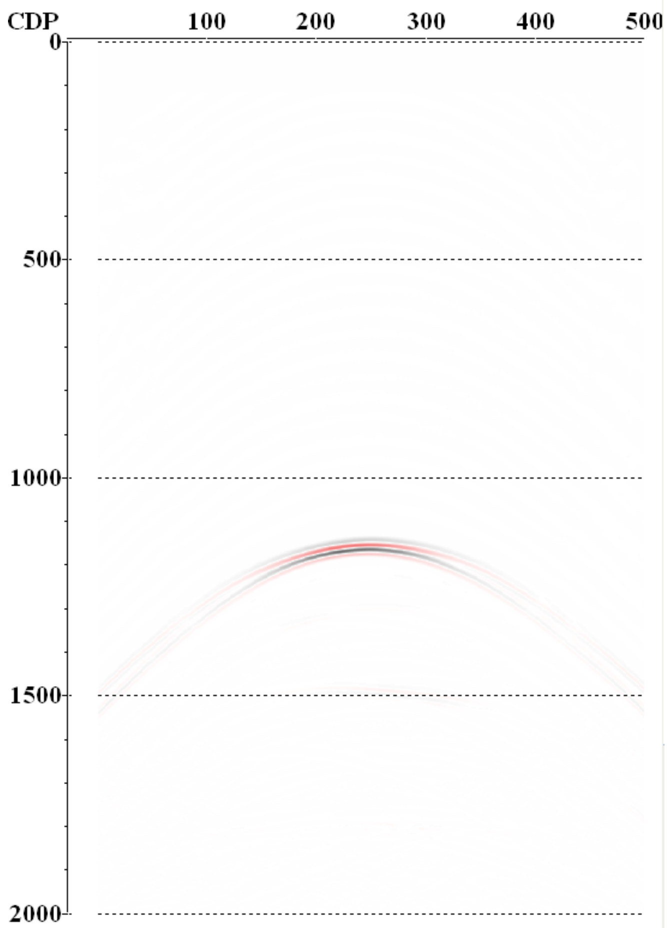
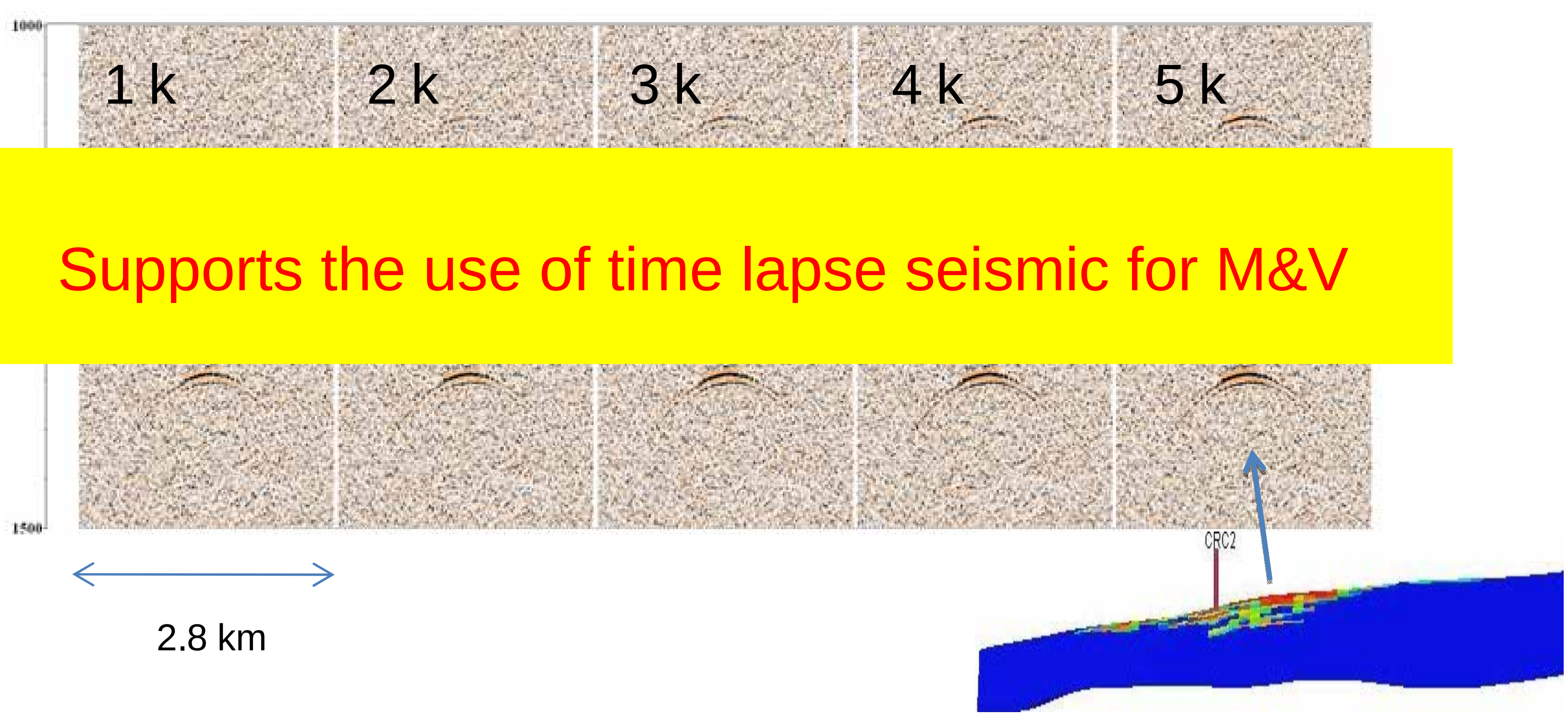
2D numerical modelling of small amount of CO2 present in Paaratte





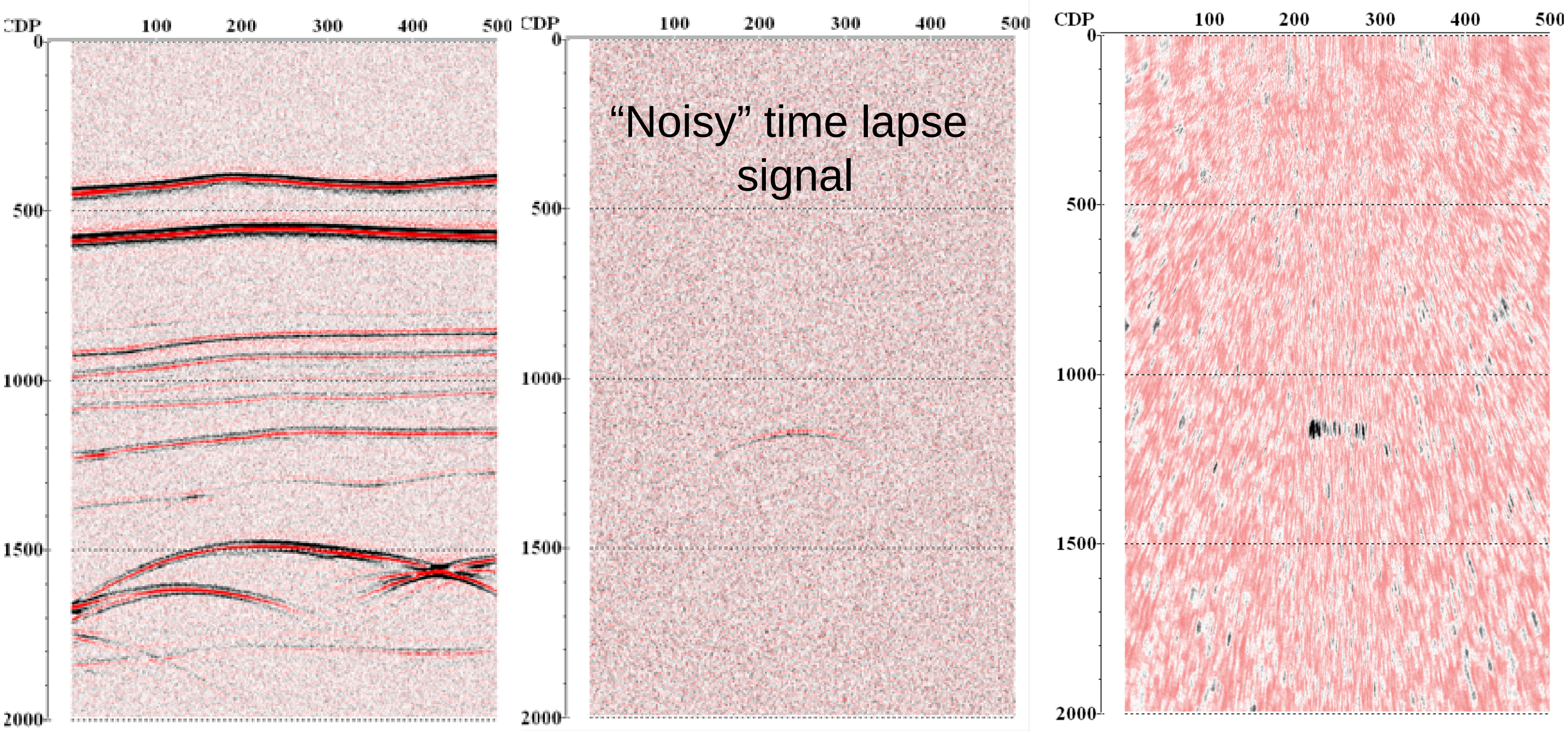
2D sensitivity modelling of a CO_2 “leak” into the Paaratte saline formation - model from reservoir simulation



Supports the use of time lapse seismic for M&V

The CO_2 quantities shown in thousand tonnes. CO_2 occupies thin layer, with small areal extent (less then Fresnel radius) - diffracted energy is roughly proportional to CO_2 volume; 30% of background noise.

Application of diffracted wave analysis to leakage detection



4 Kt of CO_2 readily detectable

How can we monitor Stage I injection?

Need TL surveys that can achieve:

- High resolution
- High sensitivity
- Very good repeatability

Small target, small TL signal, traditionally poor repeatability of land seismic surveys

Other limitations: accessibility, environmental restrictions, cost, etc…

Exploring around the site...

Key issue: Repeatability versus TL signal

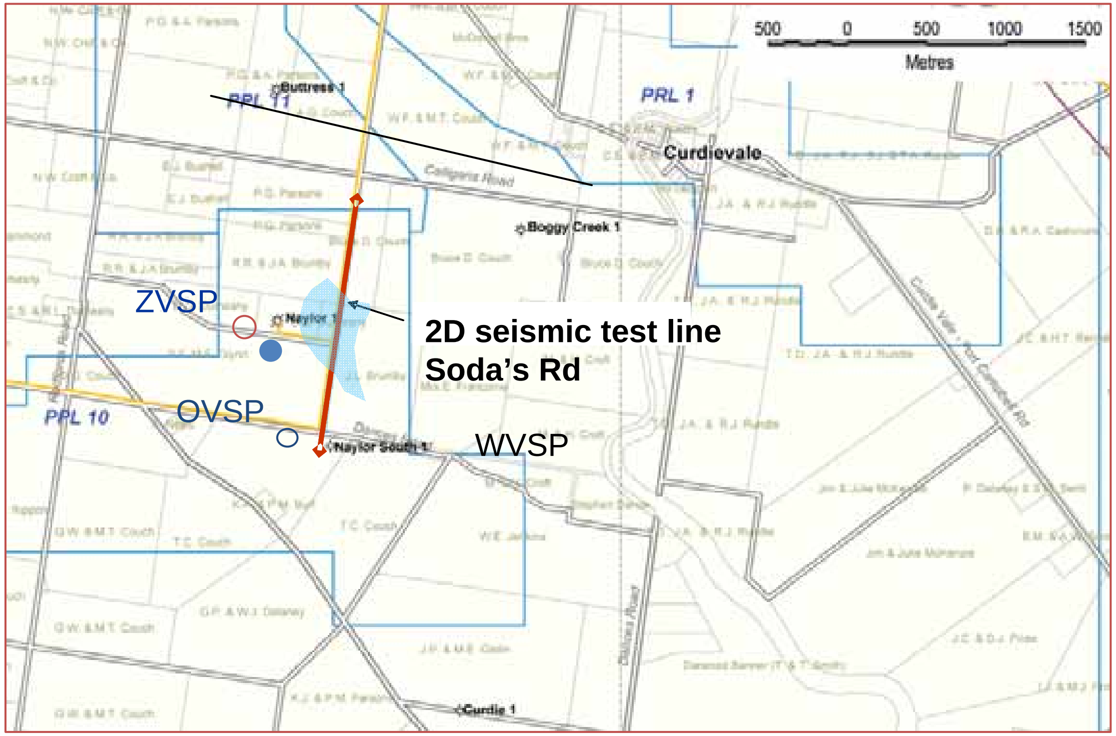
Weathering conditions: top soil (farming zone) + weathered clay-rich zone on top of corrugated limestone

Seasonal variation of Water Table

Variable scattering with WT variation

Pre baseline surveys

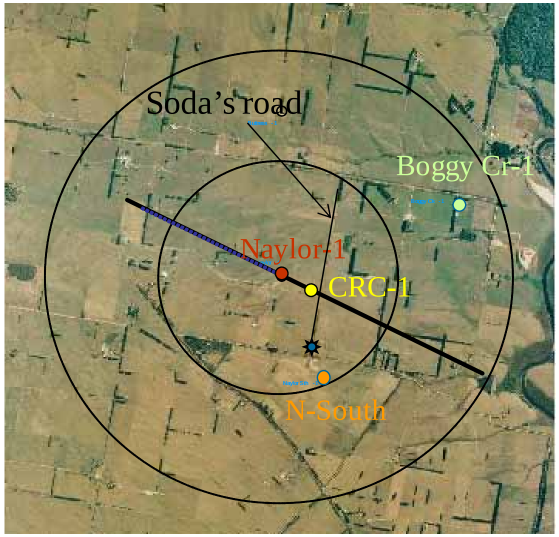
Repeatability and sensitivity tests (borehole and surface seismic program)



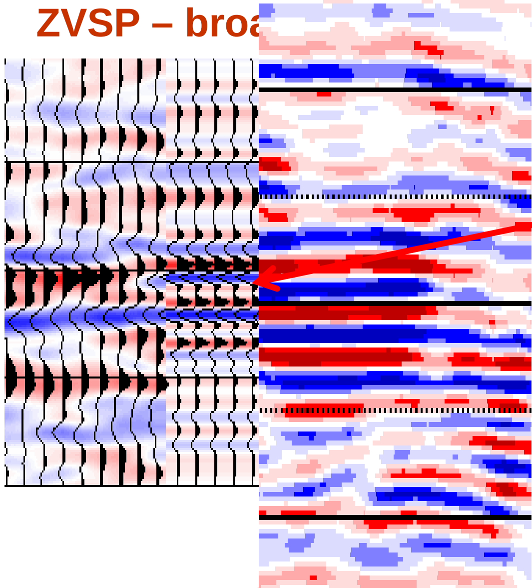
Soda's Rd tests
2Dseimic test line
Dry/wet conditions
Different sources
7 repeats

Objectives: establish repeatability, performance of different sources, related energy loss, seasonal variation effects, survey logistics, accessibility, acquisition geometry, duration, cost, etc.

Pre-baseline borehole seismic tests



ZVSP – broa

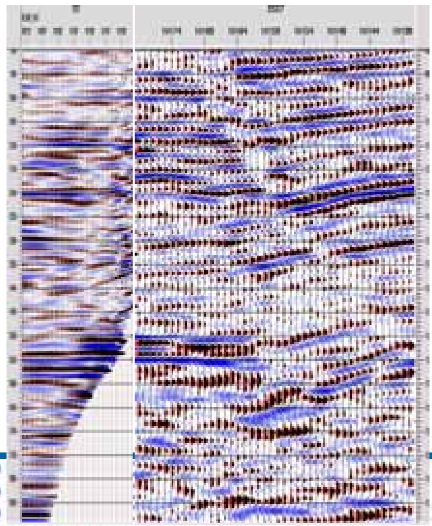


Intra reservoir shale detected

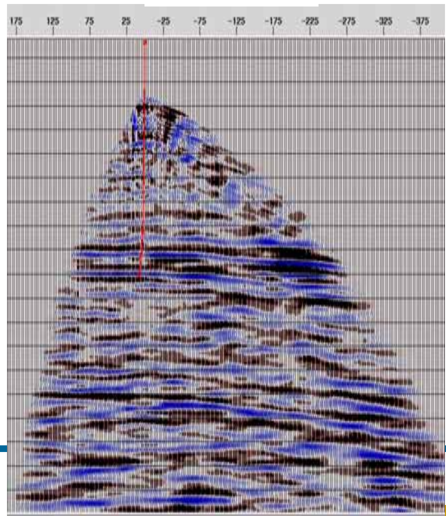
HEMI 60

Surface seismic

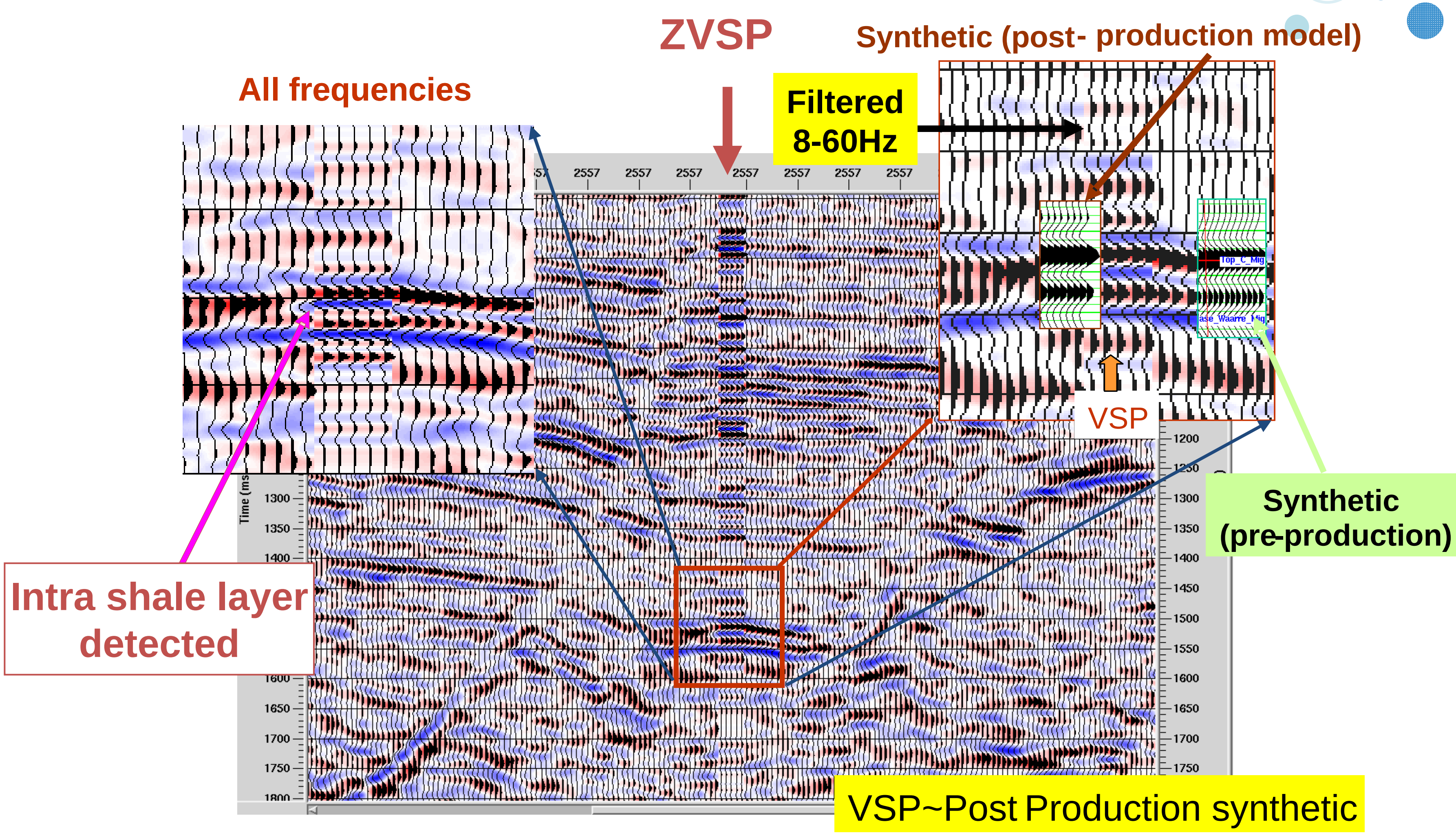
OVSP



WVSP

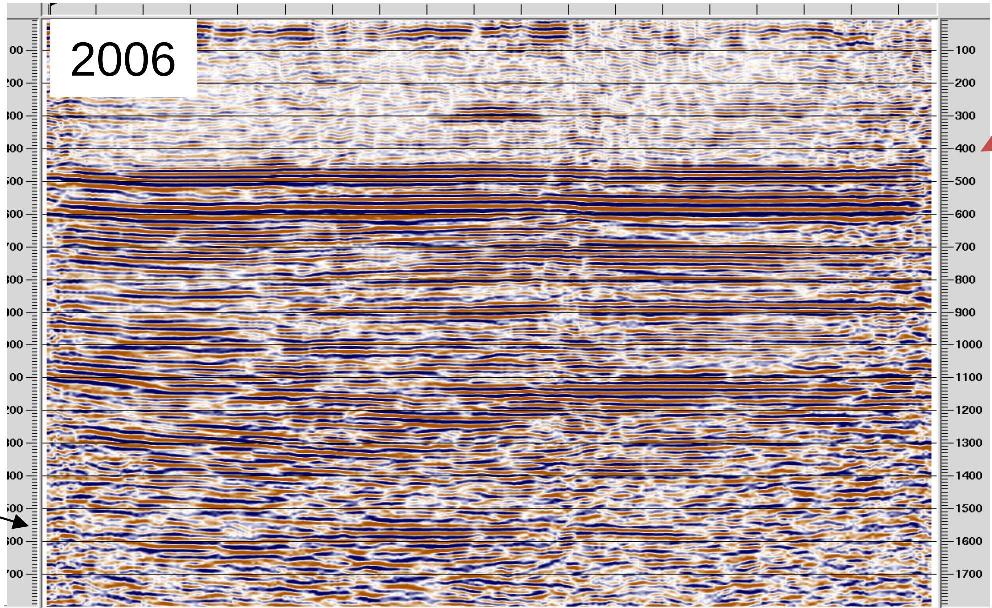


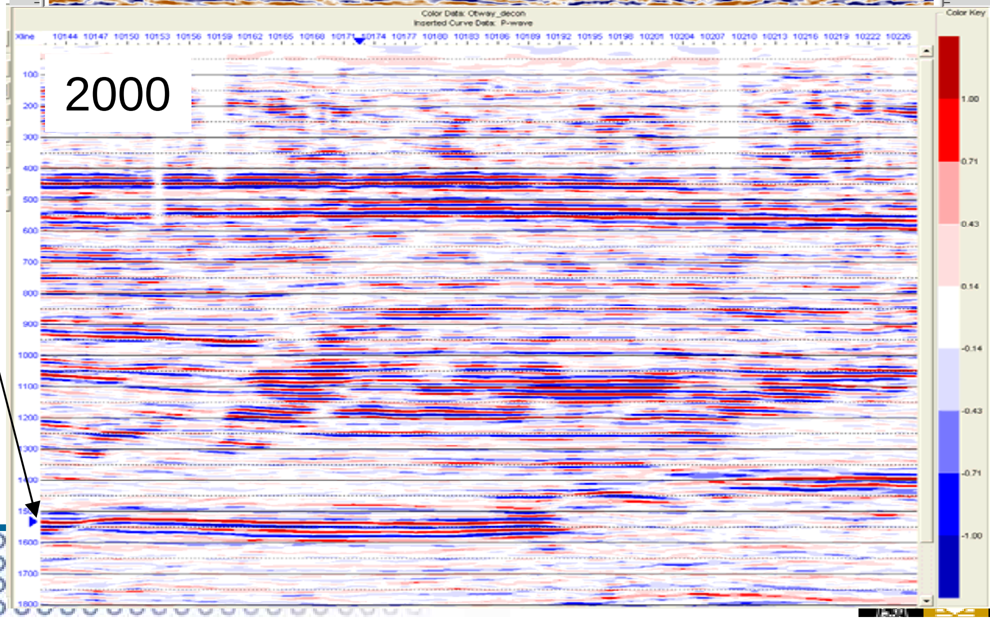
Pre baseline Z,O,WVSP surveys (2006) - very good results



Pre baseline 2D reflection surveys (2006/7)

Res.
sand





2D line extracted from 3D seismic data – approximate location

2D MV seismic data low-pass filtered to match 3D seismic

Data recorded with MV

Hemi 60, 10 x power

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It is always about the seismic sources…

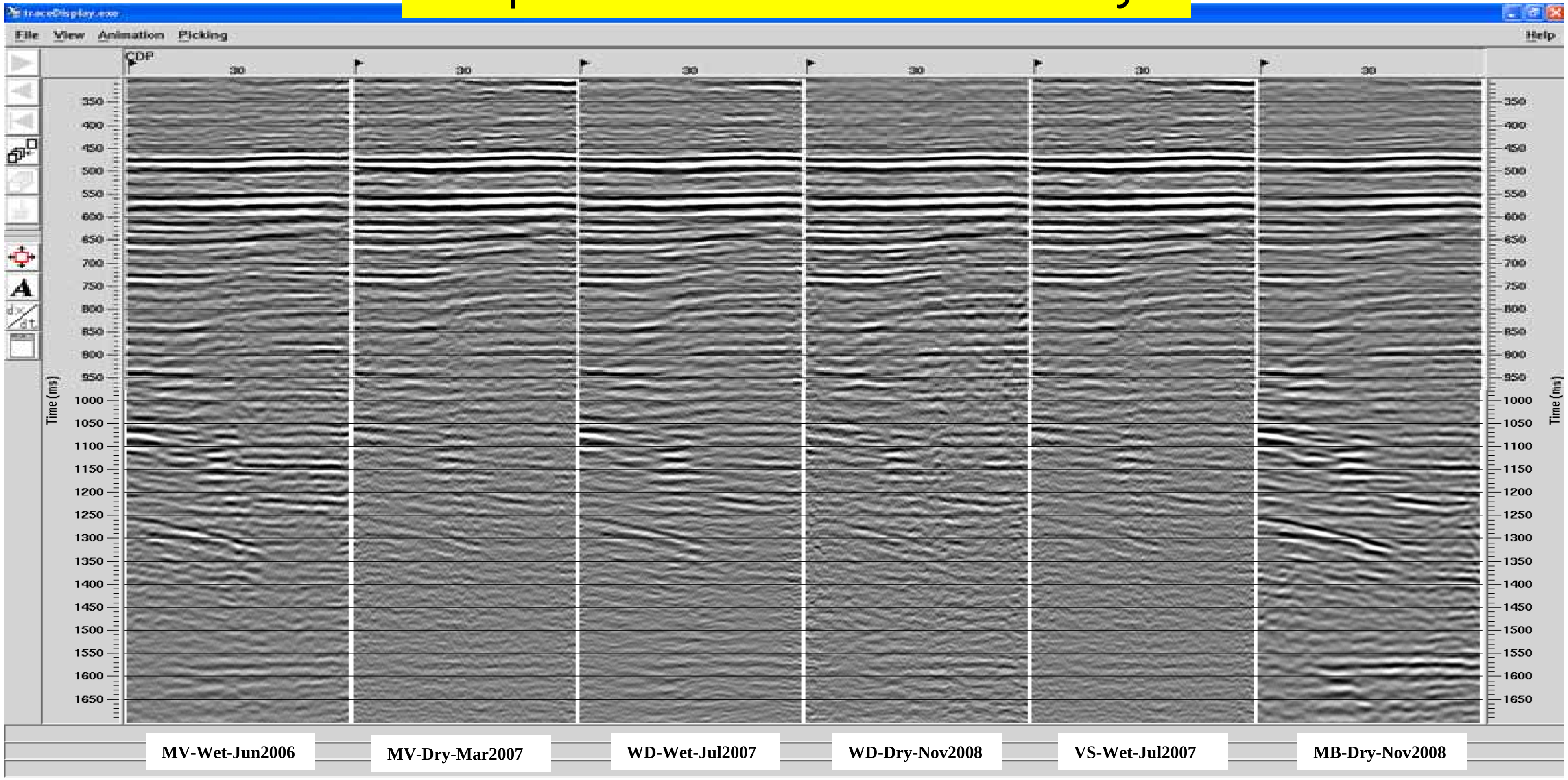
MV- 6000 lb

WD – 1320 Kg

A concrete breaker !!!

MB – 15000 lb

7 repeated 2D reflection surveys



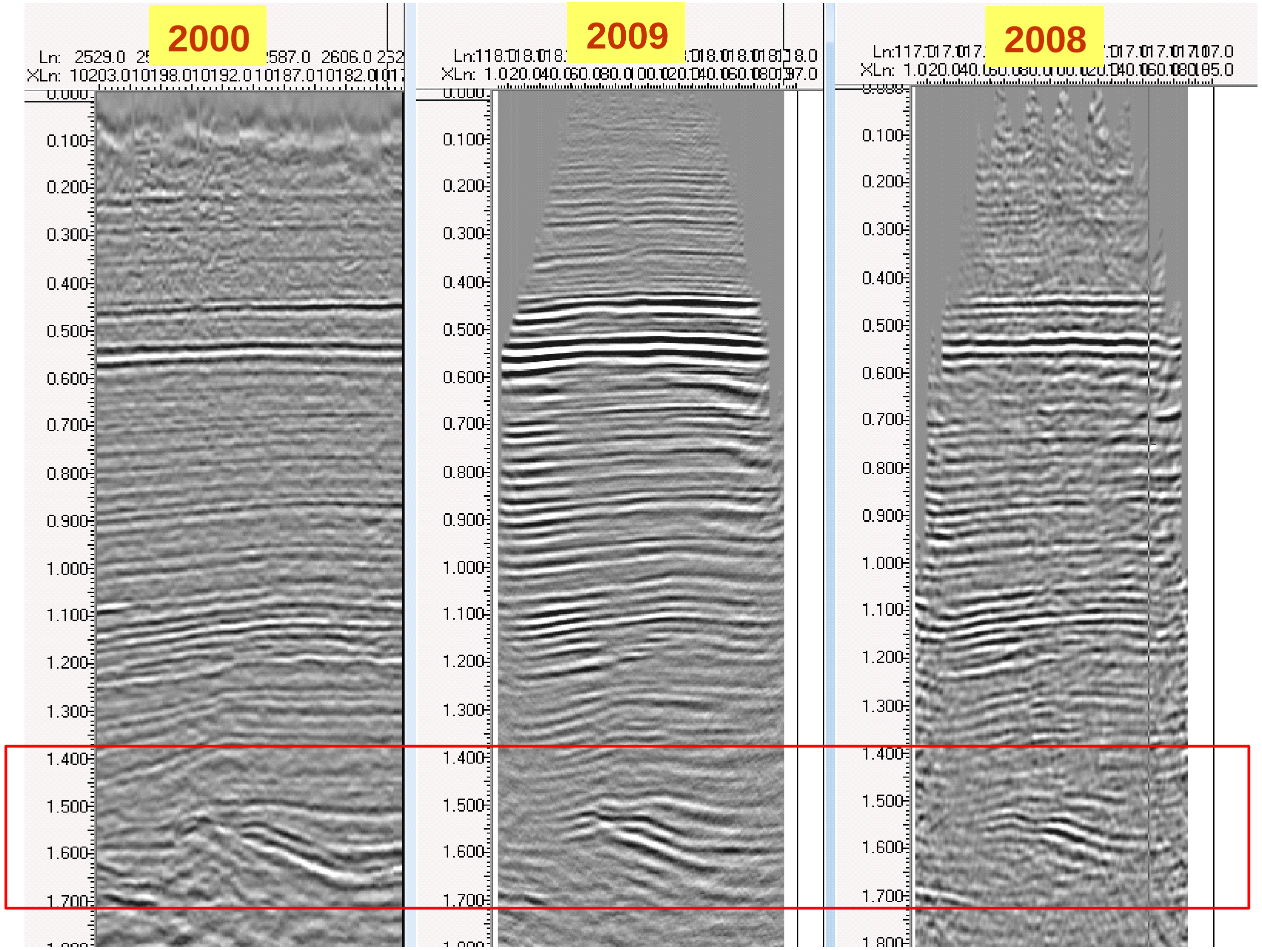
Source

Near-Surface Condition

Time-lapse 3D data using different sources

3D surface seismic (extract) from 2000 to 2009

Pre-production **Post-injection** **Pre-injection**

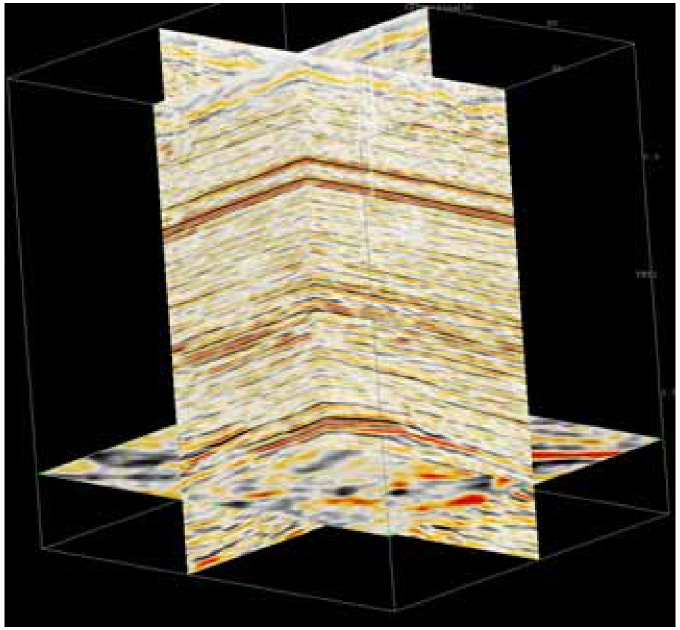


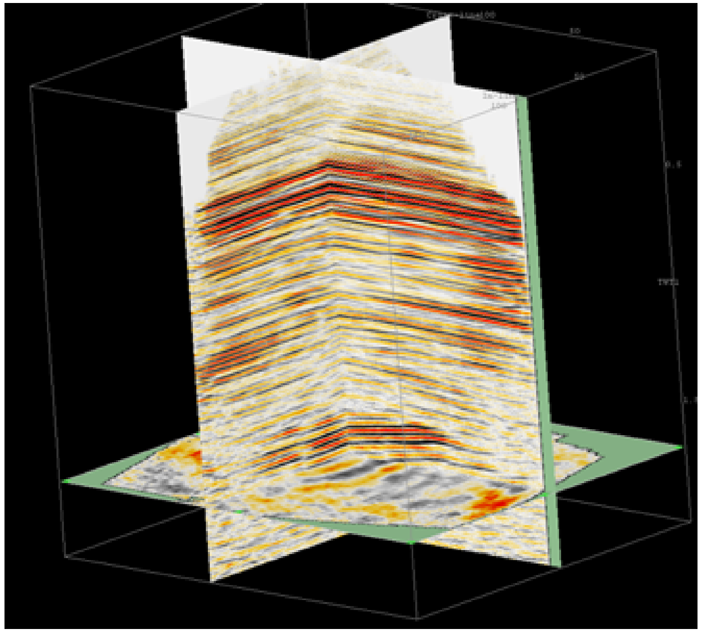
Big Vib; 3*60 Klb
Fold < 24

MB 9 Klb
Fold > 200

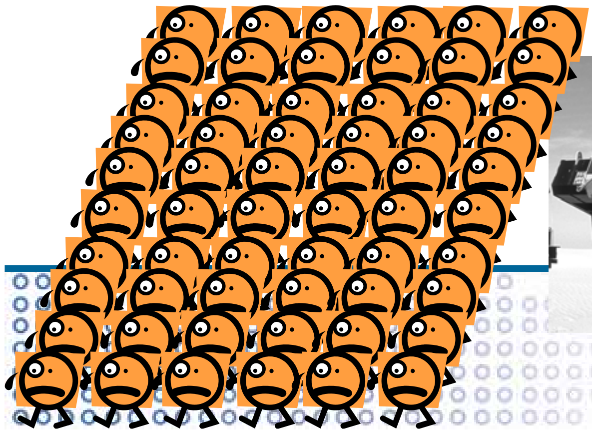
WD ~ 5 Klb
Fold > 100

Big vs Small source





Crew size



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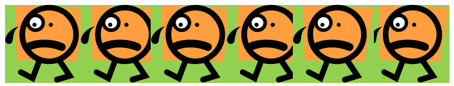
Crew size



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Factors affecting TL seismic repeatability

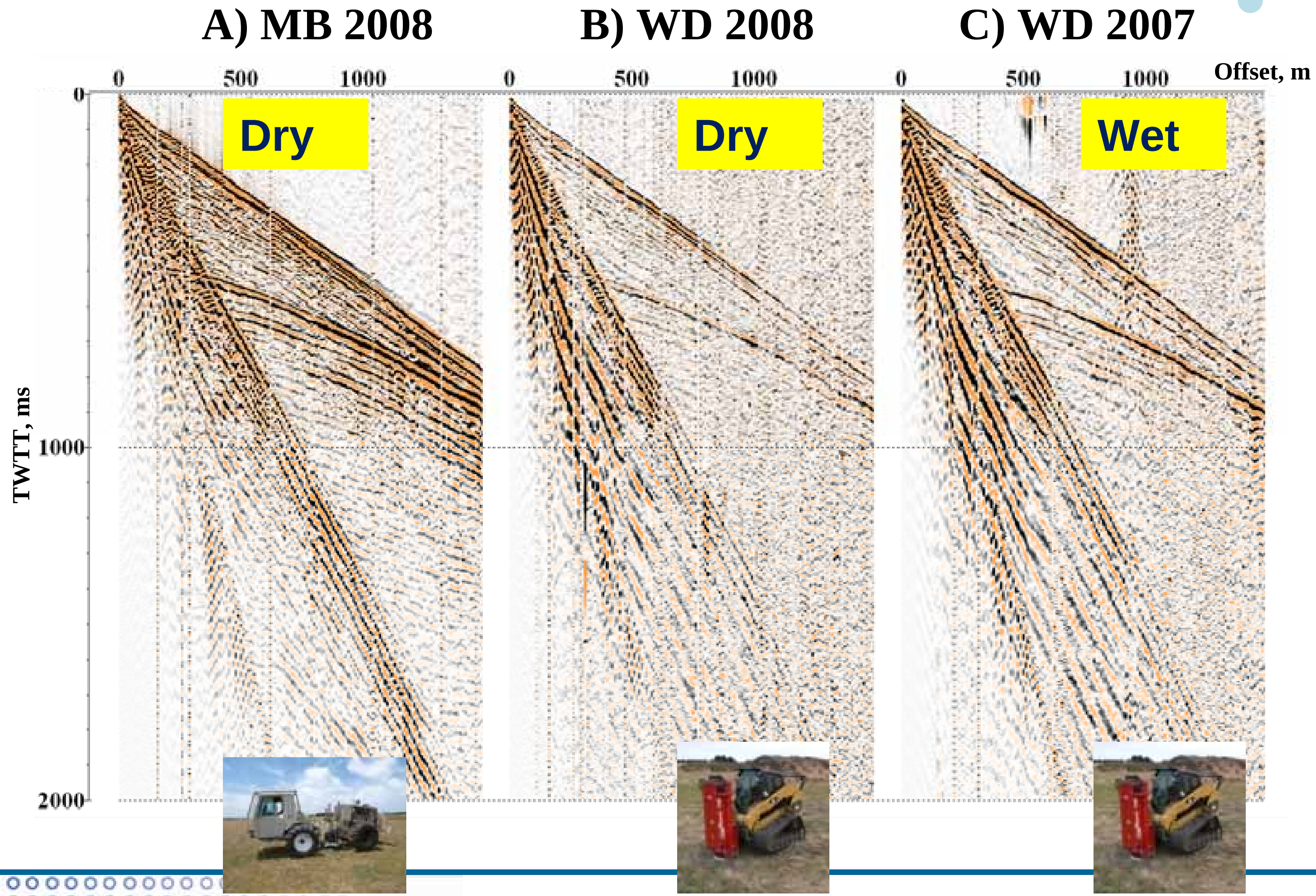
- Positioning
- Non-repeatable, ambient noise
- Changes in source/receiver coupling
- Changes in near surface conditions
- Processing approach (cross-equalisation)

Pre-base line 2D test surveys

	Test1	Test2	Test3
Source Type	Weight Drop	Weight Drop	Mini Buggy
Date	June, 2007	November, 2008	November, 2008
Weather condition	Wet	Dry	Dry
Total Number of Source positions	158	155	155
Total Number of Receivers	162	156	159
Source/Receiver Point Spacing, m	10/10	10/10	10/10
Number of Channels	162	156	159
Offset range, m	5-1605	5-1545	5-1545
Reference Character	WD 2007	WD 2008	MB 2008

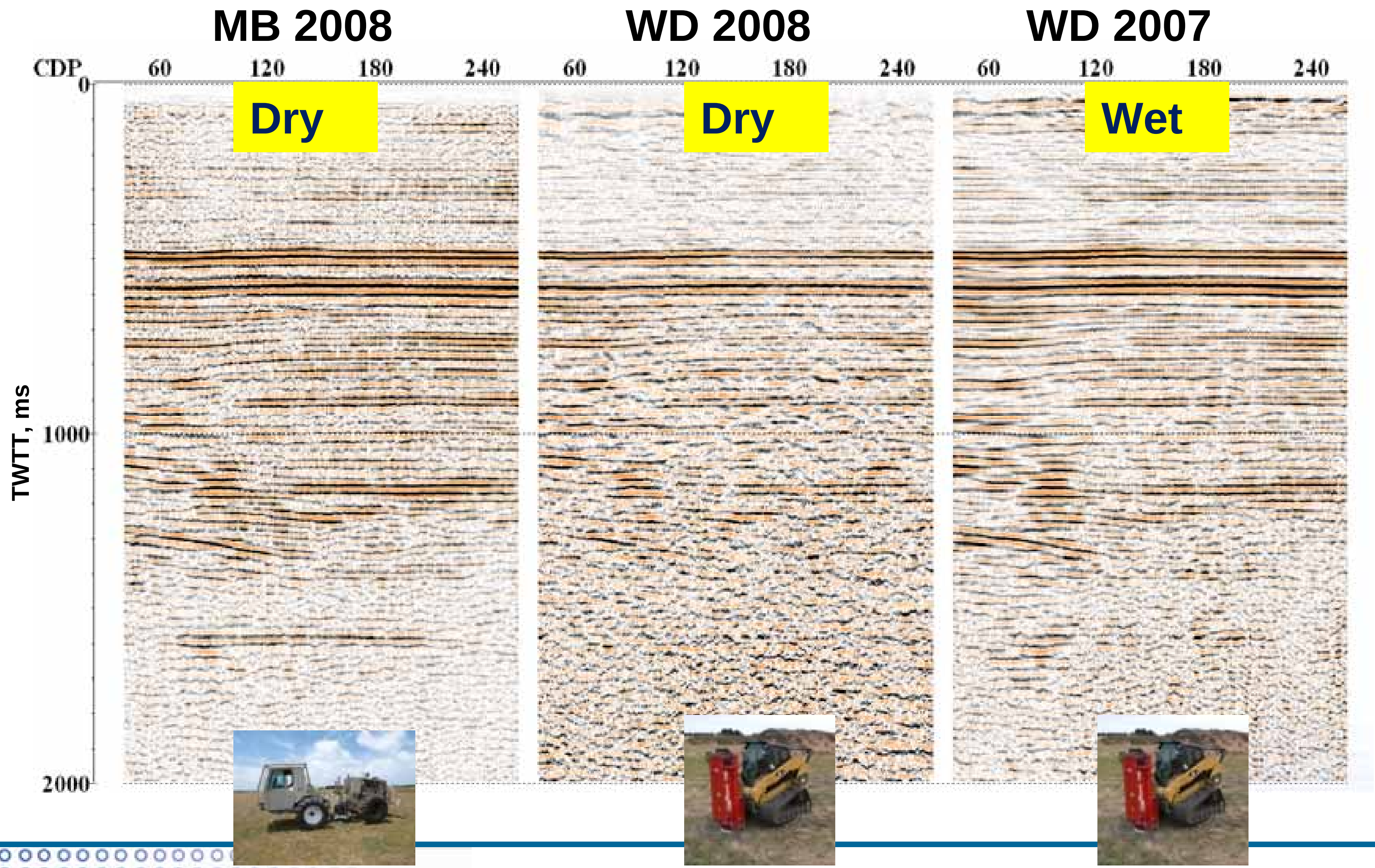
2D repeatability tests – soil saturation and source type

Raw data (Soda's Rd)



2D repeatability tests – soil saturation and source type

Cross-equalized 2D stacked sections (Soda's Rd)



Repeatability of TL seismic surveys: NRMS and S/N

$$NRMS = 200\% \frac{RMS(a-b)}{RMS(a)+RMS(b)}$$

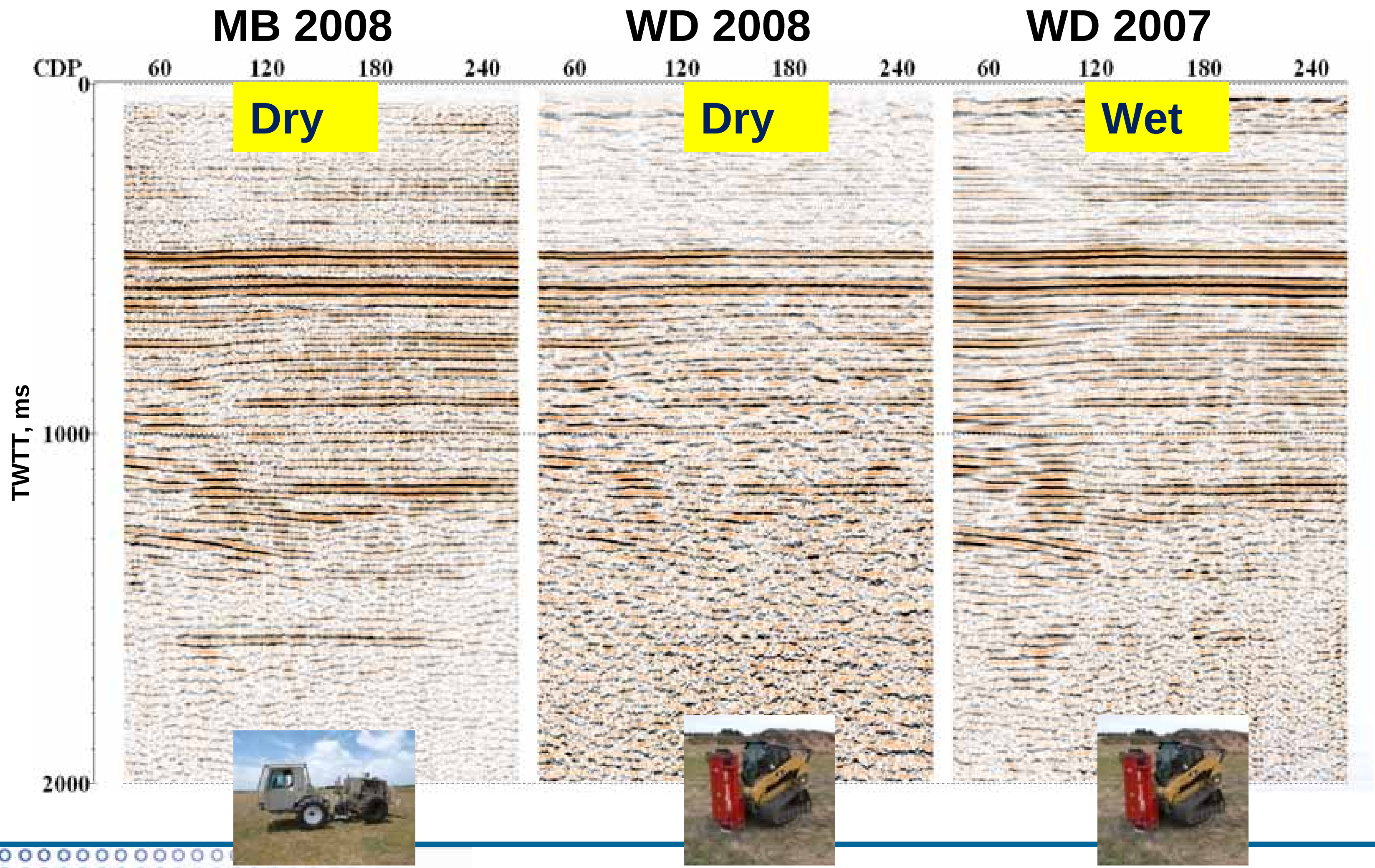
where *a* and *b* are two surveys being compared [Kragh and Christie, 2002]

$$SN_i = \sqrt{\frac{[g_{i,i+1}]_{MAX}}{1-[g_{i,i+1}]_{MAX}}}$$

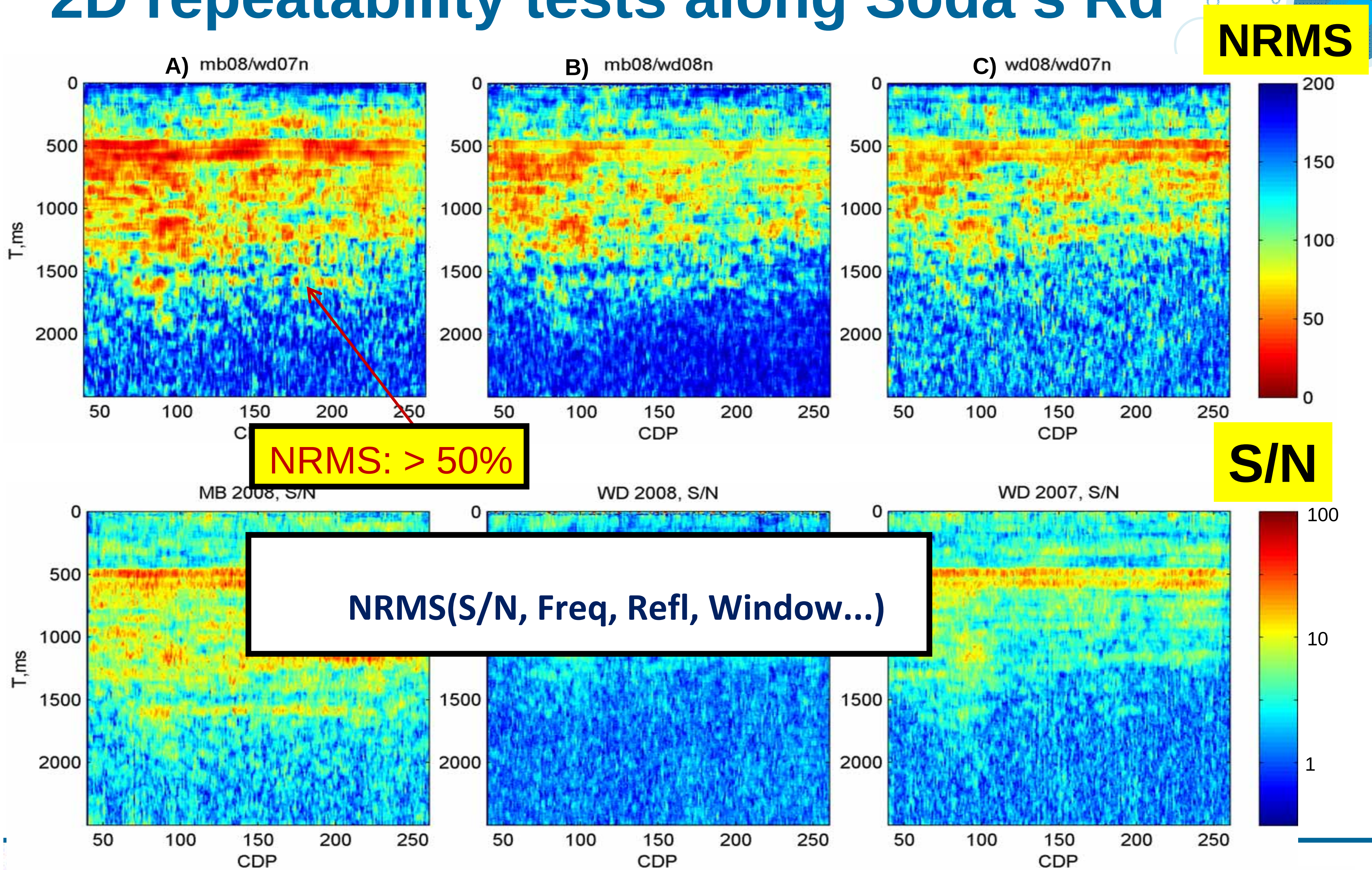
where *i* is trace number, $g_{i,i+1}$ is normalized cross-correlation function between *i* and *i+1* traces and $[g_{i,i+1}]_{MAX}$ is its maximum value

2D repeatability tests – soil saturation and source type

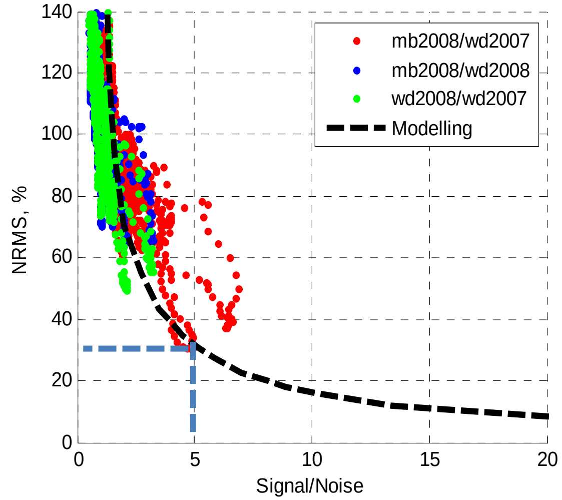
Cross-equalized 2D stacked sections (Soda's Rd)

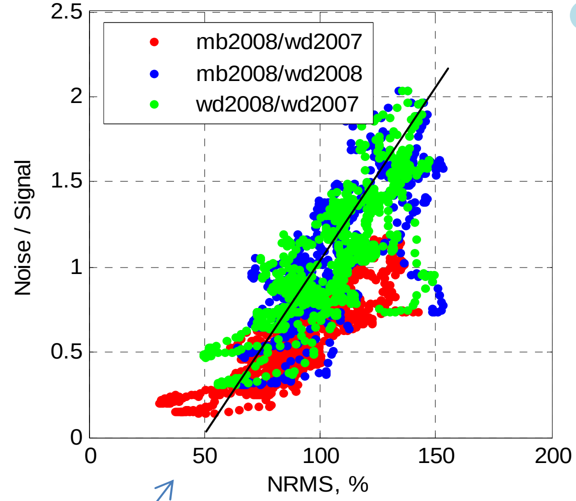


2D repeatability tests along Soda's Rd

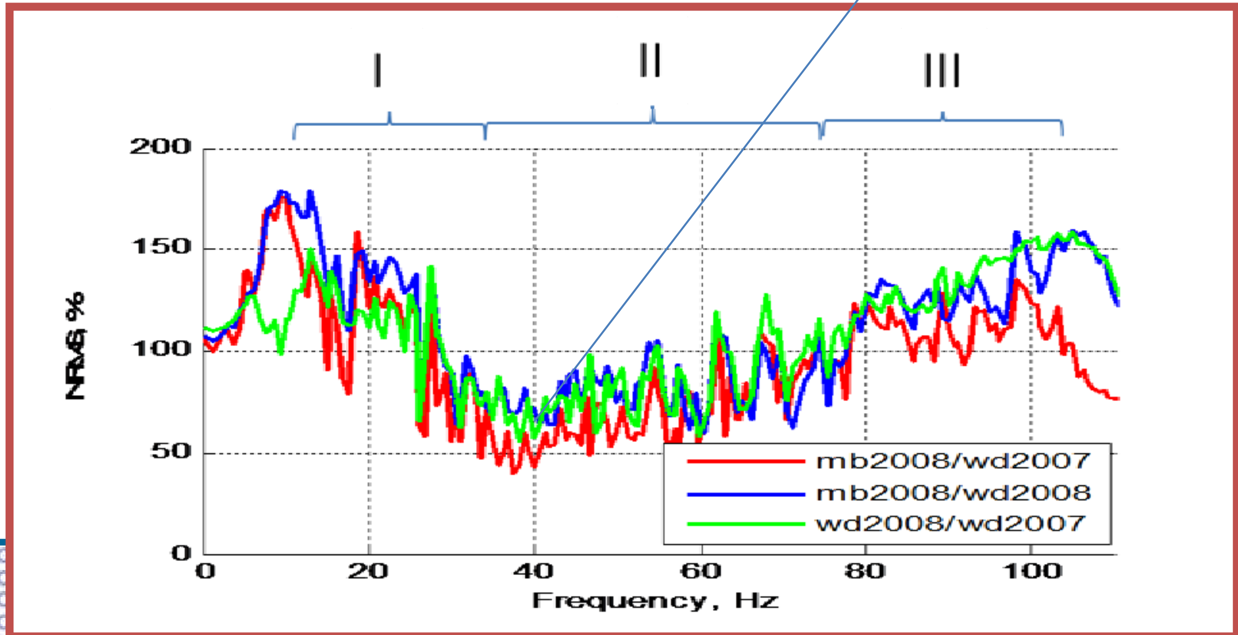


What is non-repeatability?





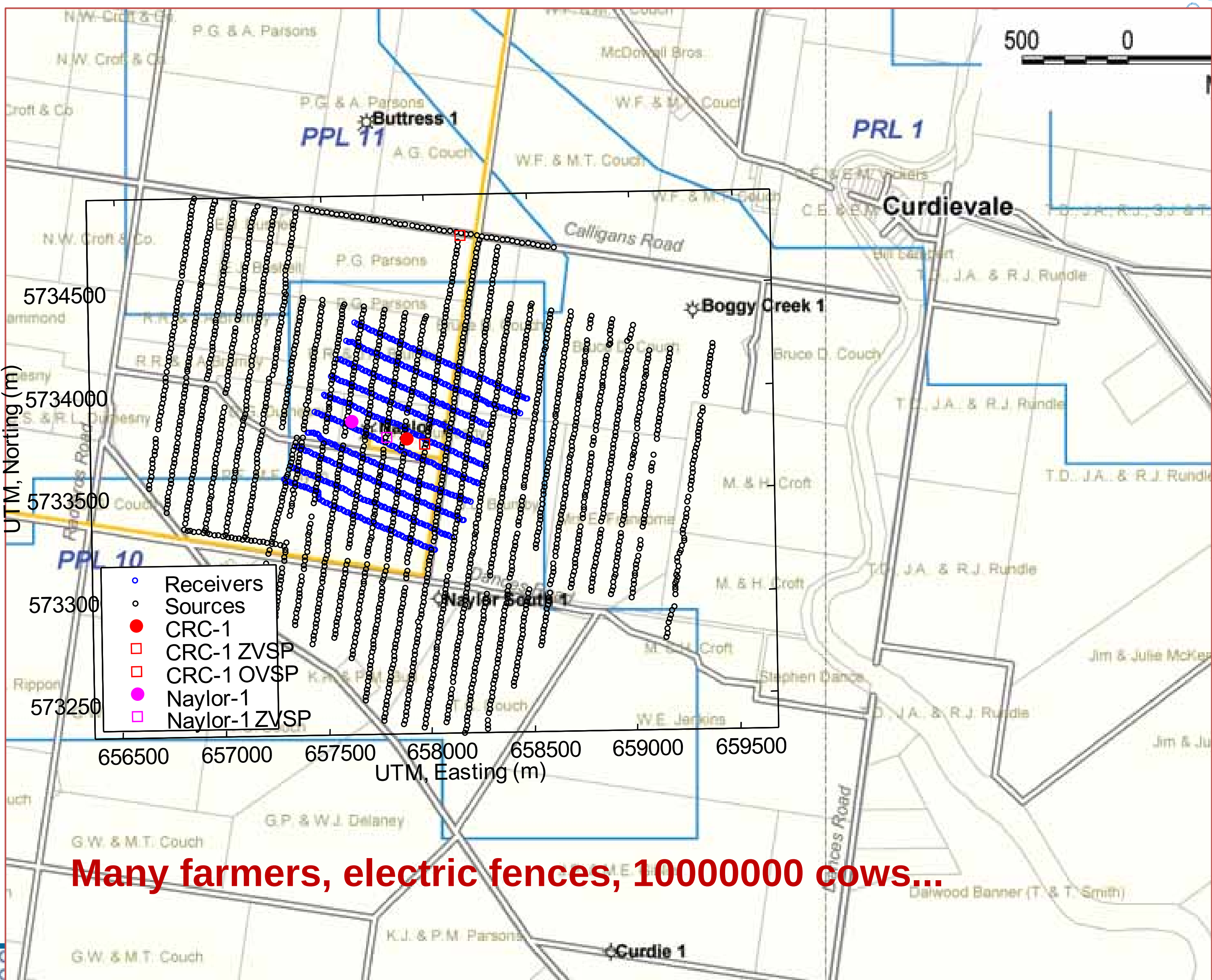
Spectral difference



2D

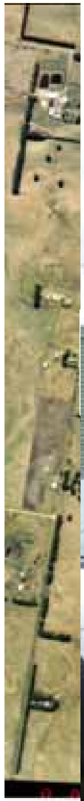
Seismic monitoring – Final program

- **Time lapse 3D surface seismic**
  - Least sensitive and repeatable but provides coverage of entire reservoir and beyond
  - Necessary for 'assurance monitoring' to detect loss of primary containment
  - No 4D effect expected in general
- **Time lapse borehole seismic**
  - CRC-1: 3DVSP with 3C geophones (Schlumberger's VSI)
    - Improved sensitivity and resolution relative to surface data, improved repeatability
    - More chance for direct CO_2 monitoring, limited coverage
  - Naylor-1: Permanent downhole sensors (LBNL)
    - Potentially most sensitive and repeatable



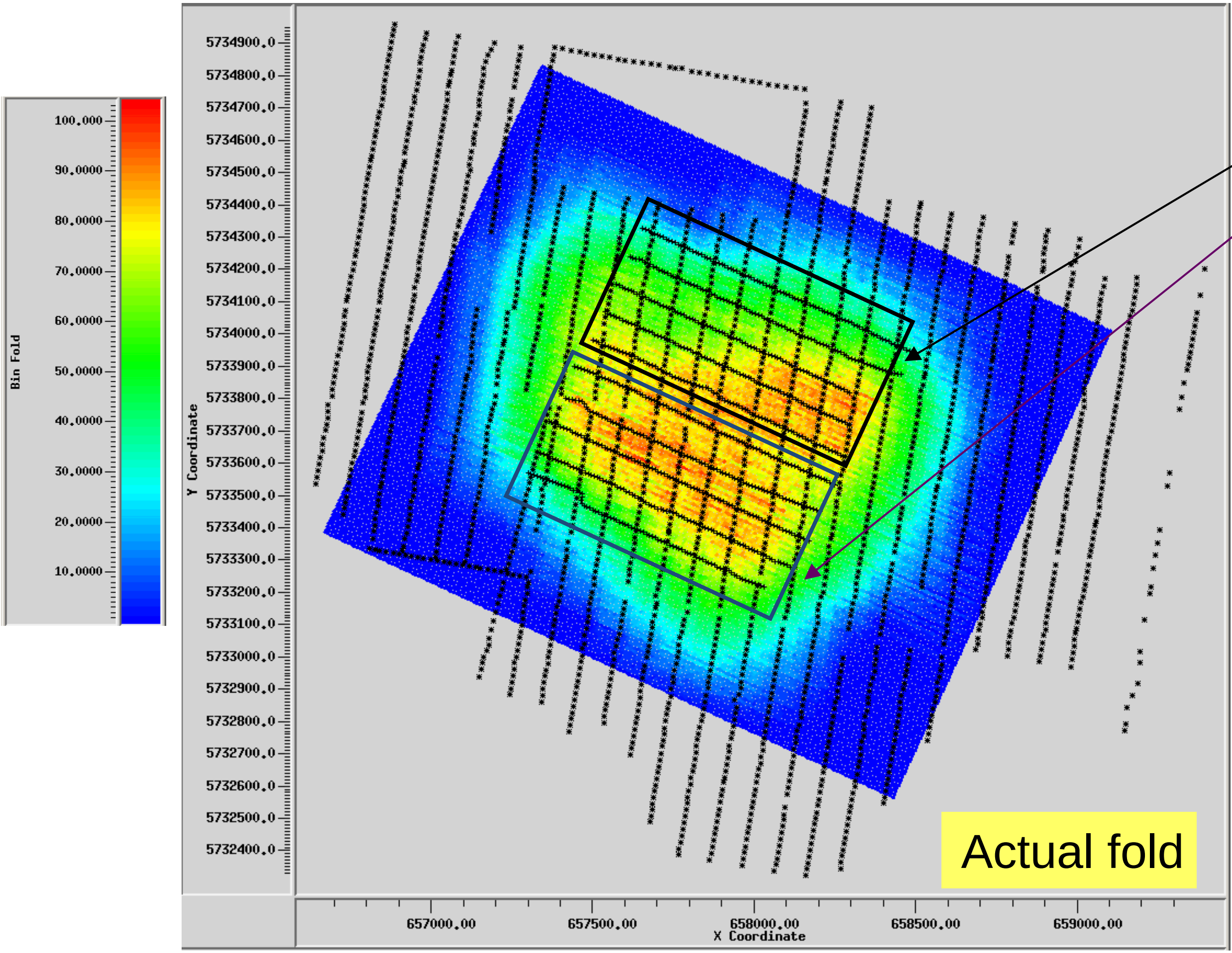
Many farmers, electric fences, 10000000 cows...

3D surface, VSP and GPS crew (2010)



- 750 kg,
m – 2008
-vibe 2009

TL - 3D surface seismic acquisition geometry



2008 Receiver lines 1-5 activ
for odd shot lines,
receiver lines 6-10 active
for even shot lines
440 active geophones

2009 we had 880 channels
active at all times
Double the fold + much
stronger source than WD

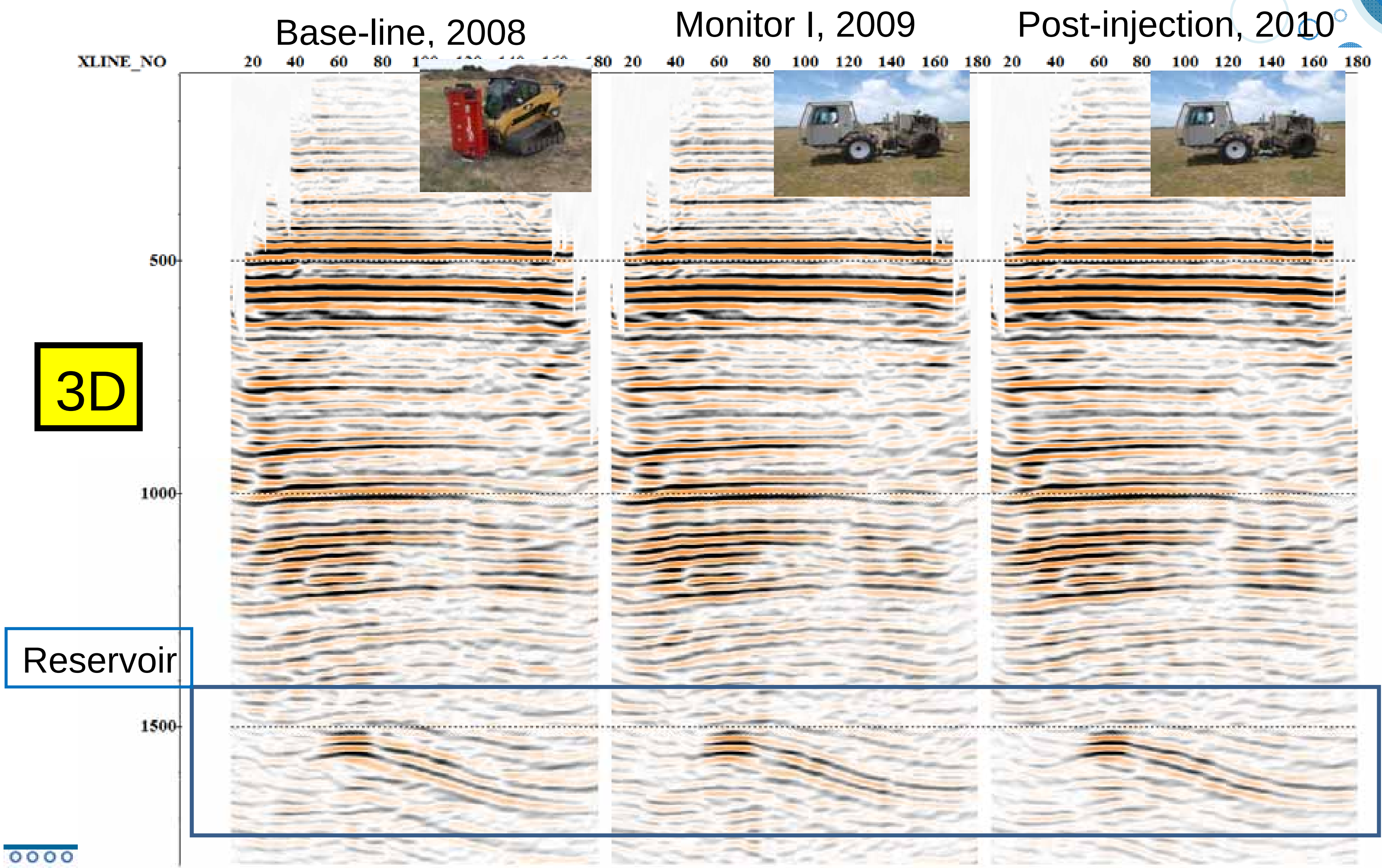
3D VSP acquired simultaneously


Sumer in Warrnambool....

Basic 3D processing flow-chart

- Data input and correlation for 2009
- Data equivalence and binning (bin size 10x10m)
- Elevation statics (30 m, 1800 m/s)
- Trace Editing
- Bandpass filtering (7-10-150-160 Hz)
- Spike and Burst Noise Attenuation
- Automatic gain control (500 ms, applied before deconvolution and removed after)
- Spiking Deconvolution (minimum phase for 2008 and zero-phase for 2009)
- Velocity Analysis (two iterations)
- Residual Static Correction
- Radon filter in cone window (AGC 500ms applied before and remove after)
- FX deconvolution before stack
- Normal Moveout Correction
- CDP stack
- Post-processing (TV Whitening, FXY Deconvolution)
- Explicit FD 3D Time Migration

Key issue: Repeatability versus TL signal strength



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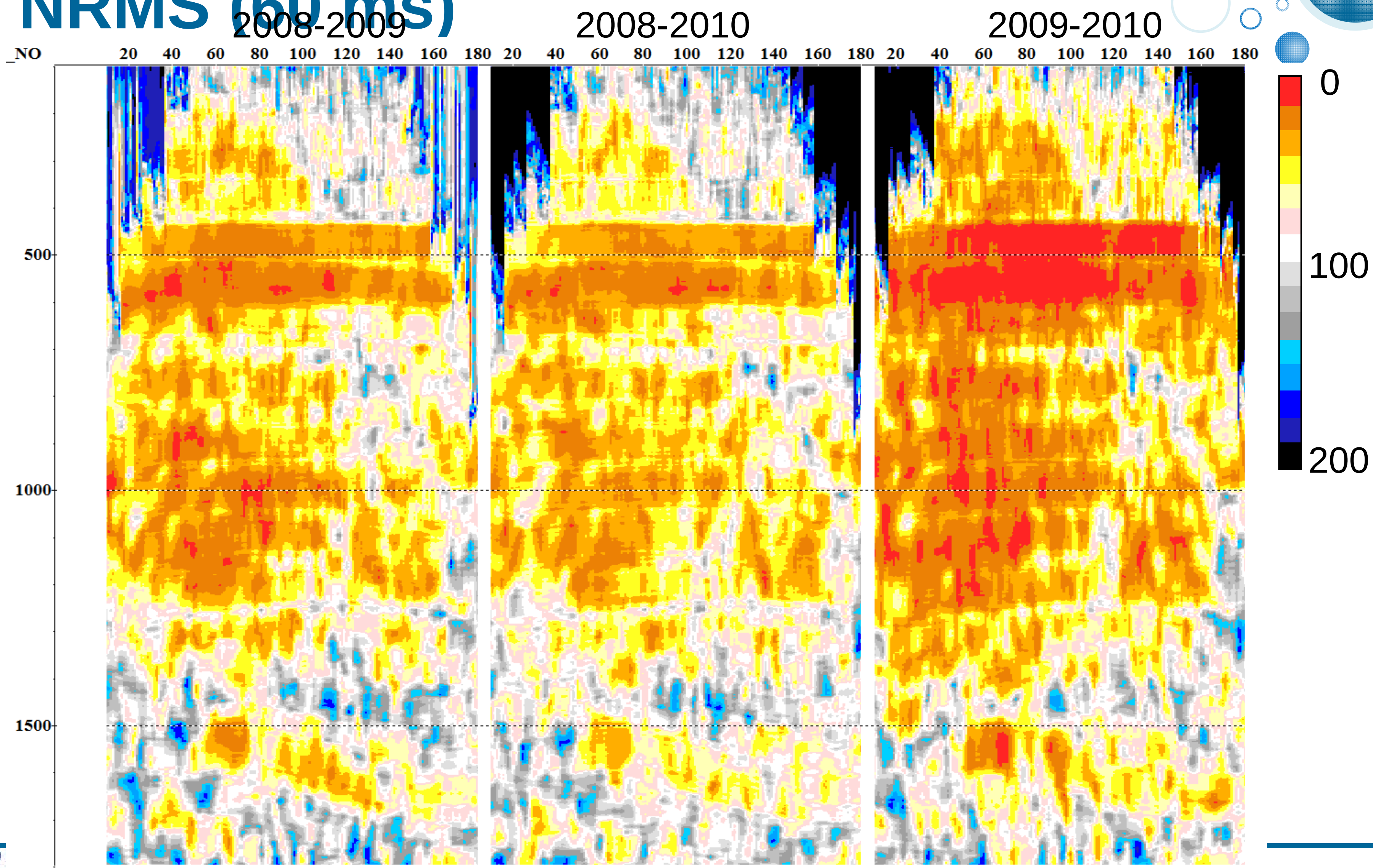
NRMS (60 ms)



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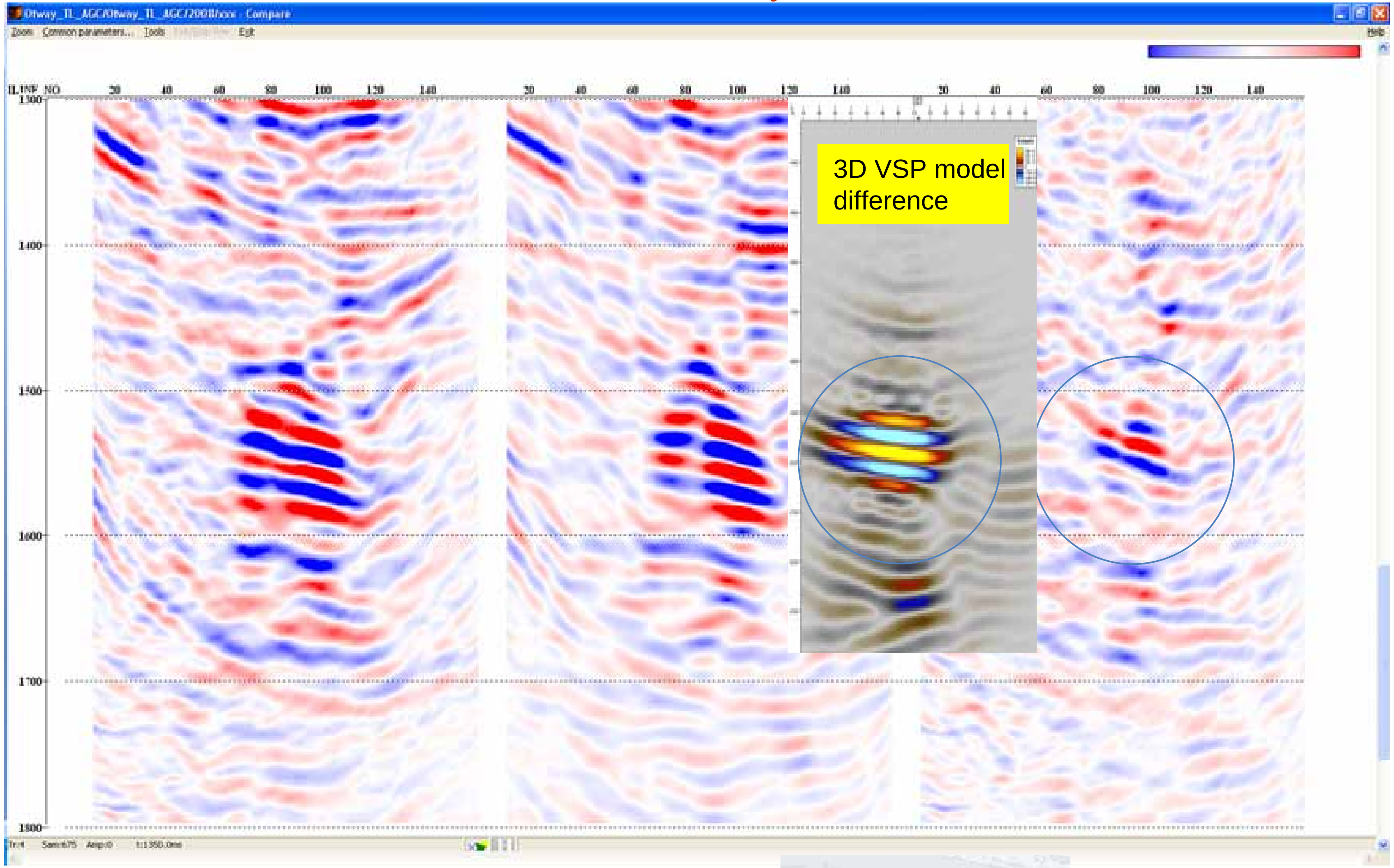
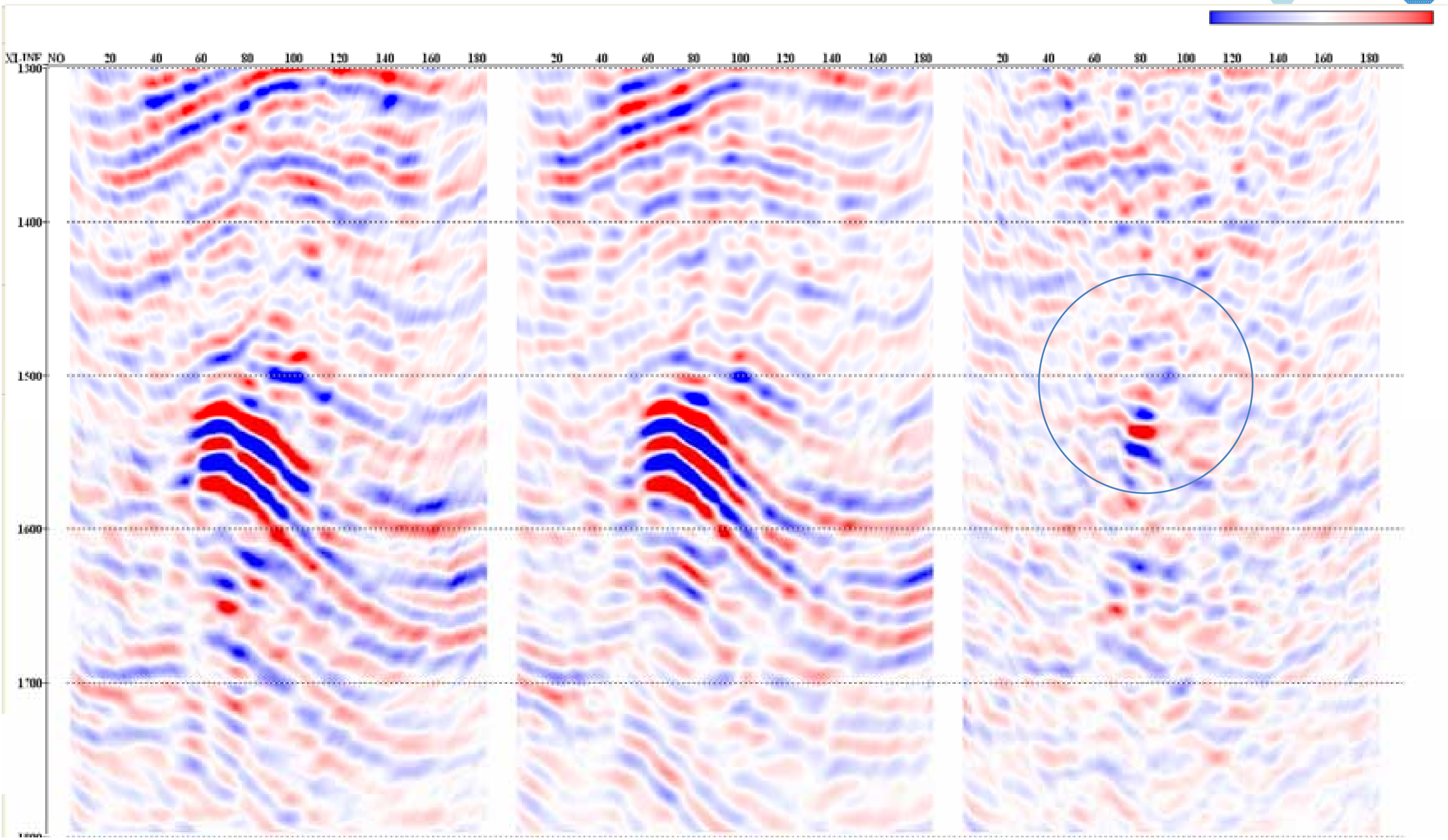
Difference 08-09, Xline 81

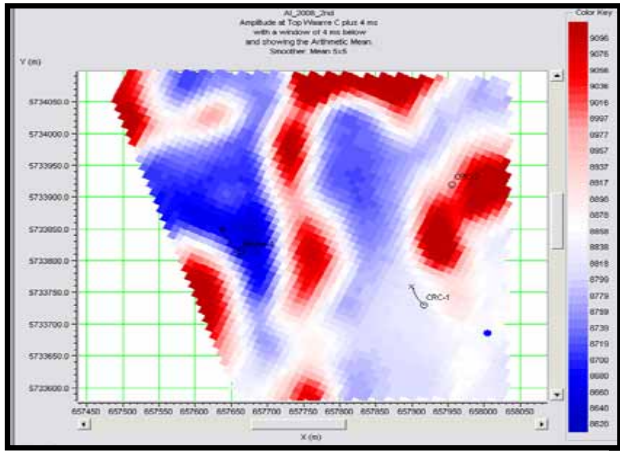


Initial 3D TL result: difference 08-09, first pass

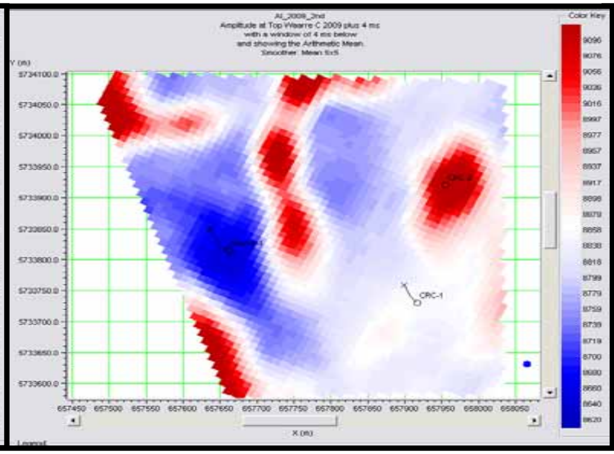


3D acoustic inversion

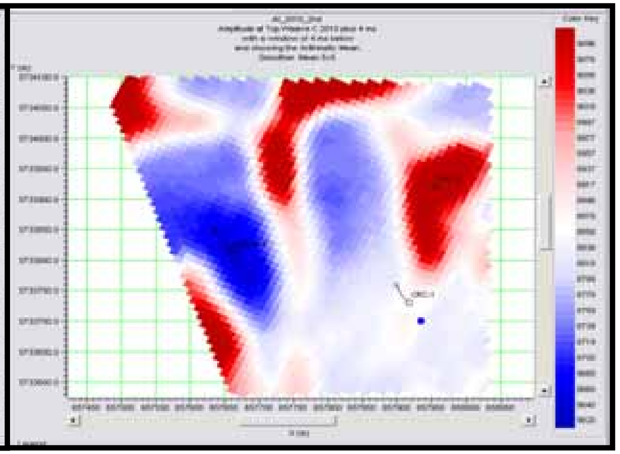
AI -2008



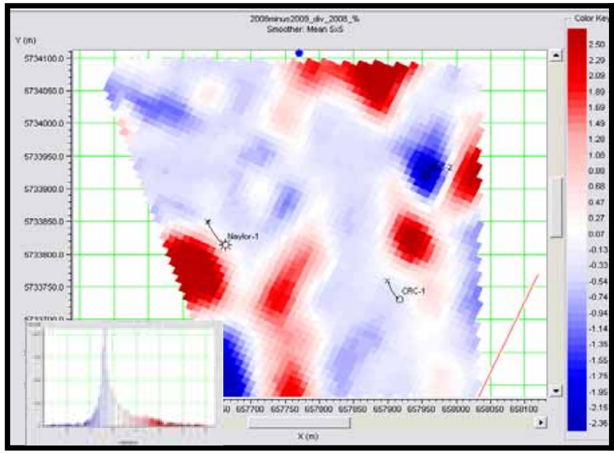
AI -2009



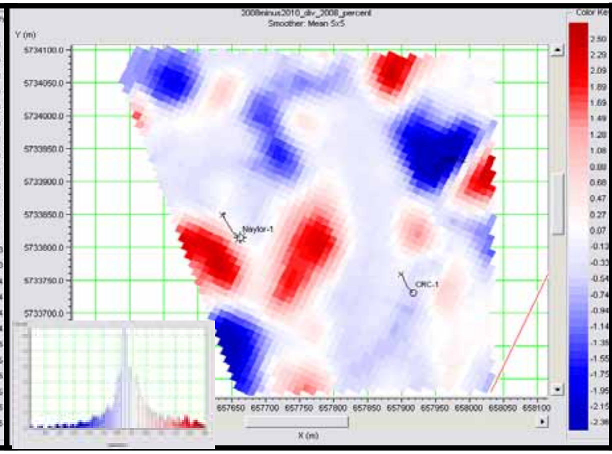
AI -2010



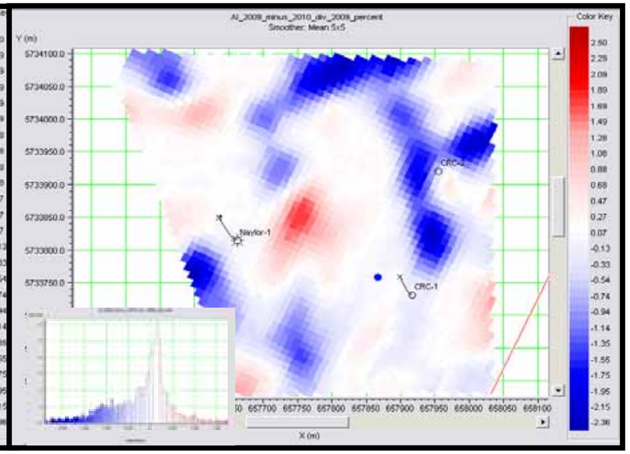
2008-2009



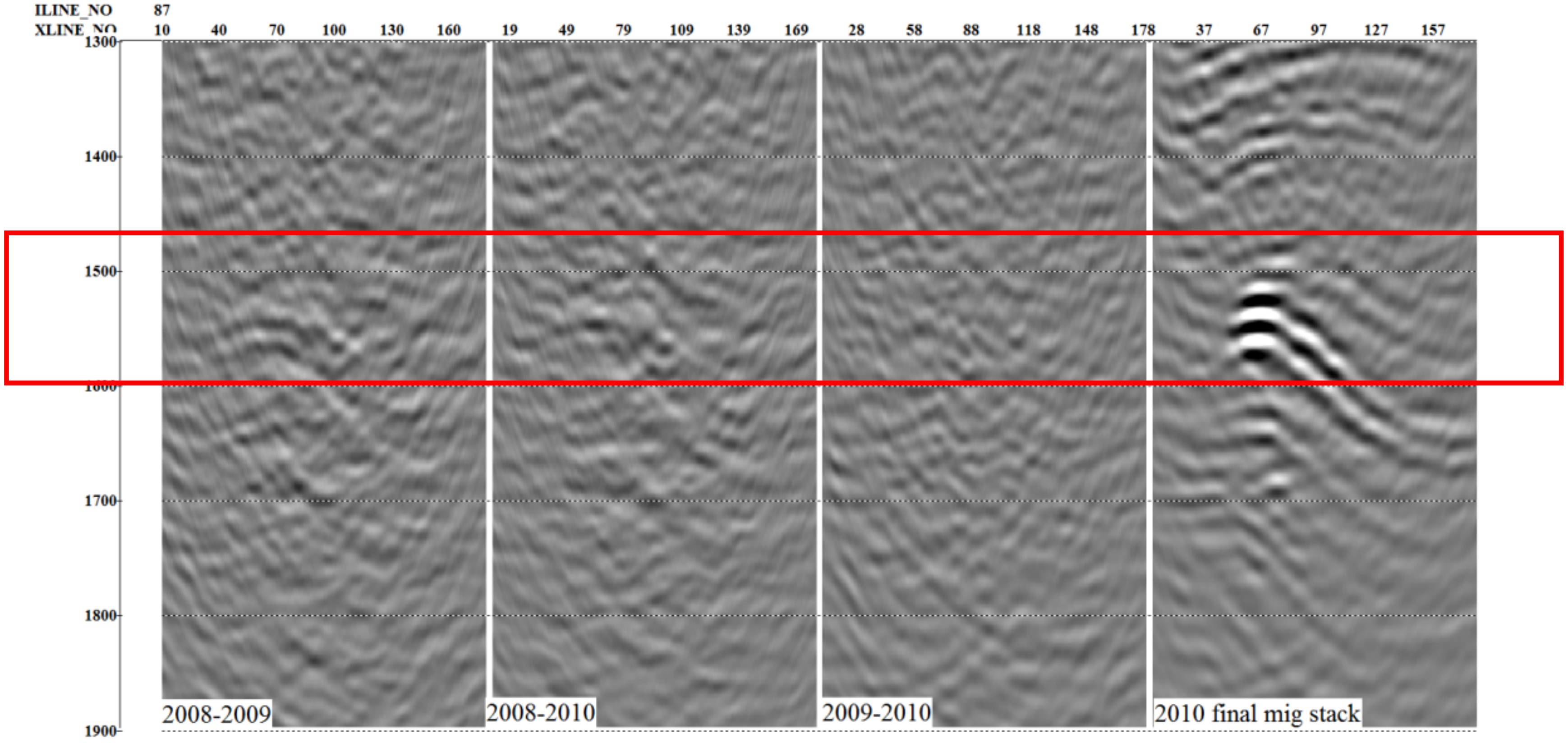
2008-2010



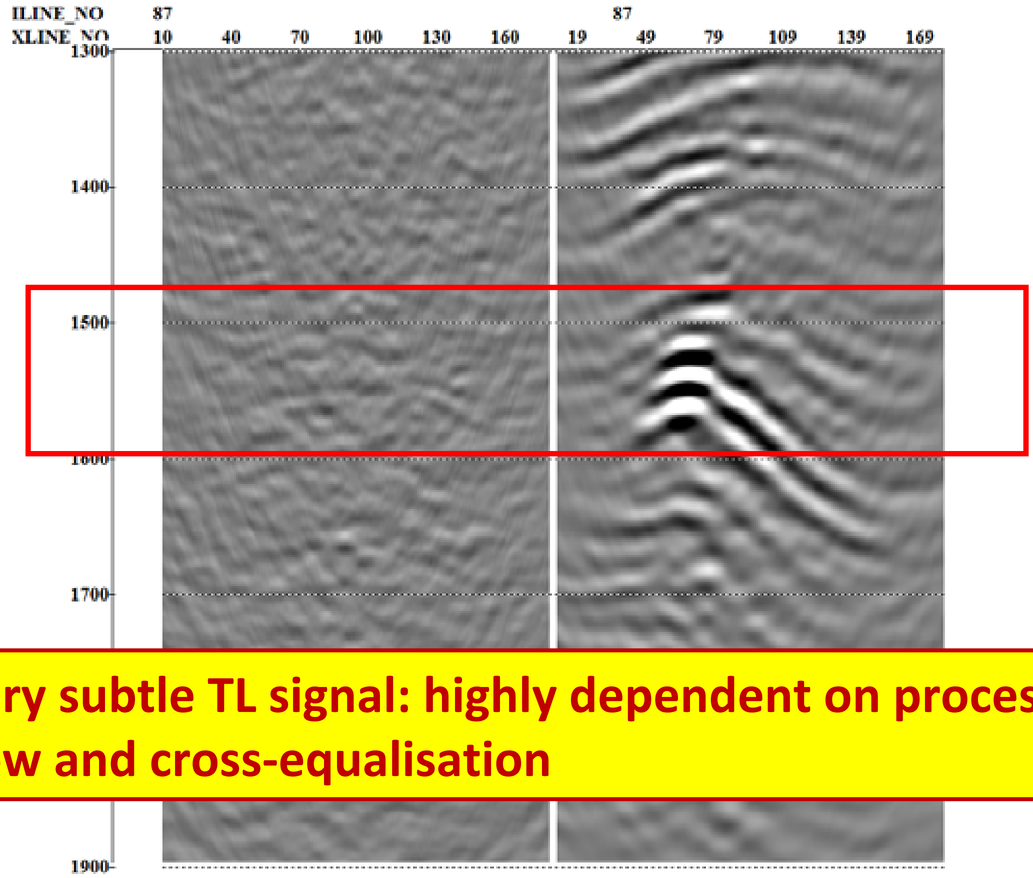
2009-2010



Difference volumes, reduced geometry

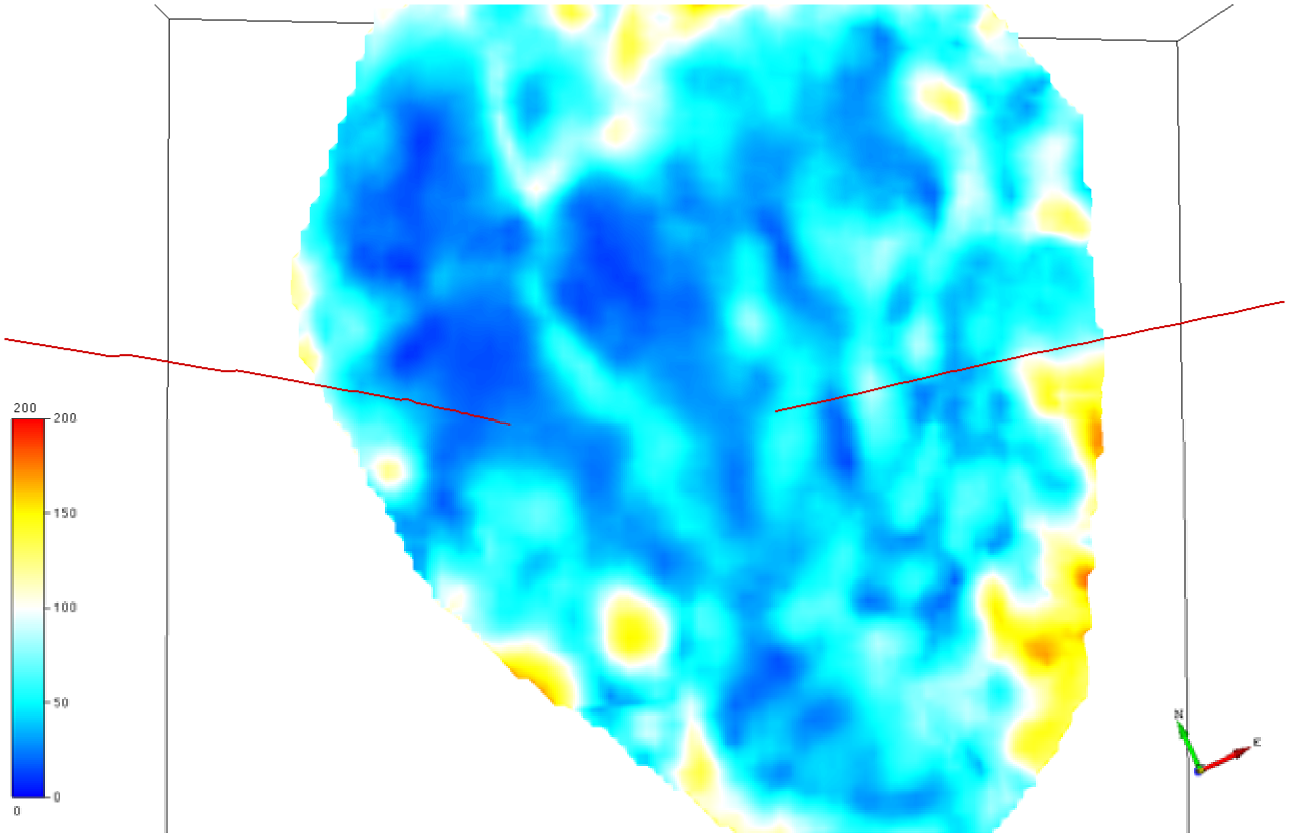


2010-2009, full geometry

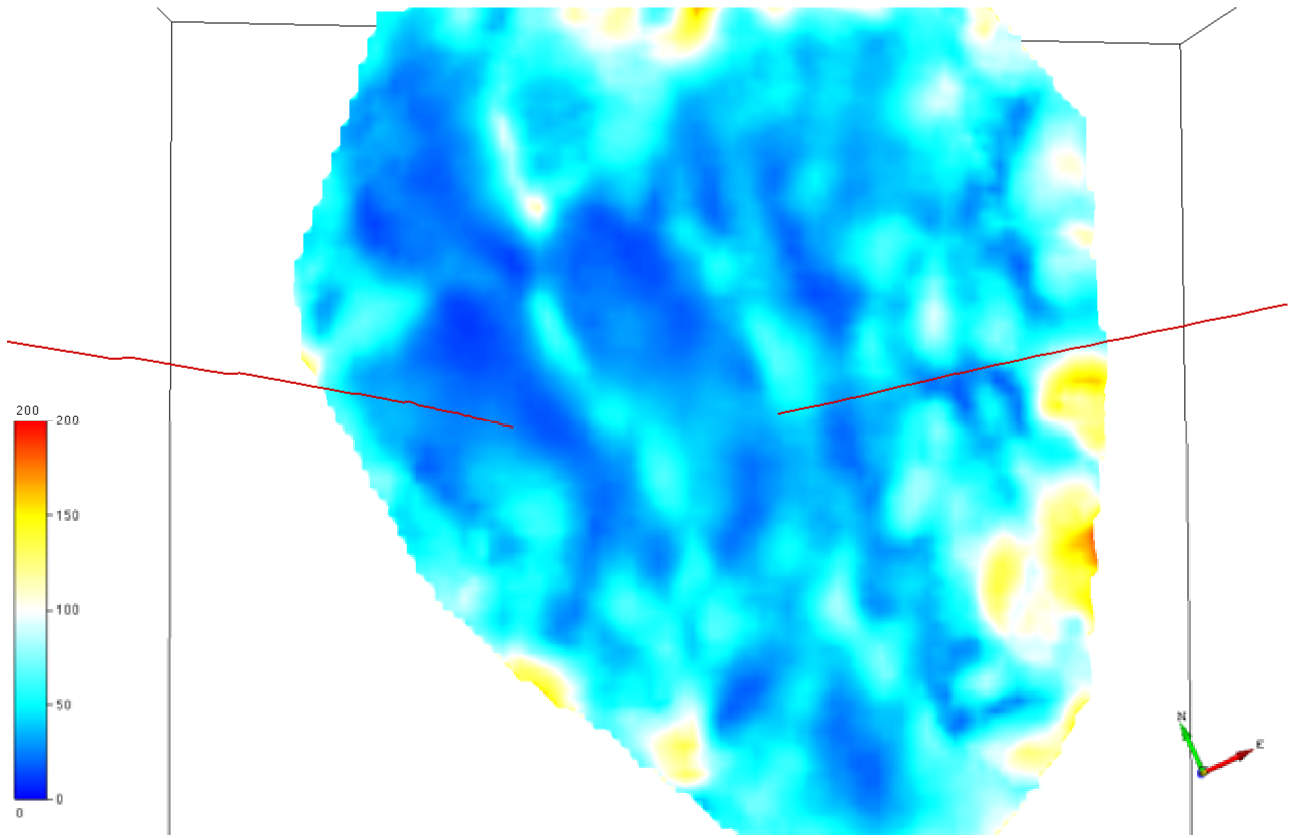


Very subtle TL signal: highly dependent on processing flow and cross-equalisation

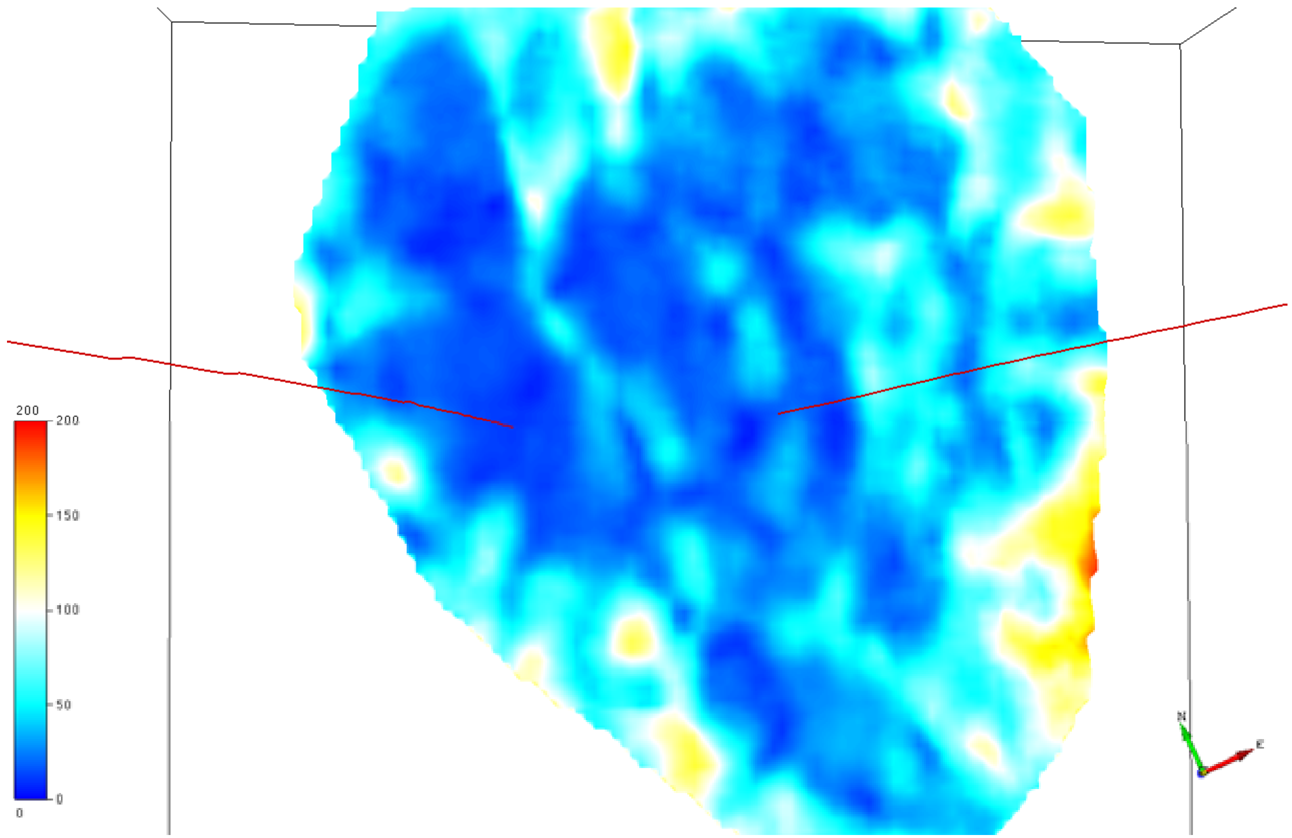
2009-2008, NRMS, 60 ms



2010-2008, NRMS, 60 ms

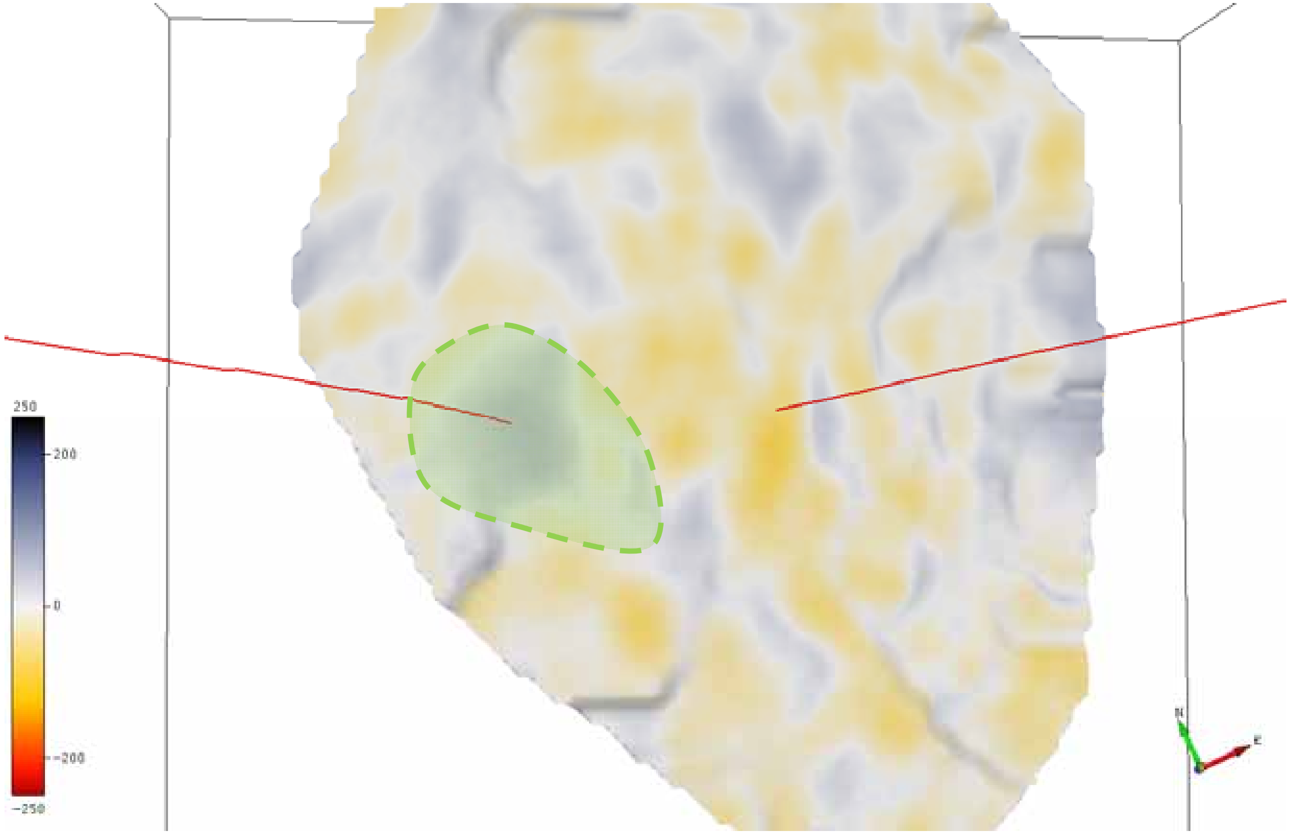


2010-2009, NRMS, 60 ms



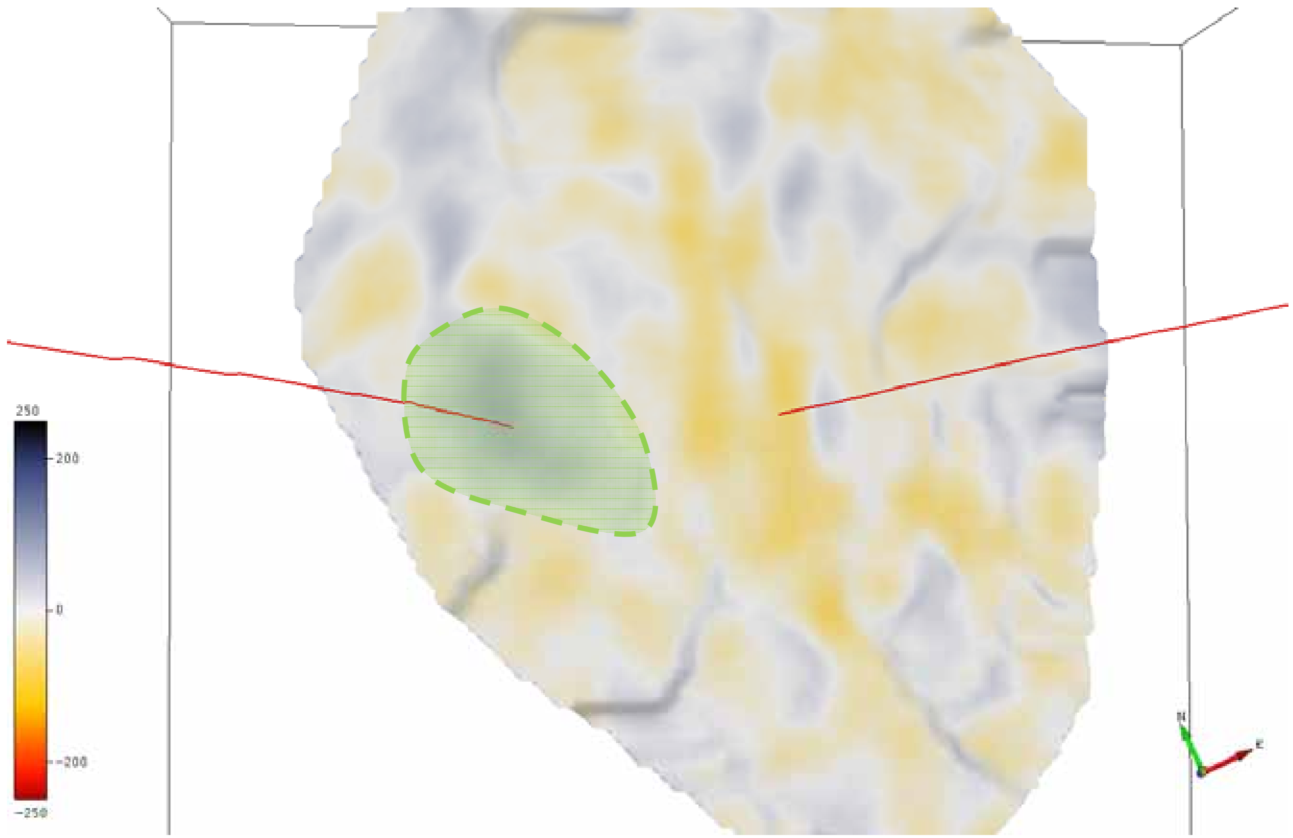
2009-2008

Small TL signal



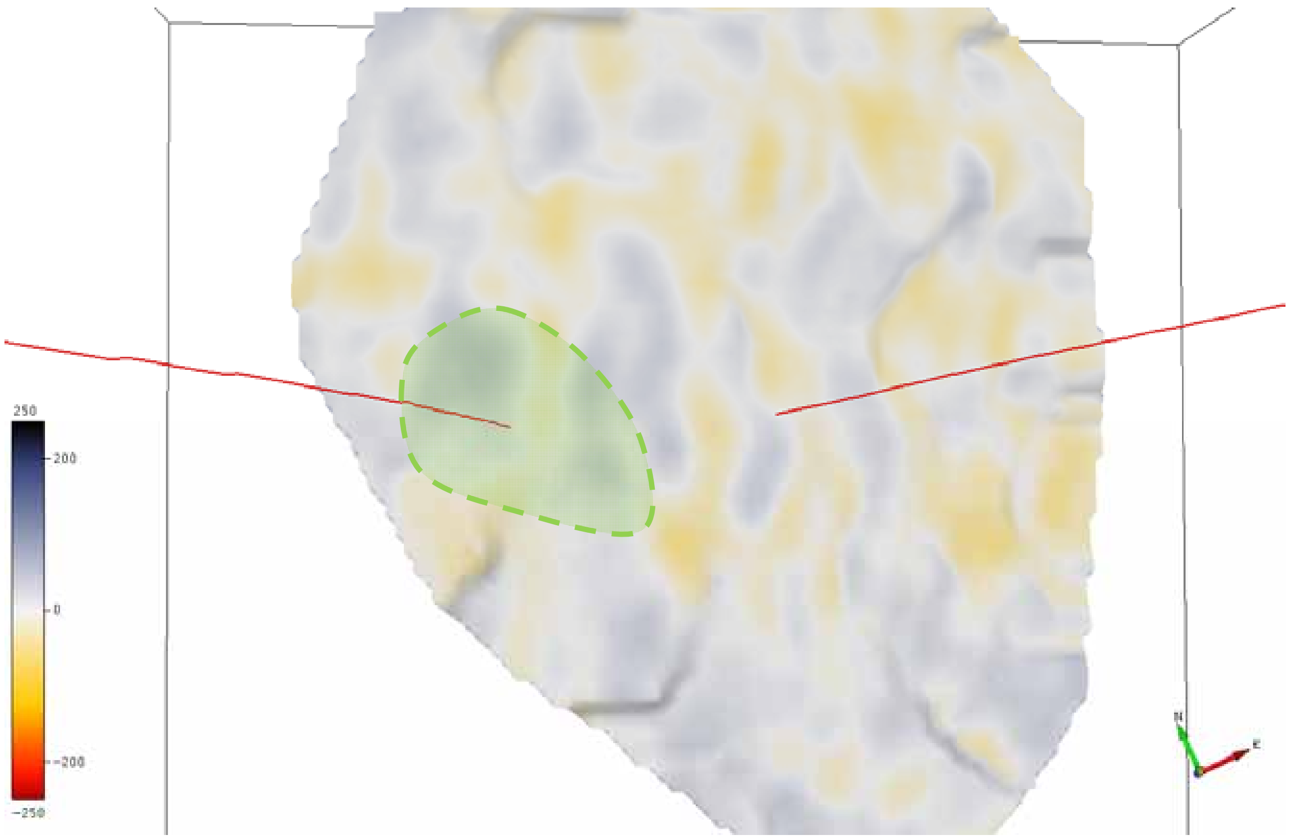
2010-2008

Small TL signal



2010-2009

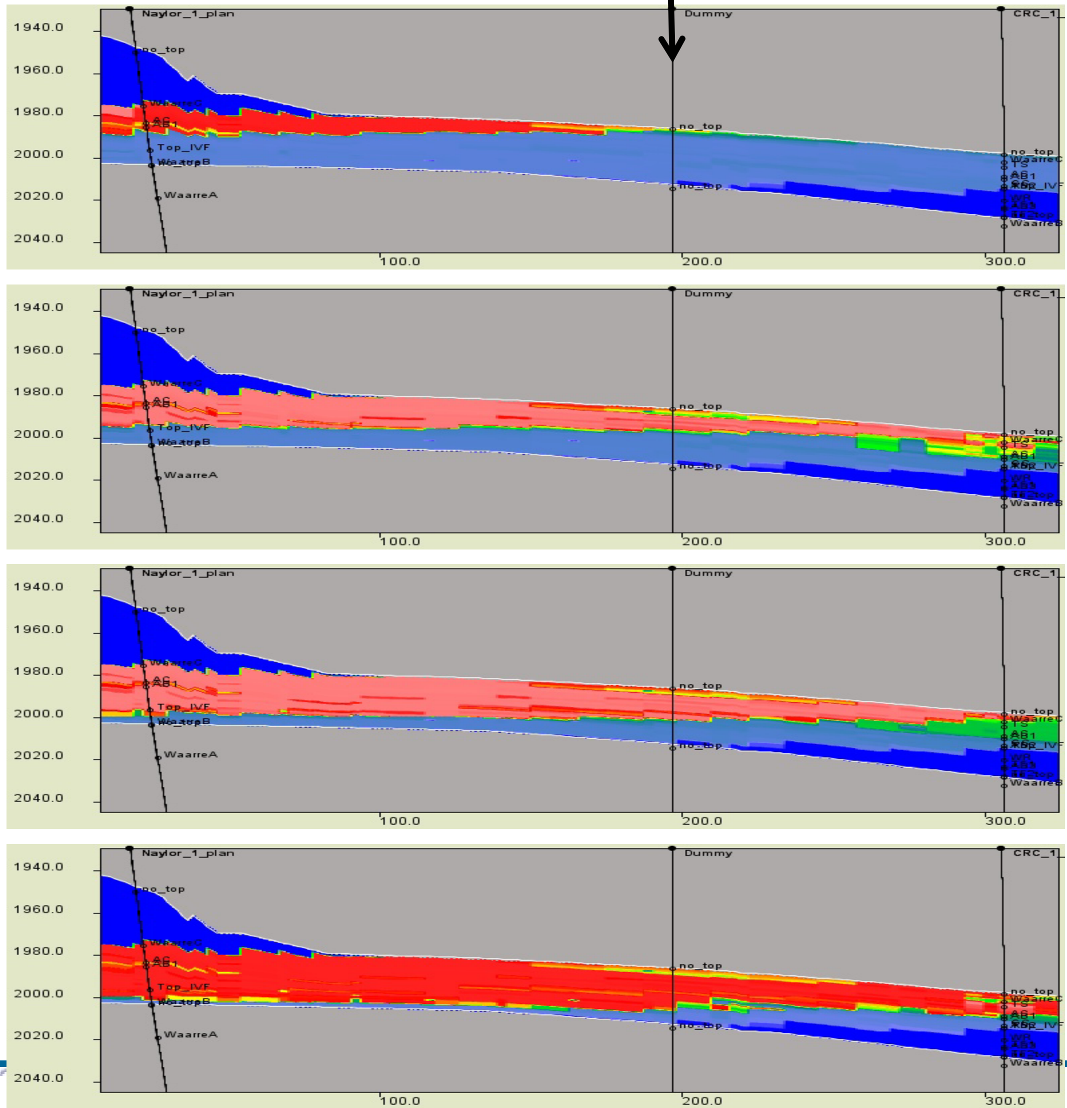
No TL signal



Extended Stage I injection simulation

Time of injection		Amount of CO_2/CH_4 injected
2008 Base line		0 Kt
2009		33 Kt
2010		65 Kt
2011		100 Kt

Naylor-1 Dummy well CRC-1

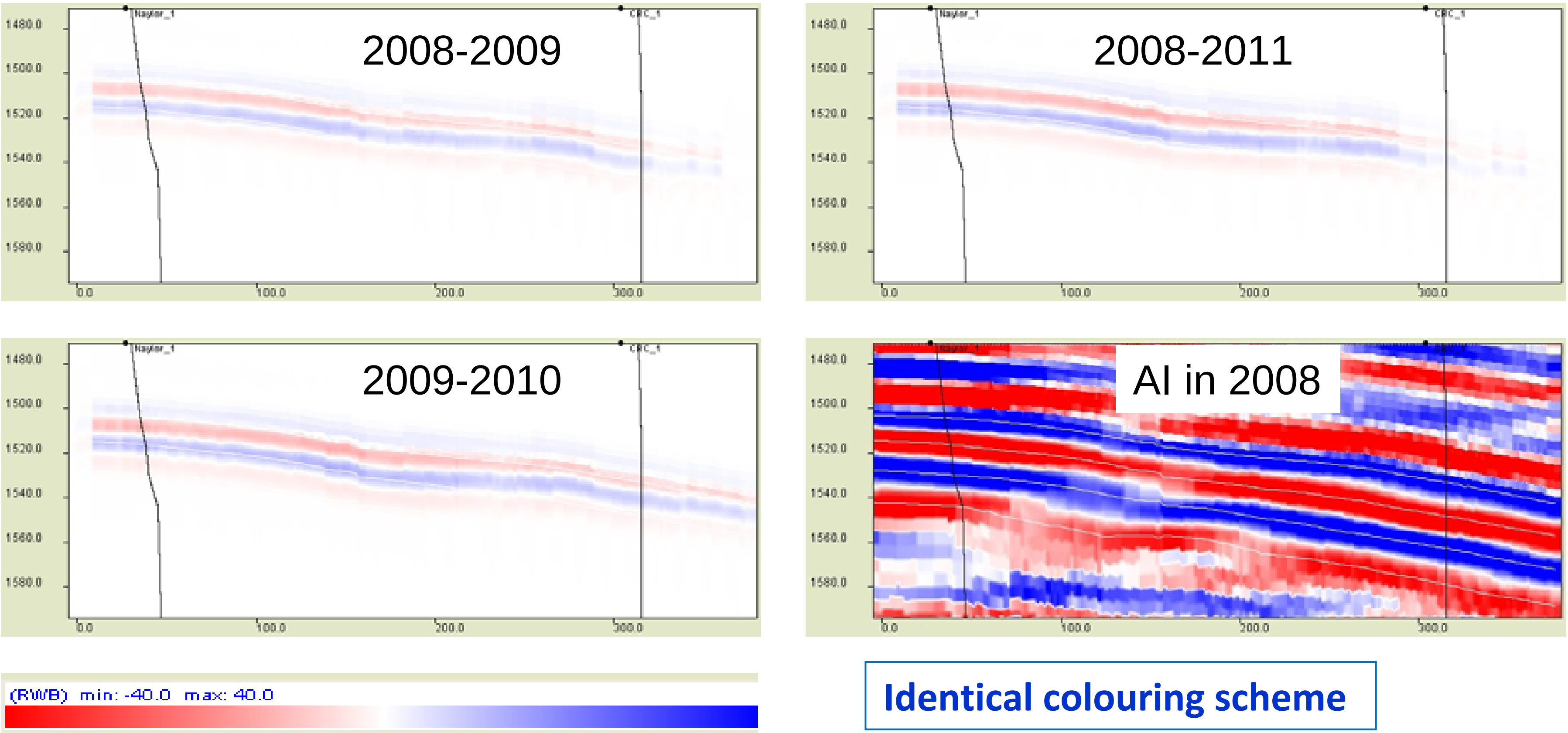


Saturation

0.0 Property) min: 0.0 max: 1.0 1.0

J. Ennis-King, 2010

Modelling of extended Stage I injection

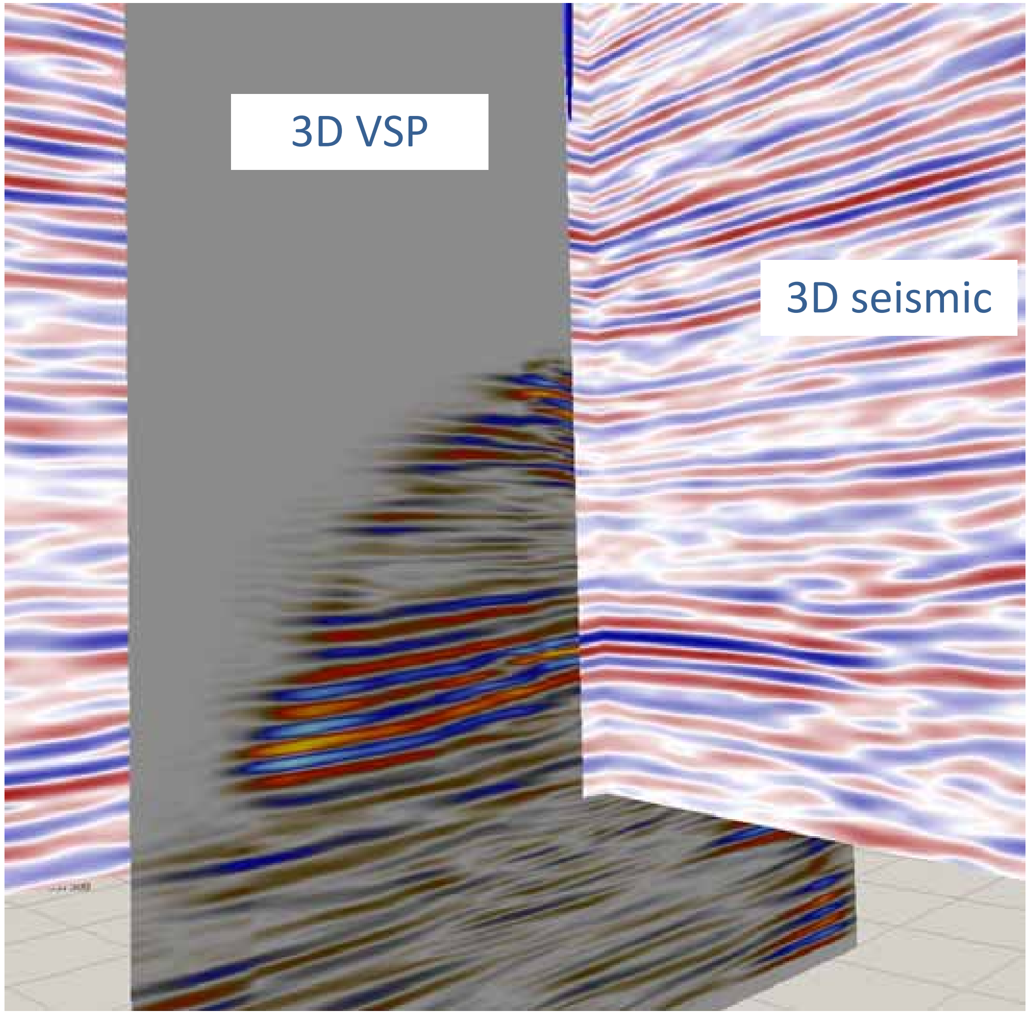


Identical colouring scheme

Curtin University CSIRO CO2CRC

Borehole seismic time-lapse studies

TL 3D VSP imaging

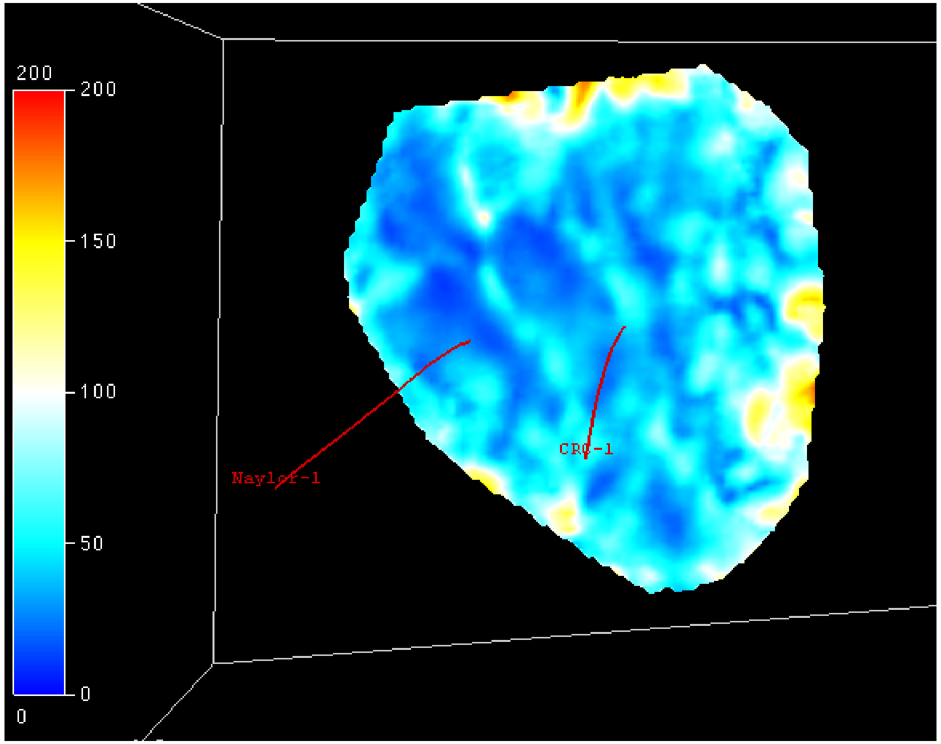


3D VSP inserted into surface seismic (baseline)

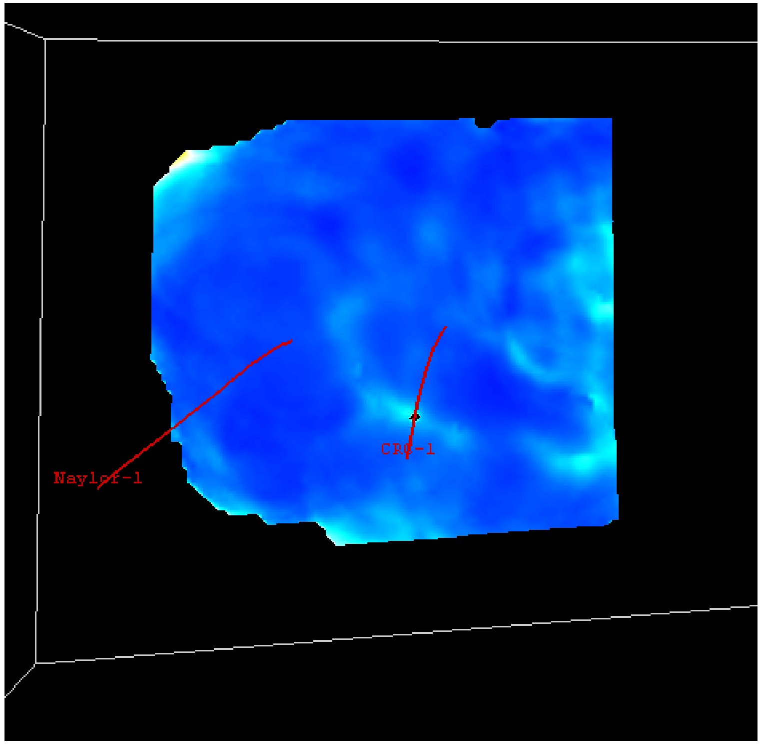
A. Campbell
Schlumberger

Repeatability at Waare C level, surface seismic vs VSP

2008-2010, 3D Surface seismic

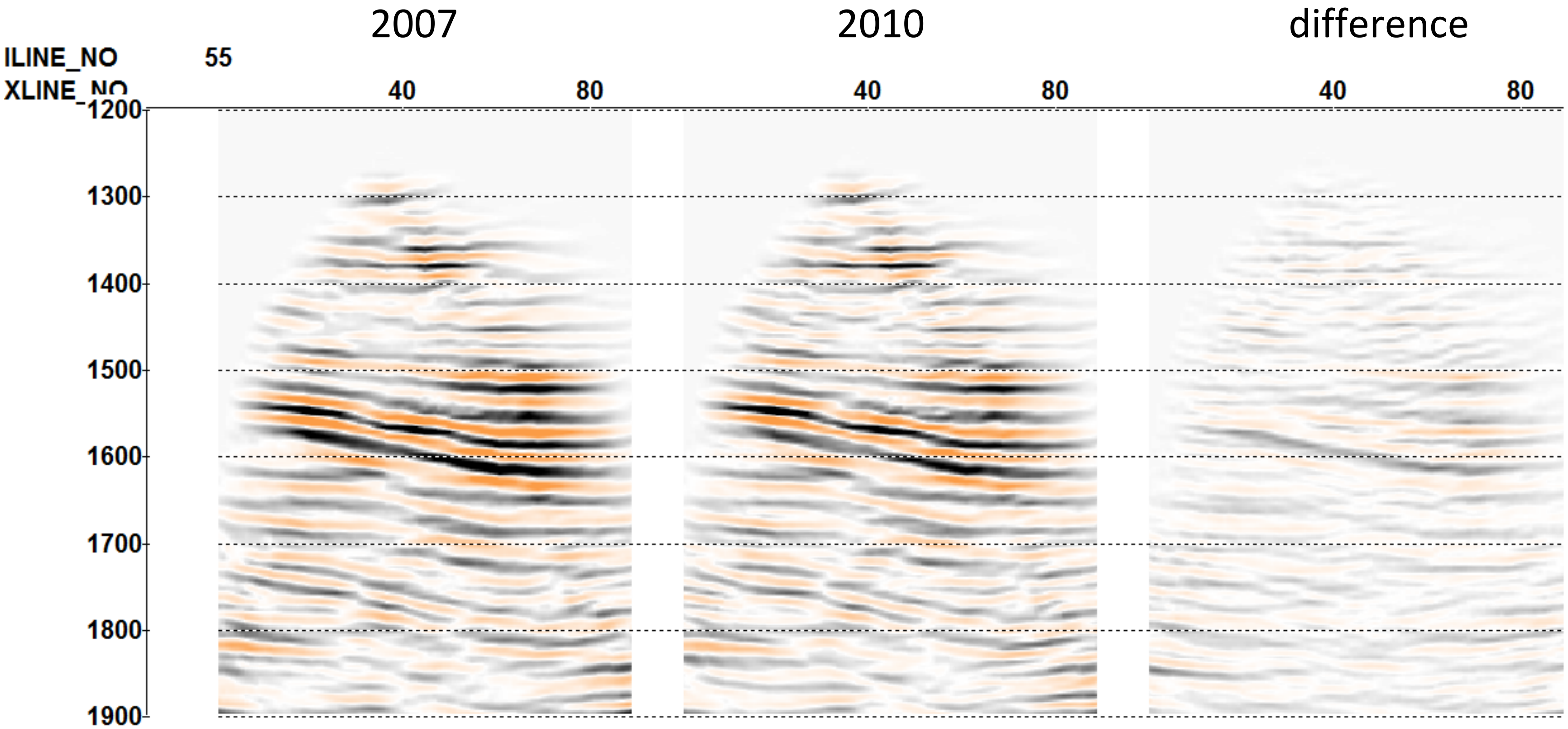


2008-2010, 3D VSP



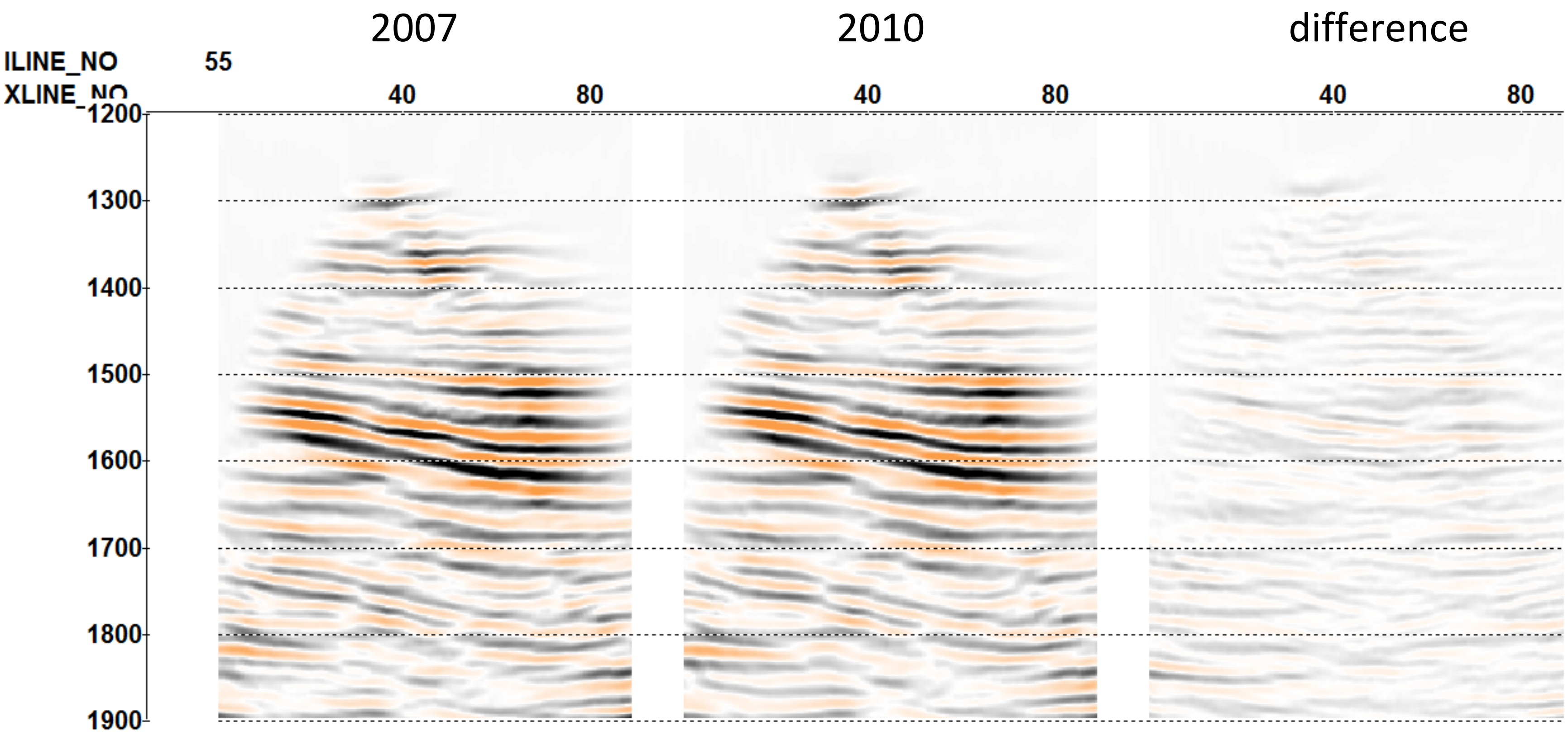
VSP repeatability

Processed data

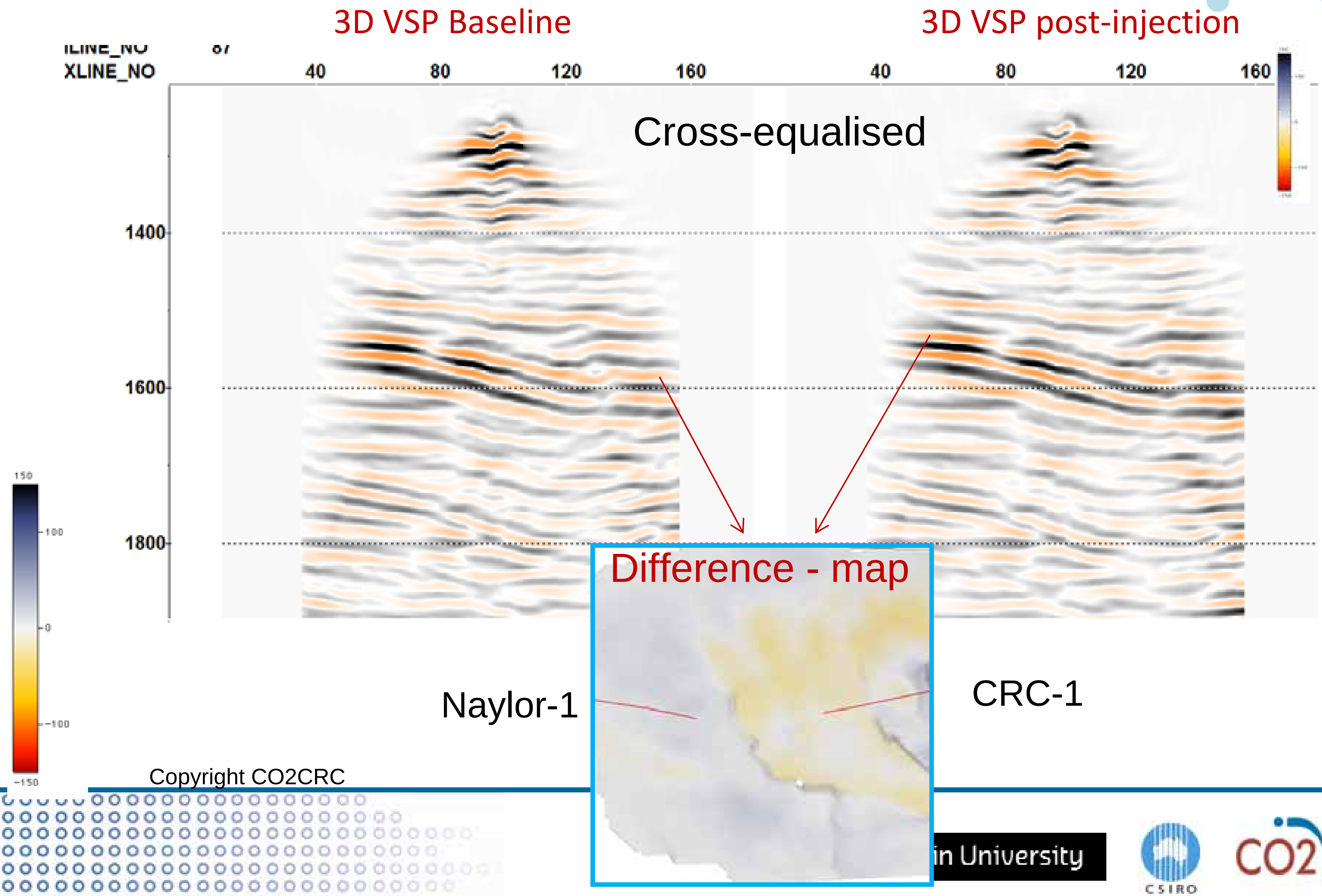


VSP repeatability

Processed and cross-equalised data

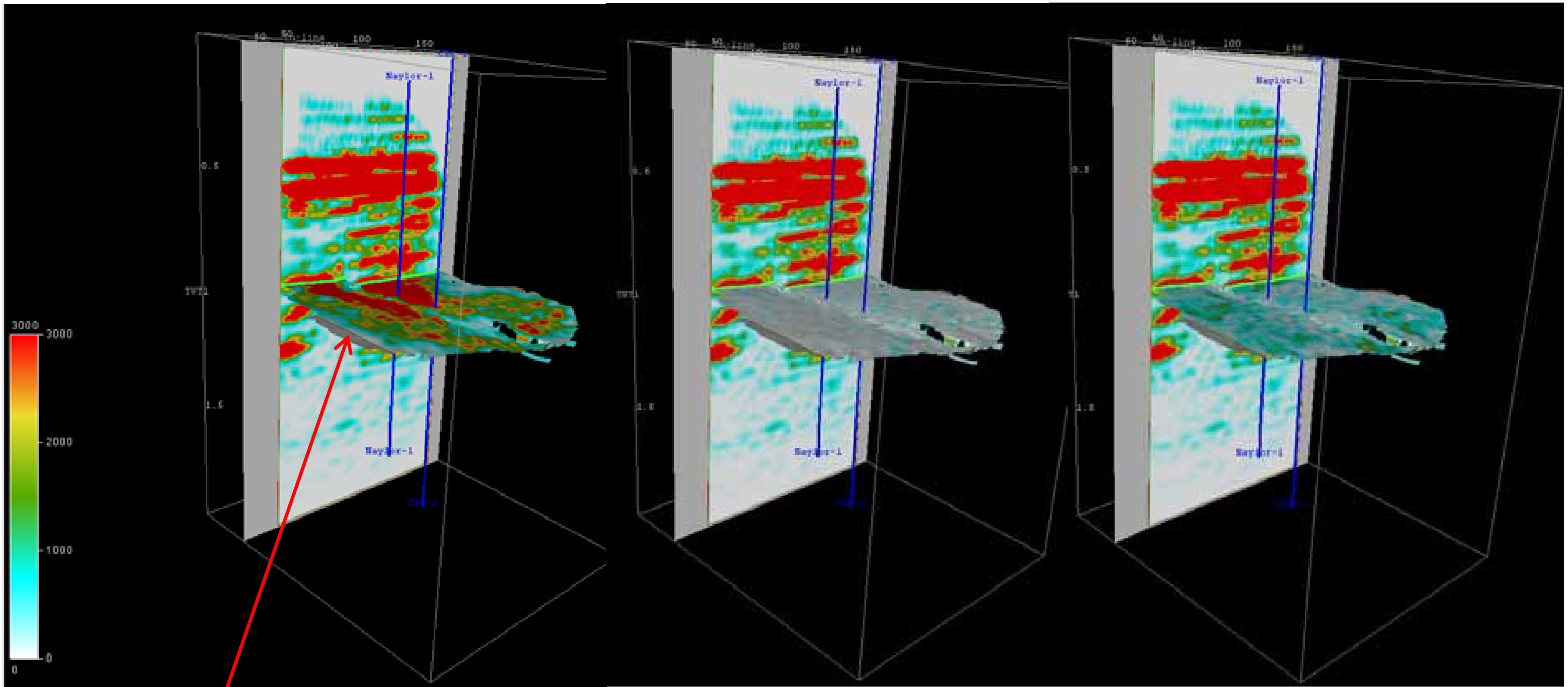


3D VSP Time-Lapse analysis



Assurance monitoring: Paaratte TL studies

CO2 leak into Paaratte – very strong TL signal

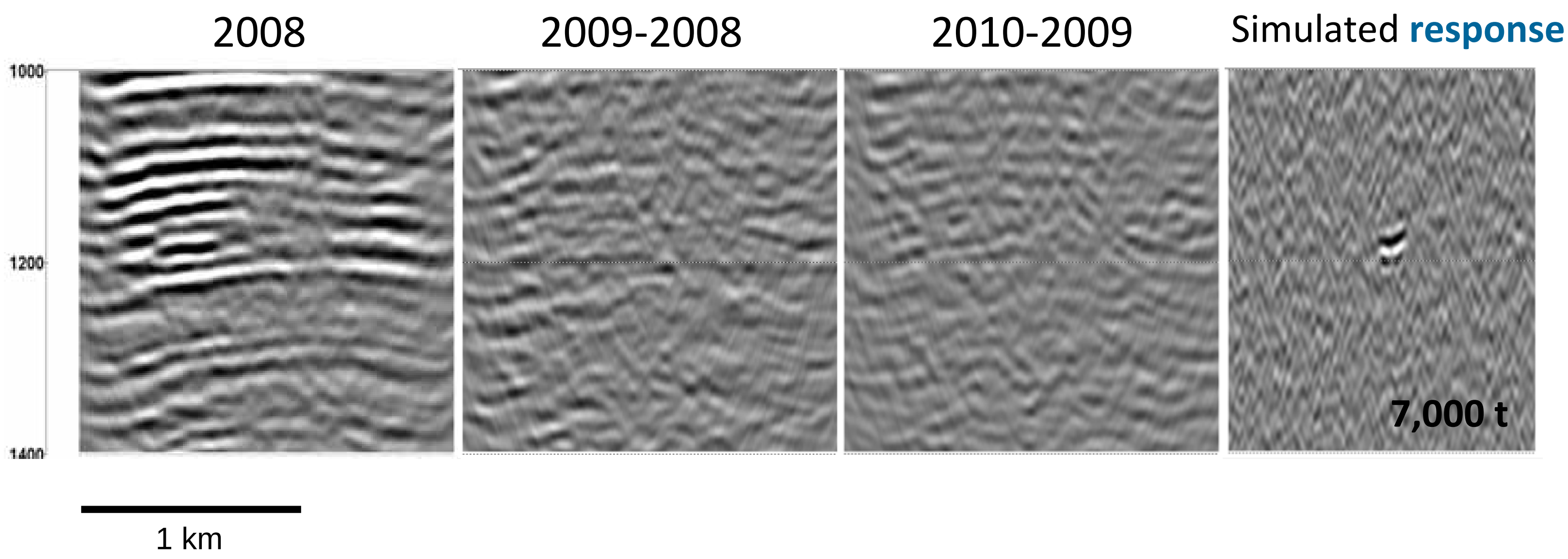


Paaratte Level 1 Energy

2008-2009

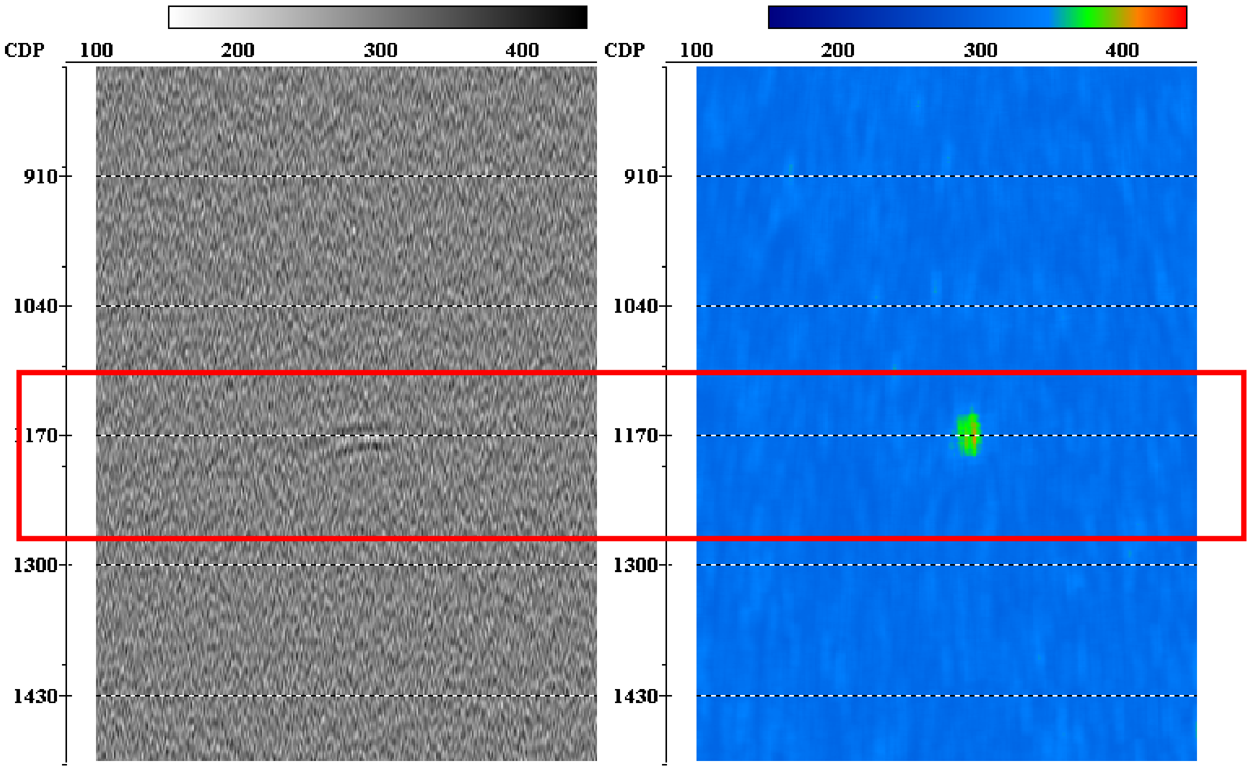
2008-2010

Expected TL signal vs actual seismic response in Paaratte



Can we see less then 4,000-5,000?

TL section for 2000t of CO2 ***Imaged difference section***



Curtin University

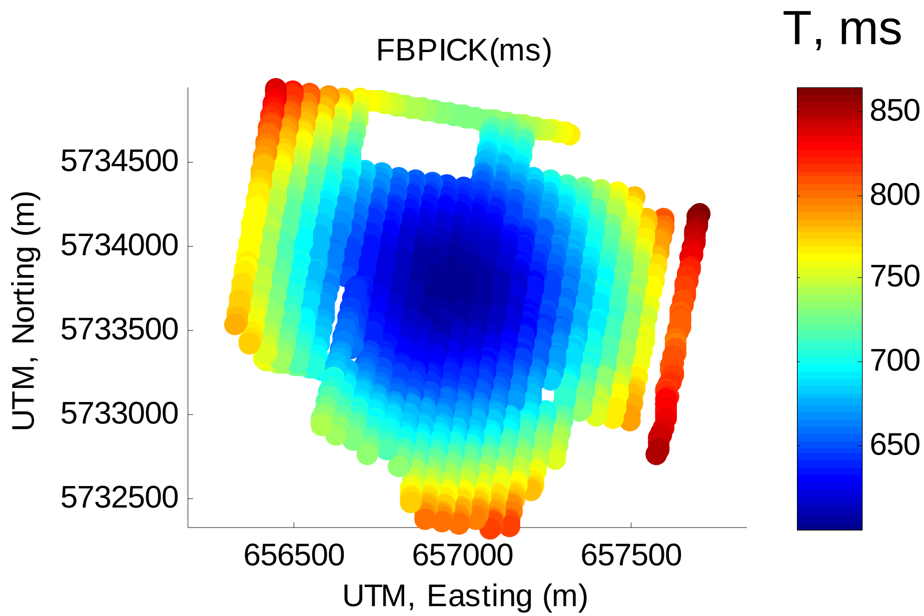
CSIRO

CO2CRC

Current work

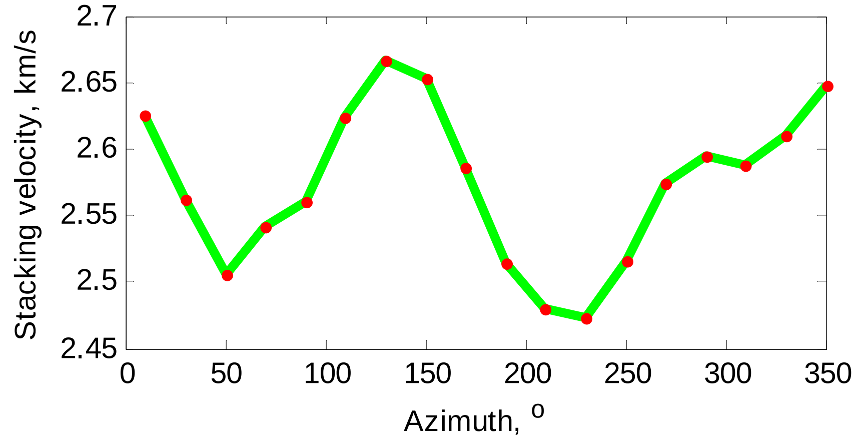
Full 3C analysis
TL seismic anisotropy studies
Recovery of the full stiffness
Repeatability – near surface

2D/3D TL VSP 3C studies



"Stacking" velocity analysis

P-wave azimuthal anisotropy

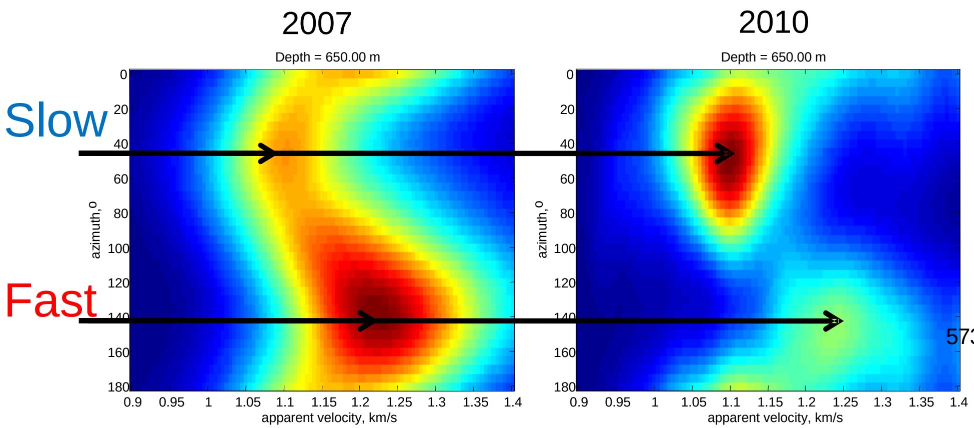


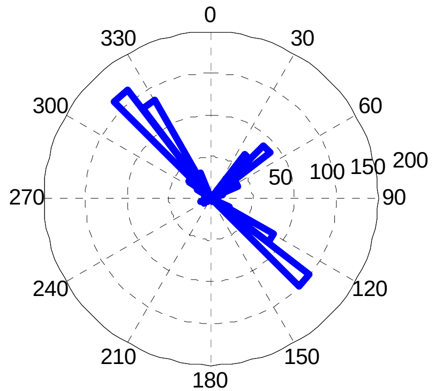
-Elevation statics

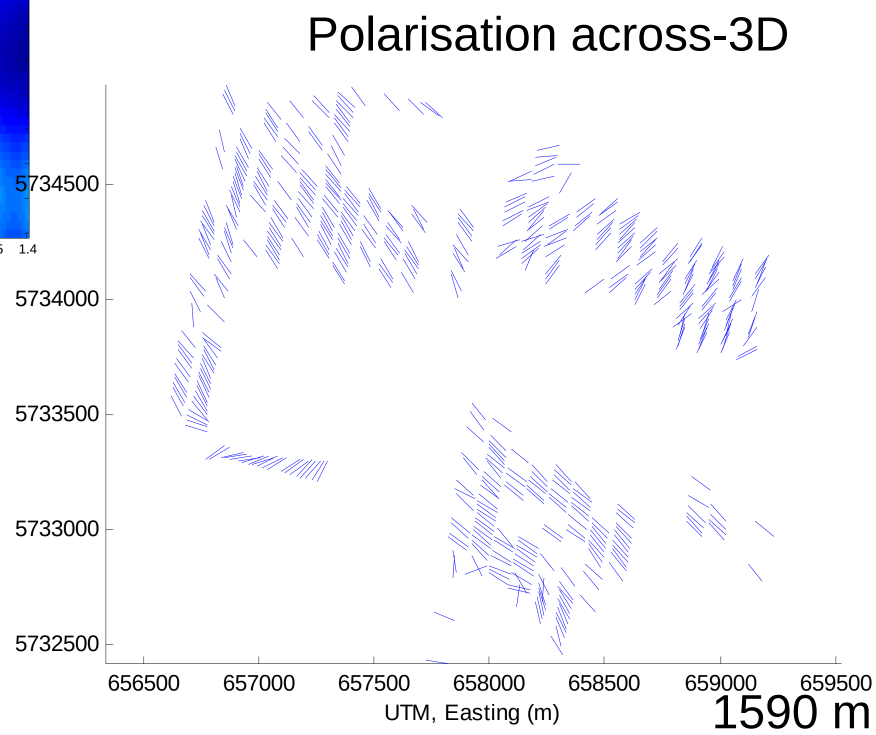
-First breaks approximated with hyperbola for each 15 ° azimuthal segment

Converted S-wave anisotropy

TL seismic anisotropy changes – M&V methodology?

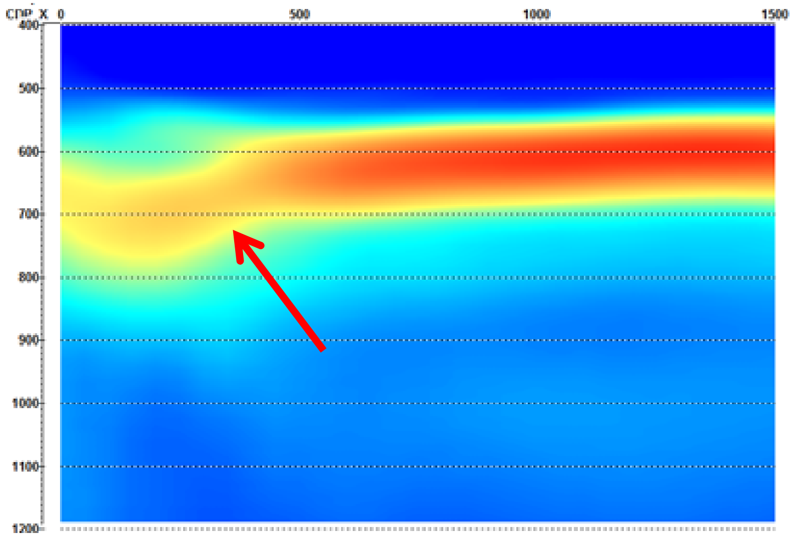




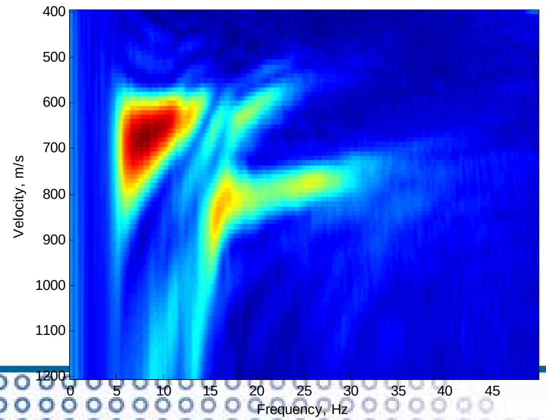


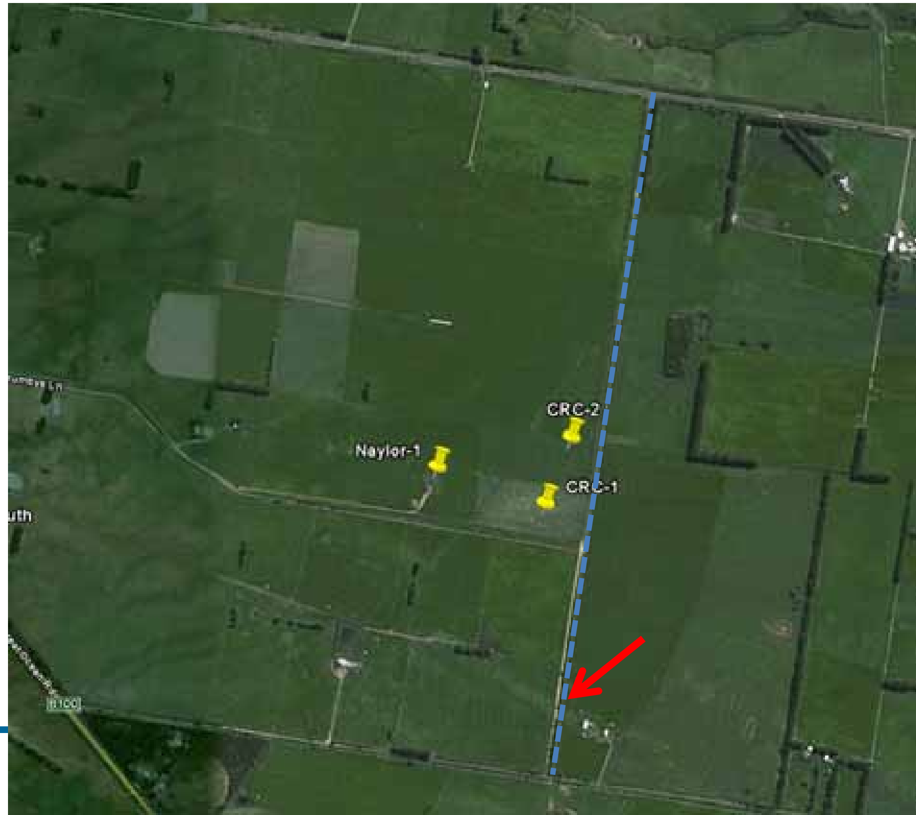
MASW for weathering characterisation

10 Hz frequency slice, WD2007, wet



X (m)





Conclusions

- Large number of unique TL data sets acquired (borehole and surface); inexpensive, good quality, acquired with small crews
- Numerous scientific studies and advances achieved
- Opportunity for further long-term cutting edge research and international colaboration

Highlights

- Very good (post-stack) repeatability achieved combining weak and different source types, thanks to high spatial data density and high fold
- CO_2 upward migration (“Leak”) readily detectable with 3D TL seismic - no indication in TL data (using diverse measurements and studies)
- Clear, unique TL signal from Waarre-C not observed (CO_2 contained); very subtle TL signal – sensitive to processing/cross-equalisation schemes (analysis still ongoing)
- VSP shows superior repeatability and sensitivity with respect to surface seismic (also measure full wave field; possibility for development of alternative M&V methodologies)

CO2CRC Participants

Supporting Partners: The Global CCS Institute | The University of Queensland | Process Group | Lawrence Berkeley National Laboratory

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