

Wave-Equation-Based Target-Oriented Inversion for Reservoir Characterisation

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Abstract

We present target-oriented full waveform non-linear inversion of seismic data for the purpose of obtaining seismic-driven quantitative input for reservoir modelling. The method solves directly for the rock compressibility modulus and the shear modulus on a fine grid (down to 3 m) over an approximately 500-m-long depth interval containing reservoir units and top and bottom seals. Solving directly for the elastic parameters allows the detection and mapping of DHIs that would not show up from conventional inversion approaches aiming at impedances. In addition, the non-linear character of the relationship between seismic data and the rock-properties make it peremptory that 4D effects are analysed with the help of a full waveform non-linear approach. The new full waveform inversion approach consists of two alternating steps. First, we solve the wave-equation for the total wavefield in the target domain. Then, we invert the measured data for the rock-properties over the same domain, driven by our best current knowledge of the total wavefield. This iterative approach solves the full non-linear problem, with considerably reduced risk of getting trapped in local minima. The keys to the success of the scheme are the regularisation of the inversions and the stabilisation of the iterative solution of the wave-equation-based on still inaccurate properties. The results presented in this article are both synthetic examples and real data cases. The synthetic examples give insight in the method and illustrate the benefits of non-linear full waveform inversion. Particularly illustrative are the results from a very elaborate synthetic reservoir model based on real outcrop data. Also, the importance of the new technology for 4D is demonstrated with the help of a controlled synthetic experiment. Several real data examples will be presented covering various geological settings, ranging from onshore Tertiary deltaic to deep North Sea Carboniferous. Common features of all real data cases are that the non-linear full waveform inversion is very robust against poor quality input data and that it generally produces a higher spatial bandwidth for the property images than could have been expected on the basis of the temporal bandwidth of the input data. This is due to the

non-linear relationship between data and properties. In the deep North Sea example a gas-related amplitude effect was revealed that had not been identified on the seismic data.

Reference Cited

Beller, M. P. Doulgeris, A. Gisolf, P. Haffinger, R. Huis in't Veld, and A.K.T. Wever, 2015, Resolving Carboniferous stacked channel sequences with a non-linear AVO technology (summary-extended abstract): 77th EAGE Conference and Exhibition 2015 June 1, 2015, Madrid, Spain. Website accessed December 23, 2015, <http://www.earthdoc.org/publication/publicationdetails/?publication=81053>.

Wave-equation based target-oriented inversion for reservoir characterisation

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Motivation

- AVO (AVA, AVP) inversion should yield high-res absolute elastic properties that can be translated to relevant reservoir properties.
- Current AVO techniques can only invert for impedances and are poorly protected against noise, therefore lacking in bandwidth and lateral continuity.
- Wave-equation-based AVO inversion gives better reservoir indicators, is more robust against noise, and gives a higher spatial bandwidth, without constraining the results.

Outline

- Introduction
- Target-oriented non-linear inversion
- Real data case study: Tertiary deltaic, land
- Real data case study: Carboniferous, North Sea
- Discussion and conclusions

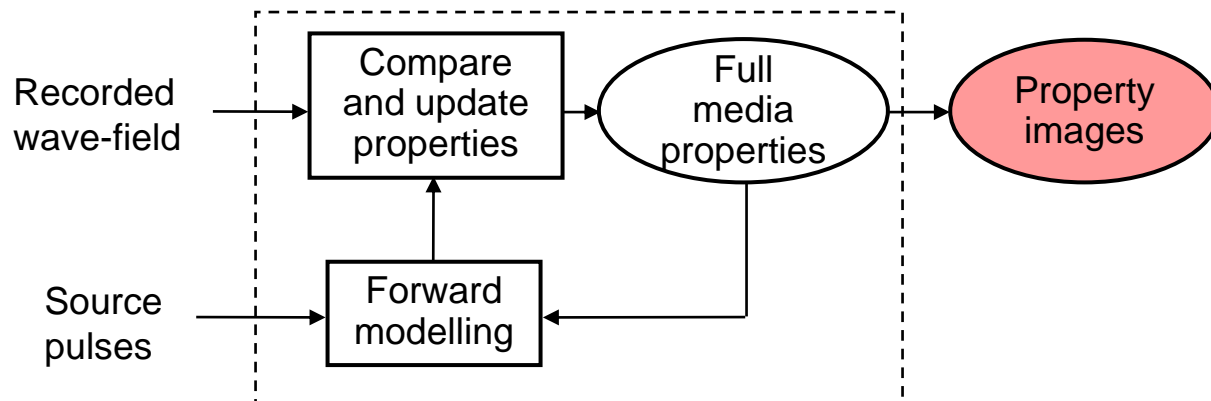
Inversion currently in industry

- Full wave-form inversion (FWI):
 - Low frequencies only.
 - Long offsets only (diving waves).
 - Finite Difference propagator.
 - Single parameter (velocity).
 - Serves the purpose of obtaining a velocity model for migration.
- Conventional AVO inversion for reservoir characterisation
 - Linearised theory based on primary reflection coefficients and primary travel times.
 - Inversion result band-limited by seismic wavelet.
 - Absolute property predictions strongly reliant on low frequency model from interpolated well data.

Wave-equation based AVO (FWI-*res*)

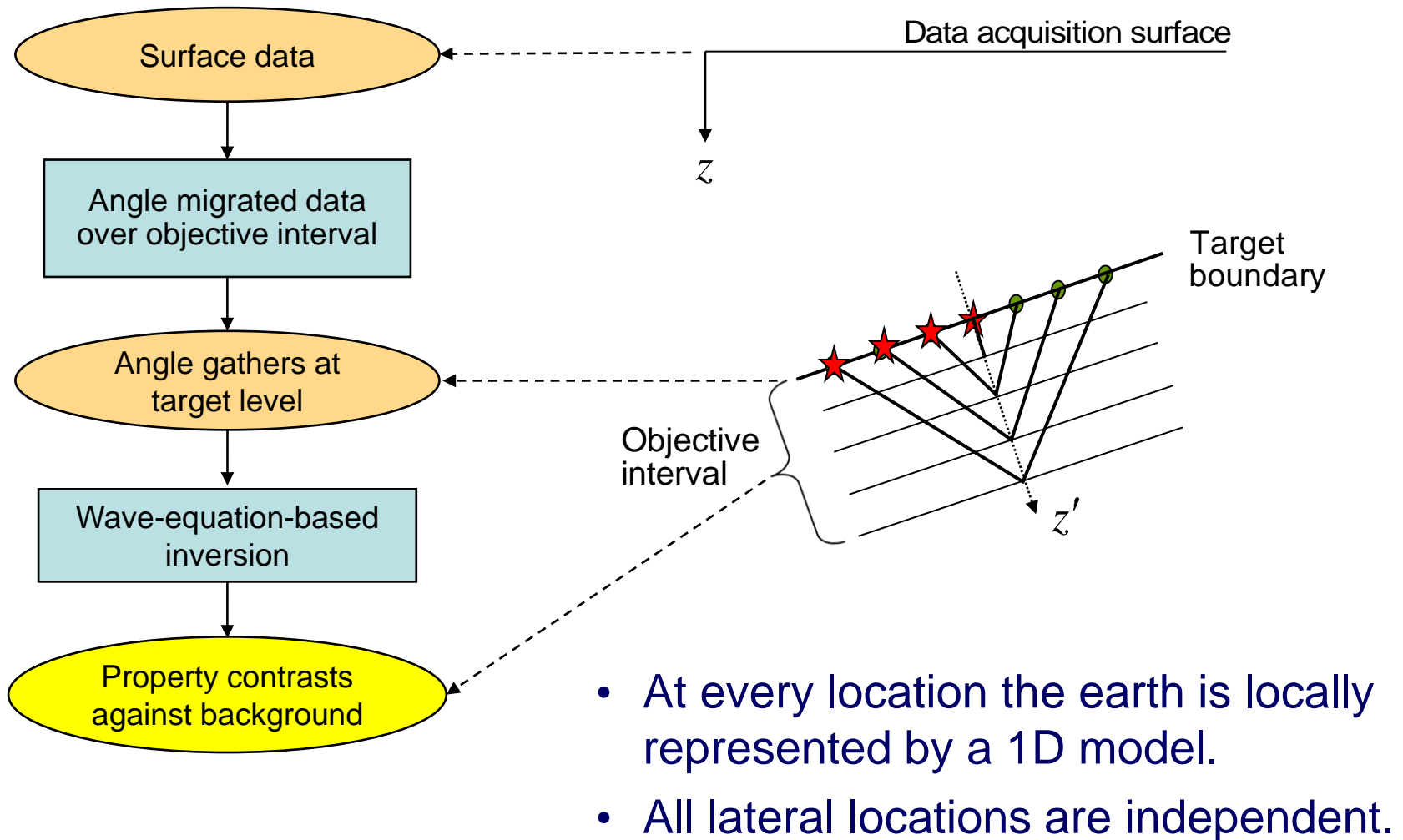
- Wave-equation AVO inversion for reservoir characterisation:
 - Uses migrated angle stacks over target interval as input.
 - Applies full elastic seismic wave theory over the target interval.
 - Uses full seismic data spectrum.
 - Spatial bandwidth of inversion result broader than seismic bandwidth, particularly on the low wavenumber side.
 - Absolute property predictions therefore less reliant on low frequency model from wells.
 - Serves the purpose of obtaining absolute properties useful for reservoir characterisation on a fine grid (3-5 m), over a 500 m target interval.

Inversion



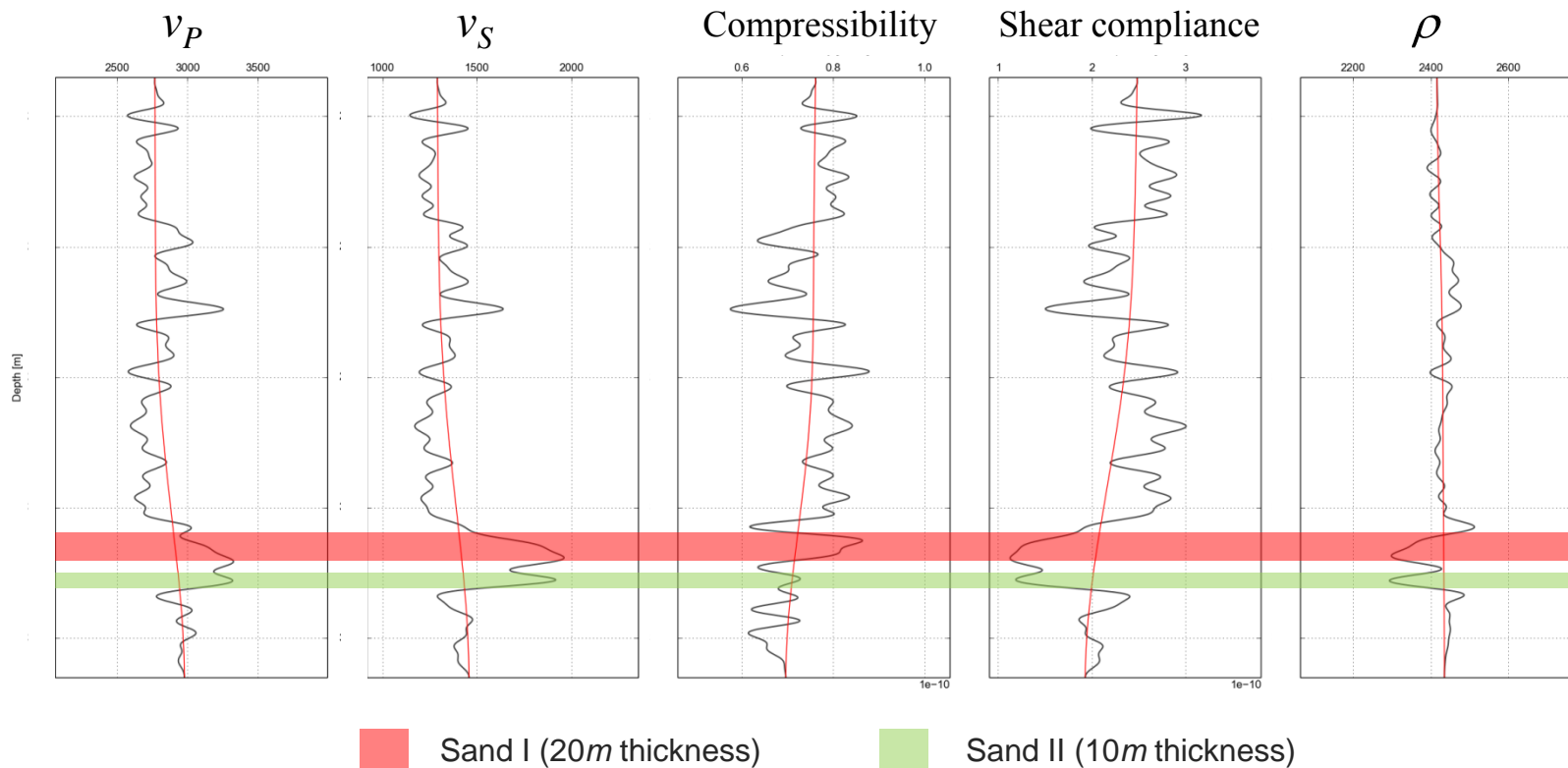
- Forward modelling, with propagation in a background medium and primary reflections only, is linear modelling.
- Wave-equation based modelling, with propagation in the full medium, transmission effects, multiple internal scattering and mode conversions, is non-linear modelling.
- Depending on the kind of forward modelling that is used, inversion can be linear, or non-linear.
- In wave-equation-based inversion, the natural parameters to invert for are compressibility and shear modulus, rather than v_P and v_S .

Target-oriented, wave-equation inversion



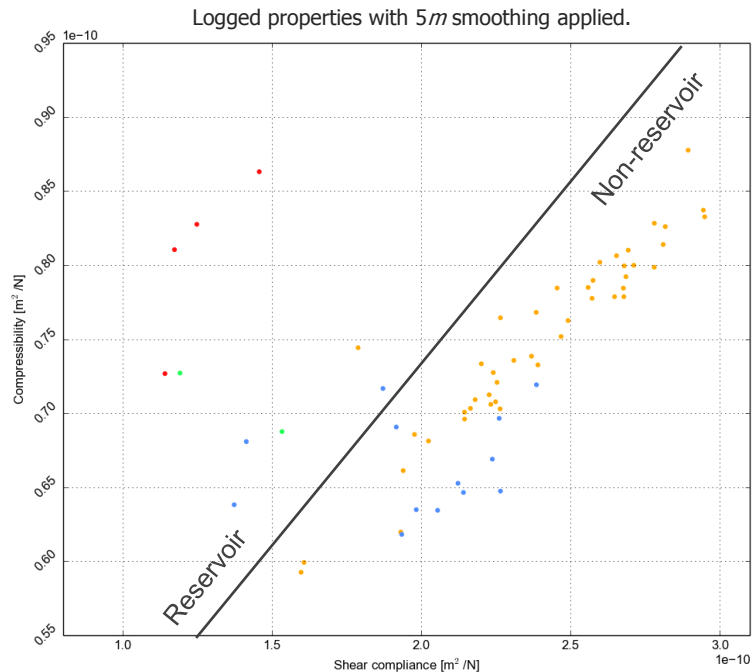
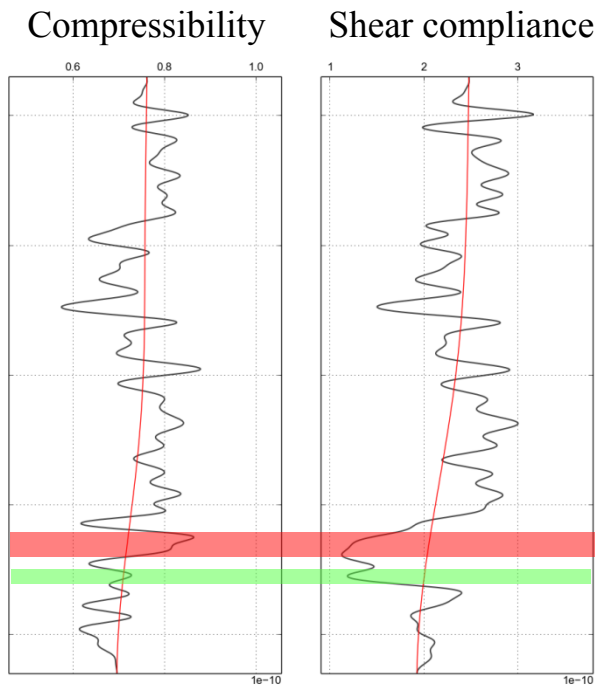
Tertiary deltaic land case study

- Well logs on .1524 m grid with 5m smoothing applied.
- Smooth red curves are the low wavenumber background models.
- Note the difference in compressibility between upper and lower sand, indicating reservoir depletion in the lower sand.



Property cross-plot

- Compressibility (κ) vs. shear compliance (M)
- Clear separation between reservoir and non-reservoir samples



Sand I (20m thickness)

Sand II (10m thickness)

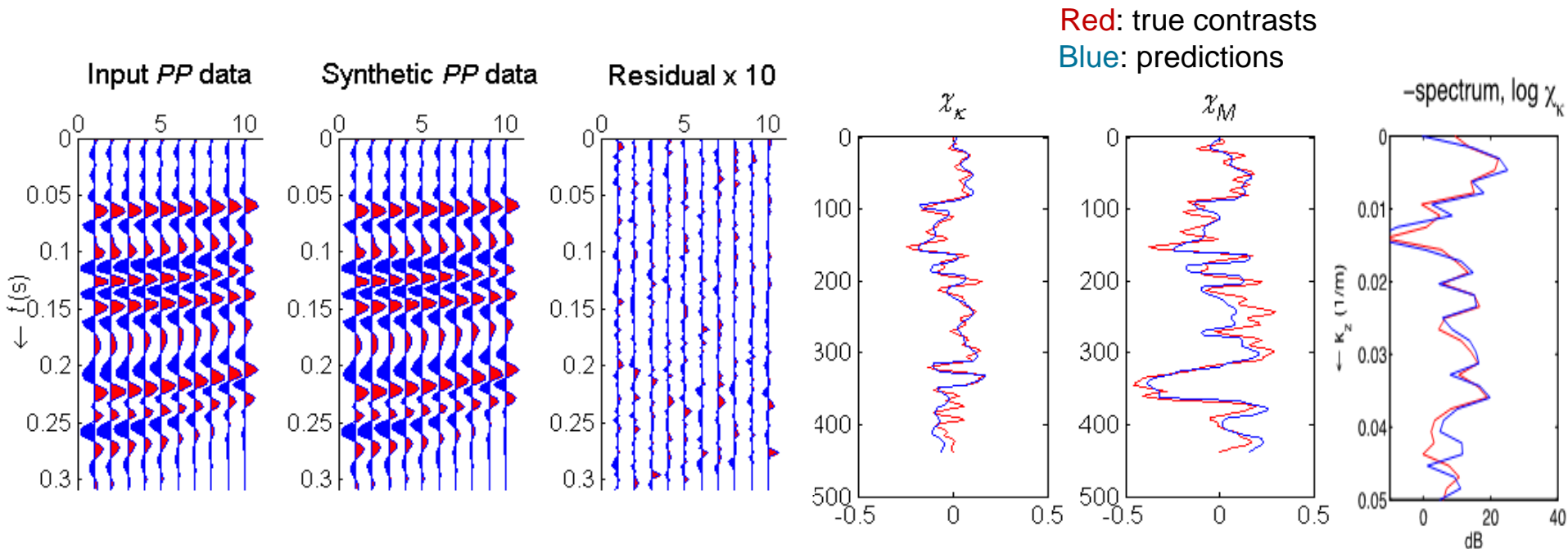
Inverting the full waveform well synthetics

- Inverted for are the dimensionless contrasts:

$$\chi_{\kappa} = \frac{\kappa - \kappa_b}{\kappa_b} \quad \text{and} \quad \chi_M = \frac{M - M_b}{M_b}$$

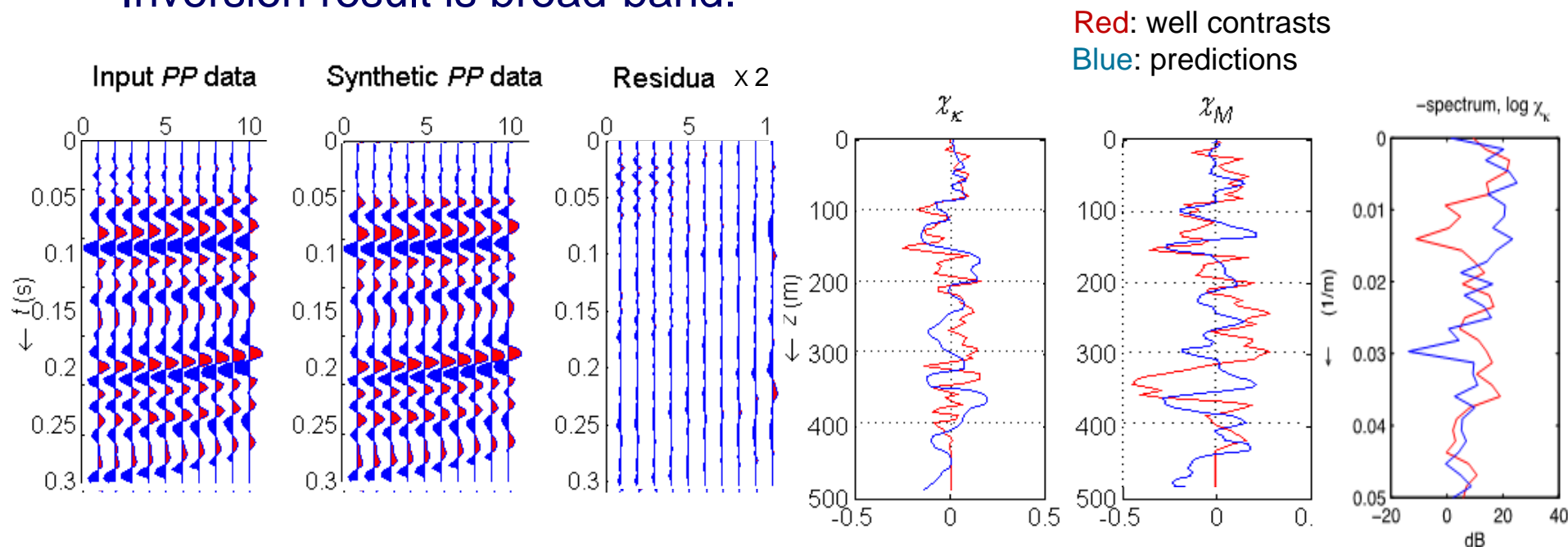
where κ_b and M_b are the background models.

- In case of a perfect seismic-to-well match, the same result should be obtained from seismic.



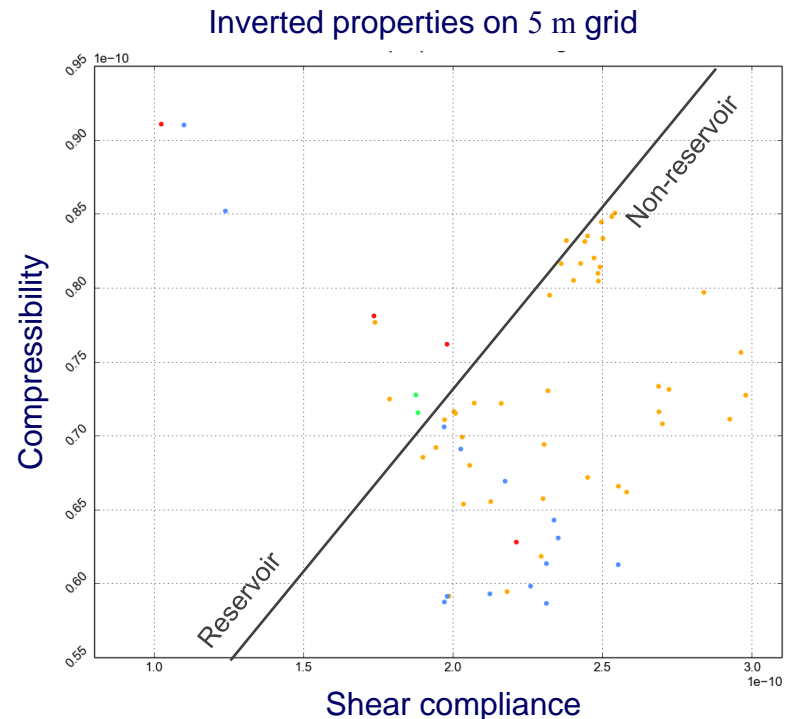
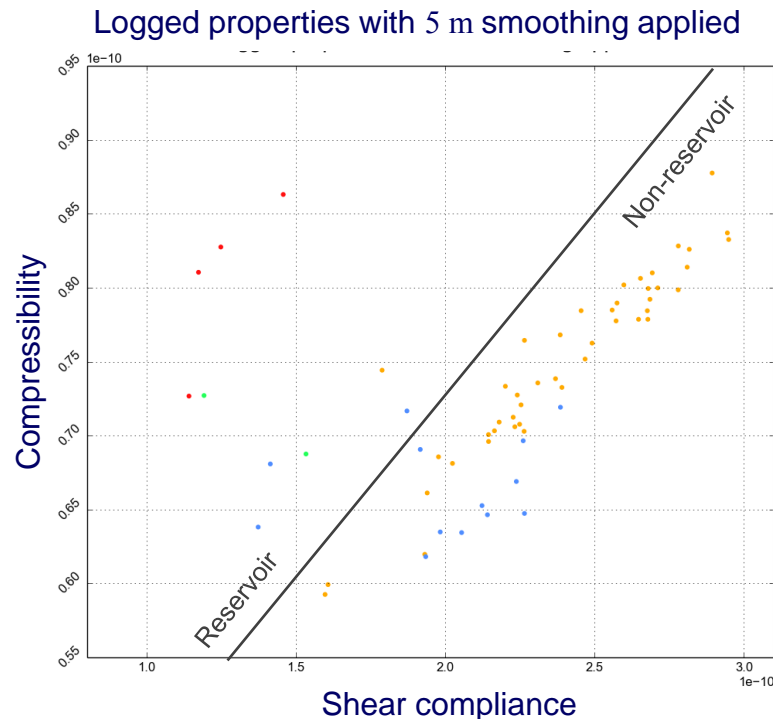
Inverting seismic at the well location

- Input data is PSDM common offset cubes. These were converted to slowness gathers, by ray-tracing in a stratified overburden model.
- Seismic data quality looks very good.
- The data is very well explained by the inversion.
- The mismatch at the deeper reservoir level is due to a seismic-to-well mismatch (fault cut-out?).
- Inversion result is broad-band.



Property cross-plot at well location

- Cross-plot for properties from inversion shows similar pattern to cross-plot of logged properties.
- The gas-bearing upper sand samples stand out in κ / M space

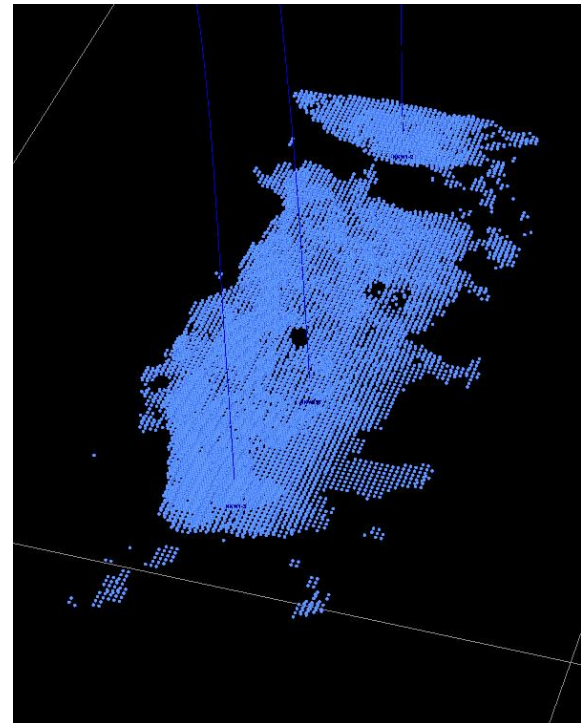
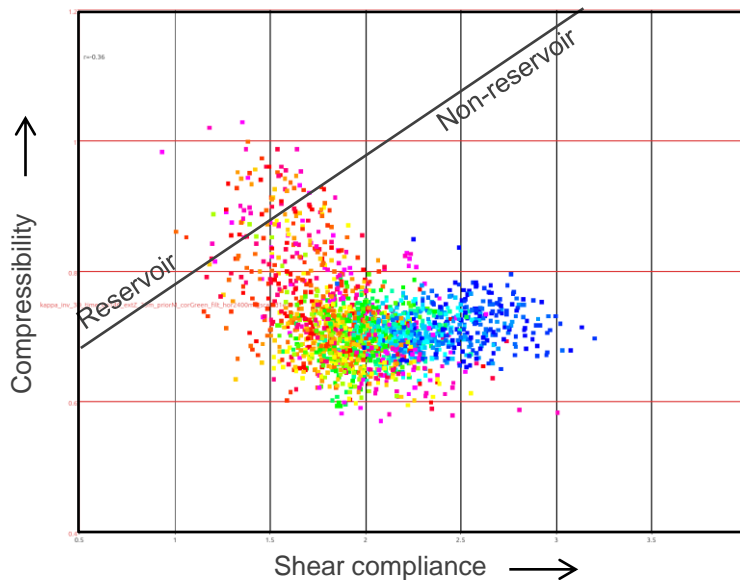


■ Sand I (20m thickness)

■ Sand II (10m thickness)

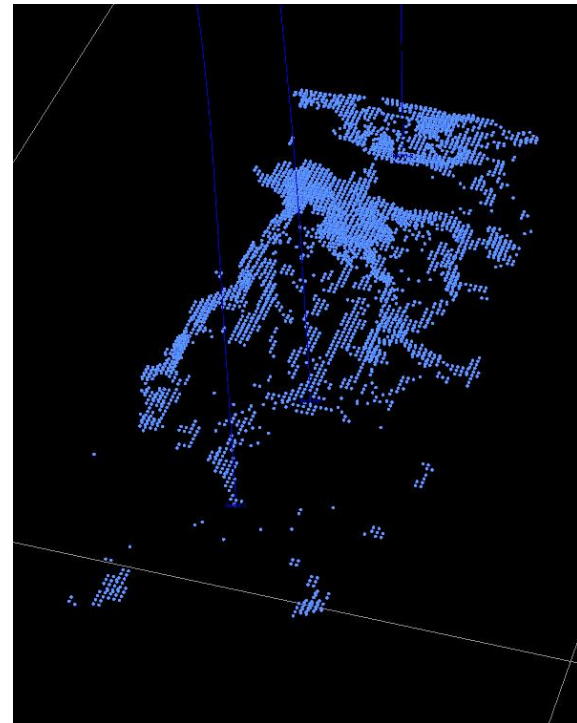
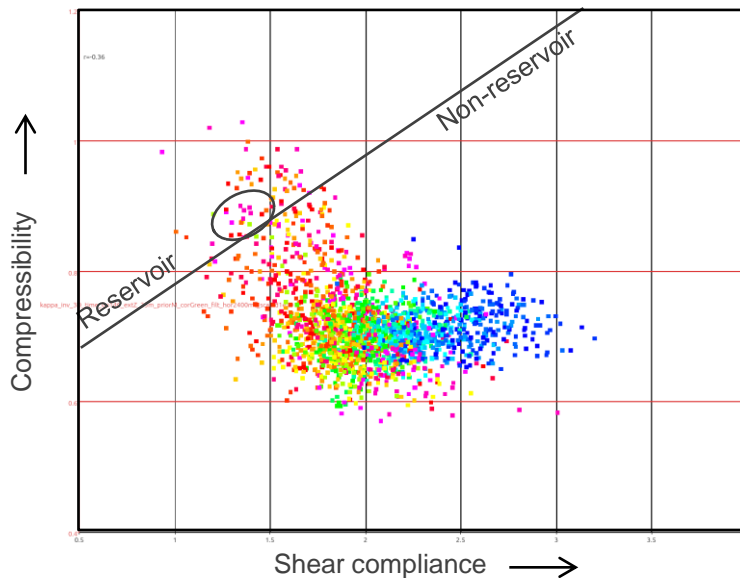
Inversion of 3D seismic cube

- Geo-body extraction based on κ / M cross-plots.
- Two main bodies can be extracted if selection is driven by reservoir/non-reservoir cut-off.
- Reservoir bodies confirmed by two blind well tests.



Internal structure of geobody

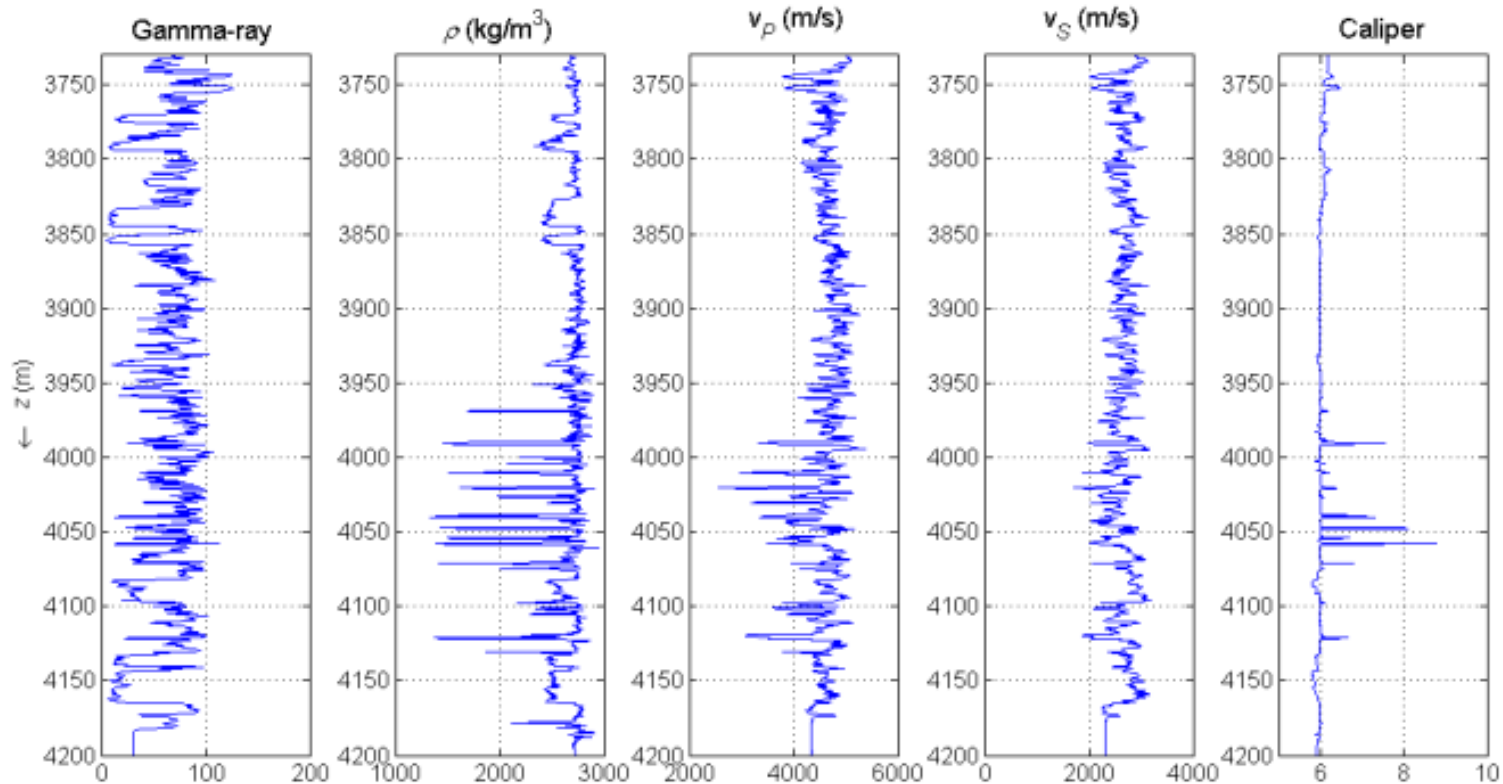
- Internal reservoir structure (channel system) can be identified if selection is refined.
- This way the geometry of deposit of a specific reservoir quality can be mapped.



North Sea data example

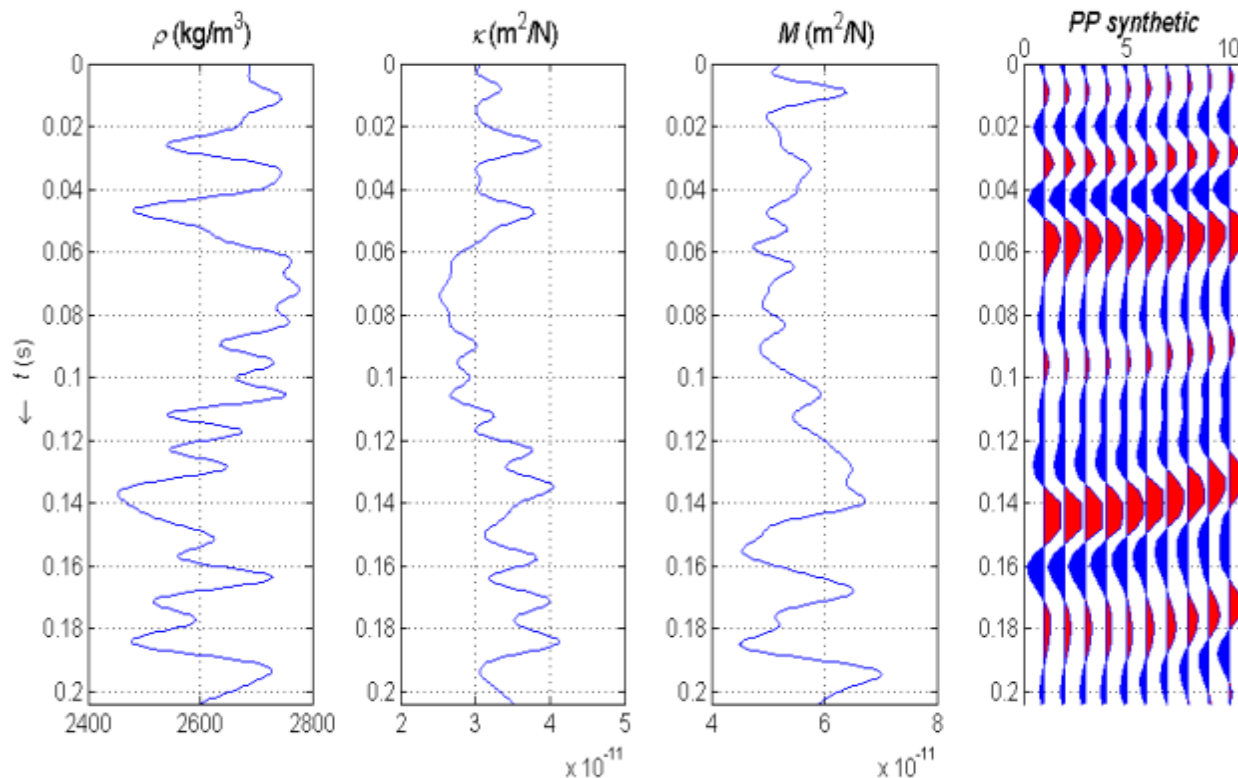
- North Sea marine streamer data.
- Target depth is 4 km, but maximum offset is only 3 km. Maximum usable angle is only 15°.
- Single well used for calibration and background.
- Work carried out for Wintershall. Has been published at the EAGE Conference, Madrid 2015.

Well data



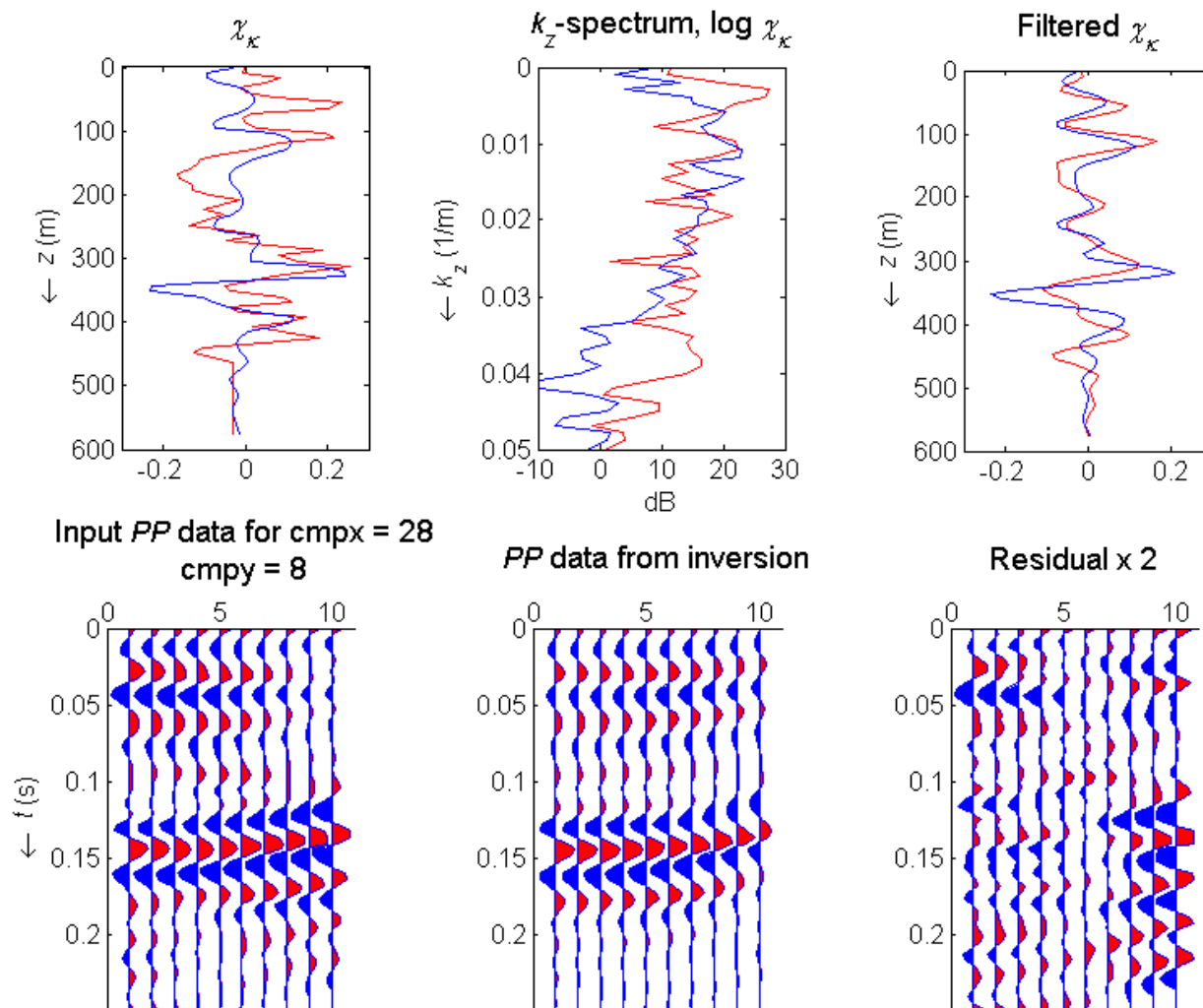
- Input logs for well used in the study
- The spikes on the density are mostly real and indicate coal

Well synthetic



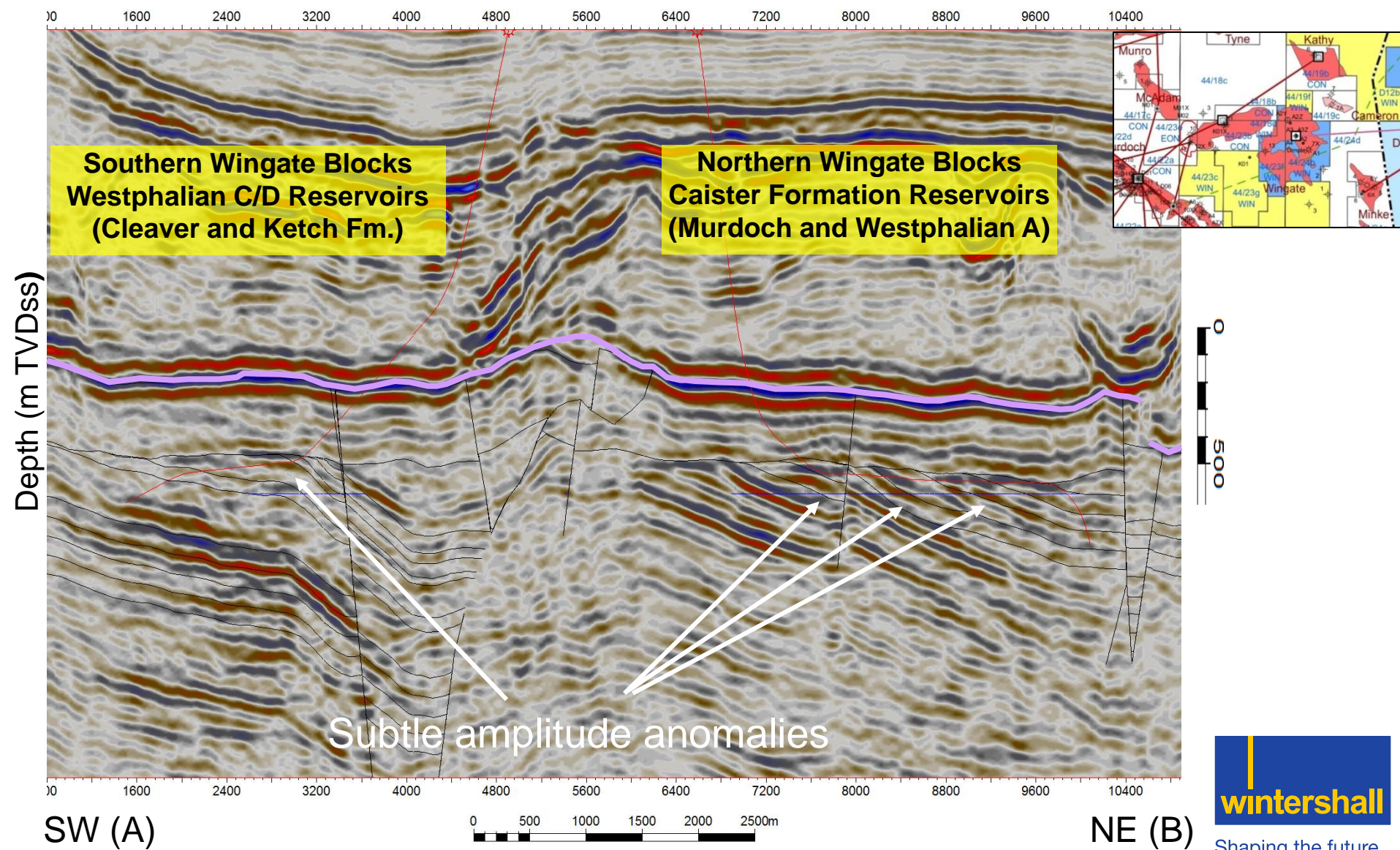
- PP synthetic data for 10 different horizontal slownesses (ray-parameters), computed from the smoothed logs of the well.
- The objective sands stand out much better on the compressibility curve

Invert seismic at well location

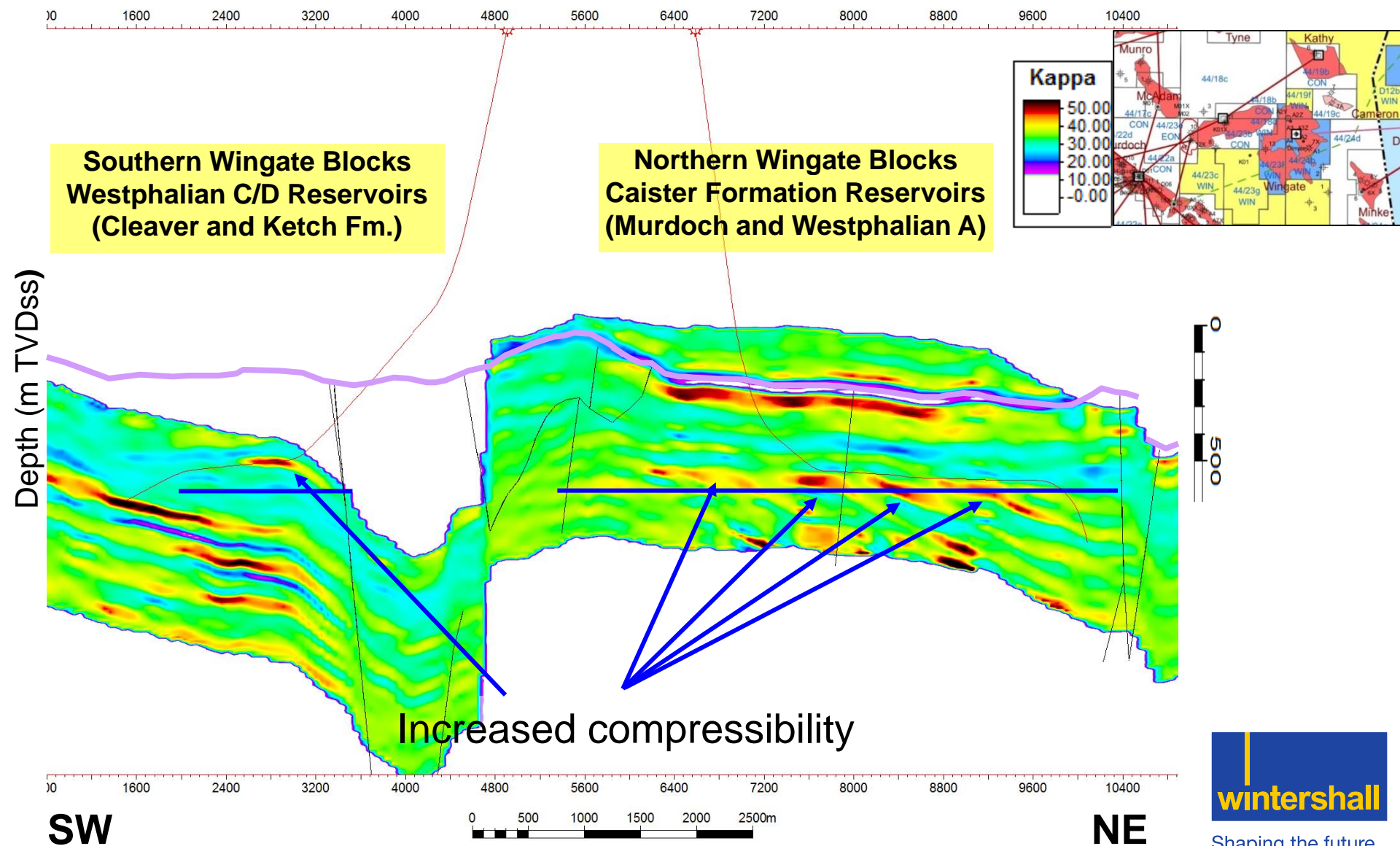


- Because of poor seismic data quality and very low angles, there is only a good fit over the seismic bandwidth.

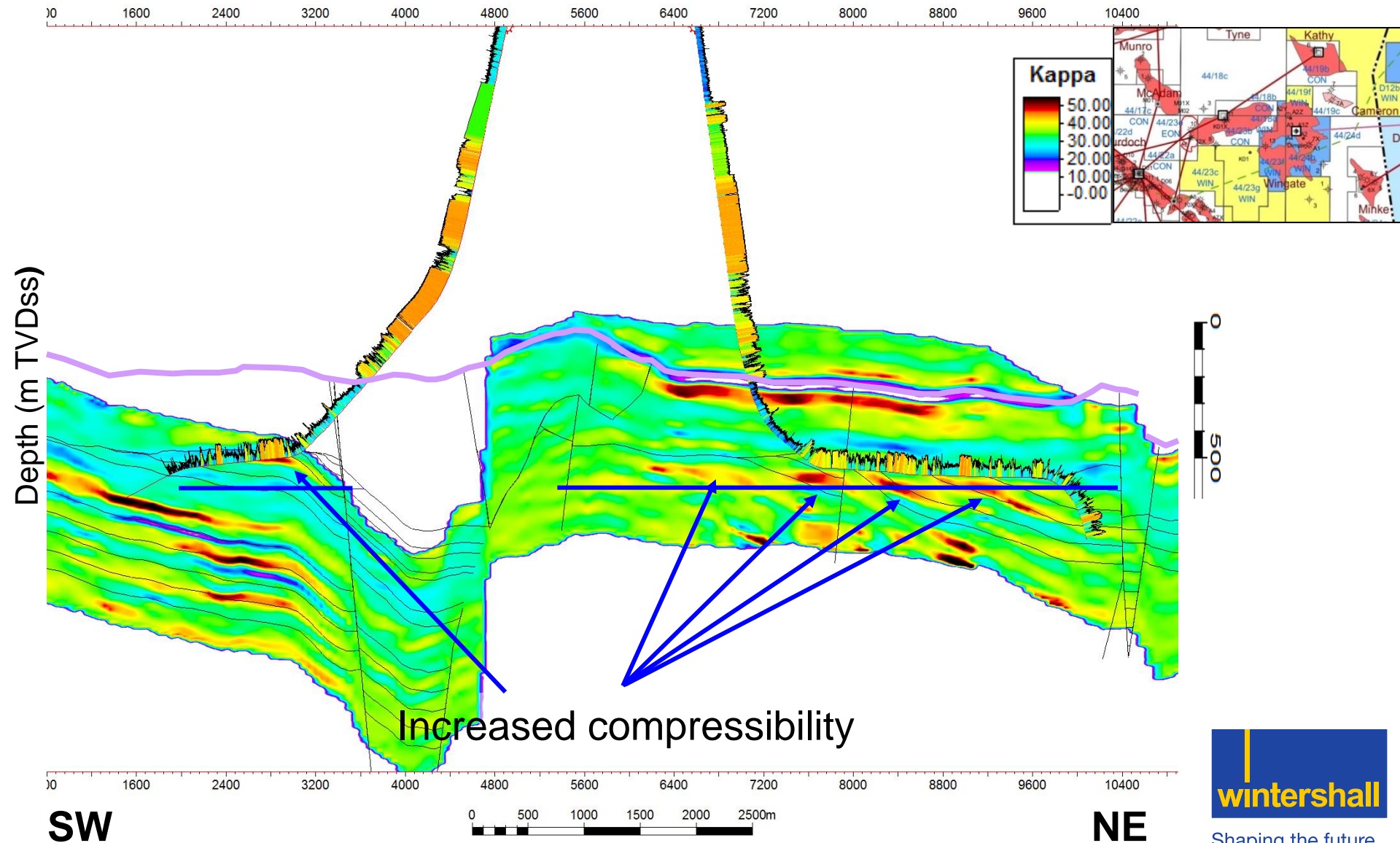
PSDM Volume Random SW-NE Section



Non-Linear AVO Inversion (FWI-Res)



Well correlations with reservoir zones



Discussion and Conclusions

- Wave-equation-based AVO inverts directly for parameters that are much more sensitive to porosity and hydrocarbon saturation than the usual impedances conventional approaches invert for.
- Compressibility and shear compliance, which are the natural parameters to invert for in FWI-res, are much better reservoir/pore-fill indicators than v_P and v_S .
- Therefore, FWI-res inversion results will show the presence, or absence, of (hydrocarbon-filled) reservoir much more clearly than would be visible on seismic sections, or conventionally derived acoustic and/or elastic impedance sections.
- As a result of the full wave-equation-based inversion, FWI-res results will show a wider spatial bandwidth than would have been expected on the basis of the temporal bandwidth of the seismic data, particularly in the low wave-number range.

Discussion and Conclusions

- FWI-res seems to be a very good tool for AVO (AVA, AVP) type reservoir-oriented inversion.
- All results from the case studies presented were confirmed by blind tests.
- FWI-res is very robust against noise.
- Neither lateral nor vertical constraints are applied in the inversion, beyond a regularisation based on minimum vertical total variation.
- FWI-res is ideal for time-lapse, because it fully honours the non-linearity of the time-lapse effect on the data.
- Therefore, FWI-res is also eminently suited for the monitoring of underground CO₂ storage.