From Inversion Results to Reservoir Properties*

M. Kemper[1] and N. Huntbatch[1]

Search and Discovery Article #40869 (2012)
Posted January 30, 2012

*Adapted from oral presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

[1] Technical, Ikon Science, Perth, WA, Australia (nhuntbatch@ikonscience.com)

Abstract

This paper is a quick guide to modern inversion techniques and its uses. The authors categorize inverted data, and introduce six reservoir characterization methods.

Since 1978 the rules applied to the booking of reserves have been very strict and have not kept up with modern oil exploration and development techniques including inversion. For some time the industry has been requesting a change. Recently this has occurred with the introduction of PUD (proved undeveloped) class where reservoir continuity can be shown making the case using "reliable techniques." This could include seismic inversion. The new category has been met with skepticism because of perceived uncertainty believed to be inherent in the technologies used to estimate these reserves.

These days most seismic data is of a quality that allows us, to gain an accurate understanding of the rock properties of the subsurface and ultimately the volumes of hydrocarbons in place that reduce uncertainty and make PUD reliable. However it is key that interpreters understand which inversions are available and when they can be run. The first part of the paper categorises inverted data (deterministic/stochastic, elastic/petroelastic) and provides insights on considerations and correct practice.

The second part introduces reservoir characterisation methods. Seismic surveys are particularly sensitive in terms of rock differences and the consideration to and understanding of reservoir characterisation is becoming increasingly more important and valuable.

References

Whitcombe, D.N., P.A. Connolly, R.L. Reagan, and T.C. Redshaw, 2002, Extended elastic impedance for fluid and lithology prediction: Geophysics, v. 67/1, p. 63-67.

Connolly, P., 2010, Robust workflows for seismic reservoir characterization: Recorder, v. 35/4, p. 7-8, 10.

Connolly, P., 2007, A simple, robust algorithm for seismic net pay estimation: The Leading Edge, v. 26/10, p. 1278-1282.

Connolly, P., and M. Kemper, 2007, Statistical uncertainty of seismic net pay estimations: The Leading Edge, v. 26/10, p. 1284-1289.

From inversion results to reservoir properties

M. Kemper, N. Huntbatch, Ikon Science Ltd.

OPTIMISE SUCCESS THROUGH SCIENCE

Agenda

Not the 3D Highway

Inversion Products

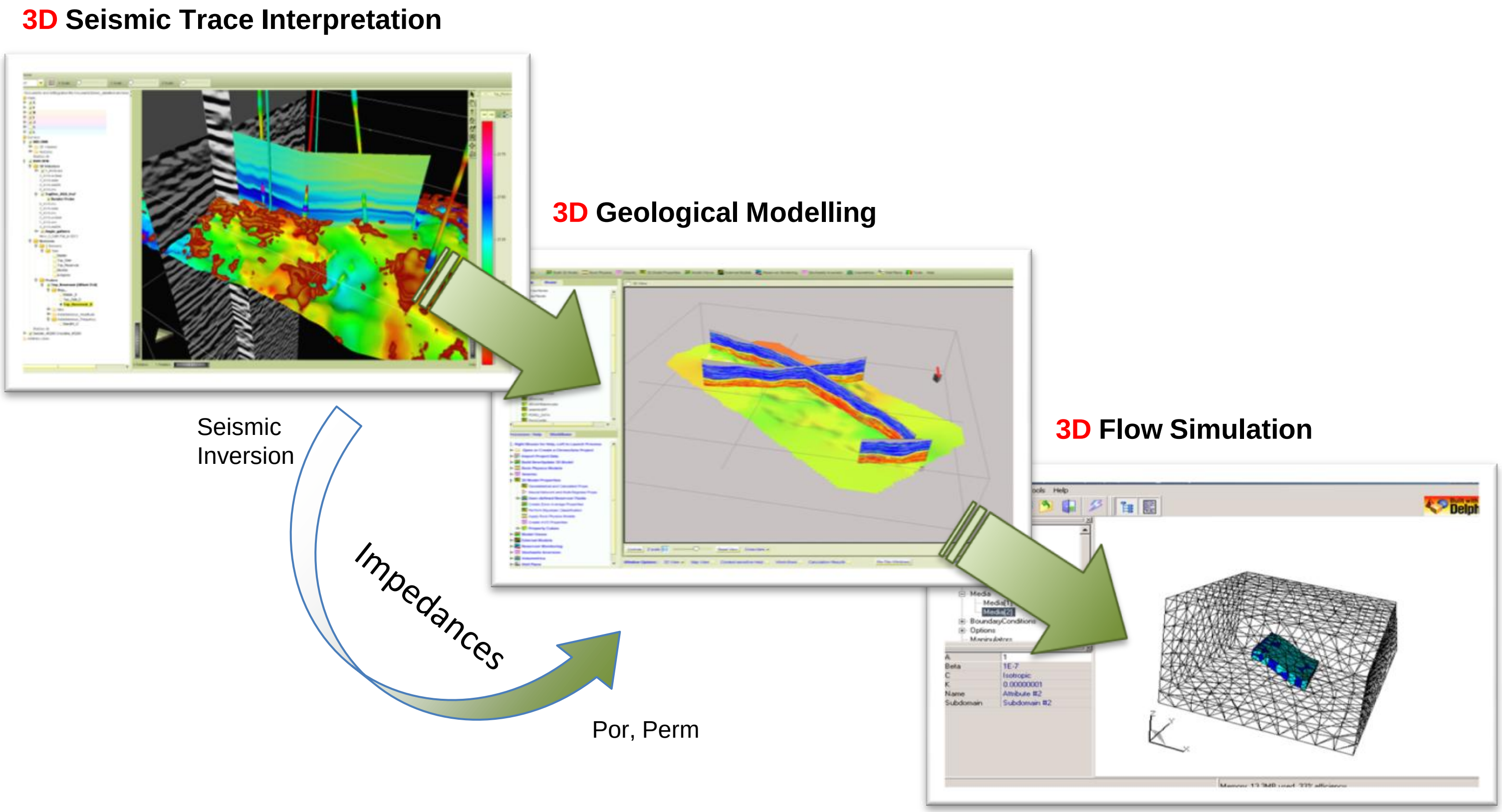
Reservoir Properties

- Bayesian Classification
- EEI Illumination
- Rock Physic Model Template inverse modelling
- Seismic Net Pay
- Colocated co-Kriging
- Multi-Realisation Analysis

Conclusions

Not the "3D highway"

Inversion results are used to good effect by Development Geophysicists on the "3D Highway".



3D Seismic Trace Interpretation

3D Geological Modelling

3D Flow Simulation

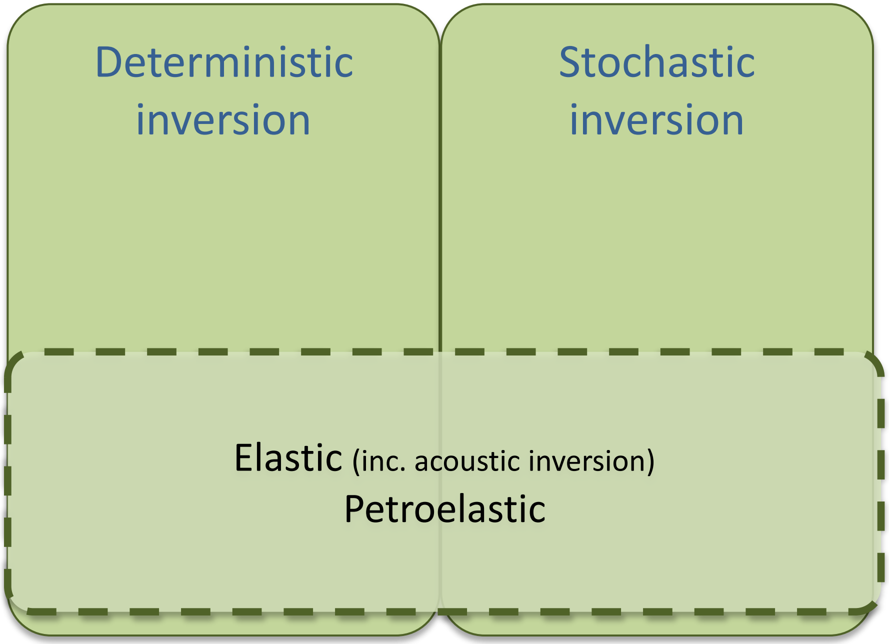
Seismic
Inversion

Impedances

Por, Perm

This is a big and interesting topic, but in this presentation the focus is on using impedances earlier on, focussing less on flow simulation quantities (Por, Perm) and more on geological reservoir properties (Por, Vshale, Sw).

From inversions and inversion products...


Deterministic inversion

Stochastic inversion

Elastic (inc. acoustic inversion)

Petroelastic

So a total of 4 types of inversion products.

Elastic:	invert to impedances
Petroelastic:	invert to petrophysical properties (via Rock Physics Models (RPMs) and PetroElastic Models (PEMs)

...to reservoir properties

In this presentation we take impedances from elastic inversions and perform the petroelastic step separately, with the practitioner in full control. Six techniques are covered:

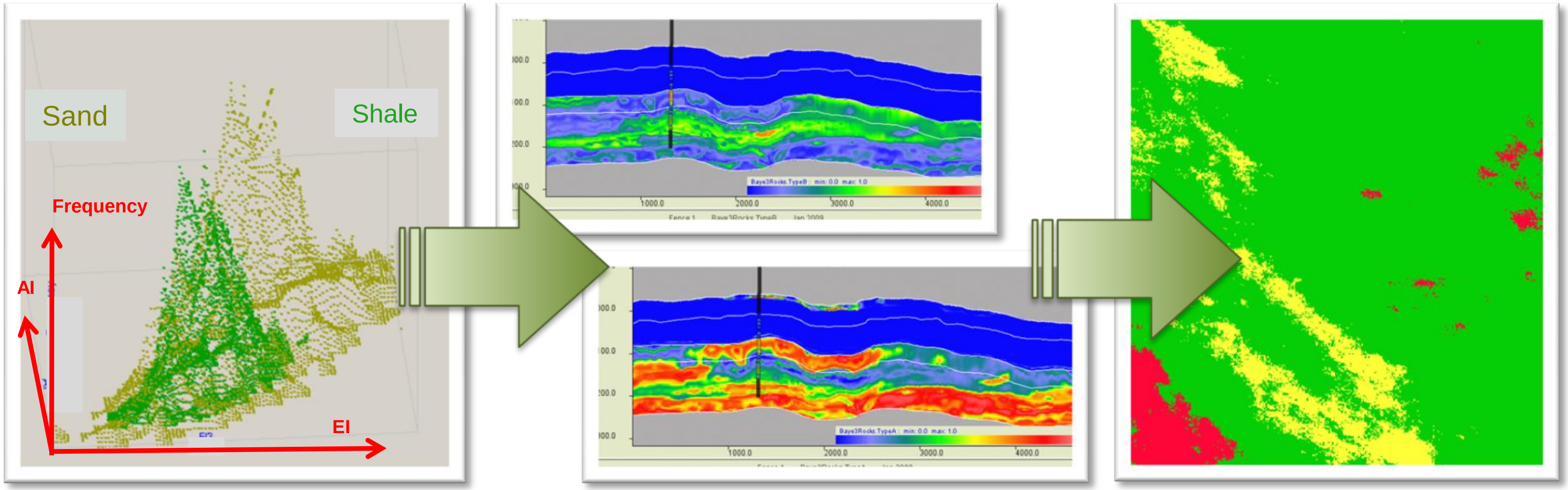
1. Bayesian classification
2. EEI illumination
3. Rock Physic Model (RPM) inverse modelling
4. Seismic Net Pay
5. Colocated co-Kriging
6. Multi-realization analysis
   - Statistical connectivity analysis
   - P90, P50, P10 Net-to-Gross
   - Probability of being inside a polygon

1. Bayesian Classification

$$P(A|B) \propto P(B|A)P(A).$$

Bayes' Theorem: Posterior $\propto$ Prior x Likelihood

You have a Prior idea/model of something (in this case overall facies distribution at the wells). With new data (the impedance cubes) you determine the likelihood that your Prior model fits the data.

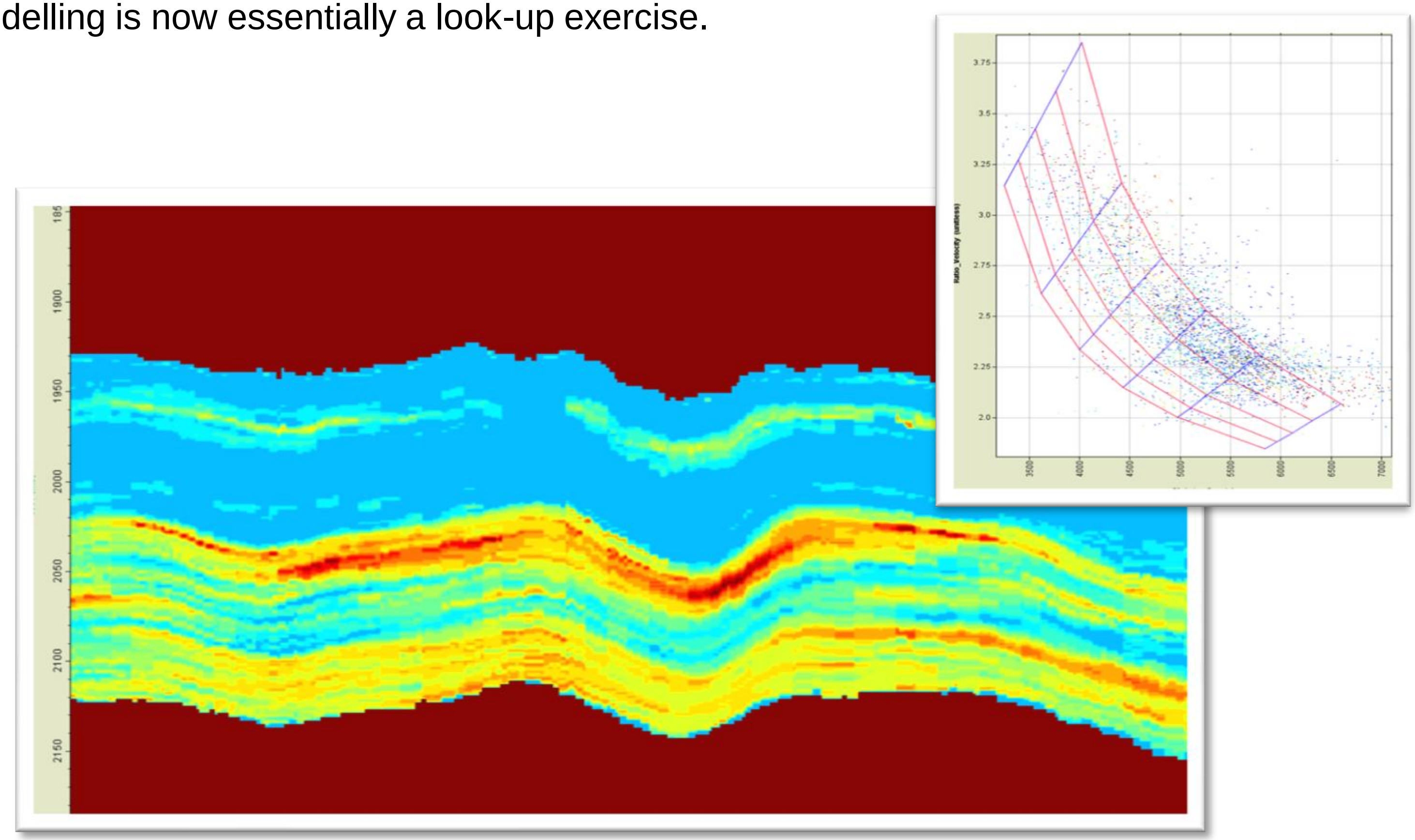


Maximum A-Posteriori Probability

2. RPM Template Inverse Modelling

Workflow:

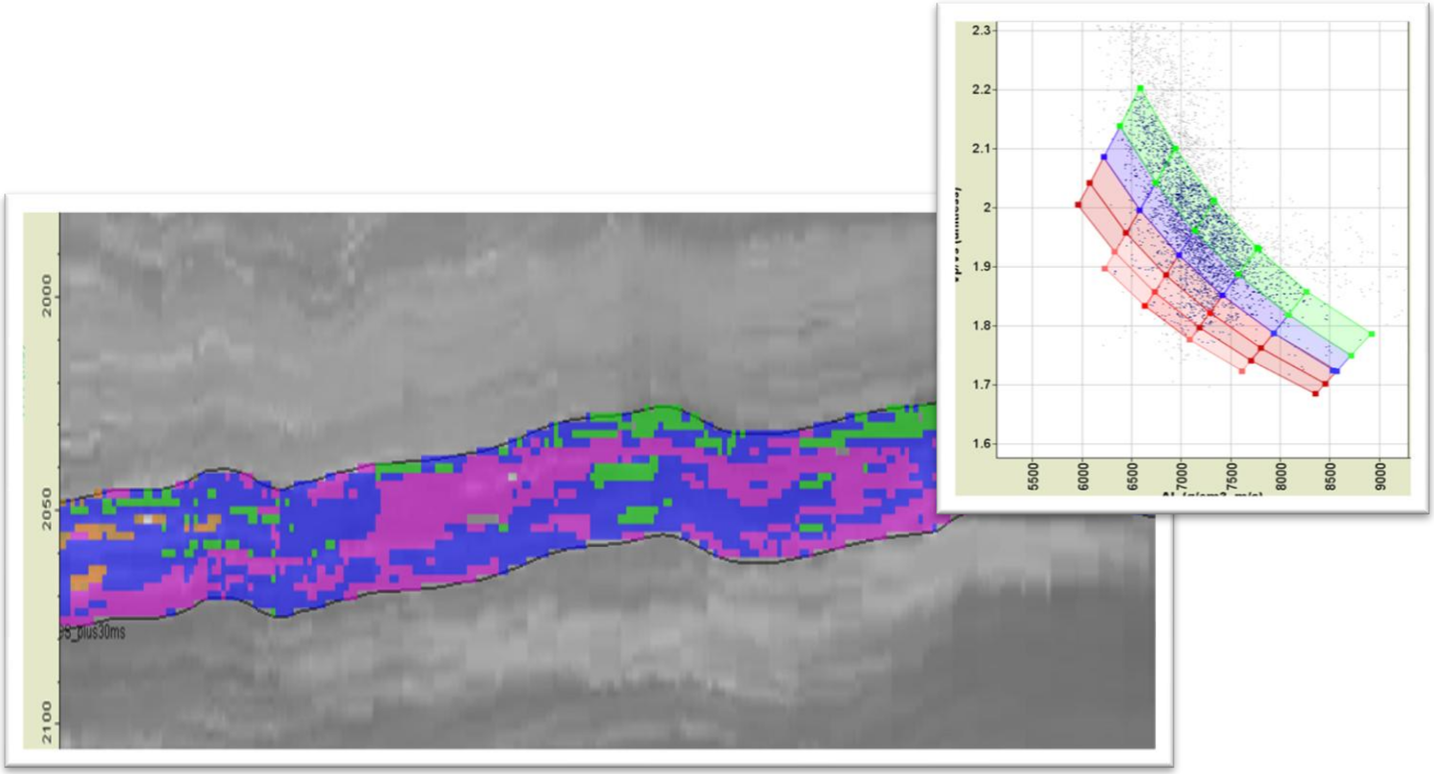
✓ Cross-plot well log data and overlay the appropriate rock physics model(s).
✓ Calibrate the rock physics model to the log data using (guidance from a petrophysicist required).
✓ Create a family of lines by stepping two of the input parameters (e.g. saturation and porosity).
✓ Add *calibrated/scaled* impedance data to the plot, limited to the reservoir.
✓ Inverse modelling is now essentially a look-up exercise.



Porosity obtained from AI and Vp/Vs data using a rock physics template

2. RPM Template Inverse Modelling: categorical

Another example, here we turn our rock physics template mesh into polygons and use them to classify our inversion data. We end up with a discrete classification based on the RPT.



Green = oil sands
Blue = brine sands
Pink = shales

EEI Background

- ✓ Extended elastic impedance (or reflectivity) is a concept introduced by Whitcombe et al 2002

- ✓ Linearised form of the Shuey 2 term AVO equation, where $\mathrm{Sin}^2\theta$ is replaced with TanX – a linear extrapolation beyond physically observable range of θ

- ✓ Provides a simple robust means of deriving lithological and fluid sensitive seismic impedance volumes – EEI at various Chi angles proven to be proportional to numerous elastic parameters e.g. K, λ, μ

- ✓ Very useful technique because it requires no background model – a common flaw of other techniques – particularly useful in areas with little or no well control

- ✓ It does have its limitations – rapidly varying geology (both vertically and laterally), boundary effects etc

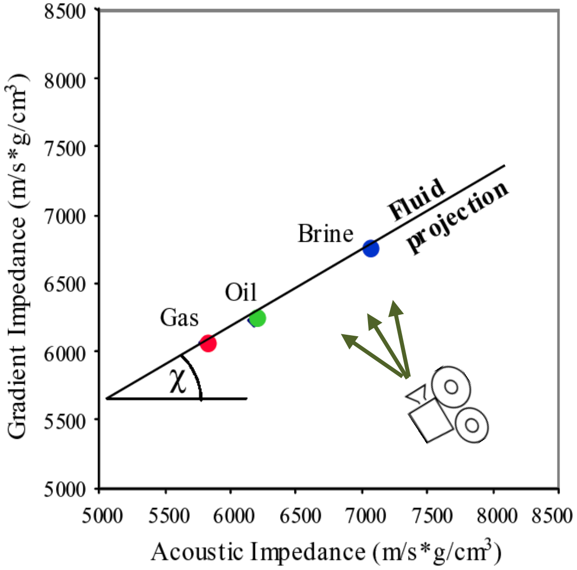
- ✓ Requires accurate determination of Intercept and **Gradient** (as do all inversions!) – Most time is spent here

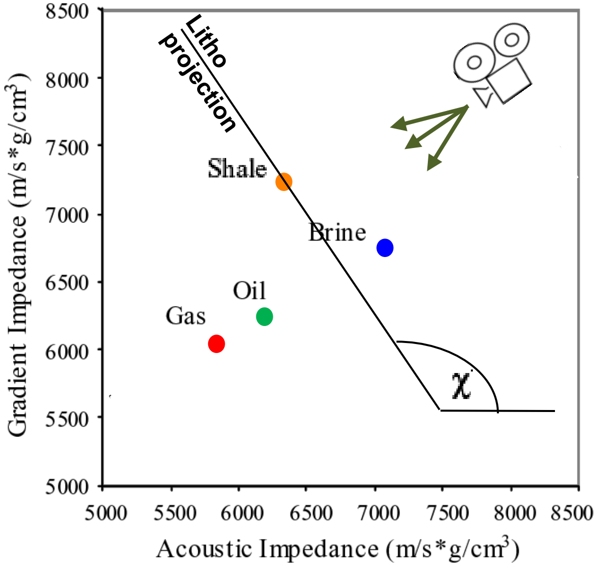
3. EEI illumination

Intercept we can invert → Acoustic Impedance = $V_p\ \rho$

Gradient we can invert → Gradient Impedance = $V_p\ V_s^{-8K}\ \rho^{-4K}$

In AI/GI cross-plot space we can linearly combine these two impedances, which we call Extended Elastic Impedance: EEI ≈ AI cosχ + GI sinχ

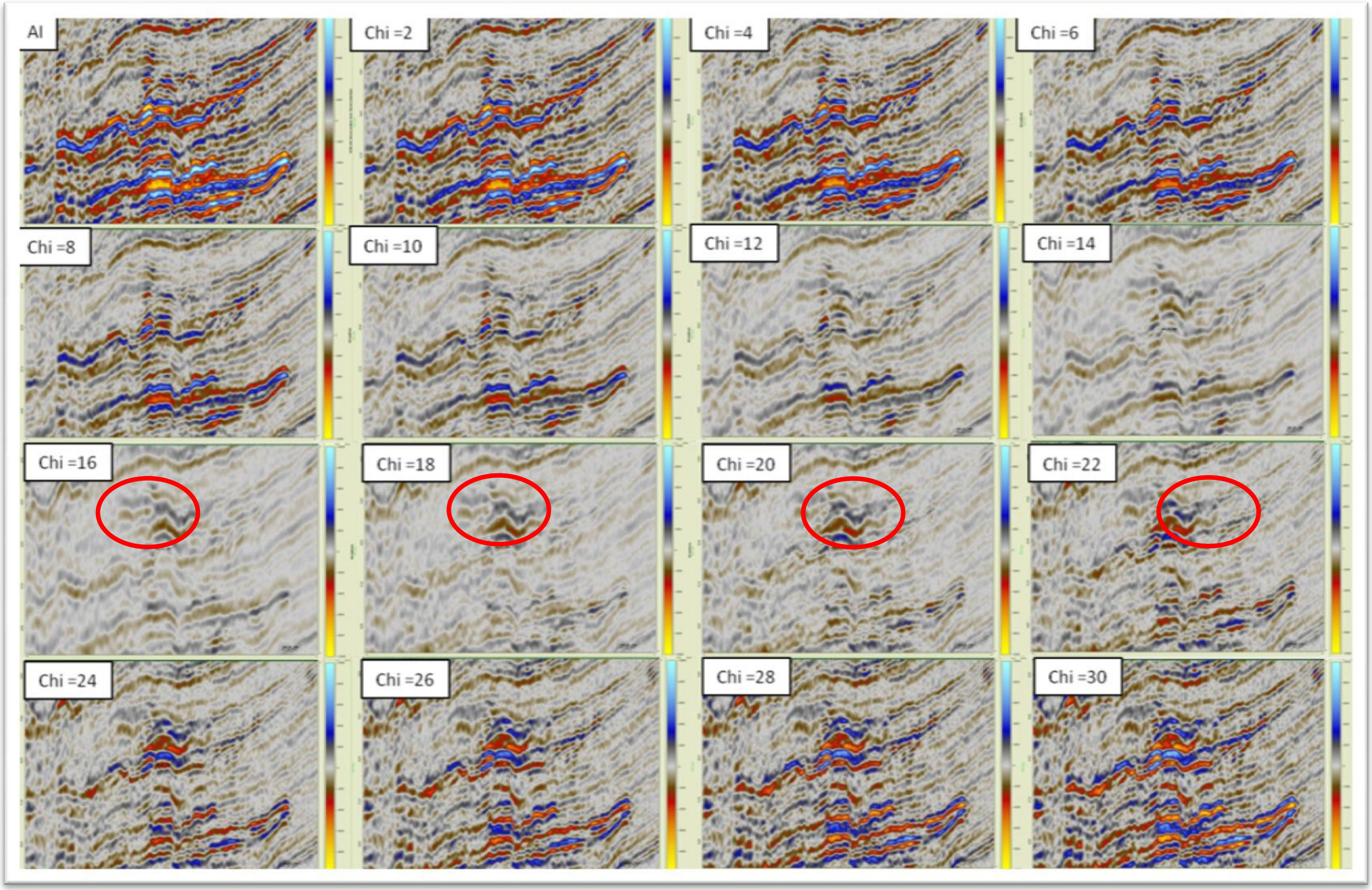




Whitcombe, D.N., Connolly, P.A., Reagan, R.L. and Redshaw, T.C. [2002] Extended Elastic Impedance for fluid and lithology prediction. ***Geophysics****, 67(1), 63−67.*

3. Or even simpler, just scan…

In this case we use χ increments of 2º.
Note how a fluid effect appears at ca. 16º and disappears (gets swamped) after ca. 24º

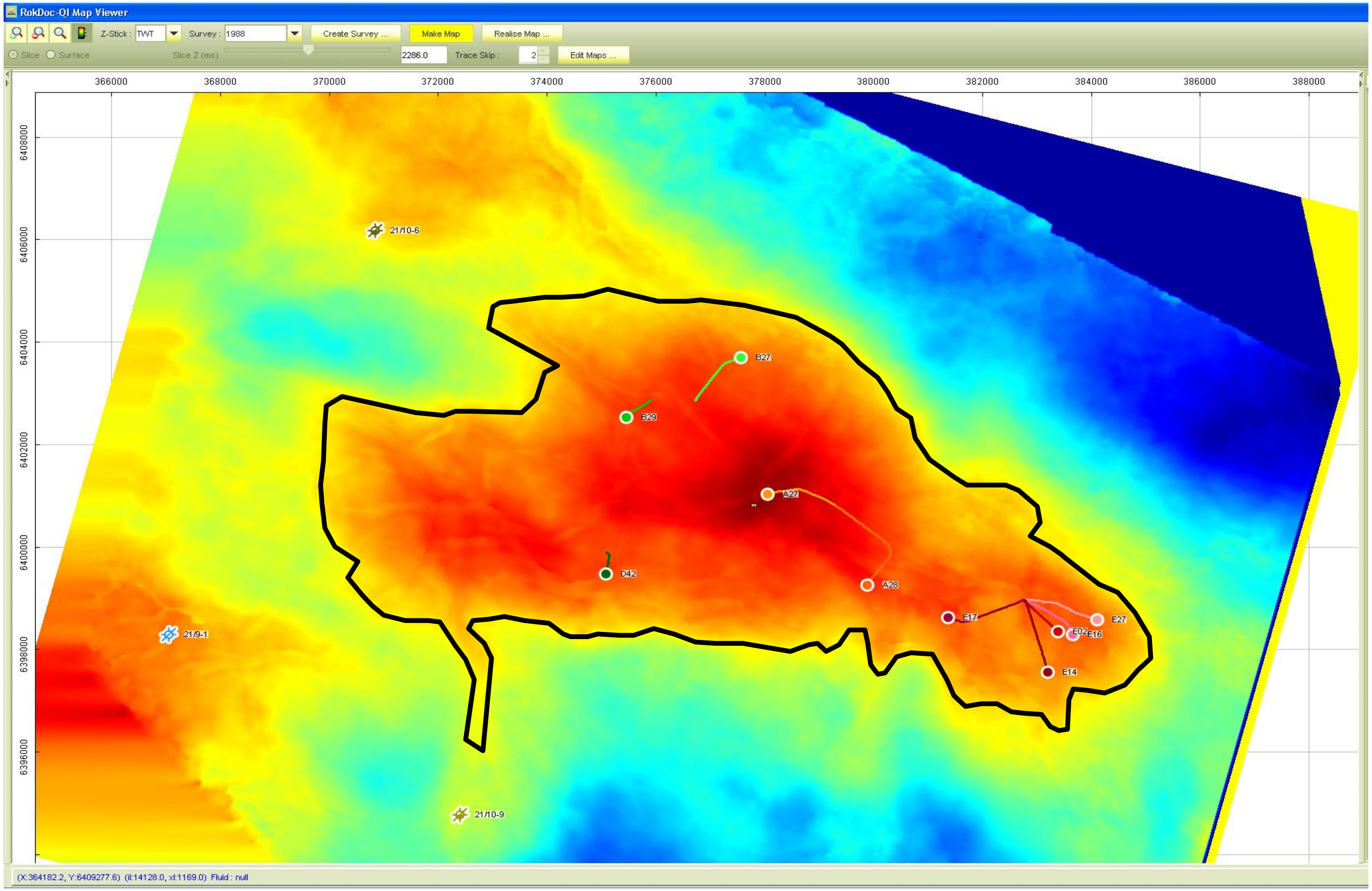


3. Addressing the issue of seismic noise

Seismic noise tends to rotate the projection angle away from where the well data suggests it should be. Below is one workflow that can help counter this issue:

- Determine χ (chi) angle from well data, generate a corresponding EEI log.
- From the EEI log create EEI reflectivity and convolve with an appropriate wavelet.
- Generate I and G from seismic angle gathers (or angle stacks).
- Combine I and G to give EEI and find the χ angle which produces EEI reflectivity that corresponds best to well based EEI reflectivity (from step 2).
- Using this χ angle create an EEI reflectivity cube.
- Colour invert this to band-limited EEI.

3. EEI illumination, an example



Z-Stick : TWT

Survey : 1988

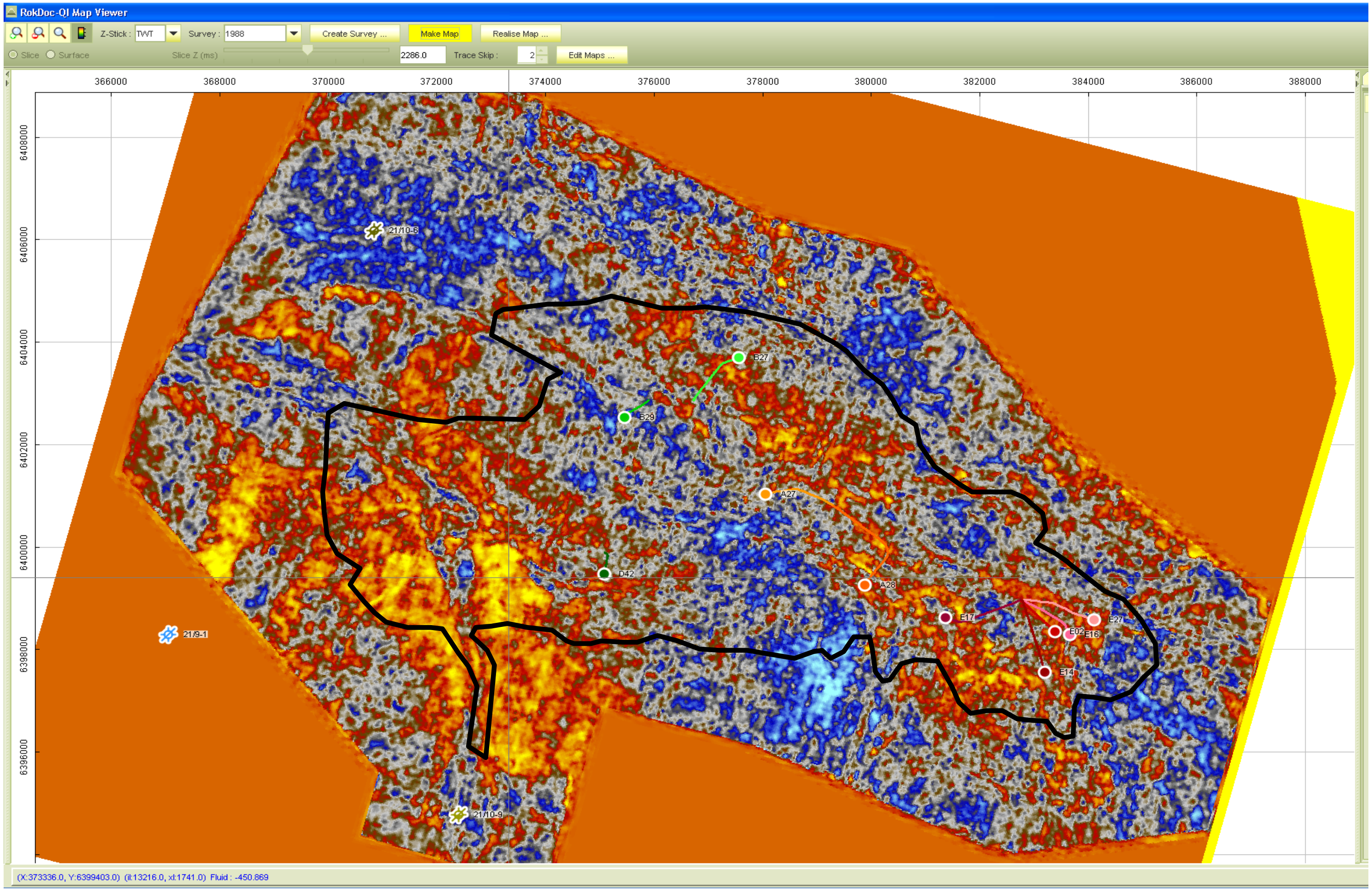
Slice Z (ms) 2286.0

Trace Skip : 2

(X:364182.2, Y:6409277.6) (il:14128.0, xl:1169.0) Fluid : null

TWT Structure

3. RAI



Z-Stick : TWT

Survey : 1988

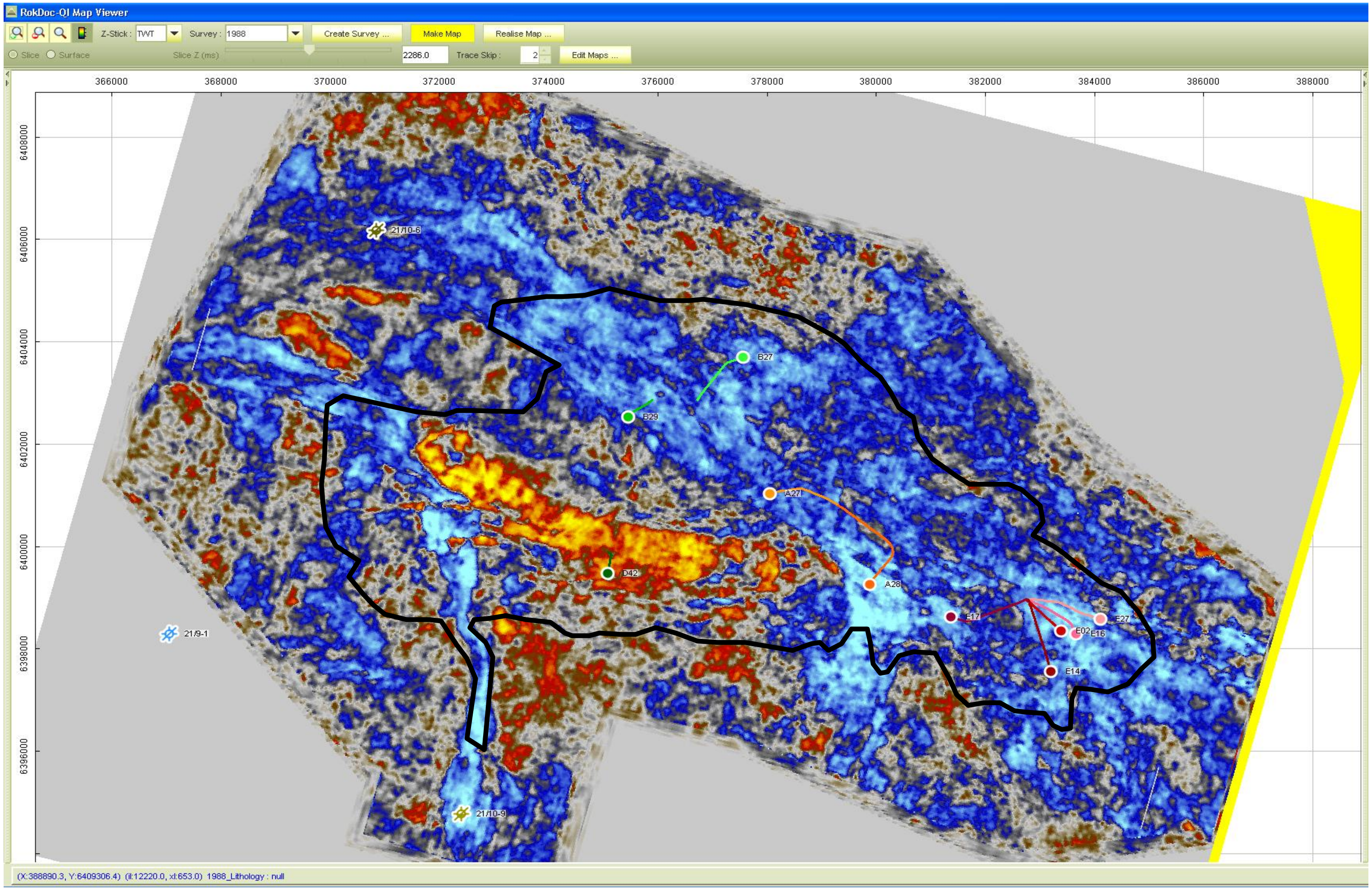
Slice Z (ms) 2286.0

Trace Skip : 2

(X:373336.0, Y:6399403.0) (il:13216.0, xl:1741.0) Fluid : -450.869

RAI sensitive to both lithology and hydrocarbons – difficult to interpret!

3. EEI -65 Window Extraction



Z-Stick : TWT

Survey : 1988

Slice Z (ms) 2286.0

Trace Skip : 2

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(X:388890.3, Y:6409306.4)  (il:12220.0, xl:653.0)  1988_Lithology : null
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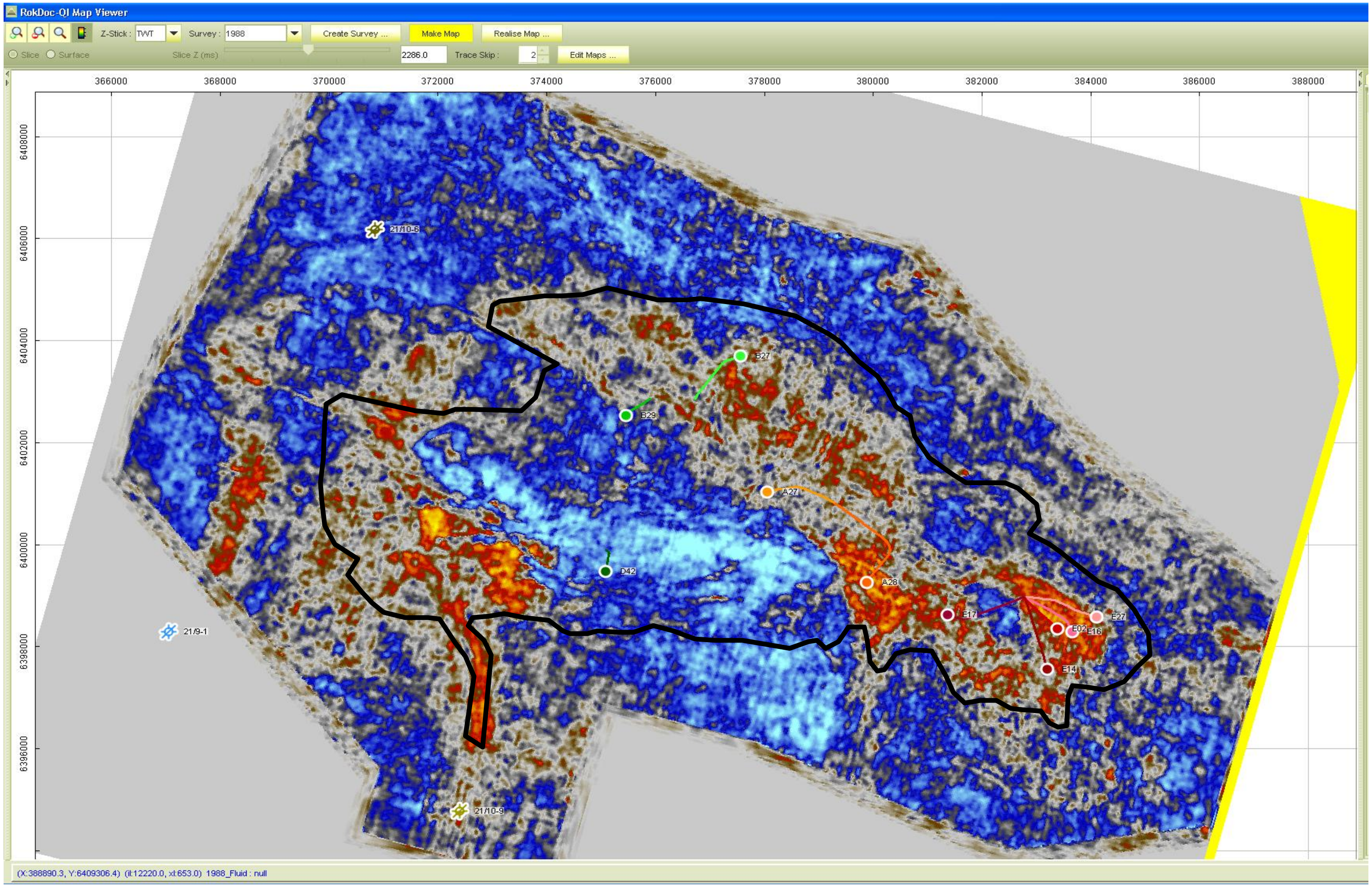
Lithology Angle – channel and fan/lobes highlighted (blue = sand)

3. EEI 25 Window Extraction



RokDoc-QI Map Viewer

Z-Stick : TWT

Survey : 1988

○ Slice ○ Surface

Slice Z (ms) 2286.0

Trace Skip : 2

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(X:388890.3, Y:6409306.4)  (il:12220.0, xl:653.0)  1988_Fluid : null
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Fluid Angle – illumination of hydrocarbon filled sand bodies (yellow = hydrocarbons)

4. Seismic Net Pay

We start with the obvious formula:

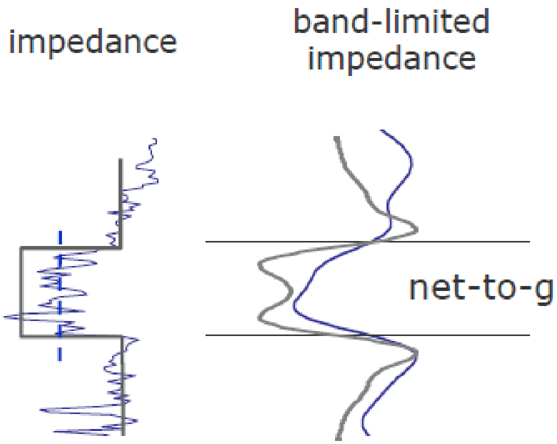
Net Pay = Gross-Thickness x Net-to-Gross

Both terms are actually difficult to get from seismic, as you would have to fully de-tune. So we term *seismic* net pay:

***Seismic** Net Pay =* ***Seismic** Gross-Thickness x* ***Seismic** Net-to-Gross*

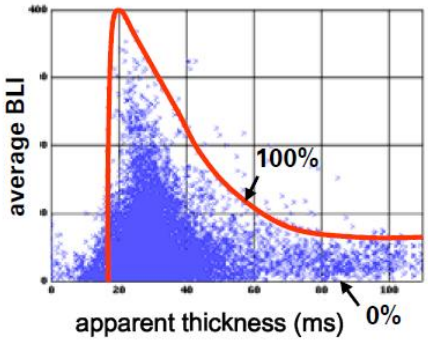
Seismic gross thickness comes from top and base reservoir horizons (depth converted). Seismic net-to-gross is the ratio of the average band-limited impedance for a given reservoir to the average band-limited impedance for a 100% net reservoir.

4. Seismic net-to-gross



net-to-gross = $\dfrac{\text{average value of reservoir*}}{\text{value of sand*}}$

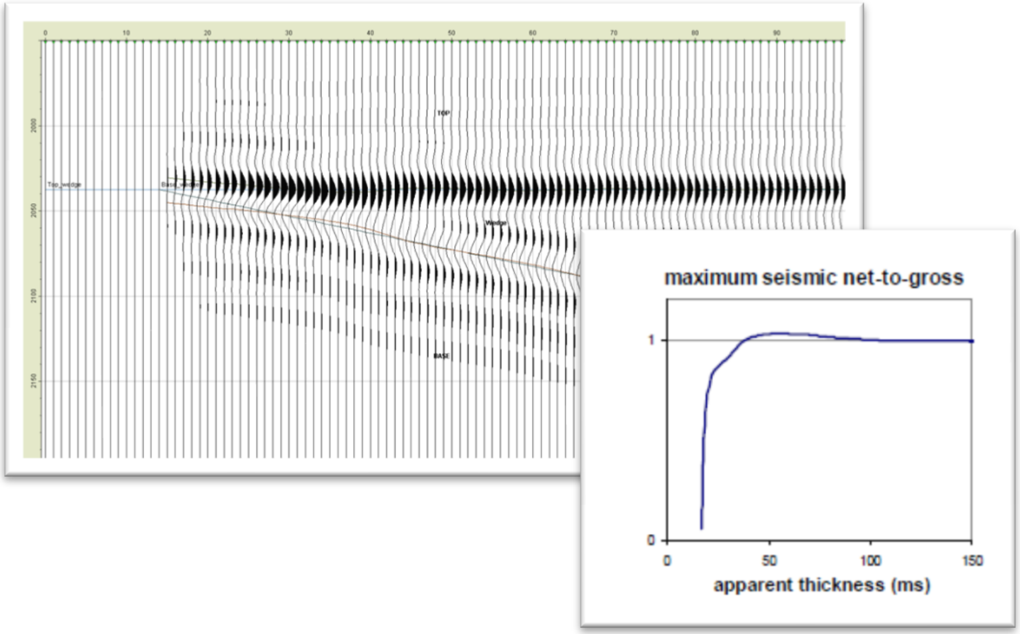
**relative to shale base-line*



The red pick is the average BLI for a 100% net reservoir, this curve is scaled to the response from a given reservoir. This scaling can be improved using well data.

From “Robust Workflows for Seismic reservoir Characterisation”, P. Connolly, **SEG Distringuished Lecture Series**, Spring 2010

4. Seismic net-to-gross: sub-tuning



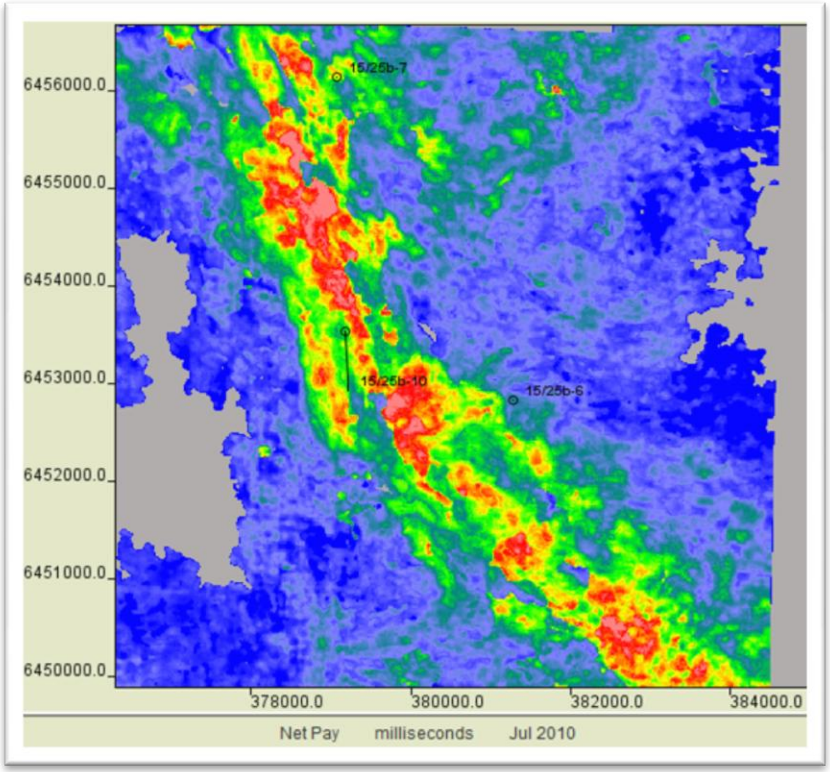
The apparent seismic thickness will be greater than true thickness sub-tuning (due to tram-lining). This means that the maximum net-to-gross will be less than one for sub-tuning thicknesses.

This means that we have to scale seismic net-to-gross using a correction function that is generated by multiplying the maximum seismic net-to-gross by the inverse average BLI.

From “Robust Workflows for Seismic reservoir Characterisation”, P. Connolly, **SEG Distringuished Lecture Series**, Spring 2010

4. Seismic net-pay

The net-pay map is calculated by multiplying the net-to-gross map by reservoir thickness (isopach).



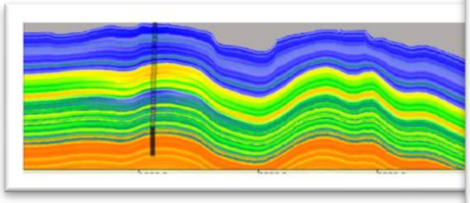
This can be used in volumetrics and well planning.

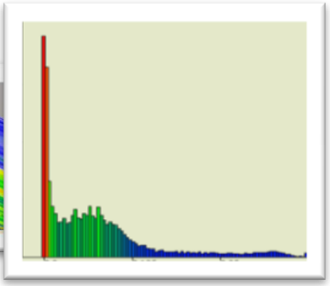
Note that there are also tools to determine uncertainty in Seismic net Pay.

“A simple, robust algorithm for seismic net pay estimation”, Patrick Connolly, **TLE, Oct 2007**

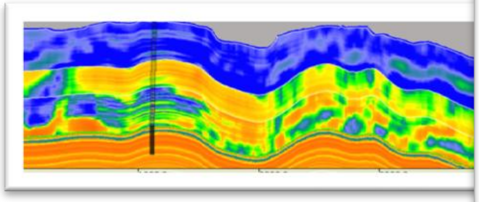
“Statistical estimation of reservoir characterization uncertainty”, Patrick Connolly and Michael Kemper, **TLE, Oct 2007**

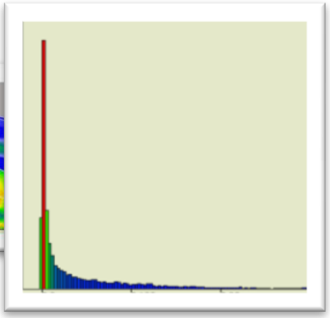
5. Colocated cokriging



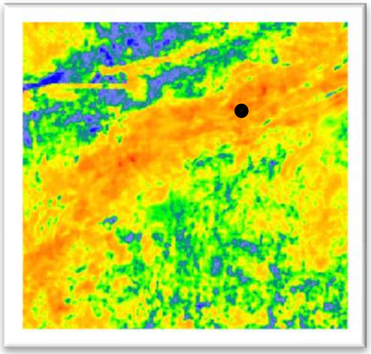


Porosity by Kriging well data only

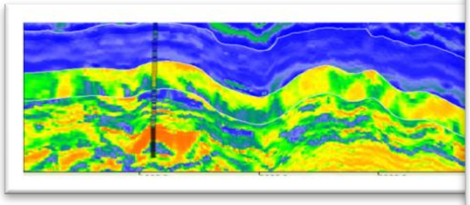


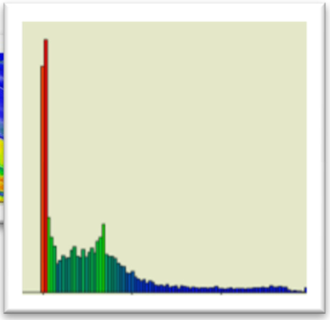


Porosity from a neural network trained at the wells to predict porosity from AI → No fit at the wells is guaranteed, and statistics are poor



Colocated co-kriging
(map view)





Porosity by combining seismic Inversion with well data using colocated co-kriging

This results honours the wells and has statistics closer to the well data.

Porosity sections

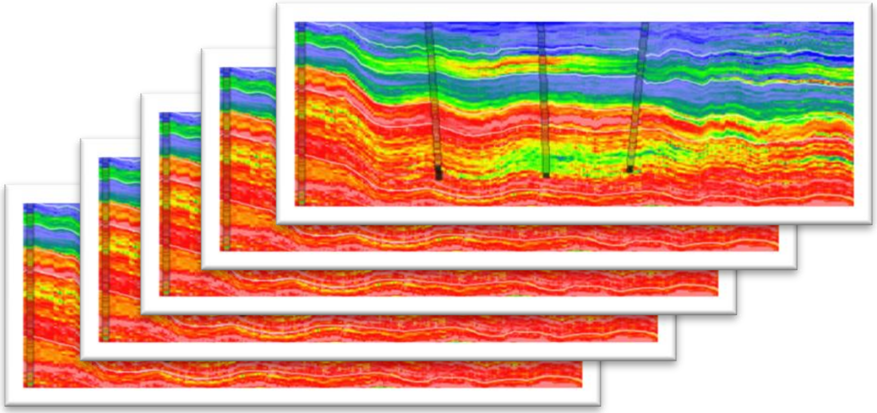
Porosity Histograms

6. Multi-realisation analysis

From (Joint) Stochastic Inversion we can obtain a number of equi-probable impedance realisations (or pairs, trios of realizations).

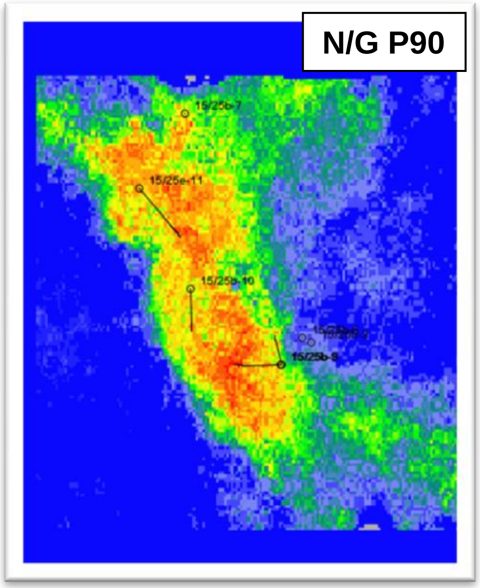
We can then analyse the whole set and not just pick one, or if we do pick a number we have to choose a representative suite. Below are some examples of multi-realisation analysis types:

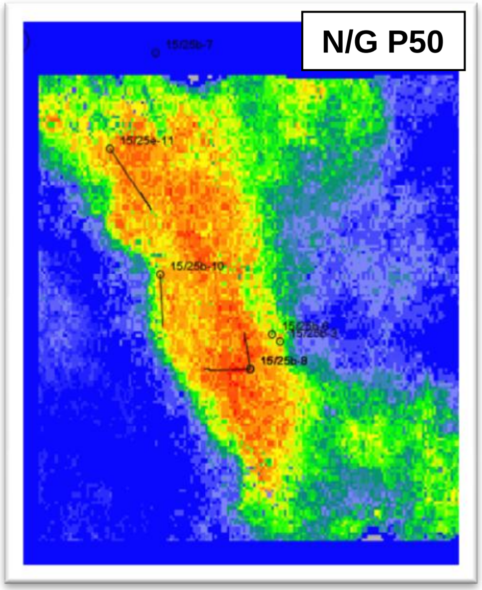
i. Statistical Connectivity analysis
ii. P90, P50, P10 Net-to-Gross
iii. Probability of being inside a polygon

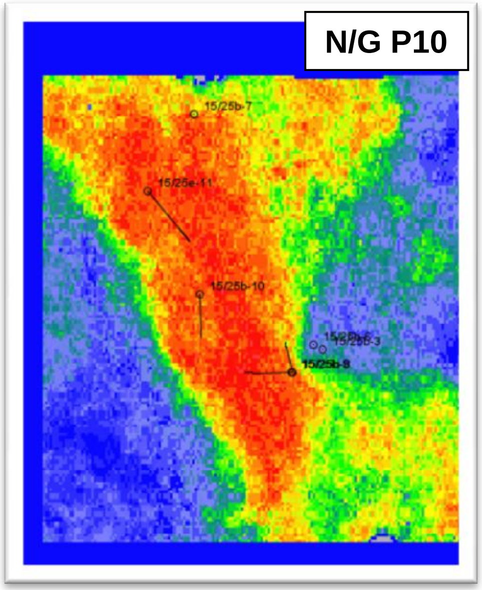


6. P10, P50, P90 Net to Gross

Similarly using impedance criteria we can make Net-to-Gross maps for all realisations, and then create the P90, P50 and P10 N/G maps shown after ranking.





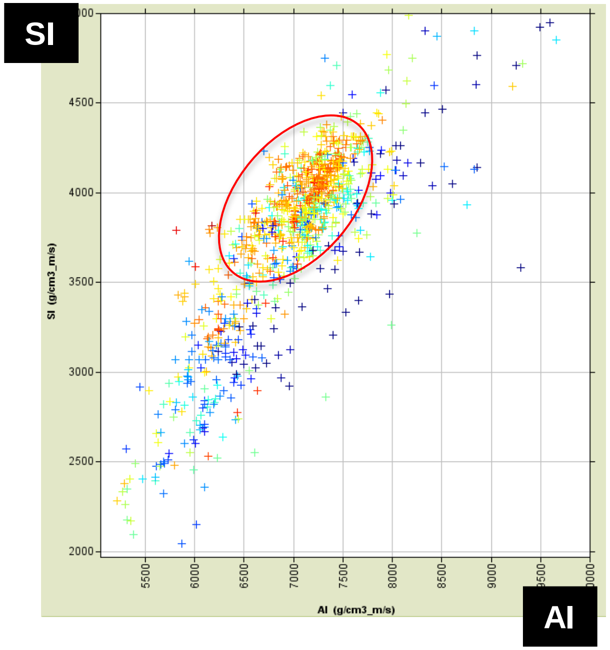


For volumetrics purposes, you would also need an isochore map.

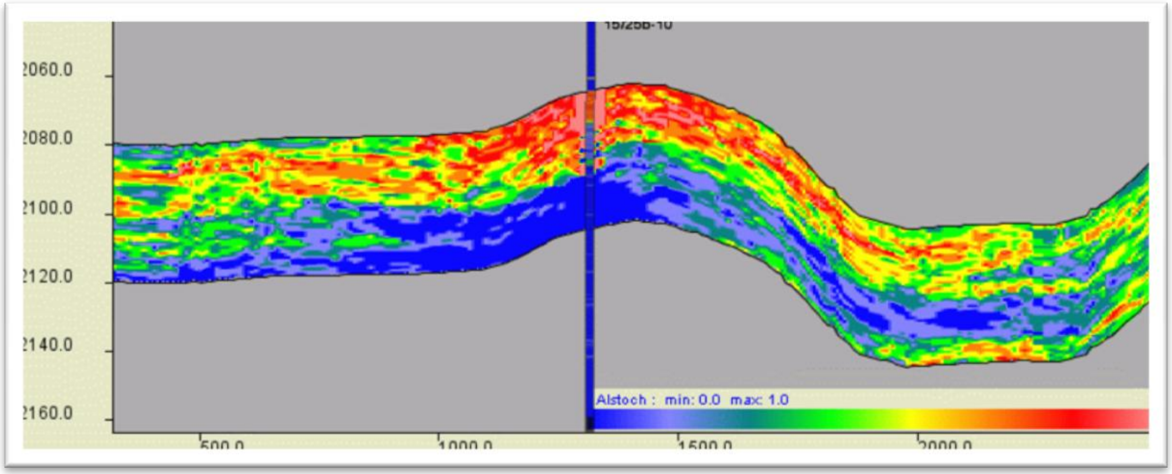
6. Probability of being inside a Polygon

Using rock physics analysis, the user digitizes a polygon around the region of interest on a cross-plot of well log data.

For each xyz point count how many of the AI-SI pairs are inside/outside the "Pay-Polygon", and you have a Probability of Pay Sand cube.



AI/SI cross-plot from well data



Probability of Pay Sand section

Conclusions

In field development the use of impedance results to populate 3D geological models, for subsequent flow simulation, is well established. In this presentation we have shown that impedance results can be used to good effect earlier in the process:

- ✓ Bayesian Classification and EEI illumination are techniques that can be used very readily indeed.
- ✓ ‘RPM Template Inverse Modelling’ and ‘Seismic Net Pay’ techniques are a bit trickier - ask your friendly Rock Physicists to give you a hand.
- ✓ Colocated co-Kriging is actually easy to do, but you need to create an accurate geological model.
- ✓ Multiple realisations (from a stochastic inversion) should be analysed in their entirety. Once a multi-realisation analysis tool is available, the analyses are easy and very powerful.

Thanks to Apache North Sea Ltd. for the data used to illustrate some of the examples in this PowerPoint.

Any Questions?

Nicholas Huntbatch
nhuntbatch@ikonscience.com