Technical Note:

Coloured, Deterministic & Stochastic Inversion

http://www.sorviodvnvm.co.uk

Earthworks Ltd - Company Overview

Earthworks Environment & Resources Ltd. was formed in June 2001 to provide services and consultancy internationally to the oil and gas industry. Specialising in subsurface geosciences, Earthworks has a broad set of skills in geophysics, geostatistics and risk and uncertainty evaluation.

Earthworks is a specialised company offering the latest technology through staff fully conversant with all technical aspects of the work. Our expertise and understanding in geophysics and geostatistics is second to none and as a consequence we are also a leading trainer to the industry in these disciplines, through courses and technical conferences.

Based in the historic medieval town of Salisbury in the heart of the English countryside, we offer the most modern technology and electronic communications in ancient surroundings. We have ready access to London, the City and its international airports, allowing Earthworks to provides services and consultancy to any locale or operation worldwide.

Earthworks Environment & Resources Ltd
Prestex House
Edison Road
Churchfields
Salisbury
Wiltshire
SP2 7NU

Tel: 01722 343990
Fax: 01722 343991
Web: http://www.sorviodvnvm.co.uk

Introduction

This brief technical note is intended to provide information on Earthworks' capabilities to undertake inversion. In addition, it also serves as a briefing document on our ultra-fast stochastic inversion software with which we can perform stochastic inversion studies on a routine basis.

Overview of Seismic Inversion Workflow

Our seismic inversion workflow, illustrated opposite, is based on a phased approach. Subsequent phases depend on completion of previous phases of work. The end of each phase is a convenient break-point at which the work and results can be evaluated with the client and a decision made to proceed to more sophisticated analysis in subsequent phases.

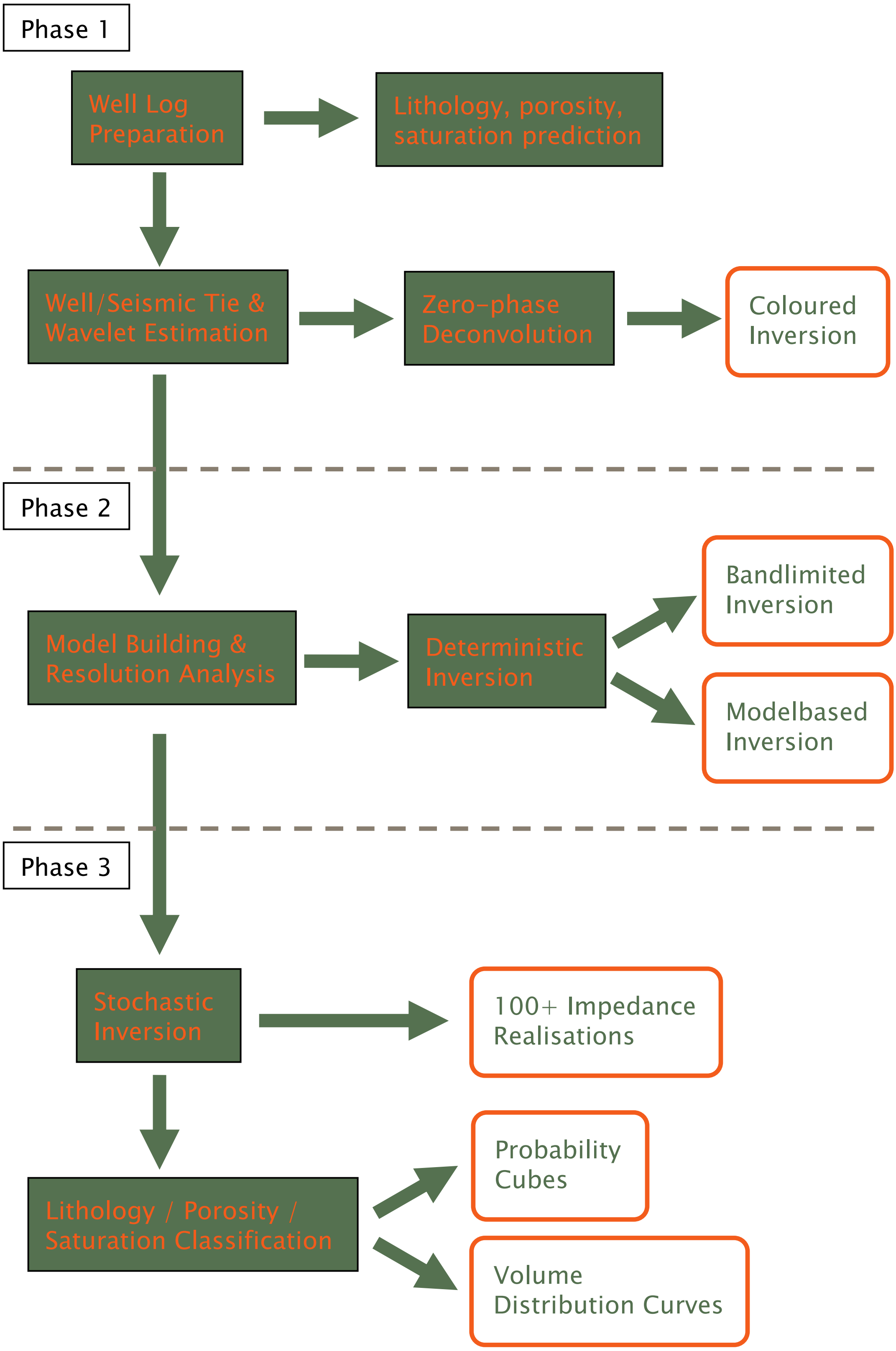
Phase 1 involves the most time consuming aspects of any inversion study. Objectives of Phase 1 include preparing the well logs, investigating relationships between impedance and reservoir properties and tying the well logs to the seismic.

After tying to the seismic, the well log data is used to estimate a seismic wavelet. By application of zero phase deconvolution a broad-band zero-phase dataset is obtained which forms the input to coloured inversion (Lancaster and Whitcombe, 2000). Coloured inversion converts the seismic data to a relative impedance data set. The advantages of coloured inversion are the speed of calculation and avoidance of artefacts that may be introduced by a model. Coloured inversion, whether acoustic or elastic impedance (Connolly, 1999), is an excellent qualitative interpretation tool.

Phase 2 attempts to obtain more resolution from the seismic and to provide absolute impedances through the procedure often referred to as deterministic inversion. A model of impedance is built from the wells and seismic horizon interpretation and this model used to constrain the subsequent inversion. Our model building method is geostatistical and involves 3D anisotropic variogram analysis and kriging. We offer two deterministic inversion approaches, both of which are delivered as standard to the client. The first is band-limited inversion, in which a scaled relative impedance from the seismic data is mixed with a low frequency element from the model. The second approach is model-based inversion technique (Russell and Hampson, 1991).

Phase 3 uses the geostatistical model constructed in phase 2 but instead of using deterministic inversion to obtain the expected value of impedance we compute alternative realisations of the impedance through our ultra-fast stochastic inversion technology (Francis, 2001; 2002). The set of impedance cubes represent the uncertainty or non-uniqueness in the inversion. The realisations can be calculated at any resolution and reproduce the well log impedance distributions. This allows relationships defined on the well logs to be applied directly to the impedance realisations, something which cannot be done with deterministic inversion. In addition, the forward convolution of each impedance realisation will match the seismic traces. Application of classifiers or transforms from impedance to reservoir properties, identified in Phase 1, across the impedance realisations give the typical output from the stochastic inversion in the form of a single seismic cube representing the probability of sand, porosity or saturation distribution through the reservoir.

Seismic Inversion Workflow



Phase 1 – Coloured Inversion

Well Log Preparation

After data loading and checking, well log preparation comprises a series of procedures designed to prepare the log data for comparison with the seismic. Typical procedures applied include log editing, application of Gassman fluid substitution, checkshot calibration and calculation of acoustic and elastic responses.

Impedance Analysis

In order to understand the predictive capabilities of impedance, forward modelling will be used to investigate resolution issues and sensitivity of seismic to changes in lithology and reservoir parameters. Cross-plotting of impedances and reservoir parameters such as lithology, saturation or porosity allow quantitative relationships and reservoir property predictors to be established. Predictors might be defined by impedance cutoffs, probability density functions or fuzzy classifications and may include near and far offset information. In the example (page 7, top left) porosity is poorly discriminated, but an impedance cutoff (> 8,150 m s^{-1} * g cm^{-3}) or fuzzy classification can discriminate clean sands, as shown by the separation on the histograms (page 7, top right) (Francis, 1997). It is important to remember that these relationships are defined at well log scale and can only be used for prediction based on stochastic inversion, which reproduces the impedance distribution through geostatistical conditional simulation.

Well Ties

After preparing the well logs and reaching an understanding of the reliabilty of impedance for predicting reservoir properties the wells are converted to the time domain and tied to the seismic. Our well tie procedure includes phase independent methods based on amplitude envelope and Backus upscaling. Backus upscaling attempts to account for wave propagation through thin-layered formations and can be a useful additional tool in improving the tie of the well to the seismic.

At Earthworks we never apply stretch or squeeze in order to arbitrarily improve well ties. In our experience, these practices are unnecessary and tend to propagate noise into the wavelet estimation. This in turn tends to result in inconsistent wavelets estimated at the different wells.

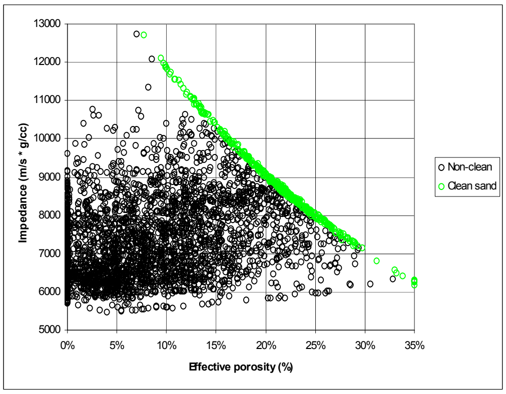
An example well tie and some of the individual estimated wavelets at different wells are shown on page 7 (centre).

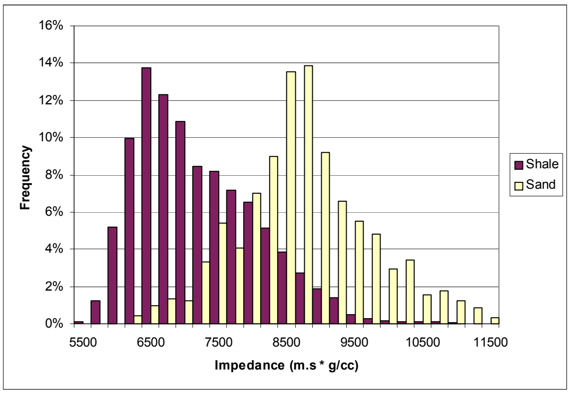
Wavelet Estimation & Zero Phase Deconvolution

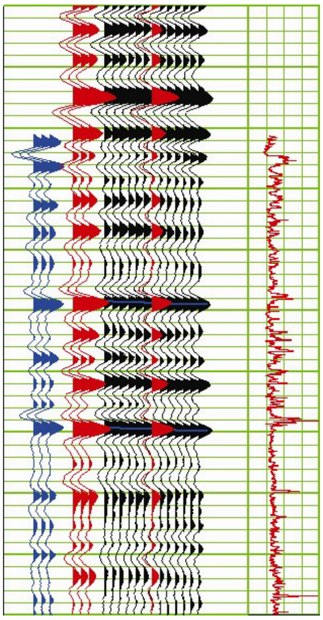
Wavelet estimation proceeds through a choice of three methods:

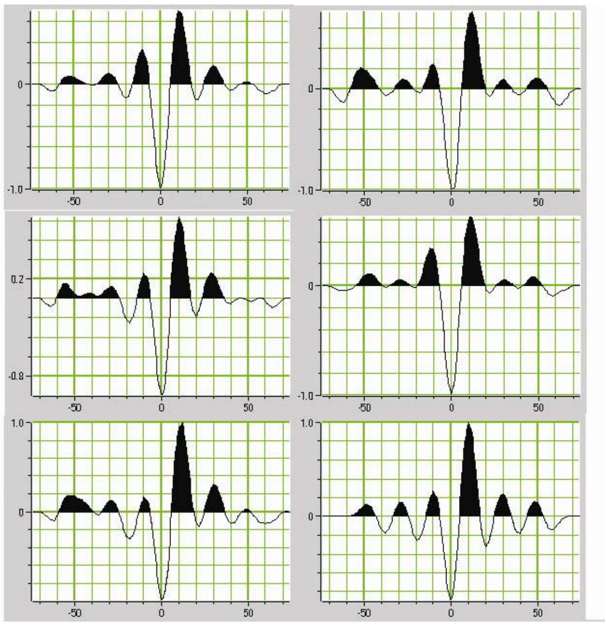
- Constant Phase
- Wiener-Levinson full phase
- Roy White method (White, 1980; Walden and White, 1984)

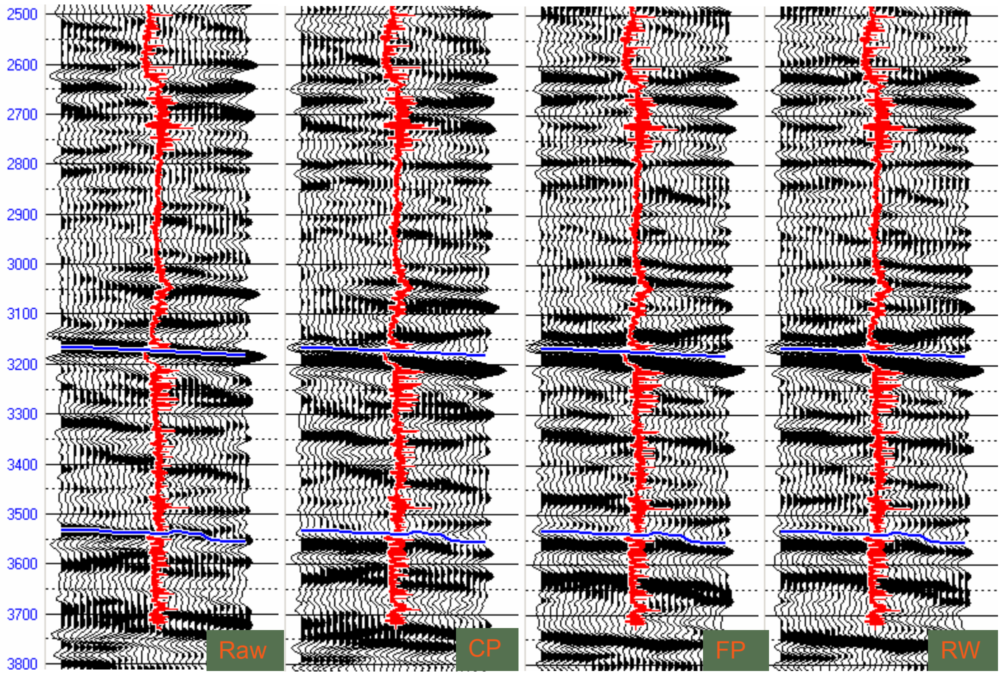
These are tested in turn to select the most suitable given the seismic data quality. Examples are shown on page 7 (bottom), the results of de-phasing using constant phase (CP), full phase (FP) and Roy White (RW) are compared to the raw seismic.


13000
12000
11000
10000
9000
8000
7000
6000
5000
Impedance (m/s * g/cc)
0%
5%
10%
15%
20%
25%
30%
35%
Effective porosity (%)
○ Non-clean
○ Clean sand


16%
14%
12%
10%
8%
6%
4%
2%
0%
Frequency
5500
6500
7500
8500
9500
10500
11500
Impedance (m.s * g/cc)
Shale
Sand




0
-1.0
-50
0
50
0
-1.0
-50
0
50
0.2
-0.8
-50
0
50
0
-1.0
-50
0
50
1.0
0
-50
0
50
1.0
0
-50
0
50


2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
3600
3700
3800
Raw
CP
FP
RW

Phase 1 (continued)

Relative Impedance & Coloured Inversion

After obtaining a wavelet estimate, the wavelet is used to design an inverse operator to zero-phase deconvolve the seismic. The deconvolution may be a de-phase only or a full-inverse procedure to correct both the phase and the amplitude spectra. Pre- and post-deconvolution seismic is compared on page 9.

After zero phase deconvolution, a simple approach to estimate relative impedance is by trace integration. The result obtained from this straightforward method is also shown on page 9. Generally, we do not deliver this product to clients, preferring instead to supply the coloured inversion result shown at the bottom of page 9. Coloured inversion is reliable, quick to produce and may be generated for acoustic and elastic impedances, thus conveniently capturing AVO effects.

In the Stratton Field data set used here for illustration (see notes below), there is sand characterised by higher impedances in Well-08 at a time of 1275 – 1280 ms. The sand can be qualitatively interpreted in the coloured inversion display as the mainly red interval, tracking down into the 1280 – 1290 ms interval either side of the well. The same interpretation can be made on the relative impedance, but the resolution and clarity are poorer.

At Earthworks we consider coloured inversion to be the most cost-effective, qualitative impedance product that we can deliver to our clients. Its advantages are ease of interpretation and, being a seismic attribute, it avoids artefacts which may be introduced by models used to constrain deterministic inversions (Francis and Syed, 2001). However, coloured impedance is still a relative measure of impedance changes and therefore is not suitable for use in quantitative estimation of reservoir properties, as may have been indicated by analysis of the relationships between lithology or reservoir properties and acoustic or elastic impedance.

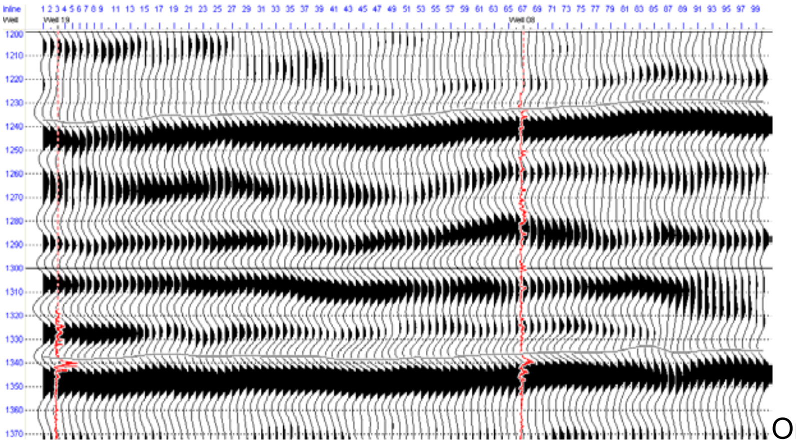
It may be that for the target reservoir under study impedance cannot predict reservoir properties quantitatively. If this is the case then consultation with the client and a decision to stop further analysis may be taken. The coloured impedance cube would then be the final deliverable for qualitative interpretation by the client.

Notes on Stratton Field 3D Seismic Data

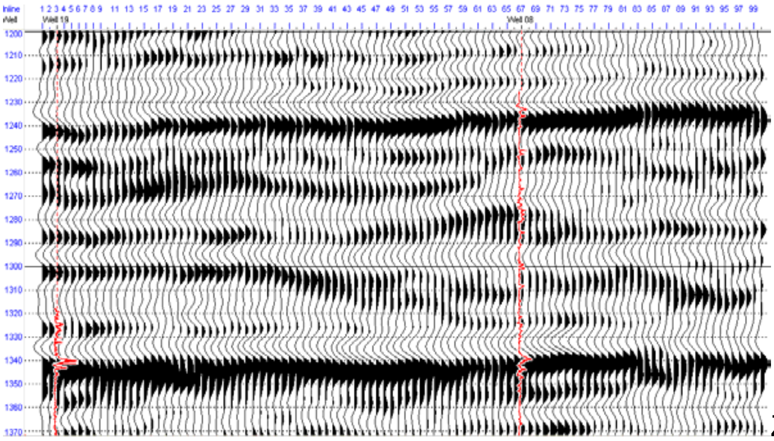
The data-set used here to demonstrate stochastic inversion is the Stratton Field 3D seismic and well log data package, prepared by the Bureau of Economic Geology, Austin, Texas, USA (Levey et al, 1994).

Stratton Field is an on-shore gas field producing from the Oligocene Frio Formation in the NW Gulf Coast Basin. The top of the middle Frio formation is about 1200 ms, the start of the data shown here. There is little faulting in this interval. Depositional environment is multiple amalgamated fluvial channel-fill and splay sandstones. The composite channel fill deposits range from 10 to 30 ft thickness and up to 2,500 ft width. Splay deposits shown typical thicknesses of 5 to 20 ft and are proximal to the channel systems.. Sands are generally indicated by high impedances and have typical velocities of 12,000 ft s^{-1}, a 30 ft sand thus being around 5 ms thick.

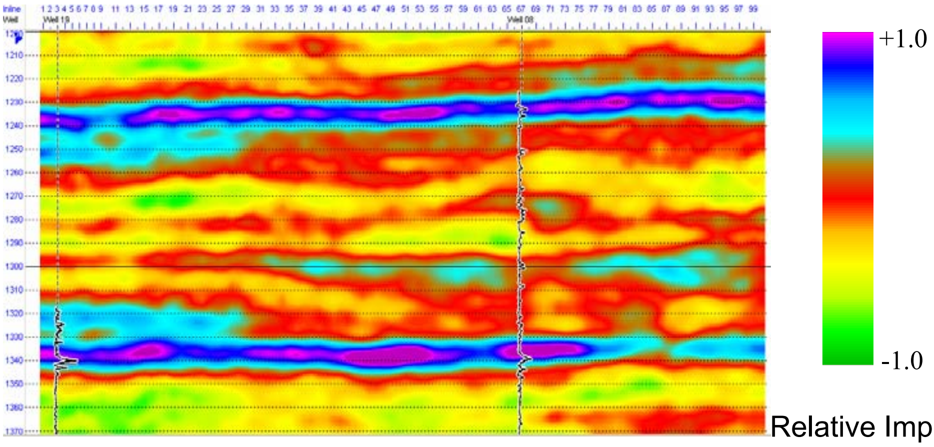
Each seismic cross-section is cross-line 154 from the 3D cube. The sand maps on pages 14 and 15 show the location of this section (as a red N-S line) and its relationship to the wells.



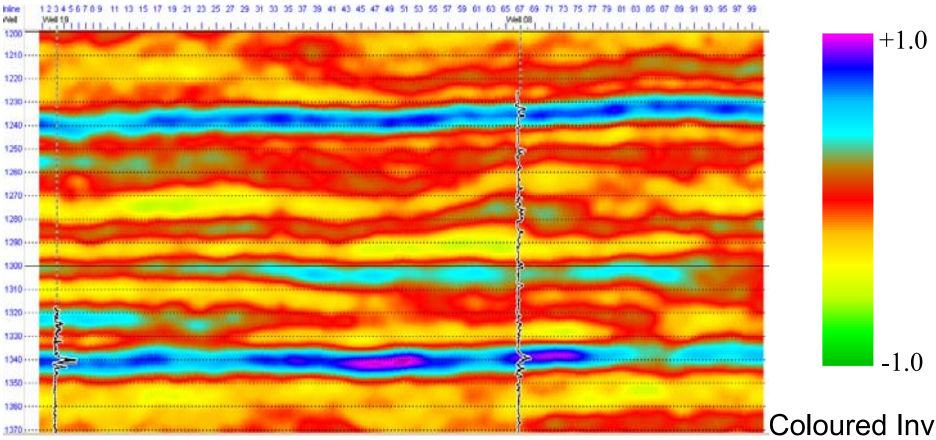
Original Seismic



Zero-phase deconvolved



Relative Impedance



Coloured Inversion

Phase 2 – Deterministic Inversion

Model Building

Earthworks has developed its own geostatistical model-building scheme, writing software specifically for this purpose. The basic framework is provided by the seismic horizons. Between the horizons, we interpolate the well impedance values using kriging, either proportional to the seismic horizons or conformal top or base to the horizons.

As our method is geostatistical and the same model will be used subsequently in stochastic inversion, we analyse the data using variograms. Each layer (bounded by the seismic horizons) is able to have its own 3D anisotropic variogram model definition.

Vertical variogram analysis is made directly from the well log data (page 11, top left). Horizontal variogram analysis is made from horizon slices through the relative impedance data obtained from the coloured inversion completed in Phase 1 (page 11, top centre). If sufficient wells are available, the variogram model from the horizontal slice analysis will be compared to the horizontal well variogram (page 11, top right). The directional variograms define the model shape and range, the vertical direction also defines the sill.

Deterministic Inversion

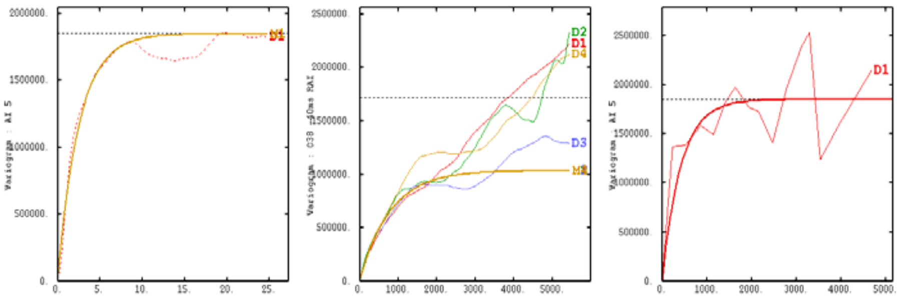
Conventional seismic inversion to absolute impedance is commonly referred to as deterministic. We usually compute these cubes as a quality control step before proceeding to stochastic inversion, but for some clients the deterministic impedance cubes may be the final delivered product from an inversion study.

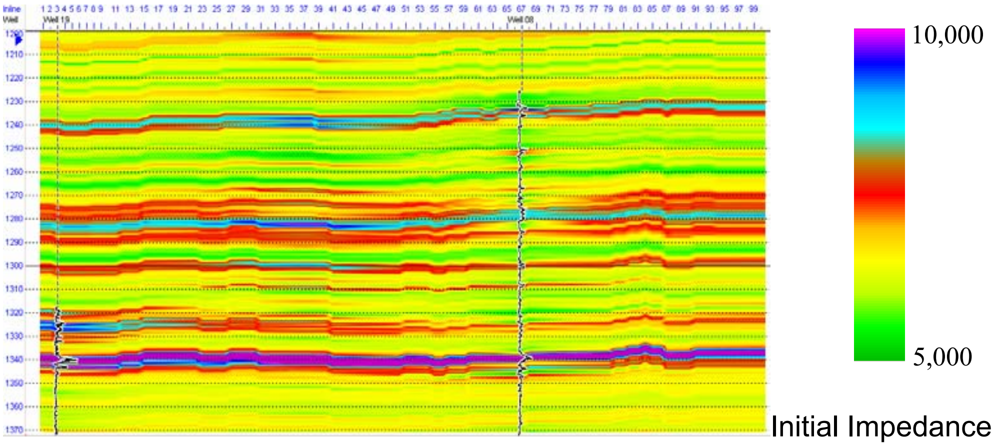
Band-limited inversion is a method in which the relative impedance component from seismic is scaled and added to a low pass filtered (low frequency) model. The result is an absolute impedance cube. Band-limited inversion is useful as a qualitative interpretation tool, but suffers from some drawbacks. In particular, the wavelet is not removed and resolution is not improved

In model-based inversion, the initial model is iteratively updated using generalised linear inversion in order to obtain an optimal impedance solution whose forward convolution is a good match to the seismic. It is a robust and reliable method, able to remove the wavelet and, given a good initial model, improve resolution and remove tuning effects.

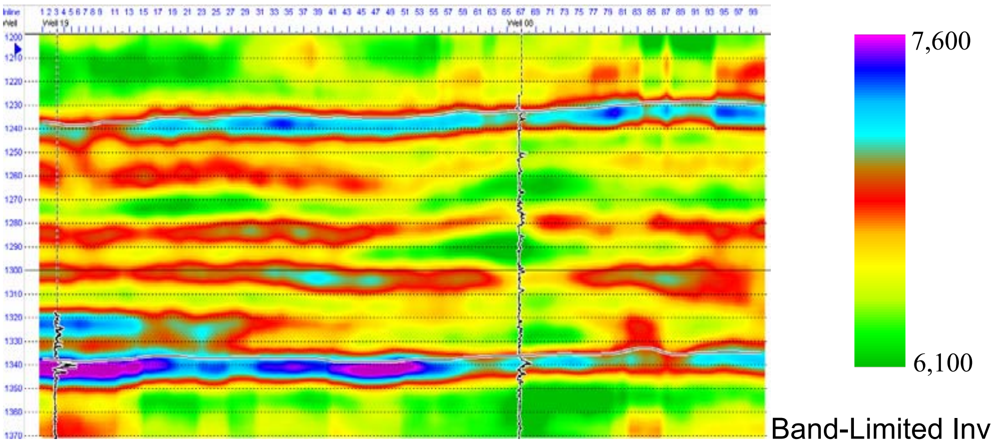
There are two significant limitations of all deterministic inversion schemes (including sparse-spike inversion). The first is that the model is embedded in the result and this may introduce artefacts which can be misleading in interpretation (see Francis and Syed, 2001; Francis, 2002). In order to reduce the risk of mis-interpretation we always deliver the model in addition to the inversion results to the client and recommend that horizon slices are compared between model and inversion.

The other limitation of deterministic schemes is that, because they produce optimal solutions, they are unable to reproduce the full range of impedance observed in the wells. This means that cutoffs or classifiers determined from well logs should not be applied to the absolute impedances obtained from deterministic inversion schemes.

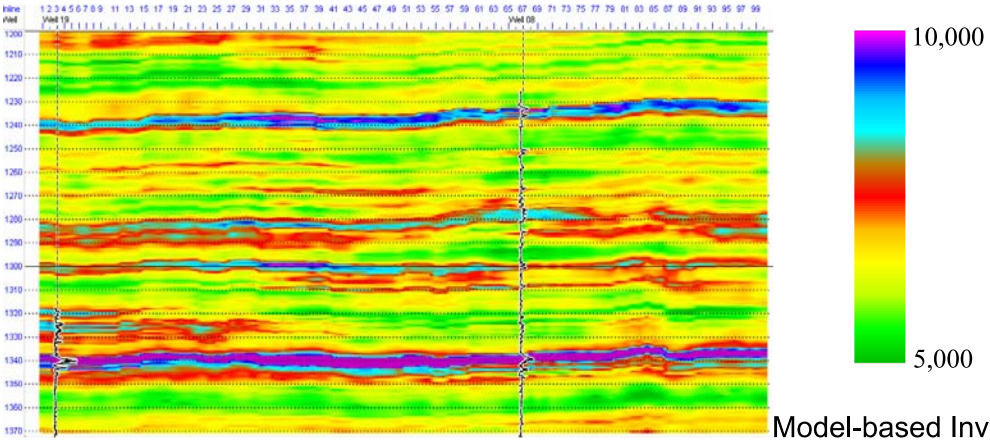




Initial Impedance Model



Band-Limited Inversion



Model-based Inversion

Phase 3 – Stochastic Inversion

The stochastic inversion technique developed at Earthworks is a hybrid approach which enables the computation of stochastic impedance realisations using a conventional inversion algorithm.

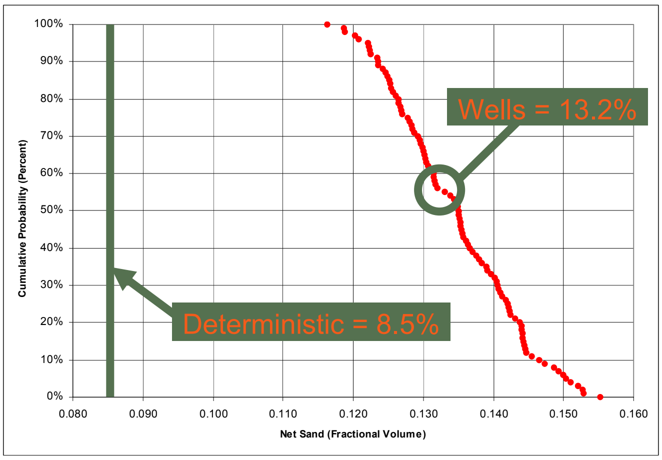
Using the same seismic horizon framework, well logs and 3D anisotropic variograms defined for kriging the initial model for deterministic inversion in Phase 2, we use a very fast FFT-based spectral simulation method to generate impedance realisations, conditional to the well impedance data. As necessary we can also generate coupled conditional realisations as may be required in joint inversion for near / far offset impedance or time-lapse studies. The initial impedance realisations are then updated by application of the generalised linear inversion (GLI) algorithm in order to make them conditional to the observed seismic.

The algorithm is ultra-fast, allowing routine calculation of 100+ impedance realisations of large 3D seismic datasets without any special computer hardware requirements. Using a conventional, high specification two processor PC the dataset shown here takes under 5 hours to compute one hundred 3D realisations.

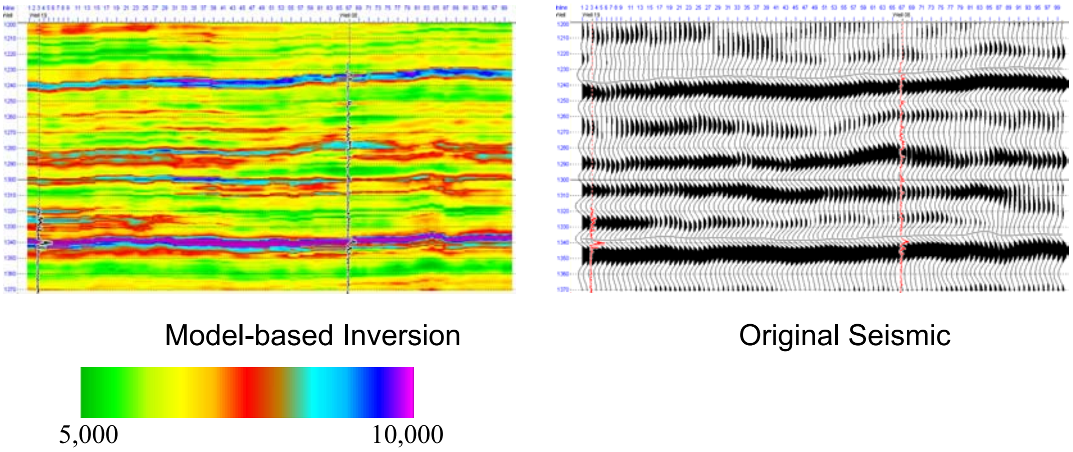
Some impedance realisations are shown on page 13. At the top is the band-limited deterministic inversion from Phase 2 and to its right the original seismic data. Below are shown four impedance realisations (left) and their forward convolution to a synthetic seismic section (right). Comparison of the synthetic sections with the real seismic at top confirms each realisation is conditional to the seismic.

Comparison between the impedance realisations shows how significant is non-uniqueness in seismic inversion. All realisations share a common colour table, with the high impedance sand previously described shown as the red to blue colours around 1280 ms. The continuity and thickness variations between just these four realisations are highly significant and there magnitude may be surprising.

Using the impedance criteria of > 8,150 m s^{-1} * g cm^{-3} to indicate clean sands, the net sand in the entire impedance cube has been computed from the model-based deterministic inversion from Phase 2 and for each of the 100 stochastic impedance realisations. The deterministic inversion gives a net sand of 8.5 % whereas the impedance realisations range from 11.6 to 15.5 % with a mean value of 13.5 % net sand. The wells show an average net sand of 13.2 %. The cumulative distribution function of net sand is shown below (red curve).

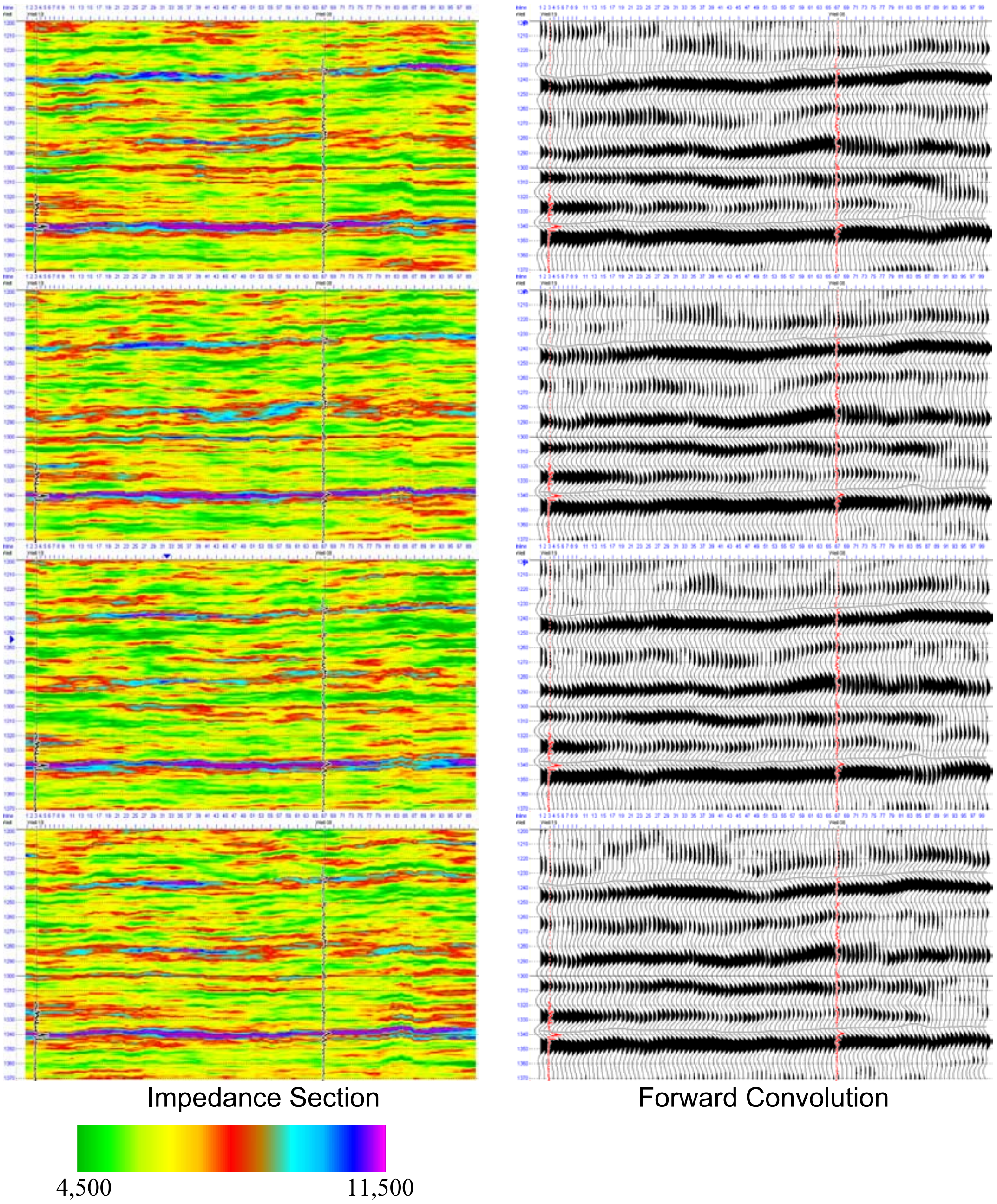


Deterministic


Model-based Inversion

Original Seismic

Stochastic Realisations


Impedance Section

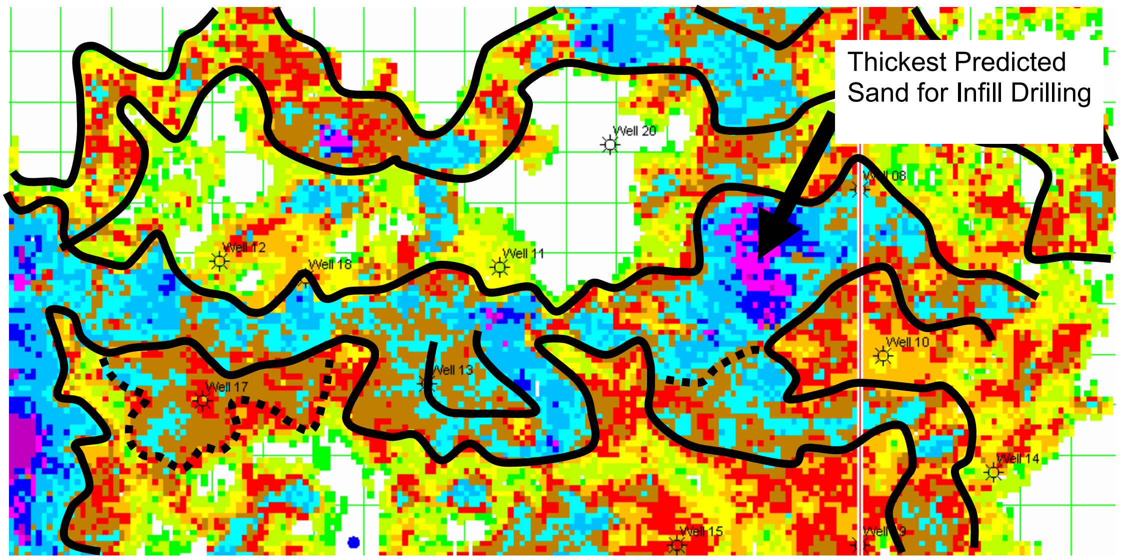
Forward Convolution

Quantitative Analysis and Probabilistic Sand Prediction

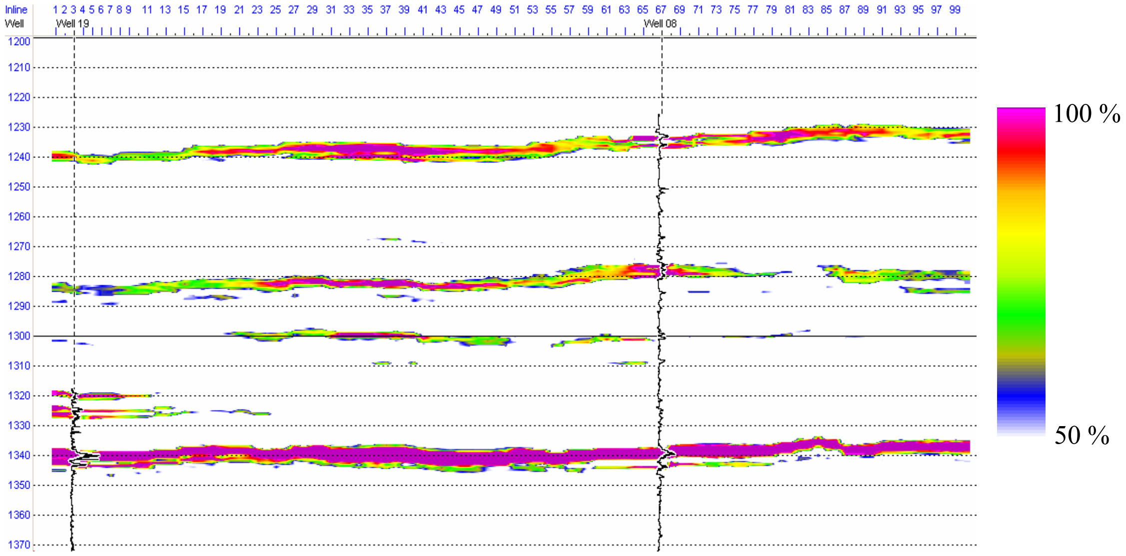
The significant under-prediction of net sand from deterministic inversion is expected from geostatistical theory. It was mentioned in Phase 2 (see page 10) that deterministic inversion schemes are unable to reproduce the full range of impedance as their output is optimal and therefore smoother than the impedance observed at the wells. If we truncate the distribution and integrate samples above the cutoff (in this case > 8,150 m s^{-1} * g cm^{-3}) we will find too few samples and hence systematically underestimate net sand. The stochastic inversions, whilst uncertain and non-unique, do reproduce the impedance distribution and therefore there is no bias when we apply the cutoff. By looking at many realisations, the uncertainty in net sand variation is quantified, as shown by the distribution curve on the page 12.

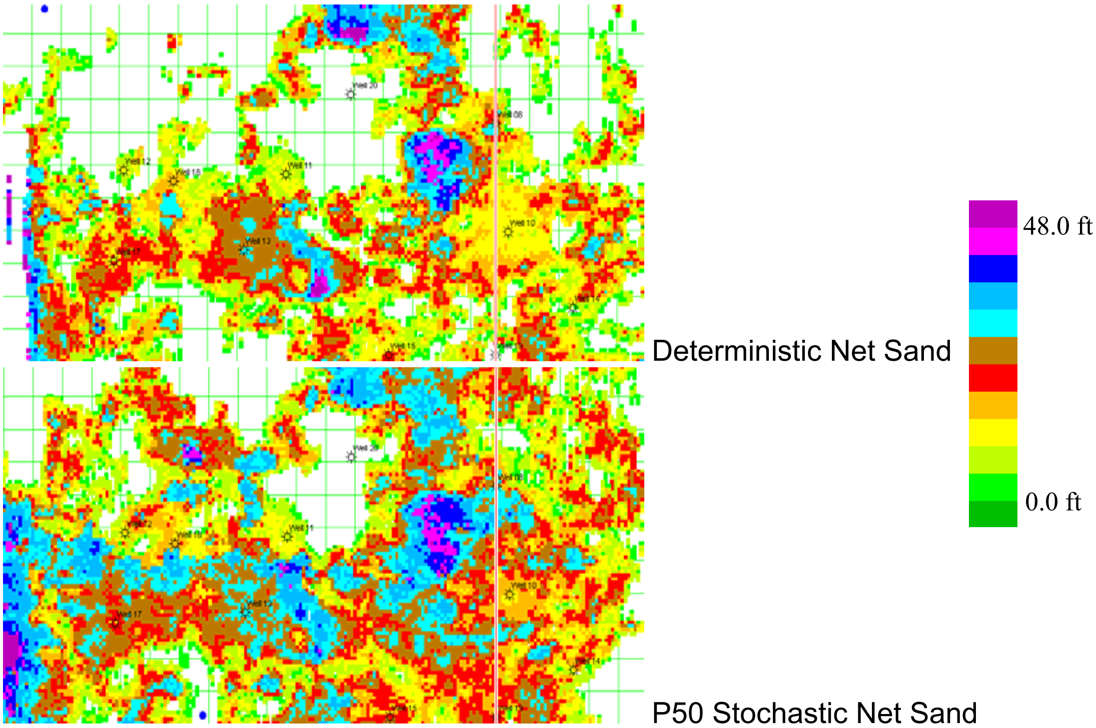
We can make further predictive use of the impedance realisations. For each stochastic inversion realisation we check if each time sample is classified as clean sand. By counting the proportion of realisations which show the sample as clean sand, we obtain the probability of sand at this sample. This resultant cube is sometimes referred to as an iso-probability cube. Cross-line 154 from the cube calculated from this data is shown on page 15 (top). The colour table shows a chance of 50% or better of being clean sand. Using a voxel system to pick the envelope of the sand around 1280 ms from this volume we can then compute the isochron and hence thickness of the sand. As a comparison this has also been done for the deterministic inversion and the two sand thickness maps are shown on page 15. The deterministic net sand map has less sand predicted and is generally thinner. The channel in the top left (NW) corner of the P50 stochastic net sand map is nicely defined but not evident at all in the deterministic net sand map.

The maximum sand probability map shown on page 15 is the peak probability within the P50 sand thickness envelope. This is similar to a standard deviation map. There is a very high probability of sand around wells with sand. From the isochron map note the thick sand SE of Well-08. The maximum probability map shows this to be high probability of sand too: a clear candidate for infill drilling. To summarise, the display below is the interpreted P50 stochastic net sand map. The channel at the top is nicely defined, together with the thick depositional trend across the centre of the area. A possible splay is interpreted around Well-17 and an abandoned meander (ox-bow) adjacent to Well-13. The infill drilling target is clearly indicated.



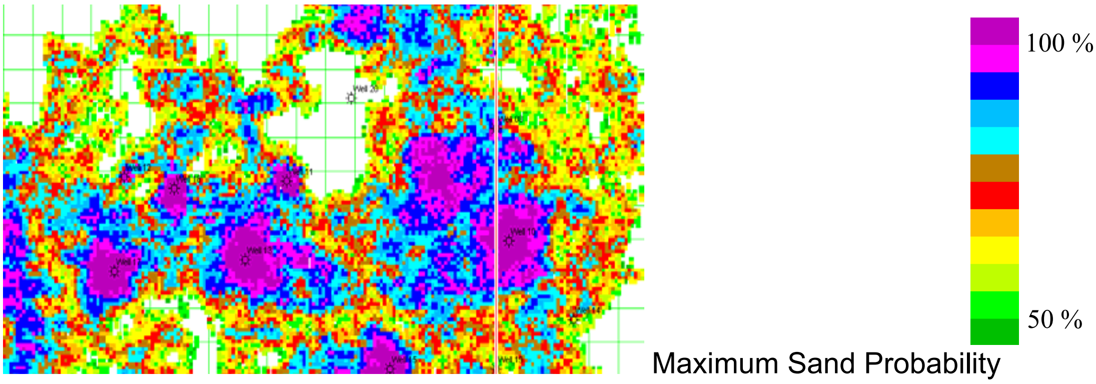
Iso-probability sand prediction – P50 Net Sand





Deterministic Net Sand

P50 Stochastic Net Sand



Maximum Sand Probability

References

Connolly, P., 1999, Elastic Impedance. The Leading Edge, April 1999, pp 438-452

Francis, A. M., 1997, Acoustic impedance inversion pitfalls and some fuzzy analysis. *The Leading Edge*, March 1997, pp275-278

Francis, A. M., 2001, Understanding and improving acoustic impedance inversion. *Presented at* SEG Development & Production Forum Taos, New Mexico.

Francis, A. M. and Syed, F.H., 2001, Application of relative acoustic impedance inversion to constrain extent of E sand reservoir on Kadanwari Field. *Presented at* SPE/PAPG Annual Technical conference, 7-8 November 2001, Islamabad, Pakistan.

Francis, A. M., 2002, Deterministic Inversion: Overdue for Retirement? *Presented at* PETEX 2002 Conference and Exhibition, London, UK.

Russell, B. and Hampson, D., 1991, A comparison of post-stack seismic inversion. 61st Ann. Internat. Mtg. Soc. of Expl. Geophys., pp 876-878

Lancaster, A. and Whitcombe, D., 2000, Fast-track 'coloured' inversion. *Presented at* SEG 2000 meeting Expanded Abstracts

Levey, R. A., Hardage, R. A., Edson, R. and Pedleton, V., 1994, 3-D Seismic and well log data set: Fluvial Reservoir Systems, Stratton Field, South Texas, Bureau of Economic Geology, University of Texas, Austin, Texas, 78713-7509, USA

White, R. E., 1980, Partial coherence matching of synthetic seismograms with seismic traces. *Geophysical Prospecting* 28 pp 333-358

Walden, A.T. and White, R.E., 1984, On errors of fit and accuracy in matching synthetic seismograms and seismic traces. *Geophysical Prospecting* 32 pp 871-891

NB: Copies of papers by Francis may be obtained either from our website at http://www.sorviodvnvm.co.uk or by email to ashley.francis@sorviodvnvm.co.uk