Building Complex Synthetic Models to Evaluate Acquisition Geometries and Velocity Inversion Technologies

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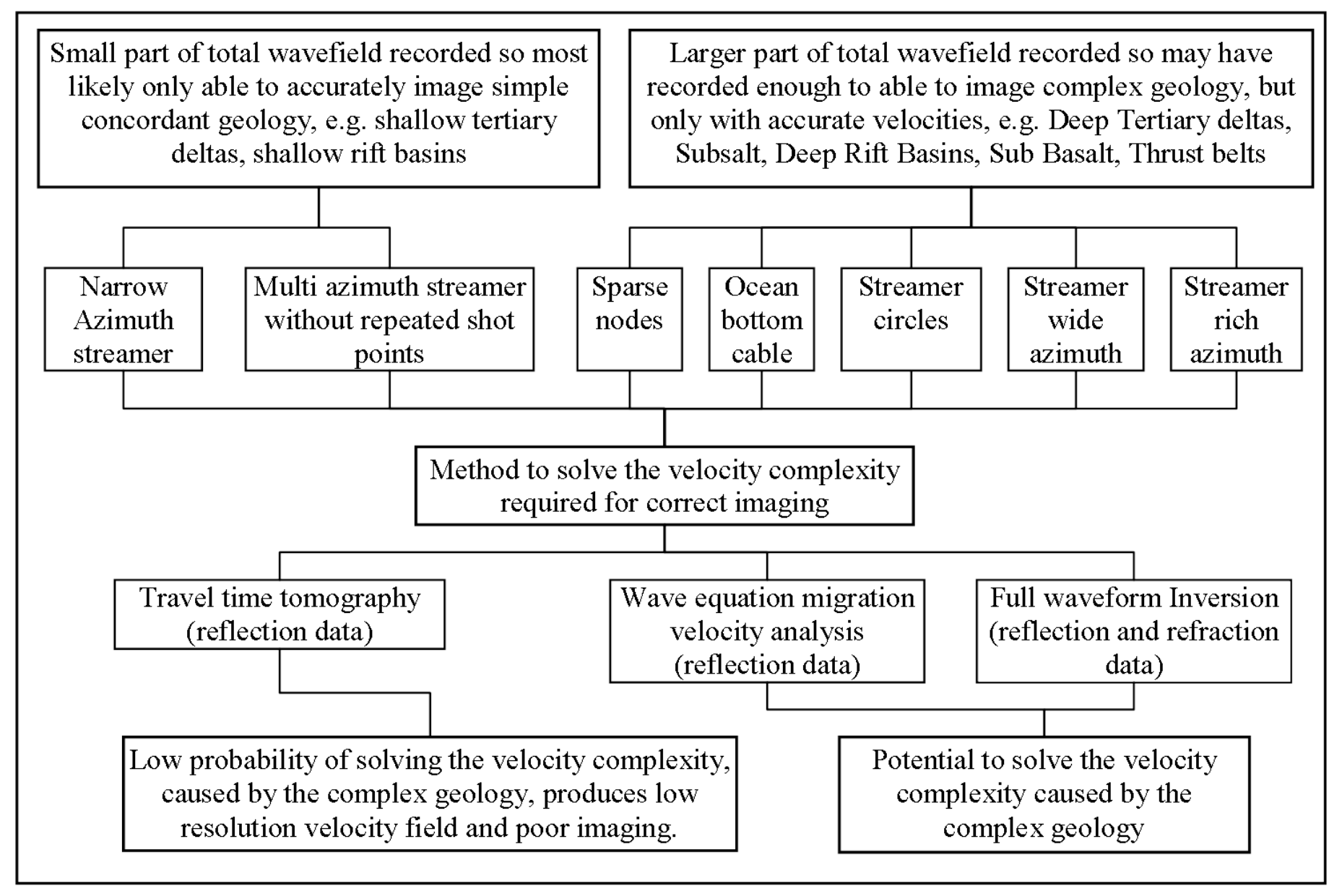
Introduction

Imaging in complex geological provinces requires many decisions when selecting data acquisition and processing technologies. One of the key challenges is to be able to produce an accurate velocity model to allow imaging of the reflection wavefield; solving this challenge is a coupled system of both the processing technology used and the amount of data acquired.

We demonstrate building broad bandwidth 3D synthetic velocity and density models in open source software (OpendTect) to aid in evaluating the multitude of acquisition and processing options (Figure 1).



Small part of total wavefield recorded so most likely only able to accurately image simple concordant geology, e.g. shallow tertiary deltas, shallow rift basins

Larger part of total wavefield recorded so may have recorded enough to able to image complex geology, but only with accurate velocities, e.g. Deep Tertiary deltas, Subsalt, Deep Rift Basins, Sub Basalt, Thrust belts

Narrow Azimuth streamer

Multi azimuth streamer without repeated shot points

Sparse nodes

Ocean bottom cable

Streamer circles

Streamer wide azimuth

Streamer rich azimuth

Method to solve the velocity complexity required for correct imaging

Travel time tomography (reflection data)

Wave equation migration velocity analysis (reflection data)

Full waveform Inversion (reflection and refraction data)

Low probability of solving the velocity complexity, caused by the complex geology, produces low resolution velocity field and poor imaging.

Potential to solve the velocity complexity caused by the complex geology

Figure 1: *Decision tree, showing that answering the question of "how much data do we need to record to get an acceptable velocity and density model for imaging and inversion?" has many possible answers when attempting to image complex geology*

The models contain many features across a broad range of wavenumbers in all three spatial dimensions and attempt to mimic real geological complexity found in fluvial, deltaic and deep water turbidite environments without replicating any particular seismic dataset. We juxtapose multiple geological environments together in a manner that is not geologically possible, but the aim of our model is to test the resolution capabilities of different technologies rather than geological interpretations.

3D Acoustic finite-difference forward modelling was used to generate synthetic shot gathers on idealised acquisition geometries of ocean bottom nodes (OBN) and wide azimuth streamers (WAZ). The large source to receiver offsets (ratio of offset to bottom of model is greater than 6), 360 degree source to receiver azimuth coverage and dense spatial sampling of the receivers on these datasets, provide the opportunity to evaluate different acquisition geometries and velocity inversion technology, such as full waveform inversion (FWI).

1.1 Summary of model building stages

The model building followed a scheme of building low wavenumber models and then adding higher wavenumber content to these models to make a broad bandwidth model, as summarised here:

a) Analysis of real log and seismic datasets,

b) Construct low wave number model from horizons and well derived gradients,

c) Addition of components of velocities from processing,

d) Seismic attribute inclusion from relative acoustic impedance after neural network waveform classification,

e) Add channel complex and gas cloud inclusion into the model,

f) Vertical concatenation of multiple models to form one model,

g) Decrease vertical sampling to increase wavenumber content,

h) Generate density model using different empirical relations for different layers in the model.

Analysis of real datasets

To define realistic wavenumber bandwidth for the model various datasets were analysed:

- Well logs - well logs were analysed using segmented linear fit method (V0-K) and used to produce background velocity model.
- Seismic - seismic volumes were selected based on the different geological regimes that were represented within them.

Extracting details from real seismic datasets has an obvious drawback - the lowering of wavenumber content caused by anelastic attenuation. We would like to be able to build a model that had a uniform bandwidth and allowed us to add attenuation into any forward modelling. To avoid this problem we have only used the shallow parts of seismic datasets and used geological unconformities to define boundaries. We can then vertically concatenate volumes along these unconformities to produce a single larger model.

Model Building

In this section our model building methodology is described in detail. This methodology was repeated on different seismic volumes from a variety of different geological provinces, but is detailed here for just one seismic dataset.

3.1 Horizons, well V0-K and logic cube

Well log P-wave velocity information was used with horizons to create a model that captures the gross geological structure (Figure 2) and the global features of the well velocity (Figure 5). This initial model provided the low wavenumber trend, but also contributed to the overall richness in vertical wavenumber since the rapid velocity changes require a broad bandwidth to be well defined. However, this model lacks fine scale lateral variation.

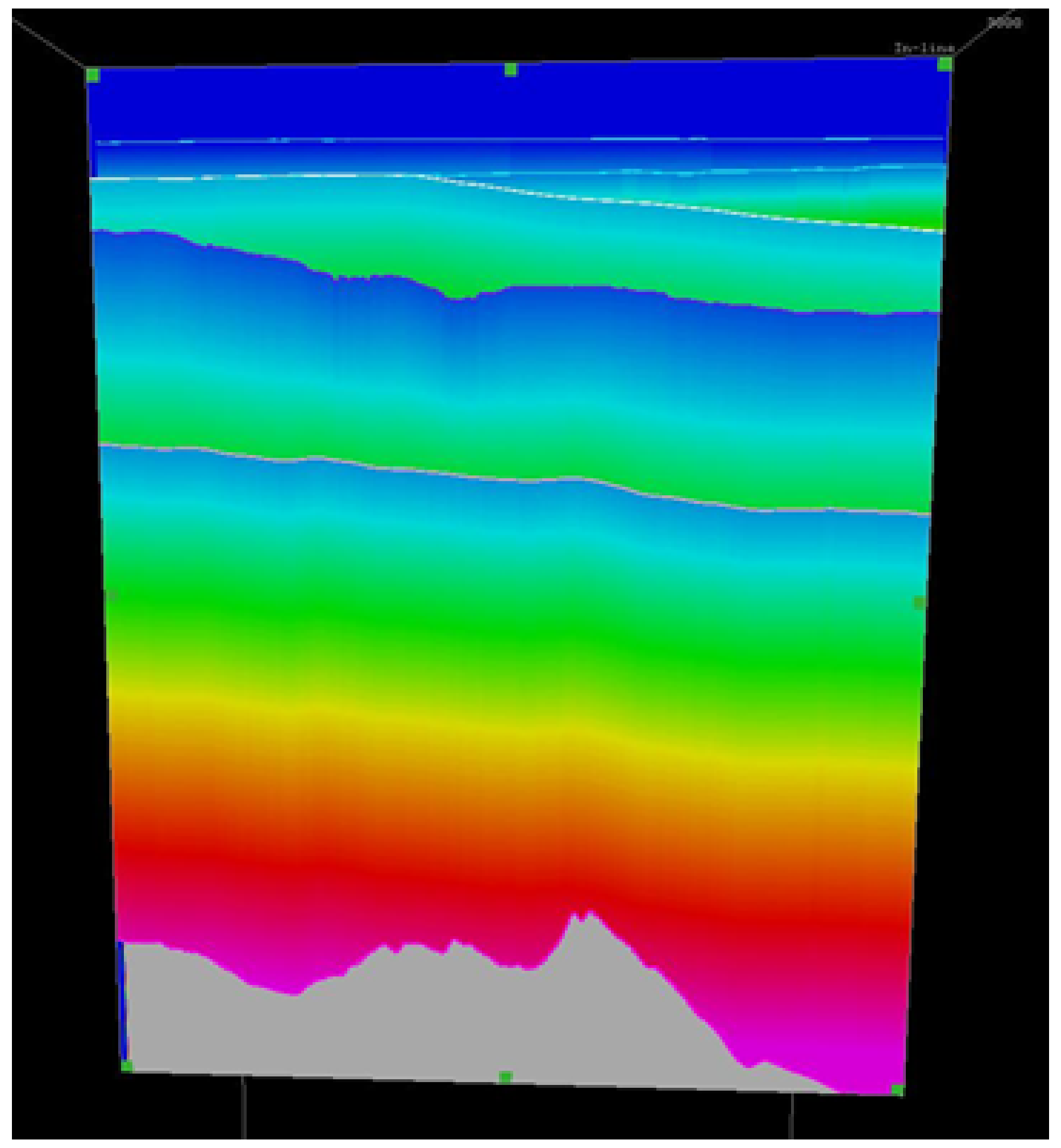


Figure 2: *Initial model: This initial model captures the global features of the well logs (Figure 5) guided by structure from picked horizons.*

A "logic cube" (Figure 3) was also created from the horizons. This volume contains the numbers 1 to 6 which correspond to the respective layers as defined by the horizons. Having this cube enabled us to use logical statements that follow structure for the volume manipulation of subsequent additions to the initial model.

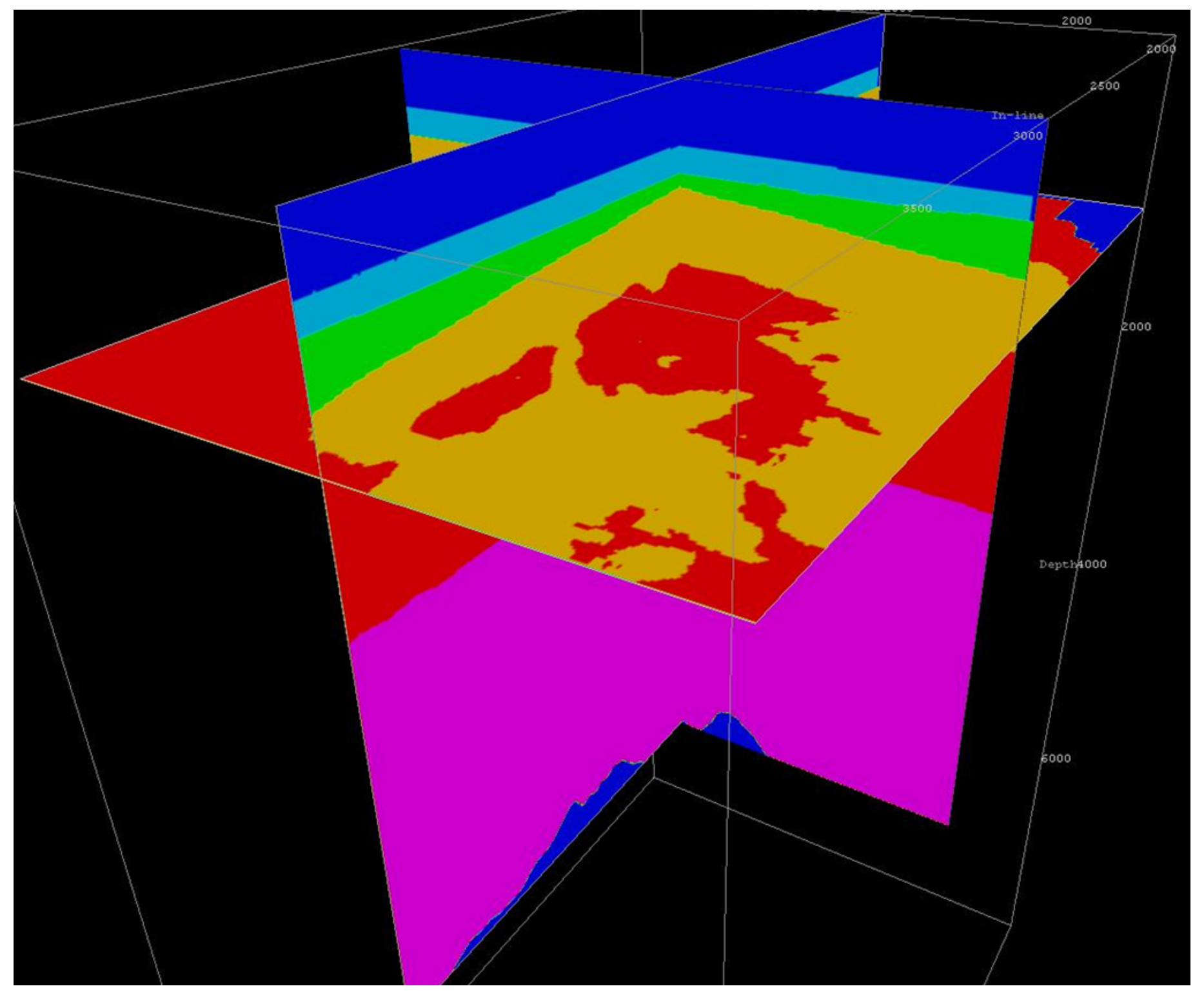


Figure 3: *Logic cube: This contains a constant value for each layer in the volume.*

3.2 PreSDM velocities

The local low wavenumber background trend was removed from a volume of PreSDM velocities. The resulting residual includes a lot of lateral variation, particularly in the shallow section. By scaling and adding these to the starting model (Figure 2) in the previous step both vertical and lateral wavenumber content is increased. The logic cube (Figure 3) was used to vary the contribution in different layers.

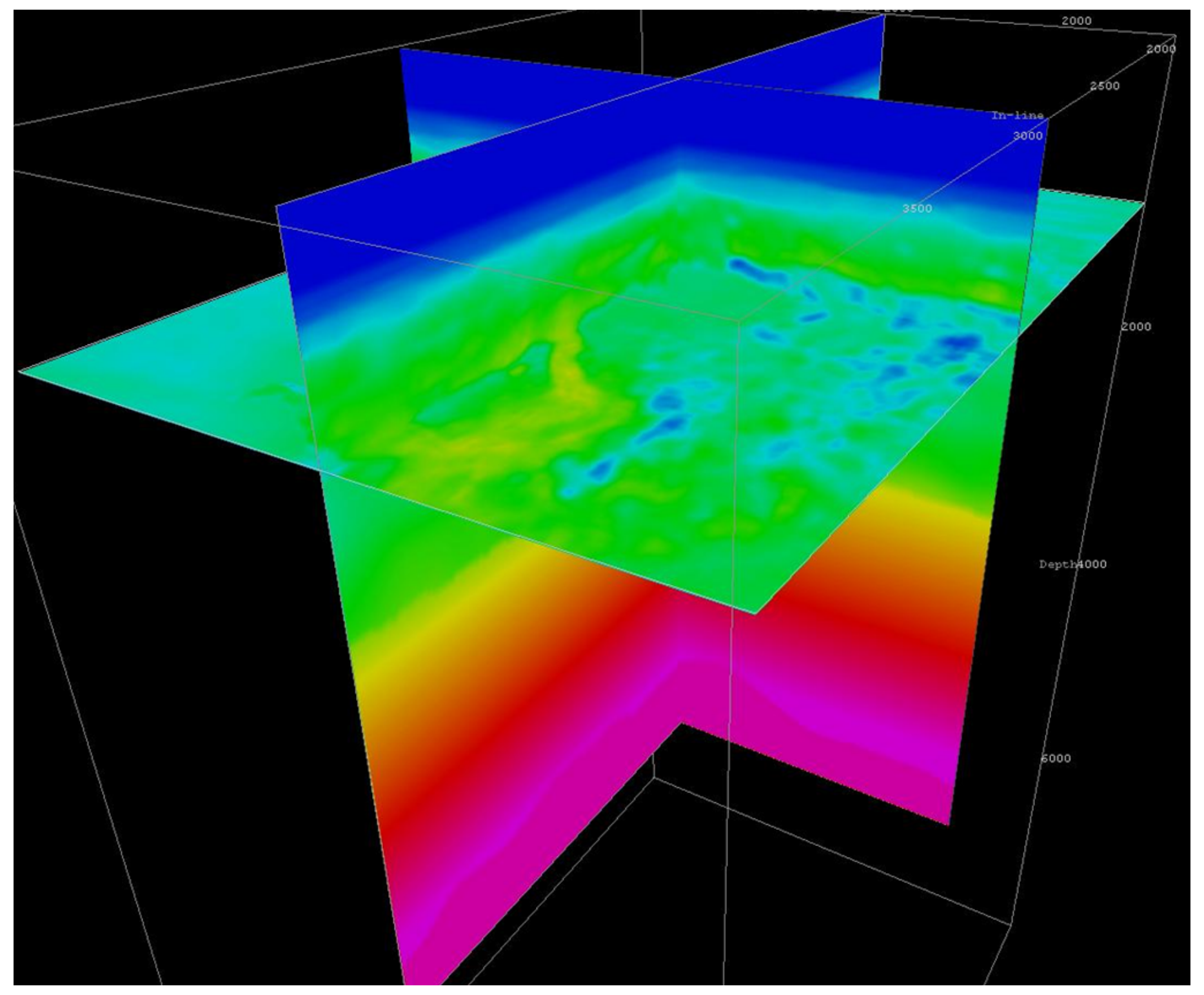


Figure 4: *PreSDM velocities: The PreSDM velocities with low wavenumber background trend removed provide wavenumber content in X, Y and Z. The X and Y spatial variation is significant because this is severely limited in the well derived velocities.*

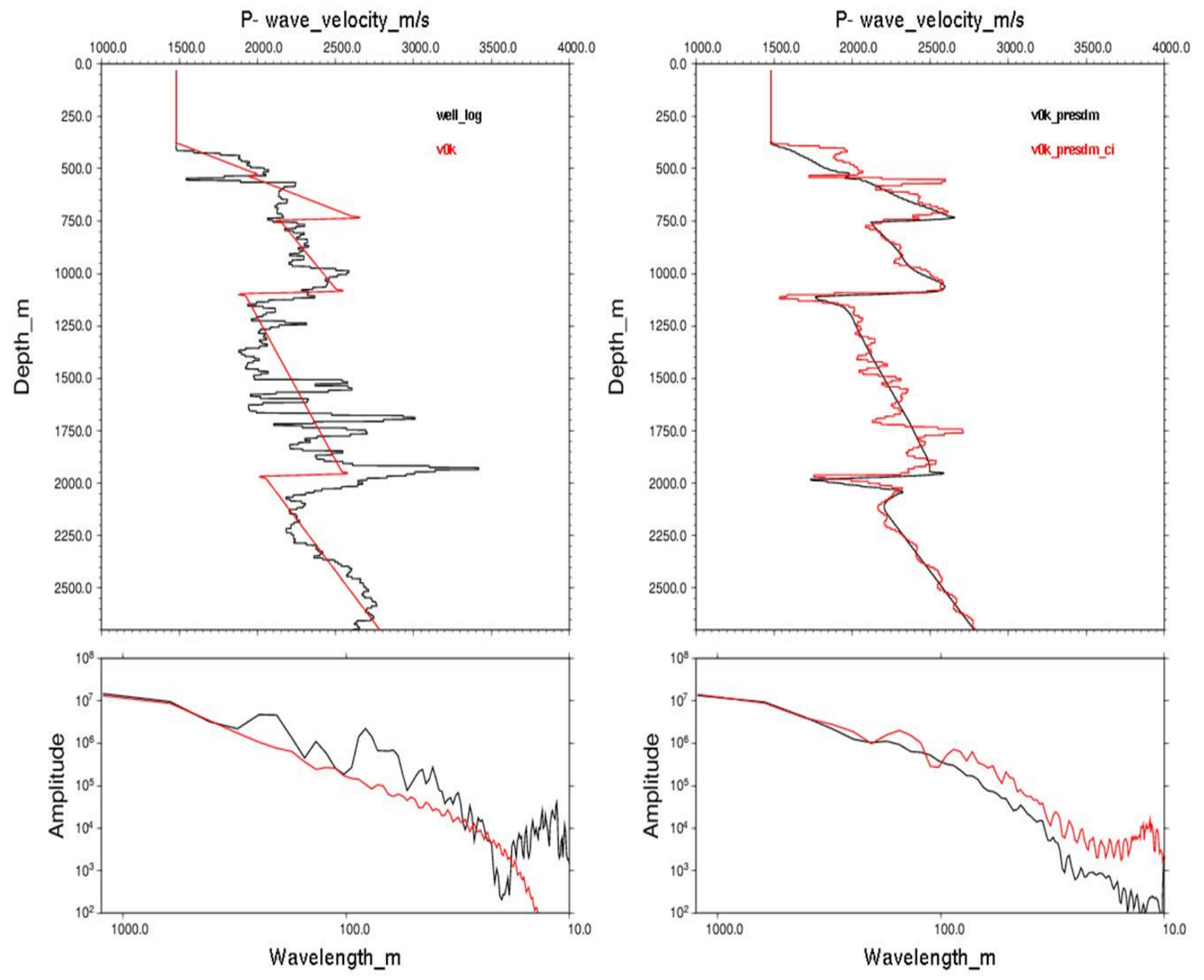


Figure 5: *Comparison of velocity profiles and the wavenumber content at various stages of velocity model building. (Left): Overlaying a well log velocity profile (black) and V0-K model (red) shows the V0-K method provides the low wavenumber component of the model. (Right) The V0-K and PreSDM velocity model (black) adds to the mid-range wavenumbers, whilst adding the neural network (NN) classified coloured inversion component to this (red = V0-K + PreSDM + NN) adds to the higher wavenumbers.*

3.3 Coloured inversion and neural network

To further enrich the wavenumber content of the model, relative impedance datasets were produced using coloured inversion (Lancaster and Whitcombe, 2000). This broadens the seismic bandwidth to approximate that of acoustic impedance well logs and gives the seismic volume a more blocky trace rather than a wiggle trace. Figure 6 shows that the coloured inversion result is blocky in the vertical direction and contains significant spatial variation, but the result requires scaling to velocity values.

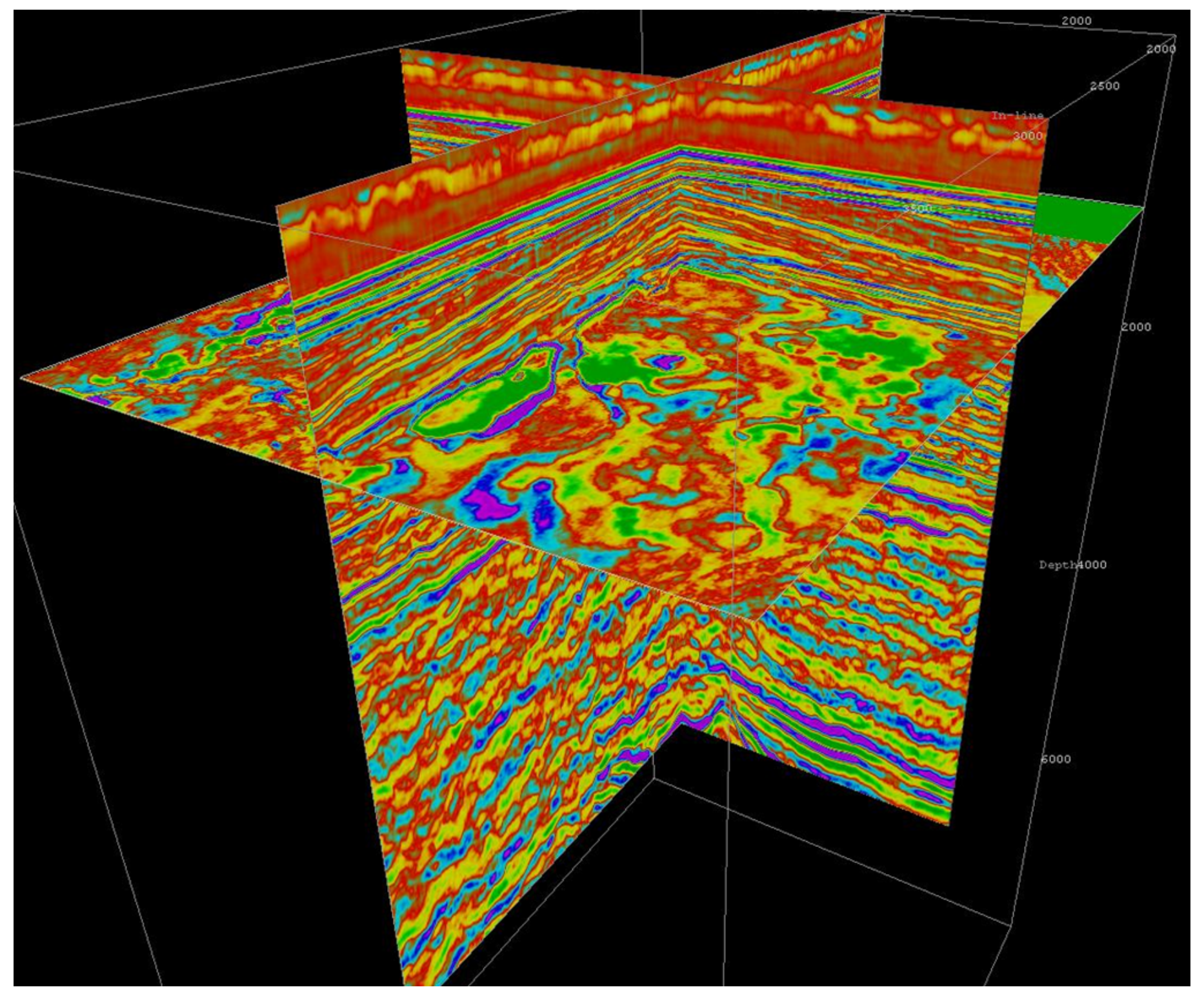


Figure 6: *Coloured inversion: Coloured inversion of different seismic datasets was used to increase the wavenumber content further.*

An unsupervised neural network was then trained to categorise the coloured inversion result into 25 bins based on waveform shape. This process creates an extremely blocky output which is laterally continuous and follows structure. This was further blocked by manually binning to between 5 and 10 bins per layer in the logic volume. These bins were then scaled to add to the velocity model thus adding higher wavenumber content and blocky perturbations typical of a blocked well velocity log.

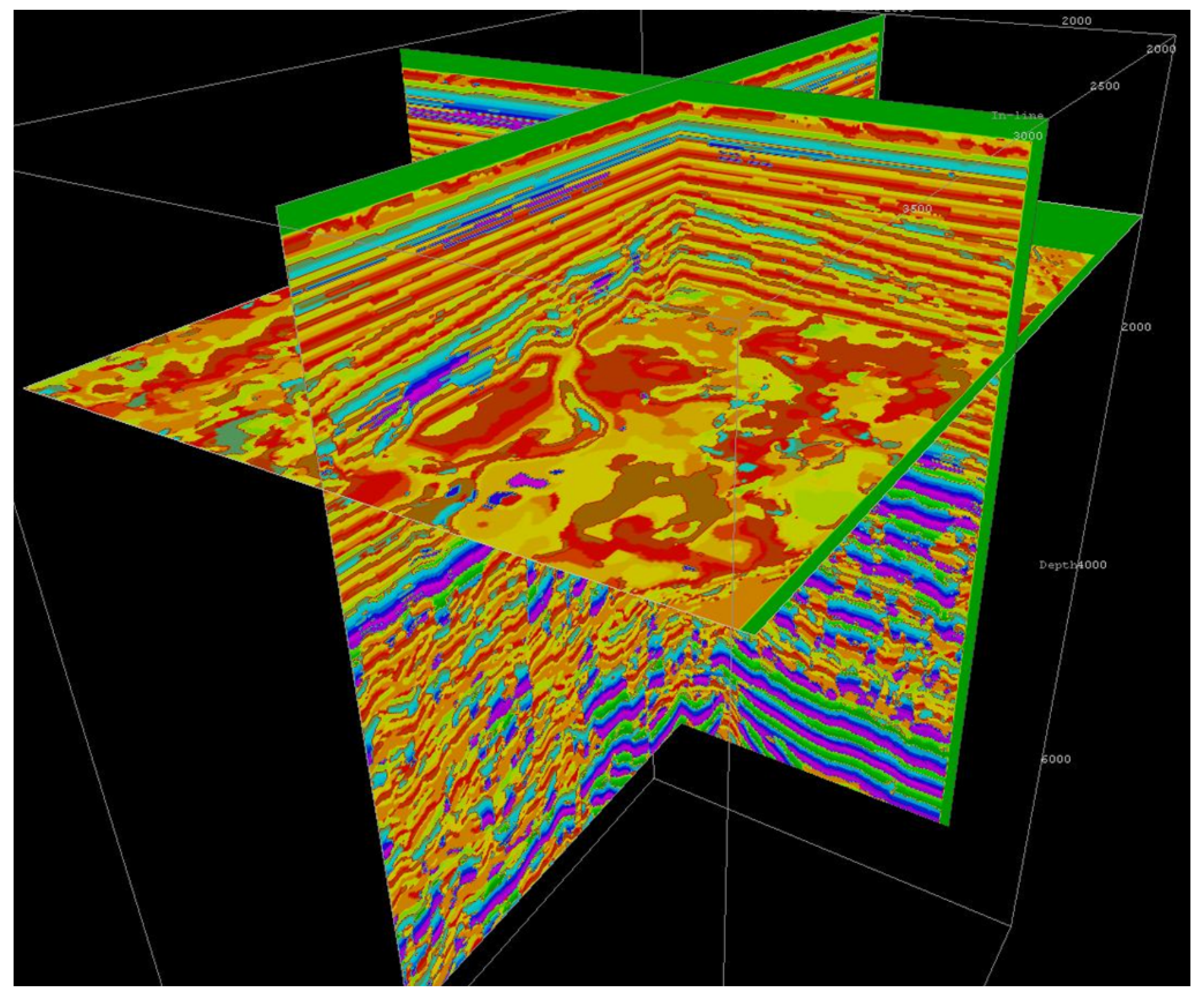


Figure 7: *Neural network: A neural network was used to classify the coloured inversion result into discrete classes which where further blocked into 5 to 10 bins, before scaling and adding to the model.*

In order to include higher wavenumber variation to the velocity model we used spectral blueing of seismic (Lancaster and Whitcombe, 2000) to the impedance logs of wells. The resultant volume was amplitude scaled such that it could be added to the velocity model as an adjustable, high wavenumber perturbation

3.4 Channel fill and gas cloud

A channel feature was introduced into the model using the interpretation of a top and base channel made

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on a seismic volume. The channel defined between these horizons was given a constant velocity scaling so as to provide a spatially continuous velocity anomaly in the dataset.

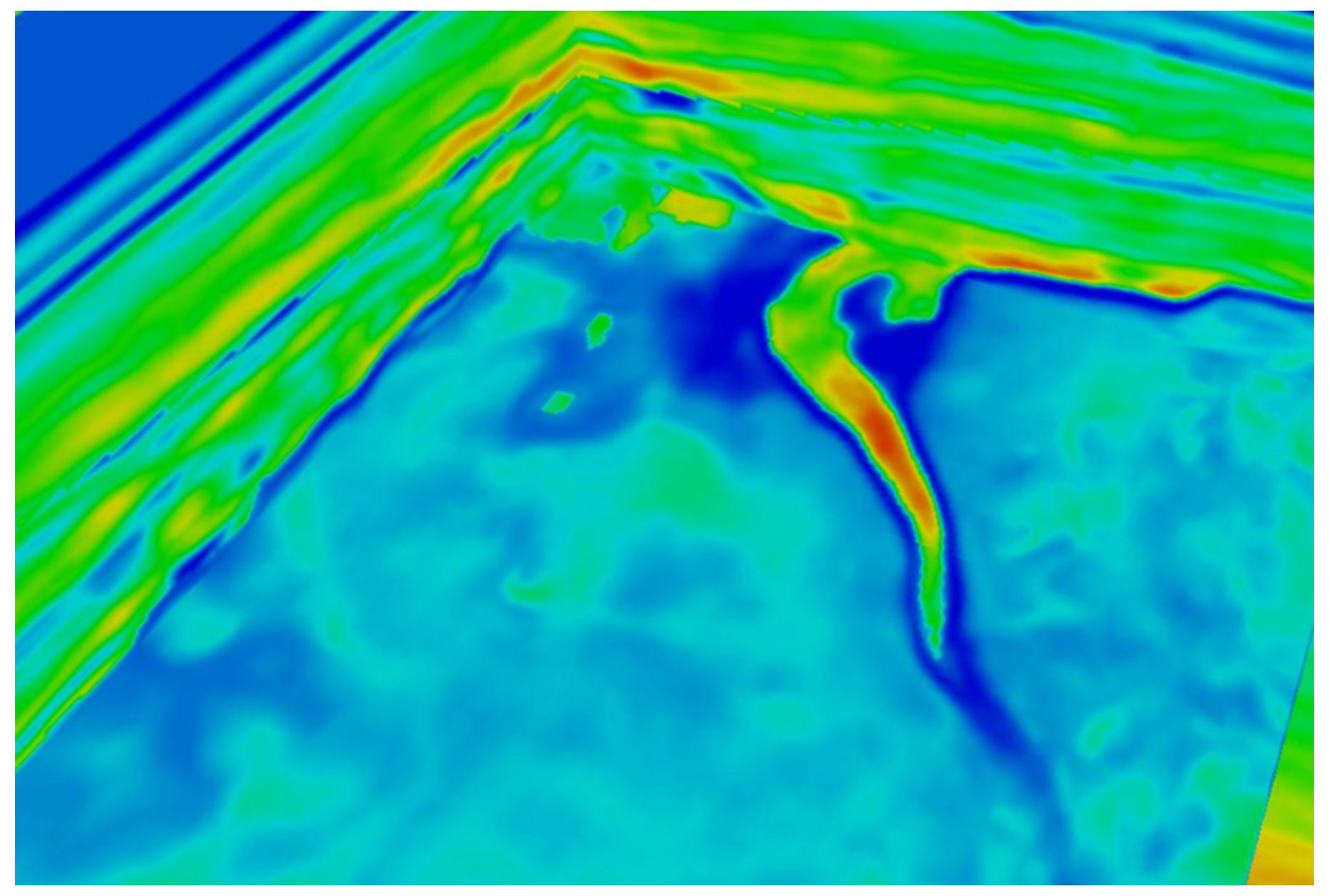

Figure 8: *Channel fill: A channel system was introduced into the model.*

To add more complexity to the model, another neural network was trained to recognise gas clouds (Meldahl et al. 1999) within seismic data. This was used to extract a gas cloud from seismic data and import it into the model as a perturbation honouring the true effect gas has on velocity. The gas cloud was positioned as if emanating from the major fault system.

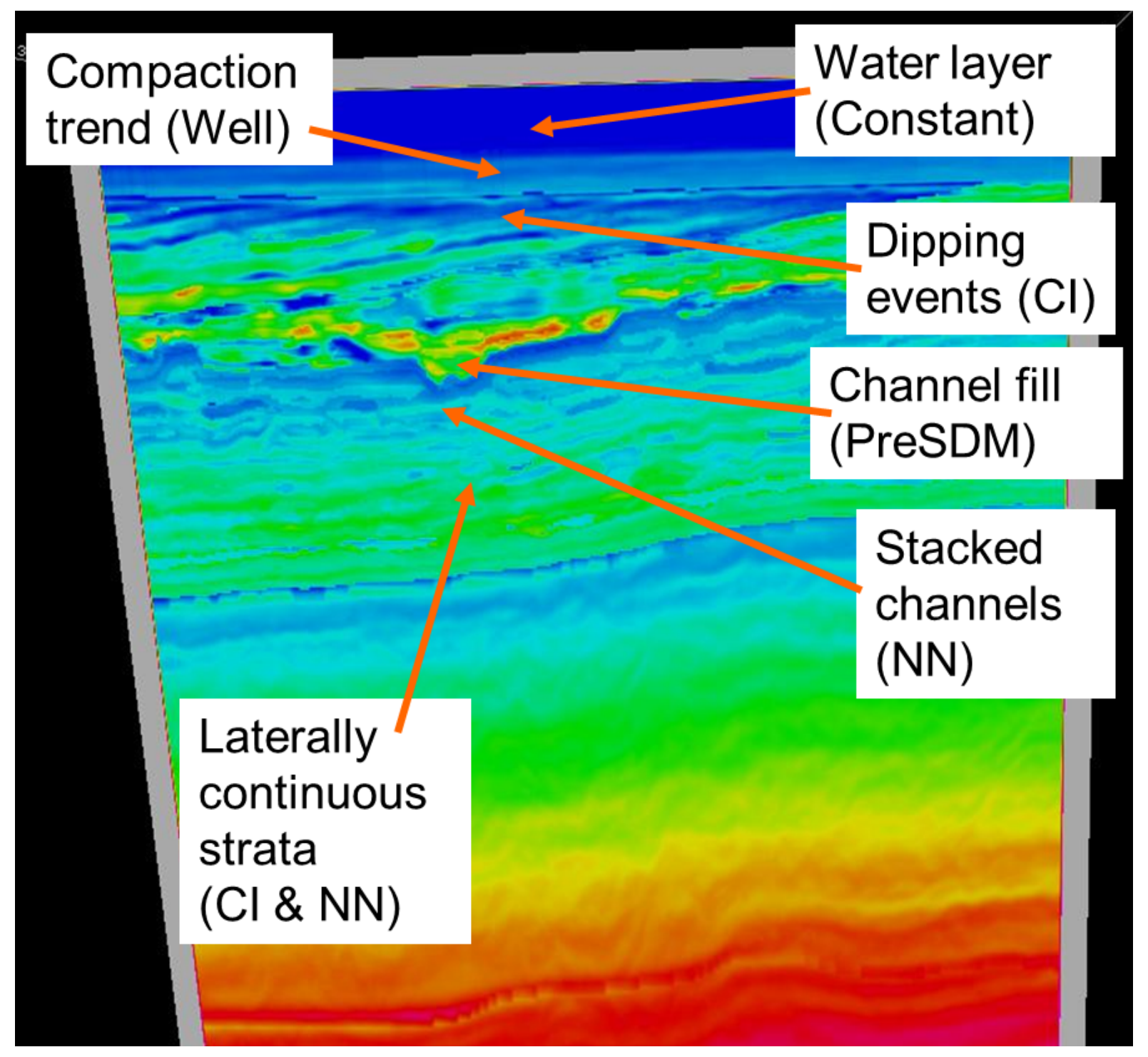

Figure 9: *Summary of contributions to one of the models after addition of all the components as described in previous sections.*

3.5 Combining and blending of datasets

Geological unconformities defined boundaries at which we vertically concatenated the models to produce a single final model. This was achieved using logic cubes and mathematical attributes as shown in Figure 10.

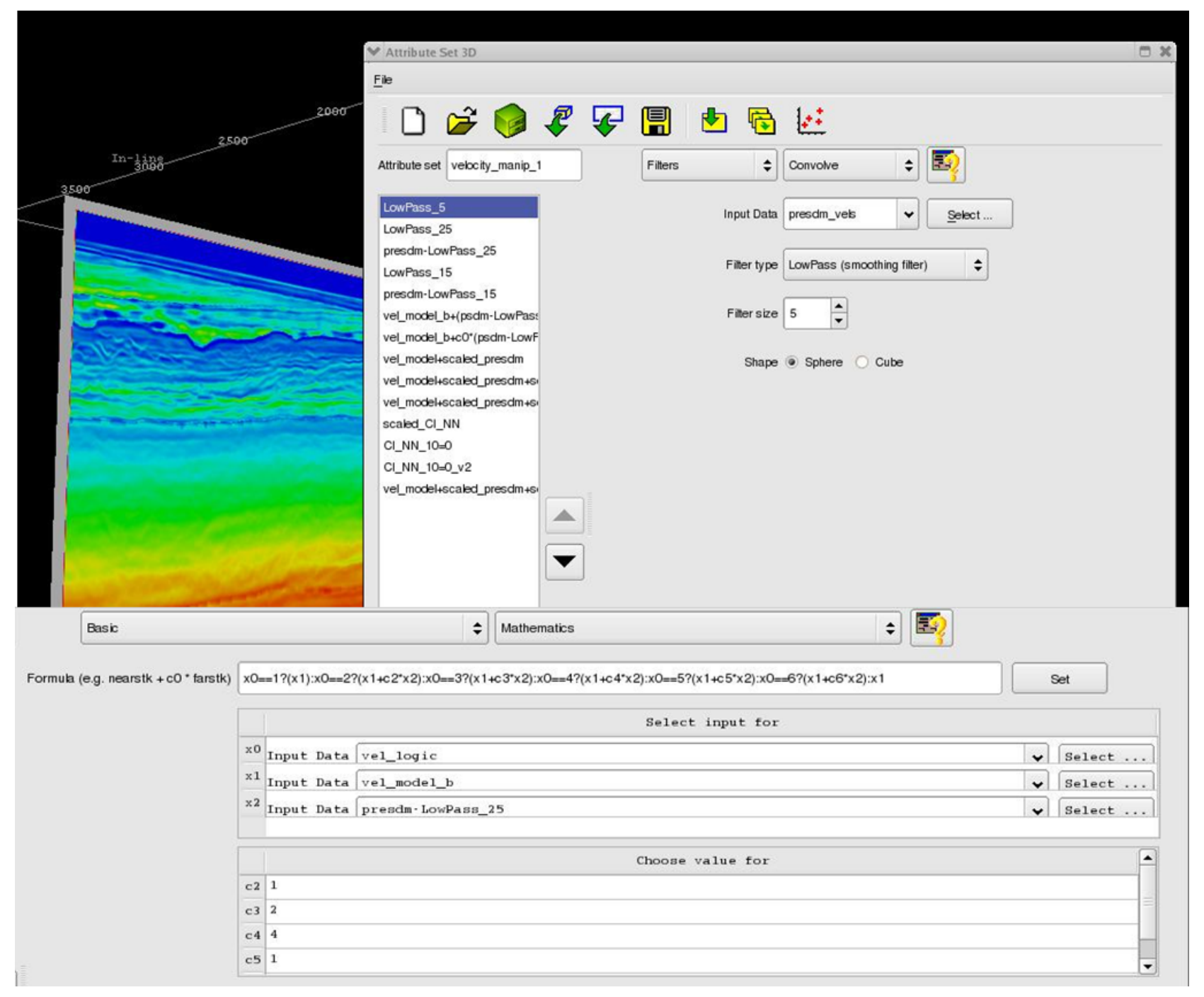

Figure 10: *Attribute set for combining models: A logic cube is used in the attribute set to control the contributions from different models to the final velocity model.*

Final models

The final velocity model is shown in Figure 11. The final model dimensions are: Y axis 68.225km, increment 25m; X axis 47.750km, increment 25m; Z axis 2.040km, increment 6m

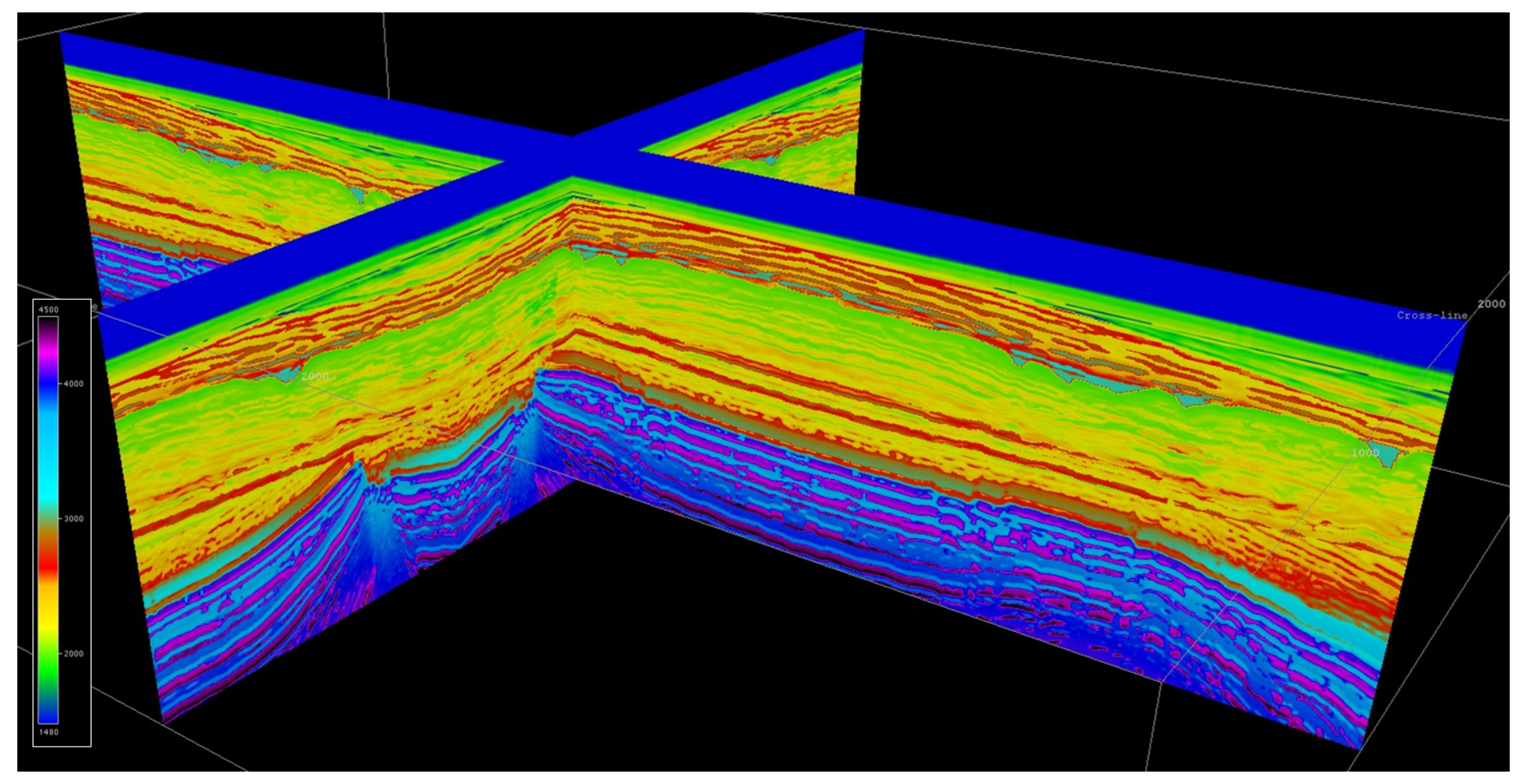

Figure 11: *Inline and crossline slices from final velocity model. Velocity range is 1480 to 4500m/s.*

A density model (Figure 12) was created based on the final velocity model using different empirical relations (Gardner 1974 and Wood 1955) for different layers in the model. The gas cloud was used to perturb the density to mimic the true effect of gas on density. Therefore, the density model is not a simple linear function of the velocity model.

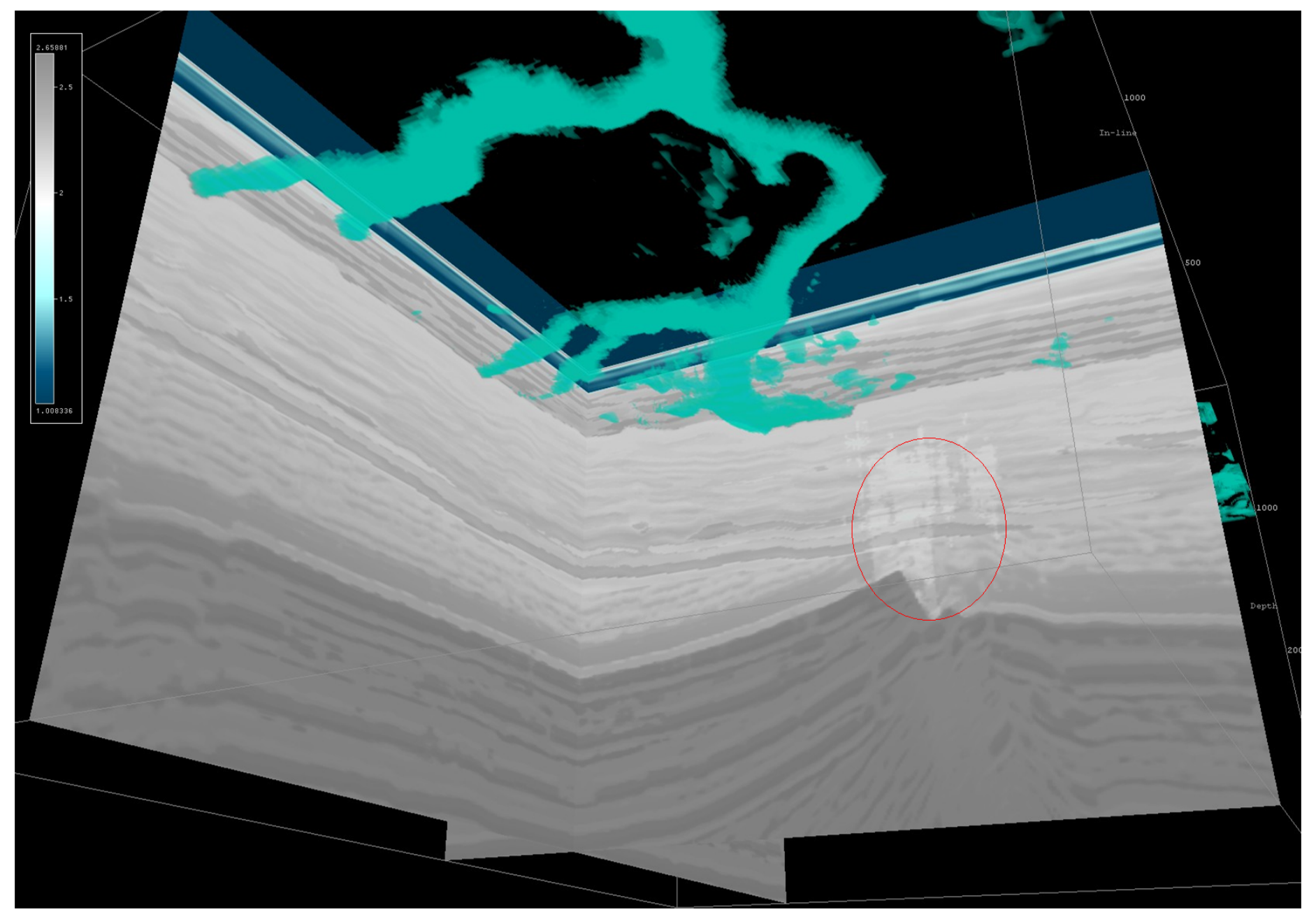

Figure 12: *Inline and crossline slices from final density model. Densities range from 1.00 to 2.66g/cc. Note channel system and the gas cloud.*

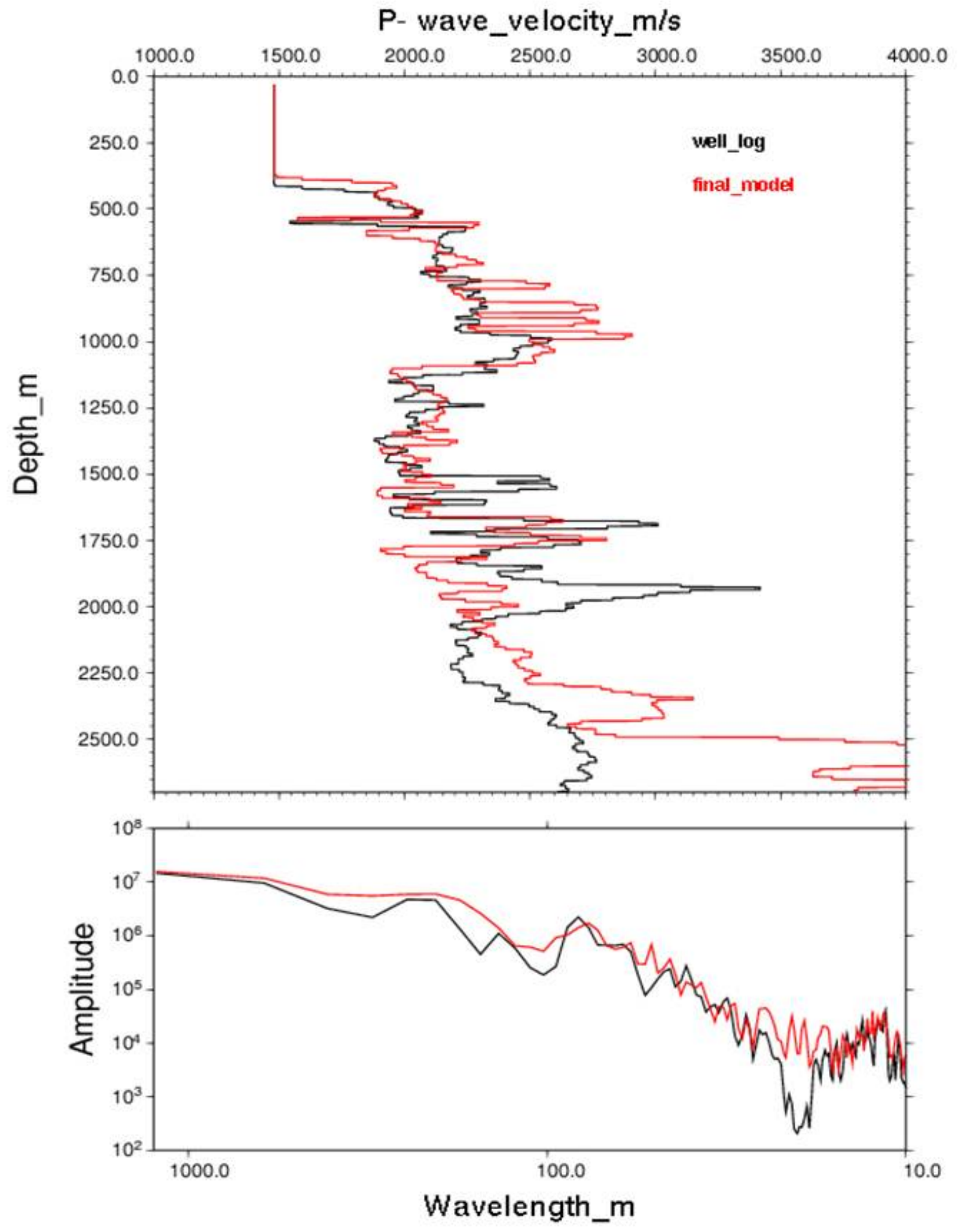

Figure 13: *Comparison of the velocity profiles and wavenumber content of the final velocity model and an example well P wave log. The well log velocity profile (black) overlain by the final velocity model (red) shows that the velocity model contains similar wavenumber content to the well log.*

Forward modelling

Synthetic seismic shot datasets were created using 3D acoustic finite-difference (FD) modelling.

The datasets were recorded with an absorbing free-surface to eliminate all free-surface related multiples. This also avoids other seismic forward modelling codes variations in implementing ghost effects from the free surface. This does then leave a direct arrival that is much higher amplitude than primary reflections. The complex interactions between the direct arrival and water bottom require a very small FD grid size to forward model through the full model with enough numerical precision to match a forward model though an all water model. However, this was found to be too computationally expensive to pursue. So an average direct arrival from all the shots was subtracted from each shot, leaving a small amount of residual direct arrival on them.

Two different acquisition geometries were used: an ocean bottom node (OBN) geometry optimised to record refraction data (Figures 14 and 15) and an idealised wide azimuth streamer (WAZ) geometry optimised to record reflection data.

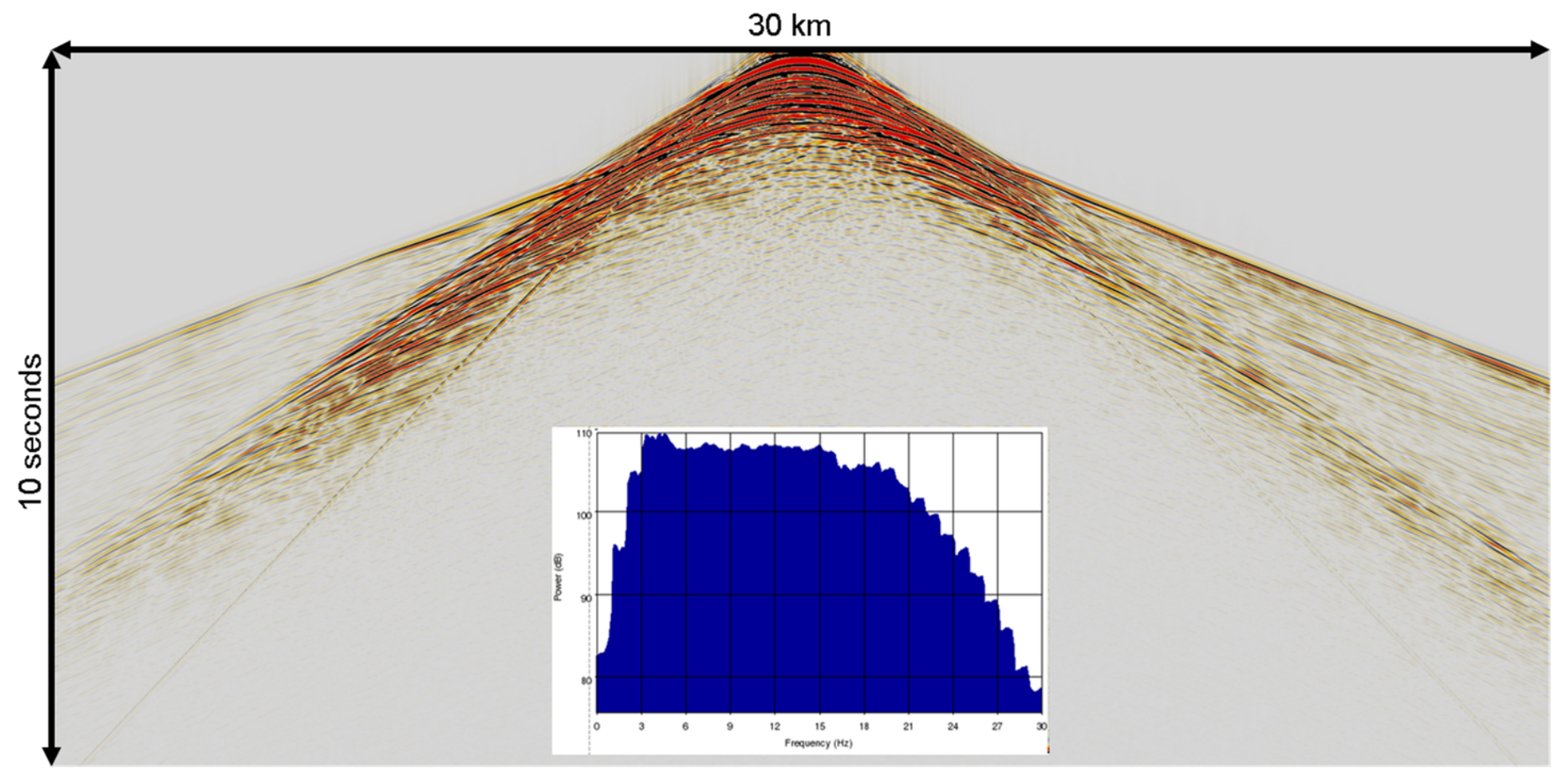

Figure 14: *Example of a vertical slice through an OBN shot generated through the model is shown. Note the very long offset range and amplitude spectrum.*

The node survey was generated with a 'moving node' configuration. A 10km x 10km grid of shots, separated by 150m in x and y, were fired sequentially into a 30km x 30km grid of receivers centred on the live shot. The grid of receivers moved with each shot, ensuring every shot point created a full range of offsets and azimuths. The receiver spacing was 25m in x and y. The low-cut and high-cut frequencies were 1Hz and 30Hz respectively. A total of 4624 shots were generated over an area of 100km^2, each with 1,442,400 receivers. The total area over which shots were recorded was 1600km^2 with a record length of 10,000ms and a time sampling rate of 10ms.

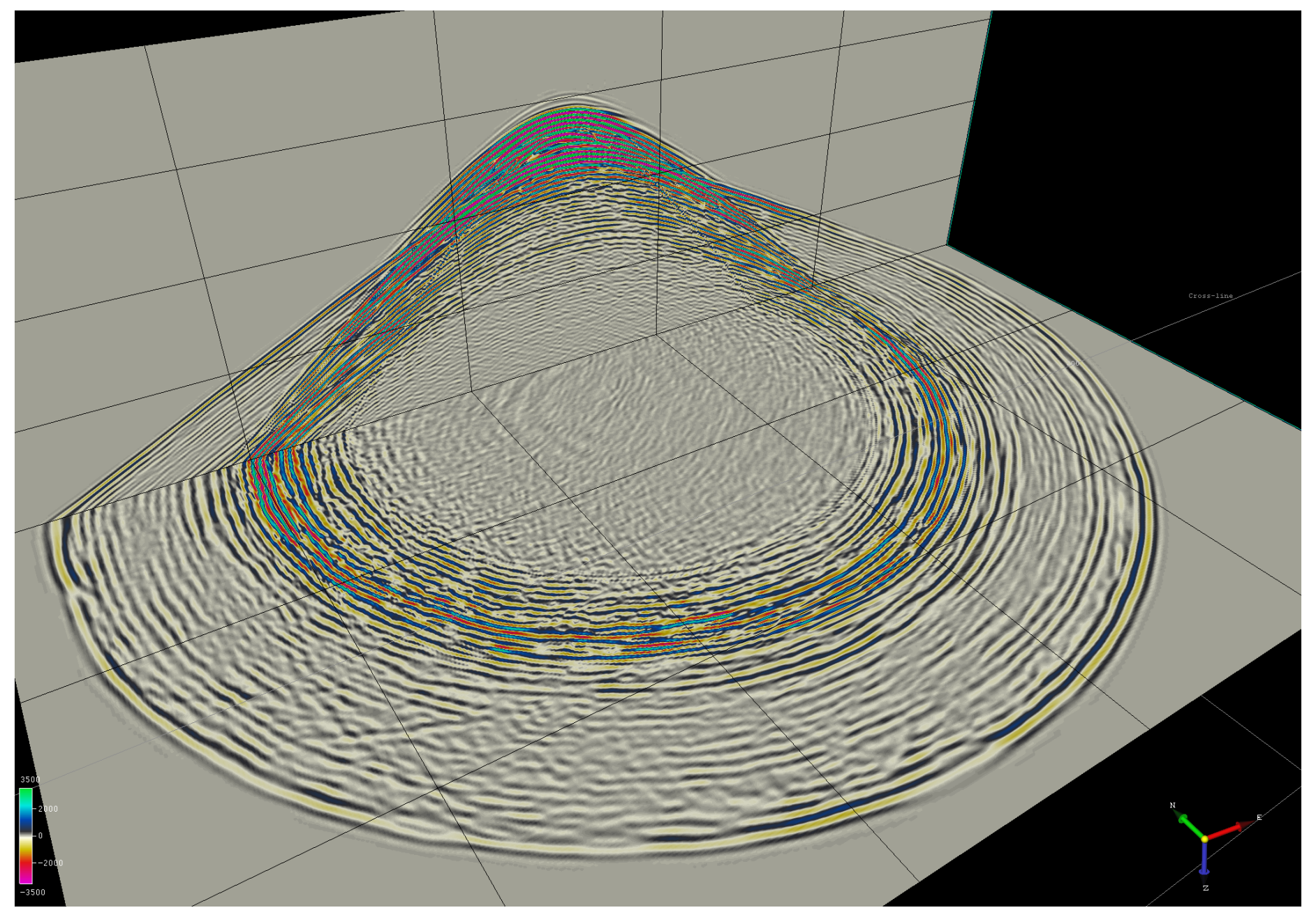

Figure 15: *Timeslice at 4 seconds from OBN shot.*

The WAZ survey was generated with an idealised WAZ streamer configuration using 321 streamers, making a spread width of 8km and 4km streamer lengths in front and behind the shot point in a split spread configuration. The channel interval and streamer separation were 25m and the shot interval was 25m. The low-cut and high-cut frequencies were 3Hz and 45Hz respectively. A total of 8336 shots were generated over an area of 104km^2, each with 103,041 receivers. The total area over which shots were recorded was 336km^2 with a record length of 5000ms and a time sampling rate of 6ms.

Usage of model

Both the model and synthetic seismic dataset have been used to answer questions on data acquisition and processing technologies.

6.1 Illumination compensation

The synthetic NAZ and WAZ shot datasets were migrated with reverse time migration (RTM) using the exact velocity model to examine the azimuths required to best image the model.

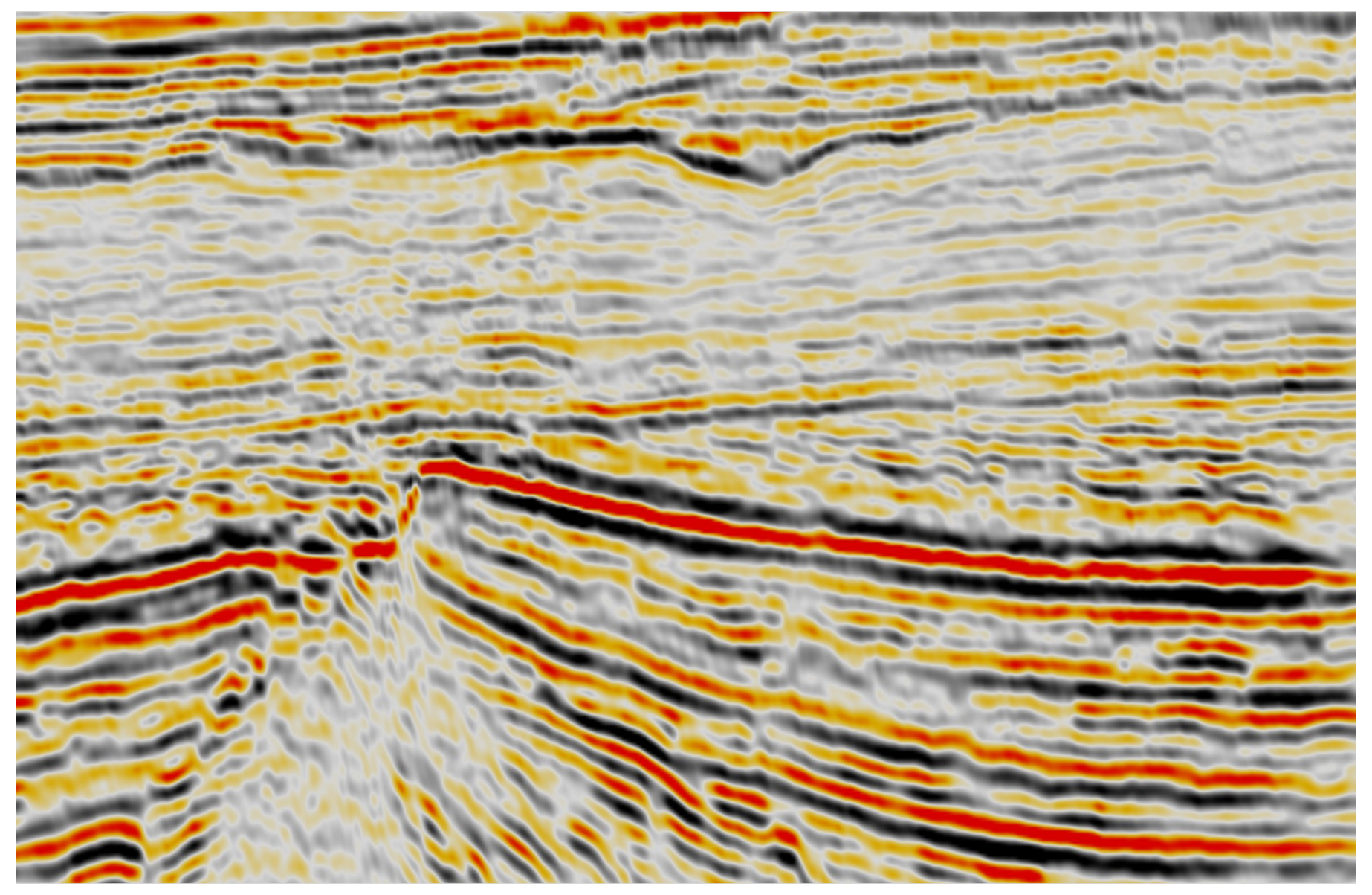

Figure 16: *Reverse time migration of synthetic shots from NAZ dataset using exact velocity model.*

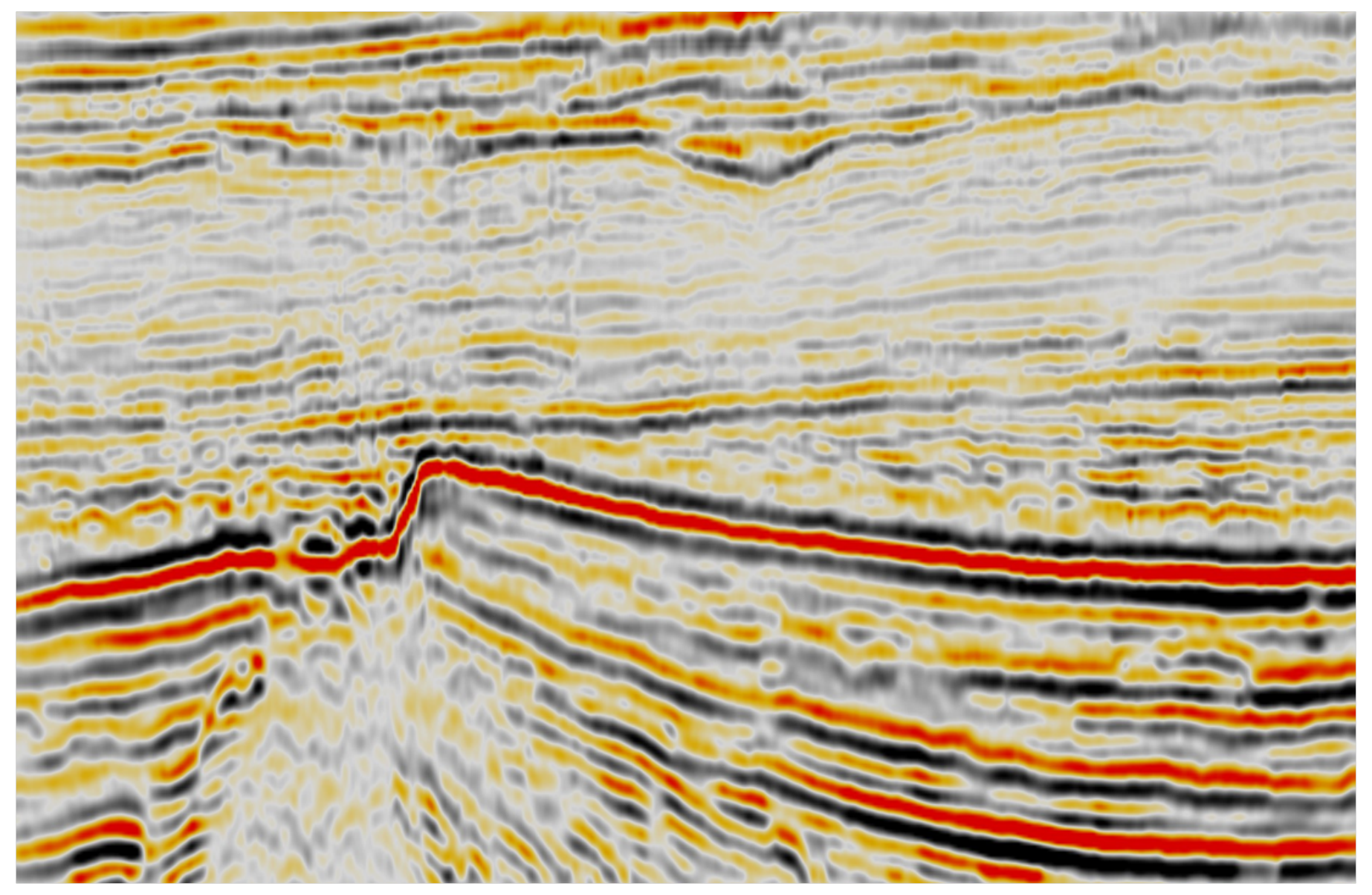

Figure 17: *Reverse time migration of synthetic shots from WAZ dataset using exact velocity model.*

6.2 Bandwidth comparisons

The large range of wavenumber content in the model has been used to investigate broad bandwidth seismic sections and explore the differences in seismic geological interpretation with changes in bandwidth.

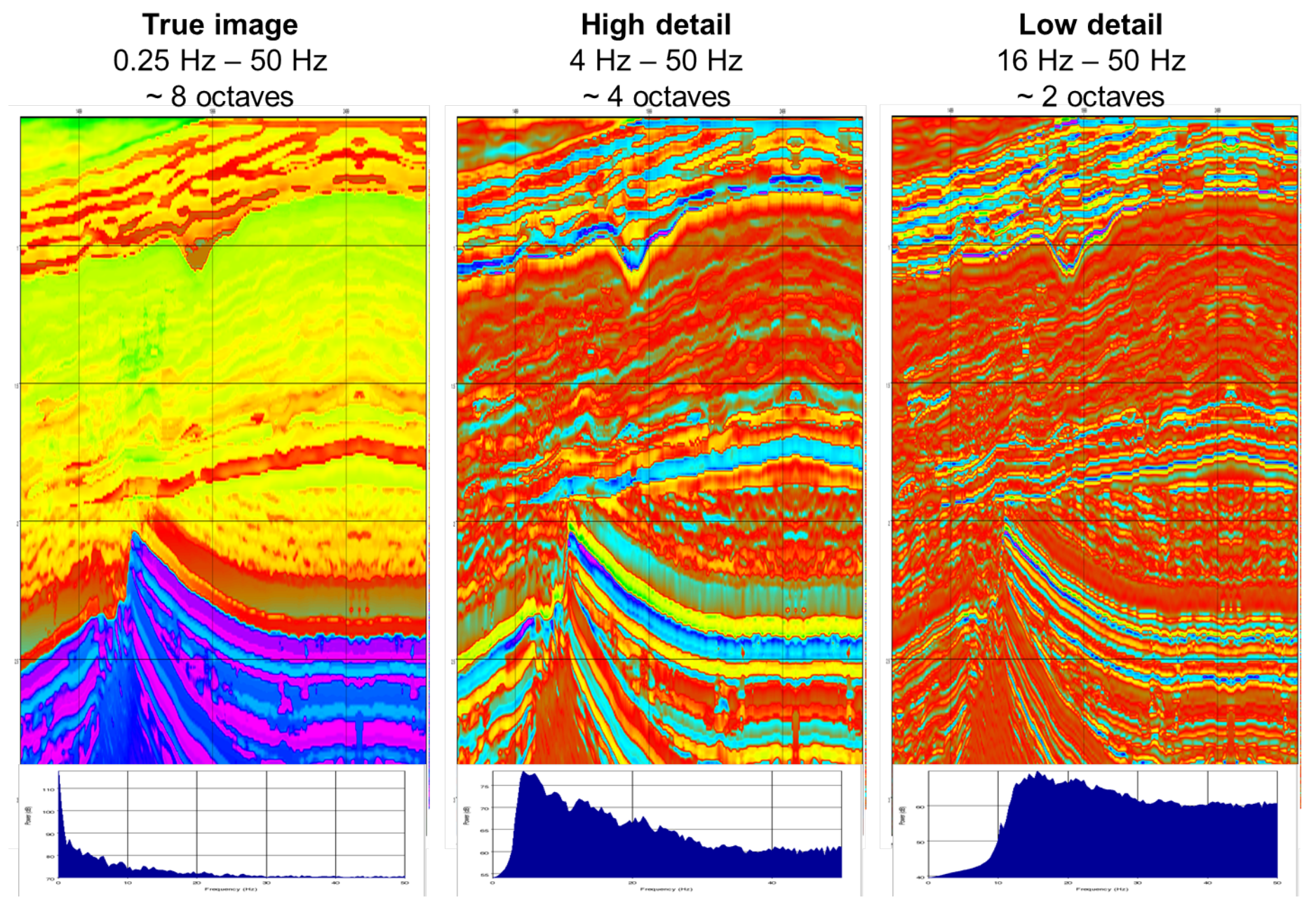

Figure 18: *Bandwidth comparison: Preserving bandwidth maintains image detail.*

6.3 Full waveform inversion

The forward modelled datasets are currently be used by UBC-Seismic Laboratory for Imaging and Modelling (SLIM) and Imperial College FULLWAVE Game Changer Joint Industry Projects (JIPs) to test full waveform inversion codes.

6.4 Improvements to model building method

Bayesian classification of elastic impedance inversion could be used to form facies probability volumes. This requires creation of synthetic probability density functions such as acoustic impedance verses Vp/Vs velocity ratio which could then be constructed for different facies. This Bayesian classification also requires a priori volumes of probability that can be constructed using many of the methods described in this poster. The facies probability volumes could then be turned into multiple solid bodies by connectivity tracking tools to add additional geological features.

Proportional slicing cubes could be be used to add other sedimentary environments by including spatial variations in the depositional rates.

Conclusion

- It has been shown that standard processing and interpretation techniques can be used to create velocity and density models that honour the detail and complexity of well logs and have spatial variations across a broad range of wavenumbers that approximate real geological features.
- Synthetic seismic shot datasets were generated from these velocity and density models using 3D acoustic finite-difference modelling. These datasets provide various acquisition options to allow the evaluation of different velocity inversion technologies.
- The synthetic shots are available upon request from BG Group.

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References

Lancaster, S. and Whitcombe, D., 2000. Fast track 'coloured' inversion. Society of Exploration Geophysicists Expanded Abstracts 19, 1572-1575.

Meldahl, P., Heggland, R., Bril, B. and de Groot, P., 1999. The chimney cube, an example of semi-automated detection of seismic objects by directive attributes and neural networks: Part 1; Methodology. Society of Exploration Geophysicists Expanded Abstracts 18, 931-934.

Gardner, G.H.F., Gardner, L.W., and Gregory, A.R., 1974. Formation velocity and density – the diagnostic basics for stratigraphic traps. Geophysics 39: 770-780.

Wood, A.W., 1955. A Textbook of Sound. New York: McMillan Co.