Applications of finite-difference modelling to coal-scale seismic exploration

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Introduction

Geological environments with significant structures can yield seismic imagery which is complex and of variable quality. In turn, this can reduce the value of the resultant seismic interpretations. Such sub-optimal outcomes can be the result of incorrect acquisition parameters, problems with the processing design, or ambiguities with interpretation. In such situations it is important to minimise the risks where possible. Seismic modelling provides a powerful tool for better understanding the seismic process, and optimising its value.

This paper describes practical applications of a powerful modelling scheme which utilises viscoelastic finite-difference modelling (Robertsson et. al. ,1994). This allows for the generation of all wave types (P, S surface) and includes anelastic attenuation. Realistic shot records are produced which are then fed through a full CMP processing sequence. This step is important, because the processing scheme will strongly influence the final seismic image. This modelling package thus provides a meaningful simulation of the full sequence of seismic acquisition and processing (e.g. Strong and Hearn, 2008). The scheme can accommodate 2D models at a range of scales and complexities (e.g. Figure 1). This paper includes three case studies, demonstrating possible uses for modelling at the coal-scale.

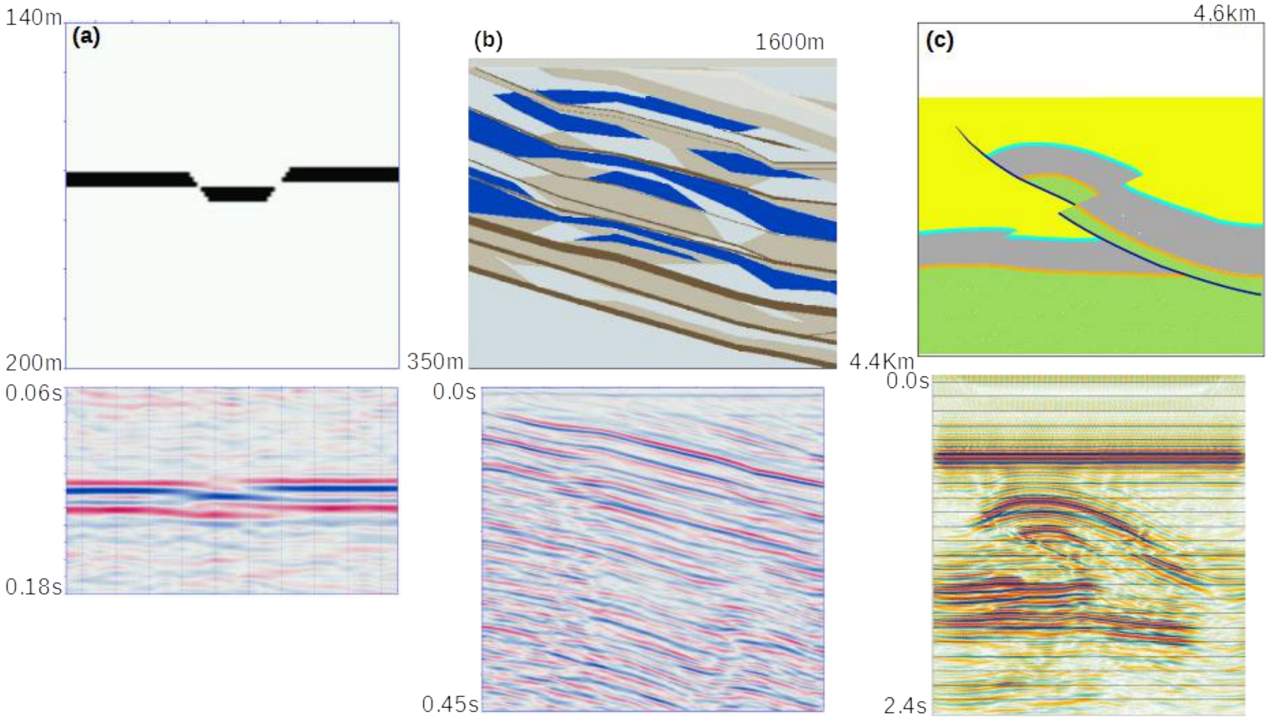

Figure 1: A range of different models can be handled using viscoelastic finite difference modelling. (top) geological models. (bottom) processed seismic sections. (a) simple coal structure, (b) complex coal structure, (c) petroleum structure.

Image Resolution Analysis

When designing an exploration program it is important to know what structures can be imaged and what acquisition parameters are required. For example, the ability of a seismic wave to resolve a geological feature is strongly dependent on the frequency content of the source. Generally, a broader bandwidth with higher dominant frequency tends to give better resolution (e.g. Hearn and Hendrick, 2001).

The first case study presents an example of using modelling to determine the ability of the seismic method to measure the horizontal extent of sand channels within a coal seam. Figure 2 shows the geological model considered. This includes sandstone channels ranging in width from 5 to 100m

For this examination a small explosive source was assumed to produce best-case imaging. Based on this, the modelling used a source with a bandwidth ranging from 30-250Hz and a dominant frequency of 145Hz. This would be typical for a coal-scale dynamite source.

A simulated seismic survey was carried out over the model in Figure 2. Figure 3 shows the resulting processed seismic section. This shows strong reflections associated with the top and bottom of the coal seam and intermittent reflections between these that are related to the sandstone channels. The 20, 50 and 100m wide lenses have reasonable responses. However the weaker responses of those less than 15m are likely to be difficult to identify in real data. These results indicate the best case seismic response that could be derived from a high-frequency 2D coal-scale survey of this type.

The usable frequency content of surface sources is highly dependent on the weathering layer. This can limit the dominant frequency of the seismic data, which would make the resolution poorer. If a surface source was used on this survey without a prior modelling investigation, it is likely that none of the channels would be identified.

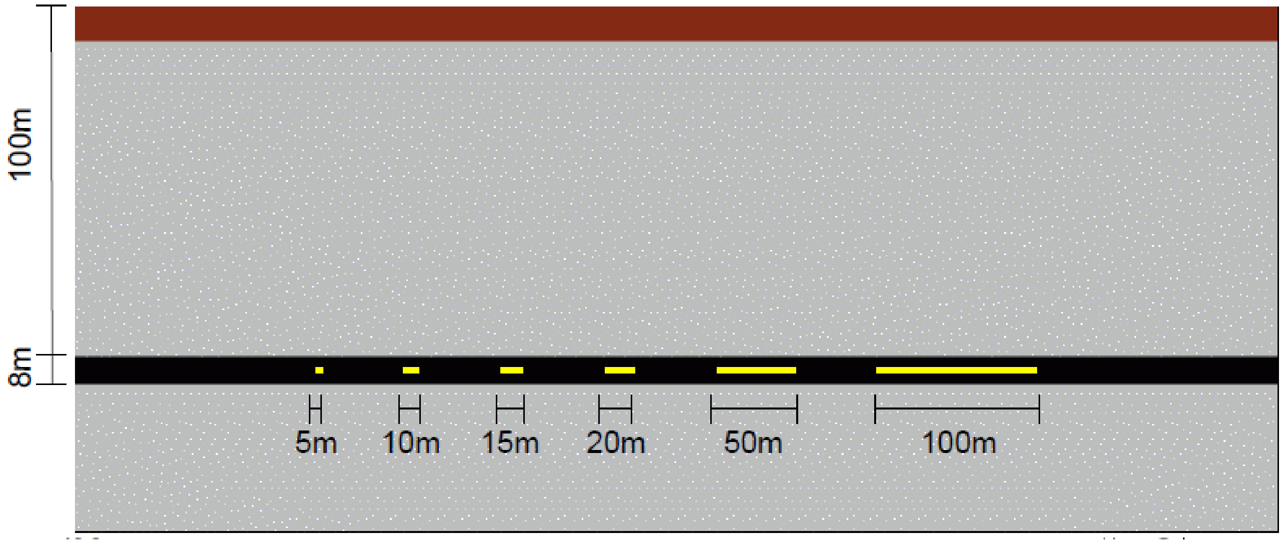

Figure 2: Geological model of 2m thick sandstone channels (yellow) embedded within a coal seam (black).

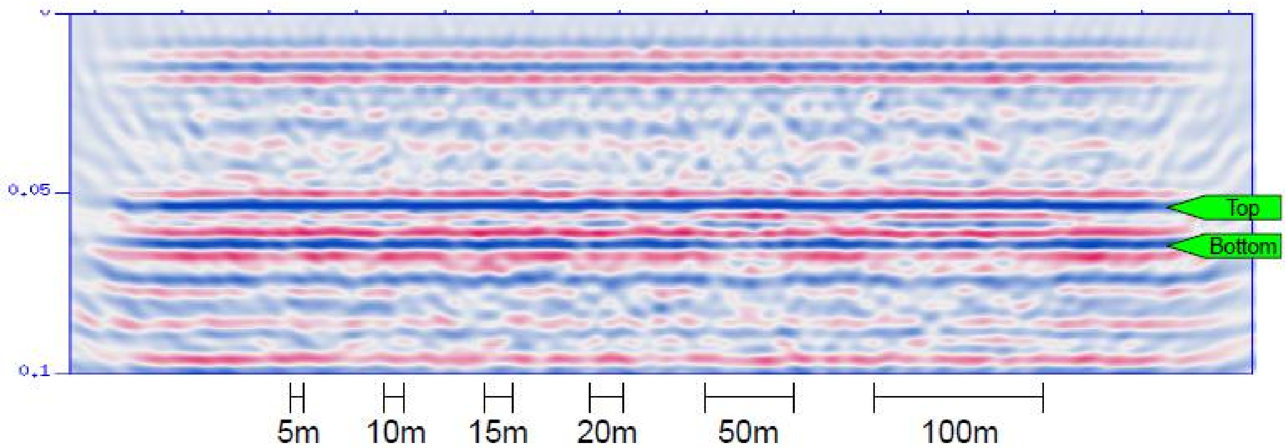

Figure 3: Processed seismic section derived from viscoelastic finite-difference modelling and corresponding to the geology in Figure 2

Coherent Noise Investigation

The second case study shows how modelling can be used to test acquisition and processing parameters. In particular, it examines the influence of ground roll energy and its removal. Ground roll is undesirable noise travelling horizontally near the surface. Because it has very low velocity it can interfere with desirable reflection events.

Prior to this investigation a seismic survey had been acquired with a surface source. During the processing stage, it became clear that the shallow structures were being contaminated by strong ground roll. Before acquiring more data it was decided that viscoelastic finite-difference modelling should be used to develop an understanding of the geological factors contributing to the strength and complexity of the ground roll, and investigate methods of removing it.

Figure 4 gives an example of one semi-realistic weathering profile used in the analysis. It consists of a soil layer at the surface, layers of gradually increasing density and velocity (caused by variable weathering and/ or water content), through to the water table and sub-weathering. (Note that the full model also includes target coal seams, beneath the weathering section shown here.)

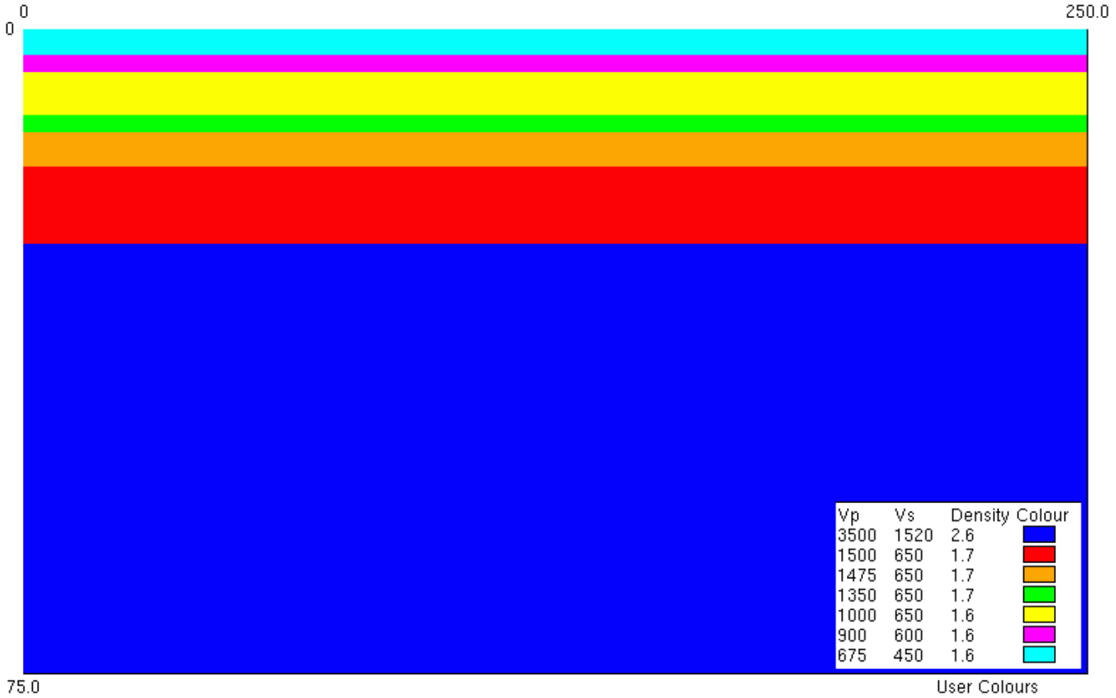

Figure 4: Weathering profile used to analyse ground roll. The vertical extent is 75m. The layering ranges from loose soil at the surface (light blue), through layers of increasing density and velocity (caused by variable weathering and/or water content) to the water table proper (red) and sub-weathering (dark blue).

Of particular interest is how the ground roll events behave on shot records. Figure 5 shows modelled shot records for geophone spacings of 1.5m (a) and 6.0m (b). The finer geophone spacing in Figure 5(a) gives a much clearer idea of the nature of the ground roll. The ground roll is the strongest energy, cutting diagonally across the record and interfering with reflections. The overall character of the modelled ground roll does resemble what is seen on real data. This is because of the detailed weathering model which has been used. For this model the ground roll has significant complexity. This alone makes it hard to determine where the target coal reflection events are on the shallow near offsets.

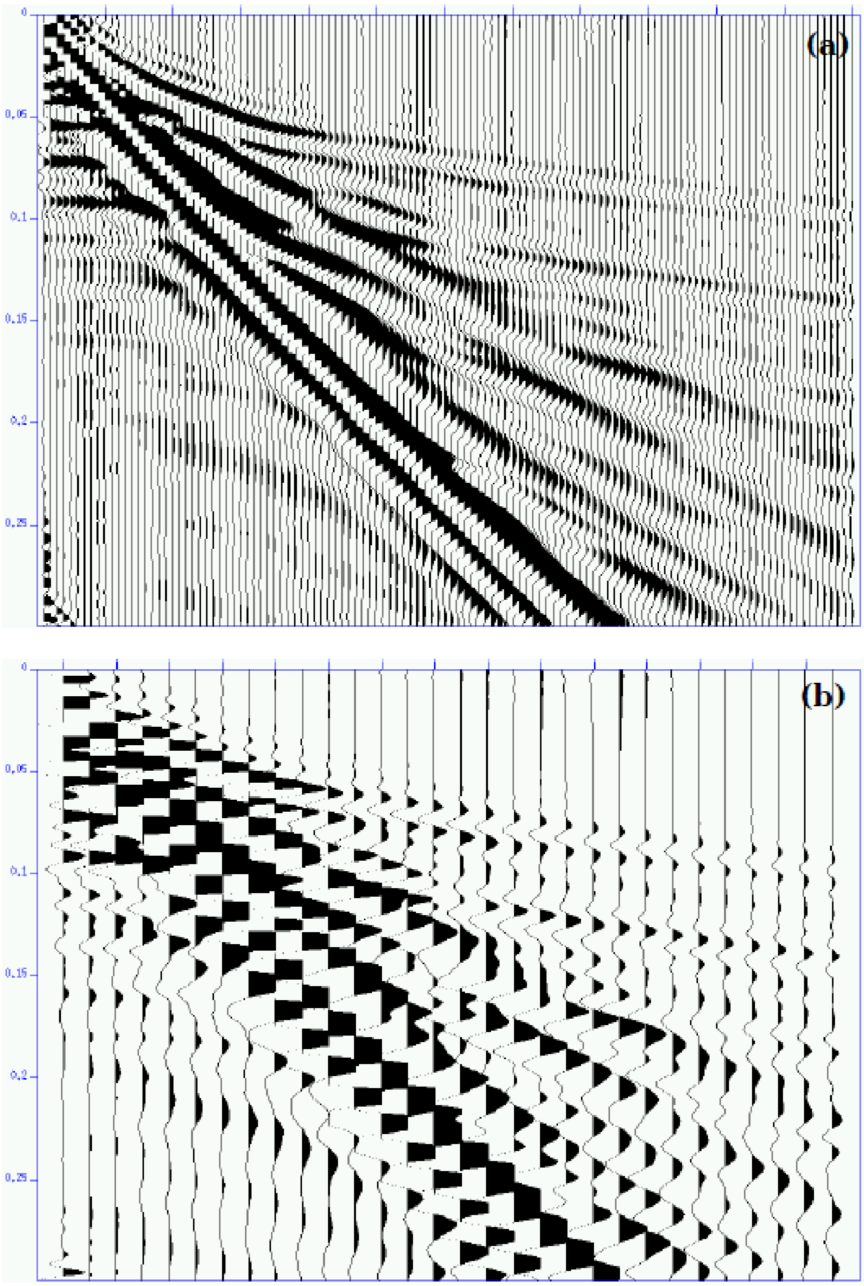

Figure 5: Modelled shot record having an offset of 165m and a maximum time of 0.3s and geophone spacing of 1.5m (a) and 6m (b). Ground roll is aliased on the 6m record.

Figure 5(b) models a geophone spacing (6m) more typical for production coal seismic work. Comparison with Figure 5(a) clearly shows that, if the station spacing is too large, slow events such as ground roll are not sampled adequately in space (aliased). This makes it even more difficult to identify the reflections on the near traces. In addition, this aliasing makes it much harder to remove the ground roll noise in processing.

A processing technique often used to remove strongly dipping coherent noise, such as ground roll, is FK dip filtering. Figure 6 shows the 1.5m-station-spacing record before (Figure 6a and 6b) and after (Figure 6c and 6d) a FK dip filter has been applied. This has done a good job of removing the ground roll such that reflection events are clearly revealed (Figure 6c).

Figure 7 shows corresponding images for the 6m geophone spacing. The FK spectrum of these records clearly show that the groundroll is aliased. The dip filtering cannot remove this without removing signal. Consequently after FK dip filtering the groundroll still obscures the reflection events (Figure 7c).

This case study illustrates that ground roll removal can be restricted by geophone receiver spacing. In this case, the modelling dictates that geophone spacing needs to be minimised if quality reflections are to be achieved.

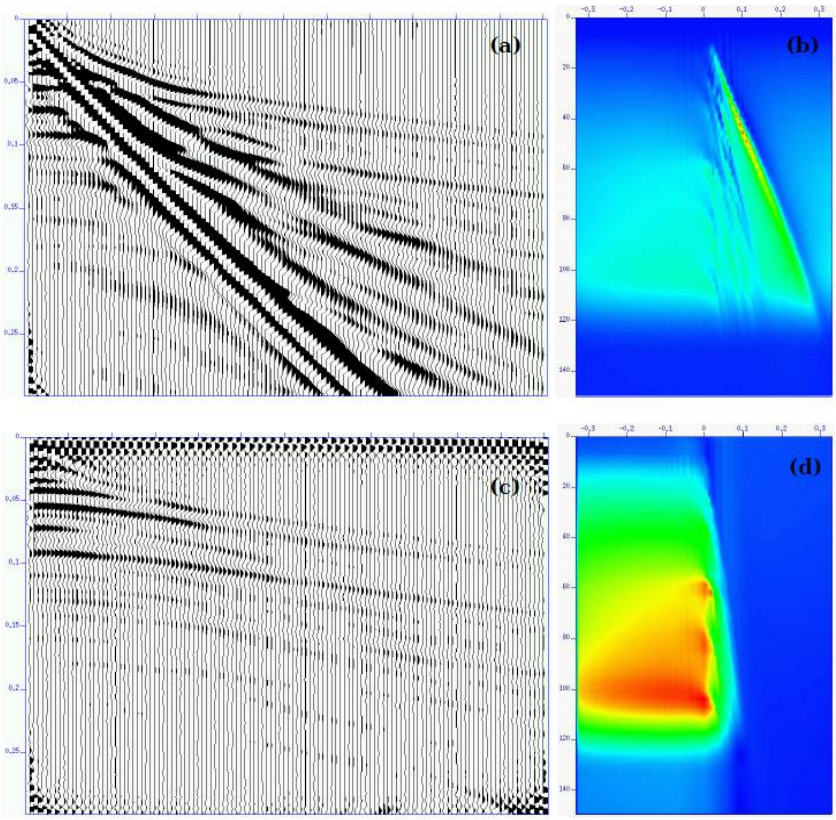

Figure 6: FK filtering – 1.5m geophone spacing. Figures (a) and (b) show a shot record and its FK spectrum. Figures (c) and (d) show the corresponding images after FK filtering has been applied. These indicate that the filtering has performed well, with reflection events now well defined.

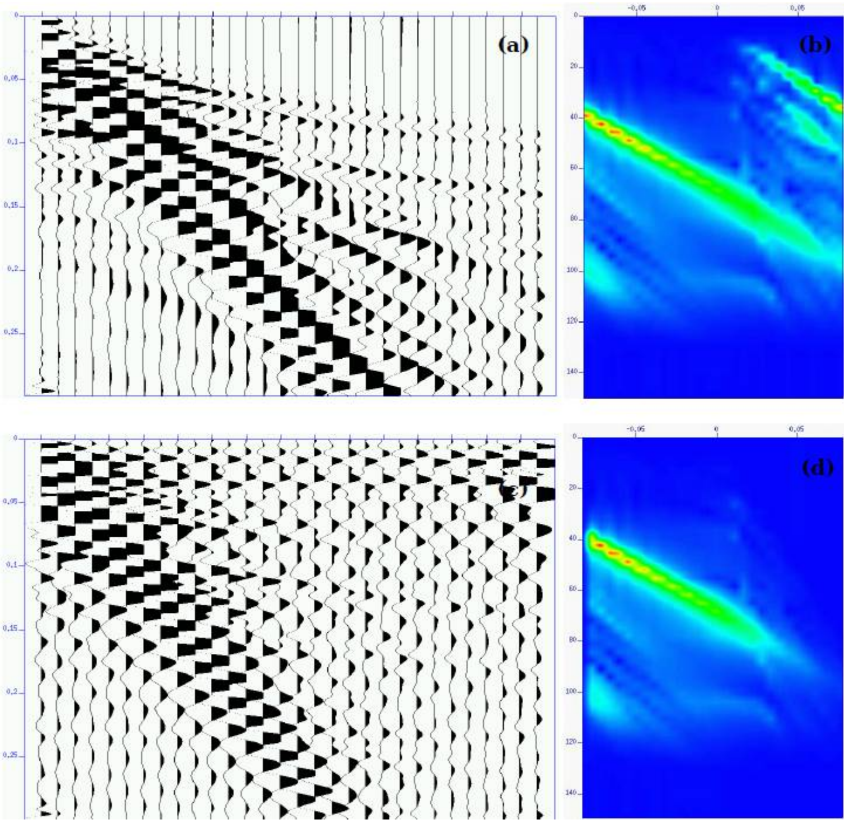

Figure 7: FK filtering – 6m geophone spacing. Figures (a) and (b) show a shot record and its FK spectrum. Figures (c) and (d) show the corresponding images after FK filtering has been applied. In these figures the aliased ground roll noise can not be removed without removing significant portions of the signal.

Interpretation Analysis

The final case study demonstrates how modelling can be used to increase our confidence in seismic interpretation.

Figure 8 shows a representative seismic section from a field site. The target horizon is the deeper event (dotted line). Based on the initial interpretation of this line it was unclear if the small undulations in the target seam were due to “pull-ups” from the overlaying basalt intrusions or were an extension of the shallower faulting into the deeper section.

To investigate this, two complex coal-models (Figure 9) were created. These are identical for the shallower structures and only vary by the presence of faulting in the deeper target horizon (Model 2 has no faulting).

Synthetic seismic surveys have been carried out across these models, and Figure 10 shows the resulting processed sections corresponding to Models 1 and 2 (faulted and unfaulted target seams respectively). These are compared to the real seismic section. All three sections show remarkable similarity in structure and seismic amplitude. In particular the faulting and the structure associated with the thinning of the basalt in the shallower seams are clear on the models and the real data. There is also quite a good match in the wavelet character.

In Figure 10 the target seam has been indicated with a black dotted line. Model 2 which has the structure removed from the target appears to provide a better match to the real data. This suggests that the faulting in the shallower seam either does not continue to the deeper seams, or has significantly reduced displacement at depth.

This example illustrates how realistic seismic modelling can be used to understand relatively subtle image features resulting from quite complex geologies. The outcome is a more reliable interpretation.

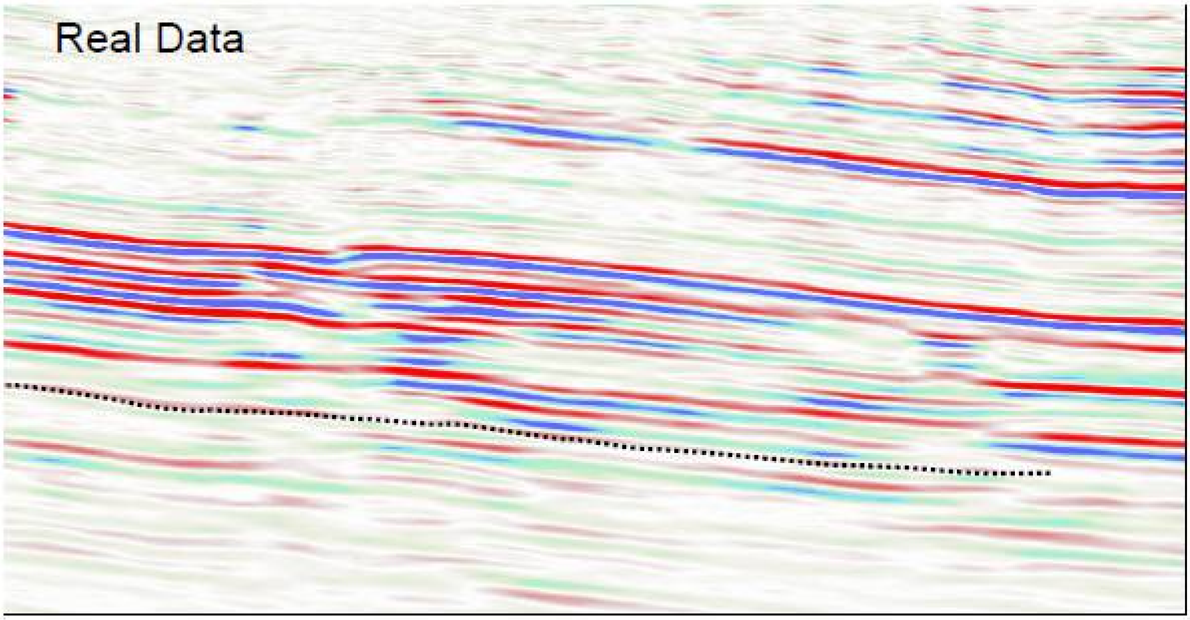

Figure 8: Processed 2D section with the target horizon marked by the dotted line.

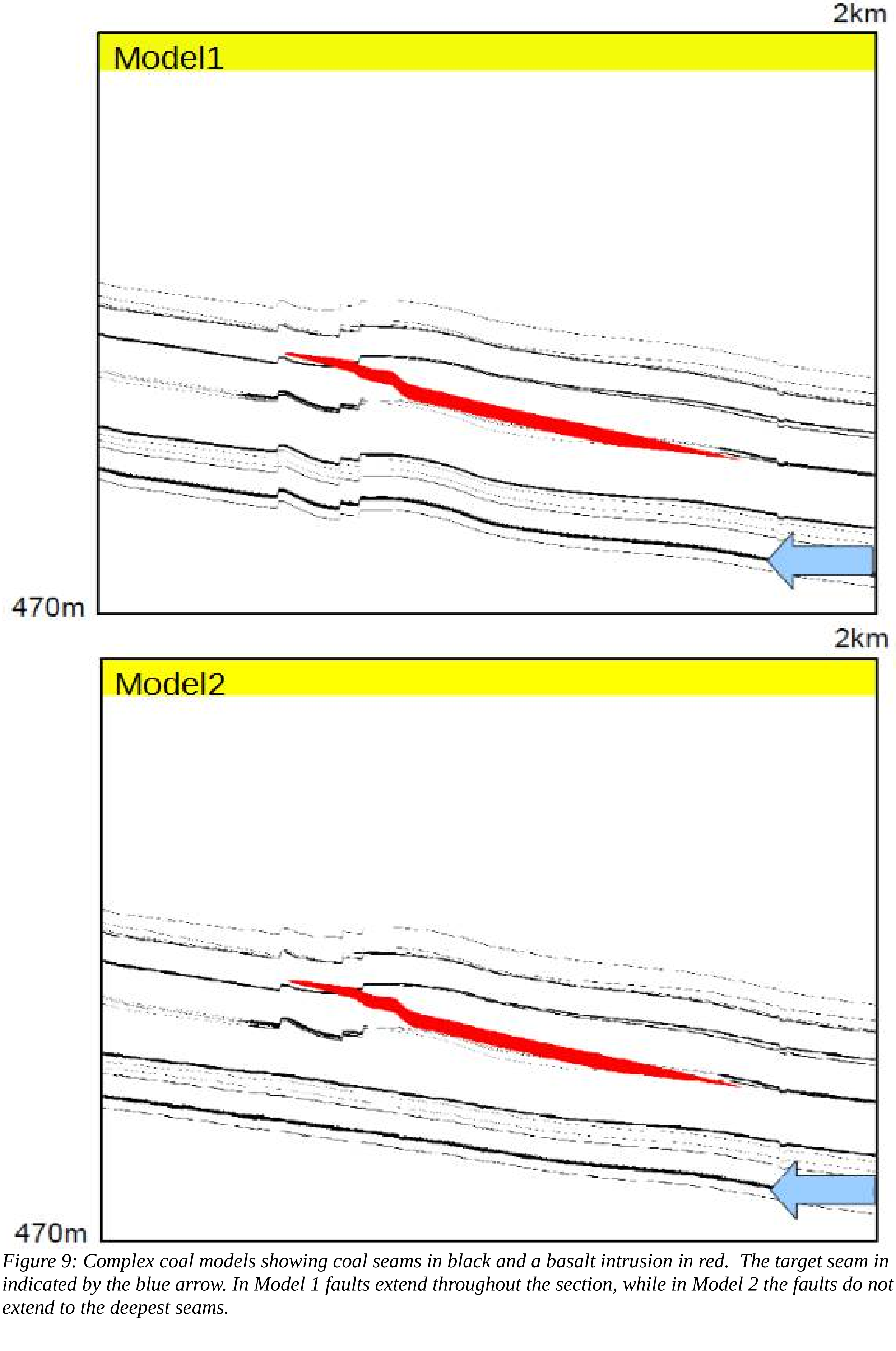

Figure 9: Complex coal models showing coal seams in black and a basalt intrusion in red. The target seam in indicated by the blue arrow. In Model 1 faults extend throughout the section, while in Model 2 the faults do not extend to the deepest seams.

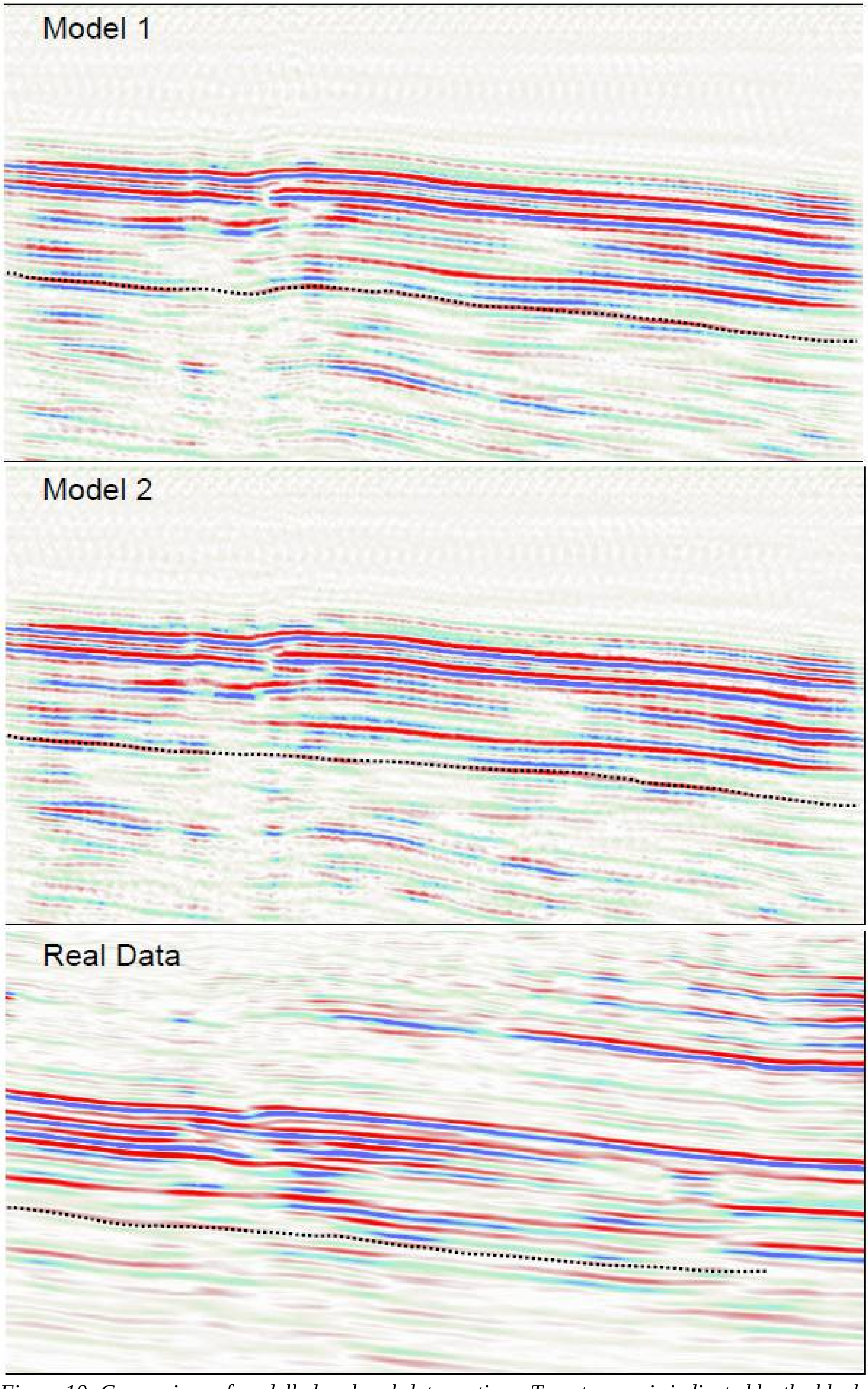

Figure 10: Comparison of modelled and real-data sections. Target seam is indicated by the black dotted line. The structure of the target seam on the real data appears to more closely resembles that on Model 2. This suggests that the shallow faulting may not extend to the deepest seams.

Conclusion

If seismic modelling is to provide real value, it must be carried out with a methodology which can reasonably reproduce the complexities of real seismic acquisition and processing. The examples shown here have been obtained using a full viscoelastic finite-difference scheme which produces realistic shot records incorporating all wave types (P-wave, S-wave, surface waves etc). A full seismic survey is simulated, with a large number of shots being recorded across a defined model, followed by a realistic processing scheme.

With this approach, seismic modelling is an important tool that can be used to add significant value and risk reduction to a seismic exploration program. In particular, it is a valuable component in the design of the acquisition and processing schemes. In addition it can significantly enhance the understanding the significance of the interpreted results.

References

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