Restoring the Seismic Image

Stuart Bland, Paul Griffiths, Dan Hodge and Antonio Ravaglia
Midland Valley Exploration Ltd, 14 Park Circus, Glasgow, G3 6AX, UK

Seismic imaging is a primary source of information used in the exploration of hydrocarbons. Analogies have been drawn between the uses of seismic in exploration and production (E&P) and that of medical imaging in healthcare. There are similarities in the core functions of the seismic interpreter and the radiologist; both rely on high-resolution images as 2-D sections or 3-D models to reveal what can't be seen by eye. In both disciplines the key aims are to note salient symptoms in order to produce an accurate diagnosis of the situation and to advise others of their conclusions. Neither driller nor surgeon will appreciate surprises and will expect to have been appraised of critical factors and potential risks. While the surgeon is interested in the location and most efficient route to an injury, so too is the drilling engineer in the hydrocarbon accumula tion. In both scenarios, however leading edge the technology applied, the outcome is dependent on the inter pretation of the data that until drilling or surgery remains an estimation of reality. At a fundamental level, the interpretation of the data is the product from a continual stream of decisions; 'What does the horizon look like?' 'Is it folded?' 'Can it be correlated across faults?' 'Where do the faults ter minate?' 'Are the faults linked?'

One technique available to help the geophysicist is to flatten the seismic on key marker horizons. Since horizons are both spatial and temporal objects – they are defined by geometry and age, flattening can reveal significant features present at a particular time. Unfortunately this process has a number of drawbacks that require the interpreter to overlook distortions in the image, artefacts of the flattening process. These can arise where the horizon is interpolated across a fault or more generally because the flattening does not replicate the deformation observed in the section. Where the Doctor can refer to records to gain an insight into the patient's medical history, the geologist can restore the section to understand its evolution. Structural restoration is the sequential removal of the effects of sediment compaction, isostatic adjustment and fault related folding that have altered the present day section since deposition. Structural validation aids the decision process between alternative interpretations by testing the results within a structural framework. Inclusion of the seismic enables validation of the geohistory within the context of the data.

Three case studies are presented to illustrate the techniques involved in restoring the seismic image and the benefits from adopting this approach. Each case study has a distinctive setting, characteristic, key issues and associated risks. The first example is set within an extensional fault system of the Gullfaks, northern North Sea and depicts an untested interpretation. The second, an inverted series of half grabens in the southern North Sea, typifies the problem of degrading seismic quality at depth. The final case study is taken from a complex thrusted foreland basin in the Alberta Foothills, Canada. Each example demonstrates an enhanced level of detail and reduced risk of error in the final interpretation.

Extensional Case Study : Gullfaks northern North Sea

Issue :	Untested seismic interpretation
Approach:	Move-on-fault restoration to match footwall and hangingwall cut-offs
Outcome :	Current interpretation shown to include mis-picks.
	Hangingwall volumetrics adjusted
	Fault displacement values updated (significant for fault seal analysis)

At the exploration stage of the E&P cycle it is critical to establish structural rigour to quickly identify any 'first order' errors, to choose between alternative fault pick and horizon interpretations and to generate a structurally consistent model. Move-on-fault restoration offers a means by which to validate the structural integrity of the horizon fault blocks at depth. It is assumed that folding is related to faulting and that the hangingwall geometry is intrinsically linked to the shape of the fault. By selecting an appropriate restoration algorithm a geologically viable geometry should result as the fault displacement is removed.

The restoration step is considered complete when the hangingwall and footwall cut-offs are joined. Bedding thickness and dip should be similar across the fault unless the hangingwall has been subjected to growth faulting or variable compaction. The procedure is illustrated in the following sequence of diagrams.

The present day section shown in Figure 1 is adapted from Fossen *et al* 2000 and was taken from line NSDP84-1. The width of view is approximately 5km, the image quality is reasonable and the broad structural fabric is readily identifiable in an apparently simple structure. The figure shows three sub parallel tilted horizons (red, green and blue) cross cut by a steeply dipping extensional fault and a lowangle listric detachment. The listric detachment bisects an apparently continuous marker (circled in purple), which is thought to be the result of the coincidental alignment of two different reflecting surfaces.

Assuming a process of hangingwall collapse, the last fault thought to have developed is restored first. In this case the hangingwall objects overlying the listric detachment were restored using an inclined shear algorithm appropriate

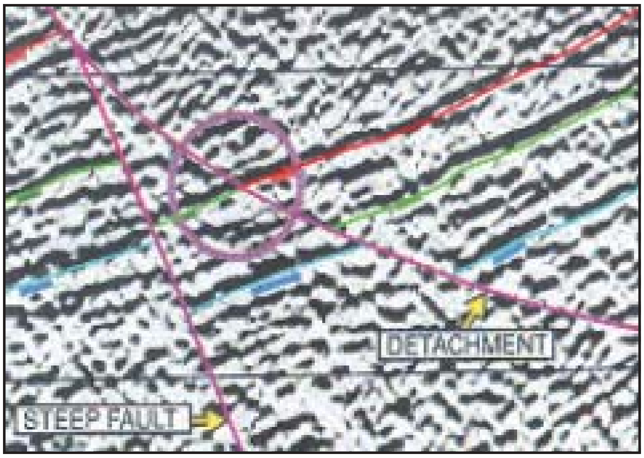

Fig.1 : Present Day two-way time section, of an extended fault block from the southern North Sea, adapted from Fossen *et al*, 2000

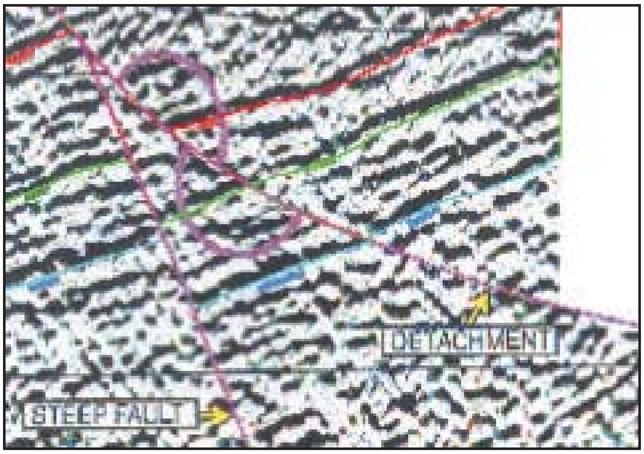

Fig.2: the far right hangingwall block was restored on the listric detachment and cut-offs matched on the green and blue horizons.

for extensional tectonic domains. The fault displacement of a few hundred metres was removed by matching the cut-offs of the green and blue horizons; the seismic image was included in the restoration step. Since the restored profile is geologically viable producing a restored block with regional tilt lacking distortion, the restoration method can be considered satisfactory and the fault geometry valid.

Fault displacement was removed on the steeply dipping fault in order to complete the restoration. A different result was reached to that published by Fossen *et al*. While the green and blue horizon cut-offs are successfully matched, the red reflector is shown not to restore exhibiting a thickness mismatch across the fault. Although the apparent continuous marker cut by the listric detachment in the present day section is still thought to be a coincidental juxtaposition of reflectors, it is not likely to involve the red horizon. The current interpretation is invalid and suggests the red hangingwall horizon should be pickes several cycles higher.

Whilst this example was originally used to demonstrate the presence of low-angle detachments in the northern North Sea within an apparently simple structure, there are significant commercial implications for hydrocarbon prospects and fields. Were this set within a prospective trap the volumetric calculations for a hangingwall reservoir would need to be revised in favour of the explorer. This may be a critical deciding factor in the commercial viability of developing the prospect. Additionally, were hydrocarbons thought to occur within the fault block located between the steep fault and listric detachment, the fault seal analysis would need to be reassessed for a reduced fault displacement of the red hangingwall.

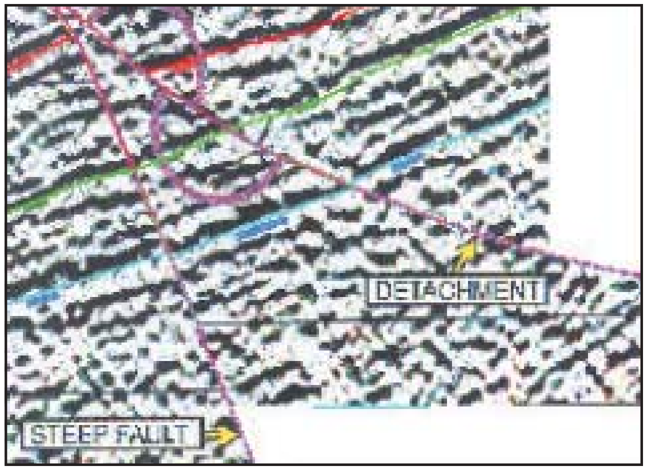

Fig.3 : the hangingwall block was restored on the steep fault and cut-offs matched on the green and blue horizons. Note that the red horizon exhibits a mis-pick across the faults in the current interpretation

Inverted Case Study	**:**	UKCS, Southern North Sea.
Issue	:	Seismic quality degrades at depth
Approach	:	Backstrip the section and include the seismic image
Outcome	:	Enhanced correlation of internal stratigraphic markers Established geological evolution

Traditional 2D cross-section validation and restoration techniques are limited to the detail of the interpretation made from the seismic data. This level of detail is in turn constrained by the quality and complexity of the seismic image and tectonic setting. Analysis of the manipulated seismic resulting from the restoration and backstripping workflows allows the interpreter to test the interpretation and visualise the internal architecture of the seismic data between interpreted horizons throughout the structural evolution of the section. The seismic manipulation workflow also allows the interpreter to re-evaluate mispicks during restoration without the need to consult the original data. In this example the horizons and faults are readily identifiable in the post Westphalian sequence, but the quality of the seismic deteriorates with increasing depth. Interpretations made in the deeper part of the section carry a higher risk.

The case study, illustrated in Figure 4, shows a series of tilted half grabens. The central fault block shows evidence of inversion (or out-of-plane movement), with positive displacement above the regional at the base Zechstein level, note that there is net extension at the Intra Westphalian level. The restored seismic has been used to reveal and reconstruct sequence stratigraphic architecture previously obscured by faulting. This process exposes the data to more detailed scrutiny, augmenting seismic stratigraphic interpretation to reveal a lithofacies model. Forward modelling of such retro deformed interpretations can then be applied to predict reservoir quality sand targets within apparently complex seismic data.

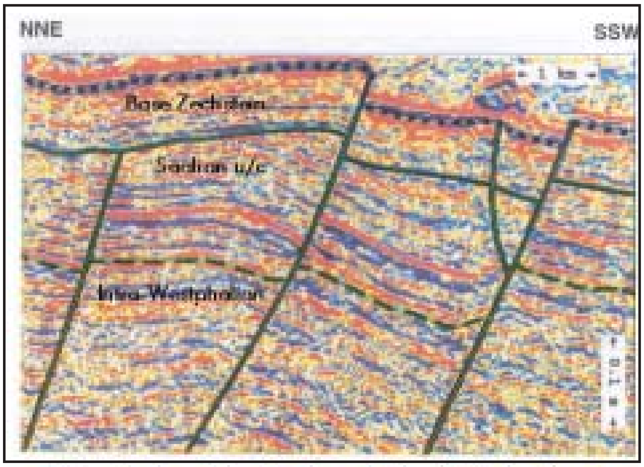

Fig. 4 : Present Day section in travel time, of an inverted series of half grabens from the southern North Sea.

Structural restoration was achieved sequentially. Initially the time section was depth converted, the Zechstein salt layer was backstripped and the remaining section modified for the effects of sediment offloading. Fault displacements in the Base Zechstein (Top Rotliegende) were removed in the reverse order that faulting was thought to have occurred so that the latest formed faults were restored first. After the effects of faulting were accounted for, folding deformation was removed by unfolding the Base Zechstein, (Top Rotliegende horizon) to horizontal via vertical simple shear. Figures 5a to 5c depict the full restoration sequence of the Base Zechstein.

Once the palinspastic reconstruction of the Base Zechstein was achieved, the horizon was backstripped and the remaining horizons modified for the effects of decompaction and isostatic adjustment. Fault displacement and folding deformation was removed in the Saalian Unconformity as previously described for the Base Zechstein, see Figure 6a to 6c.

Finally faulting displacements on the Intra-Westphalian marker were removed and the remaining section unfolded to show the geometry at the end of deposition of the Intra-Westphalian, see Figure 7a and 7b. Uninterpreted, internal markers of similar amplitude were more easily correlated across fault boundaries than in the deformed Present Day section. The final restored section provides confidence in the Present Day interpretation and allows the mapping of otherwise obscured internal architecture across the section, without reference to Well control.

The subtle stratigraphic architecture of internal reflectors in the poorly imaged deep section previously obscured by faulting, can only be correlated in the restored section. This process opens up the data to further analysis including a sequence stratigraphic interpretation and a lithofacies interpretation – detail not easily resolved from the data in its deformed state without well control. These improved and enhanced lithofacies interpretations can be forward

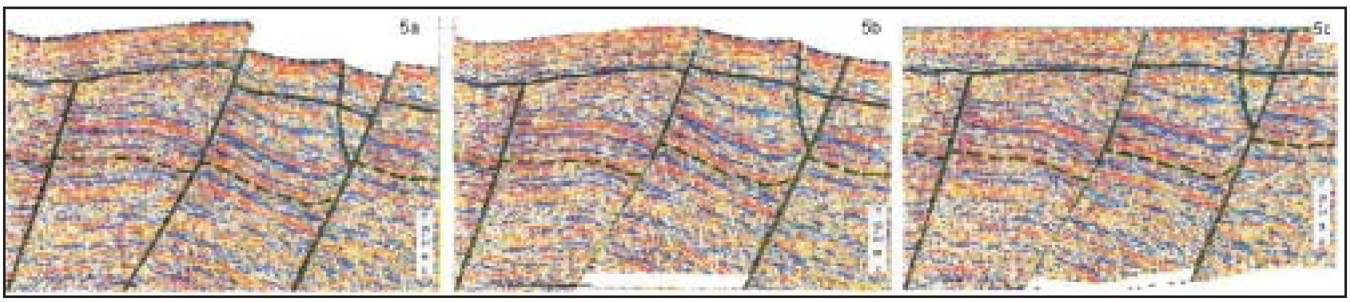

Fig. 5a, Present Day depth section with post Zechstein sequence decompacted and backstripped. Figure 5b, shows removal of fault displacement at the Base Zechstein level. Figure 5c, depicts the section after unfolding, showing the geometry during deposition of the Rotliegende horizon.

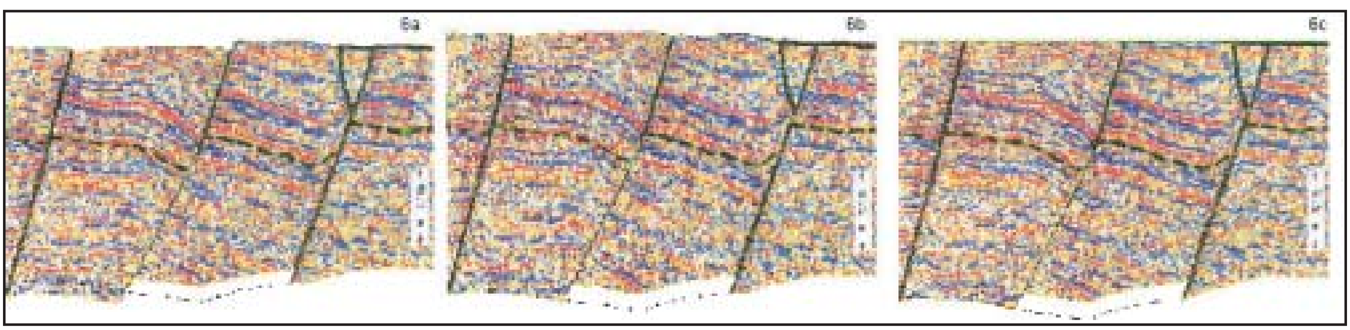

Fig. 6a, Palinspastic geometry after removal of the Rotliegende. Figure 6b, Shows the removal of faulting offset at Saalian Unconformity level. Figure 6c reveals the geometry at the formation of Saalian Unconformity.

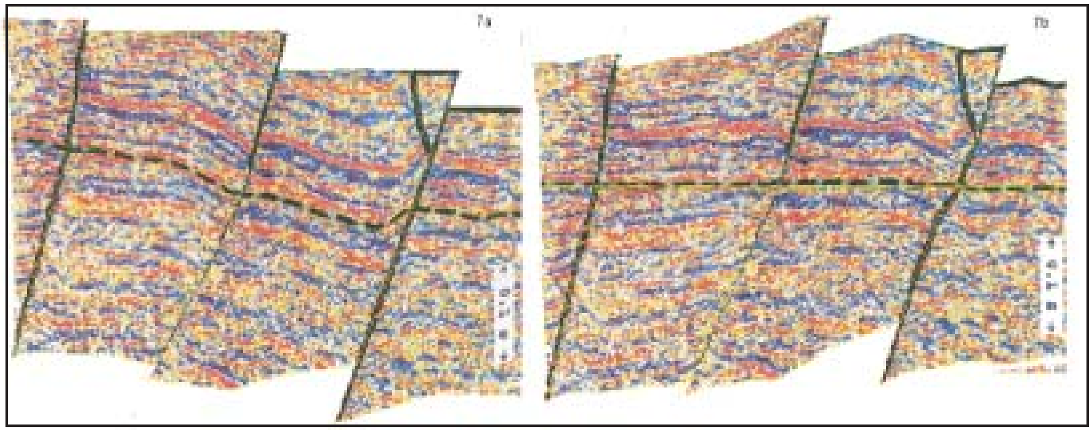

Fig. 7a: Fault displacement on the Intra-Westphalian marker removed. Figure 7b, Remaining structure unfolded showing the geometry at the end of deposition of the Intra-Westphalian.

modelled to their present-day state and used in the prediction of reservoir quality sand targets within the apparently poor resolution seismic data.

Compressional Case Study :

Shaw Basing, Alberta, Canadian Foothills

Issue	:	Untested seismic interpretation of trapping structure in east (left) of section
Approach	:	Simulate deformation processes to check the interpretation via move-on-fault restoration to match footwall and hangingwall cut-offs and unfolding validation.
Outcome	:	New interpretation required additional fault through crest of the major trapping geometry.

In the final case study seismic restoration was applied to a foreland thrust and fold belt structure from the Alberta Foothills, Canada. Figure 8 shows the current interpretation published by Yan and Lines (2001), of a thrusted duplex within a triangle zone from the Shaw Basing area. The structural style is complex and is characterised by a duplex cored triangular back-thrust. The triangle zone is constrained by a lower and upper detachment.

Attention was focussed in the trapping geometries of the delaminated upper sequence, overlying the thrusted duplex. The tectonic wedge was unfolded via flexural slip unfolding to a horizontal datum using the pink reflector as a reference template. The flexural slip algorithm replicates the deformation mechanisms observed in thrust folds. Using a pin, a slip-system was calculated parallel to the template bed to control the unfolding of the beds. Unlike line-length methods, flexural slip unfolding maintains bed thickness variations. Additionally it maintains the line length of the template horizon in the direction of unfolding as well as the orthogonal bed thickness between the template horizon and other passive objects. The area of the fold and the model are maintained, as are the line lengths of passive objects that are parallel to the template bed. For layer-parallel beds, flexural

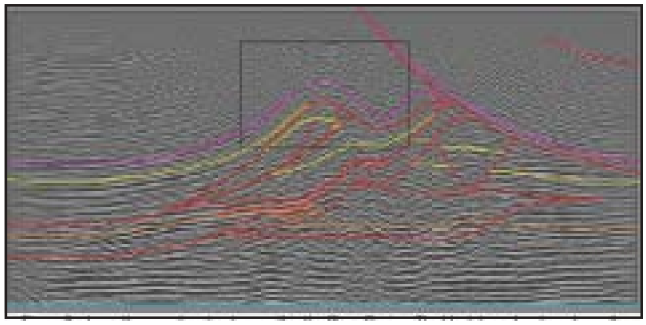

Fig. 8: The complex structures within the Shaw Basing. The black boundary box shows the location of Figures 10 & 11.

slip unfolding represents flexural slip during fold formation. As the pink horizon was unfolded, other marker horizons, fault picks and the seismic image within the fault block were carried with it as passive objects, see Figure 9. The unfolding technique allows the interpreter to check the consistency of marker units within the fault block. The turquoise line points to distortion in the unfolded seismic created due to a slight mis-pick in the pink marker on the crest of the structure. The correct amplitude on which to pick becomes clear in the unfolded state and can be easily traced in the present day geometry.

A revised interpretation of the crestal structure included an extensional fault with some 160m of throw. The revised interpretation is shown in green and can be compared to the original in pink as shown in the centre of Figure 10.

The revised interpretation was tested by a move-on-fault restoration, a fault displacement of some 160 metres was removed by matching the cut-offs of the green horizon, and the seismic image was included in the restoration. The restoration method was considered satisfactory and the fault geometry valid since the restored profile was geologically viable and reflectors within the uninterpreted seismic could becorrelated across the fault as shown in Figure 11.

The implications for any prospective traps in the delaminated layer are significant, as a new conceptual model

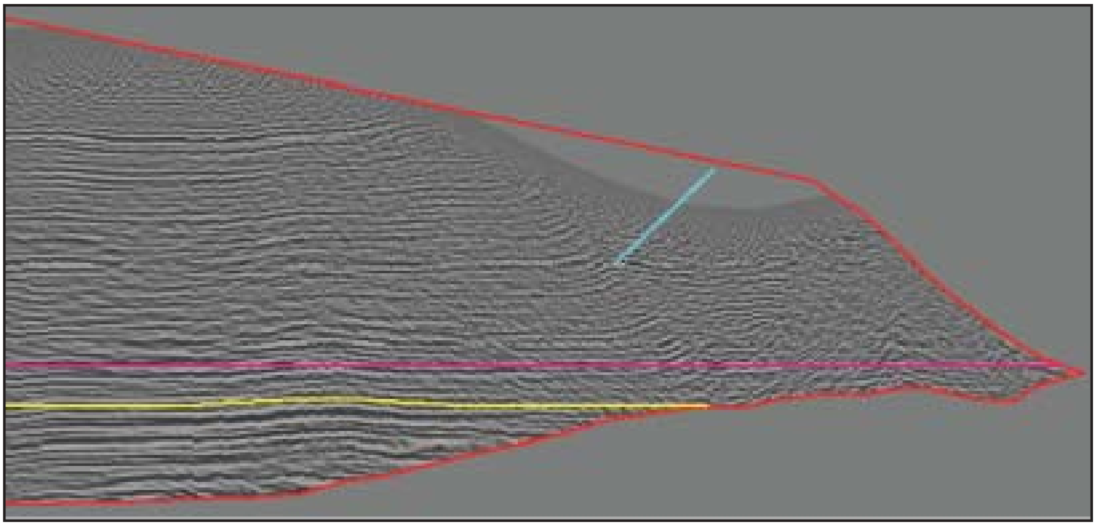

Fig. 9 : the unfolded pink horizon in delaminated fault block, the pink line highlights distortion in the seismic due to a mis-pick in the crest of the structure.

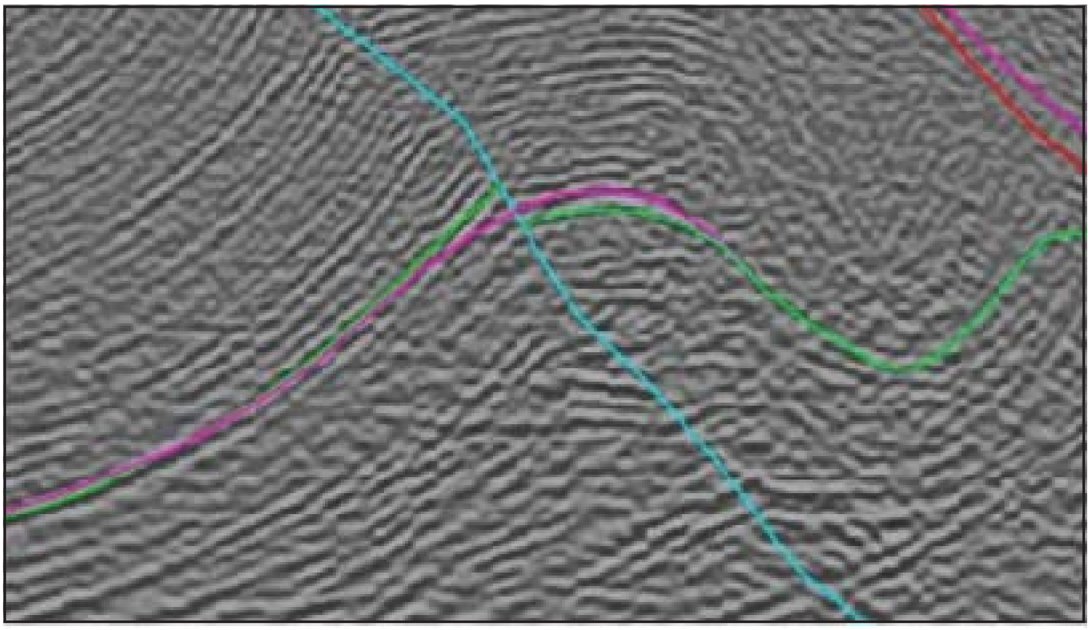

Fig.10 : revised interpretation shown in green.

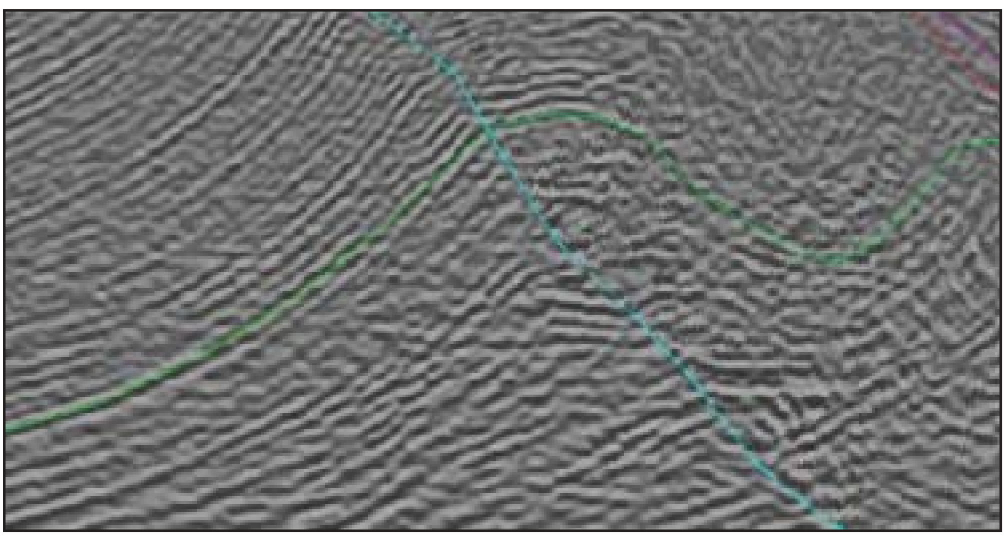

Fig. 11 : the revised interpretation restored via move-on-fault, validating the new conceptual model.

is required to understand the development of the present day structures. Typically hydrocarbon traps in this tectonic setting are assumed to form in the crest of antiforms from 4-way dip closure. By interpreting an extensional fault through the crest of the structure additional risks associated with fault seal have to be included in the overall assessment of the play prospectivity.

When an interpretation is set in the context of a viable structural framework, it becomes more than the sum of its parts; not only is it a spatial representation of known or inferred information, it can reveal an understanding of the geological evolution. It enables geological concepts to be tested against current geological rules. The greater the understanding of the structural play, the easier it is to evaluate and the lower the exploration risks. In each of the case studies described, advanced understanding was reached by analyses of the restored seismic panels. Looking at the seismic in a new way brings out a level of detail and confidence in stratigraphic and sedimentary interpretations that may otherwise have been difficult or impossible to observe. Use of sequential restorations in the unravelling of the geohistory, carrying the full information available in the seismic image, increases awareness and understanding of exploration play concepts along with reservoir and trap development.

Acknowledgements

We would like to express our thanks to Jo & Lou Michels for advise on the use and practise of imaging in medicine and Andy Newson of Moose Oils.

References

Fossen, H., Odinsen, T. Faerseth, R.B. & Gabrielsen, R.H. 2000, Detachments and low-angle faults in the northern North Sea rift system, *from* Nottvedt, A. et al (eds) *Dynamics of the Norwegian Margin*, Geological Society, London, Special Publications No. 167, p. 105-131.

Quirk, D.G. & Aitken, J.F., 1997, The structure of the Westphalian in the northern part of the southern North Sea, *from* Ziegler, K., Turner, P. & Daines, S.R. (eds), *Petroleum geology of the Southern North Sea: Future Potential*, Geological Society, London, Special Publications No. 123, p. 143-152.

Yan, L. and Lines, L.R., 2001, Imaging of an Alberta Foothills seismic survey, *The Leading Edge*, 20, p. 80-86.