High Resolution Velocity as a 4D Attribute

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Introduction

4D (also known as time-lapse or repeat) seismic has in the past few years emerged as a significant technique for monitoring fluid movement within reservoirs.

In recent years, an improved understanding of the petrophysics of the reservoir (eg. Wang, 2001) has enabled geoscientists to establish relationships between observed seismic attribute changes, and corresponding rock property changes.

Once it was established that such additional information could be extracted from surface seismic data (eg. Lumley, 1995, 2001), changes were made to seismic data processing sequences so as to better preserve relative amplitude changes, especially with regard to pre-stack differences between data vintage subsets.

Monitoring of changes as diverse as temperature (as in the case of steam injection: Lumley, 1995) and movement of fluid contacts have proved attainable and successful (Jack, 1998).

Previously, one of us (Jones & Baud, 2001) demonstrated the potential of using a dense velocity estimate as a high-resolution tool for visualizing subtle changes not clearly discernable in the seismic amplitude response. (Success of such techniques depends to a large part on the data being correctly pre-stack migrated, so that all diffraction energy is correctly collapsed).

In this work, we assess the potential of high resolution velocity, as an indicator of reservoir change in the context of a 4D study (Jones & Folstad, 2002).

4D Assumptions

The majority of 4D studies to date have made several restrictive assumptions, namely that:
- there has been no structural collapse
- all changes are restricted to the region affected by production (the reservoir)
- acquisition related differences are removed during processing
- there is no azimuthal variation in reflectivity
- a common velocity model can be used for the overburden
- a common velocity field is used for migration

In this work, we have adhered to these assumptions, but as we demonstrate, some need to be modified in order to better exploit the information available in the data.

The Methods

The technique employed here is slightly different than that described by Jones & Baud, but the objective is the same: estimation of an RMS velocity value for each pre-stack migrated CMP along a given horizon.

Whereas previous techniques worked with scan-based residual move-out (RMO) velocity analysis of CMP gathers (eg. de Bazelaire, 1988, Doicin et al, 1995, Jones, et al, 1997, 2000), in this work we employ two different approaches: a map manipulation approach and an AVO consistent approach (Swan, 1991). A motivation for comparing different techniques was to ensure that spurious conclusions based on limitations of an individual technique, could be taken into account.

Perhaps the most restrictive assumption in all these approaches is that of parabolicity in the residual move out (after NMO). Similar assumptions are common to most residual velocity analysis techniques, but from inspection of the data, the assumption is seen to be frequently violated to some degree. This can be an important drawback, as occasionally application of the residual moveout can degrade the stack for areas where the moveout was not parabolic. This assumption can be relaxed if we have long-offset data, by employing a continuous higher order analysis. This would usually be performed in two steps, firstly determining the near-vertical NMO velocity, and thereafter the fourth order terms.

In the first technique employed here, we take the near and far trace stacks from the two data vintages in conjunction with the interpreted time horizon for a key reservoir marker and the RMS stacking velocity field associated with this marker. (In this case, a common initial velocity field was determined from the superior more recent survey, and applied to both data vintages during processing: NMO, DMO, and preSTM).

Using the interpretation as the centre for a windowed operator, we perform a cross-correlation of the near and far stacks for a given data vintage. This yields an estimate of the residual time shift between the near and far traces. This is stored as an horizon based map of values. Values corresponding to low correlation coefficients are eliminated (as they are associated with noise), and replaced by interpolation from acceptable neighbouring values. These

procedures were implemented in Hampson-Russell's pro4D package.
Using an approximation for the parabolic residual moveout equation (Castle, 1994), we convert this time shift map to an associated RMS velocity map for the horizon of interest. This is done for each data vintage. Results from this horizon cross-correlation approach are labelled as 'hcc' in the figures.

Differences between the resulting two continuous high-resolution velocity fields are inspected as an indicator of changes in fluid content for markers in the reservoir interval, and for other effects for markers outside the reservoir interval.

The second technique is a more classical continuous estimator, but uses an AVO criterion as its objective function (Swan, 1991). Results from this approach are labelled as 'AVO' in the figures. Conventional velocity analysis techniques use criteria such as semblance to determine the 'best' stacking velocity, but Swan's technique uses

F(Vrms) = Im{An[R0] * cnj[G]}Where the first term on the RHS is the analytic trace of the zero-offset reflectivity, the second term is the conjugate of the gradient trace, and the imaginary part of their product constitutes the objective function. This provides an excellent measure of the optimum stacking velocity in the presence of AVO.

Norwegian North Sea Example

The example shown is from the Ula oil field, in the Vestland Arch in the Norwegian-Danish basin. The main reservoir is capped by the Top Ula event. Above this, we have the BCU horizon, which being outside the reservoir should not show production related effects. The baseline for this 4D study was shot in 1984, orthogonal to the 1999 repeat survey Thus the data are not ideal for 4D attribute estimation, but this study was an attempt to see what information could be extracted using legacy data**.** Analysis of the Ekofisk BCU events was used to check for non reservoir related acquisition related problems. Figure 1 shows the general geological setting, and production related changes in the reservoir properties are indicated in Figure 2.

Figure 1: Main seismic horizons of the Ula Field.

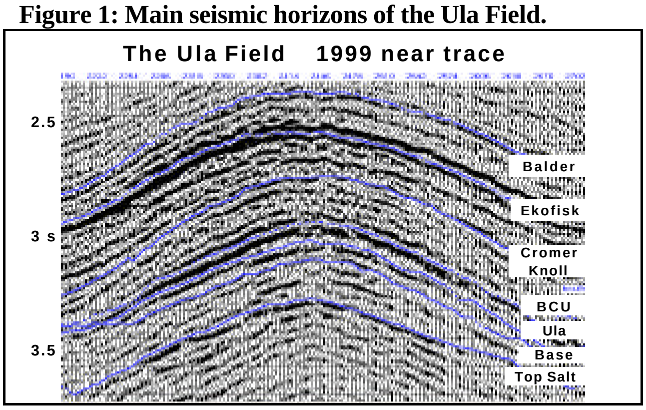
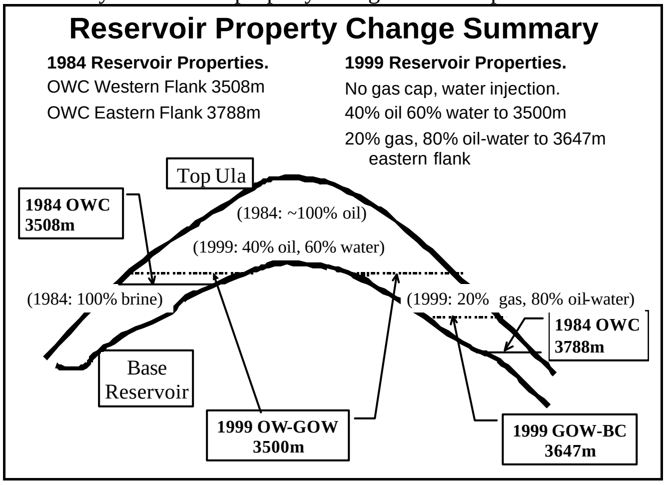


Figure 2
Summary of reservoir property changes over the period 1984-1999



Elastic Modelling of the Time-Lapse Reservoir Response

As part of the assessment of 4D potential for the field, an elastic modelling and illumination study was performed (Jones, et al, 2002).

Initial studies of the illumination for the two surveys (which were shot orthogonally) indicated that no large differences in illumination exist other than near the major crestal fault on the anticlinal structure.

By processing synthetic data (figures 3a & b) generated by elastic modelling of the reservoir response both before and after production (using the GXII software package), we were able to compute synthetic difference sections representative of the expected changes in the reservoir due to production. In addition, we were able to show that production related velocity differences should be measurable from the surface seismic data.

In figures 3a & 3b we see the migration results from synthetic data computed along a crestal crossline through an exploration well. Figure 3c shows the amplitude differences between the 1984 and 1999 stacks for these synthetic migrated data.

Results

It was observed that there were consistent changes between the 1984 and 1999 vintages outside the reservoir (on the BCU event and to a lesser extent on the shallower Ekofisk event). This was interpreted as being related to the acquisition differences: the surveys were shot orthogonally. It is also possible that these azimuthal variations in velocity are related to fracturing in the overburden, or to ray path differences resulting from near surface heterogeneities.

Figure 3a
Results for the 1984 baseline survey. 2D preSDM of synthetic 40 fold data created using offsets 100 - 4100m, with CMP ray tracing at 12.5m intervals.

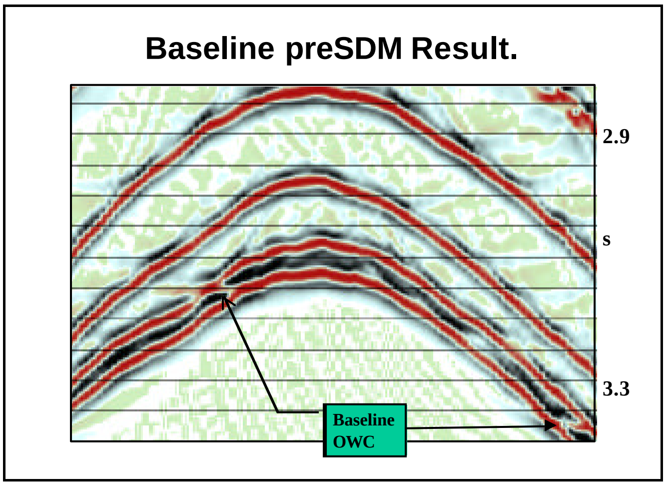


Figure 3b
Results for the 1999 repeat (monitor) survey

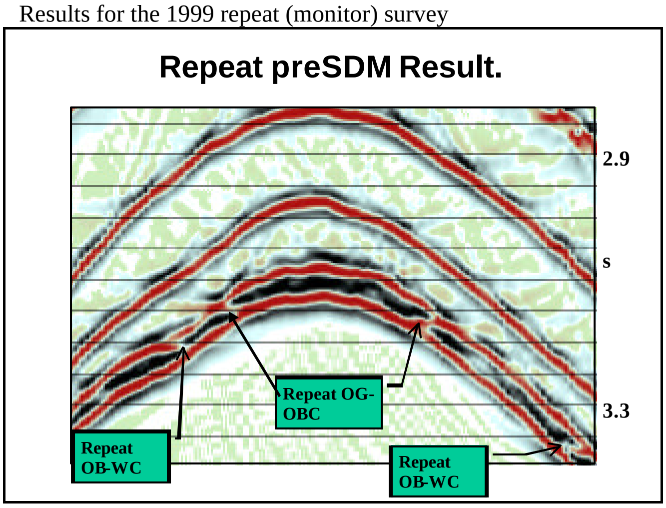
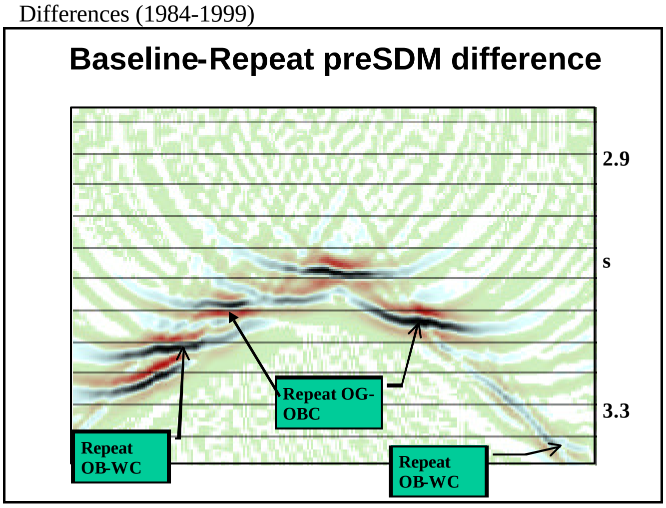


Figure 3c
Differences (1984-1999)



To give an aerial perspective of the prospect, in figure 4 we see the two-way time contour map for the preSTM volume at the Ula horizon. An interpretation of the crestal fault is superimposed on the map in addition to the 3190ms contour of the top reservoir (Ula). Figure 5 shows the amplitude difference map for the BCU, just above the reservoir. Differences at the BCU are assumed to be related to the differing acquisitions or processing, and not production related.

In Figures 6a & b, we have the RMS high resolution velocity maps for the BCU, estimated with a trace sampling of 50m * 50m for the 1984 and 1999 data vintages. In figure 6c, we see the difference map showing velocity variations of between +-40m/s in the crestal region. These results were produced using the 'hcc' method.

It can be seen that we have distinct regions within the crestal zone. The area to the right of the fault shows up in red-brown colours, corresponding to no velocity change. To the left of the fault, we have a yellow-orange region showing changes of about -40m/s, indicating that the velocity is higher in the 1999 data (shot orthogonal to the crestal fault).

The efficacy of the whole volume AVO RMO technique is demonstrated on a collection of gathers in figures 7a & b. In 7a, we see the 1984 gathers corrected with the 1999 velocities. And in 7b, the same gathers after correction with the velocities derived from the AVO whole-volume velocity estimator. Figures 8a & b compare the velocity differences obtained using the two approaches: hcc horizon based, and AVO whole-volume based: both techniques give similar results.

Figure 4
Contour map for the Ula horizon showing the crestal fault interpretation, the bounding contour of the reservoir unit, and a box for which detailed results will be displayed in the following figures

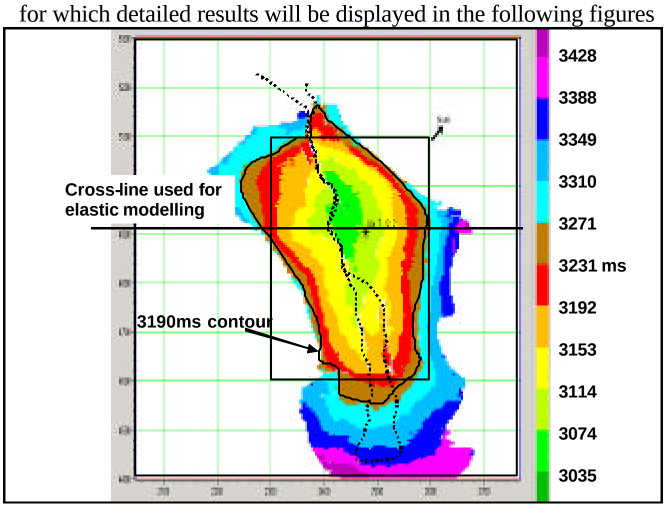


Figure 5
Seismic amplitude difference map for the BCU horizon indicating differences above the reservoir (1984-1999). The anomaly around the well is due to an acquisition ‘hole’ resulting from the presence of the platform for the repeat data.

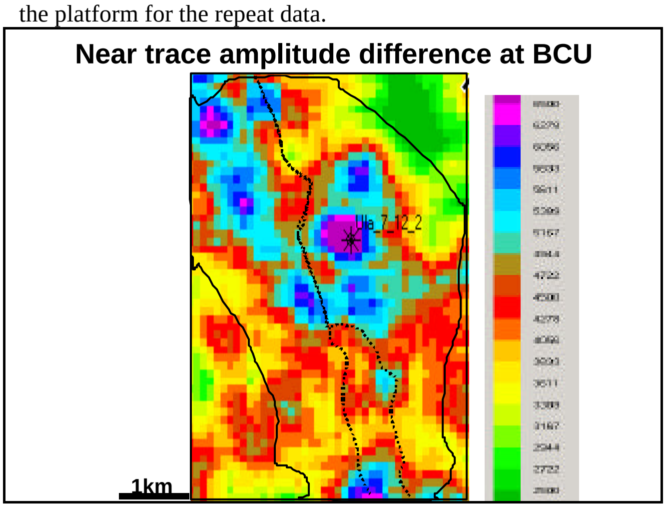


Figure 7a
1984 gathers corrected with 1999 velocities

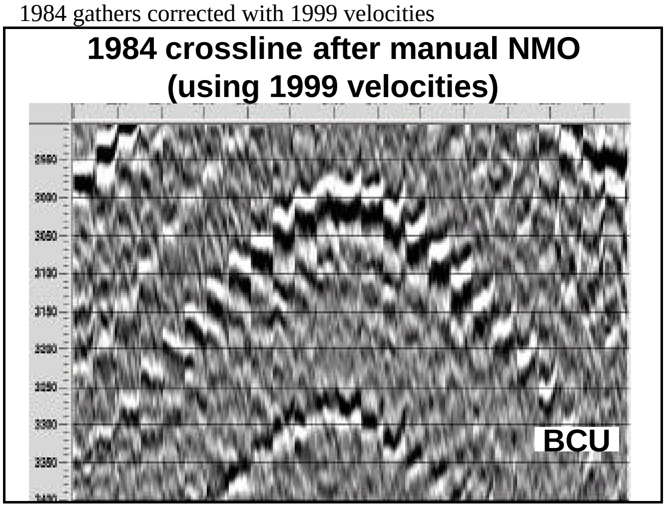


Figure 7b
1984 gathers corrected with continuous AVO RMS velocities

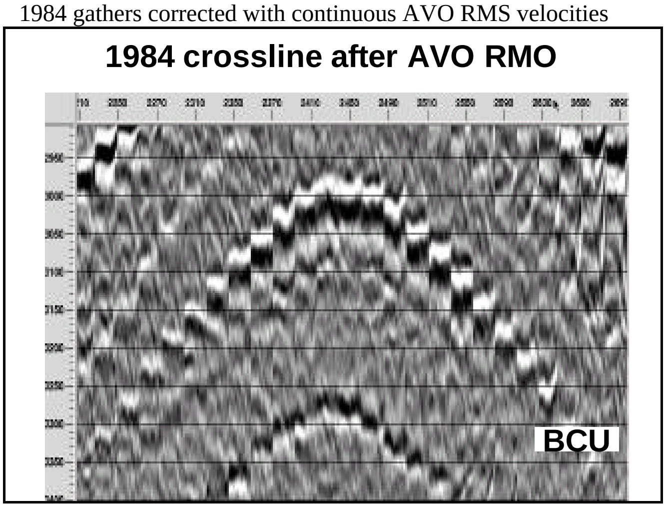


Figure 6a
High resolution RMS velocity estimate using the hcc technique for the 1984 data for the BCU

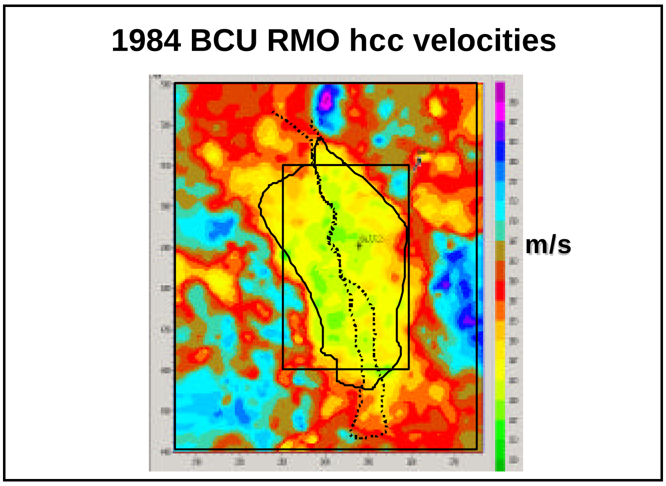


Figure 6b
High resolution RMS velocity estimate using the hcc technique for the 1999 data for the BCU

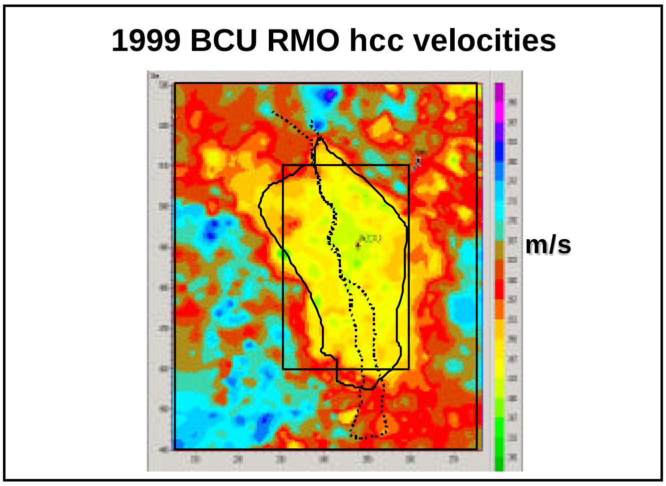


Figure 6c
High resolution RMS velocity differences for the BCU
Velocity differences show a clear compartmentalization within the marked contour, to the left and right of the main crestal fault.

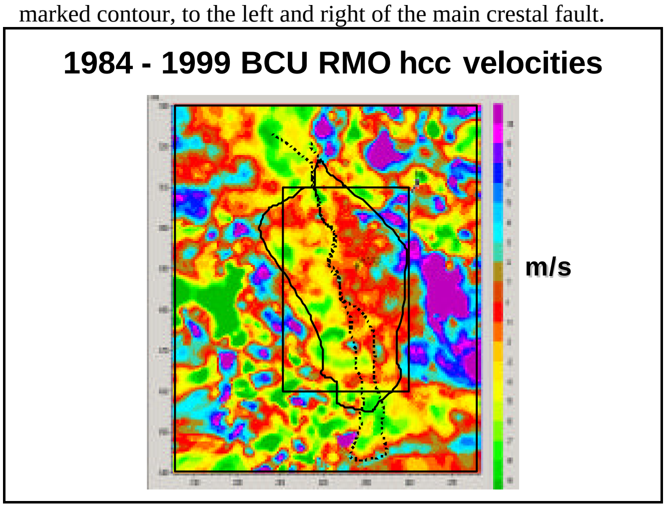


Figure 8a & b
Comparison of the high resolution RMS velocity differences for the BCU for the two estimation techniques.

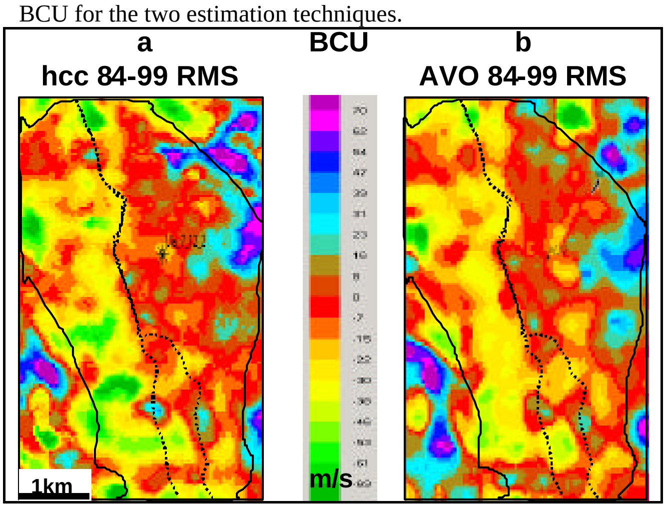


Figure 9a & b
1984 velocity and velocity difference for the reservoir interval using the whole volume AVO technique

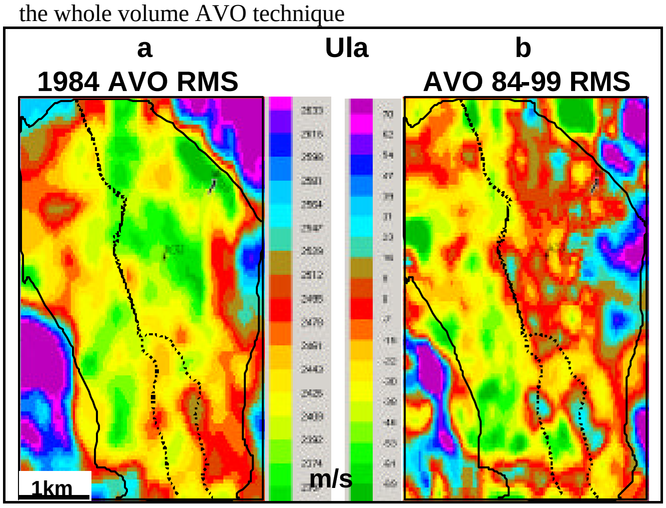
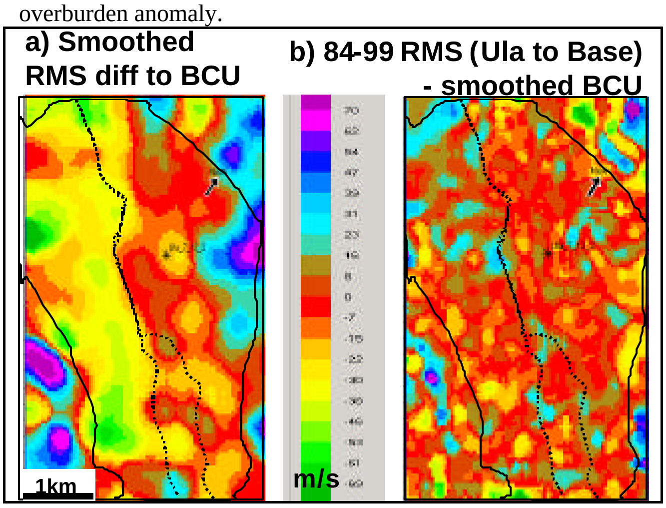


Figure 10a & b
Velocity differences in the reservoir interval after subtracting the overburden anomaly.



If we consider the reservoir interval, (Figure 9), and referring to the AVO volume technique, we see a similar looking picture for the velocity differences (9b). However, there is a clear imprint of the overburden obscuring any real reservoir differences. In an attempt to back out the overburden effects, we have subtracted a smoothed version of the BCU velocity difference map (10a) from the reservoir velocity difference map. After this operation, little coherent difference remains (Figure 10b). Ideally, we should investigate differences in the reservoir by considering the interval velocity differences. However, due to the small thickness of this interval, we were unable to get stable Dix inversions from the RMS quantities, hence we have relied on differences in the RMS quantities as difference indicators.

Discussion
Both the velocity field and the seismic amplitudes show 4D differences above the reservoir. This is in violation of one of our assumptions.

The repeat acquisition was shot orthogonally to the baseline. Furthermore, in the vicinity of the platform, for the repeat survey the data to the west of the platform (near the crest of the structure) was shot north-to-south, whilst to the east of the platform, it was shot south-to-north. However, from plausibility arguments based on reciprocity principles, it can be shown that any dip or directionally dependent 'artefact' imprint of the shooting should not give 1984-1999 difference pictures showing anomalies simply to the left and right of the platform. In making this statement, we assume that reciprocity is not being violated.

Initially, we considered the possibility of fracture related anisotropy in the overburden, as the near trace volume seemed to show more corrugation on the Ekofisk horizon to the left of the crestal fault. However, more detailed investigation using coherency analysis did not support this conclusion.

Consequently, although we observe significant differences in the velocity fields of the two surveys, primarily in the overburden between the Ekofisk and the BCU (about 2 % on RMS velocity), it is not yet clear what the source of these differences is.

This could be due to near surface heterogeneity, acquisition factors, or possibly to fault related azimuthal anisotropy. Overburden amplitude differences could be associated with inconsistent amplitude behaviour in the processing algorithms used (particularly DMO).

In addition, below the top reservoir (Ula) we note that the AVO continuous velocity analysis technique finds anomalously low RMS values. This was shown to be due to remnant multiple contamination. The horizon based technique was less prone to multiple contamination than the continuous AVO estimator, but the base reservoir horizon was difficult to pick, thus no hcc attribute map could be computed.

The acquisition or azimuth dependency on velocity in the overburden indicates that a common velocity model should not be used for the migration of both surveys. In addition, it is probably best to abandon the DMO route and use either amplitude preserving preSTM or preSDM. In the case of preSDM, we would have to convert back to time prior to subtraction, as the differences in the velocity models would result in differing depths between the baseline and repeat results.

However, a benefit of the DMO route is the ability to produce bin-centred regularized gathers ready for input to a Wavefield Extrapolation type algorithm (as opposed to a TXY Kirchhoff migration). Hence the amplitude preservation could be better.

Conclusions

We have shown that high-resolution continuous horizon consistent velocity estimation can be used to deliver a 4D attribute.

In the example shown, the fourth 'D' appears to be dominated by ACQUISITION or AZIMUTH and not TIME !

Interestingly, the figures shown here highlight acquisition related phenomena. The imprint of this anomaly on the reservoir attribute maps must be taken into account during interpretation.

In addition, remnant multiple and possible localized polar (VTI) anisotropy further complicate the problem.

Modelling studies help us to understand the nature and magnitude of the seismic response to reservoir fluid changes. The magnitude of the expected 4D (time lapse) change in velocity based on elastic modelling results is very similar to that observed in the overburden from factors which violate our 4D assumptions.

Further work is underway in an attempt to remove overburden effects, and a new survey, shot with the same acquisition parameters and orientation as the 1999 survey has recently been acquired.

References

de Bazelaire, E., 1988, Normal move-out revisited: inhomogeneous media and curved interfaces, Geophysics v53, p143.

Castle, R.J., 1994, A theory of normal moveout, Geophysics, v.59,no.6, pp983-999.

Doicin, D., Johnson, C., Hargreaves, N. and Perkins, C., 1995, Machine-guided velocity interpretation, 65th Ann. Internat. Mtg: Soc. of Expl. Geophys., 1413-1416.

Jack, I. G., 1998, Time-lapse seismic in reservoir management, SEG/EAGE Dist. Instrctr. Series, No.1, Soc. of Expl. Geophys.

Jones, I.F., Audebert, F., Martin, S., & Ibbotson, K, 1997, Continuous 3D preSDM velocity analysis: 67th Ann. Internat. Mtg: Soc. of Expl. Geophys., 1819-1821

Jones, I.F., Ibbotson, K., Henry, B., Strachan, A., Baud, H., 1998, Enhancements to 3D preSDM salt-flank imaging, Journal of Seismic Exploration, v7, No.3/4, 329-346..

Jones, I.F., Baud, H., Ibbotson, K, Audebert, F., 2000, Continuous 3D preSDM velocity analysis: The Leading Edge, March issue, v19, no.3. 263-269.

Jones, I.F., Baud, H., 2001, Velocity as an attribute: continuous velocity estimation from 3D preSDM CRP gathers, First Break,: v19 No.1, 19-23.

Jones, I.F., Folstad, P.G., 2002, Continuous High Resolution Velocity as a 4D Attribute, 64th Ann. Internat. Mtg. Europ. Assoc. Expl. Geophys., P038.

Jones, I.F., Bridson, M.L, Folstad, P.G., Goodwin, M.C., 2002, 4D illumination and elastic modelling, 64th Ann. Internat. Mtg. Europ. Assoc. Expl. Geophys P037.

Kan T.,K., Kilsdonk, B., West, C., 1999, 3D geopressure analysis in the deepwater Gulf of Mexico. The Leading Edge, v18, No.4, 502-508.

Lee, W.B., & Xu, W. , 2000, 3D geostatistical velocity modelling: salt imaging in a geopressure environment. The Leading Edge, v19, No.1, 32-36.

Lumley, D. E., 1995, 4-D seismic monitoring of an active steamflood, 65th Ann. Internat. Mtg: Soc. of Expl. Geophys., 203-206.

Lumley, D., 2001, Time-lapse seismic reservoir monitoring: Geophysics, Soc. of Expl. Geophys., 66, 50-53.

Swan, H.W., 1991, Amplitude versus offset measurement errors in a finely layered medium. Geophysics, v56, No.1, pp41-49.

Wang, Z, 2001: Fundamentals of seismic rock physics, Geophysics, v66, no2, pp398-412.

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