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Quantitative Evaluation of Reservoir Fault Communication Using 4D Seismic - An Application to the Heidrun Field

A. Benguigui* (Heriot-Watt University) & C. MacBeth (Heriot-Watt University)

SUMMARY

In compartmentalized reservoir settings, it is known that fault seal properties control the fluid flow and pressure development, and strongly affect reservoir management decisions in terms of the chosen drainage strategy for field production. Fault transmissibilities inserted into the simulation model to represent the behaviour of faults are based on geological understanding and are uncertain because of the sparse nature of well data used in their estimation. Here, 4D seismic data is used to supplement and more fully resolve the spatial distribution of the fault properties. To achieve this task, inter-compartment amplitude contrast and statistics of spatial variability for the 4D signatures are considered. These 4D measures are then calibrated at the wells to the geology based estimates of fault permeability. Application of this technique to the Heidrun field provides an adjustment of the inter-compartment transmissibility factors in the simulation model. Predictions using this updated flow simulator model appear encouraging.

Introduction

The geological analysis of fault seal behaviour for the purposes of reservoir simulation is achieved by utilising well data. The shale gouge ratio method has proven to be particularly useful (Yielding 2002). Here, the net contribution of shale in a reservoir zone is linked to the trap efficiency. It has been employed by Manzocchi et al., (1999) to derive fault permeability and hence fault transmissibility multipliers. However, this approach is restricted by available well coverage, which can introduce considerable uncertainty.

More recently, time-lapse seismic has played a major role in the analysis of the dynamic connectivity (Sønneland et al. 2000). Its effects are in general a combination of pressure and saturation changes (MacBeth et al. 2006) which, for compartmentalized reservoirs, seem to be associated to the sealing behavior of the faults. Based on this observation, and in a new effort to constrain reservoir flow, this paper introduce a workflow in which 4D seismic is employed as a tool to quantify the inter-compartment communication and hence enhance the fault property assessment.

Fault Permeability estimation using 4D Seismic

Changes in the rock properties around fault planes, and in their gouge material, lead to changes in the overall effective fault permeability. This modifies fluid flow behaviour and, in particular, can cause compartmentalisation. Also, changes in fault permeability introduce disruptions to the pressure and saturation fields, which in turn control the time lapse seismic signature within each compartment. To sense these changes and hence evaluate fault permeability, two measurement parameters are derived from the 4D seismic maps (Figure 1):

a) *4D inter-compartment difference*: this measures the 4D amplitude contrast between adjacent compartments using the average of the centred differences between neighbour compartments, defined at each fault segment position.

b) *4D spatial variability*: this captures the continuity of the 4D signatures. Several 1D variograms are calculated perpendicular to the fault segment and along the fault dip direction. The correlation lengths, as defined by the range of the variogram, are extracted in each case.

Cross-plots of the above 4D-derived parameters against the fault permeability derived by geological techniques using the shale gouge ratio approach reveal that for a well-controlled sector it is possible to directly invert for fault permeability. Indeed, tests on modelled 4D seismic with a synthetic reservoir model and a typical production scenario show that a quadratic polynomial can be used as the best fit function for the fault permeability representation:

$$k_f^{4D}(x,y) = a_0+a_1x+a_2y+a_3xy+a_4x^2+a_5y^2 \qquad (1)$$

where x and y are the parameters extracted from the 4D seismic. In practice, the coefficients of this polynomial expression must be calibrated in a sector with known (geologically based) fault properties. However, once (1) is known, it is possible to calculate fault permeability in segments with no well control. In addition, to account for the uncertainty in the prediction using 4D seismic, Bayes rule is applied in order to obtain the posterior probability for the fault permeability at each location. Minimum and maximum correlation ranges are defined during the variogram process, permiting end-member cases to be defined for the function in (1). Prior and joint distributions are also calculated via the Montecarlo method and probabilities obtained by applying Bayes rule.

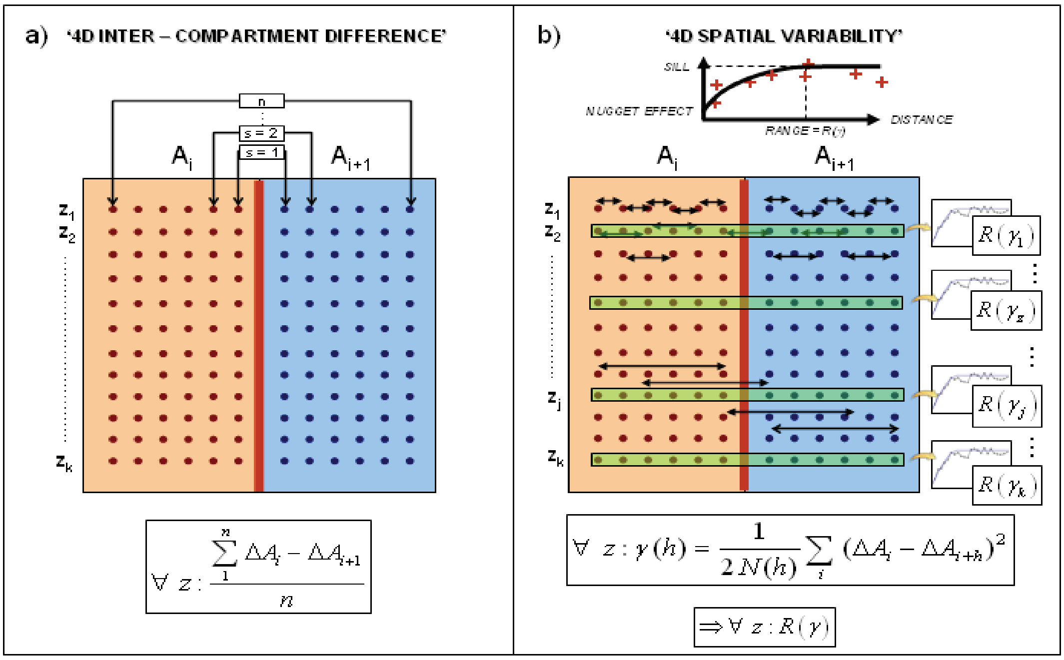

Figure 1. Measures of the time-lapse seismic signature for fault seal analysis, derived for any specific reservoir sensitive 4D-seismic attribute: (a) the inter-compartment difference and (b) multiple 1D variograms with their respective correlation range extracted along the fault segment. Both measures appear to be correlated with fault seal behavior.

Application to the Heidrun Field

Located in the area of Haltenbanken, the Heidrun field (StatoilHydro operated) is one of the largest oil discoveries in the Norwegian offshore. Included in a triangular-shaped horst block, Jurassic reservoirs are intensely affected by a main extensional north-south fault system. The high degree of compartmentalization strongly impacts the way in which its individual compartments are being depleted. The 4D character has proven to be consistent with faults (Furre et al., 2004) for which their sealing properties seem to be defining the major connectivity in the field.

To evaluate the time-lapse seismic signature in this practical case example, two seismic vintages conducted over the southern part of the Heidrun field are employed: the base-line acquired in 1986 and the first monitor in 2001. Both surveys have been simultaneously reprocessed to enhance their repeatability level (Furre et al. 2004). Considering these two surveys, RMS amplitude difference is extracted in a 16 ms window centred at the top of the Jurassic Fangst group. For these data, observation of the 4D signature for successive pairs of compartments suggests the presence of discrete long period anomalies which appear to be related to the fault seal. Qualitative comparison of the 4D signature with permeabilities derived from the geological (shale gouge ratio) method via the logs indicates a good correlation for several faults. The time-lapse anomalies and their continuity tend to increase as the fault permeability k_f^{SGR} values increase. As the sealing capacity of the fault reduces, the pressure and saturation changes (and hence the 4D signatures) start to vary more smoothly between compartments signalling an increase in the field connectivity. Due to well density, fault properties in the southern part of Heidrun field are not easily assessed by means of a geologically based algorithm. However the 4D measures described above can be extracted from a particular pair of compartments (A and B) and used to extrapolate the fault property prediction into unknown segments of the connecting fault system. This is achieved by firstly calibrating the fault permeability equation (1) in the sector with good well coverage. Fault permeability values calculated in this way are found to lie between 0.1 and 0.7 mD, with the magnitude of these results being in agreement with previous fault rock studies from the Heidrun cores. The Bayesian approach used for uncertainty characterization yields estimates which have an average probability of 67%. To define an alternate 4D seismic product, pressure and saturation changes are now separated using the 4D multiple attribute approach presented by Floricich et al. (2005). The results indicate that the pressure changes can be classified into three main groups which seem to indicate agreement with fault permeability values based on the geological analysis but also on our previous 4D analysis. As shown in Figure 2, a high pressure change contrast exists across the compartment associated with a local increase of the fault seal behaviour characterized by the lowest fault permeability values.

Given the fault permeability calculated from the 4D seismic, fault multipliers are now introduced into the Heidrun simulation model to update the transmissibilities for a major fault segment. A comparison of predictions for the well production data obtained from the original and the updated simulation model indicate some improvements when the 4D-derived fault multipliers are introduced. In particular, pressure and water cut predictions for the field and for individual producer wells located in the vicinity of the modified fault decrease the mismatch with the historical data (Figure 3).

Conclusions

Time lapse seismic help the aerial resolution of fault seal determination beyond that produced by well-based estimation. In particular, prediction via the parameters measuring inter-compartment contrast of the 4D signature and its spatial variability appear to be sensitive in this instance to fault permeability. Application of this methodology to the southern part of the Heidrun field produces encouraging results. Analysis on the 1986-2001 seismic difference suggests that this technique can be used as a tool for deriving dynamic fault seal properties. 4D seismic data can provide a quantitative way of updating the flow simulation model in areas where there is poor well control. This can therefore lead to an improvement in the matching of the production data by further constraining fault behavior.

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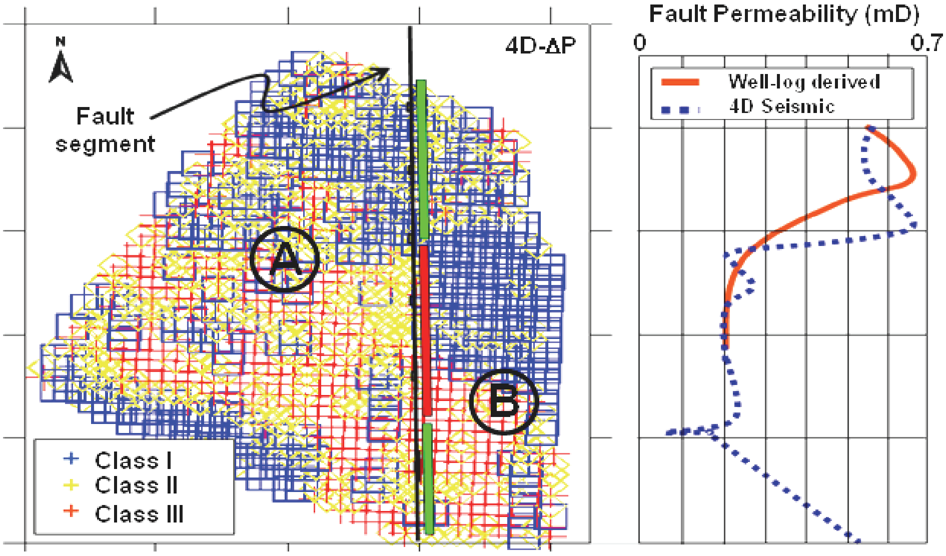

Figure 2. Classification of pressure changes derived from the 4D seismic. High pressure change contrast in between compartments (A and B) is associated with a decrease of the fault permeability (red segment) whereas the connectivity is enhanced towards the north and south edges (green segment) of the mapped sector.

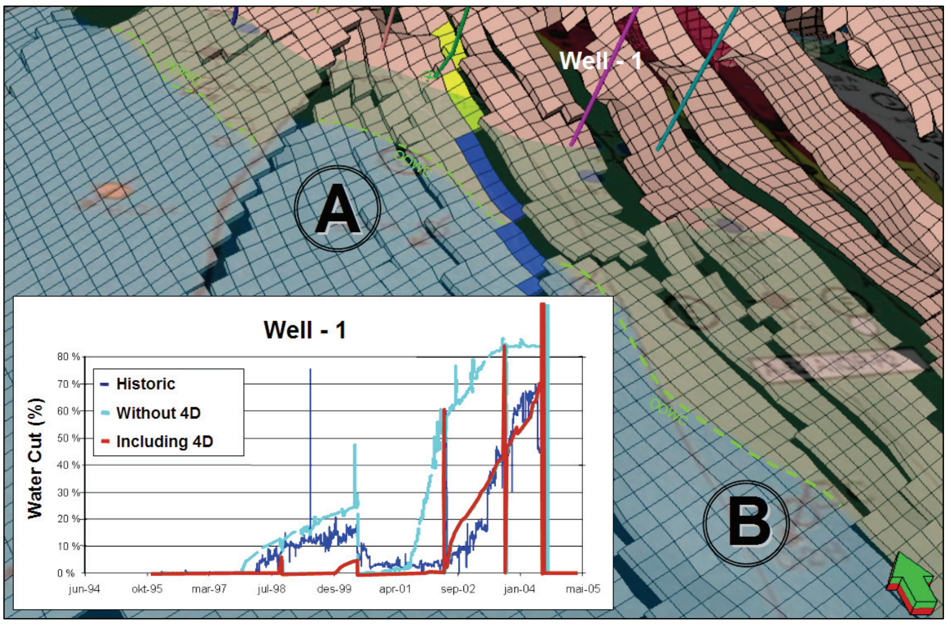

Figure 3. An updated fault segment of the simulation model. The yellow segment acts as calibration sector for the expansion of fault property prediction using the 4D seismic (blue cells). Water cut predictions are displayed for the previous model (without including the 4D results) and the improved version (including the 4D results).