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An Interpretation of the 4D Seismic Response to Gas Exsolution and Dissolution

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SUMMARY

This study examines the 4D seismic signatures of gas exsolution and dissolution in a producing hydrocarbon reservoir. The physical mechanisms for these reservoir processes are investigated using a series of simulation studies, and the primary controls on the seismic response are thus identified. It is concluded that gas can attain a steady state approximately three to six months after a major reservoir pressure change, and that in this state the seismic responds to the thickness of gas accumulations existing at either the critical and/or maximum gas saturation. Application to multiple repeated surveys over a North Sea turbidite field demonstrates the practical consequences of our findings and how this insight can be used to interpret the seismic amplitudes. Interpretation of the field example confirms a low critical gas saturation of less than 1% for the reservoir rocks. However, it is not found possible to quantify the maximum gas saturation using the 4D seismic amplitude only. Quantitative estimates of the volumes of gas liberated and dissolved in the oil are found possible by integrating material balance principles with the seismic response. It is shown that the insights gained from this application can be generalised to other moderate to high permeability hydrocarbon reservoirs.

Introduction

In oil reservoirs currently on production, reservoir pore pressure can typically vary by several megapascals, and often by much more in the neighbourhood of the producing wells. In particular, if reservoir connectivity is poor or not fully understood, injectors or active aquifers cannot adequately support pressure drops. If pore pressure falls below the bubble point of the oil in an initially undersaturated reservoir, then gas exsolution occurs (Dake 2002), and gas migrates upwards to the top of the reservoir to form gas caps. Pressure drop and gas liberation are typically controlled by the injection plan, and the normal way of stopping gas breaking out is pore pressure increase by water injection. Here, liberated gas is encouraged to go back into solution, in principle reversing the exsolution behaviour. Past 4D seismic examples in the North Sea (such as Marsh et al. 2001) have demonstrated a clear seismic brightening due to gas exsolution and a dimming due to dissolution. It is known from fluid flow simulation studies that gas exsolution and dissolution are affected by many factors, the numerical values of which remain largely uncertain. These relate mainly to the vertical and horizontal reservoir connectivity and the relative permeability behaviour. As a consequence, the exact volume of gas liberated during exsolution, dissolved during dissolution, and the gas migration in the reservoir also remain uncertain (Danesh 1998). The objective of this current study is to assess the degree to which monitoring gas saturation distributions with 4D seismic can be used to assess the reservoir dynamics and evaluate reservoir properties. To address this, a link between 4D seismic amplitudes, gas exsolution and dissolution is developed. This provides an understanding of how gas distributes and saturates the rocks within the producing reservoir, and the control on the seismic amplitudes. The results of our study are directly applied to a North Sea dataset, in which six monitor surveys are shot on a frequent basis of 24 months.

Reservoir mechanisms

As pressure decreases in the oil below bubble point, gas saturation builds in the pore space as small bubbles. As these bubbles grow in size and number, they begin to connect together until the critical gas saturation (S_{gcr}) is reached. At this point they coalesce and the gas then becomes mobile. Gas starts to migrate upward and towards the wellbore due to the actions of the gravitational force and well pressure gradients, collecting in local highs or structural traps to form gas caps in the reservoir, or being produced. After this migration, gas also remains behind in the oil leg at the critical gas saturation. Depending on the reservoir connectivity and production/injection rates this gas generation and migration process can reach a steady state very quickly in several months or less. Importantly, after equilibrium the gas saturation in the reservoir is fixed at its maximum (S_{gmax}) everywhere within the gas cap and also remains at the critical gas saturation (S_{gcr}) within the oil leg. Our fluid flow simulation studies using fine-scale models have confirmed that the gas saturations are indeed mainly concentrated around two peaks, with a smaller number in the range of intermediate values (see Figures 1(a) and (b)). The width of the peaks appears narrow (only a few percent), despite heterogeneity in the different models, and the intermediate saturations are confined to lie within a very thin (less than two cells thick) transition zone layer in the model. Once pore pressure has built up again over the entire reservoir, part of the gas at and above the gas-oil contact dissolves rapidly. Also, the gas at the critical gas saturation remaining in the oil leg dissolves in a few days. In this case we observe that there is now only one main peak at a gas saturation of S_{gmax} . The peak is again narrow, as with the gas exsolution case (Figure 1(c) and (d)).

Predictions for the seismic time-lapse response

The particular reservoir conditions described above have important implications for the calculation of the time-lapsed seismic response to gas saturation. The reservoirs of interest in our studies are typically 30m thick or less. For seismic with a wavelength of 140m (20Hz peak frequency for the seismic and a velocity of 2800m/s), these reservoirs (complete with gas cap) are below tuning thickness. Using the work of Falahat et al. (2011), it is shown that due to the bimodal nature of the gas saturation histogram, the seismic time-lapse amplitudes scale linearly with gas thickness. The near-

offset difference amplitudes for a monitor and the pre-production baseline survey arising due to gas exsolution ΔA_{exsol} are shown to be given by

$$\Delta A_{exsol}(T) = -\alpha \left[h_{gc}(T) \Delta Z_{max} + (H - h_{gc}(T)) \Delta Z_{cr} \right] \quad (1)$$

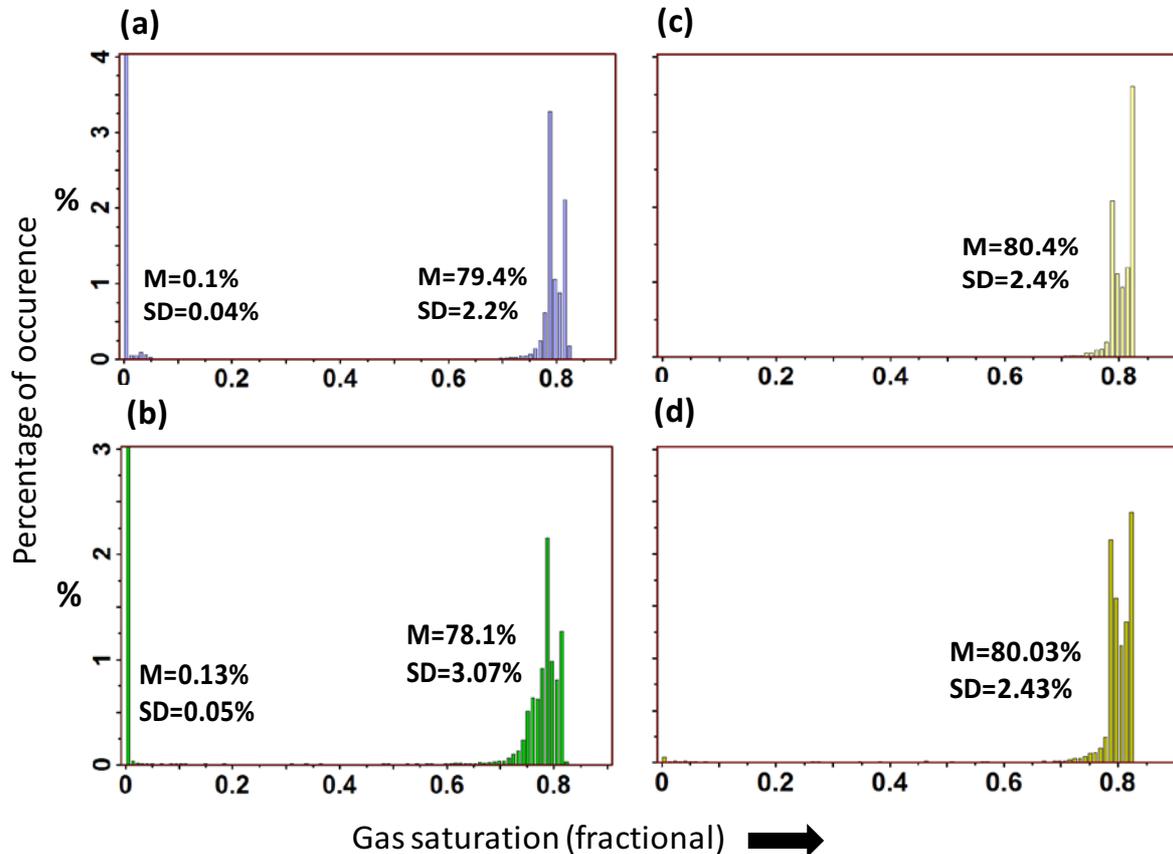


Figure 1 The gas saturation histograms resulting from fine-scale fluid flow modelling, for: (a) exsolution in a homogeneous simulation model; (b) exsolution in a heterogeneous model; (c) dissolution in a homogeneous model; (d) dissolution in a heterogeneous model.

where T refers to elapsed time between the seismic surveys. In these equations, h_{gc} is the gas cap thickness, H the reservoir thickness, and α a constant. ΔZ_{max} and ΔZ_{cr} are impedance changes in the gas cap and oil leg respectively. It is found that for dissolution an identical expression holds with $\Delta Z_{cr} = 0$. This formulation is a key point in the interpretation of the observed data in the next section.

4D seismic data analysis

The predictions of the previous section are now tested by application to observed data from a North Sea turbidite field (Martin and MacDonald 2010). In this particular field, there is known to be gas exsolution, gas mobilisation, and then re-pressurisation with subsequent dissolution. Pressure drops below bubble point with the consequent liberation of free gas from the 25° API oil. There are multiple vintages of seismic shot across this field, and the preproduction baseline in 1996 and six monitors shot in 1999, 2000, 2002, 2004, 2006 and 2008 are selected for our analysis. An isolated sector is considered, which is segmented by two major EW trending normal faults. The T31 producing interval is mapped as it is the main reservoir where gas exsolution occurs in this area. Figure 2 shows a sequence of time lapsed amplitude differences for the chosen segment. The initial (1998) pressure is around 2900 psi, which is close to the bubble point pressure of 2850psi. By 2001, the pressure is known to have dropped by 900psi in the vicinity of the production wells. Thus, gas is liberated during

the first three monitor surveys in 1999, 2000 and 2002, and it is quite obvious as an extensive softening signal on the 4D seismic maps in Figure 2. The figure indicates gas accumulations collecting in local highs during the monitor survey period, and this particular gas distribution confirms a small critical gas saturation for this reservoir. There is also some evidence of a gas signal cutting across the depth contours. This could be possibly related to pressure gradients or inaccurate contour lines from the picked seismic. A slow recovery of reservoir pressure follows in 2001 as a consequence of water injection, with a general pressure increase to 2950psi due to the activity of injectors I6 and I9 (and another injector to the west, outside the area of interest). Thus, the seismic data shot from 2002 onwards are influenced by dissolution. The time-lapse response does not reduce completely to zero, indicating that some gas remains in the reservoir after full re-pressurisation. The area of the gas signal increases slightly again in 2008 due to a pressure decrease created by two new production wells, P10 and P8. A hardening signal is visible in the western and central parts of the sector due to water saturation increase, progressively increasing after 2002 upon activation of injector I9. To the south-east I6 further pushes the gas towards the producers and into other local highs. Good agreement is found between the well activity (both production and injection) and the observed seismic response.

To further analyse the gas distribution we again follow Falahat et al. (2011), who proved a linear relationship between gas volume change ΔV_g and the integral of the time-lapsed amplitude change ΔA

$$\Delta V_g = \beta \iint_{\Sigma} \Delta A dx dy \quad (2)$$

where β is a seismic to well data calibration factor to be determined, and the integral is performed over the area Σ of the reservoir under consideration. This area is known to be hydraulically isolated from the rest of the field, therefore making this analysis possible. By applying (2) between the baseline survey and a monitors shot during the gas exsolution and dissolution stages, and expanding the lefthandside according to material balance (Dake 2002) focused only on the gas component, quantitative estimates can be obtained for the gas dissolved back into the oil during re-pressurisation. Our calculations show that on average 35% of the gas initially liberated goes back into solution. Our studies also show that this percentage is affected by the critical gas saturation, rate of production or injection, and the vertical and horizontal connectivity of the reservoir.

Conclusions

This work has shown that the 4D seismic signatures associated with the processes of gas exsolution and dissolution are controlled mainly by gas accumulations distributed in two discrete saturation states – the critical gas saturation and the maximum gas saturation. This understanding simplifies quantitative interpretation of the 4D seismic, and allows us to estimate liberated and dissolved gas volumes, and evaluate the critical gas saturation directly from the 4D seismic. We predict that these findings can be generalised to many other fields and production scenarios, provided the gas under consideration is a reasonably light hydrocarbon gas - as in this case the transition zone between the oil and gas, or water and gas-saturated regions of the reservoir is very small (less than a metre). The time period between the seismic baseline and successive monitors relative to the time taken to attain steady state also has an impact on the application of our findings. For 4D seismic surveys with a repeat time of one to several years this time scale may not be important, but for repeats with permanent sensor arrays with, say, 3 to 6 months between surveys, this may well need further investigation. Whilst gas exsolution and dissolution are often regarded as undesirable products of production and recovery from oil reservoirs, it is concluded that such processes can be useful as a quantitative tool for analysis of the reservoir and can help constrain the dynamic reservoir parameters.

Acknowledgements

We thank sponsors of the Edinburgh Time Lapse Project, Phases IV and V (BG, BP, CGGVeritas, Chevron, ConocoPhillips, EnCana, ENI, ExxonMobil, Hess, Ikon Science, Landmark, Maersk, Marathon, Nexen, Norsar, Petoro, Petrobras, RSI, Shell, Statoil, Suncor, Total and Woodside) for supporting this research. We thank Schlumberger for use of their Petrel, Eclipse and PVTi software.

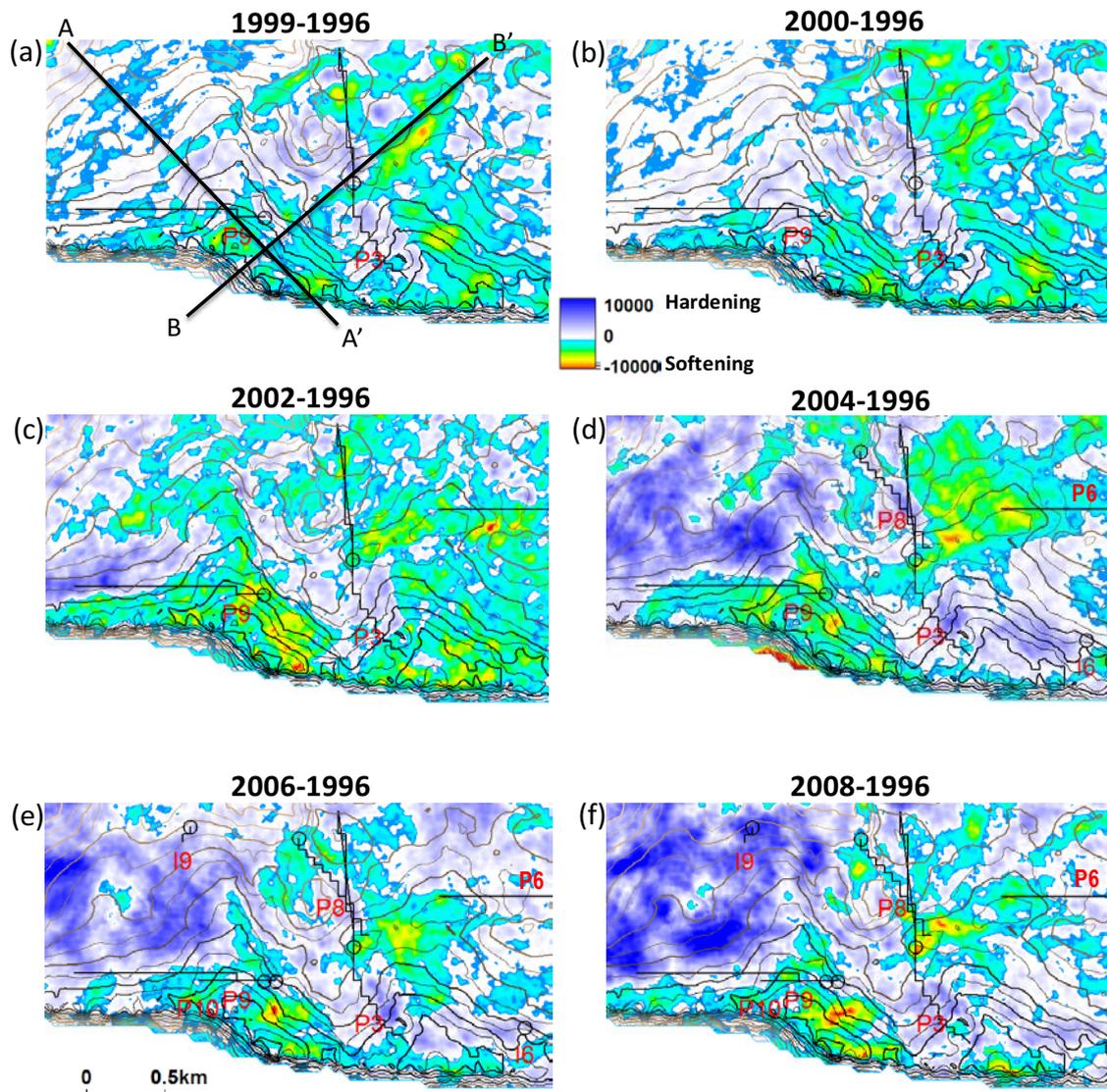


Figure 2 Amplitude change map for the period of a) 1999-1996, b) 2000-1996, c) 2002-1996, d) 2004-1996, e) 2006-1996, and f) 2008-1996. The contour map indicates the structure of the top reservoir. All negative anomalies are related to the gas accumulations, as the region was initially entirely filled with oil. Note that the 1996 survey is a baseline taken prior to the production in 1998.

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