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Quantification of Residual Oil Saturation Using 4D Seismic Data

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SUMMARY

A method has been developed to quantify residual oil saturation using 4D seismic differences interpreted at fluid contacts. The development is different from previous approaches in that it uses only the seismic amplitudes at the original and produced oil-water contacts instead of the top reservoir event. It requires that these contacts be visible in the 4D seismic data, although not necessarily in the 3D seismic. It is shown that the method can provide a quick semi-quantitative analysis of published field studies from visual inspection. The approach is further demonstrated by application to a field dataset from a North Sea oil reservoir. The results of this application show good agreement with the simulation model, but also some variations that suggest such residual oil estimates could be used in future history matching to update the simulation model.

Introduction

Residual oil saturation (S_{or}) can be defined as the remaining oil saturation that cannot be produced from gas or water displacement, but remains in the swept zone (Morrow, 1990). S_{or} is a key quantity in reservoir recovery and economic reservoir evaluation, as well as a fundamental parameter for studying water flooding and determining sweep efficiency. Furthermore, it is a necessary basis for planning enhanced oil recovery (EOR), Quantitative knowledge of the spatial distribution of the fluids is a key input in the decision making process. Despite numerous methods available to estimate it, such as laboratory test/core flooding, well based measurements, pore network modeling, it is generally acknowledged that there is no acceptable way to reliably measure S_{or}. Furthermore, the value of S_{or} depends upon the vertical and horizontal sweep efficiency, the heterogeneity of the geologic system, and the microscopic displacement efficiency (Adamski, et al. 2003), hence it is a scale dependent measurement. In this work we show a method to quantify S_{or} at the seismic scale using 4D seismic data by interpreting the fluid contacts in the far angle stack differences. We show through seismic modelling and a real data example that a map of 4D amplitudes at the picked original oil-water contact gives not only the regions of change and sweep, but also the magnitude of S_{or} if properly calibrated. The method requires that contacts be visible in the 4D seismic data, but not necessarily in the 3D seismic.

Reservoir engineering background

Capillary pressure tests performed in core samples are commonly used to estimate the relative permeabilities of oil and water (k_{ro} and k_{rw}) at reservoir conditions ($S_w = S_{wc}$) and after depletion ($S_w = 1- S_{or}$) as shown in Figure 1. Here, the connate water saturation (S_{wc}) and the residual oil saturation (S_{or}) represent the end points of the capillary pressure curves. This representation, however, only considers the small scale heterogeneities that affect the capillary forces; therefore S_{or} only represents the minimum amount of oil that can be taken out of the rock assuming a perfect sweep. In reality, the value of S_{or} will fall somewhere along the capillary pressure curves depending on *pore scale* factors such as wettability, pore structure, clay content or fluid dynamics. *Reservoir scale* factors like sedimentological structures, faults, fractures, barriers, formation and water properties and gas saturation are important, so too are w*ell behaviour* related factors such as injection/production rate, water front speed, pressure gradients, gravity and sweep efficiency. In general, the larger the scale at which S_{or} is evaluated the larger its magnitude, hence S_{or} (lab) < S_{or} (field). In this work we are concerned with the magnitude of S_{or} that can be evaluated at the field scale using seismic data.

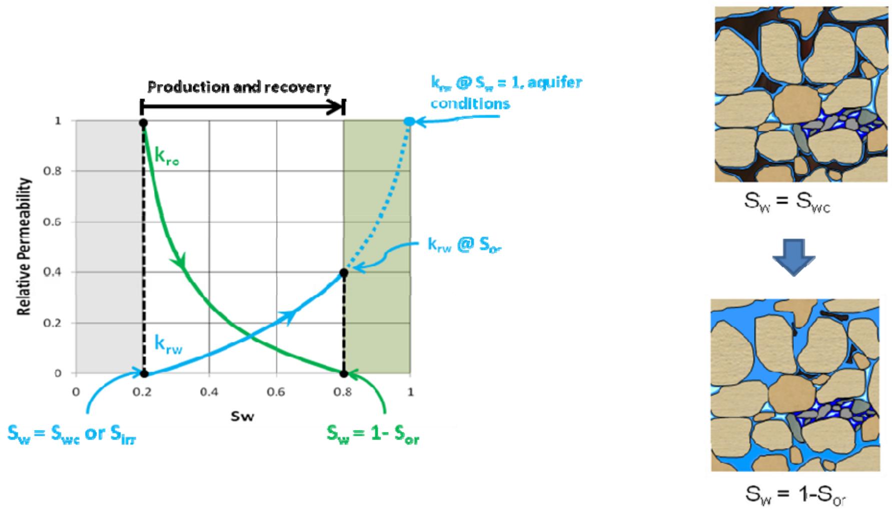

Figure 1 *End point saturations calculated from capillary pressure curves obtained from core measurements. S_{or} is oil saturation found somewhere along the green curve depending on sweep efficiency. The right hand side pictures show the different fluids that interact in the reservoir rock, oil (brown), free water (blue), connate water (light blue), clay bound water (dark blue), the latter two are not expected to change with production.*

Seismic theory and method

Literature review reveals that the majority of past work on residual oil calculation focuses on distinguishing oil from water-sands using Gassmann (1951) fluid substitution as a calibration tool for AVO or 4D seismic centered on the interpretation of the top reservoir event. However there is less attention given to the determination of S_{or} directly from the interpretation of the various fluid contacts. The main reason is that fluid contacts are not always visible in the 3D seismic, and although they are sometimes visible in 4D seismic, the interpretation is commonly performed on the full stacks by comparing the monitor and baseline vintages rather than looking at the 4D differences.

Our theoretical development starts with the conceptual model shown in Figure 2, representing an oil reservoir without a gas cap, in the pre and post-production states and showing the zone associated to the oil-water contact movement, assuming a predominantly basal aquifer drive. Following the definition of the AVO equations for fluid contacts (Wright, 1986) and equations for 4D difference interpretation (Alvarez & MacBeth, 2014) we define the changes in impedance (or amplitude) as linear functions of the changes in water saturation across each interface. Alvarez & MacBeth (2014) showed that the near angles are functions of a combination of both pressure and saturation changes, whereas the far angles, if stacked at the appropriate angle, can be nearly pressure independent. Since we are concerned only about saturation changes, we therefore concentrate on the far angles. We find that the time lapse amplitude (monitor minus base) at the original and produced oil-water contact (OOWC and POWC respectively) for the far angles is given by

$$\Delta A(\theta)_{oowc}^{far} = -C_S^{far}\left(1 - S_{sor} - S_{wc}\right), \tag{1}$$

$$\Delta A(\theta)_{powc}^{far} \approx -\Delta A(\theta)_{oowc}^{far}. \tag{2}$$

Here, the constant C_S^{far} is a function of the rock and fluid physics equations as described in Alvarez & MacBeth (2014). An important observation here is that if a map of 4D amplitudes (far angles) at the OOWC is available (ΔA_{oowc}^{far}), it indicates not only the regions of change and sweep, but also if properly calibrated can help us estimate S_{or}

$$S_{or} \approx 1 - \left[S_{wc} - \frac{\Delta A_{oowc}^{far}}{C_S^{far}}\right]. \tag{3}$$

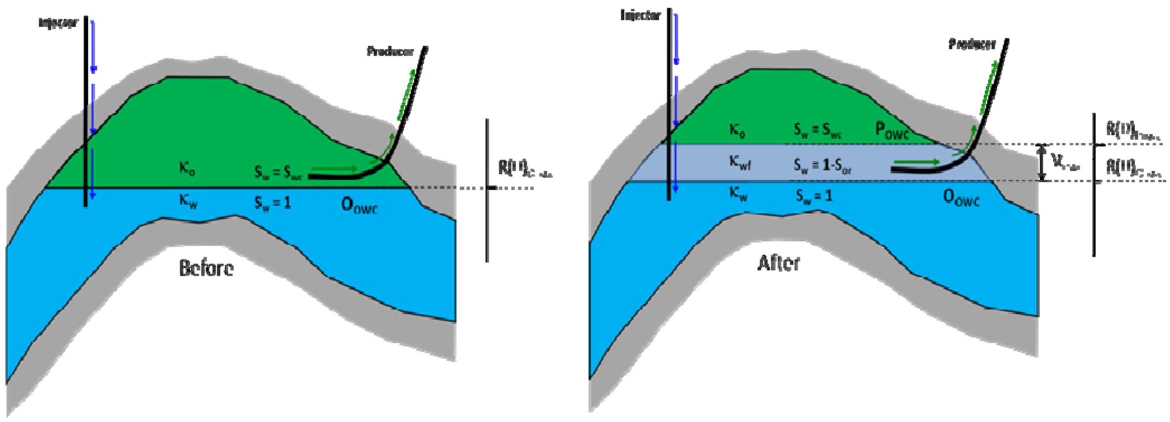

***Figure 2** Conceptual model of an oil reservoir, showing an oil-water contact movement through basal aquifer drive and the associated reflections. In the baseline we have only the reflection of the original oil-water contact ($R(\theta)_{OOWC}$), whereas in the monitor we have two reflections, the original and produced oil water contacts ($R(\theta)_{OOWC}$ and $R(\theta)_{POWC}$ respectively).*

In order to perform this calculation, knowledge of the connate water saturation, S_{wc}, is required. For our purposes, the value estimated from capillary pressure curves provides a reasonable starting point for the calculations, particularly in clastic reservoirs, since S_{wc} is not expected to change significantly with production and depends only on the pore scale factors described above. Another important finding is that, if the reservoir is sufficiently thick and clear, reflections of the original and produced contacts are visible - (2) can be used as a check during the cross-equalization process. Additionally, if the contacts are visible in the 3D seismic S_{or} can be determined from the following relation

$$\frac{A(\theta)_{oowc}^{after}}{A(\theta)_{oowc}^{before}} = \frac{S_{or}}{(1-S_{wc})} \tag{4}$$

Field data example

The equations defined above are tested on a North Sea oil reservoir with appropriate characteristics. The reservoir is between 80 and 300m thick, highly compartmentalised and geologically complex. Production is supported through water injection into the aquifer, and although the reservoir pressure is close to the bubble point and gas has been released in some areas, our study focuses on a compartment where no gas is present. The pre-production baseline and two monitors are available, all containing near (10^o) and far (35^o) angle stacks. Although no visible contacts are interpretable in the 3D seismic, the original oil-water contact is visible in well logs and it can be interpreted in the 4D difference for the far angle stacks. From capillary pressure curves available, S_{wc} varies between 0.15 and 0.25 and S_{or} from 0.25 to 0.85. Simulation to seismic modelling (sim2seis) is performed (Amini et al. 2011) to test our methodology and to compare the results with the observed 4D differences. Using the OOWC in the 4D difference, amplitude maps are generated and S_{or} is calculated using (3) (the parameters for C_S^{far} are known in this case). An example of the results obtained for the 2011Monitor – Baseline data is shown in Figure 3. In general a good correspondence is obtained between the simulated and predicted results, and the observed S_{or} shows some areas of potential bypassed oil. However there are areas of noise visible, possibly due to wavelet interference effects, suggesting that an inversion scheme might help to improve the results by de-tuning the data. The histograms of the mapped quantities shown in Figure 3 demonstrate that, despite the simplicity of our method, the results are a fair representation of S_{or} in the reservoir.

Conclusions

- A technique has been developed to calculate S_{or} from the far angle 4D differences of fluid contacts. The results of modelling suggest the scheme is practical, however wavelet interferences suggest that the use of a 4D inversion scheme may improve the method further
- Providing an estimate of the lateral distribution of S_{or} through a simple method can be of great support in the design of EOR plans as well as in seismic history matching, without the need to perform a full simulation to seismic modelling.
- The technique is based on the interpretation of the fluid contacts rather than an average map based on the top of the reservoir, therefore it requires that contacts be visible in the 4D seismic data, but not necessarily in the 3D seismic - although the latter is a bonus
- Fluid contacts are relatively easier to interpret than the top reservoir in 4D seismic data
- The technique has also be adapted to gas reservoirs, and can also be used for carbonate and thin, sub-tuned reservoirs

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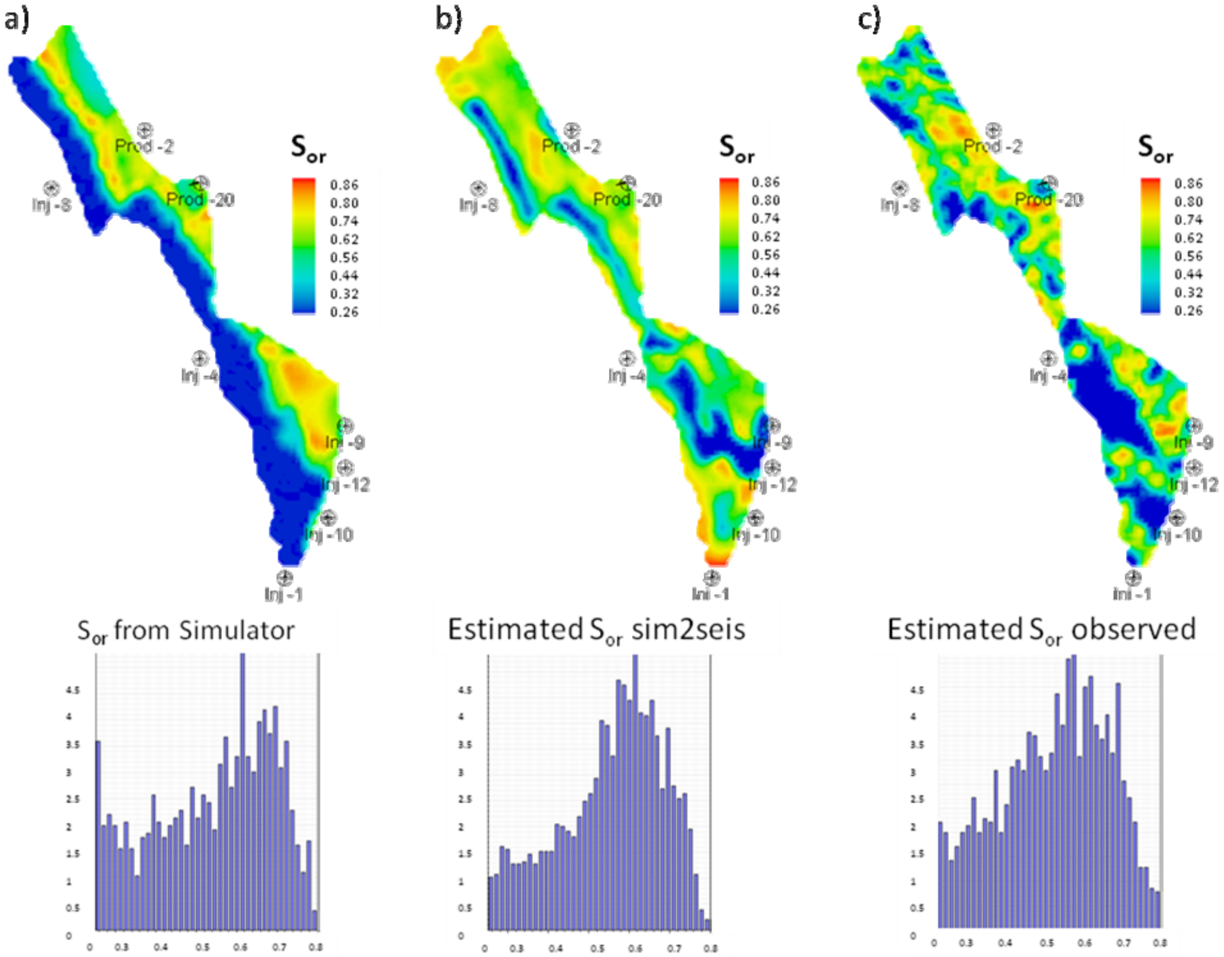

Figure 3 *Results of the S_{or} calculation: (a) from the simulator; (b) computed from the sim2seis (far angle stack); and (c) S_{or} computed from the observed far angle stack amplitudes. The histograms of each map are displayed below in each case, showing the good correspondence in the results.*

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