<table>
<thead>
<tr>
<th></th>
<th>Oil leg</th>
<th>Swept zone 1</th>
<th>Swept zone 2</th>
<th>Swept zone 3</th>
<th>Water leg</th>
</tr>
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<tbody>
<tr>
<td>$V_p$ (km/s)</td>
<td>2.563</td>
<td>2.583</td>
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<td>$V_s$ (km/s)</td>
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<td>1.372</td>
<td>1.368</td>
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<tr>
<td>$\rho$ (g/cm$^3$)</td>
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<td>2.066</td>
<td>2.076</td>
<td>2.086</td>
<td>2.096</td>
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**Table 1** Seismic properties used to calculate the reflection coefficients for the original and produced oil-water contacts shown in Figure 4. These relate directly to the North Sea field example studied in this paper. Fluid properties are calculated using Han and Batzle (2004), and saturated rock properties via Gassmann (1951). Final values of the rock and fluid parameters are calibrated against wireline logs for the field. In these calculations fluid pressure changes are ignored. The oil leg has a connate water saturation of 12.8%. Swept zones 1, 2 and 3 have residual oil saturations of 60, 40 and 20% respectively.
Table 2 Reservoir properties used for the synthetic model example in Figures 8 to 12. (a) Main reservoir parameters for the model; (b) Seismic properties for the end member saturation regimes. Values range between these end member values in the modelling exercise.
Figure 1 (a) Example of pore-scale trapping of oil, due to viscous-dominated (fast) water displacement of oil. Average water saturation moves from connate water, to predominantly water plus residual oil saturation. (b) Example of outcrop-scale trapping of oil in individual bed laminae after a water flood (after Pickup and Hern 2001). Saturation values are colour coded as follows: green/yellow – oil, light and dark blue – water.
Figure 2. Illustration of the field-scale remaining oil saturation targeted in our current study. The water-flood (in blue) progresses from two injectors (I1 and I2) in the northern and southern down-dip areas of the crestal structure, and bypasses some of the reservoir oil (zone A). The target for our studies is not this unswept oil, but the oil remaining in the zones already swept by water (zone B). (Figure adapted after Calvert 2005).
Figure 3 Schematic of the idealised ‘seismic model’ and associated fluid saturations used in this work to compute fluid contact reflectivity. (a) Initial state of the reservoir prior to production. In the oil leg, $S_w = S_{wirr}$, $S_o = 1 - S_{wirr}$; in the water leg $S_w = 1$. (b) After production, where base water has displaced the oil-water contact upward to a new location. In the swept zone, $S_w = 1 - ROS$, $S_o = ROS$. OOWC – original oil-water contact; POWC – produced oil-water contact.
Figure 4 Variation of $P$-wave reflection coefficient ($R_{pp}$) with $1+\sin^2\theta$ (where $\theta$ is the incidence angle), for the original oil-water contact (a), and produced oil-water contact (b). Curves represent different fluid saturation conditions at each contact, but the same homogeneous rock. For each curve in (a), different fluid conditions lie over the water leg: 1 – oil with Swirr = 20%; 2 – swept zone with Sorw = 60%; 3 – swept zone with Sorw = 40%; 4 – swept zone with Sorw = 20%. For each curve in (b), an oil leg with Swirr = 20% lies over the following three scenarios: 1 – a swept zone with Sorw = 20%; 2 – a swept zone with Sorw = 40%; 3 – a swept zone with Sorw = 60%. Coloured curves represent the exact solution computed from Aki and Richards (1980), dotted lines represent the linear approximation and dashed lines are the quadratic approximations. Table 1 shows the seismic properties used for each of the saturation conditions above.
Figure 5 Example of contact movement from the literature. (a) Seismic data acquired in 1985 prior to production, showing top reservoir reflection (red line) and original oil-water contact (green horizontal line). (b) Seismic data in 1999 after production and oil-water contact movement, showing a vestige of the original oil-water contact (black circled) and the produced oil-water contact (green circle). (c) Illustration of the interpreted fluid contact movement over the fourteen years period. Adapted from El Ouair and Stronen (2006), and El Quair et al. (2007). For the seismic traces, red and yellow = negative reflection coefficient, with yellow being the largest; blue and black = positive reflection coefficient with blue being the largest.
Figure 6 Time-lapse seismic data and their interpretation for the northern part of the Gannet-C field. (a) Seismic section prior to production in 1993 showing clear fluid contacts – horizontal segments in yellow. (b) Seismic section in 1998 after production, with an additional produced oil-water contact (POWC). (c) and (d) Schematics illustrating the interpretation of the fluid contacts on the seismic data. Figures adapted after Kloosterman et al. (2003).
Figure 7 Model structure and contacts for our synthetic example. Fluid saturations are displayed with a ternary colour bar for the fluid saturations. (a) baseline condition; (b) condition at the time of the first seismic monitor survey. *PGOC* — produced gas oil contact, *OGOC* — original gas oil contact — these particular contacts are not relevant to our current analysis.
Figure 8 Results of fluid-flow simulation after twelve years of production. (a) water saturation changes; (b) the computed displacement efficiency for this model; (c) known remaining oil saturation in this model.
Figure 9 Time-lapse seismic data corresponding to our synthetic model, calculated using simulator to seismic modelling. (a) Seismic section prior to production showing original gas-oil contact (OGOC) and original oil-water contact (OOWC); (b) Seismic section of the monitor survey data after twelve years of production, with an additional produced oil-water contact (POWC).
Figure 10 Displacement efficiencies for the synthetic example calculated: (a) directly from the simulation model using $E_D = (1-S_{swirr} - S_{orw})/(1-S_{swirr})$ averaged over a 10m window about the known OOWC; (b) from the seismic data using equation (9) and applied to the RMS seismic amplitudes calculated in a 10ms symmetric window about the picked OOWC reflection. The dashed line A-A’ corresponds to the seismic section in Figure 9. Note the shapes are due to shales between reservoir units (dark blue).
Figure 11 Vertical sections along a traverse (A – A’ in Figure 13) through the field that intersects wells W1 and W2.  
(a) Baseline pre-production seismic data in 1997 showing the position of the OOWC in time (light blue horizon); (b) First monitor survey after nine years of production in 2006 showing the position of the POWC as interpreted from the 4D difference section (Figure 11). Well W2 was drilled after these results; (c) Second monitor in 2010 after thirteen years of production and including production from well W2. The new interpreted position of the POWC is marked by the dark blue horizon. All sections are drawn with the same amplitude scale. Well W2 is not present in (a) and (b) above, so is drawn by a thin curve for reference. Major timing lines 100 ms apart.
Figure 12 Vertical sections for the same traverse as in Figure 11. (a) Monitor 1 – Base section (after nine years of production) showing the position of the $OWC_1$ and $POW_{C1}$. $W_2$ was drilled based on these results. (b) Monitor 2 – Base section (after thirteen years of production and including production from $W_2$), the new position $POW_{C2}$ is marked by the dark blue horizon. Major timing lines 100 ms apart.
Figure 13 Map of the RMS amplitude extractions at the OOWC picked for the base line, and two monitor seismic surveys. The amplitudes of the post-stack volumes are extracted within a 20ms window around the interpreted OOWC. A – A’ is the traverse considered in Figures 11 and 12. The dashed line boundary delineates the area within which the pick of the OOWC is reliable.
Figure 14 Maps of displacement efficiency ($E_D$) calculated from the RMS amplitude maps in Figure 13 using equation 9. The dashed line boundary delineates the area within which the pick of the OOWC is reliable.