Time lapse (4D) effect in Forties Field, UK, North Sea; reservoir strain: implication for sand production

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Summary

Reservoirs undergoing depletion in pressure and changes in fluid saturation can compact in response to increased effective stress. Such responses vary from compaction within the reservoir to dilation in the overburden shale, with the potential of causing weakening of the overburden, instability of wells and a long list of drilling challenges.

Time lapse (4D) seismic has found application not only for monitoring fluid front and compartmentalization study, it also provides a means to study stress and strain changes associated with reservoir depletion over a period of time. Forties field 1988 and 2000 3D seismic surveys have been balanced to study the 4D effect between the two surveys. Time lags observed vary from -7.0 to +0.5 ms. High time lag observed above the Charlie sandstone is due principally to increased stress in the Charlie sandstone, while the high strain in the Southern inter-channel area is due mainly to saturation change in the Upper main sand, where it is observed to be thickest.

Sand production and drilling problems remain a source of major concern in Forties field. While a number of factors, such as poor consolidation, well deviation through the reservoir, grain size and drawdown, contribute to sanding, we find that reservoir strain resulting from increasing effective stress plays a significant role in sand production and may also contribute to the long list of drilling challenges in Forties field.

Introduction

Reservoir monitoring remains a critical element of field exploitation as a means to optimize recovery in an efficient and cost effective manner. This technology has become particularly important in the face of numerous field production and development challenges. Time lapse seismic requires consecutive seismic volumes to be conformable in data acquisition and processing. Most recent 3D seismic campaigns have repeatability in mind right from the acquisition planning stage for future use as a base survey. However, that has not always been the case, the challenge thus remains how best to compare two seismic volumes that are not conformable.

The above situation describes the Forties field in the UK, North Sea. Forties field is a conventional offshore field located approximately 180 km NE of Aberdeen, Scotland. Field development commenced in the mid 1970's and the first 3D seismic survey was acquired in 1988 after a production of about 1.8 billion barrels of oil. A further 600 million barrels of oil separate the 1988 survey and the next 3D survey in 2000. The 1988 survey was designed using a 25 x 25 m bin while 2000 and 2005 surveys were acquired and processed on a tighter 12.5 x 12.5 m bin, rotated 22^0 from the initial grid. Analysis of reservoir strain can only be carried out by comparing the 1988 and 2000/2005 surveys, hence, the need to balance the 1988 and the more recent surveys to make room for time lapse (4D) effect interpretation. Figure 1 shows the available 3D surveys in the field. The 2000 and 2005 surveys were migrated on a very smooth 250 m velocity grid while the 1988 survey was migrated using a sparse 500 m velocity grid.

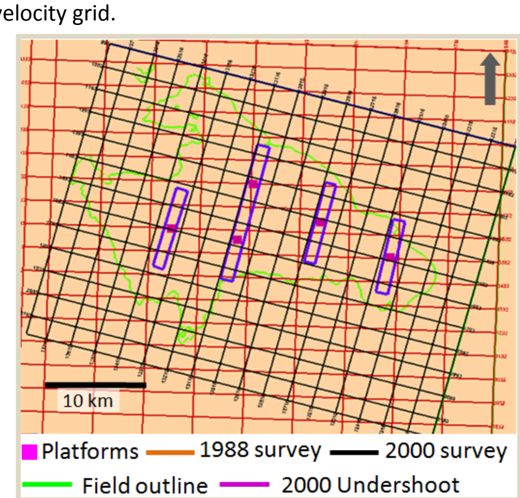

Fig. 1: Forties Field surveys: 1988 versus 2000 / 2005 surveys

Frequency spectral for the two surveys were also significantly different.

Field geology, stratigraphy and production history

The 100-200 m thick reservoir of the Forties Formation is considered to have been deposited in a middle and lower submarine environment (Hill and Wood, 1979). It comprises Late Paleocene sheet sand and channel complexes (named Alpha, Bravo, Charlie, Delta and Echo), which lie beneath a thick, monotonous section of gray to brown, variably calcareous and carbonaceous mudstones ranging from upper Paleocene to Holocene (Thomas et al.,1974). A more comprehensive description of field geology and stratigraphy is given by Thomas et al. (1974) and Hill and Wood (1979). Porosity values range from 21-33% while permeability is on the order of several hundreds of miliDarcys to a few Darcys.

Forties field cumulative production, which is supported by water injection, is in excess of 2.5 billion barrels. Reservoir pressure has been generally well maintained field-wide, though steep decreases have been recorded in Charlie sands while a steady pressure has been maintained in non-Charlie reservoirs, especially within the time interval being considered. Figure 2 shows pressure measurements for Charlie reservoir from 1975 to 2009. The marked interval (1988-2000) represents the time interval of interest.

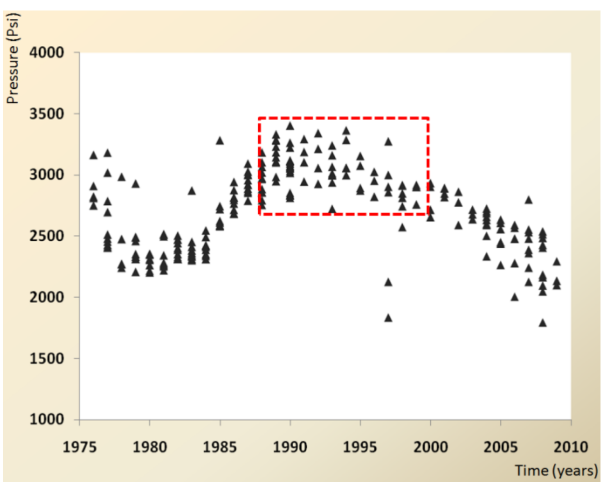

Fig. 2: Historical pressure profile of Charlie wells. Interval of interpretation is marked by the red rectangle

Forties field production began in the 1970s and the field has continued to produce through a comprehensive reservoir monitoring program. This concerted effort to keep the 'giant' alive has been faced with a series of stiff drilling, well completion and severe sand production problems.

Forties time lapse (4D) surveys on Forties: data balancing and quality control

Various reservoir monitoring studies have been published by different authors targeted at identifying and developing by-passed potentials. Ribeiro et al. (2007) reported the time lapse (4D) effect observed between 2000 and 2005 surveys. No previous studies however, have been reported on the time lapse effect between the 1988 and 2000 surveys, which perhaps has a higher 4D effect and impact on reservoir geomechanical properties. This is, in part, due to the non-conformable seismic cubes available for that period.

Workflow employed to achieve conformity between the 1988 survey and 2000 survey include: re-gridding, data projection, de-noising, frequency and amplitude spectra balancing and extensive quality control. Extensive quality control is often necessary to avoid signal distortion resulting from the use of shaping filters for spectral balancing. A comparison of the spectrum before and after the application of a shaping filter is shown in figure 3.

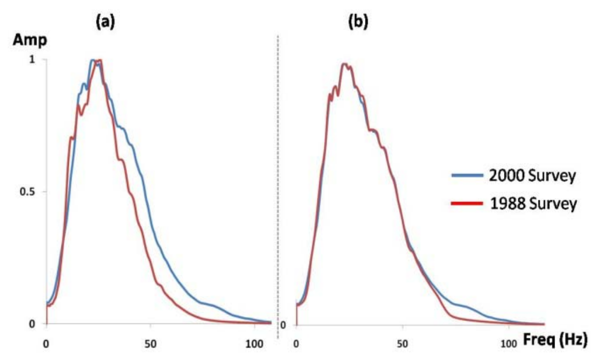

Fig. 3: Frequency spectrum: (a) before and (b) after balancing

The normalized root mean square (NRMS), an index of repeatability, defined as $\frac{2*RMS(Monitor - baseline)}{RMS(Monitor) + RMS(baseline)}$, at 200 ms above the reservoir zone was less than 30%, which is within the typical threshold for more modern 4D surveys (Helgerud et al. 2009)

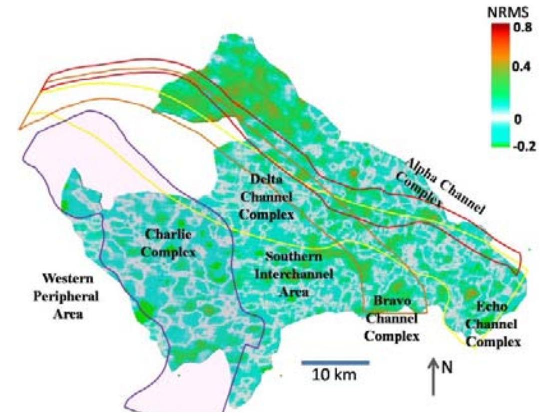

Fig. 4: Normalized Root Mean square (NRMS): Index of repeatability at 200ms above reservoir top

Time lapse effect and reservoir geomechanics:

Time lapse seismic has been a very useful tool in reservoir monitoring and production management. Not only does time lapse (4D) seismic have applications in monitoring fluid front, reservoir compartmentalization studies and fluid migration pathways analysis, it has also become an important tool for monitoring reservoir stress and strain. The time lapse effect could be interpreted in terms of amplitude changes, time lag between two surveys (Δt) and uniaxial strain (ε_{zz}). Time lapse between the 1988 and 2000 surveys was obtained by the cross correlation of the two surveys after estimating and removing the background time shift between them.

The time lag at the top of the regional seal, SELE ranges from about -7.0 ms above the Charlie sandstone to near 0.0 ms above the Echo and Alpha sandstone. This observation conforms to reservoir production and pressure depletion profile. Field pressure history shows that pressure depletion is higher in Charlie, hence the high time lapse.

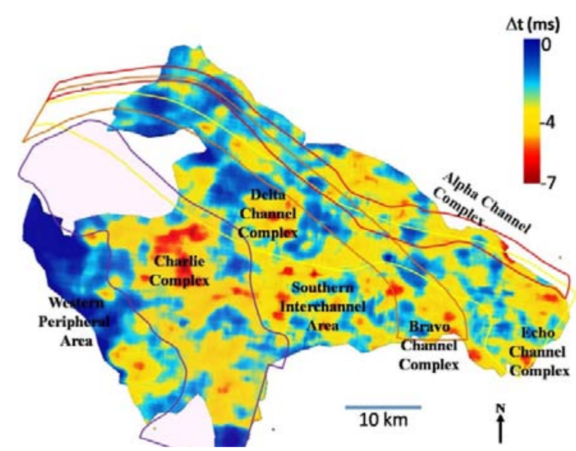

Fig. 5: Time lag (Δt) at the top of regional seal (SELE)

A decrease in pore pressure leads to an increase in stress carried by the load-bearing rock frame of the reservoir, and may be accompanied by microscale deformation mechanisms such as cement breakage at grain contacts, grain sliding and rotation (Sayers and Schutjens, 2007). This compaction in the reservoir and dilation in the overburden can cause geomechanical problems such as wellbore instability, severe sanding, subsidence, roof cracks and ultimately the failure of the overburden.

Hatchell and Bourne (2005) showed that fractional changes in velocity occur in proportion to fractional changes in path length, T, it follows that time strain τ, $(\partial T/T) = (1+R)\varepsilon_{zz}$ for normal incidence P-waves, where ε_{zz} is the uniaxial strain. Various authors have reported different values of R ranging from 1 to 3 within the reservoir and 4-6 outside the reservoir (Harchell and Bourne 2005). In this field, R was observed to be about 0.75 within the reservoir and 0.70 in the overburden. This range of values lies outside reported figures. This could be due to the high porosity and the extremely weak frame characterizing the Forties reservoir and overburden shale. Adopting R = 0.75 within the reservoir and 0.70 outside, reservoir and overburden strain have been computed for Forties field. The Charlie sands and Southern inter-channel area are observed to have high strain associated with increased stress and saturation change respectively.

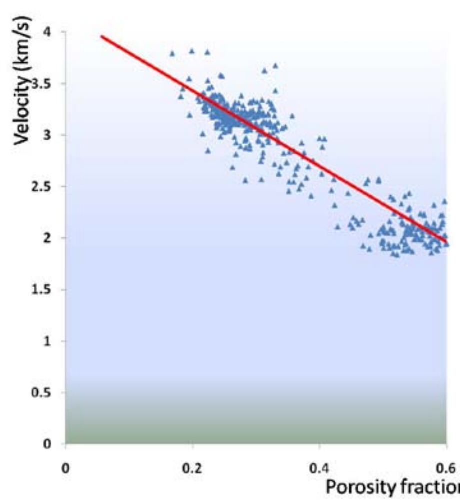

Fig. 6: Plot of velocity versus porosity for some sand intervals

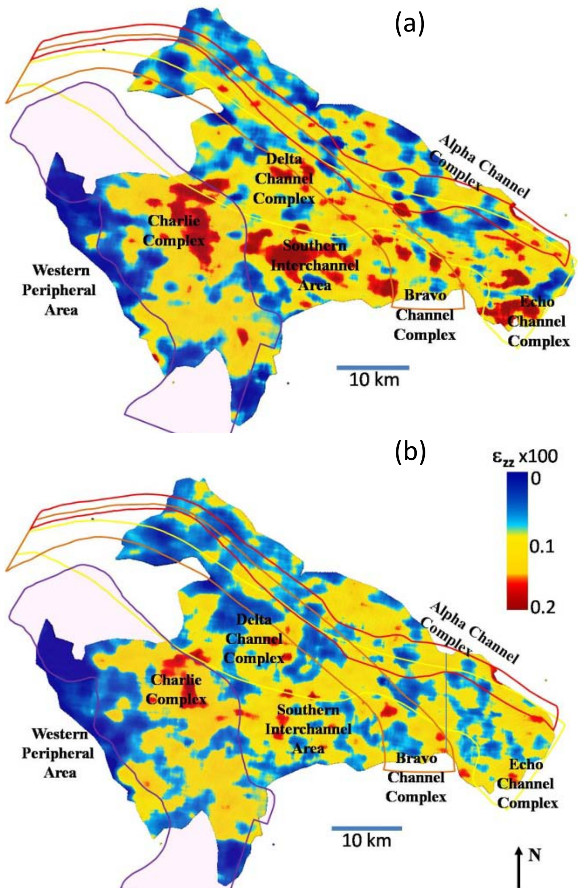

Fig. 7: Computed reservoir strain; (a): strain at reservoir top and (b) strain at the base of the reservoir

Reservoir strain and sand production:

Sand production remains a major concern as exploration activities get deeper into the basin where sediment consolidation tends to be poor. Sand production may be affected by a number of factors including: well deviation through the reservoir, fluid properties, pressure depletion, hydrocarbon and water production rates, consolidation and grain size, etc. Papamichos et al. (2001) demonstrated, using a hollow cylindrical specimen that sand production increases almost linearly with increasing flow rate as well as increasing stress on the grain framework.

Forties field has been plagued by severe sand production and an array of drilling and completion problems. This is due, in part, to its unconsolidated reservoirs as well as the increasing reservoir stress. A brief analysis of sand production data from 2002 to 2009 suggests that increasing strain is partly responsible for its sand production and some drilling problems encountered, especially in Charlie sandstone where strain increase associated with depletion is highest. Figure 8 is a plot of average sand production versus stress increase. The purple zone depicts sand production that is due purely to unconsolidated sediments while the red zone represents sand production that can be linked to increased stress.

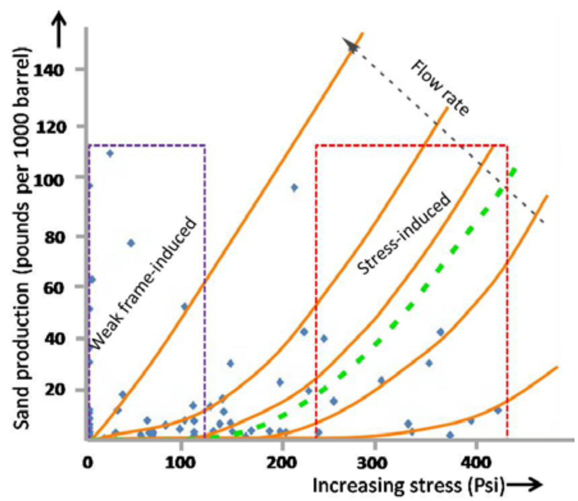

Fig. 8: Average sand production versus stress increase

Conclusion:

The Forties field time lapse seismic study using the 1988 and 2000 surveys reveals an increased strain associated with pressure and saturation changes in the Charlie sandstone and Southern inter-channel area. The high time lag in the overburden shale above the Charlie sandstone, which is due mainly to stress increase, suggests reservoir compaction in Charlie and a possible weakening of the overburden. Sanding and drilling problems observed in some parts of the field could also be attributed to strain associated with pressure changes and fluid substitution.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2010 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Hatchell, P., and S. Bourne, 2005, Rocks under strain: Strain-induced time-lapse time shifts are observed for depleting reservoir: The Leading Edge, **24**, no. 12, 1222–1225, doi:10.1190/1.2149624.

Helgerud M.B., D.H. Johnston, B.G. Jardine, M.S. Udoh, N. Aubuchon, and C. Harris, 4D Case study in the Deep Water Gulf of Mexico: Hoover, Madison and Marshall, SEG Expanded Abstract 28, 3949.

Hill, P. J., and G. V. Wood, 1980, Geology of the Forties Field, U.K. Continental Shelf, North Sea, in Giant oil and gas fields of the decade 1968-1978: AAPG Memoir, **30**, 81–93.

Papamichos, E., I. Vardoulakis, J. Tronvoll, and A. Skjaerstein, 2001, Volumetric sand production model and experiment: International Journal for Numerical and Analytical Methods in Geomechanics, **25**, 789–808. doi:10.1002/nag.154

Sayers, C. M., and M. T. M. Schutjens, 2007, An introduction to reservoir geomechanics: The Leading Edge, **26**, no. 5, 597–601, doi:10.1190/1.2737100.