The effect of intra-reservoir and non-reservoir shales on 4D seismic signatures

Yesser HajNasser and Colin MacBeth, Heriot-Watt University*

Summary

Shales are often regarded as inactive barriers in the reservoir simulation model and the surrounding rocks. Whilst this appears the correct approach for fluid flow modeling purposes, it is inaccurate for the pressure component of this process. In most clastic reservoirs experiencing pressure depletion, the sands naturally compact. This leads to the well documented extension of the non-reservoir rocks, but also the extension of the intra-reservoir shales. Less well known is that the shales have a finite, but small, permeability and pressure equilibration will occur with the reservoir sands. This diffusion process opposes the geomechanical effects. Numerical computation for a range of shale permeabilities suggests that intra-reservoir shales of 1m to 10m thickness should be considered as active when quantitatively assessing the 4D seismic signature. Also it is observed that pressure depletion in the reservoir can 'propagate' distances of as much as 50m into the shale over/under burden during the production time scale. The integration of these coupled mechanisms into forward modelling of time lapse seismic shows vertical time shift profiles different from those proposed for geomechanics alone.

Introduction

In order to interpret time lapse seismic more accurately, a quantitative understanding of the variation in the elastic properties of the reservoir and the non-reservoir surrounding rock is necessary. Fluid pressure changes induced by the production of hydrocarbons can lead to changes in the effective stresses inside and around a reservoir. At present the exact magnitude of the in-situ stress sensitivity is still largely uncertain, and cannot be relied upon (Eiken and Tøndel 2005). Ambiguity is also reported in some seismic datasets such as those of Fletcher (2004), who reveals an unexpected difference in the sign of time shifts associated with depletion. A potential reason for such seismic observations is offered by a number of well-documented factors that may act to reduce or enhance the stress sensitivity (Nunez and MacBeth 2006). It has been shown by MacBeth et al. (2008) that the existence of sub-seismic intra-reservoir shales could have a significant impact on the overall reservoir stress sensitivity, and therefore could well be a major factor contributing to uncertainty in the pressure related component of the 4D seismic response.

Often in geomechanics the overburden, sideburden and intra-reservoir shales are typically treated as passive components which are placed under extension in response to compaction in the reservoir sands (Sayers and Schutjens 2007). However shales have a non-negligible permeability and moderate porosity (Neuzil 1994, Yang and Aplin 2007), and whilst the low permeability values prevent large-scale bulk fluid exchange with the reservoir sandstones, shales do still pressure equilibrate with the adjacent depleting rock mass by the process of pressure diffusion. Here we extend and refine the prediction of our previous study focussed only on simple modeling of intra-reservoir shales by considering the combined seismic effects of geomechanics and pressure diffusion on intra-reservoir *and* the non-reservoir shales and coupled modeling. In order to account for changes occurring within and around the reservoir, an integrated workflow that combines the results of reservoir simulation and geomechanical modelling is used to update the elastic properties. The fluid flow simulation is performed using a three phase black oil simulator, and the contribution of rock deformation to fluid flow is calculated using a coupled flow and geomechanical simulator. These results are assessed by modeling the synthetic seismic response.

Intra-reservoir shale response

Past work has recognised the importance of two mechanisms acting on intra-reservoir shales. Assume at first that the intra-reservoir shales are completely impermeable. Due to pressure depletion in sands, the individual sand beds are expected to compact in response to this depletion because the effective stress acting on their rock frame has increased. Impermeable intra-reservoir shale, however, cannot respond directly to the pressure depletion in the same way as the sands, but do nevertheless interact mechanically due to tension created by the surrounding sands. Indeed, in a similar way to the more widely recognized shale overburden deformation in response to reservoir compaction (Hatchell and Bourne 2005), these shales also dilate in response to pressure depletion (MacBeth et al. 2008, HajNasser and MacBeth 2010 and 2011). In practice as intra-reservoir shales have a small but finite permeability, typically in the range 100µD to 1nD, they can deplete over time scales typical of most repeated seismic surveys. The anticipated pressure depletion however depends on the shale thickness and properties, and the specific time scale involved.

Unlike previous work, here the combined effects of geomechanics and pressure diffusion are analyzed using coupled numerical calculation of pressure diffusion and geomechanics response. The simulation model is populated with sand bodies of different geometries and aspect ratios, chosen for a variety of intra-reservoir shale thicknesses and distributions. Following Hettema et al. (2000) and Sayers (2010), reduction in fluid pressure leads to a total stress change of $\gamma_{sa}\Delta P$. In turn, this increases the effective stress acting on the sandstone rock frame by an amount $(\gamma_{sa}-\alpha_{sa})\Delta P$, where $\gamma_{sa} < \alpha_{sa}$ and hence the sand will compact due to pressure depletion. When the shale is assumed to be active in term of pressure diffusion, it becomes necessary to specify the effective stress coefficient α_{sh}, thus the change of effective stress for the shale is $(\gamma_{sh}-\alpha_{sh}\Delta P_{sh}/\Delta P_{sa})\Delta P$. The modeling study concluded that the stress arching γ ratios for the shales vary with time (and hence depletion). The combined effect of pressure diffusion and geomechanics is to equilibrate pressure; the γ_{sh} values eventually decrease below a value of $\alpha_{sh}\Delta P_{sh}/\Delta P_{sa}$. Whilst the sand continues to compact, the shales experience extension at first and as time progresses they reverse their geomechanical behaviour and start to compact in response to the increasing effective stress. In practice this process is a continuous accommodation of the geomechanical effects by the progression of pressure diffusion as depicted in Figure 1 such that the strain field in the shale is reversed towards a compaction similar to the sand's final state. The seismic scale consequence of stress changes in both sand and shale are described by the stress sensitivities of sand and shale rock frame, defined by the characteristic non-linear function observed and measured in the laboratory (MacBeth 2004). It is general the conclusions of the coupled modelling are roughly identical to those from HajNasser and MacBeth (2011). For a monitor time period of few months, a reservoir with shales of a few meters thick might exhibit an anomalous softening response, but this may only be possible for a monitor period of 10 years if thicker 5 to 10m shales are present.

Overburden/underburden shale response

Whilst it is well known that the effects of reservoir depletion and subsequent compaction lead to a strain in the overburden and underburden (for example, Hodgson et al. 2007), pressure diffusion into this region is less well documented in the geophysical literature (see for example Barkved and Kristiansen 2005). The diffusion rate is controlled by identical factors to the intra-reservoir shale problem, and although the governing equations are different, the time scales for this process are similar (Crank 1975). The combined effect of geomechanics and diffusion is investigated by performing a coupled simulation with active non-reservoir shales and a high permeability (350mD) homogeneous reservoir. The well conditions are set such that a 10MPa depletion is obtained over a period of 10 years. For this case, the effective stress output from the simulation is converted firstly to strain, then time strain by assuming an R factor (Hatchell and Bourne 2005) of 1.2 due to reservoir compaction and 6 due to shale extension. By integration, this provides a time shift distribution (and hence velocity change) both inside and around the reservoir. Although the strain in the overburden is small, it occurs over a large volume of the overburden and the cumulative effects lead to detectable time shifts.

For this study, shale permeabilities of 100nD, 1µD, and 100µD are simulated. The resultant effective stress profiles are shown in Figure 2 and the corresponding vertical time-shift profiles after 10 years of production in Figure 3. As one might expect, shales with a higher permeability give a larger surrounding volume experiencing positive effective stress changes (and hence compaction). The shale diffusion process appears to smooth out the sharp geomechanical effects over a significant zone around the reservoir. Figure 3 shows that this translates to a modification of the classic time-delay profile for shale extension alone, and this could be perceived as an effective thickening of the reservoir. Furthermore, there is a significant reversal of the measured time-shift from a slow down above the reservoir to a speed up beneath the reservoir. If no diffusion occurs, then the speed up below is reversed to a slow down. For example, for this particular model and a shale permeability of 1µD, the cumulative time shift below base-reservoir can be as much as -2ms compared to +1ms for the case of impermeable shale with less than 1nD permeability. Interestingly, such time shifts are of similar magnitude to those induced by contact movement (Aarre 2007) and may therefore be difficult to detect in observed data. This suggests careful quantitative evaluation of the pressure equilibration of non-reservoir shales is required.

Computation of the seismic response for intra- and non-reservoir shales combined

To evaluate these effects more fully in relation to the seismic response, fully coupled fluid flow and geomechanical simulation is performed again. Here, a sector of a full field simulation model from a North Sea clastic reservoir is considered. In this simulation model, all inactive shale cells are converted to being active and assigned a permeability of 1nD. In addition, non-reservoir (shale) cells of 1nD are included in the overburden, underburden and sideburden of the model for simulation purposes. These will accommodate the mechanical and diffusion effects. This modifies the numbers of cells to be simulated from 26,612 to 109,208 in the particular model used. Well production and recovery activity induces a combination of pressure increase but also decrease. After simulation for a period of 10 years, the changes in effective stress and saturation are converted into V_P, V_S and ρ changes and the corresponding time-lapse seismic is modeled using convolutional modeling (Amini and MacBeth 2011). Figure 4 shows a vertical cross section of the synthetic seismic with and without the combined effects of pressure diffusion and geomechanics. When the shales are inactive, the modeled seismic shows abrupt discontinuous values and high intensity reflectivity along events – related to the positions of the shales. These features change as the shales become active, and it is also possible to see some evidence of a polarity shift in the seismic at specific locations. It is concluded that active shales with finite permeability do need to be assigned to simulation models when realistic computation of the seismic response for time-lapse seismic interpretation is required.

Discussion and conclusions

The integration of the combined effects of geomechanics and pressure diffusion of the intra-reservoir and the surrounding shales into seismic forward modelling can affect the effective seismic response. Coupled pressure diffusion and geomechanical effects acting on these shales have an influence on the apparent in situ stress sensitivity of the reservoir and act to reduce the sensitivity from that expected by applying laboratory measurements carried out on predominantly core plugs. Under certain conditions, the reduction in stress sensitivity anticipated from our modeling may in fact reverse the polarity of the expected response, showing less contrast between sand and shale and more continuity of seismic horizons. Fully coupled numerical computation indicates that for a monitor time period of few months, a reservoir with shales of few meters thick might exhibit an anomalous softening response, whilst this may only be possible for a monitor period of 10 years if thicker 5 to 10m shales are present. Pressure diffusion into a shale overburden or under/side burden can prove to be significant over the production (and recovery) time scale from several years to tens of years. In 5 years, pressure can diffuse by as much as 50m into a 1nD shale. The surrounding shales initially experience a mechanical extension due to the stress created by compacting sandstones. However as time progresses pressure diffusion reverses this effect near to and around the reservoir, and these shales then experience a compaction. However the impact of the sedimentology of the shale should not be underestimated and this can give rise to heterogeneities such as silt layers or tensile fractures that can considerably enhance the predicted effects. Pressure diffusion can modify the time-shift profile beyond that expected of a conventional reservoir compaction-overburden extension scenario.

It is known that the results of this work are strongly controlled by the coupled mechanical, transport and elastic properties of the shales. However, the exact time scales involved in these predictions are dependent on the static and dynamic properties of the shales. There properties are currently hard to calibrate precisely due to an insufficient knowledge of these rocks for the specific depositional environments of relevance.

Acknowledgments

This work was sponsored by the Edinburgh Time-Lapse Project, Phases IV and is published with approval from its sponsors: BP, BG, Chevron, ConocoPhillips, ENI, ExxonMobil, Hess, Ikon Science, Landmark, Maersk, Marathon Oil, Norsar, Ohm, Petrobras, Shell, Statoil, and Total. We thank Peter Schutjens for stimulating and discussions on pressure diffusion and geomechanics. Schlumberger is thanked for provision of Eclipse and Visage software.

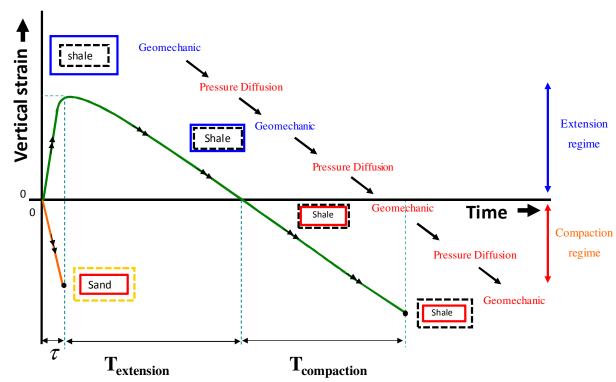

Figure 1 Strain paths for the shales and sand in an instantaneously depleting sand body. The shales slowly evolve to a strain condition similar to the compaction in the sands, crossing over between an extensional to a compactional regime.

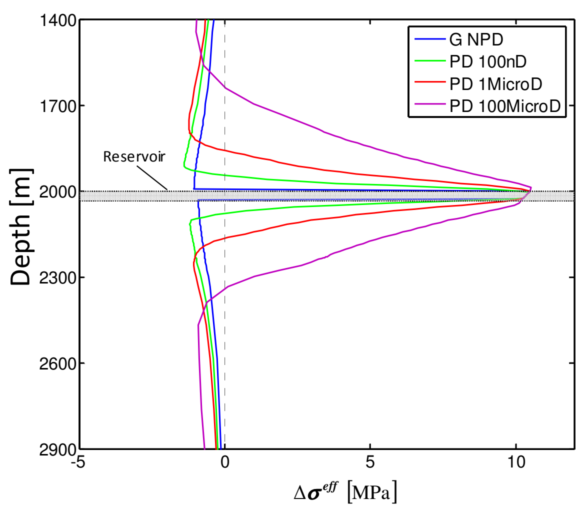

Figure 2 Effective stress changes within the reservoir and the surrounding shales after ten years of production. Cases are for: impermeable shales (blue curve), shale permeabilities of 100nD (green curve), 1µD (red curve), and 100µD (magenta curve).

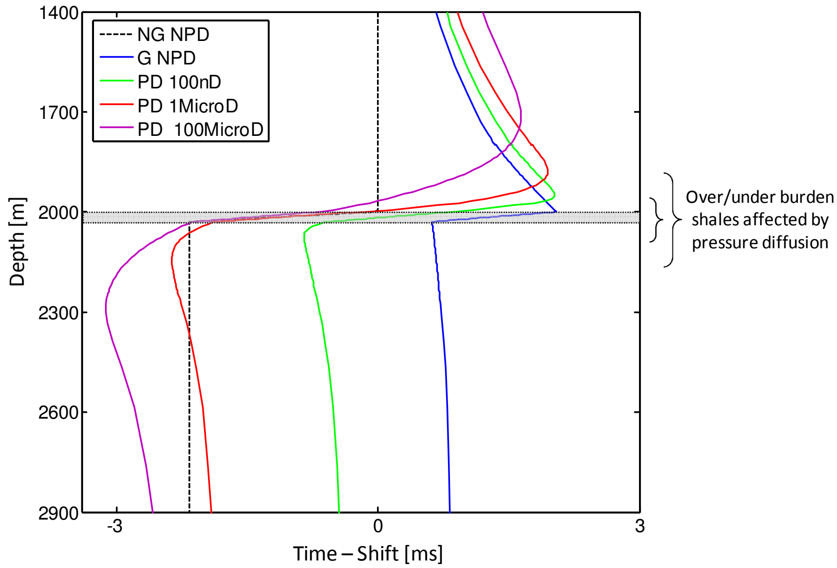

Figure 3 Computed time shift profiles after ten years production for: impermeable and mechanically *inactive* non-reservoir shales (dashed line); impermeable and mechanically *active* non-reservoir shales (blue curve); non-reservoir shale permeability of 100nD (green curve); 1µD (red curve), 100µD (magenta curve).

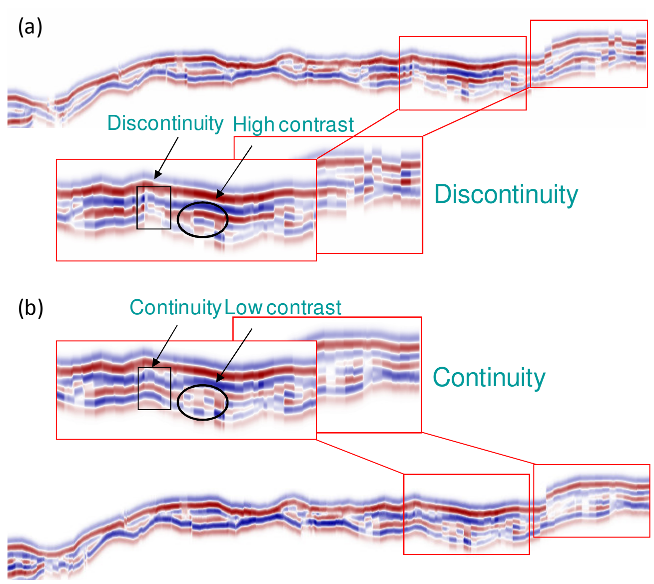

Figure 4 Vertical cross section of modeled seismic for: a) impermeable and mechanically inactive shales; b) mechanically active shales with a permeability of 1nD.

EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2011 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

Aarre, V., 2007, Estimating 4D velocity changes and contact movement on the Norne field: Presented at the Offshore Technology Conference, OTC 19049.

Amini, H., and C. MacBeth, 2011, Calibration of simulator to seismic modelling for quantitative 4D seismic interpretation: 73rd Conference & Exhibition, EAGE.

Barkved, O. I., and T. Kristiansen, 2005, Seismic time-lapse effects and stress changes: Examples from a compacting reservoir: The Leading Edge, **24**, 1244, doi:10.1190/1.2149636.

Crank, J., 1975, The mathematics of diffusion, Clarendon Press, Oxford, second edition.

Eiken, O., and R. Tøndel, 2005, Sensitivity of time-lapse seismic data to pore pressure changes, Is quantification possible?: The Leading Edge, **24**, no. 12, 1250–1254, doi:10.1190/1.2149638.

Fletcher, J., 2004, Rock and fluid physics understanding the impact of pressure changes: Presented at SPE/EAGE Joint Workshop:What do Petroleum Engineers expect from Time Lapse Seismic, and do Geophysicists answer the right questions? HajNasser, Y. and MacBeth, C., 2010, The effect of intra-reservoir shales on effective stress sensitivity: 72nd Conference & Exhibition, EAGE.

Hatchell, P., and S. Bourne, 2005a, Measuring reservoir compaction using time-lapse time shifts: 75th Annual International Meeting, SEG, Expanded Abstracts, 2500–2504.

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

Hettema, M., P. Schutjens, B. Verboom, and H. Gussinklo, 2000, Production-Induced Compaction of a Sandstone Reservoir: The Strong Influence of Stress Path: SPE Reservoir Evaluation & Engineering, **3**, no. 4, 342–347, doi:10.2118/65410-PA.

Hodgson, N., C. MacBeth, L. Duranti, J. Rickett, and K. Nihei, 2007, Inverting for reservoir pressure change using time-lapse time strain Application to Genesis Field Gulf of Mexico: The Leading Edge, **26**, no. 5, 649–652, doi:10.1190/1.2737104.

MacBeth, C., 2004, A classification for the pressure-sensitivity properties of a sandstone rock frame: Geophysics, **69**, no. 2, 497–510, doi:10.1190/1.1707070.

MacBeth, C., K. Stephen, and A. Gardiner, 2008, The impact of sub-seismic shale layers on the reservoirs stress sensitivity: Presented at the 78th Annual International Meeting, SEG.

MacBeth, C., Y. HajNasser, K. Stephen, and A. Gardiner, 2011, Exploring the effect of meso-scale shale beds on a reservoir's overall stress sensitivity to seismic waves: Geophysical Prospecting, **59**, no. 1, 90–110, doi:10.1111/j.1365-2478.2010.00897.x.

Neuzil, C. E., 1994, How permeable are clays and shales?: Water Resources Research, **30**, no. 2, 145–150, doi:10.1029/93WR02930.

NÚÑEZ, J. and MACBETH, C., 2006, Evaluation of the mismatch between observed and predicted 4D effects on the Genesis Field: GOM. XIII Venezuelan Geophysical Congress.

Sayers, C., 2010, Geophysics Under Stress: Geomechanical Applications of Seismic and Borehole Acoustic Waves Colin Sayers: SEG/EAGE Distinguished Instructor Short Course.

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

Yang, Y., and A. C. Aplin, 2007, Permeability and petrophysical properties of 30 natural mudstones: Journal of Geophysical Research, **112**, 1911–1918, doi:10.1029/2005JB004243.

Comment [j1]: CrossRef reports the first page should be "B03206" not "1" in reference "Yang, Aplin, 2007".