The impact of sub-seismic shale layers on the reservoir's stress sensitivity

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Summary

In most clastic reservoirs experiencing pressure depletion due to production, the hydraulically connected sands in the reservoir naturally compact to some degree. As a consequence, the much lower permeability reservoir shales may experience mechanical tension. The effective seismic response of the reservoir interval is thus a mix of both hardening and softening reservoir components. This phenomenon alters the predicted overall stress sensitivity from that anticipated for a homogeneous, fully connected reservoir interval. The time period over which this effect might be observed is influenced by the rate at which the shales reach pressure equilibrium with the surrounding sands. This work indicates that sub-seismic shale layers of approximately 1m thickness take less than 12 months to equilibrate, whilst thicker shale layers of 8m can take over 10 years. It is concluded that the mechanical and dynamic response of sub-seismic reservoir shale must be considered when quantitatively assessing the 4D seismic signature from frequently shot time-lapse surveys with a periodicity of 6 to 12 months, but also perhaps, for conventional 4D seismic surveys shot over 5 to 10 years. These conclusions are strongly affected by the permeability of the shale layers, the stress state, and are also a function of net to gross and depositional environment.

Introduction

A quantitative understanding of the variation in the elastic properties of reservoir rocks with changes in stress is an essential element of the petroelastic model that links saturation and pressure changes to the corresponding 4D seismic signatures. At present, the use of laboratory measurements to calibrate this link for a feasibility study or qualitative 4D signature assessment of pressure changes appear adequate for most practical purposes. However, the exact magnitude of the *in-situ* stress sensitivity is still largely uncertain, and cannot be relied upon for precise determination of pressure changes (Eiken and Tondel 2005). This point is highlighted by the results of Floricich et al. (2006) and Stephen and MacBeth (2006), who combine seismic observations and engineering data to conclude that the reservoir's stress sensitivity as observed by the seismic data is less than that anticipated. Uncertainty is also reported in other seismic datasets such as those of Fletcher (2004), who reveals an unexplained difference in the sign of the amplitudes and time-shifts associated with depletion. A possible explanation 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). The list includes: inaccuracies in specifying the 'dry' rock frame properties due to sample preparation; internal damage due to stress unloading and cutting; the bias of the plug sampling scheme; the effective stress coefficient; the true triaxial stress state of the reservoir; creep; and dispersion effects. An additional item for consideration is the existence of heterogeneities below the scale at which the stress sensitivity laws are being applied. Thus, dynamic interpretation from 4D seismic currently ignores the relatively thin (1 to 10m) shales which are smaller than the size of a typical sand body (20 to 30m) and the seismic wavelength (50m to 100m). Such shales are difficult to locate and identify within the inter-well volume. It is shown that these shales can 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.

Predictions for impermeable shales

It is assumed initially that the shales are completely impermeable and therefore act as non-conducting barriers in the reservoir. Consider the effect of pressure depletion on a sand body consisting of several sand and shale beds sandwiched between a shale overburden and underburden (Figure 1). All sands are connected to the well and hence are produced. Good horizontal and reasonable vertical connectivity within the sands ensures that the resulting pressure drop propagates quickly, such that the pressure reaches a quasi-equilibrium (the majority of the volume removed is replaced by the aquifer or injectors). Here we ignore any near-well effects that may occur in the vicinity of the producer, and consider only the pressure drop in the inter-well space. The individual sand beds are expected to compact in response to depletion because the effective stress on their rock frame has increased. Intra-reservoir shales, however, cannot respond directly to the pressure depletion in the same way as the sands, but do nevertheless interact mechanically due to the tension created by the surrounding sands (provided they are of course fully coupled to the sands). Indeed, in a similar way to the more widely recognised shale overburden deformation in response to reservoir compaction (Hatchell and Bourne 2005), these intra-reservoir or inter-reservoir unit shales may also extend in response to pressure depletion.

Consider now the effect of a pressure depletion ΔP in the sands on the elastic wave properties. For each sand, depletion leads initially to an effective stress change of $-\Delta P$ relative to the pre-production state (given a Biot coefficient of unity) and upon compaction this alters the sand stress state by $\alpha_{sa}\Delta P$ (where α_{sa} is close to -1). However, as the shale is not subjected to fluid withdrawal or pressure change due to production, its stress changes by virtue of the pull exerted by the neighbouring depleting sand layers. This, in turn, leads to a stress acting internally on the shale. In practice, the stress change in the shale due to this mechanism is given by $\alpha_{sh}\Delta P$, where α_{sh} (as with α_{sa}) is a factor influenced by the geometry of the sandbody, distribution of the shales, and external boundary conditions. In practice, α_{sh} is expected to lie somewhere between -1 (complete depletion) and 1 (complete extension). The consequences of an extension-induced stress change in the shales are illustrated in Figure 2. Here, the stress sensitivities of the sands and shales are defined by typical non-linear function. The sands and shales have a similar stress sensitivity behaviour when compacting (red curve segment), but the shale has an enhanced stress sensitivity upon extension (blue curve segment) as the magnitude upon elongation is known to exceed that of compaction (Sayers, 2007). Upon production, the sands follow the red curve and increase their impedance, whilst the shales are predicted to follow the solid blue curve and decrease their impedance. The shales reduce their impedance at a faster rate than the sands due to the shape of the stress sensitivity curve, thus amplifying this decrease.

To roughly quantify the impact of the phenomenon above, the changes in the elastic wave properties of the sandbody are calculated for vertical P-wave propagation through the stack of layers. Backus (1962) and mass balance calculation can thus be used to give the initial and final states of the composite elastic modulus. From these equations, P-wave impedance is calculated for a typical, good quality (25 percent porosity) sand from a normally pressured reservoir in the North Sea with top reservoir at 7000ft (similar to that of the Nelson and Schiehallion fields for example). A pressure change of -10 MPa away from wells is chosen for the initial state, this representing a maximum upper limit of variation in an oil-water reservoir whose pressure fluctuates due to production with partial support. As a guide for the calculation, sand stress sensitivity parameters and elastic properties published for the Schiehallion field by MacBeth (2004) are used. As measurements of shale stress sensitivity are not available, the properties are selected arbitrarily by manual adjustment of the sand parameters to be firstly greater than that of the sand, then identical to that of the sand, and finally to be stress insensitive. Density variation, judged to be no more than 0.1 to 0.2% (MacBeth 2004), is also included for completeness. The final numerical results are shown in Figure 3 for the three shale stress sensitivity scenarios and as a function of net-to-gross, with $\alpha_{sa}=-1$ and $\alpha_{sh}=1$.

The results here suggest that there is only a guarantee of an increase in the reservoir impedance with a reduction in pressure when the shales are stress insensitive. Indeed, when the shales have identical stress sensitivity to the sands, or are more stress sensitive, this statement only holds above a threshold net-to-gross value (in this case it is 0.8). As more shale is present in the reservoir (thus lowering the net-to-gross below 0.8), the composite reservoir package appears to soften (i.e. decrease it's overall P-wave impedance) with pressure depletion. The latter effect would result in a dimming of the top reservoir response instead of a brightening (or vice-versa), a result contrary to our general expectations. Note that, when there are only a very few thin sands in the reservoir, it is unlikely that their combined strain would be sufficient to produce the desired change in the shales (for a fixed pressure drop in the sands), and thus it is anticipated that, for small values of net-to-gross, the calculation might be unrepresentative of the true physics of deformation. It appears that the overall influence on the reservoir's elastic properties depends on the balance between the proportion of shales present and their *in-situ* stress sensitivity. This result also depends on the values of α_{sa} and α_{sh}, as the net-to-gross threshold value of 0.8 is only appropriate for $\alpha_{sa}=-1$ and $\alpha_{sh}=1$. For a reservoir with finite extent, such as a channel sand package subject to a triaxial stress state, this will certainly not be the case. Calculations based on geomechanical modelling for a range of channel model dimensions, geometries, mechanical properties, and shale distributions indicate that α_{sh} can in fact lie between 0.1 and 0.4. These push the net-to-gross threshold to lower values.

Predictions for permeable shales

In practice, shales have a small but finite permeability, typically in the range 1mD to 1nD ($1D=10^{-12}m^{-2}$), arising from their small pore throat size and particular mineralogical packing (see for example, Neuzil 1994). Shales, whilst being relatively impermeable compared with the surrounding sands do reach pressure equilibrium with the reservoir sands over time. The time for this process depends on the thickness of the shale and its permeability. At first, pressure change is established in the higher permeability sands, this process occurring in a matter of days. After this, a vertical gradient is set up across the top and base of each shale, which then drives the equilibration process. Reference calculations based on the 1D pressure diffusivity equation for a reservoir consisting of a single shale layer embedded between two sands yields the results of Figure 4. These indicate that a 1m thick shale takes less than 12 months to equilibrate whereas an 8m thick shale takes over 10 years. It appears that the sands may therefore deplete at first and extend the shales for the first few days but, over some months or years, the pressure drop grows in the shales and reverses the extension mechanism until the shales finally reach a compacted and depleted state similar to the sands. The effects described and calculated in the previous section are then not applicable, and the sands and shales both appear depleted.

Discussion and conclusions

The effects we observe here suggest the *in-situ* stress sensitivity of the reservoir may be larger or smaller than that calculated from laboratory tests on predominantly sandstone samples. Very low permeability sub-seismic shale layers of approximately 1m thickness will impact frequently repeated seismic monitoring surveys shot over short time periods such as 12 months or less. Thicker shale layers can affect 4D seismic surveys on longer time scales of 10 years. These shales must therefore be taken into account when quantitatively evaluating the 4D seismic signature. However, due to the dependence on shale thickness and properties, these effects are important in 4D seismic data only for particular depositional environments. The reservoir must be a moderately thick sandstone-dominated interval containing laterally continuous or discontinuous shales 1m to 8m thick. Such sandbodies are known to occur in range of depositional environments, including channelised turbidites (Clark and Pickering 1996), onlapping turbidite sheets (Smith and Joseph, 2004) and multistorey/multilateral fluvial sandbodies (e.g. Campbell, 1976). In these cases, the associated shales may either be clay-rich, with very low permeabilities or more silty, with higher permaeabilities, so the full range of responses described above may be seen in different systems. Thus, each depositional setting must be evaluated separately and data for these particular shales extensively collected.

It is concluded that the results above are strongly affected by the permeability of the shale layers, and are a function of net to gross and depositional environment. However, the exact time scales involved in these predictions are dependent on the static and dynamic properties of the shales – these are currently difficult to assign precisely due to a generally insufficient knowledge and sampling of these rocks for the specific depositional environments of relevance.

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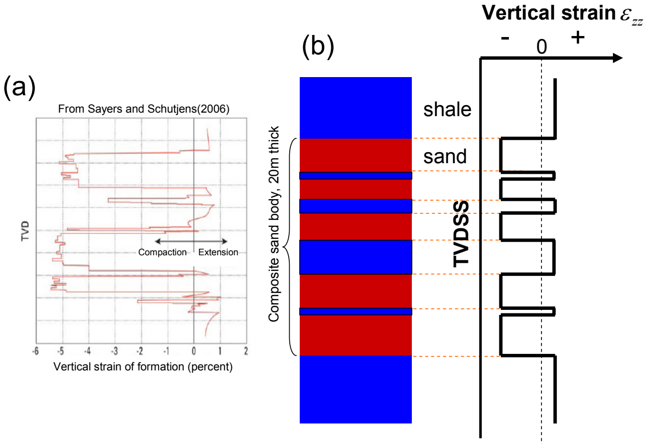

Figure 1. (a) Modelled vertical strain alternation at the location of a well in a deepwater Gulf of Mexico turbidite as a function of TVD (Sayers and Schutjens 2006). (b) Schematic illustrating the impact of production on a sequence of sands separated by shales.

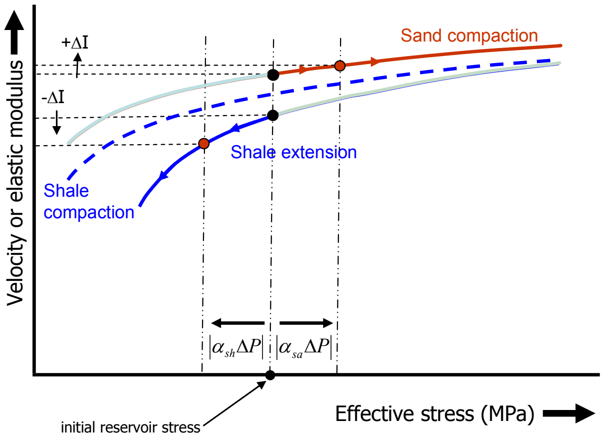

Figure 2. Stress sensitivity curves for reservoir sand and shale, illustrating the effect of pressure depletion and compaction versus dilation or extension on changes of the elastic properties. Light blue segments indicate portions of the curve not accessed by the rocks *in-situ*.

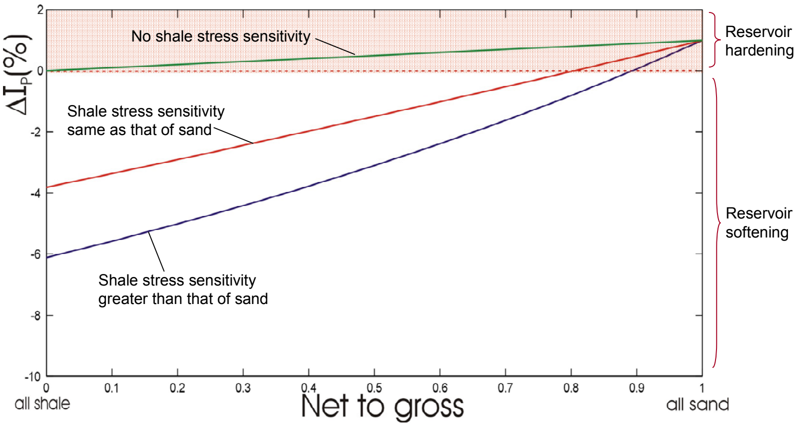

Figure 3. Calculated percentage changes in P-wave impedance (ΔI) for a reservoir comprising of a mixture of sand and impermeable shale layers undergoing a pressure depletion of 10MPa. For the generation of this figure $\alpha_{sa}=-1$ and $\alpha_{sh}=1$.

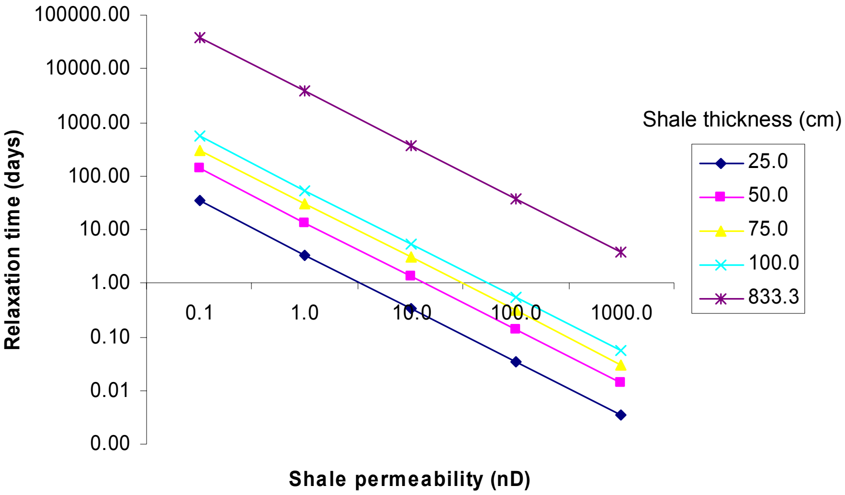

Figure 4. Relaxation time for a thin shale sandwiched between two high permeability sands. The relaxation time is defined as the point at which the induced pressure perturbation in the shale is 1/10th of the initial value in the sand. This is derived from the solution of the 1D pressure diffusivity equation.

EDITED REFERENCES

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