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The Effect of Intra-reservoir Shales on Effective Stress Sensitivity

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SUMMARY

In most clastic reservoirs experiencing pressure depletion, the sands in the reservoir naturally compact. As a consequence, the much lower permeability reservoir shales may experience extension. This extension is counteracted to some degree by pressure equilibration of the shale. The effective seismic response of the reservoir interval may thus be a mix of both hardening and softening reservoir components, depending on the balance of these phenomena. This effect is predicted to alter the overall stress sensitivity of the seismic properties from that anticipated for a homogeneous, fully connected reservoir interval. However, the final resultant response depends on the time period over which this effect is observed. Numerical computation using simplified geological models indicates shales of 1m to 10m thickness should be taken into account when quantitatively assessing the 4D seismic signature from frequently shot time-lapse surveys with a periodicity of 3 to 12 months, whilst 5 to 10m thick shales could impact conventional 4D seismic surveys shot over 5 to 10 years. These conclusions are strongly affected by the mechanical and transport properties of the intra-reservoir shales, their thickness and distribution, and are hence also a function of the depositional environment.

Introduction

A quantitative understanding of the variation in the elastic properties of reservoir rocks with changes in stress is an important element of the petroelastic model that links saturation and pressure changes to the corresponding 4D seismic signatures. At present, 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). 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 (MacBeth 2004). An additional item for consideration is the existence of heterogeneities below the (seismic) scale at which the stress sensitivity laws are being applied. In particular, dynamic interpretation from 4D seismic currently ignores 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, particularly if distributed stochastically, are difficult to locate and identify within the inter-well volume (Figure 1). It has been shown by MacBeth et al. (2008) that such 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. Here, we extend and refine the predictions of the previous study by considering the joint interaction of the mechanical and pressure diffusion effects.

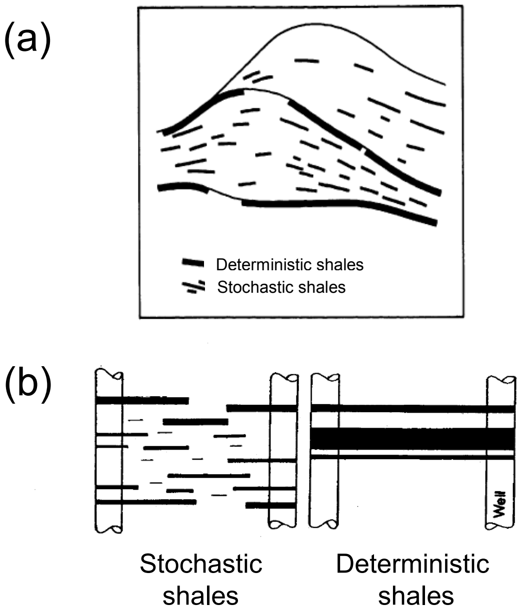

Figure 1 *In this work thin sub-seismic shales are considered, similar in character to that shown above. (a) Example of intercalcating shales from the turbiditic Frigg field (Skaug and Gunesø 1986). (b) Thin sub-seismic shales can be distinguished as laterally continuous 'deterministic' shales or the more laterally discontinuous 'stochastic' shales.*

Predictions for impermeable, but mechanically active shales

Consider the effect of pressure depletion on a sand body consisting of several sand and shale beds sandwiched between a shale overburden and underburden. Assume at first that the shales are completely impermeable and therefore act as non-flowing barriers. The individual sand beds are expected to compact due to depletion as the effective stress on their rock frame increases. The impermeable shales, however, cannot respond directly to pressure depletion, but do nevertheless interact mechanically due to the extension created by the surrounding sands. Indeed, in a similar way to the more widely recognised overburden deformation due to reservoir compaction (Hodgson et al. 2007), intra-reservoir (or inter-reservoir) unit shales may also dilate in response to pressure depletion. MacBeth et al. (2008) evaluated the effect of pressure depletion on the overall elastic wave properties. Each sand responds instantaneously to an overall stress change of $\alpha_{sa}\Delta P$ relative to the pre-production state (where α_{sa} is the effective stress coefficient). Upon sand compaction, the total stress state inside the reservoir is now changed by $\gamma_{sa}\Delta P$ (where γ_{sa} is the stress arching ratio), this in turn changing the effective stress acting on the rock frame by (γ_{sa}-α_{sa}) ΔP where $\gamma_{sa} < \alpha_{sa}$. However, as the shale is not subjected to fluid withdrawal, the total stress change due to extension is given by $\gamma_{sh}\Delta P$, where γ_{sh} is the stress arching ratio for the shales. Here, we ignore the small reduction in the shale pore pressure that occurs due to extension as quantified by Skempton's coefficient. The consequences of an extension-induced stress change in the shales on the stress sensitivity relation for the elastic waves are illustrated in Figure 2(a).

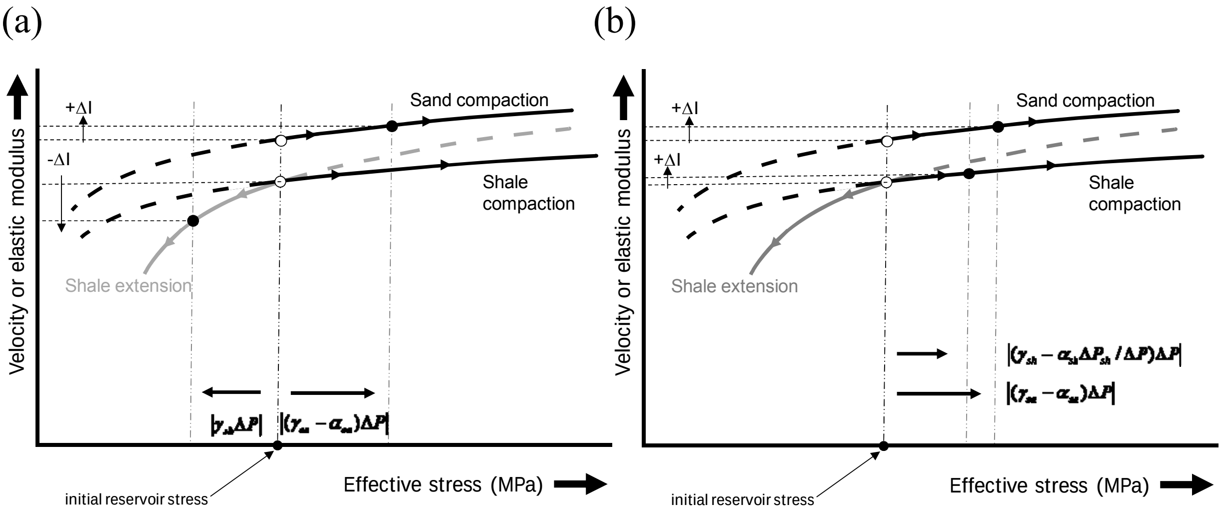

***Figure 2** Stress Sensitivity curves for reservoir sand and shale, illustrating the effect of pressure depletion and compaction versus extension on changes of the elastic properties. (a) For impermeable shales; (b) for permeable shale, once pressure equilibration has occurred.*

Upon depletion, the sands increase their impedance, whilst the shales are predicted to decrease their impedance with the results being shown in 3(a). To select values for γ_{sa} and γ_{sh} in our specific case, extensive geomechanical modeling was carried out for a range of sand channel models. Good quality (25 percent porosity) sands, from a normally pressured reservoir in the North Sea with top reservoir at 7000ft, are considered using the Schiehallion field as a guide. This field is also used to assign the pressures, channel dimensions, geometries, mechanical properties, and bed distributions. In the absence of appropriate data, the effective stress coefficient α_{sa} for the sands is taken to be unity. The results in Figure 3(a) indicate that there may only be a complete guarantee of an increase in the reservoir impedance with pressure depletion when the shales are stress insensitive. The greater the amount of shale in the composite reservoir package, the greater the probability of the 'softening' (i.e. decrease in overall P-wave impedance) effect with pressure depletion.

Predictions for permeable and mechanically active shales

In practice, shales have a small but finite permeability, typically in the range 1μD to 1nD (see for example, Neuzil 1994). Shales, whilst being relatively impermeable compared with the surrounding sands therefore do reach pressure equilibrium with the reservoir sands after some time. The exact time scale for this process depends on the shale thickness and its permeability. Diffusion counteracts the geomechanical extension effect driven by the stress difference across the sand-shale boundary. Total stress change in response to sand depletion is (almost) instantaneous, whereas the pressure diffusion acts over an extended time period. To analyse the joint effects of geomechanics and pressure diffusion in more detail, numerical calculation of the deformation of sand bodies with different geometries and aspect ratios is performed for a variety of intra-reservoir shale thicknesses and distributions. The calculation is performed at each shale pressure equilibration state, ranging from $\Delta P_{sh}=0$ (no shale depletion) to $\Delta P_{sh}=\Delta P_{sa}$ (shales fully depleted) where ΔP_{sa} is that of the sand). When the pressure in the shales starts to equilibrate, it becomes necessary to also specify the effective stress coefficient, α_{sh}, for the shale - thus the change of effective stress for the shale is now $\left(\gamma_{sh} - \alpha_{sh}\dfrac{\Delta P_{sh}}{\Delta P_{sa}}\right)\Delta P_{sa}$.

The results indicate that stress arching ratios for the shales decrease with time (and hence depletion), being rapid at first followed by a slower variation. Indeed, as time progresses γ_{sh} reduces below $\alpha_{sh}\Delta P_{sh}/\Delta P_{sa}$ and the shales reverse their geomechanical behaviour and start to compact after an initial extension. In practice this process is a continuous accommodation of the geomechanical effect as the pressure diffusion progresses as illustrated in Figure 4, such that the change of the strain field in the shale slowly reverses polarity and evolves towards its final, fully depleted, state. The consequence of pressure equilibration and elapsed time on the original impermeable geomechanics prediction is shown in Figures 2(b) and 3(b). The pressure considered in these examples is $\Delta P_{sh} = 0.3\Delta P_{sa}$, this occurring after 7 days, the $\gamma_{sh} < \alpha_{sh}\Delta P_{sh}/\Delta P_{sa}$ condition being achieved by the time 46 days have elapsed. Beyond 46 days, the reservoir is expected to only to harden. By contrast a 10m thick shale takes 250 days to equilibrate to $\Delta P_{sh} = 0.1\Delta P_{sa}$, 520 days to reach $\Delta P_{sh} = 0.3\Delta P_{sa}$ and 3600 days to reach the $\Delta P_{sh} = 0.7\Delta P_{sa}$ point. It is generally concluded that, for a return time period of a few months, a reservoir with shales of a few metres thick might exhibit an anomalous softening response, whilst this may only be possible for a return period of 10 years if thicker 5 to 10m shales are present.

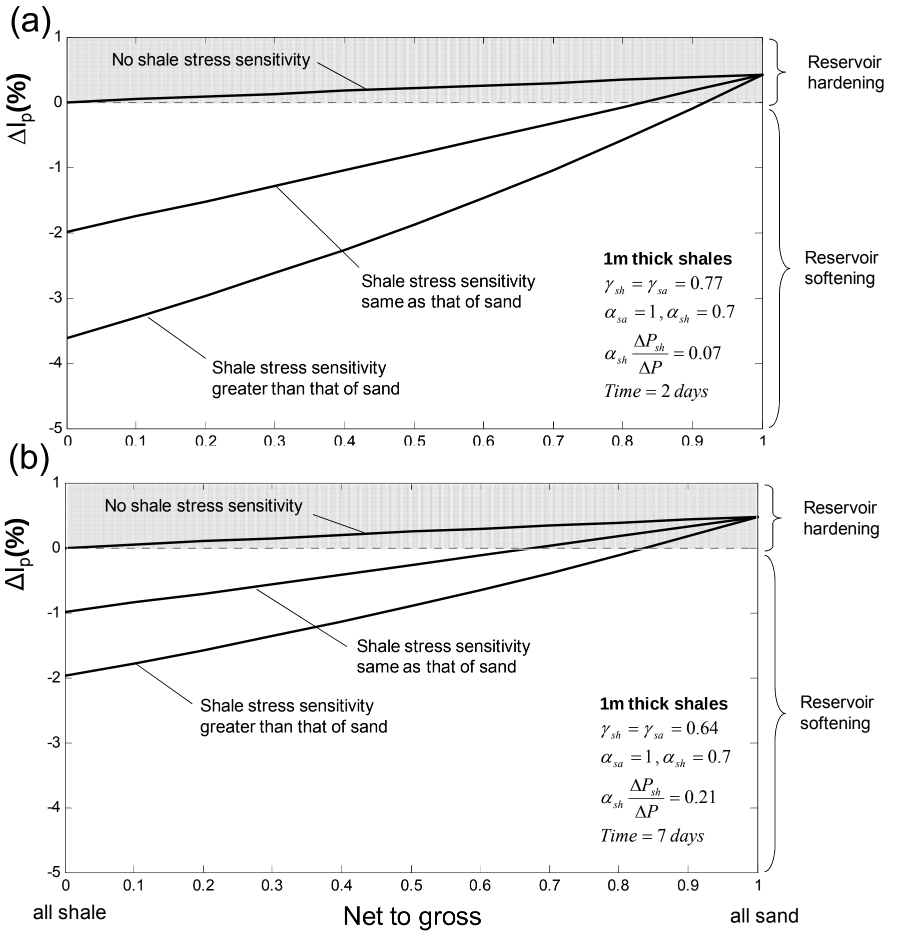

Figure 3 *Calculated percentage changes in P-wave impedance (ΔI_P) for a reservoir comprising of a mixture of sand and impermeable shale layers undergoing a pressure depletion of 10MPa. Time-lapsed change in impedance for a reservoir composed of sands and shales distributed with a varying net-to-gross. Results are for shales of thickness 1m and permeability 1nD. Results are after an elapsed time of (a) 2 and (b) 7 days and 30% depletion, which gives the stress arching coefficient specified.*

Discussion and conclusions

The effects we observe here suggest the *in-situ* stress sensitivity of the reservoir interval may be smaller than that predicted from laboratory tests on predominantly sandstone core plugs. Our numerical computations based on idealised geological models indicate that very low permeability sub-seismic shale layers of approximately 1m to 10m thickness will impact frequently repeated seismic monitoring surveys shot over short time periods of 3 to 12 months. The thicker end of this range can affect 4D seismic surveys on longer time scales of 5 to 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 dependent on the particular depositional environment - geological scenarios were outlined by MacBeth et al. (2008). Each reservoir setting must be evaluated separately and data for these particular shales extensively collected. It is generally concluded that the final seismic properties are strongly affected by the mechanical and transport properties of the shale layers, and are a function of net to gross and sedimentology. However, the exact time scales involved in these predictions are dependent on a variety of overlapping phenomena which must be calculated on a case specific basis. These phenomena are currently difficult to calibrate precisely due to an insufficient knowledge and sampling of these rocks for the specific depositional environments of relevance.

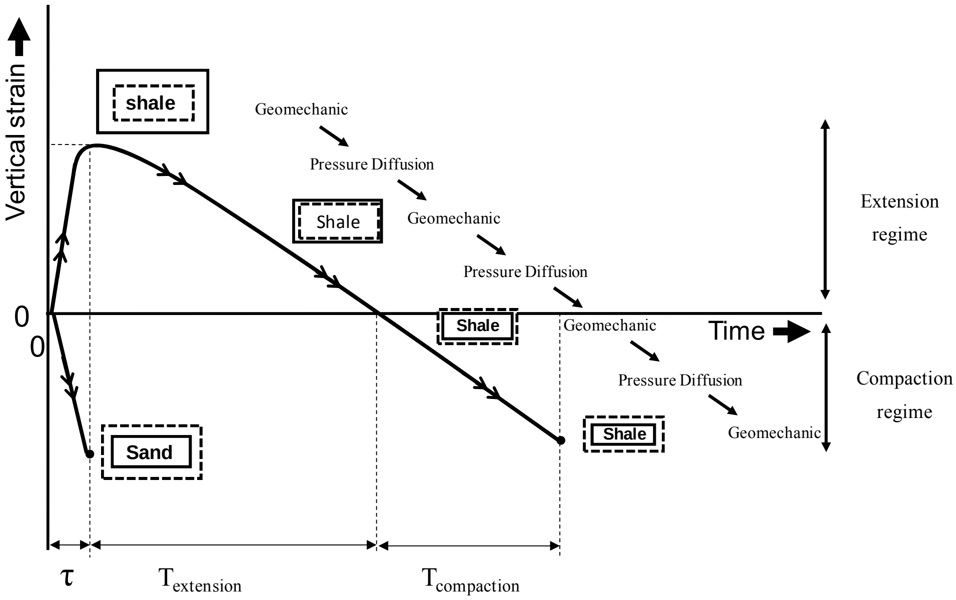

***Figure 4** Strain paths for the shales and sand in an instantaneously depleted sand body. The shales slowly evolve to a strain condition similar to the compaction in the sands, crossing over between an extensional and compactional regime.*

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