Thermal Rock Physics Modelling of Shales

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Summary

Thermal oil production introduces elevated temperatures in the subsurface, leading to deformation of the porous matrix. In the near-borehole environment, an elevated temperature in shales can cause a pore pressure pulse that diffuses outward from the wellbore, creating a measureable velocity change visible from surface seismic data. Time-lapse seismic anomalies of this type have been observed on Devon Energy Canada's Jackfish II SAGD project and are compared with approximate linear thermoporoelastic models using a simple rock physics connection that is consistent with core measurements. The results show a qualitative match, but the models are underestimates of the actual field observations. Further core testing and refinement of the rock physics models is necessary to achieve a calibrated result.

Introduction

Thermal oil recovery is an important component of Canadian heavy oil production, currently accounting for approximately 42% of all oil sands production. The elevated subsurface temperatures associated with these methods create a complex environment in which material properties change with temperature as well as with the application of geomechanical forces that develop. Most of the scientific effort applied to understanding the geophysical signature of thermal production relates to reservoir properties (e.g. Batzle *et. al.,* 2004, Makarynska et. al. 2010). However, the properties of shales (both in the reservoir and overburden) require attention to enable operators to properly interpret changes in the subsurface during the life of the field, both to maximize reservoir sweep and to monitor for environmental concerns.

Recent time-lapse seismic surveys carried out by Devon Energy Canada at their Jackfish II Steam Assisted Gravity Drainage (SAGD) project have shown velocity anomalies in the overburden surrounding boreholes. These velocity reductions appear to be time-dependent. In this study these features have been analyzed on PP and PS data to localize their origin. Rock physics modelling in conjunction with thermoporoelastic modelling was then carried out to gauge the applicability of a temperature-induced increase in pore-pressure to explain the observations.

Theory and/or Method

Linear elastic theory is a simplification of a fully coupled finite element scheme that can account for both convective fluid flow and plastic / non-linear elastic behaviour that may arise under different circumstances (Azad and Chalaturnyk, 2011). However, linear theories (McTigue,1986; Booker and Savvidou, 1985) do have a role where they are used to rapidly gain an understanding of sensitivities. Wong and Sameih (2000) have used an integral form of Booker and Savvidou's point heat source response in a medium with incompressible fluids to characterize a homogeneous medium's susceptibility to fracturing in the near wellbore region. One shortcoming of this approach was the use of a constant heat flux from the source, which overestimates the energy entering the formation. We adapt these results to a constant temperature condition more applicable to steam injection and oil production wells. Like Wong and Sameih (2000) and others we find that the ratio of hydraulic diffusivity to thermal diffusivity is key to understanding whether pore pressures build up in the near wellbore region. Low-permeability shales tend to prevent the dissipation of fluid, and therefore it is in shales that we see the build up of pore pressures and volumetric expansion occurring.

The result of the linear thermoporoelastic models can be used in conjunction with a rock physics model (RPM) which translates stress and strain into P- and S-wave velocity changes. There is no consensus in the literature on the best method to calculate the response of seismic velocities (dynamic moduli) to stress; core studies and in-situ studies often show quite different results (Herwanger, J., and P. Koutsabeloulis, 2011; Holt *et. al.*, 2008). The addition of changes in temperature futher complicates the situation, and few studies have addressed this need, with the notable exceptions of Johnston (1987) and more recently Bauer *et. al.* (2014). The rock physics model chosen in this study represents the fractional change in velocities as directly proportional to volumetric strain, with the scaling constants taken from the laboratory results of Bauer *et. al.* (2014).

One of the interesting facets of the Bauer *et. al.* (2014) testing was the observation of shale compaction after a heating-cooling cycle, a plastic rather than a (reversible) elastic effect. This has been observed by others and several models have been proposed to understand the behaviour (Xu and Wang, 2011; Graham *et. al.*, 2001). This is important geophysically as compaction of a shale will result in a velocity increase, while expansion of a shale will lead to a velocity decrease. Sensitivities may be carried out using linear elastic models assuming a uniformly compacting shale (compacting shales often do not have a fixed linear proportionality between strain and temperature), in which we would see an exacerbation of the pore pressure effect in the short term, due to the reduction of accommodation space for the brine.

Example

An example of excess pore pressure around a borehole with a constant temperature of 225 ^{o}C at various time is shown in Figure 1. The calculations are performed for a 30m shale with a Young's Modulus of 0.88 GPa, a Poisson's ratio of 0.27, a thermal diffusivity of 3.6e-7 m^2/s, a hydraulic diffusivity 1.8e-7 m^2/s and a thermal expansion coefficient of 2.6e-5 /^{o}C. We see that a pressure pulse develops and diffuses into the surrounding medium on the timescale of a SAGD wellpair production.

The RPM chosen produces a velocity slowdown as shown in Figure 2, which is of a spatial scale visible from surface seismic (the dominant wavelength is about 30m). However, the modelled anomaly is between 1-2%, and the field data shows anomalies up to 5% for PP waves and in places 10% for PS waves, indicating that we have underestimated the either the pressures or the link between the strain and the velocity changes.

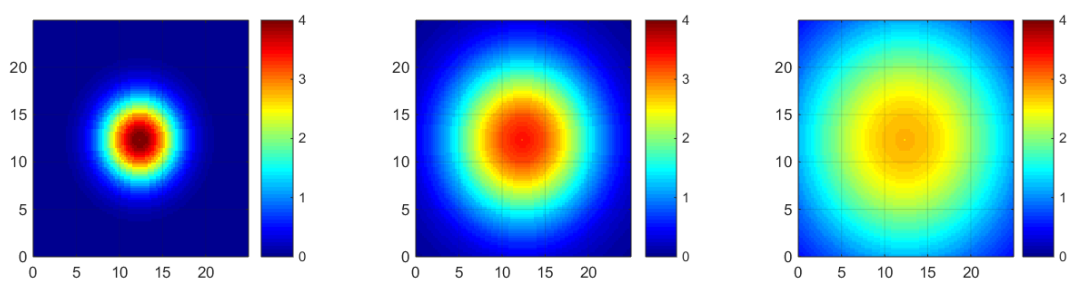

Figure 1: The pore pressure transient around a constant temperature steam injection well calculated for (from left to right) 6 months, 2 years and 5 years of continuous operation. Colour scale is in MPa and axis distances in metres.

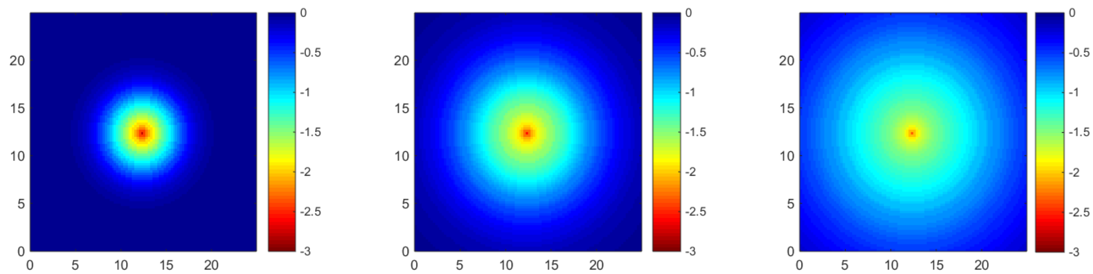

Figure 2: The change in P-velocity surrounding a steam injection well calculated for (from left to right) 6 months, 2 years and 5 years of continuous operation. Colour scale is in percent and axis distances are in metres.

There are many uncertainties in the modelling we have shown, from the choice and scaling of the RPM to the elastic model parameters governing the geomechanical response. For lower permeability shales the pore pressure and velocity decrease would be larger. Further modelling indicates that compacting shales may also generate a larger response. Other mechanisms (fluid loss into the formation from a borehole, possible fracturing generated by excess pore pressure) must also be considered, but we do see a seismically measureable velocity slowdown associated with a thermoporoelastic model of a heated wellbore in a homogeneous shale. Over a longer time frame, the pore pressure shown above will dissipate and this may be something that can be observed as more seismic is acquired.

Conclusions

Linear thermoporoelastic models can provide useful indications of the forces generated by wellbores in thermal recovery operations. We do see that in low permeability shales, a pore pressure buildup is possible that is large enough to be measured by time-lapse PP or PS surface seismic data. The current generic model underestimates the size of the anomalies seen at the Jackfish II Field, and would benefit from local geomechanical testing. The modelled seismic response to pressures and stresses depends heavily on the rock physics model employed, and again, further testing with local shales from overburden formations would surely improve the accuracy of the results.

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