Patchy cementation and implications for stress and fluid sensitivity in sandstones

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Abstract

In this study, we suggest an approach to predict stress sensitivity in cemented sandstones using non-uniform contact theory. We assume that the cemented rock will consist of a binary mixture of cemented and uncemented grain contacts. In this way we are able to predict the pressure sensitivity in cemented rocks. We apply a hybrid rock physics model where we combine Hertz-Mindlin contact theory for unconsolidated grain contacts, and Dvorkin-Nur contact cement model for cemented grain contatcs. A weight factor, W, is determined from bulk modulus – porosity relations, where the two contact theories represent lower and upper bounds, respectively. Using this approach, we are able to quantify expected changes in seismic properties, including acoustic impedance and Vp/Vs, as a function of both saturation and pressure, and hence we can create 4-D rock physics templates of these parameters.

Introduction

Our ability to predict the sensitivity to pressure from first principles is poor. The current state of the art requires that we calibrate the pressure dependence of velocity with core measurements (e.g. Ebenhart-Phillips, et al., 1989; MacBeth, 2002; Vernik et al., 2008). However, a major challenge is the fact that consolidated rocks often break up during coring, and hence the stress sensitivity is likely to be overpredicted in the laboratory relative to the in situ conditions (e.g., Holt et al., 2005). For unconsolidated sands, acquisition of core samples is not very feasible due to the friable nature of the sediments. One physical model that has been applied to predict pressure sensitivity in unconsolidated granular media is the Hertz-Mindlin contact theory (e.g., Duffaut and Landrø, 2007). However, it is often found to overpredict shear wave velocities, and Bachrach and Avseth (2008) provided a workflow to correct for this discrepancy using an effective medium approach with non-uniform contacts and heterogeneous stress propagation.

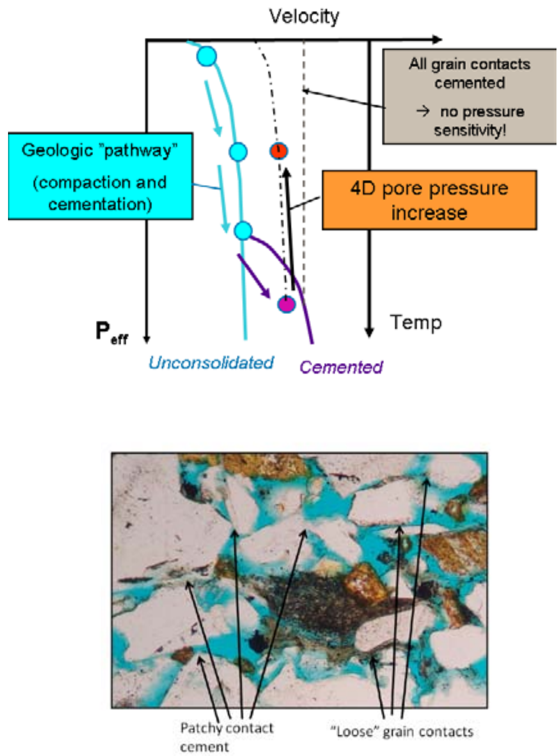

Figure 1: Conceptual illustration of pressure sensitivity in cemented sandstones (upper) and thin-section documenting "patchy" behaviour of quartz contact cement in Heimdal reservoir sandstones (lower). We assume stress sensitivity will be maintained through the "loose" (uncemented) grain contacts, whether these are due to structural mica grains, coating clay, or just loosly attached quartz-to-quartz contacts.

Figure 1 shows a conceptual illustration of what will happen during burial, compaction and diagenesis. The geological pathway is illustrated as a transition from mechanical compaction in the shallow subsurface to chemical compaction and cementation in the deeper subsurface. This transition is normally occurring at around 70^0C for quartz-rich sandstones (e.g. Bjørlykke and Egeberg, 1994, Avseth et al., 2009). During the mechanical compaction domain, cracks are closed due to increasing effective pressure, and velocity increases accordingly. As the rock starts to become cemented, cracks and grain contacts are closed by cement, and velocity increases drastically. However, the stress sensitivity is drastically reduced. This has implications to velocity changes during production, and our ability to discriminate fluid and pressure changes from 4-D (e.g., Landrø, 2001). If we for instance increase pore pressure during injection, the rock will not follow the geological pathway in a reverse manner, but a much lower velocity drop will occur because the cemented grain contacts will normally not open.

Method

In order to estimate a weight function of cemented versus uncemented grain contacts, we apply the approach of Marion and Nur (1991) referred to as the Bound Average Method (BAM). Figure 2 (left) shows the model assumption, where a weight function is defined between a lower unconsolidated bound (i.e., at zero effective pressure) and contact cemented upper bound. The weight function, W, is a measure of consolidation, defined as follows:

$$W = \frac{K_{sat} - K_{unc}}{K_{cem} - K_{unc}} \tag{1}$$

where K_{sat} is the saturated bulk modulus (modelled or observed), K_{unc} is the unconsolidated bulk modulus at same porosity, and K_{cem} is the cemented bulk modulus at this porosity value. The unconsolidated bulk modulus as a function of porosity is given by the combination of Hertz-Mindlin contact theory and the modified lower bound Hashin-Shtrikman, at zero or some reference effective pressure. The cemented bulk modulus is given by the Dvorkin-Nur contact cement model (Dvorkin and Nur, 1996). Due to reduced shear (slip), (Bachrach and Avseth, 2008) the same weight cannot be directly estimated from shear modulus. However, we assume that the reduced shear factor follows upper and lower bounds between 0 and 1, in a manner that reflects the normalized shear moduli versus porosity. Hence, we obtain a simple relationship of Ft as a function of porosity and W according to the following formulation:

$$F_t = \frac{(1-W)\cdot G_{unc}}{G_0} + \frac{W \cdot G_{cem}}{G_0} \tag{2}$$

Here, the unconsolidated shear modulus is given by the combination of Walton Smooth (Hertz-Mindlin with slip) model and the lower bound Hashin-Shtrikman, and the cemented shear modulus is given by the Dvorkin-Nur contact cement model. The resulting function is shown in Figure 2 (right), where we have assumed an upper (critical) porosity of 0.35. Note that the Ft is correlated with porosity, still it shows a large spread at a given porosity, depending on the consolidation expressed by the weight factor, W. Hence, we see the plausible result that the reduced shear factor, Ft, is strongly correlated with cement volume. In addition, for unconsolidated sands, increasing effective pressure will also cause increasing Ft.

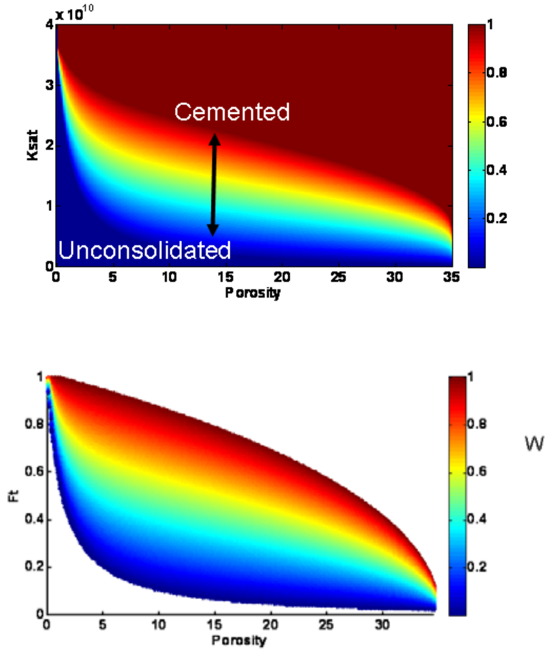

Figure 2: Weight function between unconsolidated and cemented sandstones in terms of saturated bulk modulus versus porosity (upper); and weight function between unconsolidated and cemented sandstones in terms of saturated reduced shear factor (Ft) versus porosity (lower).

Fluid sensitivity

Using the methodology outlined above, we can estimate the consolidation weight factor W and the reduced shear factor Ft from selected well log data. Figure 3 shows well log data from Heimdal gas and sands. The figure includes shale volume and brine saturation (left subplot), bulk modulus relative to cemented and unconsolidated values (middle subplot), and estimated weight function and Ft (right subplot). In the moderately consolidated reservoir sandstones, we estimate a weight increasing from around 0.6 at 2100m to above 0.8 at 2300m. Ft is ranging between 0.4 and 0.5. Figure 4 shows the rock physics template for the Heimdal sandstones (gas and oil saturated) with ca. 3% cement volume (see Avseth et al., 2009 for estimation of cement volume from rock physics models), where we first assume reduced shear factor Ft=1. Note the relatively poor match between the gas-filled sandstone data and the sandstone model the AI-Vp/Vs domain. However, if we adjust the slip factor Ft=0.4 (as derived in Figure 4), we obtain a close to perfect match between data and models (Figure 5, right).

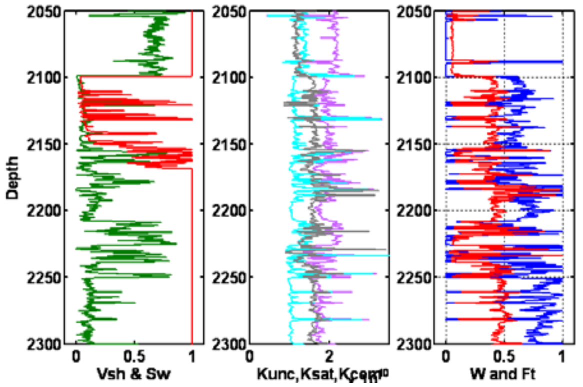

Figure 3: Left subplot: petrophysical logs (Vsh in green and gas saturation in red); Middle subplot: saturated rock incompressibility(cyan=unconsolidated, purple=cemented, grey=observed); Right subplot: estimation of W (blue) and Ft (red) for Heimdal sands (North Sea).

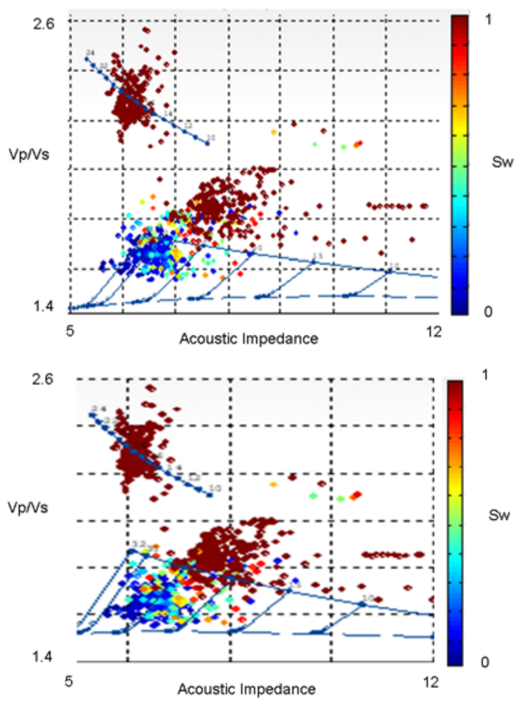

Figure 4: RPT analysis of facies and fluid trends in Lista shales and Heimdal sands (gas and brine saturated). The upper plot includes sandstone model where no slip is assumed. The lower plot shows updated sandstone model with slip factor estimated from the weight function, using the approach suggested in this study. The match between fluid trends and well log data is perfect when we use the Ft and W estimated in Figure 3.

Pressure sensitivity

The weight function derived above also allows us to estimate vertical pressure sensitivity in cemented sandstones. By combining the Walton smooth pressure sensitive model for unconsolidated sands with stiff contact cement model, we obtain a modified contact model for heterogeneous contacts that is pressure sensitive via the fraction of unconsolidated grain contacts. Figure 5 shows the resulting pressure verus P-wave velocity for the Heimdal sands shown in Figure 4. The target sandstone interval (Gassmann estimated to brine saturation) is superimposed. This hybrid model can be applied to predict the effect of pressure changes for example during 4-D monitoring analysis. As we see, the pressure sensitivity is much less than for the unconsolidated contact theory, but still we see significant velocity drop with decreasing effective pressure (ca. 250 m/s drop at zero effective pressure). Future effort should focus on quantifying stress anisotropy induced by the non-uniform contact cement modelled in this study (c.f., Sayers, 2006).

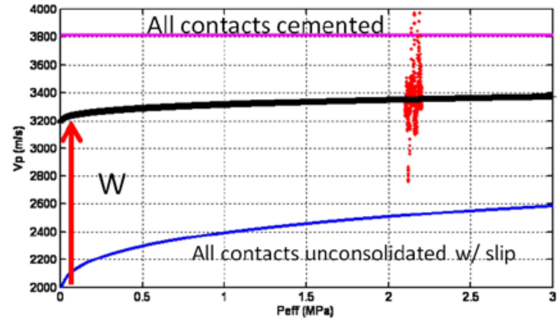

Figure 5: Predicted models for effective pressure versus Vp for the Heimdal sandstone case. Purple line is the contact cement model at the average porosity for the reservoir, and is not pressure sensitive. Blue line is the Walton smooth model, when all grain contacts are slipping. The black line is the hybdrid model resulting from the estimated weight function, W.

Conclusions

We have demonstrated a new approach to estimate fluid and pressure sensitivity in cemented sandstones. We estimate a weight function, where we assume grain contacts are either uncemented or cemented. We assume that this weight function is also applicable to reduced shear stiffness (i.e., fraction of non-slipping contacts, Ft) versus porosity, hence we can estimate slip factor from this weight. Consequently, this approach solves two problems: it estimates pressure sensitivity and slip factor in cemented sandstones.

Acknowledgments

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