

# Modeling Seismic Velocity in Ekofisk Chalk

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## Introduction

The Ekofisk formation in the Norwegian North sea has been under production for over 20 years. A project is under way to determine the feasibility of performing time lapse (4-D) seismic analysis to more accurately map the distribution of hydrocarbons. One part of this project was to model the seismic velocity of the chalk reservoir in terms of its porosity and fluid saturations.

## Discussion

In order to create a model for the velocity-porosity transformation in chalks, we analyzed the data for well K13. Figure 1 shows porosity and water saturations versus depth. We first transformed velocity ( $V_p$  and  $V_s$ ) to bulk and shear modulus using standard elastic equations. Next we transformed the log velocity to dry conditions using Gassmann's equations and the average solid and fluid properties given in Table 1. The velocity-porosity model we used connects the highest-porosity point with the zero-porosity point in

**Table 1: Elastic Moduli and Density of the Components used in Calculations**

Component	Bulk Mod.(GPa)	Shear Mod. (GPa)	Density (g/cm <sup>3</sup> )
Calcite	65	27.1	2.71
Quartz	36.6	45	2.65
Clay	20.9	6.85	2.58
Brine	2.627	0	0.997
Oil	0.997	0	0.650

the modulus-porosity plane. At the zero-porosity point the moduli will be those of the solid phase. For example, if at porosity  $\phi$ , the mineralogical composition of the solid phase includes quartz, clay and calcite, the resulting effective bulk ( $K_s$ ) and shear ( $G_s$ ) moduli of the solid phase will be found using the Voigt-Reuss-Hill average of the individual components. This gives us the zero-porosity elastic moduli values. Density and modulus for the component minerals and fluids are shown in Table 1.

The next step is to determine the highest-porosity elastic moduli values. There are at least two ways of doing this. The first one is to plot the dry-rock bulk and shear moduli (obtained from a typical well) versus porosity and pick these values. For example, for well K13, these values are about 4 GPa for both dry-rock bulk and shear moduli at porosity of 0.4. The second one is to use the contact cement theory (Dvorkin and Nur, 1996). The basic assumption behind this theory is that at high porosity chalk is made up by calcite grains enveloped by cement (calcite) rims. By using this theory one can accurately pick the high-porosity elastic moduli end members. Specifically, we recommend that the critical porosity value be selected at 0.42 for this data set. Then the end member elastic moduli values have to be picked at the critical porosity value minus 0.02. Next we describe the model that connects these end points in the moduli-porosity plane.

The modified Upper Hashin-Shtrikman model (UHS) connects two end members in the elastic modulus - porosity plane. This approach is similar to one used by Anderson, 1997. One end member ( $K_0$ ,  $G_0$ ,  $M_0$ ) is at the highest porosity point  $\phi_0$  and can be calculated from the contact cement theory. The other end member is at zero porosity and is the modulus of the solid phase ( $K_s$ ,  $G_s$ ,  $M_s$ ) calculated from Voigt-Reuss-Hill. In this text, K is for the bulk modulus, G is for the shear modulus, and M is for the compressional modulus:  $M = K + 4G / 3$ . For porosity  $\phi$  that is between zero and  $\phi_0$ , the dry-rock effective

bulk and shear moduli ( $K_{Eff}^{UHS}$  and  $G_{Eff}^{UHS}$ , respectively) are:

$$\begin{aligned}
K_{Eff}^{UHS} &= \left[ \frac{\phi / \phi_0}{K_0 + \frac{4}{3} G_s} + \frac{1 - \phi / \phi_0}{K_s + \frac{4}{3} G_s} \right] J^{-1} - \frac{4}{3} G_s; & G_{Eff}^{UHS} &= \left[ \frac{\phi / \phi_0}{G_0 + Z_s} + \frac{1 - \phi / \phi_0}{G_s + Z_s} \right] J^{-1} - Z_s, \\
Z_s &= \frac{G_s}{6} \frac{9K_s + 8G_s}{K_s + 2G_s}; & M_{Eff}^{UHS} &= K_{Eff}^{UHS} + \frac{4}{3} G_{Eff}^{UHS}.
\end{aligned} \tag{2}$$

The lower bounds for the dry-rock effective bulk and shear moduli ( $K_{Eff}^{LHS}$  and  $G_{Eff}^{LHS}$ , respectively) can be found from the modified Lower Hashin-Shtrikman model (LHS):

$$\begin{aligned}
K_{Eff}^{LHS} &= \left[ \frac{\phi / \phi_0}{K_0 + \frac{4}{3} G_0} + \frac{1 - \phi / \phi_0}{K_s + \frac{4}{3} G_0} \right] J^{-1} - \frac{4}{3} G_0; & G_{Eff}^{LHS} &= \left[ \frac{\phi / \phi_0}{G_0 + Z_0} + \frac{1 - \phi / \phi_0}{G_s + Z_0} \right] J^{-1} - Z_0, \\
Z_0 &= \frac{G_0}{6} \frac{9K_0 + 8G_0}{K_0 + 2G_0}; & M_{Eff}^{LHS} &= K_{Eff}^{LHS} + \frac{4}{3} G_{Eff}^{LHS}.
\end{aligned} \tag{3}$$

Notice that these theories use the dry-rock moduli. In order to calculate the bulk modulus of the saturated rock we use either Gassmann's relations or the P-wave only equations of Mavko, et al, 1995.

Comparisons of the model to the data are shown in Figures 2 though 5. The porosity range is from about 10% to 40%. There is more scatter in the bulk modulus results than in the shear modulus, probably as a result of the transformation from water and oil saturation to dry conditions. Also there is an upward offset of the prediction at higher porosities that may be due to errors in mineral volume determination. The model is now being applied to about 10 additional wells, and we are also testing it against laboratory core data to see if further refinements are needed.

## Conclusions

The modified upper Hashin-Shtrikman model convincingly describes the velocity-porosity behavior in Ekofisk well K13. Solid mineral moduli can be determined using the mineral volume and the Voigt-Reuss-Hill average. The high porosity end member can be estimated using the grain cement model of Dvorkin, et al. We believe this is the first application of the combined cementation theory and modified upper Hashin-Shtrikman model to chalk. This relationship will allow seismic velocity to be predicted in a wide range of reservoir and non-reservoir quality chalk from the Ekofisk formation. This in turn allows us to predict with confidence the changes in seismic properties that will occur with changes in reservoir porosity, pressure, and saturation. This is a key step in the feasibility evaluation of 4-D seismic in the Ekofisk formation.

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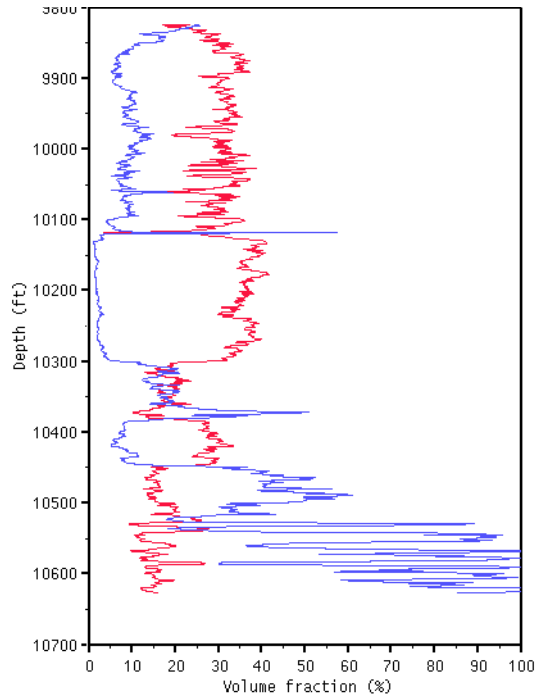


Figure 1: Porosity and water saturation in Ekofisk Well K13.

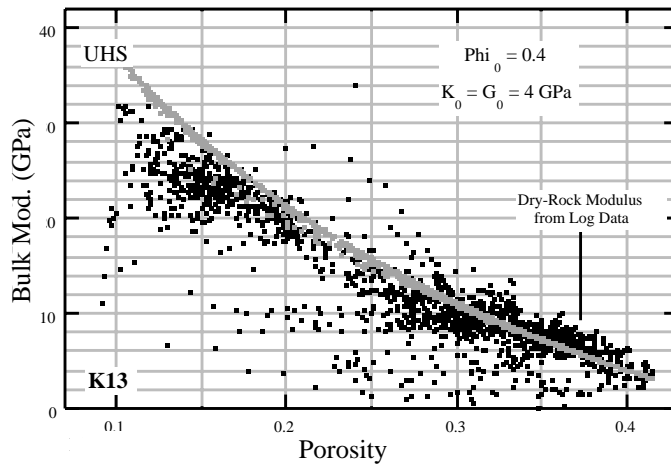


Figure 2: Bulk modulus from modified upper Hashin-Shtrikman model superimposed on data from Well K13.

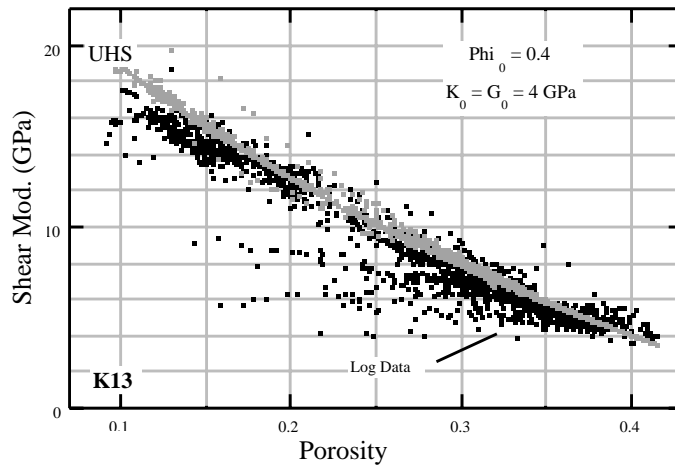


Figure 3: Shear modulus from modified upper Hashin-Shtrikman model superimposed on data from Well K13.

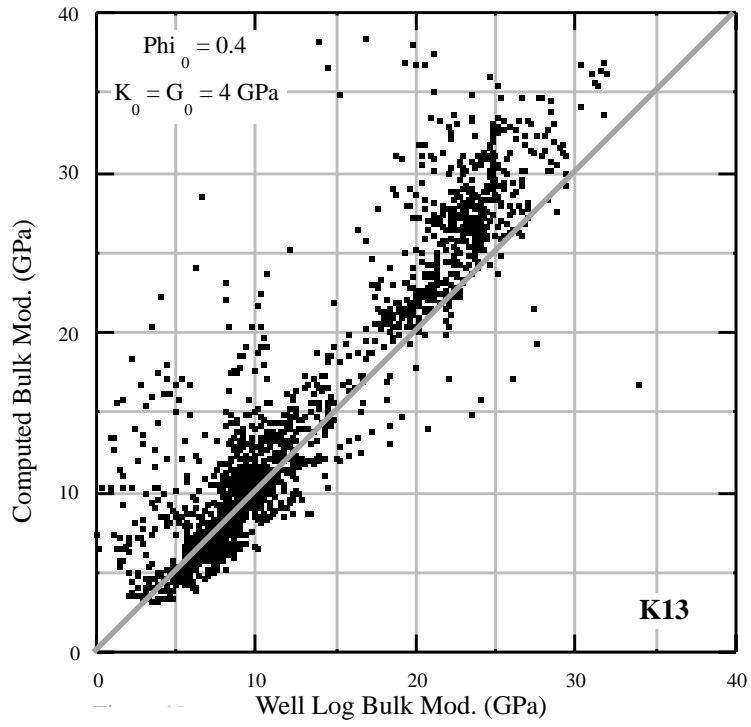


Figure 4: Bulk modulus from UHS model vs. data

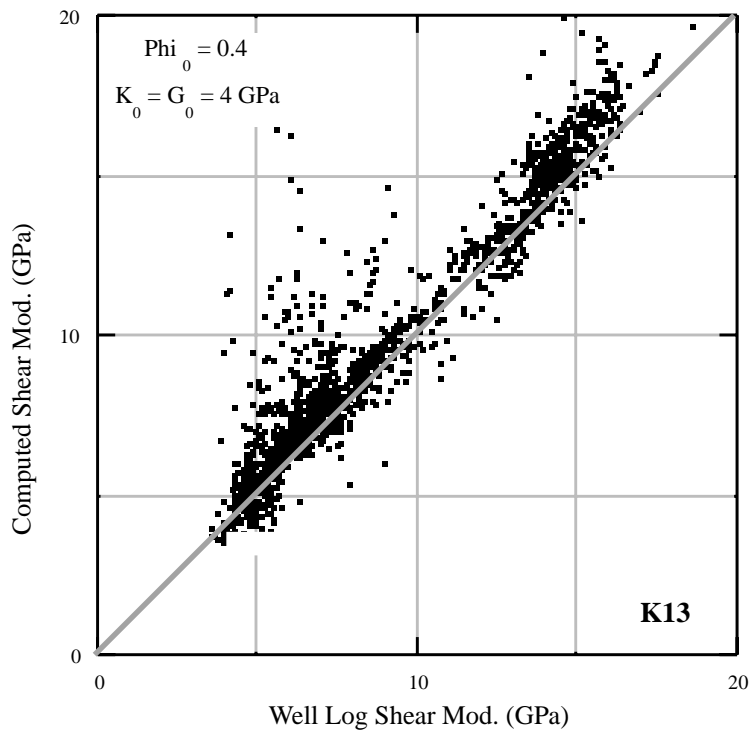


Figure 5: Shear modulus from UHS model vs. data