Dispersed Clay Identification and Modeling in Sandstones

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Summary

While laminated sand-shale sequences dominate deepwater sequences, shallow water depositional systems often produce dispersed clay shaley sandstones. The classical dispersed clay granular rock physics models for shaley sandstones called YMGDA (Mavko et al., 2020) are not strictly valid for well cemented sandstones. There is also often inconsistency surrounding diagnosis of dispersed clay, and we review best practice as well as recent cross-disciplinary results in particle packing and mixture models. For cemented media we propose an extension of the existing Vernik-Kachanov consolidated sandstone model (Vernik, 2010) by empirically modifying the pore-shape factors to account for the presence of clay. The results provide a model that extends the applicability of the Vernik-Kachanov sandstone model to provide valid outputs from clean sandstones to shales.

Theory

Sediments are a mixture of grains of varying size, with diameters varying from a few microns for clays to hundreds of microns for coarse silts. The relative position of these grains has a direct impact not only on the porosity and permeability of the rock, but also on the effective elastic properties of the medium. The Thomas-Stieber (1977) framework employing porosity-clay cross-plots is commonly used to diagnose rock fabric, with end-members including clean sandstone, dispersed clay sandstone and shales, the latter distinguished by the suspension of silt within a clay framework. More recent work with reconstituted sediments and simulated packing arrangements shows predictable relationships between permeability and porosity, scaled by the effective packing arrangement (El-Husseiny, 2021), which are useful relationships for characterizing the flow properties of a reservoir. However, there is an inherent ambiguity distinguishing laminated sand-shale combinations from partial mixing of sediments without additional core or image log verification.

Sandstones with dispersed clay exhibit velocity invariance or increase with clay content. This reflects the nature of the particle arrangement, with softer clays not occurring between grain contacts and hence not reducing the bulk modulus of the composite. The process of cementation complicates the picture, as quartz overgrowths are impeded by the presence of clay, depending upon its arrangement (Jizba, 1991, Woolridge et al., 2018).

The Yin-Marion-Dvorkin-Gutierrez-Avseth Elastic Model (YMGDA) for binary mixture velocity modeling (Mavko et al., 2020) is a well-known result developed for unconsolidated or poorly consolidated lithologies, and its applicability to fully consolidated sandstones is an open question. Lui et al. (2014) approach this problem using inclusion models, achieving reasonable results. Recent work (Sayers, 2023) has shown empirical moduli being independent of clay content, for a cemented sandstone with dispersed clay.

The Vernik-Kachanov sandstone model is a useful micromechanics-based approach to modeling consolidated sandstones. However, it is limited to $V_{Clay} < 15\%$ and is therefore not applicable to shaley sandstones which may contain V_{Clay} to 35%. There are two components to the model that must be altered by the presence of additional clay, namely the mineral modulus and the pore shape factors. The mineral modulus is the effective combination of all solid components of the rock, and we use the well known the Voigt-Reuss-Hill average (Mavko et al., 2020). The pore shape factors (denoted p and q) represent a scaling for bulk and shear moduli that account for the variable stiffness of different pore shapes with smaller values representing stiff (spherical) pores and larger values representing softer rocks with more cuspate-shaped pores. These typically scale with porosity (Vernik, 2016) but the significant presence of clays complicates the geometry. We approach this by empirically fitting the coefficients using well log data. What we find is that p-values and q-values must increase with V_{Clay} with an approximate quadratic dependency. This indicates an initial low dependence on V_{Clay}, rising quickly at high clay values.

Results

We calculate the rock physics models using log data for a group of well-consolidated arenites that span from late Cretaceous to Eocene from the Llanos basin, Colombia. Figure 1 below contains porosity-Vp plots for the measured log data (left) the YMGDA formulation (center) and the extended Vernik-Kachanov model (right). For the YMGDA model, we use the quartz-brine modified upper Hashin-Shtrikman bound to represent cemented sandstones and a brine-clay suspension modeled with an average of the upper and lower Hashin-Shtrikman bounds for the porous clay end-member, plotted in grey. We see an increase in velocity as clay is added to the to the shaley sandstone, transitioning to a silty shale at approximately V_{Clay}~30%, forming the classic inverted 'V' shape. The right-hand plot shows the Vernik-Kachanov sandstone (yellow line) and the Vernik conventional shale (grey lines, with V_{Clay} ranging from 30 to 90%). The shaley sandstone model also produces an increase in velocity with clay content and merges with the Vernik shale model. Both the YMGDA and the extended Vernik-Kachanov models show a reasonable match to the data, indicating that consolidated sandstone to shale lithologies can be modeled by both methods.

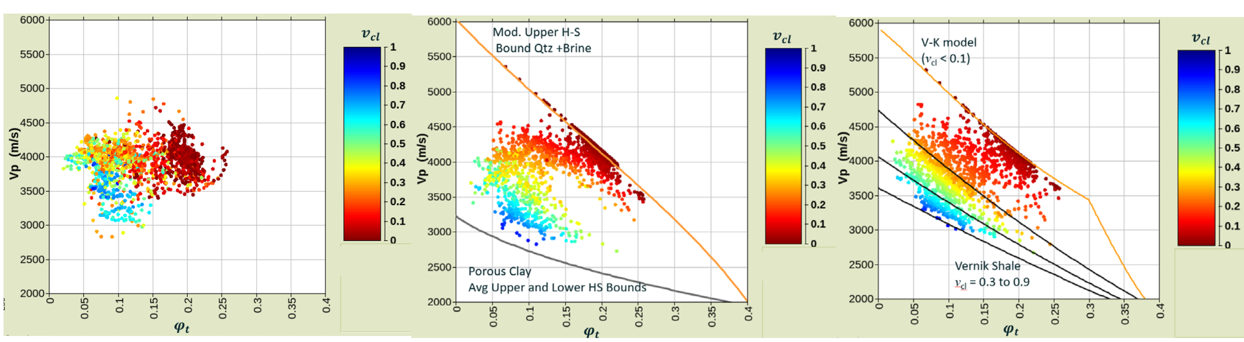

Figure 1: Porosity-Vp cross-plots for Llanos basin data (left), YMGDA models (center) and the extended Vernik-Kachanov Sandstone model (right). All plots are colored by V_{Clay}.

Additive Information

This work provides an update to the existing suite of rock physics models that account for dispersed clay in sandstones, with one focused on consolidated (cemented) sandstones. This provides a bridge between the Vernik shale and the Vernik-Kachanov sandstone models. It also includes a comparison with the YMGDA model, which is shown to provide reasonable results as well, despite employing a different underlying model.

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