The Effective Stress Coefficient in Pierre Shale

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Any process related to shale gas production requires knowledge of the rock properties under some particular combination of external stress and pore pressure. The combined effect of external stress and pore pressure on rock properties is typically expressed with an effective stress law. Because of the majority of rock properties (e.g. strain, permeability, wave velocities) depend on external stress and pore pressure it is possible to formulate a separate effective stress law for the rock property in question. For example, pore pressure prediction based on seismic data requires the formulation of an expression that relates changes in shear or compressional wave velocities to stress and pore pressure. The effective stress law for elastic properties is given by

$$\sigma_{eff} = \sigma - nP_p \quad (1)$$

where σ is the external stress and n is the effective stress coefficient. Alternatively, n can be determined in a dynamic fashion from

$$n = 1 - \frac{\left[\frac{\delta Q}{\delta P_p}\right]_{P_d}}{\left[\frac{\delta Q}{\delta P_d}\right]_{P_p}} \quad (2)$$

where Q is the property of interest and P_d is the net stress (Todd & Simmons 1972). The parameter n in (1) equals one for soft sediments and hence, the Terzaghi law applies (Terzaghi 1943). The effective stress coefficient n is less than one for cemented rocks such as sandstones (Todd & Simmons 1972, Siggins & Dewhurst 2003). There are only three experimental studies on the effective stress properties of for the acoustic (Hornby 1996, Sarker & Batzle 2008) and hydraulic properties (Kwon et al. 2001) in shale. These studies reported values of n that are less than one hence indicating that external stress has a greater effect than pore pressure for the acoustic properties of shales. The effective stress coefficient for permeability was found to be equal to one (Kwon et al. 2001). However, as far the authors are concerned this is the first study on the effective stress properties of Pierre shale. The Upper Cretaceous Pierre shale is a host formation for commercial oil deposits as well as shale gas. The experimental procedure involved subjecting cylindrical cores to a series of pore and confining pressures. The effective stress coefficients for elastic and acoustic properties were determined from (2). The experimental results indicate that the effective stress parameters for p-wave velocities and volumetric strain are not equal to one. The effective stress parameter for the volumetric strain ranges from 0.88-1.00 as shown in figure 1. At 0.73-0.93 the effective stress coefficients for p-wave velocities are slightly less than for the volumetric strain. The results for the Pierre shale exhibit similar dependence on net stress and loading path as experimental results on North Sea shale. Our observations show that the effective earth stress in shale cannot be obtained simply by subtracting pore pressure from the overburden pressure. These observations have important implications for understanding the state of stress in overburden rocks as well as for the purpose of predicting pore pressure in shale.

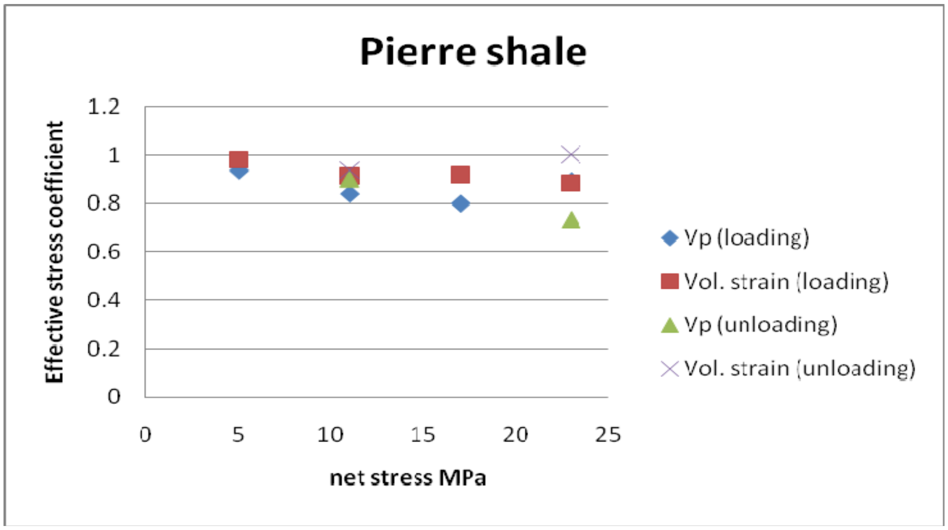

Figure 1. The effective stress coefficient for elastic and acoustic properties of Pierre shale.

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