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Seismic rock-physics model for carbonates at low effective stress levels

When considering the seismic response from the Dammam aquifer, the first required component is a simple model relating porosity and stress state to frame moduli assuming a carbonate matrix. We explored two such relationships, one based on the empirical regression presented by *Domenico* (1984) and a second using the critical porosity model of *Nur et al.* (1998) calibrated to the ultrasonic measurements of *Nur and Simmons* (1969). Once frame properties for a given porosity/pressure state were estimated, the effect of fluid changes were calculated using the low-frequency form of the Biot-Gassmann model, better known as Gassmann fluid substitution (*Mavko et al.*, 1998).

Our development of a model mapping porosity/pressure to frame properties is hampered by both the absence of site calibration data and the paucity of experimental measurements on carbonates at low effective stress values (≤ 5 MPa) available within the open literature. This experimental gap is problematic for shallow aquifers, which are well within this pressure regime. Additionally, the pressure/velocity relationships for most rocks often exhibit a high gradient at low stresses due to the presence of open micro-cracks. Investigation of a large set of carbonate pressure versus V_P measurements culled from publicly available datasets confirms highly variable frame properties due to variations in porosity, porosity type (vuggy vs. micro-porosity), and grain mineralogy. More details on the dependence of carbonate elastic properties on calcite, aragonite, and dolomite fractions is available in *Rafavich et al.* (1984). The

datasets we examined have at most only 2 data points below 5 MPa making low pressure calculations somewhat unreliable.

For the limestones within our primary reservoir unit, we assume a matrix composed of 90% calcite and 10% quartz, which is within the range of values presented in *Rafavich et al.* (1984). Effective grain moduli are calculated using an average of the Hashin/Shtrikman upper and lower bounds as suggested by *Mavko et al.* (1998). Grain density is calculated using the arithmetic average of the component phases weighted by volume fraction. Pure calcite is assumed to have a bulk modulus (K_g) of 70 GPa, a shear modulus (μ_g) of 29 GPa, and a density (ρ_g) of 2710 kg·m⁻³. Pure quartz is assumed to have the following properties: $K_g = 37.9$ GPa, $\mu_g = 44.3$ GPa, and $\rho_g = 2650$ kg·m⁻³.

The first model examined is based on the empirical regressions presented in *Domenico* (1984). A model of the form

$$V = \frac{1}{A + B\phi} \quad (1)$$

is fit to a large suite of measurements including those documented by *Pickett* (1963). The regression coefficients A and B are tabulated for limestones at a variety of pressures for both V_P and V_S . To estimate porosity/velocity relationships within our reservoir unit, we interpolate A and B to intermediate pressures using a low-order spline. Because the resulting empirical curves are based on water saturated measurements, dry frame properties are extracted using Gassmann's equation and effective grain moduli.

The second model considered is based on the critical porosity model presented in *Nur et al.* (1998) and *Mavko and Mukerji* (1998). In the critical porosity model, the elastic moduli of a porous rock are assumed to be a Voigt average between the suspension state, which exists at the critical porosity, and the pure mineral properties (*Mavko et al.*, 1998). While the critical porosity model provides a reasonable approach to building porosity/velocity relationships at high pressures where compliant cracks are closed, additional adaptation is required to include pressure dependence. Instead of using the pure mineral phase as the end-member of the Voigt average, we calibrate the model to a rock modulus measurement at a known porosity and a given pressure; this process provides a mechanism for incorporating pressure dependence into the critical porosity model. In our modeling experiments we assume a critical porosity of 0.6 as suggested by *Mavko et al.* (1998) and calibrate the models to the properties of Bedford limestone as documented in *Nur and Simmons* (1969).

Figure 1 shows the predictions of both models in terms of porosity/velocity at fixed pressure (A) and pressure/velocity at a fixed porosity (B). As can be seen in Figure 1B, the modified Domenico model exhibits higher V_P gradients near low effective stress levels. This implies a higher sensitivity to variations in pore pressure during the aquifer injection process when compared to the modified critical porosity model.

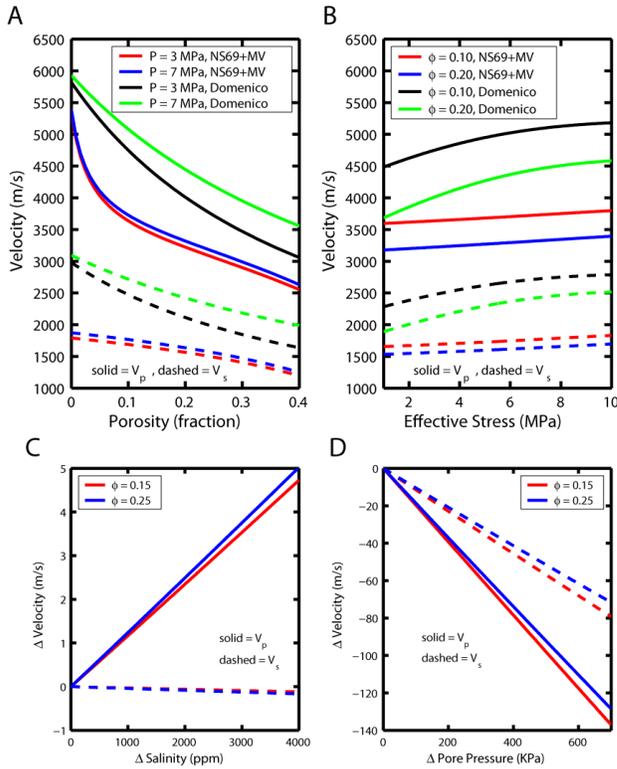


Figure 1: (A) and (B) compare the modified Domenico regression model and the critical porosity model calibrated to the Nur-Simmons dataset (NS69+MV). (A) Velocity as a function of porosity at two pressures (3 MPa, 7 MPa). (B) Velocity as a function of effective stress for two porosities (0.1, 0.2). (C) Sensitivity of seismic velocities to changes in pore fluid salinity and (D) pore pressure for two different porosities. Panel D uses the Domenico regression model. In all plots, solid lines denote V_p while dashed lines indicate V_s .

The second component of our rock-physics model involves estimating the effects of changes in pore water salinity on the bulk seismic properties within the aquifer formation. Such an estimate relies on an accurate model of the way in which water's density and bulk modulus depends on salinity, temperature, and pressure; for this purpose we adopt the empirical model detailed in *Batzle and Wang (1992)*. Because rock frame properties are calculated using the previously detailed empirical models, pore fluid effects are added using Gassmann fluid substitution.

Figure 1C and D shows the sensitivity of V_p to changes in pore water salinity and pore pressure, respectively. In both plots the relationship between pressure, porosity, and frame moduli are calculated using the modified Domenico regression. Changing the brine salinity exerts a relatively weak effect on seismic velocity; in our case we

observe a P-wave velocity increase on the order of $5 \text{ m}\cdot\text{s}^{-1}$ at 4000 ppm. When compared to a baseline velocity between 3000 and 5000 $\text{m}\cdot\text{s}^{-1}$, it seems highly unlikely that changes of this magnitude could be detected using either VSP or surface seismic geometries. In contrast, a change in pore pressure on the order of 700 kPa can induce a decrease in V_P of close to $150 \text{ m}\cdot\text{s}^{-1}$ with simultaneous reductions in V_S . This level of change might be detectable assuming highly repeatable experimental conditions, an adequate survey geometry, and a sufficient affected spatial domain.

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