AAPG Datapages/Search and Discovery Article #90174 CSPG©2014 CSPG/CSEG/CWLS GeoConvention 2012, (Vision) May 14-18, 2012, Calgary, AB, Canada

An Effective Medium Model for a Fractured Carbonate Reservoir Undergoing CO_2 Flood at Weyburn Field, Saskatchewan

Chris Blackwood*, Cenovus Energy, Calgary, Alberta
christopher.blackwood@cenovus.com

Summary

Carbonate reservoirs such as the Midale Member of the Weyburn field are often characterized by variable pore types and pore shapes and one or more oriented sets of natural fractures. These characteristics make forward seismic modelling and fluid substitution challenging, and confidence may be lacking in model results and relevance to recorded seismic data.

An effective medium model for fluid substitution is presented here that incorporates elastic properties of the host rock and fluids and the aspect ratio of pores. The method is extended to the case of horizontal transverse isotropy (HTI) by incorporating fluid-saturated fractures through linear slip theory.

Introduction

The Weyburn Field in southern Saskatchewan produces oil from the Mississippian Midale member of the Charles Formation. The reservoir is divided into a limestone-dominated Vuggy unit and a younger dolostone Marly unit. Since 2000, CO_2 has been injected for enhanced oil recovery (Li, 2003).

In carbonate rocks, porosity types are highly variable due to depositional and diagenetic processes. While magnitude of porosity impacts elastic properties of carbonate rocks, the pore type is perhaps equally important (Eberli et al., 2003). Elongate pores are “weak” and rocks dominated by such pores have lower elastic properties than equivalent porosity rocks comprised of “strong” pores with more spheroid shape (Sayers, 2008). To remove uncertainty when modelling carbonates, it is important to incorporate pore shape information in calculations. As a compounding influence, many reservoirs are naturally fractured (Aguilera, 1998), and these fractures further reduce the elastic properties of their host rocks (Schoenberg and Sayers, 1995). Failure to account for fractures and the fluids filling the fractures will also limit reliability of effective media models. In the case of Weyburn, pore shape variability and the presence of natural fractures necessitated the development of a detailed effective medium model.

Method and Results

Effective medium modelling may be achieved through many methods, perhaps most commonly through use of the Gassmann-Biot theory (numerous methods summarized in Mavko et al., 1998). Seismic characteristics of fluids may be obtained through use of relations developed in Batzle and Wang (1992). Gassmann theory has general applicability, but assumes that the shear modulus of the saturated rock is unaltered from the shear modulus of the dry rock. While this assumption may not have a large impact on results, there is evidence to show that it is incorrect (Verwer et al., 2010). One complexity in Gassmann modelling is that it is often difficult to resolve the dry rock parameters for the log or seismic scale. When applied to Weyburn logs and seismic data, the Gassmann models did not adequately match recorded observations.

An alternate modelling method for isotropic rock is developed here based on the work of Sayers (2008) and Sayers and den Boer (2011). The method makes use of effective field theory, where elastic stiffnesses of rock are calculated by placing a pore in an effective stress field. The rock is treated as a two-phase material, with material one the mineral matrix and material two the pore-filling fluid. The pores are considered uniformly dispersed and randomly orientated in three dimensions. The key inputs are the elastic moduli of the mineral and fluid, the porosity, and the aspect ratio of the pores. The elastic properties of the effective medium are output. This fluid substitution method avoids the difficulty in establishing dry rock parameters, and does not assume that shear modulus is unaltered by fluids.

Figure 1 shows the bulk modulus and shear modulus measured from logs through the Weyburn reservoir for a well with minimal fracturing and a mixed oil-water saturation. Predicted elastic moduli obtained from the effective medium model are overlain and compared with the bulk modulus from Gassmann. The effective medium and Gassmann models use the same values for porosity and mineral and fluid properties. Gassmann Kdry parameters were measured from a single core sample of appropriate porosity and pore aspect ratio, and extrapolated across the entire porosity range. The effective medium method required no such laboratory derived data. The effective medium model is a better match to the observed data, particularly at low porosities.

To account for near-vertical fractures, the modelling scheme is further extended to the HTI case through the work of Schoenberg and Sayers (1995) and Bakulin et al. (2000). The output elastic parameters from the effective field model are used as the input host material, and one or more fracture sets are added such that the total elastic compliance of the fractured effective material is equal to the sum of the compliance of the background unfractured rock and the excess compliance due to the fractures. Fracture weaknesses are described in terms of crack density and crack aspect ratio, plus the elastic parameters of the fracture-filling fluids. It is possible to saturate the matrix pores and fractures with different fluids. An anisotropic elastic stiffness matrix is output for the fractured effective medium, and Thomsen parameters (1986) are calculated and employed in the Ruger equation (1996) to understand amplitude variation with offset (AVO) and azimuth (AVAZ) behaviour.

Figure 2 presents P-wave reflectivity (Rp) vs. angle of incidence for several scenarios. Effective medium 1 is the output predicted in figure 1 taken at a single porosity. Effective medium 2 uses effective medium 1 as input, and adds the effect of fractures, using CO_2 as the fluid filling the fractures. The curves in figure 2 are (1) effective medium 1 (unfractured) using the isotropic Fatti equation (Fatti et al, 1994), (2) effective medium 2 (fractured) using the isotropic Fatti equation, (3) effective medium 2 (fractured) parallel to fracture strike using the Ruger equation, and (4) effective medium 2 (fractured) perpendicular to fracture strike using the Ruger equation. Note that the Rp value at 0 degrees (AVO intercept) as predicted by the Fatti equation is lower for the fractured medium than for the unfractured medium. This agrees with the assertion of Sayers (2008), that fractures in carbonates may be detected at a narrow range of incidence angles. The lowered AVO intercept is shared by both Ruger curves. The Ruger curve for acquisition parallel to the fracture strike is very similar to the Fatti curve for effective medium 2, while the Ruger curve for acquisition across the fractures shows a distinct AVO gradient.

Conclusions

An isotropic effective medium model using effective field theory is presented that provides a strong match with Weyburn field observations for a well with minimal reservoir fractures. The predictions from this model are then used as inputs to an HTI extension that incorporates fluid-saturated fractures through linear slip theory. Results from the HTI extension are encouraging as models have been produced that match shear wave anisotropy recorded at a known fractured well. The HTI extension will be further validated by future work in reservoir simulation and fracture estimation from seismic data.

Acknowledgements

I am grateful to Dave Cooper (Cenovus Energy) for countless discussions critical to the development of this method and to Cenovus Energy for permission to publish the work.

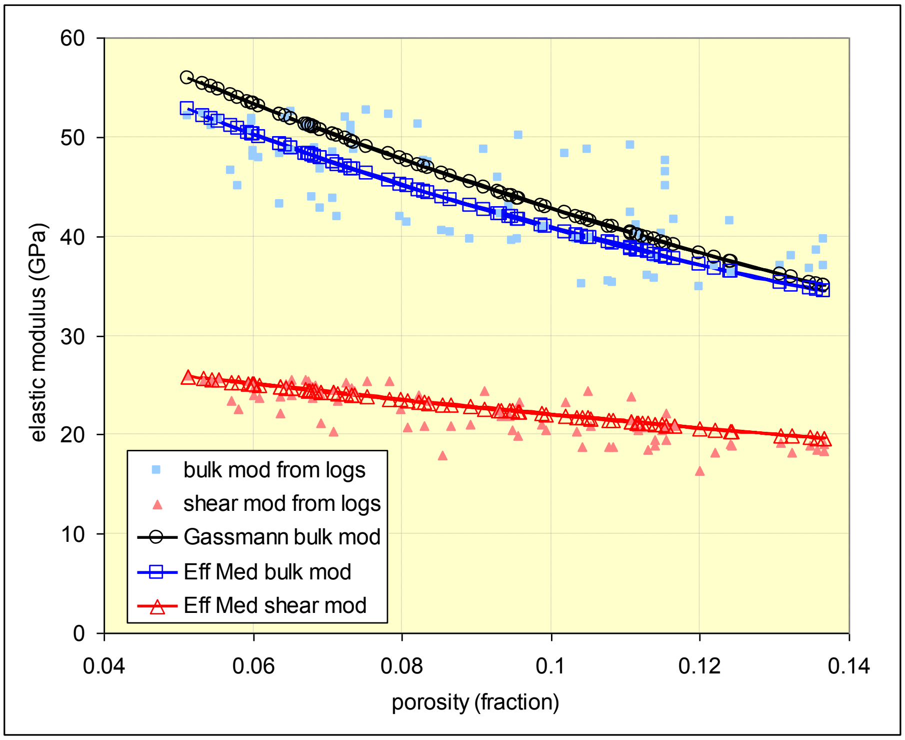

Figure 1: Comparison of bulk and shear modulus as measured in logs and predicted through effective media models for the Weyburn reservoir.

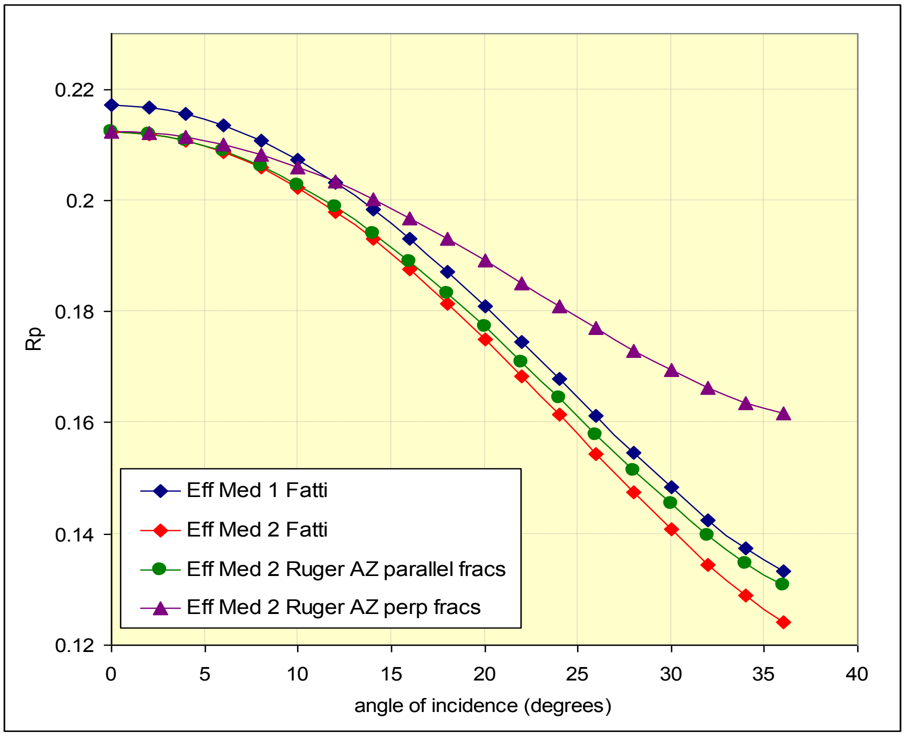

Figure 2: Comparison of predicted AVO curves (Rp) for effective medium 1 and effective medium 2 for the cases of isotropy and HTI, plus variations in acquisition azimuth with respect to fracture orientation.

References

Aguilera, R., 1998, Geologic aspects of naturally fractured reservoirs: The Leading Edge, **17**, 1667-1670.

Bakulin, A., Grechka, V., and Tsvankin, I., 2000, Estimation of fracture parameters from reflection seismic data – Part 1: HTI model due to a single fracture set: Geophysics **65**, 1788-1802.

Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: Geophysics **57**, 1396-1408.

Eberli, G.P., Baechle, G.T., Anselmetti, F.S., and Incze, M.L., 2003, Factors controlling elastic properties in carbonate rocks: The Leading Edge, **22**, 654-660.

Fatti, J.L., Smith, G.C., Vail, P.J., Strauss, P.J., and Levitt, P.R., 1994, Detection of gas in sandstone reservoirs using AVO analysis: A 3-D seismic case history using the Geostack technique: Geophysics, **59**, 1362-1376.

Li, G., 2003, 4D Seismic monitoring of CO_2 flood in a thin fractured carbonate reservoir: The Leading Edge, **22**, 690-695.

Mavko, G., Mukerji, T. and Dvorkin, J., 1998, *The Rock Physics Handbook,* Cambridge University Press.

Ruger, A., 1996, Variation of P-wave reflectivity with offset and azimuth in anisotropic media: SEG Expanded Abstracts, 1810-1813.

Sayers, C., 2008, The elastic properties of carbonates: The Leading Edge, **27**, 1020-1024.

Sayers, C.M., and den Boer, L., D., 2011, Rock physics-based relations for density and S-velocity versus P-velocity in deepwater subsalt Gulf of Mexico shales: The Leading Edge, **30**, 1376-1381.

Schoenberg, M., and Sayers, C., 1995, Seismic anisotropy of fractured rock: Geophysics **60**, 204-211.

Thomsen, L., 1986, Weak elastic anisotropy: Geophysics **51**, 1954-1966.

Verwer, K., Eberli, G., Baechle, G., and Weger, R., 2010, Effect of carbonate pore structure on dynamic shear moduli: Geophysics **75**, E1-E8.