The Calibration of Rock Physics Models in Carbonate Reservoirs

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Rock physics models provide a link between the reservoir properties, such as lithology, porosity and saturation, and the elastic properties that control seismic reflection amplitudes. The complex nature of the pore microstructure observed in carbonate reservoirs is generally considered to be a significant challenge to rock physics. The ultimate objective is the exploitation of the rock physics link to use seismic reflection amplitudes to accurately predict and spatially map lateral changes in the pore space structure that will inform reservoir production.

The development and implementation of rock physics models to carbonate reservoirs is an area of growing maturity and understanding. Marion and Jizba (1997) describe the relationships between velocity (compressional and shear) and porosity measured in core samples using a set of empirical linear relationships between the inverse bulk and shear moduli and porosity. Kitteridge (2015) investigated the application of several different rock physics models, including the modified Voigt and modified Hashin-Shtrikman bound-filling models. These two approaches use theoretical bounds between the zero-porosity, mineral point, and a conceptual high porosity limit, defined as the critical porosity.

More theoretical approaches have generally made use of either the self-consistent approximation (SCA) (O'Connell & Budiansky, 1974), or a modified version of the differential effective medium (DEM) model (Zimmerman, 1991, Kuster and Toksöz, 1974). These two models calculate the elastic properties of a solid medium containing inclusions of defined shape. In similar approaches, Kumar and Han (2005) and Baechle et al. (2008) used a modified version of the DEM model, with two sets of ellipsoidal inclusions with representative aspect ratios, to estimate the relative volume fractions of different pore space components within core samples. Following this work, Xu and Payne (2009) presented a carbonate specific adaptation of the model by Xu and White (1995), which is a further extension of the DEM model.

Vernik and Kachanov (2012) point out an important misconception in expressing the effective elastic properties as a function of using crack aspect ratio. As an alternative to the DEM approach, Mur and Vernik (2020) apply the rock physics model by Vernik and Kachanov (2010) to describe the elastic properties of a database of published measurements on carbonate core samples.

In this paper, we do attempt to identify a new or recommended rock physics model. Instead, we focus on a detail assumed in all approaches described above, which is the elastic moduli of the mineral matrix. We discuss the range of values used in publications and identify an accurate reference for future investigations. We also review the apparent offset in mineral moduli that is apparent in many wireline datasets.

A review of the calcite mineral moduli used in publications from the field of exploration geophysics indicates that most authors rely on the table compiled by Mavko et al. (2009). The table contains 5 sets of published values from 1945-1968, expressed in terms of the bulk and shear moduli (K and G). A pair of box and whisker plots are shown in Figure 1 to illustrate the range of values. Based on the values of compiled by Mavko et al. (2009) it is possible to erroneously interpret that the mineral moduli of calcite is either poorly constrained, or highly variable. An alternative list of published values has been compiled by Duffy (???) and is shown in full in Table 1. The alternative list was compiled from a list of more modern publications and excludes some of the values from sources in the original list that may be questioned for robustness based on modern techniques.

The elastic properties listed in Table 1 include the tensor components to fully describe the intrinsic triclinic symmetry of calcite minerals. Calcite minerals within rock samples are assumed to be randomly orientated, which minimizes the velocity anisotropy associated with the mineral symmetry. The effective elastic moduli of the rock forming calcite mineral can be represented at the sonic and wavelength scale by the Voigt-Reuss-Hill averages listed in Table 1. The range between the Voigt and Reuss averages can be considered the uncertainty due to mineral intrinsic symmetry.

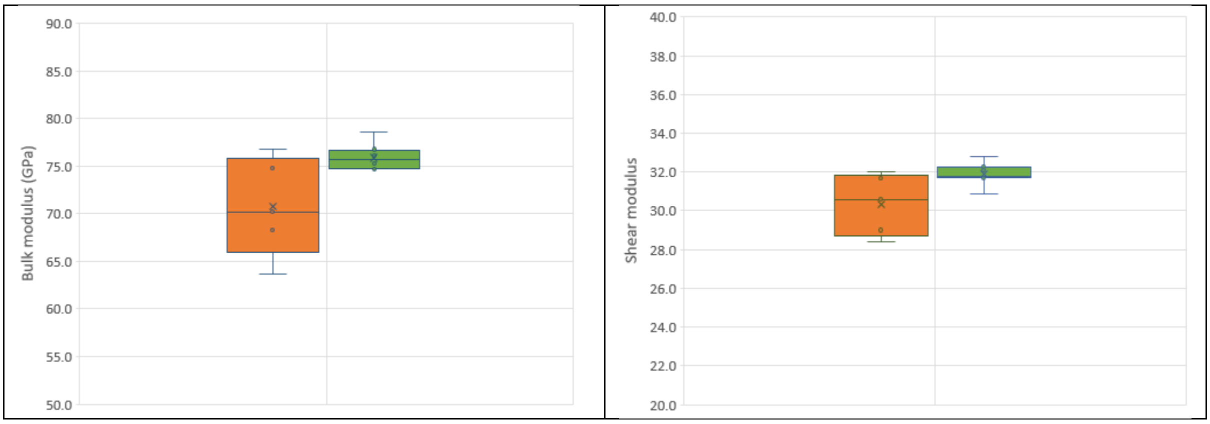

Figure 1: Box and whisker plots to show the range of values of (a) the bulk modulus and (b) the shear modulus of calcite, reported by Mavko et al. (2009) in orange and Duffy (????) in green.

It is apparent from the revised compilation that the mineral moduli of calcite are relatively well constrained parameters in our rock physics models. The compilation by Duffy (xxxx) should therefore be considered a more accurate reference for future studies. We now discuss the practical application of the mineral moduli and rock physics models to a wireline dataset from offshore Canada. The dataset comes from the Panuke M-79 well, located on the Scotian Shelf, approximately 290 km southeast of Halifax, Canada. The vertical well was drilled in 2000 to appraise the Panuke Deep gas field and encountered approximately 1400m of Jurassic limestones. No hydrocarbon shows were reported during drilling and MDT tests indicate that the main limestone intervals are water wet. The dataset includes a modern logging suite, including compressional and shear sonic logs. A petrophysical interpretation has been performed on the wireline log data and calibrated to core measurements of porosity, Figure 2.

	Density	Single Crystal Elastic Moduli						Bulk Modulus			Shear Modulus		
								Reuss	Voigt	VRH Avg	Reuss	Voigt	VRH Avg
	g/cm3	GPa						GPa			GPa		
Source	**rho**	**11**	**33**	**44**	**12**	**13**	**14**	**K_R**	**K_V**	**K_{VRH}**	**G_R**	**G_V**	**G_{VRH}**
Peselnick and Robie		144.5	83.1	32.7	57.1	53.4	-20.5	71.66	77.77	**74.7**	25.78	35.68	**30.7**
Dandekar & Ruoff		148.1	85.6	32.7	55.8	54.6	-20.6	73.33	79.09	**76.2**	26.78	36.76	**31.8**
Dandekar & Ruoff	2.712	146.3	85.3	34.0	59.7	50.8	-20.8	71.57	77.83	**74.7**	26.83	36.70	**31.8**
Kaga		145.0	85.6	32.9	55.0	52.8	-20.3	72.15	77.42	**74.8**	26.87	36.49	**31.7**
Humbert & Plique	2.712	148.1	87.2	33.9	57.4	54.5	-20.6	73.99	79.58	**76.8**	27.46	37.10	**32.3**
Vo Thanh & Lacam		145.7	85.3	33.4	55.9	53.5	-20.5	72.52	78.06	**75.3**	26.90	36.59	**31.7**
Chen et al		149.4	85.2	34.1	57.9	53.5	-20.0	72.92	79.31	**76.1**	28.16	37.40	**32.8**
Lin	2.719	149.9	87.0	32.2	59.5	57.3	-17.9	75.56	81.67	**78.6**	28.02	36.10	**32.1**
Average	**2.71**									**75.9**			**31.9**

Table 1: A compilation of elastic mineral moduli of calcite, compiled by Duffy (xxxx). VRH refers to the Voigt-Reuss-Hill average.

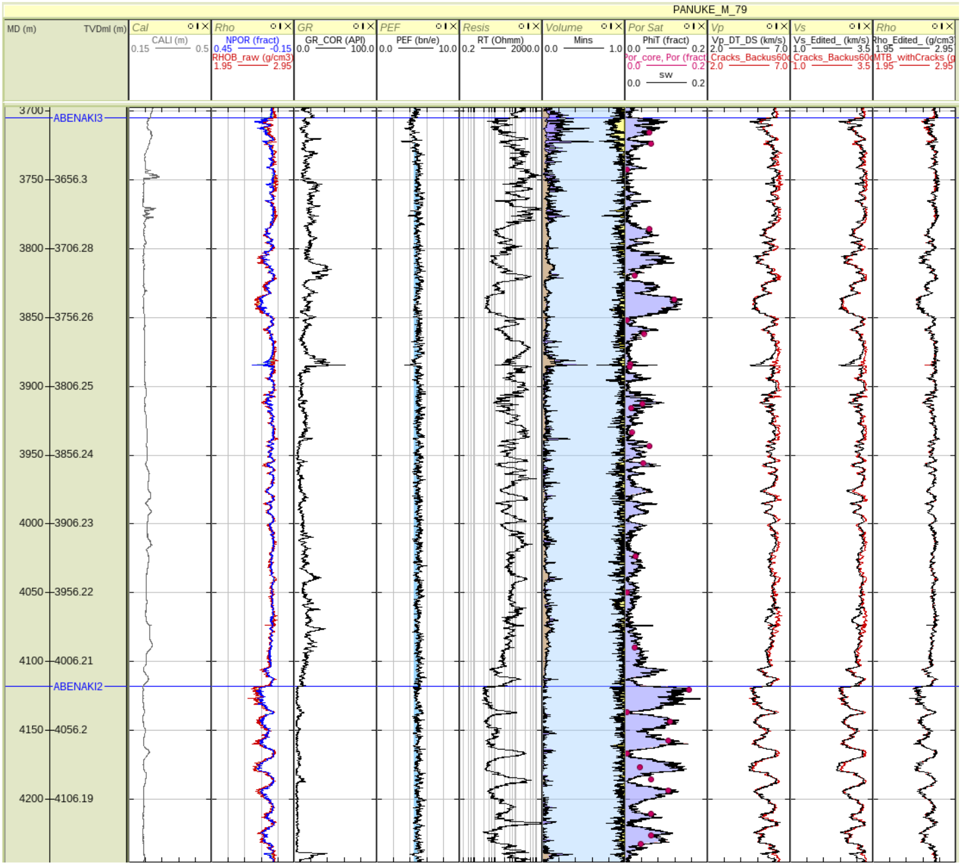

Figure 2: Wireline data from the Panuke M-79 well. The total porosity log (track 7) has been calculated from bulk density and is shown compared to core measurements (red dots). The compressional and shear sonic logs are shown in tracks 8 and 9. Also shown in these two tracks are the velocities predicted from the rock physics model (see text for details).

The wireline data are shown in terms of cross-plots of velocity and elastic moduli as a function of porosity in Figure 3. The templates show the expected range of elastic properties given the known calcite mineral moduli and fluid properties, using the Hashin-Shtrikman bounds and rock physics model by Xu and Payne (2009). A clear trend is observed in the elastic properties as a function of porosity. However, the data do not conform to the model expectations at the zero-porosity intercept, or mineral point. From experience of wireline datasets in carbonate reservoirs from around the world, this phenomenon is not unique to this particular dataset.

We put forward the hypothesis that the apparent offset in mineral properties is caused by the presence of micro-cracks in the borehole wall. The role of compliant micro-cracks in reducing the measured velocity in core samples has long been understood, especially in lower porosity rocks (e.g. Vernik et al., 1994). Measurements of velocity as a function of effective stress can be used to quantify the effect of micro-cracks further but are not always available for reservoir studies. Whether the micro-cracks are present in the formation prior to drilling or are a result of damage during drilling is an interesting question. The tendency for low porosity intervals to be drilled over-balanced will potentially result in micro-cracks forming in the borehole wall when the mud-weight exceeds the tensile failure pressure. These induced cracks will preferentially be aligned perpendicular to the direction of minimum horizontal stress. The case study Panuke M-79 well used in this paper encountered the reservoir interval without significant over-pressure and the well was drilled with a mud-weight only slightly higher than the reservoir pressure. Therefore, in this dataset, the inferred micro-cracks are believed to be present in the host formation. Image log data were acquired in the Panuke M-79 well, however, the quality of the images is not sufficient to make any interpretations with confidence.

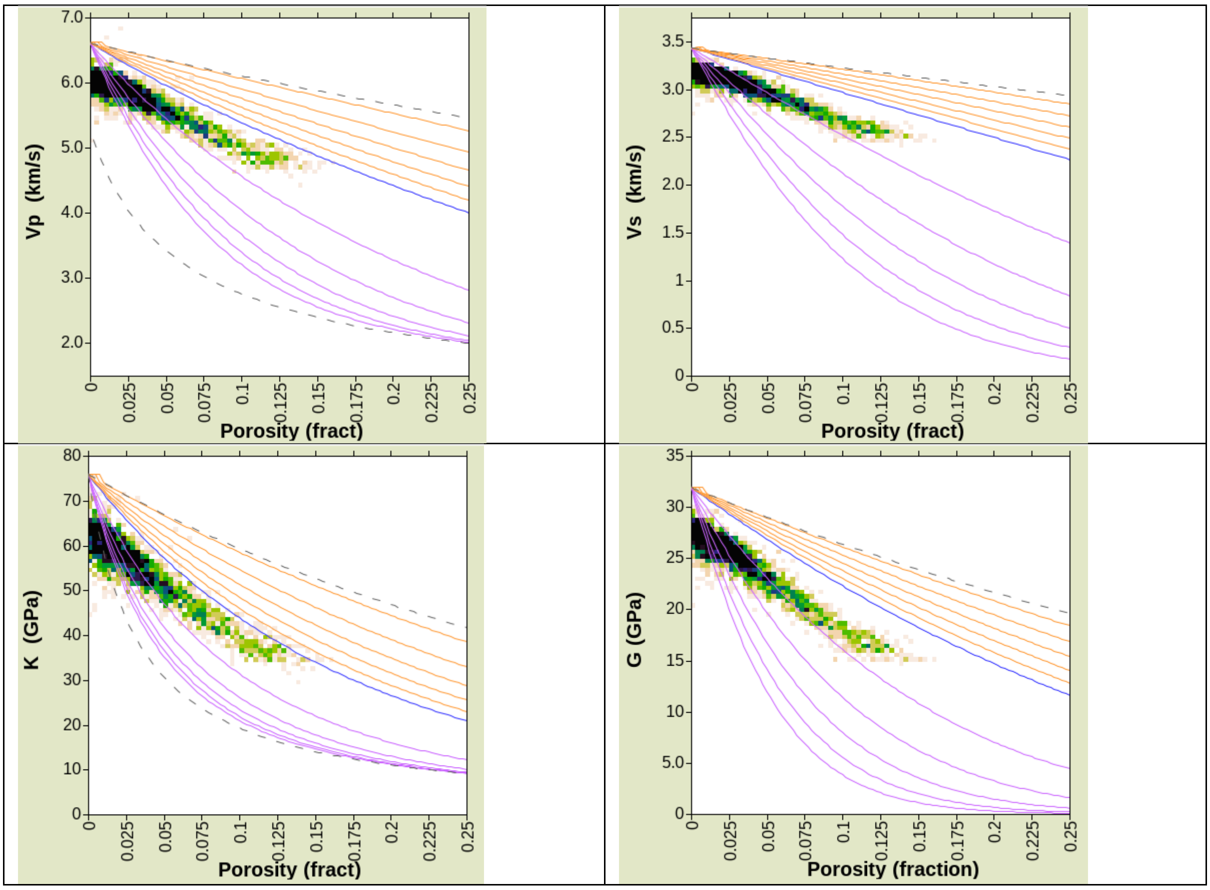

Figure 3: Cross-plots of Vp-porosity, Vs-porosity, K-porosity and G-porosity for data from the Abenaki carbonate intervals in the Panuke M-79 well. The plots are coloured by data density, with the darker colours indicating a greater number of datapoints (add colourbar!). Overlain on the data are the Hashin-Shtrikman bounds for calcite and water (grey dashed lines) and the rock physics model templates from Xu and Payne (2009). The blue curve is for a model containing only reference inter-particle pores; the purple/orange curves represent models with increasing proportions of micro-cracks and moldic pores. The A volume of calcite > 0.8 has been applied to remove data from less clean limestone intervals.

The formulation of the Vernik-Kachanov model provides a convenient approach to model and understand the effect of micro-cracks. The formulae are expressed in terms of a summation of compliances due to the matrix, pores and micro-cracks, Equation 1.

$$S_{ijkl} = S_{ijkl}^{matrix} + \Delta S_{ijkl}^{pores} + \Delta S_{ijkl}^{cracks}$$

In this case, we assume that the cracks are randomly orientated. We simplify the micro-crack term to a single crack density (η), applicable at the in-situ reservoir stress, Equation 2.

$$K_{dry} = K_m \left[1 + \frac{p\emptyset}{1-\emptyset} + A(\upsilon_m)\frac{\eta}{1-\phi}\right]^{-1}$$

$$G_{dry} = G_m \left[1 + \frac{q\emptyset}{1-\emptyset} + B(\upsilon_m)\frac{\eta}{1-\phi}\right]^{-1}$$

Where micro-structure of the pores is described by the shape factors, p and q. The shape factors are expected to be different for bulk and shear moduli in carbonate rocks, i.e. p≠q. The remaining parameters can be calculated from knowledge of the calcite mineral moduli (Vernik, 2016).

The cross-plots of the Panuke M-79 wireline data are shown overlain by templates using the Vernik-Kachanov model in Figure 4. The upper images show templates calculated with no crack density term. The blue curves show the expected elastic properties for a range of shape factors. As observed in Figure 2, the data do not conform with the mineral moduli at the zero-porosity intercept. The red curves show the same range of models with the addition of the micro-crack term, assuming a crack density of 0.05. The small volume of micro-cracks results in an apparent offset in the elastic properties from the mineral point at very low porosities, consistent with observations from the data.

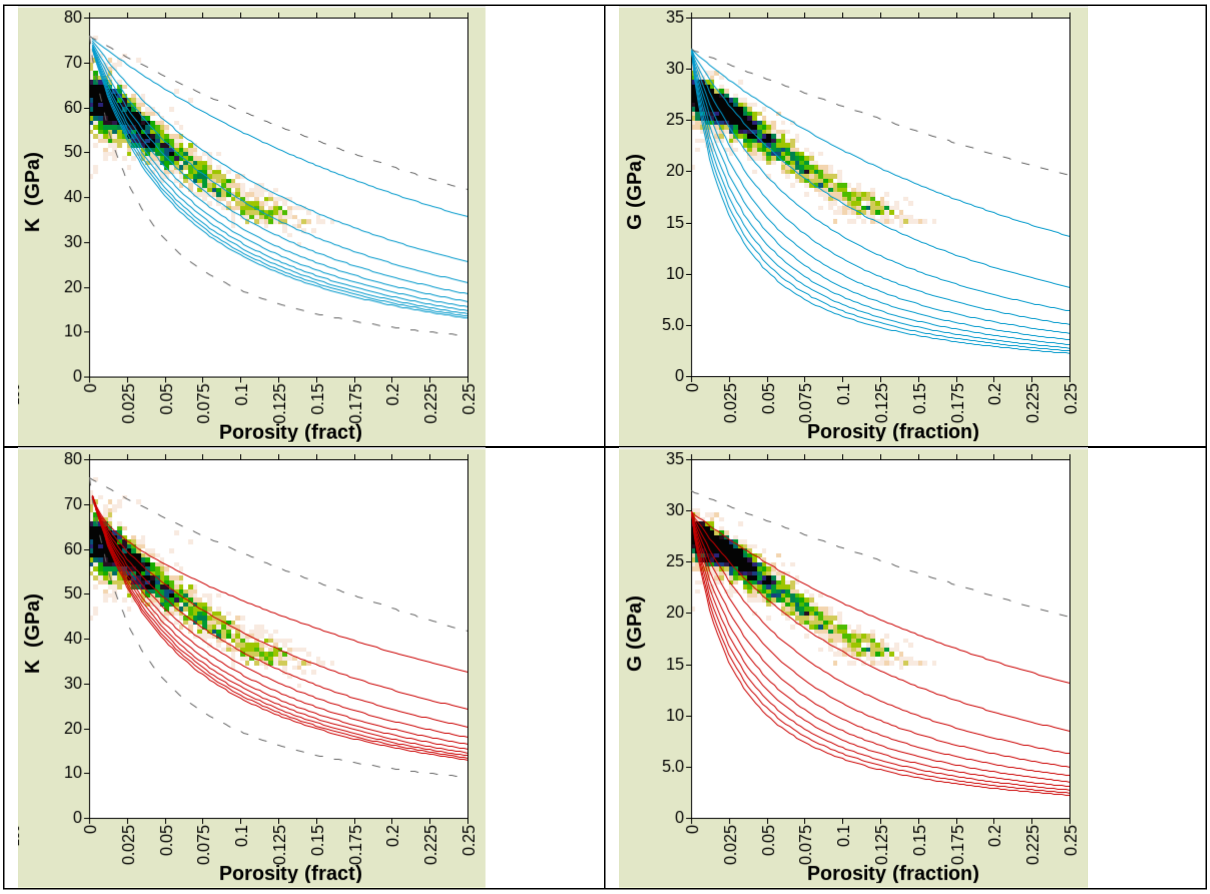

Figure 4: Cross-plots of K-porosity and G-porosity for data from the clean Abenaki carbonate intervals in the Panuke M-79 well, coloured by data density. The upper images are overlain by templates from the Vernik-Kachanov rock physics model assuming pore shape factors from 4 to 40

and no crack density term. The lower images show the model with the addition of the crack density term, assuming a crack density of 0.05.

The data from the clean carbonates intervals in the Panuke M-79 well can be accurately represented by the Vernik-Kachanov model with the following pore shape factors, p = 10 and q = 6. A cross-plot of the compressional and shear velocity data and model predictions in shown in Figure 5. Compressional and shear velocity logs calculated from the calibrated model are shown compared to the measured log data in Figure 2. A close match is observed in the clean limestone intervals. The predicted logs deviate from the measured logs where the mineralogy deviates from clean calcite.

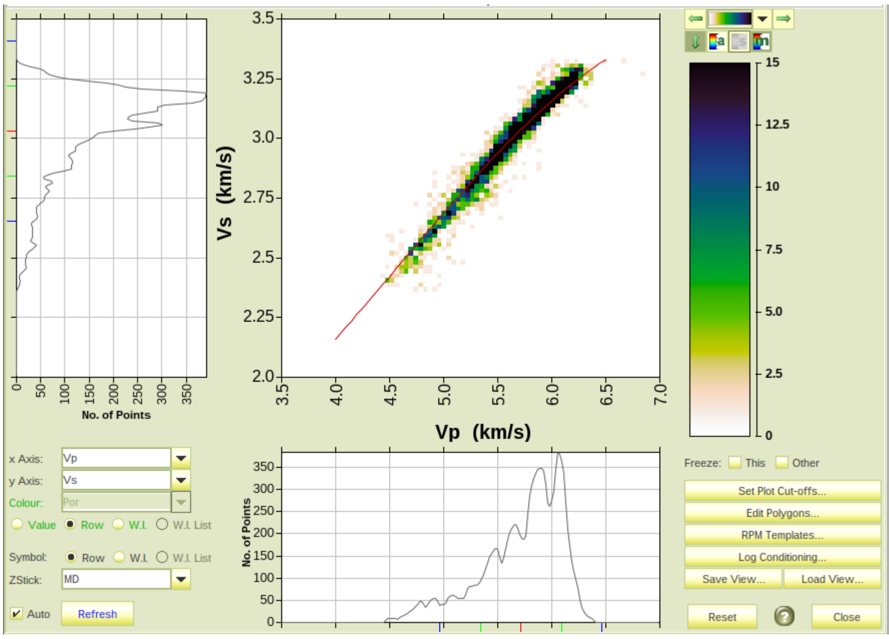

Figure 5: Cross-plot of measured compressional and shear velocity from the clean carbonate intervals in the Panuke M-79 well, coloured by data density. Overlain on the cross-plot is a template calculated from the Vernik-Kachanov model using pore shape factors, p = 10 and q = 6 and a crack density of 0.05 at the in-situ formation pressure.

Conclusions

We discuss mineral elastic moduli of calcite. The mineral moduli are important parameters for any rock physics based quantitative study of elastic and seismic properties in carbonate reservoirs. The mineral moduli are typically assumed to be known, but values in our standard reference book are out of date and misleading. We present a more robust compilation for future investigations.

We also discuss the apparent offset between the zero-porosity intercept of trends commonly observed in wireline data and the mineral moduli. We put forward the hypothesis that the offset is caused by the presence of micro-cracks in the borehole wall. The proposed effect of the micro-cracks is similar to that commonly observed in core samples. The hypothesis is supported by calibrating the Vernik-Kachanov model for a wireline dataset from offshore Cananda.

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