

Properties of pore fluids at very high pressures from equations of state

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Summary

We use software from the National Institute of Standards (NIST) to assess the adiabatic bulk modulus and density of natural gas and brine at pressures up to 200 MPa and temperatures up to 200°C. The calculations are based on the equations of state which are calibrated and verified by many experimental measurements. The results indicate that as pressure increases from the normal range of 20 to 50 MPa to the very high range of 150 to 200 MPa, the bulk modulus of methane may increase tenfold, from about 0.1 to about 1.0 GPa. The latter values are comparable to those for oil. This strong increase in the bulk modulus of natural gas may affect the seismic response of deep gas sands and, therefore, needs to be accounted for during the interpretation of deep-gas seismic events as well as in forward modeling. We show, using real well log data as input into synthetic seismic modeling, that although the character of the AVO response may be not affected by the pressure-related changes in gas properties, the magnitude of this response will be definitely affected.

Introduction

Commonly used fluid substitution equations by Gassmann (1951) indicate that the elastic properties of rocks, especially relatively soft sediments, can be strongly affected by the compressibility of the pore fluid. Consider an example in Figure 1 where the P-wave impedance measured in a North Sea well is plotted versus porosity and color-coded by the gas saturation. All the data points displayed in this figure come from a thick sand interval. The only difference among the data points is that the upper part of the interval is saturated with gas while the lower part of the interval is saturated with oil and water. The presence of gas in this well gives rise to a dramatic reduction in the impedance and thus determines the seismic visibility of the pay. This dramatic difference in seismic properties is due to the strong difference between the bulk modulus of gas (about 0.08 GPa in this example), oil (about 0.8 GPa), and water (about 2.8 GPa).

Because of such strong influence of the pore fluid properties on the seismic response, the industry needs to have reliable ways of estimating the bulk modulus and density of pore fluid, especially natural gas, versus pore pressure and temperature. Batzle and Wang (1992), in their classical Geophysics publication, provided equations that relate the bulk modulus and density of gas, oil, and water to gas gravity, oil gravity, gas-to-oil ratio, brine salinity, and, most important, pressure and temperature. These equations (BW) are widely used in the industry. Experiments on

measuring the needed fluid properties continue (e.g., Han and Batzle, 2000). However, the pressure range of applicability of the BW equations as well as recent experiments does not extend beyond 50 MPa.

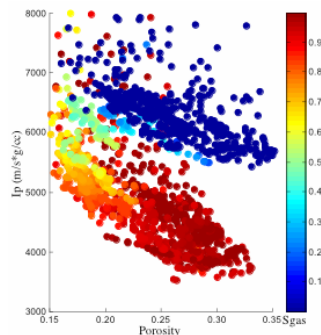


Figure 1. Impedance versus porosity in a thick soft-sand interval, color-coded by gas saturation. The presence of gas in the pore space produces a strong decrease in the impedance. The rest of the interval is filled with oil and water.

The normal pore pressure in the subsurface (in MPa) is approximately ten times the vertical depth in km. This means that 50 MPa occurs at approximately 5 km TVD. In overpressured formations, the pressure may be higher even at shallower depths. Also, tremendous amounts of domestic natural gas (55 Tcf offshore, according to MMS, and 135 Tcf onshore, according to USGS) may be available at depths below 15,000 ft (about 5 km TVD) and as deep as 25,000 ft (about 7.5 km). This promising domestic gas potential calls for improvements in the interpretation of very deep seismic events and, as part of this technical task, valid estimates for the bulk modulus and density of the pore fluid, especially gas, in deep reservoirs at very high pressure.

Approach

NIST provides two software packages, REFPROP7 for calculating the needed properties of natural gases, and NACL for calculating the properties of brine. Both packages provide adiabatic as well as isothermal properties, the former relevant to geophysics and the latter to petroleum engineering. The packages are based on equations of state calibrated by an extensive experimental database (e.g., Setzmann and Wagner, 1991).

Examples of calculations of the density and adiabatic bulk modulus for pure methane versus pressure at temperature 50, 125, and 200°C are shown in Figure 2. In the same

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figure we present curves calculated for the same conditions according to the Batzle and Wang (BW) equations. Although the BW equations have not been validated above 50 MPa, we use them in the entire range of pressure under examination.

Remarkably, the NIST and BW density curves are essentially the same below 50 MPa and only slightly deviate from each other in the range between 50 and 200 MPa. The bulk modulus NIST and BW curves are the same below 50 MPa and deviate from each other, although not very strongly, at higher pressures. The difference between the NIST and BW bulk modulus increases with increasing temperature and pressure. The maximum difference at the extreme conditions of 200°C and 200 MPa does not exceed 25%. This means that the BW equations for the density of methane can be used with confidence at very high pressures. Although the BW bulk modulus results vary from the NIST results at very high pressure, the former still can be used in approximate estimations.

Effect on Elastic Properties of Sand

In order to understand how the properties of methane at high pressure and temperature affect the elastic properties of sand, we select two high-porosity sand samples from the North Sea. One sample comes from the Troll field. It is friable and has 34% porosity and the room-dry P- and S-wave velocity 2.224 and 1.394 km/s, respectively. The other sample comes from the Oseberg field. It is slightly cemented fast sand of 30% porosity and the dry-room velocity 3.330 km/s for P- and 2.073 km/s for S-waves.

Gassmann's fluid substitution was used to calculate the impedance and Poisson's ratio (PR) of these two samples as the air in the pores was replaced by methane in the range of temperature and pressure considered in the previous section. During this exercise, the elastic properties of the samples remained fixed. The only variables were the density and bulk modulus of methane versus temperature and pressure.

The results shown in Figure 3 indicate that the impedance in both samples will be affected, although not strongly, by the changes in methane's properties due to temperature and pressure. The effect on PR is more pronounced, especially, in the softer Troll sample. In this sample, the increase in PR is from about 0.2 to about 0.3 as the pore pressure varies between zero and 200 MPa. This change may eventually translate into the AVO type of a deep soft sand. Remarkably, the BW equations can be reliably used outside of their published applicability range to estimate the impedance in sand – the difference between BW and NIST results is virtually nonexistent in the impedance curves in Figure 3. Same is true for PR at low temperature.

Effect on AVO

We use full-offset synthetic seismic modeling to evaluate how gas property change with pressure may affect the AVO signatures of gas sand. For this purpose we select a well with gas sand at the bottom (Figure 4). First we calculate synthetic seismic traces for the conditions existing in the well. Next we theoretically substitute the original gas in the pay at not-very-high pressure by gas at ultrahigh pressure, according to gas property calculations shown in Figure 2. This fluid substitution affects both the impedance and PR of the gas sand in the well. These elastic property changes affect the AVO response of the sand extracted from the synthetic gather. While for the real in-situ conditions the AVO response at the top of the sand is of Class 3, the response for the sand with gas at ultrahigh pressure is much weaker and merges towards weak Class 2.

Properties of Brine

Figure 5 gives an example of how the properties of brine can be affected by temperature (from 25 to 250°C) and pressure (fixed at 100 MPa). The difference between the NIST and BW results is essentially nonexistent both for the density and bulk modulus.

Conclusions

Ultrahigh pressure may affect the properties of natural gas to a degree that translates into seismic signature type in very deep gas targets.

The Batzle and Wang equations can be used outside of their published range to estimate the density and compressibility of methane, however the equations of state by NIST are preferred.

Acknowledgement

We thank Eric Lemmon, Mark McLinden, and Marcia Huber of NIST for their help and advice.

References

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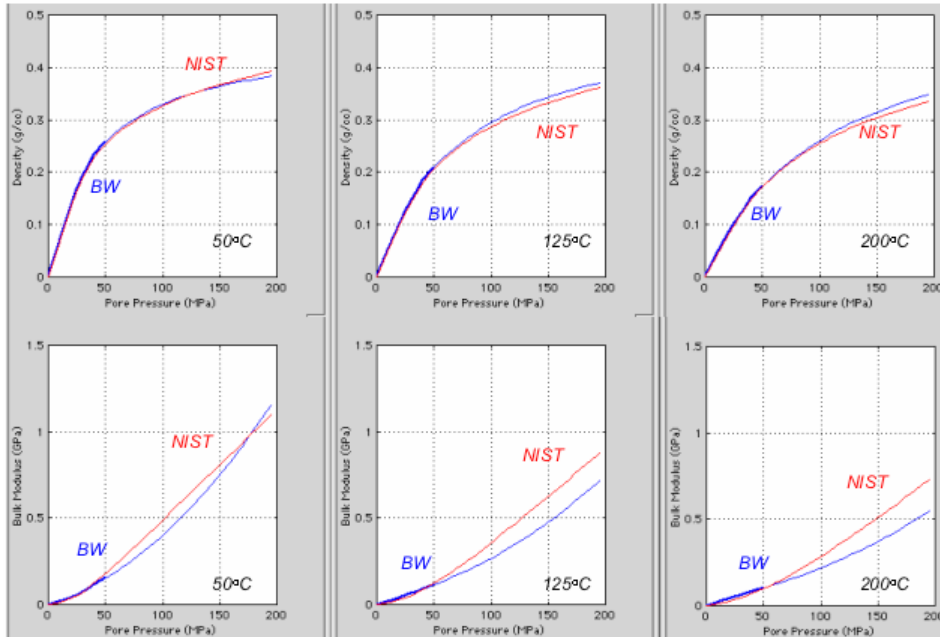


Figure 2. The density (top) and bulk modulus (bottom) of methane versus pressure and at varying temperature. The red curves are according to NIST while the blue curves are according to BW. The bold parts of the BW curves are for pressure below 50 MPa in which range the BW equations have been validated.

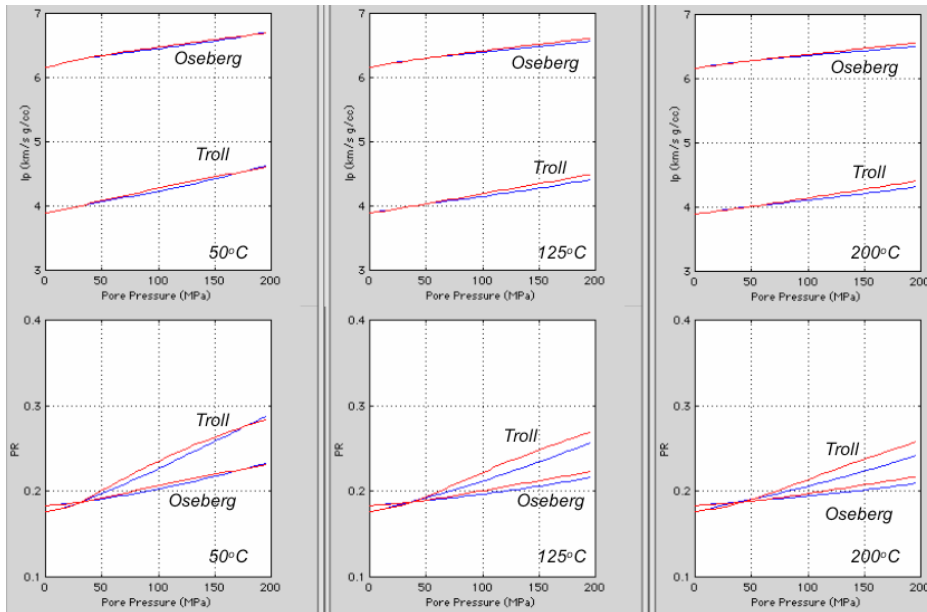


Figure 3. The impedance (top) and Poisson's ratio (bottom) for the Troll and Oseberg samples versus pressure and at varying temperature. In these calculations the only variables were the density and bulk modulus of methane as displayed in Figure 2. The red curves are according to NIST while the blue curves are according to BW.

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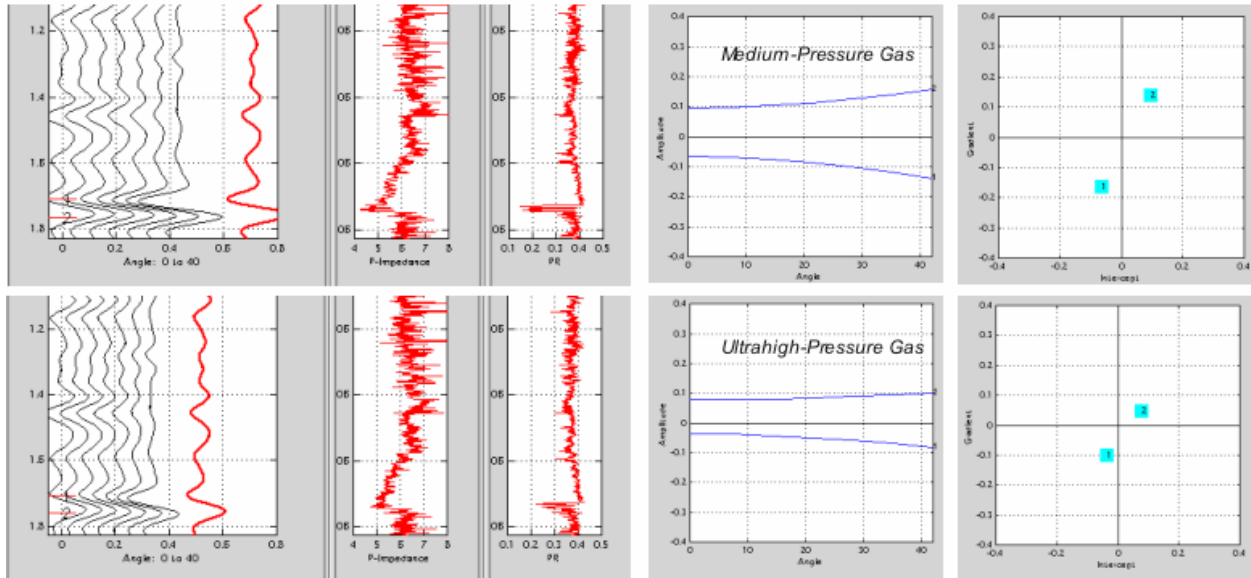


Figure 4. Synthetic seismic for a well with gas sand for the in-situ (top) and ultrahigh pressure (bottom) conditions. From left to right: gather (black) and stack (red); impedance and PR in the well; AVO curves extracted from the gather at the top of the sand (lower) and bottom of the sand (upper); gradient versus intercept for these AVO curves. The numbers in the large blue circles correspond to those at the AVO curves and at the gather.

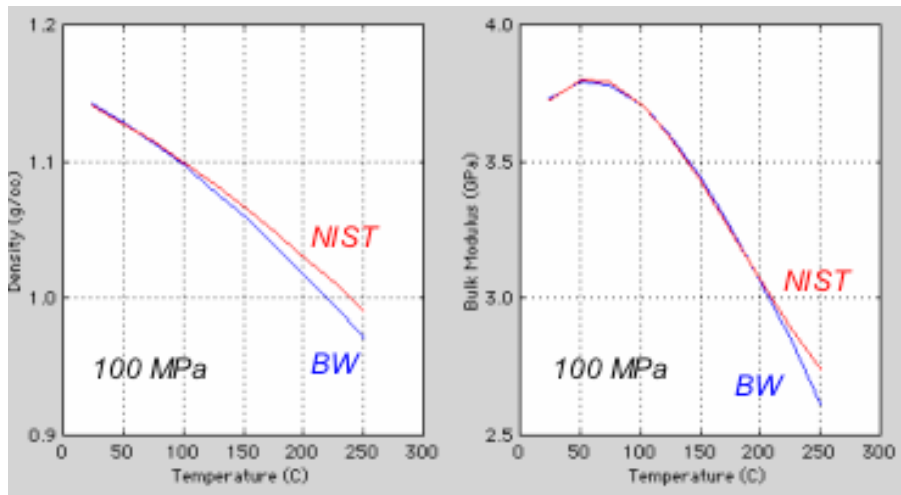


Figure 5. The density (left) and bulk modulus (right) of brine of 150,000 ppm salinity versus temperature at 100 MPa. The red curves are according to NIST while the blue curves are according to BW.