Effects of pore fluid properties at high pressure and temperature on seismic response

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Summary

We use software from the National Institute of Standards and Testing (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^{o}C. The calculations are based on 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. For heavier hydrocarbon gases (ethane, propane, butane, and their mixtures) the modulus will be even higher.

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. This difference in seismic properties is due to the strong difference between the bulk modulus of gas, oil, and water.

Because of the 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.

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.

Comparison to Batzle-Wang (1992)

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 200oC are shown in Figure 1. In the same 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.

The NIST and BW density curves for pure methane 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 from NIST and BW are similar below 50 MPa and get progressively farther apart as pressure increases to 200 MPa. The maximum difference at the extreme conditions of 200oC and 200 MPa is about 25%. This means that the BW equations for the density of methane can be used with confidence at very high pressures, but the bulk modulus values at 100 MPa and above will be substantially underestimated.

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 only variables were the density and bulk modulus of methane versus temperature and pressure.

The results shown in Figure 2 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. The difference in the impedance curves between BW-92 and NIST results is small, as shown in Figure 2. However, Poisson's ratio is more sensitive to the differences, especially at certain combinations of pressure and temperture.

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 3). 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 1. 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

We have computed the properties of NaCl brine versus temperature (from 25 to 250oC) and pressure (fixed at 100 MPa). The difference between the NIST model and BW-92 is minimal both for the density and bulk modulus.

Heavier Hydrocarbon Gases

To explore the effects of high pressure and temperature on gases other than methane, we also computed bulk modulus and density for pure ethane, propane, and butane. As shown in Figure 4, these computations show that for methane (specific gravity 0.56), BW-92 modulus is about 26% lower than NIST at 125 MPa and 200 C. For propane (specific gravity 1.52), BW-92 modulus is about 56% higher than NIST at 125 MPa and 200C. For butane (specific gravity 2.01) the differences are even larger.

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 and NIST model for NaCl brine give similar results for density and compressibility over a wide range of pressure and temperature. For gas density, BW-92 and NIST models gives similar results over a wide range of pressure and temperature. However for adiabatic bulk modulus, there are substantial differences between BW-92 and NIST at high pressure and temperature, and the differences depend on the gas specific gravity.

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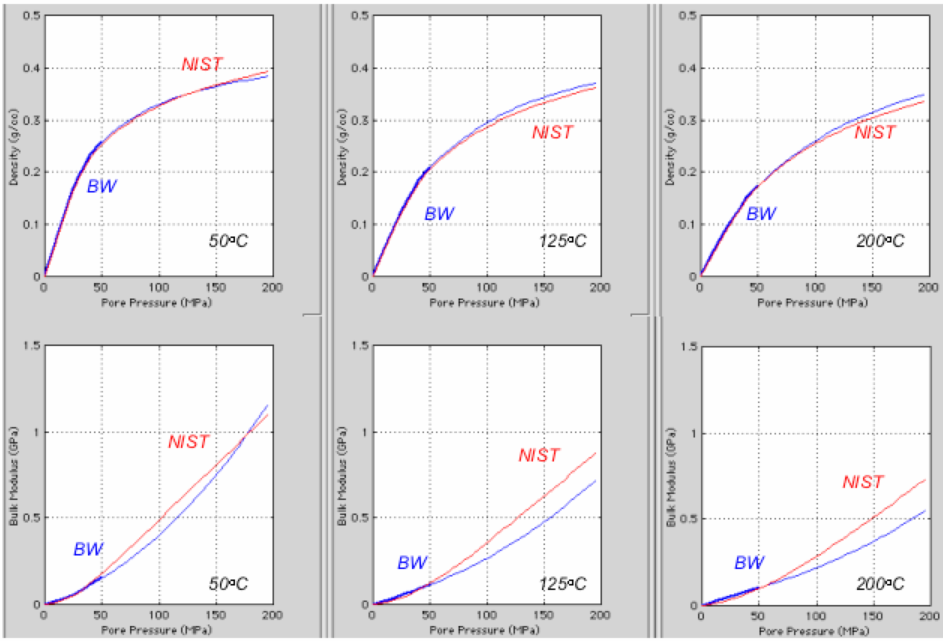

Figure 1. The density (top) and bulk modulus (bottom) of methane versus pressure and at varying temperature. The red curves are according to NIST while the blue curves are according to BW. The bold parts of the BW curves are for pressure below 50 MPa in which range the BW equations have been validated.

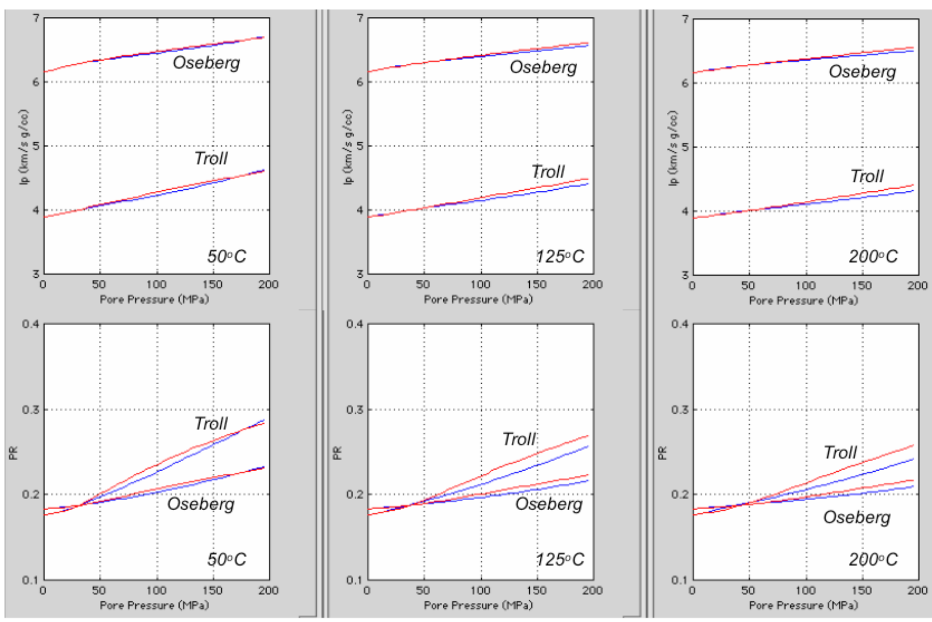

Figure 2. The impedance (top) and Poisson's ratio (bottom) for the Troll and Oseberg samples versus pressure and at varying temperature. In these calculations the only variables were the density and bulk modulus of methane as displayed in Figure 2. The red curves are according to NIST while the blue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

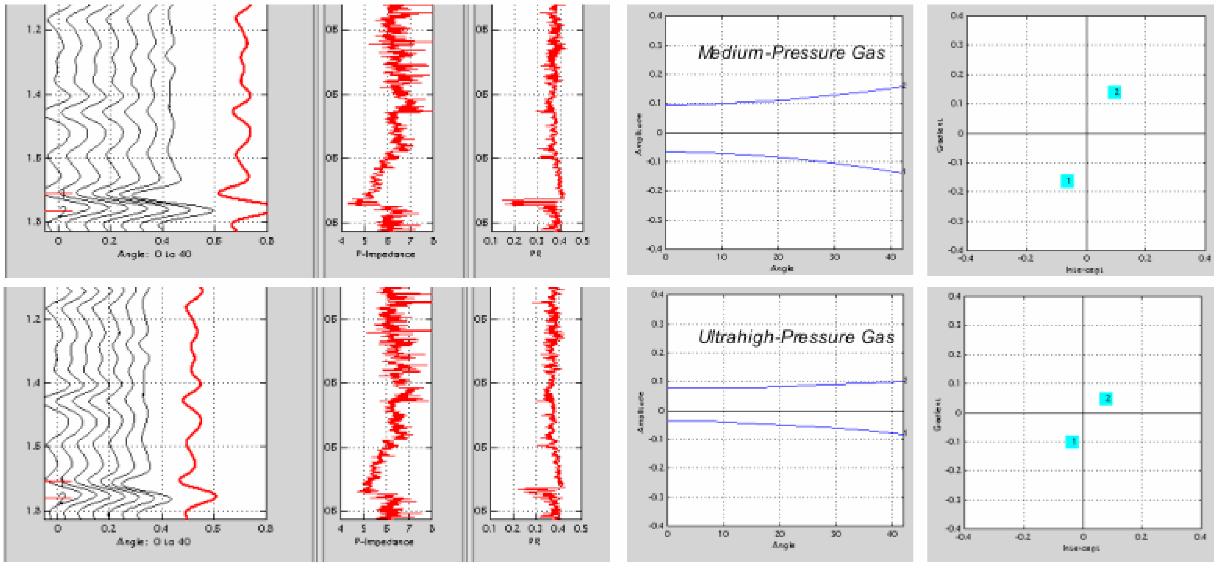

Figure 3. Synthetic seismic for a well with gas sand for the in-situ (top) and ultrahigh pressure (bottom) conditions. From left to right: gather (black) and stack (red); impedance and PR in the well; AVO curves extracted from the gather at the top of the sand (lower) and bottom of the sand (upper); 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.

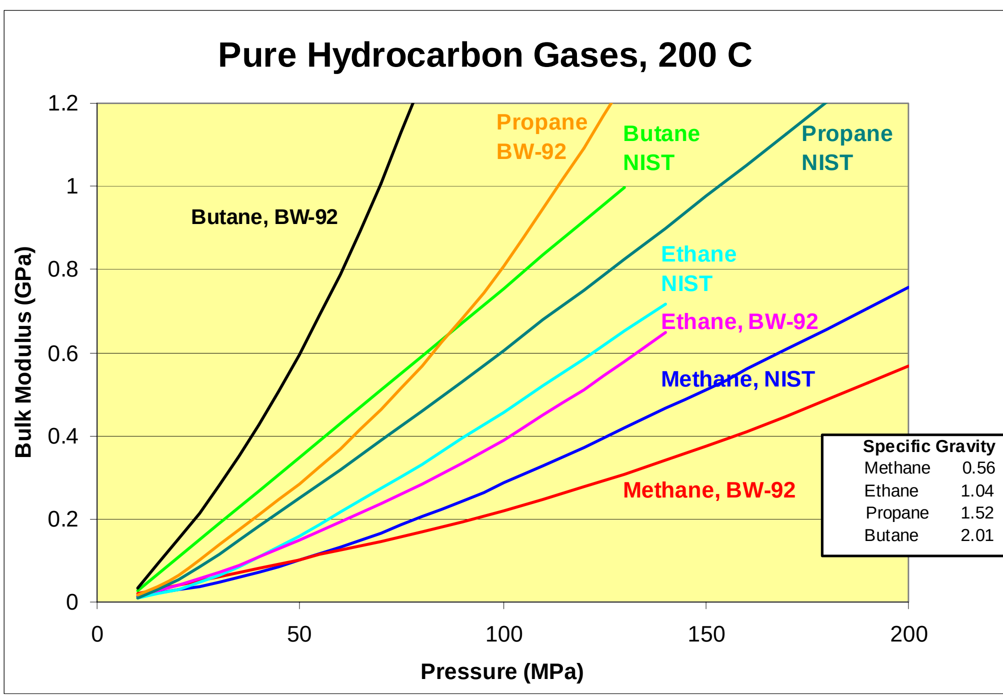

Figure 4: Effect of pressure on adiabatic bulk modulus of methane, ethane, propane and butane as computed by Batzle-Wang, 1992 and NIST model (200 C)