GEOPHYSICS, VOL. 65, NO. 2 (MARCH-APRIL 2000); P. 646–651, 3 FIGS., 2 TABLES.

Sound velocity of drilling mud saturated with reservoir gas

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ABSTRACT

Knowledge of the in-situ sound velocity of drilling mud can be used in mud-pulse acoustic telemetry for evaluating the presence and amount of gas invasion in the drilling mud. We propose a model for calculating the in-situ density and sound velocity of water-based and oil-based drilling muds containing formation gas. Drilling muds are modeled as a suspension of clay particles and high-gravity solids in water or oil, with the acoustic properties of these fluids depending on pressure and temperature. Since mud at different depths experiences different pressures and temperatures, downhole mud weights can be significantly different from those measured at the surface. Taking this fact into consideration, we assume constant clay composition and obtained the fraction of high-gravity solids to balance the formation pressure corresponding to a given drilling plan. This gives the in-situ density of the drilling mud, which together with the bulk moduli of the single constituents allow us to compute the sound velocity using Reuss's model. In the case of oil-based muds, we take into account the gas solubility in oil. When gas goes into solution, the mud is composed of solid particles, live oil and, eventually, free gas. A phenomenological model based on a continuous spectrum of relaxation mechanisms is used to describe attenuation due to mud viscosity. The calculations for water-based and oil-based muds showed that the sound velocity is strongly dependent on gas saturation, fluid composition, and drilling depth.

INTRODUCTION

Drilling muds are used to balance subsurface pressures, lubricate the drillstring, clean the bottom of the hole, remove cuttings, and aid formation evaluation (Moore, 1986). During drilling, the mud is pumped down the drill pipe and returns via the annulus between the drill string and the formations. If the pore-fluid formation pressure exceeds that of the mud column, reservoir gas can enter the wellbore, creating a kick which can cause severe damage. Knowledge of the in-situ sound velocity of drilling mud can be useful for evaluating the presence and amount of gas invasion in the drilling fluid, mainly when oil-based muds are used, since early detection of abnormal pressures is more difficult with oil-based muds because of the solubility of gas in oil (Thomas et al., 1982). Technologies such as mud-pulse acoustic telemetry require this information.

The paper is organized as follows. In the next section, we obtain the acoustic properties of water- and oil-based drilling muds as a function of temperature and pressure. The fraction of high-gravity solids is calculated as a function of depth to comply with a given pressure profile. Then, the gas properties are obtained by using the van der Waals equation. Finally, the sound velocity of the drilling mud is computed by using Wood's formula, taking into account the fact that a fraction of gas is absorbed by the oil in the case of oil-based muds.

ACOUSTIC PROPERTIES OF DRILLING MUD

Let us assume a given drilling plan, where the pore pressure p is provided as a function of depth z. The density of drilling mud required at each depth is $\bar{\rho}_{\rm mud} = p/(gz)$, where g is the acceleration of gravity. However, as we shall see below, $\bar{\rho}_{\rm mud}$ is an equivalent density, since the density of the drilling mud depends on temperature and pressure through the depth z.

Moreover, we assume a constant geothermal gradient G, such that the temperature variation with depth is

$$T = T_0 + Gz, \tag{1}$$

with a surface temperature T_0. Typical values of G range from 20 to 30°C/km.

Many types of drilling mud are used in the industry. Major categories include oil-based and water- or brine-based drilling muds, with clay suspensions such as sodium montmorillonite (bentonite) and attapulgite, or salt gel (Moore, 1986), and

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various chemical additives. For simplicity, we consider that the mud consists of suspensions of clay (quartz) particles and high-gravity solids, such as barite (in water-based muds) and itabarite (an iron ore, in oil-based muds), whose properties are assumed temperature and pressure independent. We exclude aerated muds in this analysis, although, in principle, they can be modeled by introducing an additional component (air, mist, foam, etc.).

The fluid properties depend on temperature and pressure, and on API number and salinity, if the fluid is oil or water, respectively. Batzle and Wang (1992) and Mavko et al. (1998, p. 214–220) provide a series of useful empirical relations between the state variables and velocity and density. For completeness, we give these relations here. Oil density (in g/cm^3) versus temperature T (°C) and pressure p (MPa) can be expressed as

$$\rho_o = \frac{\rho_0 + (0.00277p - 1.71 \times 10^{-7} p^3)(\rho_0 - 1.15)^2 + 3.49 \times 10^{-4} p}{0.972 + 3.81 \times 10^{-4}(T + 17.78)^{1.175}}, \tag{2}$$

where ρ_0 is the density at 15.6°C and atmospheric pressure. This density is related to API gravity by

$$\mathrm{API} = \frac{141.5}{\rho_0} - 131.5. \tag{3}$$

The expression relating wave velocity of dead oil (oil with no dissolved gas) to pressure, temperature, and API gravity is

$$V_o = 15450\,(77.1 + \mathrm{API})^{-1/2} - 3.7T + 4.64p + 0.0115\,(0.36\,\mathrm{API}^{1/2} - 1)Tp, \tag{4}$$

where V_o is given in m/s and p in MPa. Using these relationships, we get the oil modulus as $K_o = \rho_o V_o^2$.

The density of brine in g/cm^3 is given by

$$\rho_B = \rho_w + S\{0.668 + 0.44S + 10^{-6}[300p - 2400pS + T(80 + 3T - 3300S - 13p + 47pS)]\}, \tag{5}$$

with

$$\rho_w = 1 + 10^{-6}(-80T - 3.3T^2 + 0.00175T^3 + 489p - 2Tp + 0.016T^2 p - 1.3 \times 10^{-5} T^3 p - 0.333p^2 - 0.002Tp^2), \tag{6}$$

where S is the weight fraction (ppm/1 000 000) of sodium chloride. Finally, the velocity function for brine is

$$V_B = V_w + S(1170 - 9.6T + 0.055T^2 - 8.5 \times 10^{-5} T^3 + 2.6p - 0.0029Tp - 0.0476p^2) + S^{1.5}(780 - 10p + 0.16p^2) - 1820S^2, \tag{7}$$

where V_w is the velocity of pure water given by

$$V_w = \sum_{i=0}^{4} \sum_{j=0}^{3} w_{ij} T^i p^j, \tag{8}$$

with constants w_{ij} given in Batzle and Wang's (1992) Table 1. Using these relationships, we get the brine modulus as $K_B = \rho_B V_B^2$.

Mass balance requires an arithmetic average of the different phases. Then, the composite density is simply the volume-weighted average of the densities of the constituents.

The mud density is given by

$$\rho_{\mathrm{mud}} = \phi_q \rho_q + \phi_b \rho_b + (1 - \phi_q - \phi_b)\rho_f, \tag{9}$$

where ϕ_q, ρ_q, and ϕ_b, ρ_b are the volume fractions and densities of the clay particles and high-gravity solids, respectively, and ρ_f is the fluid density. Let us assume, for simplicity, that the clay composition ϕ_q is constant. The fraction of high-gravity solids ϕ_b corresponding to an equivalent mud density $\bar{\rho}_{\mathrm{mud}}$ at depth z is obtained from the following balance equation:

$$\int_0^z \rho_{\mathrm{mud}}(z')\,dz' = \bar{\rho}_{\mathrm{mud}} z, \tag{10}$$

where the depth variable z' determines the temperature profile (1) and the pressure profile according to the drilling plan.

Note that ρ_{mud} will vary since it depends on pressure and temperature which vary with depth. Also, despite the fact that chemical interactions between the single constituents are not taken into account, the model is in very good agreement with measured data (McMordie et al., 1982) and the empirical equation proposed by Kutasov (1989) for water- and oil-based drilling muds (see also Babu, 1996).

Reuss's model (Reuss, 1929) is used to model the acoustic properties of drilling mud. This model describes the properties of a fluid suspension or fluid mixture. Reuss's model averages the reciprocal of the bulk moduli (isostress assumption). The assumptions and limitations of this model are discussed in Mavko et al. (1998). The composite bulk modulus of the drilling mud is obtained from

$$\frac{1}{K_{\mathrm{mud}}} = \frac{\phi_q}{K_q} + \frac{\phi_b}{K_b} + \frac{1 - \phi_q - \phi_b}{K_f}, \tag{11}$$

where K_q, K_b, and K_f are the bulk moduli of clay, high-gravity solids, and fluid, respectively. Equation (11) is also known as Wood's equation (Wood, 1955).

In the preceding analysis, we have assumed constant clay composition. However, this constraint can be relaxed, and the composition of the solid particles for a given drilling plan can be computed by using both the fraction of clay particles and the fraction of high-gravity solids as fitting parameters.

ACOUSTIC PROPERTIES OF RESERVOIR GAS

In-situ reservoir gas behaves as a real gas, which satisfies approximately the van der Waals equation (Friedman, 1963):

$$\left(p + a\rho_g^2\right)(1 - b\rho_g) = \rho_g R(T + 273), \tag{12}$$

where p is the gas pressure, ρ_g is the gas density, and R = 1.986 cal/mol °K is the gas constant. Moreover, for methane, $a = 0.225$ Pa (m^3/mole)^2 = 879.9 MPa (cm^3/g)^2 and b = 4.28×10^{-5} m^3/mole = 2.675 cm^3/g (one mole of methane, CH_4, corresponds to 16 g). Equation (12) gives the gas density as a function of pressure and temperature (which can be related to depth), if we assume that the gas pressure is equal to the expected formation pressure.

The isothermal gas compressibility c_T depends on pressure. It can be calculated from van der Waals equation using

$$c_T = \frac{1}{\rho_g}\frac{\partial \rho_g}{\partial p} \tag{13}$$

to obtain

$$c_T = \left[\frac{\rho_g RT}{(1 - b\rho_g)^2} - 2a\rho_g^2\right]^{-1}. \tag{14}$$

For sound waves below 1 GHz or so, it is a better approximation to assume that the compression is adiabatic, that is, that the entropy content of the gas remains nearly constant during the compression (Morse and Ingard, 1986). Adiabatic compressibility c_S is related to isothermal compressibility c_T by $c_S = c_T/\gamma$, where γ is the heat capacity ratio at constant pressure, which depends on measurable quantities (Morse and Ingard, 1986). For polyatomic gases, we may use the approximation $\gamma \approx \frac{4}{3}$ (Morse and Ingard, 1986). In this case, the gas bulk modulus can expressed as

$$K_g = \frac{4}{3c_T}. \tag{15}$$

It can be shown that equation (12) can be a good approximation to the behavior of natural gas (i.e., multicomponent gases), since the differences between the experimental data [as represented by Standing's results (Standing, 1952)] and the van der Waals results are only about 15% over the depths of interests. An alternative but similar expression for the acoustic properties of gases can be found in Batzle and Wang (1992) and Mavko et al. (1998).

SOUND VELOCITY OF THE DRILLING MUD/GAS MIXTURE

The acoustic properties of water-based muds are obtained by using Reuss's (1929) model under the assumption that the gas is present in the form of bubbles. In the case of oil-based muds, we take into account the gas solubility in oil. When gas goes into solution in dead oils, it generates live oils, and a different approach must be used. The analysis is based on an interpretation of the equations for live oil given by Batzle and Wang (1992). The solubilities of hydrocarbon gases in water are very small when compared to the solubilities of the same gases in oil. In the following, we obtain the drilling-mud velocity when formation gas enters the wellbore at a given drilling depth.

Water-based muds

We use Reuss's (1929) model for the velocity of sound in a water-gas mixture. The composite density is

$$\rho = \phi_{\mathrm{mud}}\rho_{\mathrm{mud}} + S_g\rho_g, \tag{16}$$

provided that $\phi_{\mathrm{mud}} + S_g = 1$, where S_g is the saturation of gas, and the composite bulk modulus is obtained from

$$\frac{1}{K} = \frac{\phi_{\mathrm{mud}}}{K_{\mathrm{mud}}} + \frac{S_g}{K_g}. \tag{17}$$

In order to model dissipation mechanisms due to the presence of viscous stresses in the mud, the presence of gas bubbles, and other causes, we assume that attenuation of the sound wave is modeled by multiplying the modulus K by a frequency-dependent factor of the form

$$M(\omega) = \left[1 + \frac{2}{\pi Q}\ln\frac{\tau_2}{\tau_1}\right]\left[1 + \frac{2}{\pi Q}\ln\left(\frac{1 + i\omega\tau_2}{1 + i\omega\tau_1}\right)\right]^{-1} \tag{18}$$

(e.g., Ben-Menahem and Singh, 1981), where ω is the angular frequency, τ_1 and τ_2 are time constants (with $\tau_2 < \tau_1$), and Q defines the value of the quality factor of the drilling mud, which remains nearly constant over the selected frequency band. Equation (18) corresponds to a continuous distribution of relaxation mechanisms. For high frequencies, $M \to 1$.

For attenuation due to the presence of bubbles, we assume that Q has the following dependence with gas saturation S_g:

$$Q = [4S_g(1 - S_g)]^{-\alpha} Q_{\min}, \tag{19}$$

where $Q_{\min}$ is the minimum quality factor (at midrange of saturations) and α is an empirical coefficient. This model assumes that the attenuation has a maximum at midrange of saturations. Similar quality factor peaks versus saturation are observed for partially saturated rocks (Murphy, 1982). Since, to our knowledge, there is no experimental values of attenuation for a fluid containing gas bubbles, we choose $Q_{\min}$ and α in agreement with values reported for fluid-filled rocks. An alternative attenuation model for the viscous damping mechanism was developed by Urick (1948) for a dilute suspension of clay particles, and extended by McCann (1969) to concentrated suspensions.

The sound velocity is then given by the frequency ω divided by the real part of the complex wavenumber $\omega/\bar{V}$, where $\bar{V} = \sqrt{KM/\rho}$ is the complex velocity. We obtain

$$V = \mathrm{Re}\left[\left(\sqrt{\frac{\rho}{KM}}\right)^{-1}\right], \tag{20}$$

where K is the unrelaxed bulk modulus. The effect of attenuation is to decrease the velocity, mainly at midrange saturations, according to the attenuation model proposed in equations (18) and (19).

Oil-based muds

When gas enters the wellbore, a fraction of it goes into solution and the rest remains as free gas. The process is illustrated in Figure 1—in stage (1), the mud is free of gas; in stage (2), a volume v_g of gas invades the drilling mud, with v_{g1} going immediately into solution (stage 3) and v_{g2} remaining as free gas bubbles. We need to calculate the acoustic properties of the live oil, and then use Reuss's (1929) model to obtain the properties of the drilling fluid saturated with gas.

In the following, we obtain the fractions of solids, live oil, and free gas at stage (3). The volume ratio of liberated gas to remaining oil at atmospheric pressure and 15.6°C is

$$R_G = 2.03 G_r [p \exp(0.02878\ \mathrm{API} - 0.00377T)]^{1.205}, \tag{21}$$

where G_r is the gas gravity; R_G, given in liters of gas/liters of oil, represents the maximum amount of gas that can be dissolved in the oil (Batzle and Wang, 1992). At depth z, temperature T, and pressure p, the equivalent ratio is

$$R'_G = \frac{\rho_{gs}}{\rho_g}\frac{\rho_o}{\rho_{os}} R_G = \frac{v_{g1}}{v_o}, \tag{22}$$

where ρ_{gs}, ρ_{os} and ρ_g, ρ_o are the gas and oil densities at the surface and at depth z, respectively, and v_o is the volume of dead oil. The gas densities can be computed from the van der Waals equation (12).

First, let us assume that the oil has absorbed the maximum amount of gas (i.e., there is free gas). After the absorption of gas, the volume of oil increases from v_o to v_{lo}. The mass of live oil $\rho_{lo} v_{lo}$ is equal to the mass of dead oil $\rho_o v_o$ plus the mass of gas absorbed into solution $\rho_g R'_G v_o$, where ρ_{lo} is the live-oil density. Then, the volumes are related by

$$v_{lo} = \left(\frac{\rho_o + \rho_g R'_G}{\rho_{lo}}\right) v_o \equiv \beta v_o, \tag{23}$$

where

$$\rho_{lo} = \rho_G + (0.00277p - 1.71 \times 10^{-7} p^3)(\rho_G - 1.15)^2 + 3.49 \times 10^{-4} p \tag{24}$$

with

$$\rho_G = (\rho_0 + 0.0012 G_r R_G)/B_0, \tag{25}$$

the saturation density, and

$$B_0 = 0.972 + 0.00038\left[2.4 R_G \left(\frac{G_r}{\rho_0}\right)^{1/2} + T + 17.8\right]^{1.175}, \tag{26}$$

the oil volume factor (Batzle and Wang, 1992). When computing the density of live oil, the temperature effect was considered twice in Batzle and Wang (1992): in B_0 and in their equation (19) (M. Batzle, personal communication, 1999). Equation (24) gives the correct density.

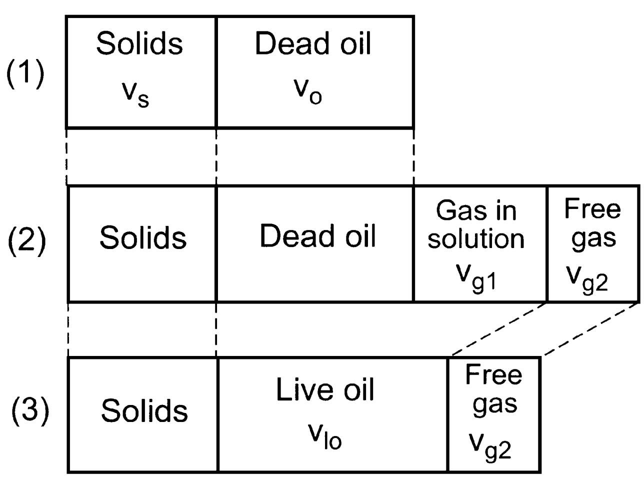


FIG. 1. Absorption of formation gas by oil-based drilling mud. The solids represents the clay particles and high-gravity solids.

As a result of the balance equation (10), the fraction of dead oil is known; it is given by

$$\phi_o = 1 - \phi_q - \phi_b = \frac{v_o}{v_s + v_o}. \tag{27}$$

The saturation of gas is equal to

$$S_g = \frac{v_g}{v_s + v_o + v_g}, \tag{28}$$

where $v_g = v_{g1} + v_{g2}$ at stage (2) (see Figure 1). A critical saturation S_{gc} can be obtained when $v_{g2} = 0$, or $v_g = v_{g1}$; from equation (28), $v_g = (v_s + v_o)S_g/(1 - S_g)$, and using equations (22) and (27), we obtain

$$S_{gc} = \frac{\phi_o R'_G}{1 + \phi_o R'_G}. \tag{29}$$

When $S_g \geq S_{gc}$, part of the gas is dissolved in the oil and the rest is in the form of free gas. In this case, the oil absorbes the maximum quantity of gas. Using equations (22), (23), (27), and (28), we obtain the fractions of live oil, free gas, and solid at stage (3):

$$\phi_{lo} = \beta\left[\frac{1}{\phi_o} + \beta + \frac{S_g}{\phi_o(1 - S_g)} - R'_G - 1\right]^{-1}, \tag{30}$$

$$\phi_g = \frac{\phi_{lo}}{\beta}\left[\frac{S_g}{\phi_o(1 - S_g)} - R'_G\right], \tag{31}$$

and

$$\phi_s = 1 - \phi_{lo} - \phi_g. \tag{32}$$

The fraction of solid is the sum of the volume fractions of the clay particles and high-gravity solid $\phi_s = \phi'_q + \phi'_b$, such that

$$\phi'_q = \frac{\phi_s}{1 - \phi_o}\phi_q \tag{33}$$

and

$$\phi'_b = \frac{\phi_s}{1 - \phi_o}\phi_b. \tag{34}$$

The sound velocity of the saturated live oil, V_{los}, is calculated by using a pseudodensity ρ' based on the expansion caused by gas intake,

$$\rho' = \frac{\rho_0}{B_0}(1 + 0.001\ R_G)^{-1} \tag{35}$$

(Batzle and Wang, 1992). In order to obtain V_{los}, the density ρ_0 should be substituted by ρ' in equations (3) and (4).

Then, the drilling mud composite density is

$$\rho = \phi'_q \rho_q + \phi'_b \rho_b + \phi_{lo}\rho_G + \phi_g \rho_g, \tag{36}$$

and the composite bulk modulus is obtained from

$$\frac{1}{K} = \frac{\phi'_q}{K_q} + \frac{\phi'_b}{K_b} + \frac{\phi_{lo}}{K_{los}} + \frac{\phi_g}{K_g}, \tag{37}$$

where $K_{los} = \rho_G V_{los}^2$.

When $S_g < S_{gc}$, all the gas goes into solution, but the oil is not saturated since it absorbs less than R'_G liters of gas; it absorbs $(S_g/S_{gc})R'_G$ liters. The density, ρ_{lo}, and the velocity, V_{lo}, of live oil are obtained by substituting R_G by $(S_g/S_{gc})R_G$ in equations

(24), (25), (26) and (3), (4) and (34), respectively. The bulk modulus is $K_{lo} = \rho_{lo} V_{lo}^2$.

Then, the mud density and bulk modulus are given by

$$\rho = \phi_q' \rho_q + \phi_b' \rho_b + \phi_{lo} \rho_{lo} \quad (38)$$

and

$$\frac{1}{K} = \frac{\phi_q'}{K_q} + \frac{\phi_b'}{K_b} + \frac{\phi_{lo}}{K_{lo}}, \quad (39)$$

respectively, where

$$\phi_{lo} = \eta \left(\frac{1}{\phi_o} + \eta - 1 \right)^{-1}, \quad (40)$$

$$\eta = \frac{1}{\rho_{lo}} \left[\rho_o + \rho_g \left(\frac{S_g}{S_{gc}} \right) R_G' \right], \quad (41)$$

and $\phi_s = 1 - \phi_{lo}$. Finally, as in the case of water-based muds, attenuation can be modeled by using equation (18) and (19), and the sound velocity is given by equation (20).

EXAMPLE

The pore pressures for a drilling plan corresponding to a deep, relatively high-pressure well are given in Table 1, in which mud weight and pressure are related by

$$p(\text{psi}) = 0.052\, M_w(\text{lb/gal})\, z(\text{ft}). \quad (42)$$

We recall that 1 MPa = 145 psi and 1 g/cm^3 = 8.34 lb/gal. Therefore, $\bar{\rho}_{\text{mud}}$ (g/cm^3) = M_w/8.34.

The environmental conditions and material properties for calculating the acoustic properties of gas-saturated drilling mud are given in Table 2, where the gas is assumed to be methane. The attenuation parameters are chosen to model the Q levels observed in suspensions and high-porosity sediments (Hovem, 1980; Ogushwitz, 1985). In particular, the values of the time variables are chosen to model a constant Q factor over the seismic frequency band. Solving equation (10), the water-based mud requires a fraction of barite ranging from 0% for 1000 ft (305 m) to 6.4% for 16 000 ft (4877 m), in order to balance the formation pressure. The range of itabarite for the oil-based mud is 5.6% for 1000 ft (305 m) to 10.4% for 16 000 ft (4877 m).

Figures 2 and 3 show the sound velocities of water-based drilling mud and oil-based drilling muds, respectively, versus gas saturation at different depths, for a frequency of 25 Hz. In Figure 3, the gas saturation is that at stage (2) (see Figure 1); a fraction of this gas dissolves into the oil, such that the real gas saturation is ϕ_g [stage (3)]. The $z = 0$ ft curve is the velocity at atmospheric pressure p_0 and temperature T_0. At full gas

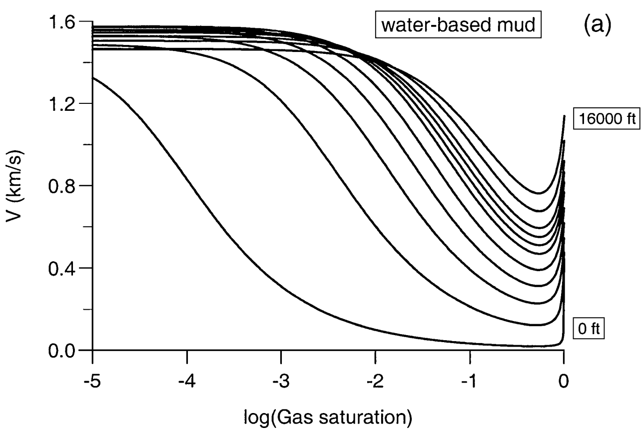
Table 1. Drilling plan pore pressures.

Depth z (ft)	Pore pressure p (psi)	Mud weight M_w (lb/gal)
1000	468	9.0
3000	1404	9.0
5000	2340	9.0
7000	3276	9.0
9000	4212	9.0
10000	4836	9.3
11000	5434	9.5
12000	6115	9.8
14000	7280	10.
16000	8736	10.5

Table 2. Material properties and environmental conditions.

Clay bulk modulus (quartz), K_q, 36 GPa
Clay density (quartz), ρ_q, 2.65 g/cm^3
Clay fraction, ϕ_q, 0.03
Barite bulk modulus*, K_b, 55 GPa
Barite density, ρ_b, 4.2 g/cm^3
Itabarite bulk modulus, K_b, 80 GPa
Itabarite density, ρ_b, 5.1 g/cm^3
Weight fraction of sodium chloride, S, 50000 ppm/10^6
API gravity of oil, API, 50°
Gas gravity, G_r, 0.56
Lower relaxation time, τ_1, 0.1 s
Upper relaxation time, τ_1, 1000 s
Minimum quality factor, $Q_{\min}$, 50
Attenuation coefficient, α, 1
Atmospheric pressure, p_0, 0.1 MPa
Acceleration of gravity, g, 9.81 m/s^2
Surface temperature, T_0, 15.6°C
Geothermal gradient, G, 30°C/km

*Ellis et al. (1988).



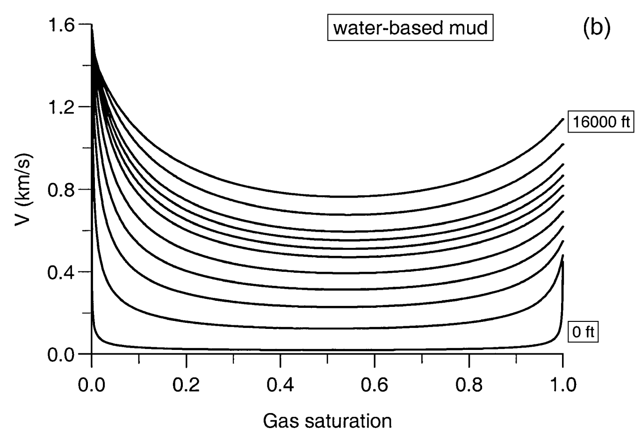


FIG. 2. Sound velocity of water-based drilling mud versus gas saturation S_g at different depths, at a frequency of 25 Hz. The curves are represented in a logarithmic scale (a) and a linear scale (b). Increasing velocity at full gas saturation corresponds to increasing depth. The $z = 0$ ft curve is the velocity at atmospheric pressure p_0 and temperature T_0.

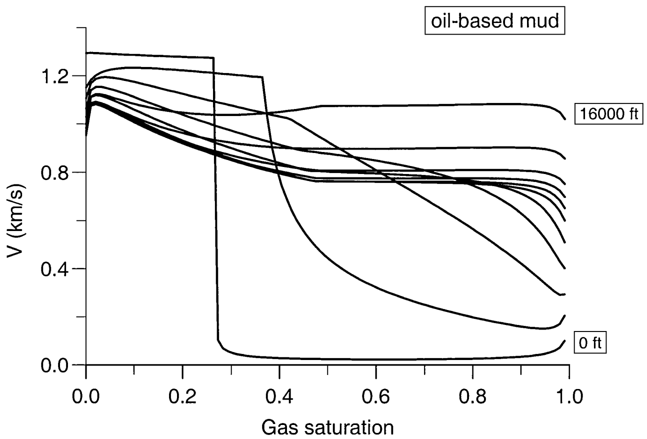


FIG. 3. Sound velocity of oil-based drilling mud versus gas saturation S_g at different depths, for a frequency of 25 Hz. The gas saturation is that at stage (2) (see Figure 1); a fraction of this gas dissolves into the oil, such that the real gas saturation is ϕ_g [stage (3)]. Below the critical saturation S_{gc} [see equation (29)], all the gas is in solution in the oil. This threshold is clearly evident as a discontinuity in dV/dS_g. Increasing velocity at full gas saturation corresponds to increasing depth.

saturation, the velocity increases approximately in proportion to the velocity of sound in air. In general, gas at greater depths, and therefore at higher pressure and temperature, has a higher sound velocity, since the bulk modulus increases faster than the density (this is not always the case for oil-based drilling mud). The oil-based–mud curves change substantially below the critical saturation S_{gc} ($\phi_g = 0$), when all the gas goes into solution. Above this threshold (i.e., when $\phi_g \geq 0$) , there is a fraction of free gas, and the behavior of the curves is, generally, quite different. At deep depths, this threshold cannot be distinguished, since the gas behaves much like the gas-saturated (live) oil.

The attenuation effect is more important at greater depths and midrange of saturations. For instance, the sound velocity of water-based drilling mud at 16 000 ft (4877 m) and $S_g = 0.5$ is 20 m/s less than the corresponding velocity in the lossless case. For higher attenuation, say, $Q_{\min} = 10$, the difference is 250 m/s. The effect starts to be important for Q less than 20, approximately. Clay particles in suspension are modeled as pure quartz particles. Actually, this may not be very realistic, since in suspension some flocculation is likely to occur. However, the results are not sensitive to changes in density and bulk modulus of the grains in suspension: decreasing the modulus by a factor of ten decreases the mud velocity a few meters per second.

CONCLUSIONS

We obtained the sound velocity of drilling mud when formation gas enters the wellbore at a given drilling depth, including the effect of gas absorption in the case of oil-based muds. For water-based muds, the velocities are higher at low gas saturations and greater depths, with minimum values at midrange of saturations. On the other hand, the velocities for oil-base muds have a dissimilar behavior depending on the presence of free gas (gas bubbles). The curves change substantially below a critical saturation, when all the gas goes into solution in the oil. This critical saturation decreases with decreasing depth, meaning that at shallow depths the gas is in the form of bubbles rather than dissolved in the oil.

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