Sonic attenuation in the JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate production research well

G. Guerin[1], D. Goldberg[1], and T.S. Collett[2]

Guerin, G., Goldberg, D., and Collett, T.S., 2005: Sonic attenuation in the JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate production research well; in *Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore and T.S. Collett; Geological Survey of Canada, Bulletin 585, 9 p.*

Abstract: The JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate research well was drilled to 1166 m through about 200 m of subpermafrost gas-hydrate-bearing sediments under the Mackenzie Delta, Canada. An extensive logging program was completed to characterize in situ the physical properties of the sediments where gas hydrate fills as much as 80% of the pore space. Analysis of sonic logging waveform show that the presence of gas hydrate increases sonic attenuation in agreement with previous results in the Mallik 2L-38 well. When applied to the Mallik 5L-38 well attenuations, the relationships between gas hydrate saturation and attenuation derived in the Mallik 2L-38 well provide concentrations in agreement with other estimates, showing that sonic attenuation can be used to quantify gas hydrate deposits. We use an improved model for wave propagation in frozen porous media to simulate these results and to understand the interaction between the gas hydrate and the host sediments.

Résumé : Le puits de recherche sur les hydrates de gaz JAPEX/JNOC/GSC et al. Mallik 5L-38, qui s'enfonce sous le delta du Mackenzie (Canada) jusqu'à une profondeur de 1 166 m, traverse sous le pergélisol environ 200 m de sédiments renfermant des hydrates de gaz. Un programme approfondi de diagraphie y a été mené afin de caractériser in situ les propriétés physiques de ces sédiments, dans lesquels les hydrates de gaz occupent jusqu'à 80 % de l'espace interstitiel. L'analyse des formes d'ondes obtenues dans les diagraphies acoustiques montre que la présence d'hydrates de gaz augmente l'atténuation des ondes acoustiques, ce qui concorde avec des résultats obtenus antérieurement pour le puits Mallik 2L-38. Lorsqu'appliquées aux données obtenues pour le puits Mallik 5L-38, les relations établies pour le puits Mallik 2L-38 entre la saturation en hydrates de gaz et l'atténuation des ondes acoustiques fournissent des valeurs de concentration en accord avec des estimations obtenues par d'autres méthodes. Ceci indique que l'atténuation des ondes acoustiques peut être utilisée pour quantifier les accumulations d'hydrates de gaz. Nous utilisons ici un modèle amélioré de propagation des ondes en milieu poreux gelé afin de simuler ces résultats et de comprendre la nature des interactions entre les hydrates de gaz et les sédiments qui les renferment.

[1]Borehole Research Group, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York 10964 U.S.A.
[2]United States Geological Survey, Denver Federal Center, Box 25046, MS-939, Denver, Colorado 80225 U.S.A.

INTRODUCTION

During the winter of 2001–2002, the international 2002 Gas Hydrate Production Research Well Program drilled three research wells at the mouth of the Mackenzie Delta, Canada, to complete the investigation of a major gas hydrate deposit that had been previously studied with the JAPEX/JNOC/GSC Mallik 2L-38 well (Dallimore et al., 1999; Dallimore and Collett, 2005). The 2001–2002 campaign drilled three wells (JAPEX/JNOC/GSC et al. Mallik 3L-38, 4L-38, and 5L-38) in order to perform production and geophysical experiments in addition to the coring and logging programs that were run in the central production well, Mallik 5L-38. In particular, crosshole geophysical measurements identified strong energy losses in the gas-hydrate-bearing intervals (Bauer et al., 2005), similar to the energy loss observed in the sonic logging waveforms recorded in the Mallik 2L-38 well (Guerin and Goldberg, 2002). The authors' main objectives with the sonic logging program in Mallik 5L-38 was to confirm with additional data the energy loss in sonic waveforms in the presence of gas hydrate that had been documented previously only in Mallik 2L-38. These additional data in a slightly different environment would determine whether accurate estimation of gas hydrate saturation could be derived from sonic attenuation. A further goal was to expand the understanding of the gas hydrate–sediment interaction by refining the authors' model for wave propagation in gas-hydrate-bearing sediments.

Herein, the authors first review the main logs recorded in Mallik 5L-38, and compare them with the Mallik 2L-38 data, in order to identify possible differences between the two wells, which are located about 100 m apart. Sonic attenuation was derived from the monopole and dipole waveforms and an attempt was made to use preliminary relationships derived in Mallik 2L-38 to quantify gas hydrate concentration in Mallik 5L-38 well from sonic attenuation. Finally, results are presented of a model for wave propagation in frozen porous media, improved from preliminary results from Guerin and Goldberg (2002), to illustrate the interactions between gas hydrate and the host sediments that could account for the energy loss.

LOGGING DATA

The logging program in Mallik 5L-38 benefited from very good hole conditions (*see* calliper log in Fig. 1a) and was extremely successful. A complete account of the different tools and data sets was made by Collett et al. (2005), but some of logs that could have significant implications for the characterization of sonic attenuation in gas-hydrate-bearing sediments are shown in Figure 1. In Figure 1b, the low values in the gamma-ray log indicate sand-rich intervals, whereas higher gamma-ray counts indicate more silt-rich or clay-rich formations (*see* Medioli et al., 2005). In Figure 1b, the gamma-ray readings in Mallik 5L-38 are overall higher than in Mallik 2L-38 (in brown, Fig. 1b), indicating generally higher clay content in Mallik 5L-38. This comparison shows also that the main sand-bearing intervals have the same character and can be correlated between the two wells; however, some of the sand units in Mallik 5L-38, particularly between about 980 m and 1050 m, are not as sharply defined as in Mallik 2L-38. Because these intervals are where most gas hydrate occurs, this distinction between the two sites might have considerable implication on the gas hydrate distribution and its effect on sonic waveforms.

Except for some spikes created by thin coal beds, the density and the porosity logs in Figure 1c display little variability over the entire hole, and indicate only a slight compaction-driven trend. In Figure 1d, the high values of the resistivity log in several intervals between 900 m and 1100 m are the most commonly recognized indicators for the presence of gas hydrate (Collett, 1998). The present authors used a 'quick look' Archie relationship to derive the gas hydrate saturation estimate (in red, Fig. 1e) from the resistivity log. In this method, the resistivity data recorded in formations without gas hydrate is used as a baseline profile (R_o) from which any increase is attributed to the presence of gas hydrate. The equation for the baseline in the Mallik 5L-38 well is calculated with a third-order polynomial fit as a function of depth, z, to the data in gas-hydrate-free intervals (above 900 m and below 1120 m). The saturation (S_h) is expressed in decimal fraction of the pore space as a function of R_o and of the recorded resistivity R(z) :

$$R_o(z) = 352 - 1.147z + 1.248\times10^{-3}z^2 - 4.484\times10^{-7}z^3 \quad (1)$$

$$S_h = 1 - (R_o(z)/R(z))^{1/1.9386} \quad (2)$$

where 1.9386 is an empirical constant determined by Pearson et al. (1983) and R(z) is the deep resistivity recorded with the Schlumberger array induction tool (AIT). The results show that gas hydrate occupies up to 80% of the pore space in the most gas-hydrate-rich intervals. The green curve in the same track (Fig. 1e) is the result of the 'standard' Archie formulation described by Collett et al. (1999)(Archie, 1942):

$$S_h = 1 - (aR_w/(R\Phi^m))^{1/1.9386} \quad (3)$$

where a and m are empirical constants that were used for similar estimations in the Mallik 2L-38 well (Collett et al., 1999; Guerin and Goldberg, 2002) and R_w is the formation water resistivity, calculated with Arp's formula (Desai and Moore, 1969), using a linear regional temperature profile (T(°C) = -23.1 + 0.036z for z > 613 m; Majorowicz and Smith (1999)) and a salinity of 25 ppt (Collett et al., 1999). The results of both 'standard' and 'quick look' Archie methods are similar, with a maximum difference on the order of 10%. Because it has slightly less scatter, the results of the 'quick look' method for crossplots are used in the following sections.

In Figure 1f, the compressional and shear velocity logs (V_p and V_s, respectively) are also strong indicators of the presence of gas hydrate. The higher velocity measured in intervals where gas hydrate is present reflects the indurating effect of gas hydrate replacing water in the pore space and partially cementing the matrix.

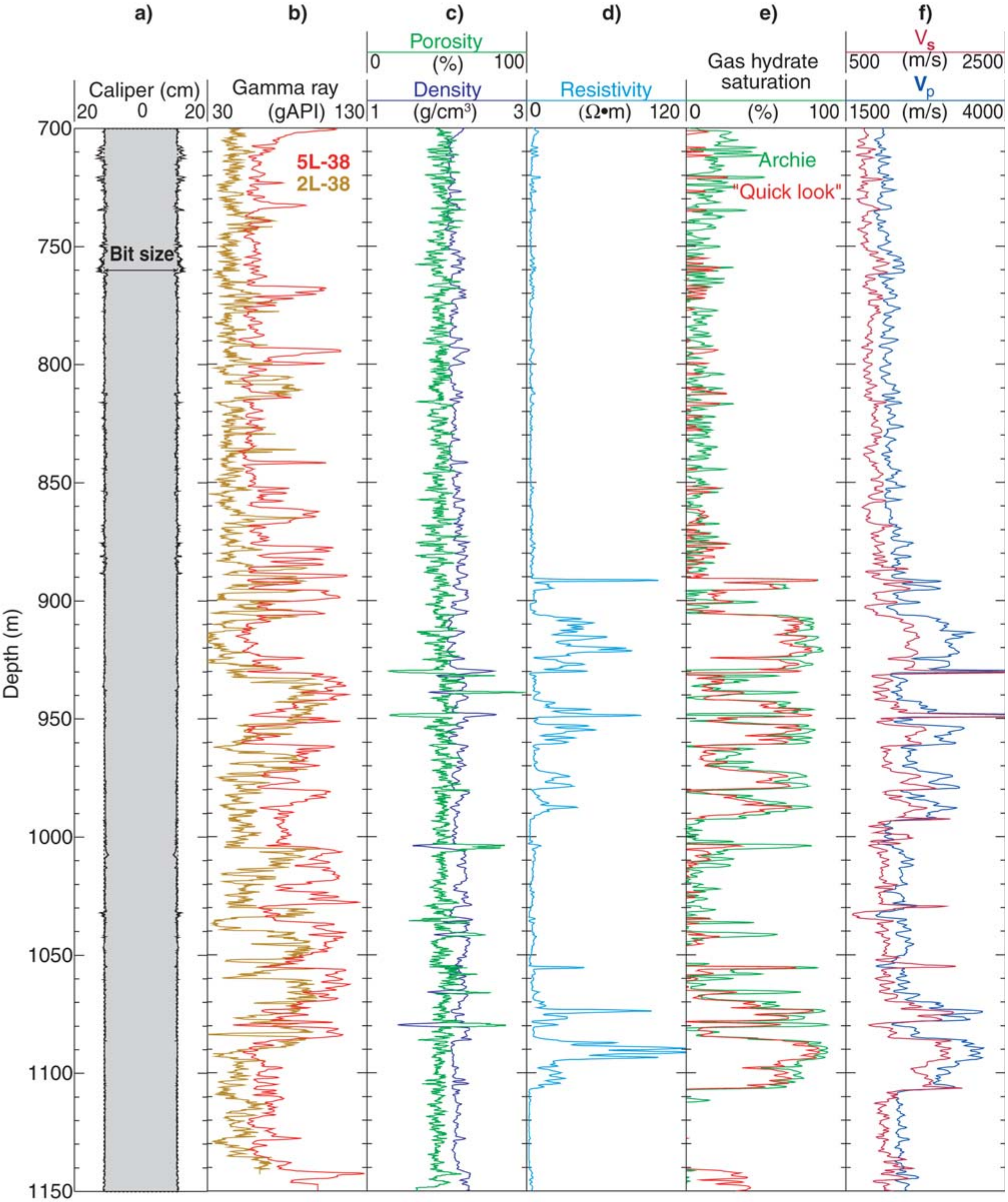

__Figure 1.__ Logs recorded in the Mallik 5L-38 production well: __a)__ calliper (in centimetres from the centre of the well; the bit size is indicated by the grey area); __b)__ gamma-ray logs recorded in Mallik 2L-38 and Mallik 5L-38; __c)__ porosity and density; __d)__ deep resistivity measured by the Schlumberger array induction tool (AIT); __e)__ gas hydrate saturations derived from the resistivity log, using the standard Archie relationship and the 'quick look' method; __f)__ compressional (V_p) and shear (V_s) sonic velocity.

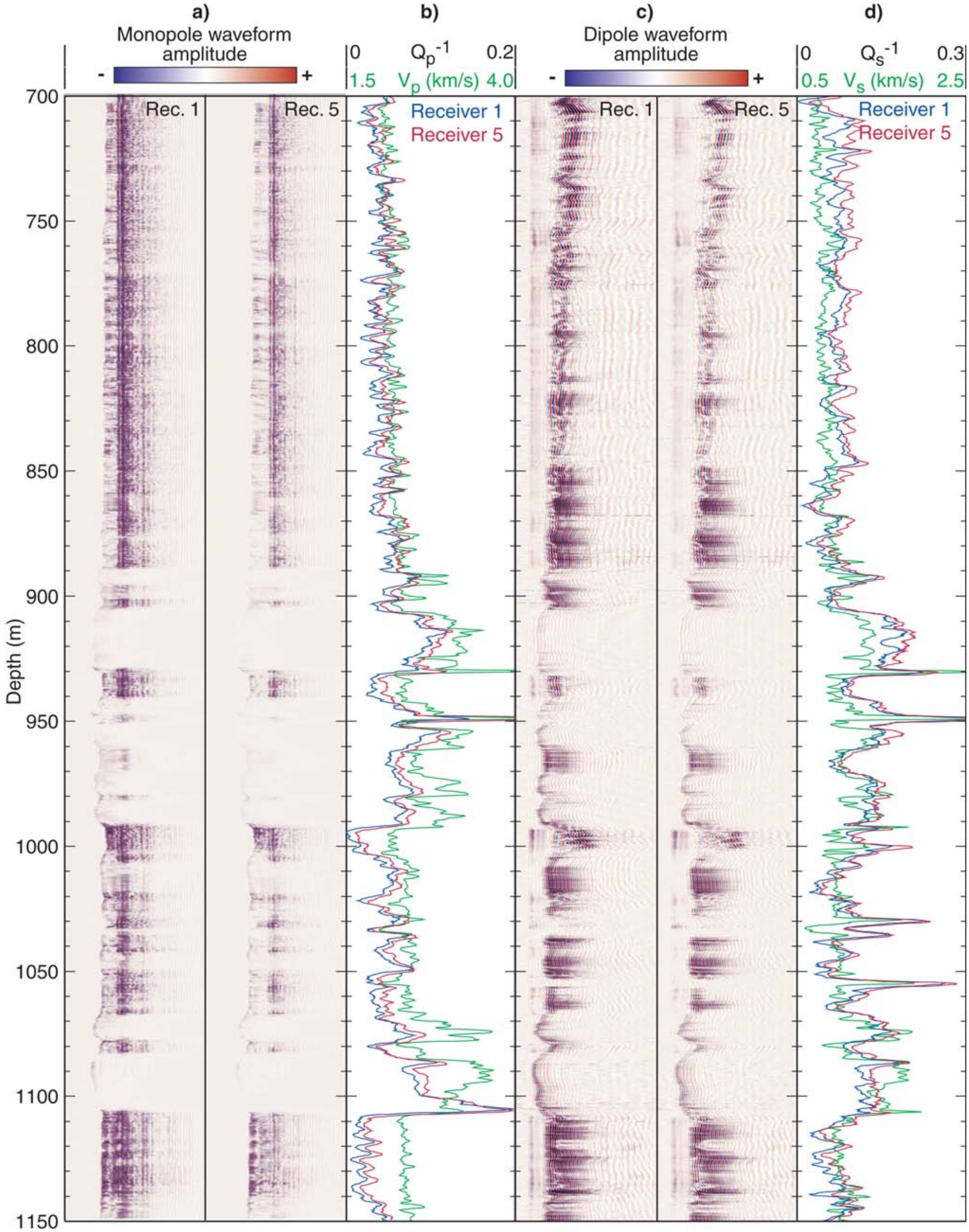

Figure 2. a) *Monopole waveforms recorded by receivers 1 and 5 of the DSI.* ***b)*** *Compressional attenuation (Q_p^{-1}) and velocity (V_p) calculated from the monopole waveforms.* ***c)*** *Lower dipole waveforms recorded by receivers 1 and 5 of the DSI.* ***d)*** *Shear attenuation (Q_s^{-1}) and velocity (V_s) calculated from the dipole waveforms.*

SONIC ATTENUATION

The V_p and V_s logs were derived from monopole and dipole sonic waveforms recorded with the eight receivers of the Schlumberger dipole shear sonic imager™ (DSI) . Monopole and lower dipole waveforms are shown in Figures 2a and 2c, respectively. These figures show that, in addition to the earlier arrivals due to higher velocity in the presence of gas hydrate, waveform amplitudes are much lower in intervals with high gas hydrate concentration. This energy dissipation is similar to what was observed in the Mallik 2L-38 well (Guerin and Goldberg, 2002). While some energy loss is attributed to the greater velocity contrast between the borehole fluid and the formation in the gas-hydrate-bearing intervals, numerical modelling of waveforms by Guerin and Goldberg (2002) showed that the formation intrinsic attenuation has to be significantly higher to account for the observed amplitude loss. Intrinsic attenuation can be quantified by the Q factor shown in Figures 2b and 2d. Attenuation was derived with the same method as described in Guerin and Goldberg (2002) and originally developed by Frazer et al. (1997) and Sun et al. (2000). The slightly higher values calculated for receiver 5 than for receiver 1 for both monopole and dipole waveforms result from the deeper penetration of the acoustic wave to get to the farther receivers. Overall, results from all receivers are in good agreement and show increased attenuation in intervals where gas hydrate can be identified in Figure 1. The relationship between attenuation and gas hydrate saturation measured with the 'quick look' Archie method is shown in Figure 3. The least-squares linear fit for each type of attenuation are also shown with their respective equations (regression coefficients in square brackets):

$$Q_p^{-1} = 0.0342 + 0.076S_h \text{ [0.688]} \quad (4)$$

$$Q_s^{-1} = 0.0785 + 0.135S_h \text{ [0.748] (upper dipole)} \quad (5)$$

$$Q_s^{-1} = 0.0615 + 0.134S_h \text{ [0.697] (lower dipole)} \quad (6)$$

where S_h is in decimal fraction. While the data are more scattered and the regression coefficients are lower than in Mallik 2L-38 (with coefficients >0.80, Guerin and Goldberg (2002)) these relationships are similar to the Mallik 2L-38 results and confirm a strong correlation between intrinsic attenuation and gas hydrate concentration. This relationship also suggests that it might be possible to use attenuation to estimate gas hydrate saturation.

In Figure 4, gas hydrate concentration in Mallik 5L-38 is estimated by using the calculated attenuation values and the relationships derived by Guerin and Goldberg (2002) between attenuation and gas hydrate concentration:

$$Q_p^{-1} = 0.029 + 0.12S_h \text{ and } Q_s^{-1} = 0.065 + 0.17S_h. \quad (7)$$

The reciprocal relationships that can be used to estimate saturation are

$$S_h = 8.33Q_p^{-1} - 0.242 \text{ and } S_h = 5.88Q_s^{-1} - 0.382 \quad (8)$$

For comparison, dashed lines on Figure 4 indicate the saturations calculated with the reciprocal relationships for equations 4–6 derived in the Mallik 5L-38 well. Because the relationships between attenuation and saturation calculated at

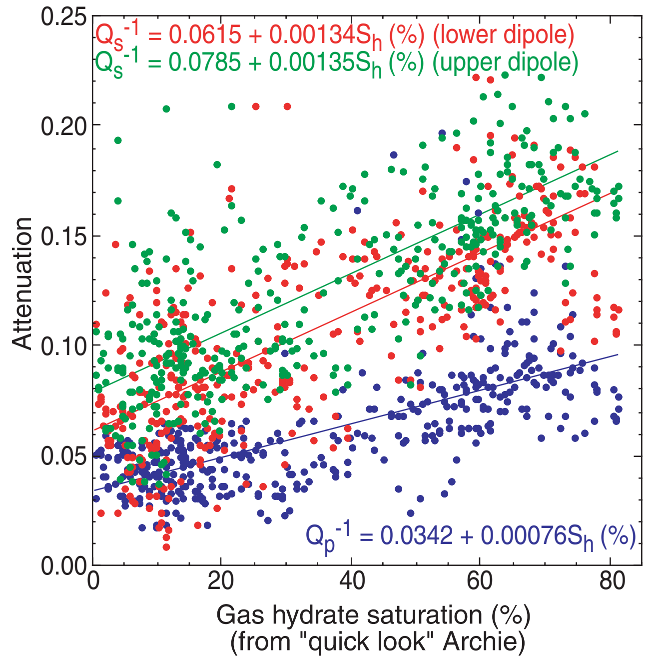

Figure 3. *Relationships between gas hydrate saturations and sonic attenuations calculated from the three recorded modes (monopole, upper dipole, and lower dipole). The attenuations are the values calculated for the first receiver.*

the two sites are very similar, the results produced by the two sets of equations are in very good agreement. In the same figure, the comparison of these results with the saturations derived by the 'quick look' Archie method from the resistivity log shows that values derived from sonic attenuation provide a reliable estimate of gas hydrate saturation. Because the regression coefficients in equations 4–6 were derived from the 'quick look' Archie results, the agreement with these values is slightly better, but both sets of equations identify the same gas-hydrate-bearing intervals and provide very similar saturation values. Saturations calculated from the monopole attenuation are in slightly better agreement with the 'quick look' Archie saturations than the values calculated with either dipole, in particular between about 980 m and 1050 m where the gamma-ray logs display more significant differences between the two sites. The authors infer that the dipole attenuation may be more sensitive than monopole attenuation to additional parameters, such as lithological variations, which are not reflected in these simple least-squares linear relationships.

MODELLING OF ELASTIC WAVES IN GAS-HYDRATE-BEARING POROUS MEDIA

The waveform amplitudes and attenuations measured in Mallik 5L-38 provide a confirmation of previous observations in Mallik 2L-38, and suggest that sonic attenuation can be a quantitative indicator of gas hydrate concentration; however, in order to use attenuation as a reliable measure of gas hydrate concentration in other gas hydrate fields and geological conditions, it is necessary to understand the nature of the interaction

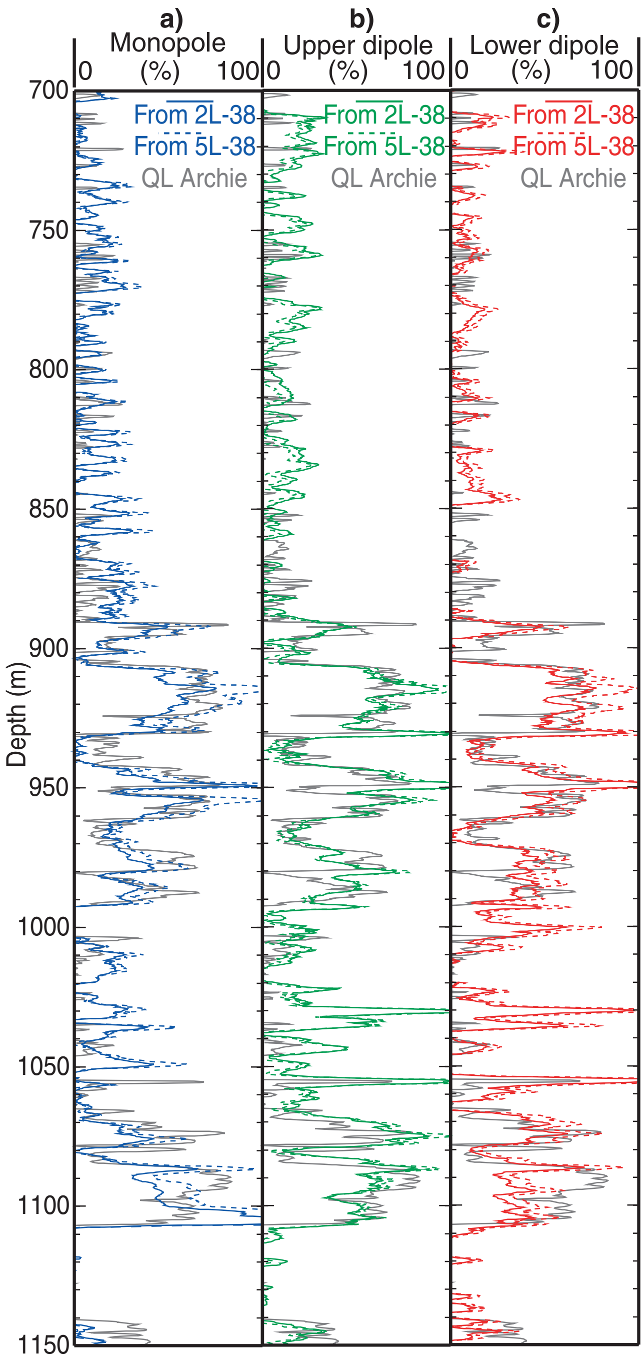

Figure 4. *Estimation of gas hydrate saturation from sonic attenuations in Mallik 5L-38 well:* ***a)*** *monopole,* ***b)*** *upper dipole, and* ***c)*** *lower dipole. Continuous lines show the results using the relationship derived in Mallik 2L-38 (equation 8). Dashed lines show the results using the relationships derived in Mallik 5L-38 (equations 4–6). All results can be compared with the results of the 'quick look' (QL) Archie method (grey lines).*

between the host sediments, the pore fluid, and the gas hydrate. Several models have been described to explain the velocity increase in gas-hydrate-bearing sediments, but most of them do not provide any measure of attenuation. Guerin and Goldberg (2002) and Gei and Carcione (2003) both used the Leclaire et al. (1994) numerical formulation for wave propagation in frozen porous media to determine elastic properties in the presence of gas hydrate. Gei and Carcione (2003) suggested that attenuation should decrease with gas hydrate, but results from this study in the two Mallik wells contradict their conclusion.

Assuming that Biot's (1956) theory for wave propagation is still valid in the presence of gas hydrate, which is the basis of the Leclaire et al. (1994) model, some parameters and assumptions were added in this study that were dismissed by Leclaire et al (1994).

In particular, one major simplification by Leclaire et al. (1994) was to neglect any interaction between ice and the grain matrix; however, the fact that shear velocity increases in the presence of gas hydrate shows that some shear energy is transmitted between grains and gas hydrate, which can occur only if there is interaction between the two media. Carcione and Tinivella (2000) expanded the Leclaire model to include gas hydrate–grain interaction by adding terms in the stiffness, shear, and density matrices for the equations of wave propagation. The authors have included these new components and have also added a coefficient of friction between gas hydrate and grains, b_{13}, in the dissipation matrix, and a coupling shear modulus, μ_{si}, in the expression of the gas hydrate–grain coefficient, μ_{13}, in the shear matrix. Carcione and Tinivella (2000) assumed that these coefficients were null, however the present authors have found that their inclusion can have a significant effect on the attenuation. At this point these new terms have been given arbitrarily simple expressions as a function of gas hydrate saturation:

$$b_{13} = b_{\text{grain/gas hydrate}} S_h^2 \text{ and } \mu_{si} = \mu_{\text{grain/gas hydrate}} S_h^2 \quad (9)$$

where $b_{\text{grain/gas hydrate}}$ and $\mu_{\text{grain/gas hydrate}}$ are constant empirical coefficients.

In addition, the Leclaire model, following directly from Biot's (1956) theory, considered energy dissipation only in the direction of wave propagation, not transverse propagation. Dvorkin and Nur (1993) proposed the BISQ (Biot/Squirt) flow theory, where squirt flow is added to the Biot formulation, as fluid is squeezed laterally from pores deformed by a passing elastic wave. Diallo and Appel (2000) proposed a modification to the pore-fluid pressure in the BISQ model, allowing for squirt flow without requiring a 'squirt length' to be defined. To introduce squirt flow into the Leclaire model for frozen porous media, Diallo and Appel's (2000) expression for pore pressure has been used to replace the pore-fluid stress-strain (a stress versus strain) relationship in the Leclaire (1994) model.

This study also tried to take into account the fact that gas hydrate forms preferentially in sand-dominated intervals. Figure 5 clearly illustrates gas hydrate saturation inversely varying with gamma-ray counts in the Mallik 5L-38 well. While the gamma-ray log is not an absolute measure of shale content, Figure 5 shows that gas hydrate concentrations higher than 20% occur only in intervals with low gamma-ray values. There is nearly a linear reduction in saturation with increasing gamma-ray values. An inverse linear relationship has been assumed between shale content and gas hydrate saturation in the present model, with shale fraction ranging from 20% to 80%. The matrix is assumed to be only a mixture of sand and shale. This assumption affects only the values of the grains and frame elastic moduli, and of the matrix permeability. The frame moduli was calculated with the approach of Dvorkin et al. (1999). The matrix permeability, κ_s, is expressed as a function of the shale decimal fraction, γ, using the results of McCarthy (1991):

$$\kappa_s = \kappa_{so}(1-\gamma)^3 \tag{10}$$

where κ_{so} is the permeability of the clean sand. The mechanisms for attenuation due to the interaction between sand and shale are not included in the current model.

Figure 6 shows the results of the model from this study for V_p, V_s, Q_p^{-1}, and Q_s^{-1}, for three values of the coupling shear modulus $\mu_{grain/gas\ hydrate}$. The values of all the parameters used are shown in Table 1. The gas hydrate elastic moduli are from Helgerud et al. (1999). In the background of each figure the actual data from the Mallik 5L-38 sonic waveforms is shown. While the model results do not reproduce exactly the trends of the measured attenuation, this figure shows that it is possible to reproduce the observed general trends of the increase in velocity and attenuation with increasing gas hydrate saturation, for both compressional and shear waves. To achieve these results, very low, or practically null, values were used for the inertia coefficients between gas hydrate and both water and the grains (r_{13} and r_{23} in Leclaire et al. (1994) and Carcione and Tinivella, (2000)), which implies a very small transfer of kinetic energy between gas hydrate and the other phases. These values were essential to the simulation of the high attenuation observed in gas hydrate.

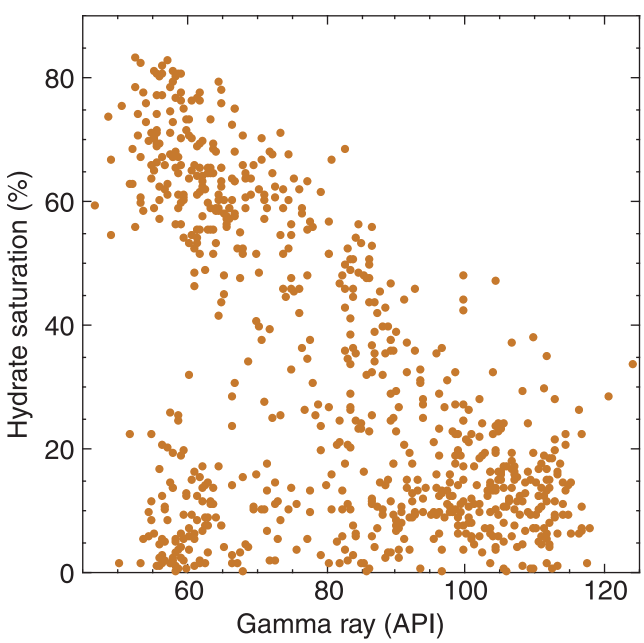

Figure 5. Relationship between gamma-ray log and gas hydrate saturations calculated with the quick look' Archie method in the Mallik 5L-38 well.

Table 1. Parameters used in the model.

Parameter	Value
Porosity (%)	35
Grain density (kg/m^3)	2590
Water density (kg/m^3)	1000
Hydrate density (kg/m^3)	900
Sand permeability (κ_{so}) (m^2)	1x10^{-11}
Sand bulk modulus (x10^{9}Pa)	38
Sand shear modulus (x10^{9}Pa)	44
Shale bulk modulus (x10^{9}Pa)	21.2
Shale shear modulus (x10^{9}Pa)	6.67
Water bulk modulus (x10^{9}Pa)	2.67
Hydrate bulk modulus (x10^{9}Pa)	7.9
Hydrate shear modulus (x10^{9}Pa)	3.3
Hydrate permeability (κ_{io} in Leclaire et al. (1994)) (m^2)	10^{-5}
Grain/hydrate coefficient of friction ($b_{grain/hydrate}$, kg/m^{3}s)	4.0x10^7
Monopole frequency (Hz)	12 000
Dipole source frequency (Hz)	2000
Water viscosity (kg/m^{3}s)	1.8x10^{-3}

DISCUSSION AND CONCLUSIONS

These results show that Biot's (1956) theory, combined with the formulation of Leclaire et al. (1994) for three phase media, can be used to describe sonic wave propagation in gas-hydrate-bearing sediments. The model attenuation is generally lower than the measured values, but this could be due in part to the fact that the model presented herein does not simulate the attenuation due to the different mineral phases in the matrix itself. In the model, attenuation is almost null at zero gas hydrate concentration, whereas the high clay content could contribute to additional energy dissipation.

Interactions between gas hydrate and the host sediments that occur at various levels have been added to the model: through cementation (μ_{si}), friction (b_{13}), and with low inertial transmission ($r_{13} = r_{23} \sim 0$). These model results reproduce the data better than previously reported for the Mallik 2L-38 data (Guerin and Goldberg, 2002). It still remains to be determined how these modes of energy transmission physically combine at the pore scale.

The good overall agreement between the results in Mallik 2L-38 and Mallik 5L-38 wells suggests that it is possible to use sonic attenuation to estimate gas hydrate saturations. The proximity of the two sites and the similarity of the lithology make hole-to-hole correlations relatively straightforward in the Mallik field; however, it is advisable to use additional log data to make the relationships more robust and transportable

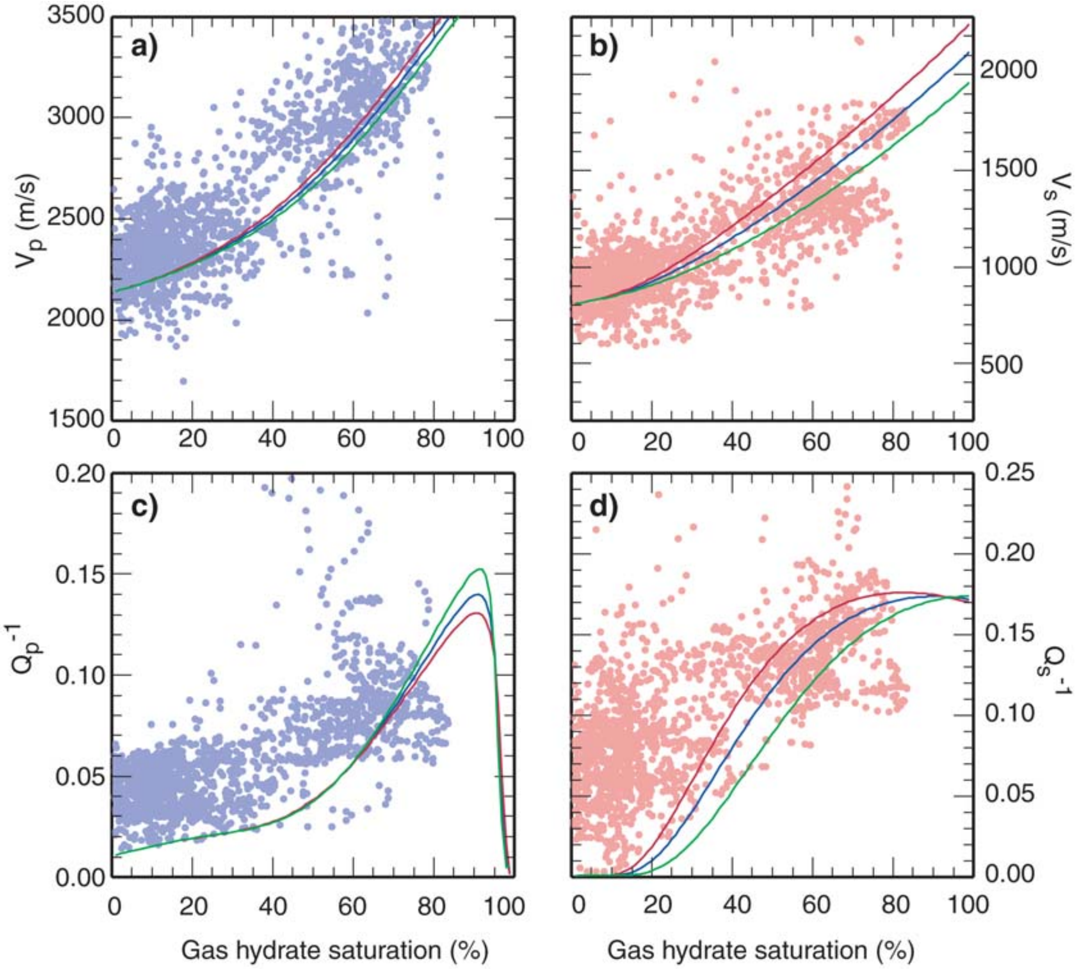

Figure 6. *Results of the modelling of wave propagation in gas-hydrate-bearing sediments for various values of the coupling shear modulus (green* $\mu_{grain/gas\ hydrate} = 6.0\mathrm{x}10^9$ *Pa; blue* $\mu_{grain/gas\ hydrate} = 8.0\mathrm{x}10^9$ *Pa; red* $\mu_{grain/gas\ hydrate} = 1.0\mathrm{x}10^{10}$ *Pa):* ***a)*** V_p, ***b)*** V_s, ***c)*** Q_p^{-1}, ***d)*** Q_s^{-1}. *The values in the background are the data recorded in the Mallik 5L-38 well.*

to other gas hydrate fields, and before attempting to make quantitative comparisons. In particular, and because of the role of clay content or lithological variations in general on sonic attenuation, a more versatile relationship should be developed to include other lithology-dependent indicators, such as the gamma-ray log, to estimate gas hydrate concentration from sonic-log waveform data.

ACKNOWLEDGMENTS

The authors acknowledge the international partnership that undertook the Mallik 2002 Gas Hydrate Production Research Well Program and gave us access to the data discussed in this paper: the Geological Survey of Canada (GSC), the Japan National Oil Corporation (JNOC), GeoForschungsZentrum Potsdam (GFZ), the United States Geological Survey (USGS), the United States Department of Energy (USDOE), the India Ministry of Petroleum and the Natural Gas (MOPNG)–Gas Authority of India (GAIL), and the BP-ChevronTexaco-Burlington joint venture parties. The program received financial support from the International Continental Scientific Drilling Program (ICDP). We thank S. Dallimore and T. Collett for the invitation to be part of Mallik 2002 research team. Reviews by T. Plona, A. Taylor, and an anonymous reviewer improved this manuscript. The International Continental Scientific Drilling Program and Lamont-Doherty Earth Observatory provided support for fieldwork at the Mallik 2002 site (D. Goldberg) and for the authors' participation in the Mallik 2002 workshops in Ottawa and Whistler (D. Goldberg and G. Guerin).

REFERENCES

Archie, G.E.
1942: The electrical resistivity log as an aid in determining some reservoir characteristics; Journal of Petroleum Technology, v. 5, p. 1–8.

Bauer, K., Pratt, R.G., Weber, M.H., Ryberg, T., Haberland, C., and Shimizu, S.
2005: Mallik 2002 cross-well seismic experiment: project design, data acquisition, and modelling studies; in Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore and T.S. Collett; Geological Survey of Canada, Bulletin 585.

Biot, M.A.
1956: Theory of propagation of elastic waves in a fluid saturated porous solid; Journal of the Acoustical Society of America, v. 28, p. 168–191.

Carcione, J.M. and Tinivella, U.
2000: Bottom-simulating reflectors: seismic velocities and AVO effects; Geophysics, v. 65, p. 54–67.

Collett, T.S.
1998: Well log evaluation of gas hydrate saturations; *in* Transactions of the Society of Professional Well Log Analysts, 39th Annual Logging Symposium, Paper MM, Society of Professional Well Log Analysts, Houston, Texas.

Collett, T.S., Lewis, R.E. and Dallimore, S.R.
2005: JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate production research well downhole well-log and core montages; *in* Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore and T.S. Collett; Geological Survey of Canada, Bulletin 585.

Collett, T.S., Lewis, R.E., Dallimore, S.R., Lee., M.W., Mroz, T.H., and Uchida, T.
1999: Detailed evaluation of gas hydrate reservoir properties using JAPEX/JNOC/GSC Mallik 2L-38 gas hydrate research well downhole well-log displays; *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett, Geological Survey of Canada, Bulletin 544, p. 295–311.

Dallimore, S.R. and Collett, T.S.
2005: Summary and implications of the Mallik 2002 Gas Hydrate Production Research Well Program; *in* Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore and T.S. Collett; Geological Survey of Canada, Bulletin 585.

Dallimore, S.R., Uchida., T., and Collett, T.S. (ed.)
1999: Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Geological Survey of Canada, Bulletin 544, 403 p.

Desai, K.P. and Moore, E.J.
1969: Equivalent NaCl concentrations from ionic concentrations; The Log Analyst, v. 10, no. 3, p. 12–21.

Diallo, M.S. and Appel, E.
2000: Acoustic wave propagation in saturated porous media: reformulation of the Biot/Squirt flow theory; Journal of Applied Geophysics, v. 44, p. 313–325.

Dvorkin, J. and Nur, A.
1993: Dynamic poroelasticity: a unified model with the squirt flow and the Biot mechanism; Geophysics, v. 58, p. 524–533.

Dvorkin, J., Prasad, M., Sakai, A., and Lavoie, D.
1999: Elasticity of marine sediments: rock physics modeling; Geophysical Research Letters, v. 26, no. 12, p. 1781–1784.

Frazer, L.N., Sun, X., and Wilkens, R.H.
1997: Changes in attenuation with depth in an ocean carbonate section: ODP sites 806 and 807, Ontong Java plateau; Journal of Geophysical Research, v. 102, p. 2983–2997.

Gei, D. and Carcione, J.M.
2003: Acoustic properties of sediments saturated with gas hydrate, free gas and water, Geophysical Prospecting, v. 51, p. 141–157.

Guerin, G. and Goldberg, D.
2002: Sonic waveform attenuation in gas hydrate-bearing sediments from the JAPEX/JNOC/GSC Mallik 2L-38 research well, Mackenzie Delta, Canada; Journal of Geophysical Research, v. 107, no. B5, p. EPM1-1 to EMP1-11.

Helgerud, M.B., Dvorkin, J., Nur, A., Sakai, A., and Collett, T.S.
1999: Elastic-wave velocity in marine sediments with gas hydrates: effective medium modeling; Geophysical Research Letters, v. 26, no. 13, p. 2021–2024.

Leclaire, P., Cohen-Tenoudji, F., and Aguirre-Puente, J.
1994: Extension of Biot's theory of wave propagation to frozen porous media; Journal of the Acoustical Society of America, v. 96, no. 6, p. 3753–3768.

Majorowicz, J.A. and Smith, S.L.
1999: Review of ground temperatures in the Mallik field area: a constraint to the methane hydrate stability; *in* Scientific Results from JAPEX/JNOC/GSC Mallik 2L-38 Gas Hydrate Research Well, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore, T. Uchida, and T.S. Collett; Geological Survey of Canada, Bulletin 544, p. 45–56.

McCarthy, J.F.
1991: Analytical models of the effective permeability of sand-shale reservoirs; Geophysical Journal International, v. 105, p. 513–527.

Medioli, B.E., Wilson, N., Dallimore, S.R., Paré, D., Brennan-Alpert, P., and Oda, H.
2005: Sedimentology of the cored interval, JAPEX/JNOC/GSC et al. Mallik 5L-38 gas hydrate production research well; *in* Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Program, Mackenzie Delta, Northwest Territories, Canada, (ed.) S.R. Dallimore and T.S. Collett; Geological Survey of Canada, Bulletin 585.

Pearson, C.F., Halleck, P.M., McGuire, P.L., Hermes, R., and Mathews, M.
1983: Natural gas hydrates deposits: a review of in situ properties; Journal of Physical Chemistry, v. 87, p. 4180–4185.

Sun, X., Tang, X., Cheng, C.H., and Frazer, L.N.
2000: P- and S-wave attenuation logs from monopole sonic data; Geophysics, v. 65, no. 2, p. 755–765.