IN-SITU THERMAL CONDUCTIVITY OF GAS-HYDRATE-BEARING SEDIMENTS OF THE JAPEX/JNOC/GSC ET AL. MALLIK 5L-38 WELL

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ABSTRACT
Detailed knowledge about the thermal properties of rocks containing gas hydrate is required in order to quantify processes involving the formation and decomposition of gas hydrate in nature. In the framework of the Mallik 2002 program three wells penetrating a continental gas hydrate occurrence under permafrost were successfully equipped with permanent fiber-optic distributed temperature sensing cables. Temperature data were collected over a period of 21 months after completion of the wells. Thermal conductivity profiles were calculated from the geothermal data as well as from a petrophysical model derived from the available logging data and application of mixing-law models. The results indicate, that variations of thermal conductivity are mainly lithologically controlled with a minor influence from hydrate saturation. Average thermal conductivity values of the hydrate-bearing intervals range between 2.35 W m\(^{-1}\) K\(^{-1}\) and 2.77 W m\(^{-1}\) K\(^{-1}\).

Keywords: Temperature logging, Gas hydrate, Thermal conductivity.

INTRODUCTION
The thermal properties of hydrate bearing rocks are a controlling factor for all processes involving the formation and decomposition of gas hydrate in nature, which are inevitably coupled with the transport of heat within the formation. The thermal conductivity of pure methane hydrate was determined as 0.45 W m\(^{-1}\) K\(^{-1}\) at 216.2 K [1]. The thermal conductivity of pure hydrate is therefore about 20 % lower than the thermal conductivity of water, and up to 80 % lower than that of ice. Because of the low thermal conductivity of pure hydrate it has often been proposed, that the presence of gas hydrate should have a significant influence on the bulk rock thermal conductivity and the geothermal gradient within hydrate-bearing formations [2]. But until now, there is a lack of thermal conductivity data measured on rock samples and only a limited number of laboratory measurements on artificially produced samples have been published.

The direct measurement of thermal conductivity on hydrate-bearing rock samples is generally hampered by the difficulties and uncertainties arising from possible degradation of hydrate during sample retrieval and preparation. Furthermore measurements have to be performed under in-situ conditions in order to maintain the proportion of the phases present within the pore space.

Stoll and Bryan [3] performed measurements of the thermal conductivity of mixtures of sand, water, gas and hydrate. They concluded, that the thermal conductivity of a propane hydrate saturated sand with 40 % porosity was reduced about 23 % compared...
to water saturated conditions. Waite et al. [4] performed measurements of thermal conductivity on porous mixtures of methane hydrate and quartz sand with varying percentages of hydrate content. They concluded, that the bulk rock thermal conductivity was influenced by two different effects: Increases of the bulk rock thermal conductivity were interpreted as the result of enhanced intergranular contact, while decreases were attributed to the low thermal conductivity of the hydrate itself.

Here we investigate the influence of methane hydrate on the transport of heat in porous rocks based on analysis of geophysical borehole logging data collected during the Mallik 2002 Gas Hydrate Production Research Well Program [5] [6]. The in-situ thermal conductivity is estimated using two independent approaches: The effective thermal conductivity of gas hydrate bearing sediments is calculated using different mixing-law models in combination with methods of formation evaluation from well-log data. Secondly thermal conductivity profiles are calculated from the measured geothermal gradients and an estimate of local heat-flow density based on Fourier’s law of heat conduction.

### GEOLOGY, PERMAFROST AND GAS HYDRATE OCCURRENCES

The Mallik site is located in the Mackenzie-Delta area in the northwestern part of arctic Canada, at the northern edge of Richards Island close to the Beaufort Sea. The gas hydrate accumulations occur within a sedimentary succession between about 800 m and 1,100 m below ground level, which is overlain by a thick permafrost layer extending to a depth of about 600 m below ground level [6].

A series of high- and low-amplitude seismic reflectors was interpreted as an interbedded succession of gas-hydrate-bearing sandstones and non-gas-hydrate-bearing shale layers [7]. The hydrate-bearing strata at Mallik have been assigned to the Mackenzie Bay and Kugmallit sequences of Oligocene and Early Miocene age [8]. The lithology of the core samples retrieved from the Mallik 2L-38 and 5L-38 wells generally varied between unconsolidated sands and gravels, to compact sandstones and shales. Medioli et al. [9] identified six informal lithological units within the cored interval of the Mallik 5L-38 well between 885.63 m \(^1\) and 1150.79 m (Table 1). Within the succession of sand- and silt-dominated sedimentary units a number of thin (0.1 m to 1.7 m) dolomite cemented sandstones and low-rank coal beds are occurring.

### DISTRIBUTED TEMPERATURE MEASUREMENTS

#### Installation of Sensor Cables and Logging Schedule

Within the framework of the Mallik 2002 Program, the three 1200 m deep wells, spaced at 40 m, were equipped with permanent fiber-optic sensor cables [6]. In the two lateral observation wells, the sensor cables were installed to a depth of 1158 m in order to determine the formation temperatures. In the central Mallik 5L-38 well temperatures were measured to about 940 m depth, and on-line temperature monitoring during a thermal stimulation experiment was performed [10].

Within recent years, fiber-optic distributed temperature sensing (DTS) has been introduced as a new technology for the measurement of temperature in boreholes [11, 12]. Through the deployment of DTS technology, quasi-continuous temperature profiles can be measured with high temporal resolution.

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1 All depths are given relative to rotary kelly bushing, which is 4.6 m above ground level, or 5.6 m above sea level, unless not otherwise indicated.
Short laser pulses are injected into an optical fiber and the temperature distribution is calculated from the backscattered and reflected light signal [13]. A special feature of the experimental design at Mallik is the permanent installation of the sensor cables behind the borehole casing. After completion of the well, the sensor cables are located in the cement annulus between casing and borehole wall (Fig. 1). The DTS logging was started one to two days after completion of the respective well, and continuous monitoring of the well temperatures was performed over a period of up to 61 days between January and March 2002. Two subsequent DTS surveys were carried out for long-term temperature monitoring in October 2002 and September 2003 with a temporary set-up of the DTS equipment. In total, the borehole temperatures were recorded over a period of 21 months after drilling of the wells. Further details about the installation procedure and the temperature logging program can be found in Hennines et al. [6].

**Processing of Temperature Data**

In order to generate temperature profiles which can be compared to the other available borehole data, the raw DTS temperature data was correlated to the elevation of the rotary kelly bushing (KB) on the drill floor as a common depth datum. The depth values were calculated with reference to the known positions of the casing connectors, the depths of which were picked from the casing-collar-locator logs (CCL). In the Mallik 5L-38 well the distinct temperature signal of the perforating gun was used for the depth correlation, because the position of the end of the sensor cable was not exactly known due to a fiber break.

Under controlled conditions within the laboratory, the measured temperatures showed an accuracy of ±0.3 °C after calibration. The temperature resolution is proportional to the square root of integration time. After completion of the measurements the temperature data was averaged over approximately two hour intervals resulting in a temperature resolution of about $6 \cdot 10^{-2}$ K. The stacked temperature data was filtered using the Fast Fourier Transformation (FFT) eliminating coherent noise generated by the DTS instrument. The resulting FFT-filtered temperature profile data was additionally smoothed using a 3-point running average filter in order to reduce the random noise prior to evaluation (Fig. 2). The estimated temperature resolution of the processed DTS data is $1.10 \cdot 10^{-2}$ K and $2.60 \cdot 10^{-2}$ K for the Mallik 3L-38, and 4L-38/5L-38 wells respectively.

**Measurement Results**

Excerpts from the recorded temperature data are displayed in Figure 1 as temperature profiles for successive points in time after the cementing of the Mallik 3L-38 observation well (shut-in time $t_s$). As a result of the thermal disturbance due to the drilling process, the borehole temperature is continuously equilibrating to the temperature of the surrounding formation during the 21-month logging period. The analysis of the temperature data from the 3L-38 and 4L-38 wells using the Horner-plot method...
showed that the well temperatures measured during the September 2003 DTS survey have returned to about ±0.1 °C from equilibrium with the formation temperatures [6]. The measured changes of temperature with depth are therefore approximately equal to the geothermal gradient.

The geothermal gradient ($\Gamma$) is defined as the change of the formation temperature ($dT$) with depth ($dz$) in vertical direction, normal to the earth’s surface:

$$\Gamma = \frac{dT}{dz}$$  \hspace{1cm} (1)

Depth profiles of the temperature gradients calculated from the measured borehole temperature data within the zone of the gas hydrate occurrences are displayed in Figure 3. Below the base of the ice-bearing permafrost, which was determined between 604±3.5 m and 609±3.5 m [6], the mean temperature gradient within the Mackenzie Bay Sequence is about 23.5 - 24.1 K km$^{-1}$. Below about 920 m, the geothermal gradient shows distinct variations and locally increases over 40 K km$^{-1}$. The onset of this interval with zones of increased geothermal gradients appears in all three wells and correlates with the boundary between the Mackenzie Bay and Kugmallit sequences, which at the Mallik 5L-38 well appears at a depth of 932.6 m [9]. Individual peaks of the geothermal gradient exhibit a good correlation between the Mallik 3L-38 and 4L-38 wells. As commonly observed, the geothermal gradient correlates with the gamma-ray log. Sand-dominated units, marked by low gamma-ray intensities, characteristically have a higher thermal conductivity than silt- or clay-dominated units with high gamma-ray intensities. In contrast to this, there is no apparent correlation of the temperature gradient and the estimated hydrate saturation.

**Figure 3:** Detail of the 10-m average temperature gradients (September 2003) within the zone of the gas hydrate occurrences (GHZ). GR: gamma-ray intensity, Mallik 5L-38; $S_h$: gas hydrate saturation (fraction of total porosity) estimated from difference of density-porosity and NMR-porosity logs of Mallik 5L-38 well (DMR method, see text for further details).

**IN-SITU THERMAL CONDUCTIVITY**

In the framework of the Mallik 2002 program only a very limited number of direct measurements of thermal conductivity on hydrate-bearing rock samples was carried out [15]. Therefore within this study the in-situ thermal conductivity was estimated from petrophysical models as well as from the measured geothermal gradient.
A Petrophysical Rock Model from Logging Data

In a simplified model, gas-hydrate-bearing sediment can be thought of as being composed of four components: The sediment matrix is mainly composed of quartz grains and shale, and the pore space is filled by water and/or gas hydrate [16]. According to the petrophysical measurements which were performed on core samples from Mallik there is strong evidence, that gas hydrate is forming a discontinuous phase within the pore fluid [17]. The volumetric proportions of each of these components are subject to changes resulting from variations in lithology and hydrate saturation. The volumetric composition, i.e. mineral content of the sediment matrix, porosity, and saturation of the pore filling phases, were estimated from the available geophysical logging data.

Shale Content

The shale content was determined from the gamma-ray log reading. The local gamma-ray intensity $GR$ is linearly scaled between the minimum and maximum gamma-ray intensities, which are equal to the gamma-ray readings in a pure sand and a pure shale within the rock type under investigation:

$$GRI = \frac{GR - GR_{\text{min}}}{GR_{\text{max}} - GR_{\text{min}}}$$  \hspace{1cm} (2)

Depending on the type of sediment, the age and the degree of consolidation, the shale content $V_{sh}$ is then calculated as a function of the gamma-ray index GRI. For the Mallik sediments, the following relation was used, which was derived empirically for weakly consolidated sediments of tertiary and younger age [18]:

$$V_{sh} = 0.083 \left(2^{3.7 \cdot GRI} - 1 \right)$$  \hspace{1cm} (3)

The calculated $V_{sh}$-values were calibrated using the available grain-size analysis data from 213 core samples from the Mallik 5L-38 well [9]. The $GR_{\text{min}}$ and $GR_{\text{max}}$ values in Equation 2 were successively adjusted until a good fit with the measured silt grain fractions was achieved.

Porosity and Gas Hydrate Saturation

Kleinberg et al. [19] have proposed the Density-Magnetic Resonance (DMR) Method in order to determine the gas hydrate saturation from geophysical well logs. The DMR method was also applied using the well logs of the Mallik 5L-38 well [20], and the estimated hydrate saturations show a good agreement with the results of measurements on core samples from Kulenkampff and Spangenberg [17]. Nuclear magnetic resonance (NMR) logging tools respond quantitatively to pore space liquid water but not to gas hydrate [19]. With the DMR method, the gas hydrate saturation $S_h$ is computed from the difference between gamma-gamma density log apparent porosity, $DPHI$, and the magnetic resonance apparent porosity, $TCMR$ [20]:

$$S_h = \frac{DPHI - TCMR}{DPHI + \alpha TCMR}$$  \hspace{1cm} (4)

where

$$\alpha = \frac{\rho_w - \rho_h}{\rho_{ma} - \rho_w}$$  \hspace{1cm} (5)

and $\rho_w$, $\rho_h$, and $\rho_{ma}$ are the densities of water, hydrate, and the sediment matrix respectively.

The effect of the density contrast between gas hydrate and water on the density porosity can be taken into account with the following equation for the true porosity $\phi$:

$$\phi = \frac{DPHI + \alpha TCMR}{1 + \alpha}$$  \hspace{1cm} (6)

Because of the relatively small density contrast between gas hydrate and water, strong effects will nevertheless only occur at high porosities (i.e. $>40 \%$) and high gas hydrate saturations (i.e. $>50 \%$).

Exceptions to the application of the DMR method described above are individual intervals containing layers of low-rank coal and dolomite-cemented sandstones. Because of the strong density contrast compared to other rock-forming materials, the DMR method is not applicable and the computed gas hydrate saturation was set to zero within the affected intervals.

The computed gas hydrate saturations are displayed in Figure 3 and 4. Ten individual hydrate-bearing zones with thicknesses between 1 m and 23 m, and average gas hydrate saturations between 25 % and 68 % were identified using the DMR method. Significant accumulations of gas hydrate predominantly occur inside the sandstone units, with maximum saturations of up to 89 %.
Thermal Conductivity Profiles from Mixing Law Models

Mixing law models are based on the concept that the effective properties of a multi-component system can be calculated as the average value of the properties of the components and their volumetric fraction of the bulk rock composition. The thermal conductivity was calculated using the following formulas for the arithmetic, harmonic, and geometric mean models [21]:

\[
\lambda_{ari} = \sum v_n \lambda_n
\]

(7)

\[
\lambda_{har} = \frac{1}{\sum v_n / \lambda_n}
\]

(8)

\[
\lambda_{geo} = \prod \lambda_n^{v_n}
\]

(9)

where \(\lambda_{ari}, \lambda_{har}, \lambda_{geo}\) are the effective thermal conductivities calculated from the respective mixing-law model, and \(\lambda_n\) and \(v_n\) are the thermal conductivities and volume fractions of the respective components.

The volumetric composition of the formation was determined from the available logging data using the different methods of formation evaluation described above. The individual volume fractions relative to the total rock volume were be computed using the following set of equations:

\[
v_{sd} = (1 - \phi) \cdot (1 - V_{sh})
\]

(10)

\[
v_{sh} = (1 - \phi) \cdot V_{sh}
\]

(11)

\[
v_w = \phi \cdot (1 - S_h)
\]

(12)

\[
v_h = \phi \cdot S_h
\]

(13)

The subscripts \(sd\), \(sh\), \(w\), and \(h\) refer to sand, shale, water, and hydrate fraction respectively.

Although only of limited extent (Figure 4), special attention had to be devoted to the intervals containing low-rank coal and dolomite-cemented sandstone beds because of the strong density contrast compared to other rock-forming materials.

Except for water and methane hydrate, where the values of the pure substances were used, effective thermal conductivities of the mineral mixtures which are represented by each component were used (Table 2). The effective thermal conductivity of shale was calculated from the average mineral composition determined by X-ray diffraction analysis [9] and the thermal conductivity of the mineral components using the harmonic mean model. The value for sand was chosen about 10% lower than the value of pure quartz, accounting for a small amount of impurities from other minerals like carbonates or feldspar, which is consistent with the procedures of other authors [22].

The thermal conductivity profiles calculated using the three different mixing laws are displayed in Figure 4. The arithmetic mean model results in the highest and the harmonic mean model in the lowest values of thermal conductivity. Intermediate values of thermal conductivity were calculated from the geometric mean model. The average thermal conductivity values calculated using the geometric mean model range between about 1.5-2.0 W m\(^{-1}\) K\(^{-1}\) within the shale-rich units and about 2.0-2.8 W m\(^{-1}\) K\(^{-1}\) within the sand-dominated units. The lowest values were calculated for the sporadic coal-bearing sections, ranging between about 0.4 W m\(^{-1}\) K\(^{-1}\) and 1.0 W m\(^{-1}\) K\(^{-1}\). Maximum values between about 4.0 W m\(^{-1}\) K\(^{-1}\) and 5.9 W m\(^{-1}\) K\(^{-1}\) were calculated for the isolated layers of dolomite-cemented sandstones.

<table>
<thead>
<tr>
<th>Component</th>
<th>Thermal conductivity (W m(^{-1}) K(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>7.0</td>
</tr>
<tr>
<td>Shale</td>
<td>1.9</td>
</tr>
<tr>
<td>Water</td>
<td>0.6</td>
</tr>
<tr>
<td>Hydrate</td>
<td>0.45</td>
</tr>
<tr>
<td>Coal</td>
<td>0.3</td>
</tr>
<tr>
<td>Dolomite</td>
<td>7.0</td>
</tr>
</tbody>
</table>

Table 2: Thermal conductivities of components for mixing law models.

Thermal Conductivity Profiles from Geothermal Data

Assuming constant heat flow by conduction, the bulk rock thermal conductivity in vertical direction (\(\lambda_{zz}\)) can be calculated from the measured geothermal gradient (\(\Gamma\)) and an estimate of the local heat-flow density (\(q\)) by a simple rearrangement of the
one dimensional form of Fourier’s equation:

\[ \lambda_{xx} = \frac{q}{\Gamma} \]  

(14)

It should be pointed out, that the success of this procedure is strongly dependent on the validity of the above stated assumption, as well as the quality of the heat-flow density estimate. The applicability of this method can only be proved by evidence from independent data, which in the current study was supplied in the form of petrophysical data derived from well log interpretation.

The temperature profiles measured at Mallik in September 2003 have returned close to equilibrium with the formation temperature and the changes of temperature with depth are approximately equal to the geothermal gradient [6]. For the calculation of thermal conductivities average temperature gradient profiles were constructed from the slopes of linear fits for the September 2003 temperature profiles over 5 m intervals.

The 5 m average temperature gradient profiles and a heat-flow density of \(55 \pm 8 \text{ mW m}^{-2}\), which was derived by Majorowicz and Smith [23] for the nearby Mallik L-38 well, were used for the calculation of the bulk rock thermal conductivities. The standard error (standard deviation, \(\sigma_\lambda\)) of the resulting thermal conductivity values was calculated from the sum of the relative errors of the temperature gradient and heat-flow density data. The standard error of the 5 m temperature gradients was determined as 2.6 K km\(^{-1}\) for the Mallik 3L-38 well, and 4.0 K km\(^{-1}\) for the Mallik 4L-38 and 5L-38 wells. The average values of the resulting relative errors for the 5 m average thermal conductivity values are 18 %, 23 %, and 25 % for the Mallik 3L-38, 4L-38, and 5L-38 wells respectively.

The calculated 5 m thermal conductivity profile for the Mallik 5L-38 well is displayed in Figure 4, together with the 95 % confidence limits, which are equal to 2\(\sigma_\lambda\). The geothermal values of corresponding sections of the three Mallik 2002 wells are in close agreement (Figure 3). Individual exceptions can be related to lithological variations between the wells. The average thermal conductivity values calculated from geothermal data range between 1.03\(\pm\)0.15 W m\(^{-1}\) K\(^{-1}\) within the shale-rich lower part of Unit IV of Mallik 4L-38 and 2.88\(\pm\)0.42 W m\(^{-1}\) K\(^{-1}\) within the sand-rich and hydrate-bearing lower part of Unit I of the Mallik 5L-38 well. Some prominent peaks of the calculated conductivities are clearly related to specific lithological features: The high conductivity interval at the base of Unit I within the profile of the 5L-38 well correlates well with the occurrence of a dolomite-cemented sandstone interval. A low conductivity value near the base of Unit IV of the Mallik 4L-38 well corresponds to a 1.4 m thick coal layer at the adjacent Mallik 5L-38 well.

**Comparison of Calculated Thermal Conductivity Profiles**

A comparison of the thermal conductivity profiles from the mixing law models and the geothermal data of the the Mallik 5L-38 well is displayed in Figure 4. The thermal conductivities calculated using the geometric mean model show the best agreement with the conductivities calculated from the geothermal gradient, both in terms of the magnitude of the absolute values as well as the amplitudes of variation. Except for a few isolated values, the geometric mean model values lie within the bandwidth of the 95 % confidence limit of the conductivities calculated from the geothermal gradient. The arithmetic mean model predicts values which are almost constantly above the confidence range. The results of the harmonic mean model lie at or below the lower boundary of the confidence range. This agrees with the results of Troschke and Burkhardt [24], who have observed a good agreement of measured and calculated thermal conductivities using the geometric mean model for sedimentary rocks with small differences of thermal conductivity between the rock matrix and the pore content.

The good agreement of the geometric mean model values and the geothermal data also holds for the 23 m thick interval with high hydrate saturations of up to 87 % above the base of Unit I. This is in accordance with the results of Wright et al. [15], who showed that reasonable estimates of the thermal conductivity of the hydrate-bearing sediments at Mallik were generated using the method proposed by Johansen [25], which for saturated soils is equivalent to the geometric mean model applied in this work.

**CONCLUSIONS**

The bulk rock thermal conductivity of the Mallik sediments can quantitatively be estimated by deter-
mining the lithological composition from logging data and calculating effective thermal conductivities applying mixing-law models. The results of the geometric mean model showed the best agreement to the thermal conductivity profiles derived from geothermal data, which were calculated from the measured geothermal gradients and an estimated local heat-flow value of 55 mW m$^{-2}$ based on Fourier’s law of heat conduction. It is therefore concluded, that the geometric mean model is generally applicable for estimation of thermal conductivity of the weakly consolidated sediments encountered at Mallik, including strata containing high saturations of disseminated methane hydrate of up to 90%. Average thermal conductivity values of the sand intervals with high hydrate saturations range between 2.35 W m$^{-1}$ K$^{-1}$ and 2.77 W m$^{-1}$ K$^{-1}$.

The results of the geometric mean model are in support of the apparently low influence of hydrate saturation on the bulk rock thermal conductivity deduced from the analysis of the geothermal gradients: The geometric mean model predicts a reduction of the bulk rock thermal conductivity of about 10% for a hydrate-saturated sand with about 35% porosity compared to water saturated conditions. Variations within this order of magnitude could nevertheless not be determined from the available geothermal data because of lithological heterogeneity and the error associated with the temperature data. Therefore precision measurements of thermal conductivity on hydrate-bearing sediments under controlled laboratory conditions are recommended, including investigations of the influence of hydrate composition and micro-structure, as well as the saturation within a porous medium on the bulk rock thermal conductivity. On the basis of the improved knowledge about thermal conductivity, which is the main factor influencing the static temperature field, the road is now paved in order to study the transient temperature response of hydrate-bearing sediments and heat-transport processes during the formation and/or decomposition of gas hydrate.

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REFERENCES


