Thermal conductivities of argillaceous sediments

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Abstract: Thermal conductivities of selected samples of shales, clay- and mudstones from the Norwegian Continental Shelf have been measured with a divided bar apparatus. The samples investigated are from conventional cores and side wall cores. Thermal conductivities for water-saturated samples measured perpendicular to the layering vary from 0.79 to 1.14 W/m K. The conductivities measured parallel to the layering are up to 1.7 times higher than those measured in the perpendicular direction. The investigation also confirms that the temperature has an influence on the conductivity. A model to predict thermal conductivity, based on water content and mineralogy has been proposed and tested.

Thermal conductivity of sediments is a key parameter in many studies of sedimentary basins because it controls the conductive heat flow, and therefore also the temperature distribution in sediment successions. Great efforts have been made to determine sediment conductivity both from laboratory measurements and from calculations from other known parameters. Still, there is lack of knowledge about the thermal conductivity of sedimentary rocks, and in particular little available information exists on the influence of clay minerals (Brigaud & Vasseur 1989).

The variation of the thermal conductivities of sediments is found to depend mainly on mineralogy, porosity and texture (Woodside & Messmer 1961; Anand *et al.* 1973; Johansen 1975; Farouki 1981; Brigaud & Vasseur 1989). Temperature will also have an influence on the conductivity (Anand *et al.* 1973; Gilliam & Morgan 1987; Blackwell & Steele 1989; Demongodin *et al.* 1993).

Factors influencing the thermal conductivity

Mineralogy

Mineralogy is the most important factor controlling thermal conductivities of sedimentary rocks. Thermal conductivities of selected rock forming minerals from Brigaud & Vasseur (1989) are shown in Table 1. These results are comparable with measurements by Horai (1971) and values applied in the basin modelling system (BMT) developed at Rogaland Research (Fjeldskaar *et al.* 1990).

Rocks with greater proportions of the clay minerals smectite, illite and mixed layer illite/smectite will have lower conductivities than rocks with the same proportion of other minerals specially quartz and pyrite. The low conductivities of smectite and illite have been explained by the layering of the minerals (Blackwell & Steele 1989; Demongodin *et al.* 1993) although kaolinite and chlorite have the same layered structure but do not have such low thermal conductivities. The various clay minerals affect pore spaces in different ways, whether they are laminated, dispersed, in pore lining or in pore bridging. These structural differences may explain the differences in conductivity between the clay minerals.

Water content (porosity)

Thermal conductivity of water is 0.60 W/m K at 20°C and lower than the conductivity of the minerals. Thus, a decrease in water content would lead to an increase in the thermal conductivity of sediments. Because of the smaller

Table 1. *Conductivity of rock forming minerals (Brigaud & Vasseur 1989)*

Mineral	K (*W/m K*)
Quartz	7.7
Feldspar	2.3
Pyrite*	19.2
Calcite	3.3
Dolomite	5.3
Anhydrite	6.3
Chlorite	3.3
Kaolinite	2.6
Smectite	1.9
Illite	1.8
Illite/smectite	1.8

* Horai (1971)

From McCann, D. M., Eddleston, M., Fenning, P. J. & Reeves, G. M. (eds), 1997, *Modern Geophysics in Engineering Geology*. Geological Society Engineering Geology Special Publication No. 12, pp. 355–363.

difference between thermal conductivity of water and clay minerals, the effect of water content is less for low conductive materials such as shales and claystones, than for high conductive sediments as quartz rich sandstones.

Porosity is a more common used factor instead of water content when considering percentage of water in water saturated samples. Porosity is the volume of the pores in the material while water content includes all water in the material, also bound and constitutional water.

Texture

Sedimentary rocks are inhomogenous and anisotropic. The thermal conductivity will vary on micro scale within the single sediment layer, and also, with orientation to the layering. The difference in the conductivities measured parallel to and perpendicular to the layering, the anisotropy effect, is found to be considerable (Gilliam & Morgan 1987; Prestholm & Fjeldskaar 1993). Variation

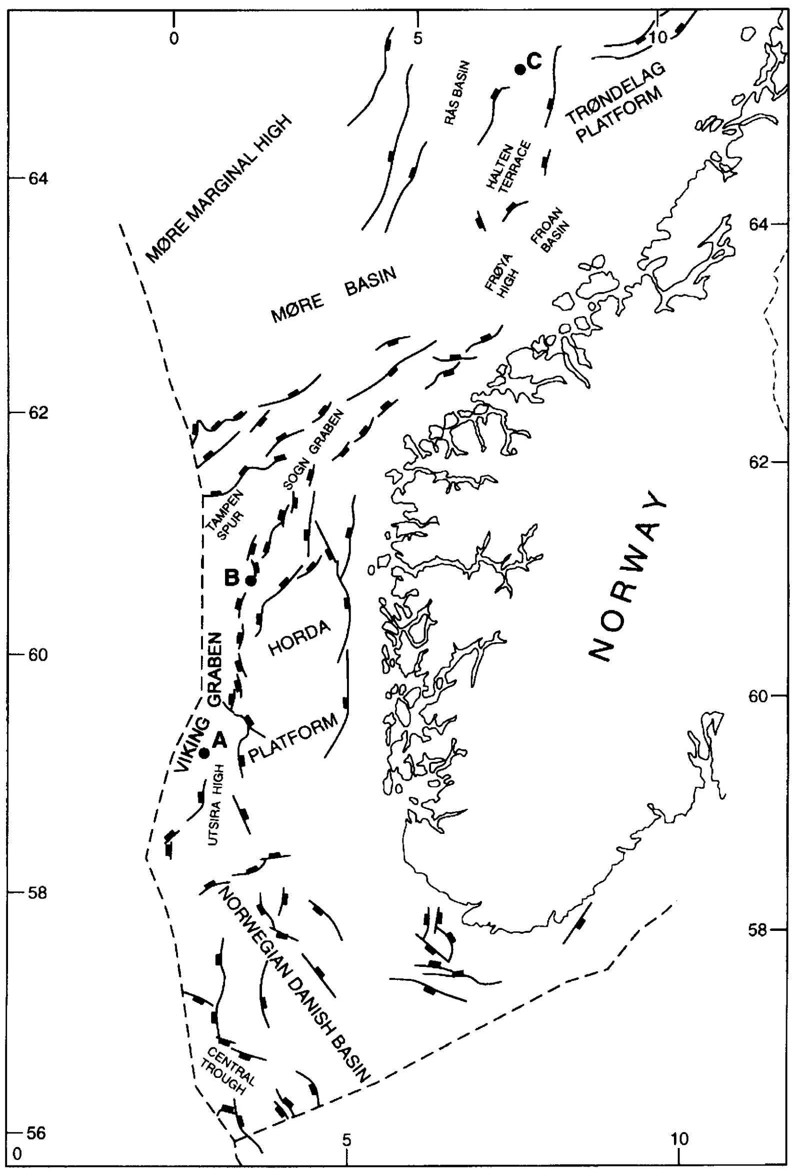

Fig. 1. Location of the three wells on the Norwegian Continental Shelf.

in conductivity caused by the texture can be divided into effects of crystal orientation for a given mineral and effects of small-scale heterogenities within a given lithology (Demongodin *et al.* 1993).

Temperature

Variation in temperature will induces changes in bulk conductivity. (Anand *et al.* 1973; Balling *et al.* 1981; Demongodin *et al.* 1993). The actual temperatures in the economic zones of sedimentary basins range from 0°C to about 200°C. Somerton (1992) reported moderate negative gradients of thermal conductivity with temperature for high conductive rocks whereas small positive gradients for low conductivity rocks. Gilliam & Morgan (1987) measurements on shales show a slight increase in thermal conductivity with increasing temperature up to about 90ºC. Both studies were based on experimental data from laboratory measurements. The effect of temperature of *in situ* conditions of the material may be more complex because the temperature also will influence other chemical and physical factors which may effect thermal conductivity. There is assumed to be two processes which will occur and effect thermal conductivity when increasing the temperature: the activity of molecules and atoms will increase and increase the thermal conductivity and to some extent there will be drying of the samples with increasing temperature which will decrease the conductivity.

Modelling of thermal conductivity

Various models have been proposed for estimating the thermal conductivity of sedimentary rocks. One of them, the geometrical mean model, has been shown to predict satisfactorily the conductivity, at least when anisotropy effects can be neglected (Woodside & Messmer 1961; Johansen 1975; Brigaud & Vasseur 1989; Demongodin *et al.* 1991). The geometric mean is a simple model which only takes account of the thermal conductivity of the matrix, k_s, thermal conductivity of the water, k_w, and water content, w. The bulk thermal conductivity of a water saturated rock is k given by Equation (1):

$$k = k_w^w \cdot k_s^{(1-w)} \qquad (1)$$

where k_w is 0.6 W/m K.

Material investigated

20 mudstone samples from three wells (A, B and C) on the Norwegian Continental Shelf were investigated (Fig. 1).

Samples from well A are of Tertiary mudstones. The well is situated on the northwestern flank of the Utsira High in the North Sea. The samples were prepared from side wall cores. The sampling interval is 1200–2500 m(RKB). Mineralogical, petrological and petrophysical investigations of the samples are reported by Tyridal (1994). The material consists of sandy mudstones where fragments of light claystones and grains of quartzite are randomly distributed in a darker clayey grey matrix. The fragmental character of the sediments is probably a result of mass flow caused by a turbidity current. Smectitic illite/smectite mixed layer minerals are found to be the dom-inating mineral. No laminations are visible. The side wall cores were contaminated with drilling fluids, and barite from the drilling fluids complicated the mineral identification by X-ray diffractograms.

Samples from well B are cut from conventional core samples from the Upper Jurassic Heather Formation. The well is located on the western flank of the Horda Platform. The sampling interval is 2125–2169 m(RKB) and the water depth is 147 m. The samples have been investigated by Zhang *et al.* (1992) and Roaldset & Gjelsvik (1993). The Heather Formation samples represent moderately to poorly sorted micaceous sandy siltstone. The material has a poorly developed lamination modified by bioturbation. The main constituents are quartz, feldspar and mica in a clayey matrix.

Well C is drilled on Haltenbanken off Mid-Norway. The two samples investigated from this well were cut from a conventional core from the Upper Cretaceous succession at a depth of 2437 m(RKB). The samples are fissile mudstones with a clay mineral content of 30% and a quartz content of 42%.

Laboratory measurements

Thermal conductivities were measured with a divided bar apparatus developed at Department of Refrigeration Engineering, Norwegian University of Science and Technology, and described by Brendeng & Frivik (1974) (Fig. 2). As the equipment originally was designed for larger samples a slightly modified method was applied were the samples were measured against a reference sample.

The samples were measured in water saturated state. To reduce the effect of water movement, the temperature gradient across the samples was minimalized to 1.0–3.5 K. The sizes of the samples were cores with radius 2.5 cm and length 3.0 cm for A and cubes with sides 3.0 cm for B and C samples.

To test the influence of the temperature on the conductivity the samples were measured at different mean temperatures. All samples were tested at two or three different mean temperatures between 10–60°C.

The mineralogy was determined by standard X-ray diffraction techniques described among others of Brindley & Brown (1980) and Moore & Reynolds (1989). The

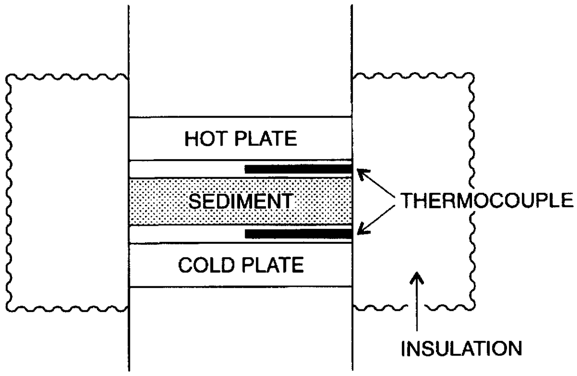

Fig. 2. A section through the divided bar apparatus.

diffractograms were interpreted manually by calculating the areas of the characteristic peaks of the untreated diffractograms. The peak areas were corrected by means of 'weighting factors' developed by H.G.Rueslåtten and generally applied at the X-ray Diffraction Laboratory at the Department of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology. The quantification is considered to be semi-quantitative with an average error in the order of 5–10% (Rundberg 1991).

Water content was calculated from measurements of bulk and grain densities (Equation 2).

$$w = 1 - \frac{\rho_m}{\rho_d} \quad (2)$$

where w is the water content (volume of water of total volume), ρ_m is the bulk density (g/cm^3) and ρ_d is the grain density (g/cm^3).

The densities were measured with pycnometer and calculated from the measured weight and volume of the samples. The samples were dried at 105°C before grain density was determined. Water content calculated in volume of water of total volume of material is often considered equal to porosity.

Results and discussion

The results of the measurements of water content, mineralogy and thermal conductivities are presented in Table 2.

The measured thermal conductivities vary in the range of 0.71–1.14 W/m K. The measured conductivities are similar to those reported by Gilliam & Morgan (1987) on shales from Green River Formation, USA, who also used a divided bar apparatus. However, the values of

Table 2. *Results of thermal measurements together with water conent, quartz and clay mineral contents*

	Sample	*Depth m RKB*	*Water content [%]*	*Content of clay minerals [%]*	*Quartz content [%]*	*Thermal conductivity perpendicular** k_I *(W/m K)*	*Thermal conductivity parallel*[1] k_{II} *(W/m K)*	*Anisotropy effect* k_{II}/k_I
Central North Sea	A1	1265	42	34	36	1.06		
	A2	1330	40	45	33	0.87		
	A3	1450	33	39	26	0.85		
	A4	1510	38	35	30	0.85		
	A5	1610	40	27	45	0.83		
	A6	1675	40	38	26	0.82		
	A7	1765	33	23	35	0.79		
	A8	1835	38	27	38	0.83		
	A9	1874	36	16	42	1.14		
	A10	2033	24	42	26	0.96		
	A11	2450	21	42	37	1.08		
	A12	2576	9	26	50	0.86		
Northern North Sea	B1	2125	13	50	21	0.97	1.65	1.70
	B2	2125	13	50	21	0.93		
	B3	2131	19	51	21	0.71	1.15	1.62
	B4	2155	11	58	18	0.97		
	B5	2161	15	70	13		1.20	
	B6	2169	17	54	19	1.02	1.54	1.51
Mid-Norwegian Shelf	C1	2437	21	30	42	0.92†	1.08‡	1.17
	C2	2437	21	30	42	1.04†	1.17‡	1.13

* Measured at temperature between 22–38°C.
† Measured 55° to the layering.
‡ Measured 35° to the layering.

this work are significantly lower than measurements on argillaceous sediments previous reported (Bloomer 1981; Brigaud & Vasseur 1989; Demongodin *et al.* 1993; Fjeldskaar *et al.* 1993). In their studies the conductivities were measured with the needle probe technique, which is considered as an easier, but not so exact, method for determination of thermal conductivities. The divided bar apparatus is considered more appropriate for measuring conductivity of anisotropic material than the needle probe technique.

The measured sample conductivity varied slightly with the test temperature. In tested temperature range of +10–+60°C the conductivity varied from −0.016 to +0.013 W/m K for increase of 10 K.

The low value of 0.71 W/m K of sample B3 differs from the other measured values. This value is probably due to drying of the material and is therefore omitted in the further discussion.

The effect of factors influencing the thermal conductivity

Water content

The measured thermal conductivities perpendicular to the layering are plotted against the water content in Fig. 3.

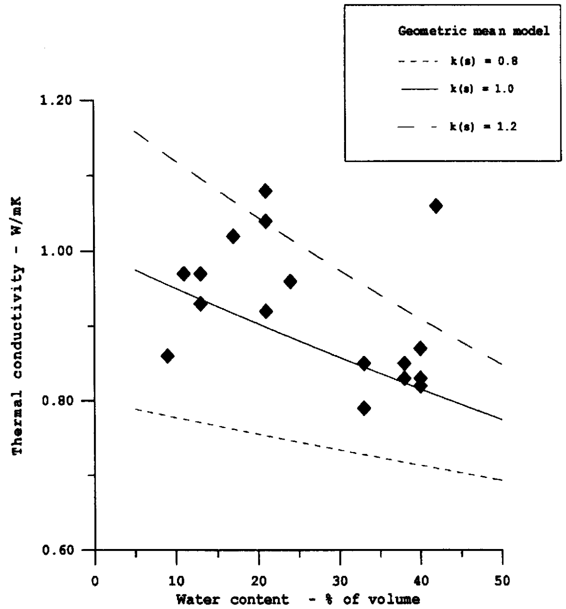

Fig. 3. Influence of water content on thermal conductivity. Geometric mean model (Eq. 1) calculated with thermal conductivity of water equal 0.6 W/m K and thermal conductivity of matrix, k_s, equal to 0.8, 1.0 and 1.2 W/m K are also plotted.

The trend is a decrease in thermal conductivity with increasing water content. This agrees with the geometric mean model. The relationship between water content and thermal conductivity with depth for samples from well A as shown in Fig. 4 show a slight decreases in water content with depth. Thermal conductivity which was expected to increase with decreasing porosity, shows a more irregular pattern with depth and seems to be more strongly influenced by a change in the lithology.

Mineralogy

The influence of the quartz and clay minerals content of the thermal conductivities can be indicated from Figs 5 & 6.

No clear trend is found between the quartz content and measured thermal conductivity (Fig. 5). Taking into consideration the high conductivity of quartz (7.7 W/m K) and a quartz content up to 50% (sample A12), the measured thermal conductivities less than 1.0 W/m K are very low. An explanation for this may be that the fine quartz grains in these samples do not have the same increasing effect on thermal conductivity as reported for material with coarser quartz grains. As frequently observed by SEM investigations of argillous sediments the quartz may occur as isolated grains in a matrix of clay minerals. Seldom is grain to grain contact for quartz visible. Such contact is considered to be very important in transfer of heat by conduction.

According to the reported values of conductivity (Table 1), we have grouped the clay minerals in two groups, a low conductive group which includes illite,

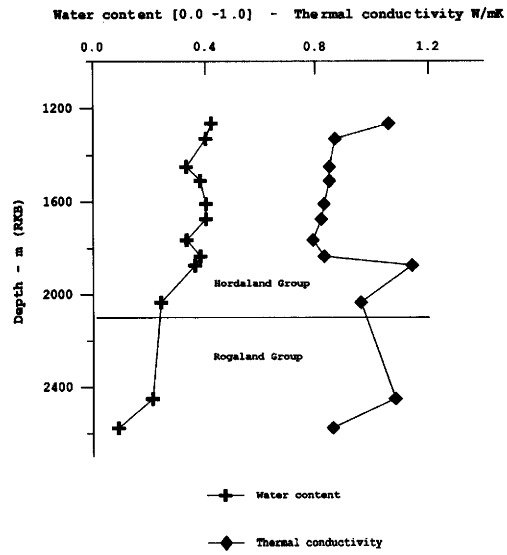

Fig. 4. Variation in water content and thermal conductivity with depth for the 12 samples from well A.

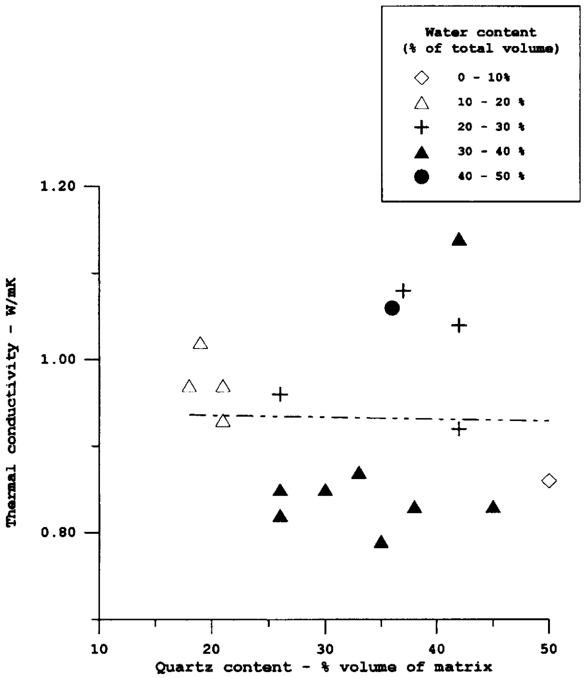

Fig. 5. Quartz content versus the measured thermal conductivities. Difference in water content is shown by different symbols. The linear regression line is marked with dotted line.

smectite and mixed layer illite/smectite (I/S) and an intermediate conductive group with kaolinite and chlorite. An increase in the volumetric proportion of the minerals in the low conductive group is assumed to reduce the bulk conductivity for clastic sedimentary rocks. Variation in the volumetric proportion of the intermediate group is expected to have low effect of the bulk conductivity.

The measured thermal conductivity show some irregularities when plotted against the two groups of clay minerals, but the general trend is a slight decrease with increasing volumetric proportion of the low conductive minerals. This trend is mainly due to the variations in the water content as shown with the different marks. For the samples with a water content in the range of 30–40% a slight increase in thermal conductivity with increasing contents of illite, smectite and mixed layer I/S is observed. We have no explanation for this trend. Figure 6 shows a slight increase with increasing volumetric proportion of the content of kaolinite and chlorite. This trend is also mainly influenced by the variations in water content.

Texture

Thermal conductivities measured parallel with the layering are considerably higher than the conductivities

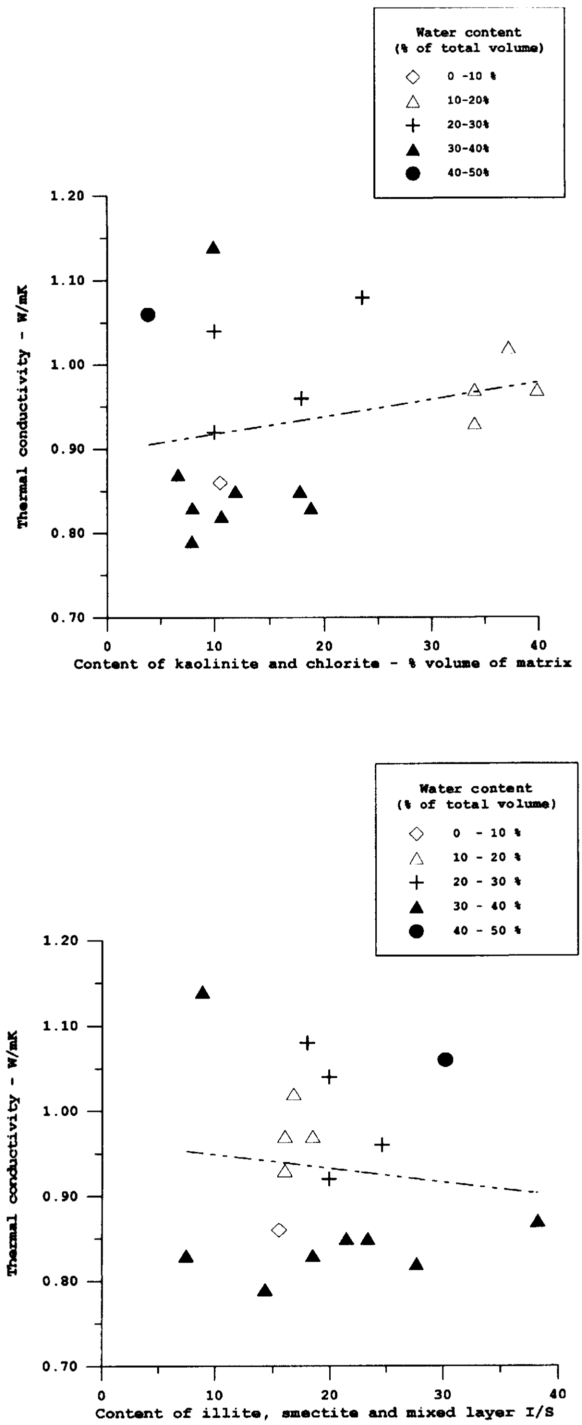

Fig. 6. Plots of clay minerals versus measured thermal conductivities. The linear regression line is marked with dotted line.

measured perpendicular to the layering. The anisotropy effect is found to be up to 1.70 (sample B1, Table 2). Because only few measurements are available, the anisotropy effect is not yet correlated to other factors, but the effect is assumed to be a function of the content of lamination and the microtextural arrangements of the clay minerals and thus influenced by the primary microtexture and burial history of the sediment.

Temperature

So far no clear correlation has been found between the effect of temperature on thermal conductivity and water content and/or mineralogy.

Calculation of thermal conductivities by the geometric mean model

Based on the measured thermal conductivities, an attempt is made to calculate the conductivity of these sediments. In this study we will only consider the measured conductivity perpendicular to the layering at room temperature. The effect of anisotropy and temperature is therefore not included. The model is based on the geometric mean equation (1) where the conductivity of the matrix, k_s, is assumed to be a function of the mineralogical composition.

First an attempt is made to predict the thermal conductivity from the literature reported values of thermal conductivity of minerals (Table 1). The conductivity of matrix, k_s, is calculated with the geometric mean equation from the estimated volumetric proportion of the minerals. The result of the calculated values is plotted versus the measured values (Fig. 7).

The plot shows no correlation between the measured and the predicted values where all predicted values are considerably higher than the measured values with a discrepancy up to 300%.

Then, to test if the geometric mean model based on mineralogical composition and water content is valid for these samples and the investigated data we used an inverse method. With a non-linear regression analysis the best fit geometric mean model was found from the data of measured thermal conductivity, mineralogy and water content. Thermal conductivity calculated with 'the best fit model' is plotted versus the measured thermal conductivities (Fig. 8) and the 'best fit conductivities' of the minerals of this model is shown in Table 3.

The 'best fit model' failed on three points: Firstly the plot on Fig. 8 and the regression coefficient ($R^2 = 0.04$), shows that there is bad correlation between the model and the measured thermal conductivities. Secondly the values of the conductivity of the minerals are of a magnitude lower than the literature reported values. Thirdly the variation of the conductivity of the minerals does not agree with values previous reported. As an example, smectite and illite have the highest conductivities in 'the best fit model'.

Conclusions

Thermal conductivities of argillaceous sediments from the Norwegian Continental Shelf are measured from 0.79

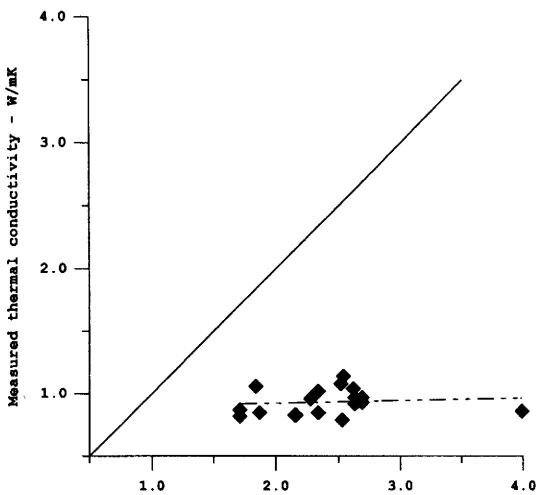

Fig. 7. Thermal conductivities measured versus calculated from literature values of conductivity of minerals.

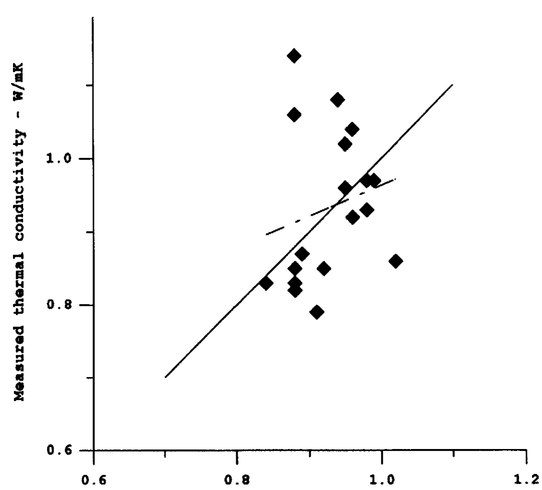

Fig. 8. Thermal conductivities calculated with 'the best fit geometric mean model' plotted against the measured values.

Table 3. *The best fit values of thermal conductivity of the minerals*

Minerals	*Thermal conductivity (W/m K)*
Quartz	1.01
Kaolinite	0.91
Chlorite	
Illite	1.42
Smectite	
I/S	
Pyrite	1.41
Feldspar	1.02
Carbonate	

to 1.14 W/m K. The thermal conductivity parallel to the layering is up to 1.70 higher than that perpendicular to the layering. The anisotropy effect may be of importance and taken into consideration when modelling in sedimentary basins with tilted strata.

The thermal conductivities presented in this work are lower than most data previously published. These earlier data have mainly been determined by needle probe techniques. The results are, however, comparable with thermal conductivities indirectly estimated from thermal studies of sedimentary basins (Blackwell & Steele 1989; Demongodin *et al.* 1991; C. Hermanrud 1993 pers. comm.).

The water content is found to have some influence of thermal conductivities. The mineralogy seems to be less important for the conductivity. An attempt to calculate thermal conductivities with the geometric mean model, from the water content and the mineralogy was not successful. An explanation may be that the mineralogical effect is lower for these fine grained sediments than for coarser samples.

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