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Thermal conductivity of selected claystones and mudstones from England

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ABSTRACT: The claystones and mudstones investigated are London Clay, Fullers Earth, Oxford Clay and Kimmeridge Clay. The thermal conductivities were measured using a divided bar apparatus and the values measured perpendicular to layering ranged from 0.68 to 0.97 W/mK. Comparative measurements of thermal conductivities were carried out by the needle probe method and Middleton's method. Deviations of up to 50% were obtained between the needle probe and the divided bar method. The thermal conductivities estimated from the geometric mean model based on mineralogy and water content ranged from 0.87 to 2.01 W/mK, considerably higher than the measured values. A correlation was found between the grain size distributions of the samples and the measured thermal conductivities. This textural effect on the thermal conductivity is assumed to be the main reason for the low measured values and the lack of correlation between the measured and the calculated values.

Thermal conductivity is a physical property describing transfer of heat through the material. A knowledge of thermal conductivity is important in understanding and modelling of the temperature in sedimentary basins. There is still a lack of reliable information on sedimentary rocks, and especially for clays, claystones and shales there are uncertainties related to the determination of thermal conductivities (Blackwell & Steele, 1989; Brigaud & Vasseur, 1989; Demongodin *et al.*, 1991; Midttømme *et al.*, 1997a). Different methods have been used to measure thermal conductivity, for which the two main techniques are the stationary divided bar method and the transient needle probe method. Comparative measurements between the two methods have been reported previously and agreement was obtained by Von Herzen & Maxwell (1959), Sass *et al.* (1971) and Brigaud & Vasseur (1989). Higher values of thermal conductivity were measured with the needle probe by Slusarchuk & Foulger (1973), Johansen (in Farouki, 1981), Somerton (1992) and Midttømme *et al.* (1997b). The discrepancies between these studies is in the range 10–20%.

Special problems related to the measurement of thermal conductivities of clays, claystones and shales have resulted in fewer and probably poorer data available for these materials (Midttømme & Roaldset, 1997). The sampling and preparation of fine-grained materials represents a major problem as the material breaks up easily in the sampling process and even if successfully cored, the samples might be subjected to desiccation whilst under laboratory conditions (Brigaud & Vasseur, 1989). The anisotropic structure, which is generally observed for fine-grained sediments, might be considered as a source of error in the determination of thermal conductivity. The anisotropy of thermal conductivity is defined as the ratio between thermal conductivity parallel to the layering, $k_{\parallel}$, and the one perpendicular, $k_{\perp}$. An anisotropy of >1.7 was measured for shales and clays (Penner, 1963; Prestholm & Fjeldskaar, 1993; Demongodin *et al.*, 1993; Midttømme *et al.*, 1997a). The measured anisotropy is probably affected by the methods of measurement and sample preparation. In the divided bar method the heat is transferred in a certain direction through the samples, whereas by the needle probe method the heat is more randomly transferred. In other methods the samples are ground to a fine powder before the conductivity is measured (Horai, 1971; Sass *et al.*, 1971; Middleton, 1994). The effect of *in situ* structure of the samples is not taken into account by these methods. Models are developed to estimate thermal conductivity from other material properties. Porosity is considered to be of importance as pore-fluids have lower thermal conductivity than the minerals (Gilliam & Morgan, 1987; Brigaud & Vasseur, 1989) (Table 1). A decrease in porosity will therefore increase the thermal conductivity. In the absence of reliable and simple methods of measuring the porosity, water content and bulk density are used to describe the material quantitatively. Thermal conductivities of unconsolidated samples were estimated with an accuracy of 80% of the measurements made using a model based on the geometric mean model (eqn. 1) with the water content (w) as an unknown parameter (Midttømme *et al.*, 1997b).

TABLE 1. Thermal conductivities of common minerals in sedimentary rocks. Determined from needle probe measurements carried out at room temperature (Horai,1971).

Mineral	Thermal conductivity W/mK
Quartz	7.8
Calcite	3.4
Dolomite	5.1
Anhydrite	6.4
Pyrite	19.2
Siderite	3.0
Orthoclase	2.3
Albite	2.3
Halite	6.5
Mica	2.3
Chlorite*	5.1
Kaolinite	2.8
Smectite (BMT)	1.8
Illite	1.8
Mixed-layer I-S	1.9
Air	0.03
Water	0.60

*Chlorite: 3.3 W/mK: Brigaud & Vasseur (1989).

$$k = k_w^w \, k_s^{(1-w)} \tag{1}$$

w - water content (volume of water content of sample volume)

k_w - thermal conductivity of water (0.60 W/mK)

k_s - thermal conductivity of the matrix, (solid part of the sample).

Thermal conductivity in more complex models is related to mineralogy and porosity (Brigaud & Vasseur, 1989; Fjeldskaar *et al.*, 1993; Middleton, 1994). These models, in some recently published studies were found not to predict the thermal conductivity satisfactorily. Comparison between measured and estimated thermal conductivities for clays and shales shows poor correlation where the measured thermal conductivities are lower than the estimated values (Blackwell & Steele, 1989; Demongodin *et al.*, 1991; Midttømme *et al.*, 1997a,b). Thermal conductivities of the main minerals in sedimentary rocks are listed in Table 1. Similar values were obtained by Brigaud & Vasseur (1989) and used in the basin modelling program, BMT, developed by Rogaland Research (Precede Users Guide, 1992).

Thermal conductivity is influenced by the texture of the material (e.g. Farouki, 1981; Brigaud & Vasseur, 1989) and this might be a reason for the poor correlation between measured and estimated thermal conductivities. The measured anisotropy of thermal conductivity is an example of this influence, where a considerable variation in thermal conductivity is measured due to the direction of heat flow through the material. Thermal conductivity is shown to depend on the grain size and grain size distribution, where coarse-grained materials have higher thermal conductivity than finer material (Johansen, 1975; Beziat *et al.*, 1992; Midttømme *et al.*, 1997b). From the conductivities presented in Table 2 (Blackwell &

TABLE 2. Thermal conductivities of sedimentary rocks at 20°C (Blackwell & Steele, 1989).

Lithology	W/mK
Claystone and siltstone	0.80–1.25
Shale	1.05–1.45
Sand	1.70–2.50
Sandstone	2.50–4.20