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Measure and modelling of factors controlling the bulk thermal conductivity of sedimentary rocks

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The bulk thermal conductivity is a key parameter for the development of models of sedimentary basin thermal regimes, because it directly controls the temperature gradient. However, deep core samples are rarely available and there are few laboratory measurements; therefore indirect reliable procedures are necessary to estimate the thermal parameters from well log data. We develop a model for calculating the thermal conductivity of sedimentary rocks as a function of mineral composition, porosity and fluid type based on fabric theory and experimental data. Thermal conductivity, thermal diffusivity and volumetric heat capacity of 31 bottom core samples, collected from 14 petroleum explorative wells and representative of the main sedimentary rocks recognized in the Po Basin (Northern Italy), were measured.

Laboratory measurements were made using devices based on the analysis of the temperature response of the analyzed material subjected to heat flow impulses. The heat flow is excited by electrical heating of plane resistor heater inserted into a probe which is in direct thermal contact with the evaluated sample. All measurements were made perpendicularly and transversally to the core axis, corresponding to the vertical direction of the well. Both experimental relative errors on conductivity measurements and reproducibility of determination are estimated to be 5%.

The lithologies sampled include terrigenous and carbonate sedimentary rocks, coming from depths between 300 and 6500 m. Thin sections and X-ray diffraction analyses were performed on each rock type. Firstly non-clay minerals were characterized, in terms of weight fractions, and secondly the weight fractions of the clay minerals were measured using the residual part of the sample. The technique used gives a good estimate of the mineral components and its accuracy is on the order of 5%. Mineralogical analysis show that many of the core samples have a matrix rich in clay minerals (smectite, illite and chlorite) and their fraction can reach about 50% in terrigenous rocks. Marls and shales are the most abundant lithologies.

The measurements made on samples under dry conditions show a great variation in thermal properties. The structurally isotropic samples have a bulk thermal conductivity, thermal diffusivity and volumetric heat capacity variables from around 0.5, 0.4 10^{-6} and 1600, respectively, for sandy marls with high porosity, to around 4.5 W/(m K), 1.8 10^{-6} m^2/s and 2000 kJ/(m^3K) for dolomites. Marly samples collected at great depths ($>$ 3000 m) show a difference on average of 0.8 W/(m K) between the thermal conductivity in the horizontal and vertical directions; for shallower samples, conductivity in the two directions is almost equal.

The matrix thermal conductivity of a rock is a function of the conductivity and of the amount and distribution of the mineral constituents. The conductivity of non-clay minerals is quite well known, but in clay minerals it is poorly defined. Therefore we apply an inverse approach in which mineral conductivities are calculated one by one, being known the sample bulk thermal conductivity and the porosity and the amount of each mineral phases. Porosity is the major variable, which controls the thermal proprieties and so it was necessary to assess carefully the void index before we could model the thermal conductivity.

Among several mathematical models proposed for multicomponent systems, the geometric distribution model is the most accurate to estimate the conductivity. In order to decrease the unknowns, conductivity values derived from the literature are assigned to quartz, feldspar, calcite and dolomite. This approach does not take into account any effect on the structure, such as crystal orientation, or grain boundaries. The results suggest that the conductivity of isotropic samples can be generally predicted to better than 10%, if the mineral content is reasonably well estimated. There are some differences between what we predicted and what we observed in some marls cored at great depths. During compaction, the clay particles in these rocks are rotated and the grain orientation is a function of the applied effective loading. This reorientation produces the occurrence of an anisotropy in the thermal conductivity of sheet minerals and a reduction of the vertical conductivity. The difference between the horizontal and vertical conductivity values increases with depth.