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Prediction of thermal conductivity in reservoir rocks using fabric theory

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Abstract

An accurate prediction of the thermal conductivity of reservoir rocks in the subsurface is extremely important for a quantitative analysis of basin thermal history and hydrocarbon maturation. A model for calculating the thermal conductivity of reservoir rocks as a function of mineral composition, porosity, fluid type, and temperature has been developed based on fabric theory and experimental data. The study indicates that thermal conductivities of reservoir rocks are dependent on the volume fraction of components (minerals, porosity, and fluids), the temperature, and the fraction of series elements (*FSE*) which represents the way that the mineral components aggregate. The sensitivity test of the fabric model shows that quartz is the most sensitive mineral for the thermal conductivity of clastic rocks. The study results indicate that the *FSE* value is very critical. Different lithologies have different optimum *FSE* values because of different textures and sedimentary structures. The optimum *FSE* values are defined as those which result in the least error in the model computation of the thermal conductivity of the rocks. These values are 0.444 for water-saturated clay rocks, 0.498 for water-saturated sandstones, and 0.337 for water-saturated carbonates. Compared with the geometric mean model, the fabric model yields better results for the thermal conductivity, largely because the model parameters can be adjusted to satisfy different lithologies and to minimize the mean errors. The fabric model provides a good approach for estimating paleothermal conductivity in complex rock systems based on the mineral composition and pore fluid saturation of the rocks.

1. Introduction

Knowledge of the thermal conductivity of fluid-filled rocks is extremely important to petroleum geologists, geophysicists, and geochemists from both theoretical and practical points of view. Many important organic and inorganic geochemical reactions in subsurface, such as hydrocarbon thermal maturation, illite/smectite transition, and feldspar alteration, are significantly controlled by geothermal temperature which is a function of the thermal conductivity of the sediments and the basin heat flow. Subsurface temperatures also may provide important constraints on fault and fluid movements, if temperature anomalies related to variations in sediment thermal conductivity can be confidently removed (Luo et al., 1994). Therefore, an accurate prediction of sediment thermal conductivity and knowledge of the uncertainties of that prediction are needed; otherwise, even the most sophisticated and appropriate model for analyzing thermal history and maturation level may fail when applied to real basins (Blackwell and Steele, 1989). However, precise measurements of rock thermal conductivity as functions of

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temperature, porosity, mineral composition, and saturated fluids are very difficult and costly, even when satisfactory samples are available. One solution is to develop a model that can accurately predict rock thermal conductivities based on rock physical properties obtained from well logs, petrology studies, and experiments. A number of published studies on determination of the thermal conductivity of reservoir rocks (Asaad, 1955; Zierfuss and van der Vliet, 1956; Kunii and Smith, 1960; Anand, 1971; Keese, 1973) have been reviewed by Somerton (1992).

In previous studies, efforts have been made to predict the thermal conductivity of shales and sandstones through measurements on various shales, siltstones, and sandstones. These models are usually derived by correlating some physical property, such as porosity, density, electrical resistivity, permeability, fractional content of quartz, or sonic velocity with a known value of thermal conductivity through regression, least-squares, or some other fitting method (Anand, 1971; Chu, 1973; Keese, 1973; Goss et al., 1975; Beck, 1976; Merkle et al., 1976; Evans, 1977; Strack et al., 1982; Somerton, 1992). The empirical models give good results for a given suite of similar type rocks, but applying such models to different suites of rocks can lead to substantial errors (Somerton, 1992). Also, the prediction of the paleothermal conductivity of sediments, including carbonates, is beyond the capability of the various empirical models.

The mixing-law model is another approach used to estimate the thermal conductivity of rocks. This model is characterized by using various ways of averaging thermal conductivity of components with respect to their volume fractions, such as a geometric mean model or a fabric model. As one of the mixing-law models, the fabric model (similar to the Ohm's law model), is characterized by distributing the rock components (solids and fluids) into series and parallel elements. The effective thermal conductivity of a composite rock is computed using a network of elements connected in series and parallel, which is "woven" into a pattern similar to a cloth fabric. Such models have been discussed in different ways by Chan and Jeffrey (1983), Davis (1984), Somerton (1992), and Cathles et al. (1993). The issue is how to assign the series and parallel elements to characterize the different reservoir rocks. For example, some studies treat lithology (e.g. "sandstone", "limestone" etc.) and water as the basic elements (Somerton, 1992; Cathles et al., 1993); others consider the mineral components and water as the basic elements, but all lithologies have the same fabric pattern (Davis, 1984).

It is not difficult to understand that rocks with the same lithologic definition may have different thermal conductivities regardless of their fluid saturation and porosity. For example, sandstones with a different fractional content of quartz have different thermal conductivities. In particular, a difference of 0.1 content fraction of quartz will result in a difference of about 1 mcal/cm·s·°C in thermal conductivity of sandstone (Somerton, 1992). Since different lithologies have different textures and sedimentary structures, the fabric patterns for different rocks should not be the same. The purpose of this paper is to develop a fabric model which uses mineral and fluid components as the basic elements to calculate thermal conductivity for different rocks at different temperatures. The geometric model, another widely used mixing-law model, will be discussed in comparison with the fabric model. As a result, the fabric model has been concluded to offer the best approach for estimating paleothermal conductivities for simulation of geothermal history.

2. Thermal conductivities of minerals and fluids

Numerous measurements of thermal conductivities of common rock-forming minerals have been published (Sass, 1965; Horai, 1971; Kappelmeyer and Haenel, 1974; Weast and Astle, 1980). These data are valuable and important because values of thermal conductivity for individual mineral components constitute the framework needed to calculate thermal conductivity of composite rock solids. Table 1 lists the thermal conductivity values at 25°C and 1 atmosphere for 48 rock-forming minerals based on the work of Horai (1971), Kappelmeyer and Haenel (1974), and Davis (1984). This list includes many minerals not commonly encountered in sedimentary rocks. Fig. 1 shows a chart illustrating the range of thermal conductivities for the common sedimentary minerals. This figure reveals several pertinent points regarding the variations among these minerals:

(1) The thermal conductivity of pure quartz is high, about 18 mcal/cm·s·°C, relative to most other common minerals. Only pyrite, which is gener-

Table 1
Thermal conductivity of rock-forming minerals at 25°C and 1 atm (data from Horai, 1971; Kappelmeyer and Haenel, 1974; Davis, 1984)

Mineral	Conductivity (mcal/cm·s·°C)	
Albite	4.41	
Amphibole	7.50	
Anhydrite	11.37	
Anorthite	4.01	
Apatite	3.30	
Aragonite	5.35	
Biotite	4.83	
Bronzite	9.99	
Calcite	8.58	
Chert	10.82	
Chlorite	12.30	
Diopside	11.79	
Dolomite	13.16	
Epidote	6.70	
Fluorite	22.72	
Forsterite	12.30	
Gibbsite	6.21	
Gypsum	3.00	
Halite	14.60	
Hornblende	6.71	
Hematite	26.95	
Illite–Mica	5.50	
Ilmenite	5.70	
Kaolinite–Sericite	6.60	
K-Feldspars	5.70	
Magnetite	12.18	
Magnesite	13.94	
Microcline	5.95	
Mixed layer clay	5.70	
Muscovite	5.54	
Olivine	11.60	
Oligoclase	4.71	
Orthoclase	5.53	
Plagioclase	5.00	
Pyrite	45.89	
Pyroxene	10.20	
Quartz	18.37	
Rutile	12.20	
Serpentine	8.40	
Siderite	7.18	
Smectite	5.70	
Sphalerite	30.40	
Sphene	5.58	
Topaz	26.86	
Tourmaline	10.20	
Volcanic glass	3.20	
Zeolites	3.51	
Zircon	10.85	

ally not abundant, is higher (~45 mcal/cm·s·°C). The thermal conductivities of feldspars, the second most important group of sedimentary minerals in clastic rocks, average only about 5 mcal/cm·s·°C. The common clay minerals of illite, smectite, mixed-layer clays, and kaolinite also fall in the range of 5–7 mcal/cm·s·°C.

(2) The carbonates calcite, dolomite, and siderite (but not aragonite) have thermal conductivities significantly higher than the feldspars and clays, ranging from ~7 mcal/cm·s·°C (siderite) to ~13 mcal/cm·s·°C (dolomite).

(3) Hydrated phases such as gypsum and the zeolites have low thermal conductivities, in the range 3–4 mcal/cm·s·°C. Anhydrite is significantly higher than gypsum, ~11 mcal/cm·s·°C, while chert (10.8 mcal/cm·s·°C), a hydrated form of quartz, is much lower than quartz.

(4) Oils (hydrocarbons) have the lowest thermal conductivities (~0.3 mcal/cm·s·°C) of any material involved in any significant volume in a sedimentary basin, even lower than pure water (H_2O ~ 1.5 mcal/cm·s·°C) or seawater.

Consequently, one would expect quartz-rich rocks to have high thermal conductivities, approaching the values associated with evaporites (11–14 mcal/cm·s·°C), while arkosic rocks would be lower, probably in the range 8–10 mcal/cm·s·°C. Because arkosic rocks contain large amounts of quartz, their average thermal conductivities can be expected to be about the same as pure carbonate rocks. In general, sandstones may be expected to have either lower or higher thermal conductivities than carbonates, depending upon the quartz content. However, the most important implication is that rocks saturated with hydrocarbons can be expected to have much lower thermal conductivities than rocks saturated with aqueous fluids (Luo et al., 1994) and that the loss of fluids by compaction and/or mineral diagenesis such as clay mineral dehydration can be expected to have an important influence on the thermal evolution of a basin (Luo, 1992).

3. Fabric model

The fabric model predicts the effective thermal conductivity of a rock based on a weighted average of the

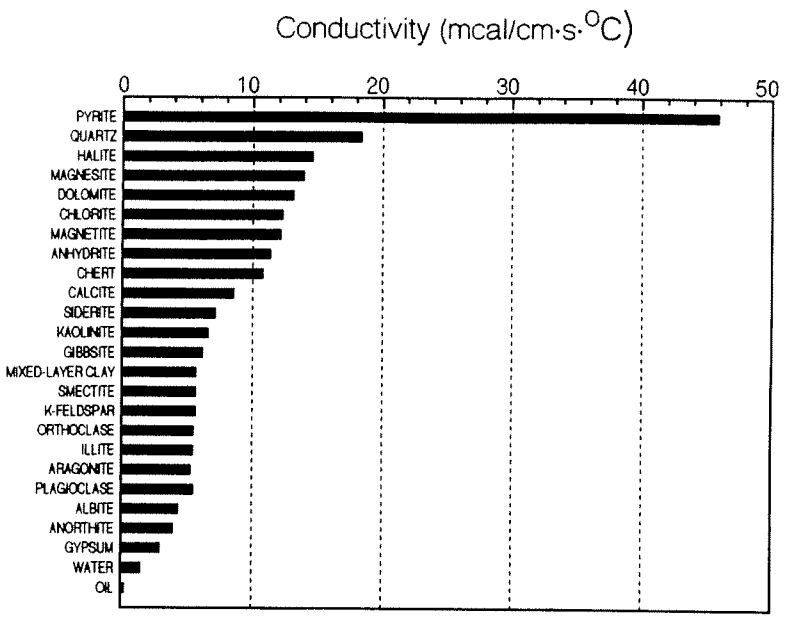

Fig. 1. Bar chart showing thermal conductivities for the common sedimentary minerals.

thermal conductivity of its mineral elements arranged in series and parallel relative to the direction of heat flow (Davis, 1984; Somerton, 1992). For the typical fabric model discussed in most publications, the solid rock matrix and the pore water are usually considered to be the two basic elements of the model. The thermal conductivity, K, may be expressed as:

$$K = FSE[(1-\phi)K_s + \phi K_w] + (1-FSE)[\frac{(1-\phi)}{K_s} + \frac{\phi}{K_w}]^{-1} \quad (1)$$

where FSE is the fraction of series elements, K_s is the averaged thermal conductivity of the solids, K_w is the thermal conductivity of water, and ϕ is porosity. Eq. (1) usually assumes that specific geometrical effects, such as the shapes of the pore spaces and the solid grains, are absent or can be ignored and that all pore spaces are water saturated.

If the element components are only in series ($FSE = 1$), the upper bound of the thermal conductivity is:

$$K = (1-\phi)K_s + \phi K_f \quad (2)$$

If the element components are only in parallel ($FSE = 0$), the lower bound of the thermal conductivity is:

$$K = [\frac{(1-\phi)}{K_s} + \frac{\phi}{K_f}]^{-1} \quad (3)$$

These bounds are also called the Wiener bounds (Chan and Jeffrey, 1983) or the arithmetic (upper) and harmonic (lower) means, respectively (Somerton, 1992).

As a practical matter, it is difficult to obtain definitive average values of thermal conductivities of the various types of rocks because of the lack of systematical measurements of the variability in fraction mineral content for similar lithologies. To overcome this difficulty in this study, we assume that the minerals which compose the rock and the saturated fluids constitute the basic fabric elements. Then Eq. (1) can be modified to the form:

$$K = FSE[\sum_{i=1}^{n_1}(1-\phi)\xi_s^i K_s^i + \sum_{i=1}^{n_2}\phi\xi_f^i K_f^i] + (1-FSE)[\sum_{1=i}^{n_1}(1-\phi)\frac{\xi_s^i}{K_s^i} + \sum_{i=1}^{n_2}\phi\frac{\xi_f^i}{K_f^i}]^{-1} \quad (4)$$

where n_1 is the number of mineral components of rock, K_s^i is the thermal conductivity of the ith solid mineral, ξ_s^i is the volume fraction of the ith mineral in the total weight of minerals, n_2 is the number of types of fluids saturated in the pore space, and K_f^i is the thermal conductivity of the ith fluid type with saturation ξ_f^i. The

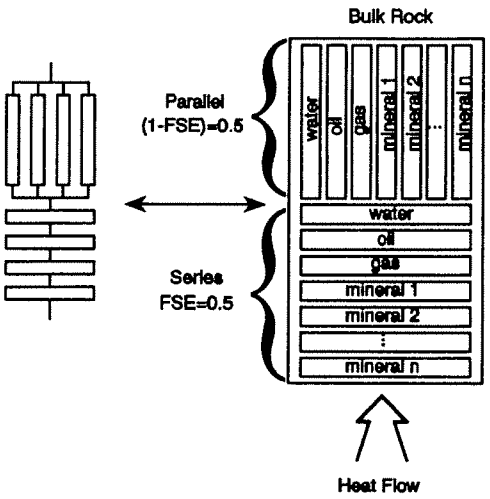

Fig. 2. Schematic diagram showing the fabric model in which the rock components (minerals and fluids) are "woven" into a series and parallel pattern relative to the direction of heat flow. The fabric pattern changes with the fraction of series elements (FSE). A fabric pattern of half parallel and half series elements ($FSE=0.5$) is assumed in this diagram.

fabric model of Eq. (4) is schematically illustrated in Fig. 2 in which a fabric pattern of half parallel and half series elements ($FSE=0.5$) is assumed. Eq. (4) makes it possible to calculate the thermal conductivity of a reservoir rock based on its quantitative mineral composition instead of its lithological definition. In this way, we can account for variations in the thermal conductivity of rocks of similar lithologic classification. In addition, the modified fabric model of Eq. (4) has two advantages: first, reliable measurements of thermal conductivities for most rock-forming minerals are available; second, it is easier to identify the mineral components and their volume fraction by petrographic and X-ray techniques than it is to measure the thermal conductivity of the rock solid.

Usually, the measured values of thermal conductivity for rock solids and minerals are made only under room temperature conditions. In particular, the values listed in Table 1 are valid only for a temperature of ~25°C. To determine the paleothermal conductivity of reservoir rocks, we must know the thermal conductivity of the rock at different temperatures. Davis (1984) proposed an approach to calculating the thermal conductivity of water-saturated sedimentary rocks as a function of temperature by fitting the data of Birch and Clark (1940) to rocks of known mineralogical composition. Using this approach, both K_s and K_w can be calculated as functions of temperature using the relations:

$$K_s = [\frac{1}{K_0}(2.142 - 0.0818\sqrt{T_K}) + 0.0172\sqrt{T_K} - 0.2978]^{-1} \quad (5)$$

and

$$K_w = 2.231(\frac{T_K}{T_0})^{1.5} - 0.8812(\frac{T_K}{T_0})^{2.5} \quad (6)$$

where T_K is the absolute temperature (K), $T_0=273.15$ K, and K_0 is the mineral thermal conductivity at $T_K=298.15$ K. Eq. (5) gives the rock grain thermal conductivities as function of temperature if the 25°C thermal conductivities are known. Eq. (6) can be used to predict values of the thermal conductivity of water at any temperature between 0°C and about 330°C (Davis, 1984). By incorporating Eqs. (5) and (6) into the modified fabric model of Eq. (4), one can estimate the paleothermal conductivity over the temperature range of about 0 to 330°C. The modified fabric model also ignores the effect of the hydrostatic pressure on thermal conductivity because the laboratory measurements indicate that an increase in thermal conductivity due to an increase in pressure is only about 0.14–0.28% per MPa (Somerton, 1992).

Table 2
Mineral composition of rocks used in this study (from Somerton, 1992; Davis, 1984)

Rock component	Volume fraction		
	Abu Gabra Shale	Abu Gabra Sandstone	Kern River Sandstone
Quartz	0.34	0.83	0.341
Orthoclase	-	-	0.010
K-Feldspars	0.02	0.05	-
Plagioclase	0.09	0.01	0.205
Kaolinite/Sericite	0.20	0.10	0.257
Illite/Mica	0.10	-	-
Smectite	0.10	0.01	-
Chlorite	0.15	-	0.070
Hornblende	-	-	0.041
Sphene	-	-	0.021
Epidote	-	-	0.018
Others	-	-	0.037
Total	1.0	1.0	1.0

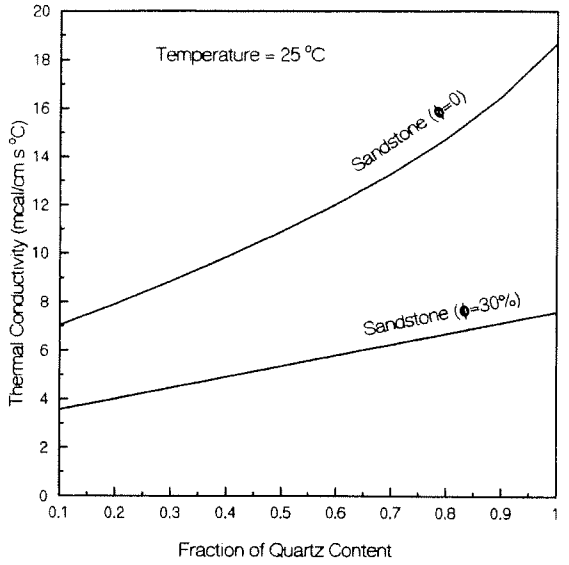

Fig. 3. Dependence of thermal conductivity on fraction of quartz content. Note that there is a large variation in thermal conductivity for lithologically defined "sandstone" at 25°C.

Since the mineralogical compositions and the volume fractions of the water-saturated Abu Gabra sandstone and shale are well known (Table 2), these rocks will be used to illustrate the application of the fabric model. The thermal conductivity of Abu Gabra sandstone has been calculated as a function of the volume fraction of quartz, assuming that the volume fractions of the non-quartz minerals in the sandstones decrease in their original ratios. Fig. 3 shows the solid and bulk thermal conductivities as functions of quartz fractional volume as the fraction of quartz increases from 0.1 to 1.0 at temperature of 25°C. If rocks with quartz content $> 50\%$ are defined as sandstones, the thermal conductivity of the Abu Gabra sandstone will vary from 10.9 to 18.7 mcal/cm·s·°C at porosity = 0 (solids) and from 5.2 to 7.6 mcal/cm·s·°C for the water-saturated bulk rock having a porosity of 30%. Such a large variation in thermal conductivity for "sandstones" implies that it would be difficult to determine a standard thermal conductivity for lithologically defined "sandstones" at 25°C.

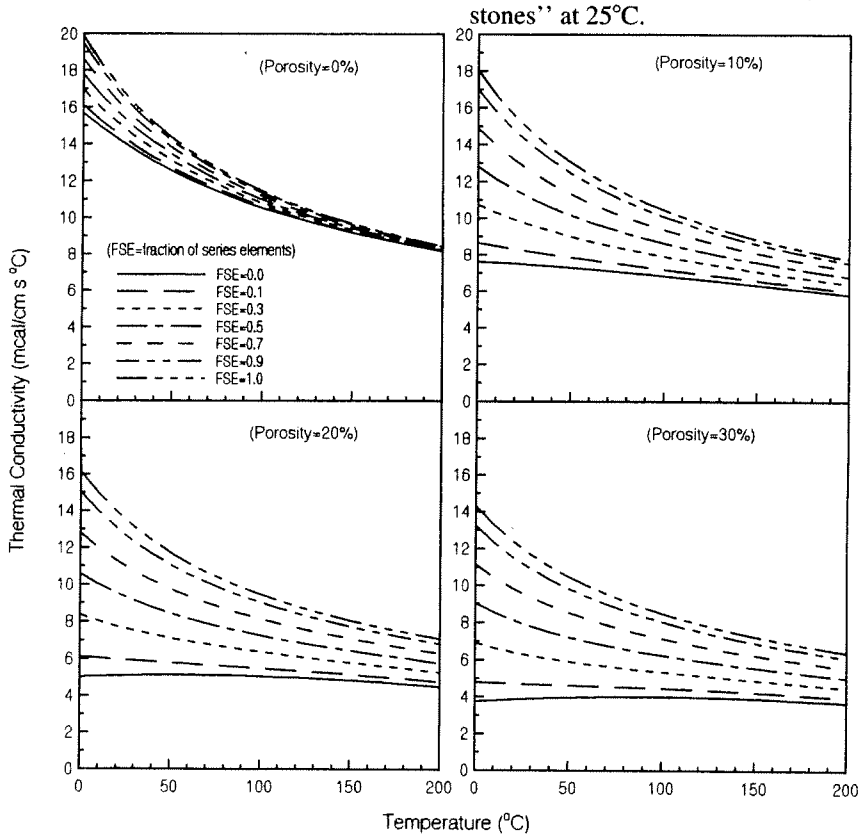

Fig. 4. Parameter variation in the thermal conductivity of Abu Gabra sandstone as a function of temperature, porosity, and *FSE* based on the fabric model. All samples are saturated with water.

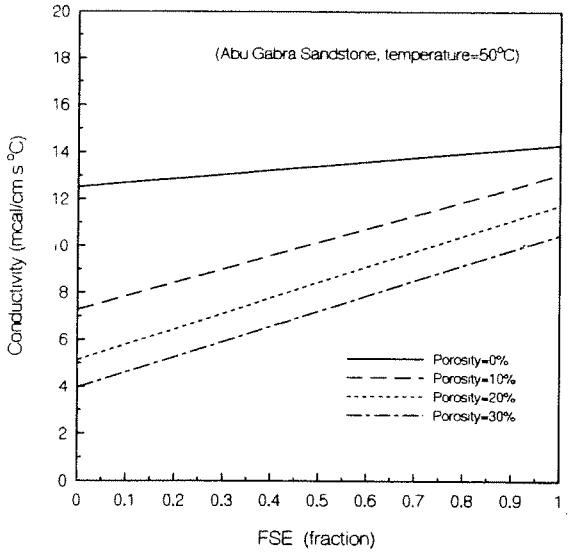

Fig. 5. Plot of thermal conductivity as a function of the fraction of series elements (*FSE*) and porosity, based on the fabric model. Pore saturating fluid is pure water.

Fig. 4 shows the temperature dependence of thermal conductivity as a function of temperature, porosity, and *FSE* and computed from Eqs. (4)–(6) of the fabric model. Generally, the thermal conductivity varies inversely with temperature; however, for smaller *FSE* and higher porosity, say, $FSE = 0$ and porosity = 30%, temperature has little effect on thermal conductivity.

Fig. 5 shows that, at a fixed temperature, the fabric model of the sandstone thermal conductivity is proportional to *FSE*. For example, the fabric model indicates that the thermal conductivity of Abu Gabra sandstone will increase from about 7.2 mcal/cm·s·°C at $FSE = 0$ to about 13 mcal/cm·s·°C at $FSE = 1$ for $\phi = 10\%$ and $T = 50°C$. It is obvious that *FSE* is a very sensitive parameter in the fabric model.

An increase in porosity results in a decrease in bulk rock thermal conductivity with the magnitude being dependent on *FSE*. For example, Fig. 5 also shows that, as porosity increases from 0 to 30%, the bulk rock thermal conductivity decreases by about 4 mcal/cm·s·°C (20%) for $FSE = 1.0$ and, more significantly, by about 12 mcal/cm·s·°C (60%) with $FSE = 0$ at a temperature of 50°C.

The thermal conductivities of the Abu Gabra shale and Kern River sandstone listed in Table 2 were also calculated using the fabric model and are plotted in Fig. 6. It is interesting to note that the Abu Gabra shale and Kern River sandstone have almost the same variation curves of thermal conductivity vs. temperature and *FSE* (Fig. 6), which implies that the thermal conductivity of shale is not always smaller than that of sandstone. The results shown in Fig. 6 also imply that thermal conductivities for rocks with the same lithologic definition of "sandstone" may vary significantly. Under

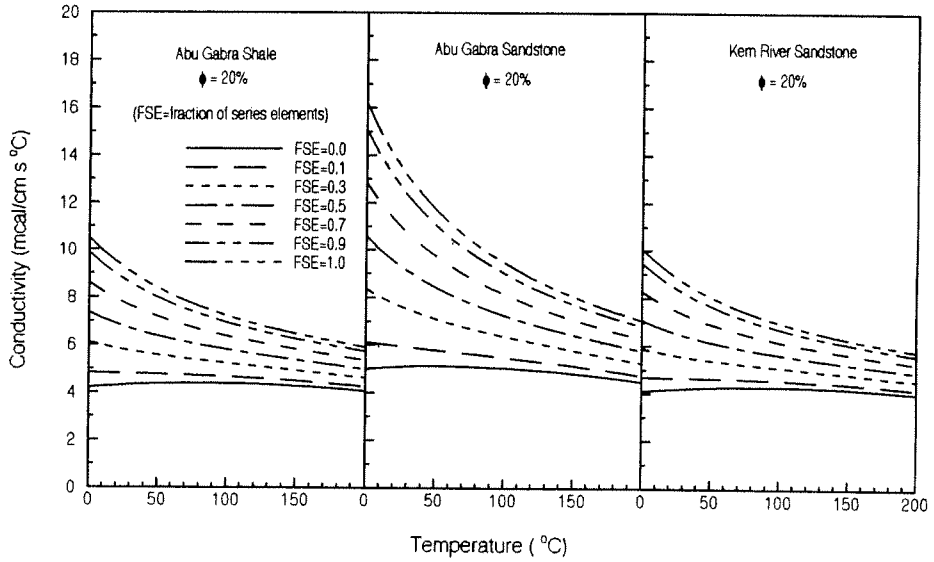

Fig. 6. Changes in the thermal conductivities of shale and sandstone as functions of temperature, porosity, and FSE based on the fabric model. Pore saturating fluid is pure water.

the same temperature, *FSE*, and porosity conditions, for instance, the thermal conductivity of the Kern River sandstone is almost equal to that of the Abu Gabra shale and is much lower than that of the Abu Gabra sandstone because of their different volume fractions of mineral composition (Fig. 6 and Table 2). For the fabric model, it is obvious that the thermal conductivity of water-saturated rocks will depend not only on temperature and porosity, but also on the volume fraction of mineral components and the fraction of series elements (*FSE*).

4. Parameter sensitivity and accuracy of the model

The most critical factor of the fabric model is the fraction of series elements, *FSE*, which essentially dominates the computation of the thermal conductivity of the rock. As shown in Figs. 3 and 4, different *FSE* values result in a significant difference in the rock thermal conductivity with other factors held constant. In previous studies (Davis, 1984; Cathles et al., 1993), half series and half parallel elements ($FSE = 0.5$) were used for their fabric models. The questions are: Is 0.5 the best *FSE* value for all of lithologies in the fabric model? If so, how good are the modeling results?

The reliability of the fabric model with different *FSE* values has been tested against the experimental thermal conductivity measurements of 111 water-saturated or moist samples reported by Brigaud and Vasseur (1989). The samples used in their analysis were taken from cores, cuttings, outcrops, and artificially recompacted samples which originally included two sets: non-clay samples and clay samples. The volume fractions of mineral composition and the porosities of the samples were available and were used in the calculations. The thermal conductivities of these samples were measured at 20°C using the transient line-source method (Von Herzen and Maxwell, 1959; Fernandez et al., 1986), which is typically accurate to within about 5% (Brigaud and Vasseur, 1989).

Based on the volumetric mineral and porosity fractions of the samples, the thermal conductivities of the samples at 20°C have been calculated by our fabric model, assuming that the rocks were evenly integrated in half series and half parallel elements ($FSE = 0.5$). Differences in thermal conductivities between the experimental measurements and the fabric model results are illustrated in Fig. 7a. The analysis of relative error, $(K - K')/K$, shown in Fig. 7b, demonstrates that 59% of the computational results have relative errors of less than $\pm 10\%$ for the various rock samples. A statistical analysis of these results shows that the mean and the standard deviations of the relative error are -8.09% and 14.57, respectively, as depicted in Fig. 7c.

To test the validity of the assumed value of $FSE = 0.5$ for all of the lithologies tested, three types of lithologies are regrouped from the data of Brigaud and Vasseur (1989) according to their predominant minerals: a clay group (29 samples) with clay mineral content greater than 50%, a sandstone group (35 samples) with quartz content greater than 50%, and a carbonate group (26 samples) with calcite or dolomite content greater than 50%. The optimum *FSE* values corresponding to the least relative mean error for the different lithological groups were separately derived.

The relative mean error $(K - K')/K$ is the criterion used to evaluate the modeling results because we are interested in the best average *FSE* value for each lithological category rather than each individual sample. Fig. 8 shows three curves characterizing the distribution of the relative mean error versus *FSE* values for the clay, sandstone, and carbonate groups. These results indicate that the optimum *FSE* values corresponding to the least mean error are 0.444 (44.4% of components arranged in series) for clay samples, 0.498 for the sandstone samples, and 0.337 for the carbonate samples. Statistics for calculated thermal conductivities using the optimum *FSE* and measured thermal conductivities for the three groups are shown in Fig. 9. Also the statistical characteristics for $FSE = 0.5$ are given in Fig. 10 in order to show the differences between the optimum *FSE* values and $FSE = 0.5$. If the optimum *FSE* values are used, the percentages of samples with relative errors less than $\pm 10\%$ will increase from 58% ($FSE = 0.5$) to 85% for the clay group, from 50% ($FSE = 0.5$) to 77% for the carbonate group, and from 58% ($FSE = 0.5$) to 61% for the sandstone group as shown in Figs. 9 and 10 and tabulated in Table 3. Obviously, the accuracy of predictions of the rock thermal conductivities for both the clay and carbonate groups has been significantly improved by optimizing the value of *FSE*. However, there is only a small deviation from $FSE = 0.5$ for sandstone group. This is because the sandstone group used in the analysis is

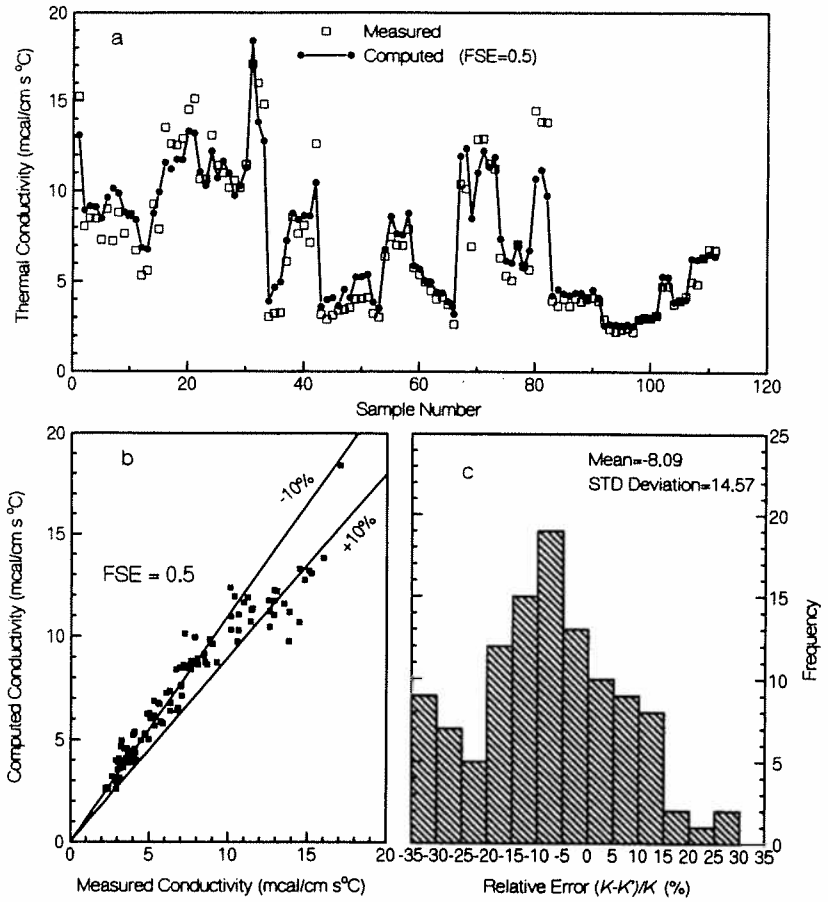

Fig. 7. (a,b) Plots of measured and computed results using the fabric model with $FSE = 0.5$. Rock samples are from Brigaud and Vasseur (1989). (c) Histogram shows the distribution of relative error, $(K - K')/K$, for $FSE = 0.5$. K = measurements and K' = fabric model values.

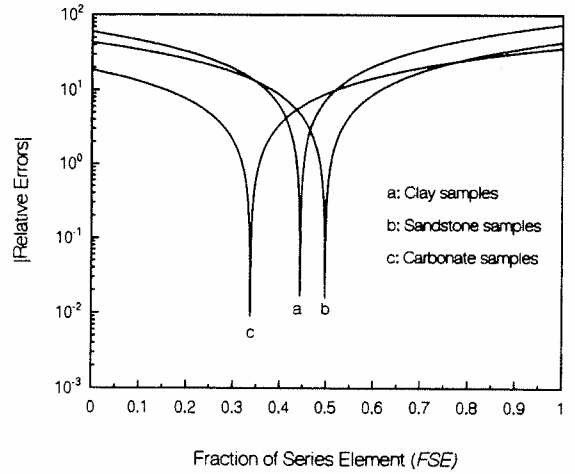

Fig. 8. Plot of the relative mean errors for the fabric model vs. *FSE*. Note that the sharply defined optimum values of *FSE* correspond to the least mean error of clay, sandstones, and carbonates, respectively.

composed of two types of sandstones which have significantly different thermal properties caused by unknown factors. This is deduced from Figs. 9d and 10d in which two sub-groups of samples can be clearly identified based on the statistics. One group has a relative mean error of about -10%, which coincidently belongs to samples with thermal conductivity less than 10 mcal/cm·s·°C. The other group has a relative mean error of about $+10\%$, which is coincidently related to samples with thermal conductivities greater than 10 mcal/cm·s·°C. The reason for this phenomenon in the sandstone group cannot be ascertained because of the lack of more complete data on the original samples. However, if the sandstone samples could be reasonably separated on a supplemental lithological or physical basis, better results could be obtained from the fabric model.

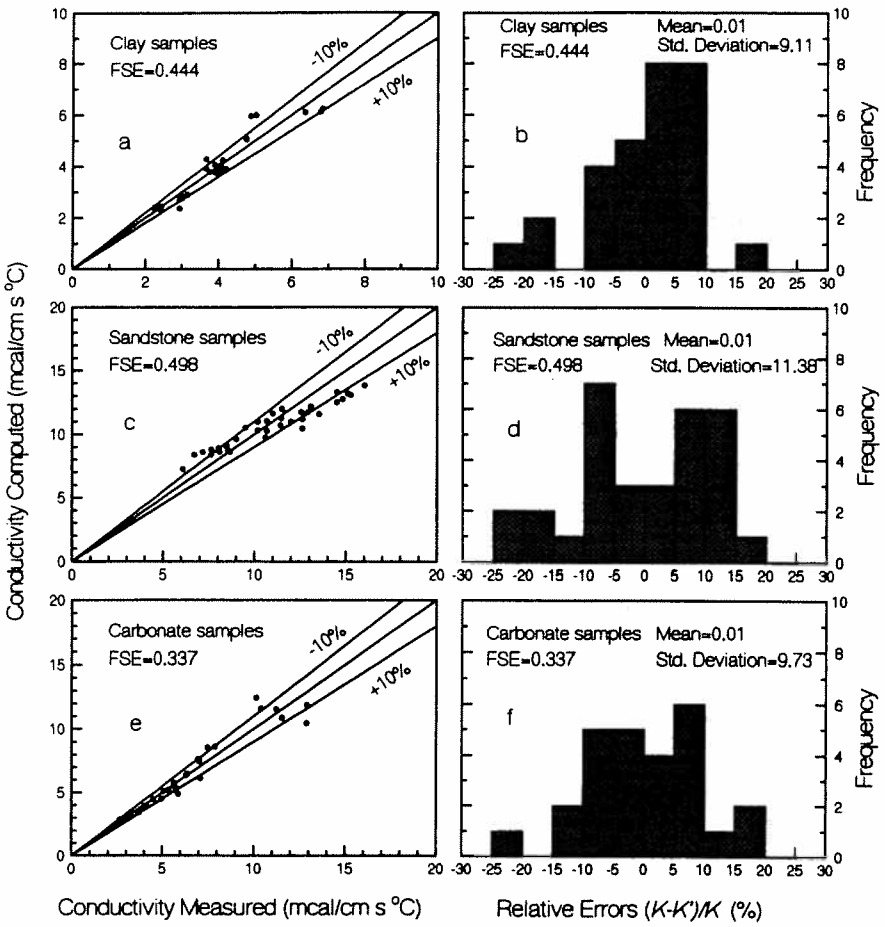

Fig. 9. Plots of measured and computed fabric model results using the optimum *FSE* values for the (a) clay, (c) sandstone, and (e) carbonate groups. Histograms show the distribution of relative error, $(K-K')/K$, for the (b) clay, (d) sandstone, and (f) carbonate groups. K = measurement and K' = computed results using the fabric model with the optimum *FSE* values.

As a result of the above validation tests, the computation of the thermal conductivity using the fabric model is very sensitive to the *FSE* value, as shown earlier in Fig. 8 and Table 3, which significantly affects the reliability of the model. For example, if *FSE* is changed from 0.5 to 0.444 for the clay group, the relative mean errors in computation of thermal conductivity of the clay samples will decrease from -7.26% to 0.01%. As a result, only 15% instead of 42% of the clay samples has a computed thermal conductivity with the relative error greater than $\pm 10\%$ in comparison with the measurements, which makes the computed thermal conductivity better. Therefore, the assumption of a constant value, $FSE = 0.5$, is not particularly optimum for any given lithology. On the other hand, to obtain the most accurate results, the *FSE* value has to be accurate to within 10^{-3} instead of 10^{-1}. Also, determination of the optimum *FSE* values for different lithological categories influences the accuracy of the rock thermal conductivity obtained using the fabric model. This implies that *FSE*, although empirical, is broadly associated with the rock composition, texture, and mineral grain architecture.

5. Comparison of fabric and geometric mean models

The geometric mean model is another mixing-law model which is also widely used to calculate the thermal conductivity of rocks. This model is also based on the mineral components and the rock porosity (Brigaud

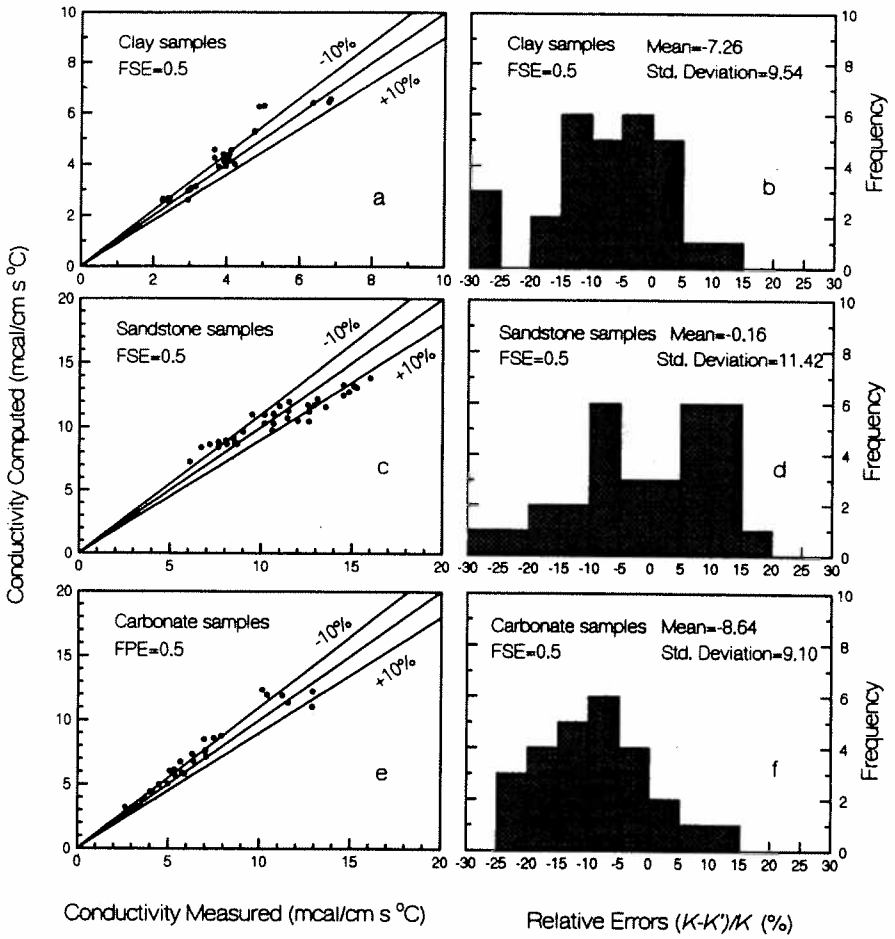

Fig. 10. Plots of measured and computed fabric model results using $FSE = 0.5$ for the (a) clay, (c) sandstone, and (e) carbonate groups. Histograms show the distribution of relative error, $(K - K')/K$, for the (b) clay, (d) sandstone, and (f) carbonate groups. K = measurement and K' = computed results from the fabric model with $FSE = 0.5$.

and Vasseur, 1989; Somerton, 1992). The geometric mean model is typically expressed as:

$$K = (K_s)^{(1-\phi)} \cdot (K_f)^{\phi} \quad (7)$$

where K is the thermal conductivity of the bulk rock, K_s is thermal conductivity of the solid rock matrix, K_f is the thermal conductivity of the fluid, and ϕ is porosity.

For the comparative analysis, we make the same assumption as in the fabric model that the thermal conductivity of the rock is affected by all of the mineral components and each mineral component follows the

Table 3
Variation in *FSE* values for different lithological groups

Factors	Clay group (29 samples)		Sandstone group (35 samples)		Carbonate group (26 samples)	
Fraction of Series Elements (*FSE*)	0.500	0.444	0.500	0.498	0.500	0.337
Mean of relative error $(K-K')/K$ (%)	−7.26	0.01	−0.16	0.01	−8.64	0.01
Standard deviation	9.54	9.11	11.42	11.38	9.10	9.73
Samples with error $< \pm 10\%$	58%	85%	58%	61%	50%	77%

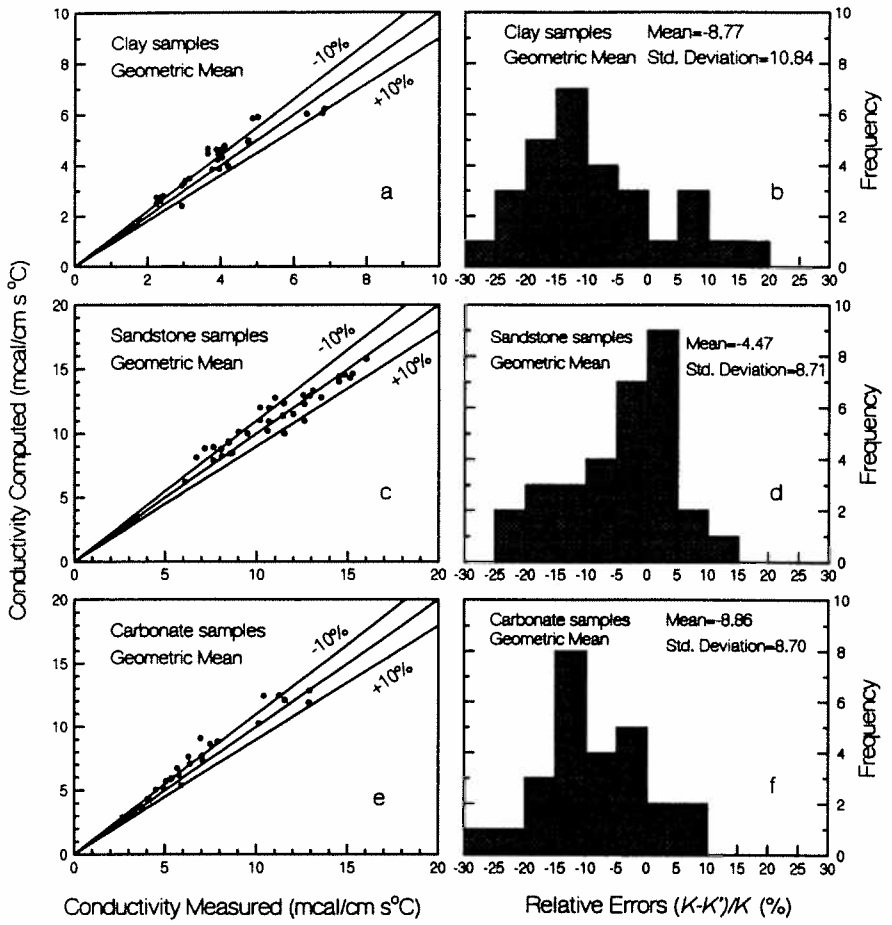

Fig. 11. Plots of measured and the computed results using the geometric mean model for the (a) clay, (c) sandstone, and (e) carbonate groups. Histograms show the distribution of relative error, $(K-K')/K$, for the (b) clay, (d) sandstone, and (f) carbonate groups. K = measurement and K' = computed results using the geometric mean model.

above geometric mean principle. Eq. (7) is therefore:

$$K = [\prod(K_s^i)^{\xi_s^i}]^{(1-\phi)} \cdot [\prod(K_f^i)^{\xi_f^i}]^{\phi} \quad (8)$$

where K^i_s is the thermal conductivity of the ith mineral at room temperature, ξ^i_s is the volume fraction of the ith mineral, K^i_f is the thermal conductivity of the ith pore fluid (water, oil, or gas) at room temperature, and ξ^i_f is the fluid saturation of the ith pore fluid. For basin modeling purposes, Eqs. (5), (6), and (8) are adopted in the geometric mean model for calculation of K^i_s, K_w, and K_0 as function of temperatures. With these relationships, the geometric mean model may be used to calculate the rock thermal conductivities in the subsurface.

In the previous discussions, the fabric model has been developed and evaluated in detail. Here, the fabric model and geometric mean model will be compared by using the same three lithological groups selected from the Brigaud and Vasseur (1989) sample data to determine the relative performance of the models for predicting the thermal conductivity.

The thermal conductivities at 20°C for the three types of lithological samples were calculated for the geometric mean model (Eq. 8) using Eqs. (5) and (6) and the mineral conductivity data of Brigaud and Vasseur (1989). The relative mean errors for each lithological category were then calculated as shown in Fig. 11 and listed in Table 4. The results indicate that the percentages of samples having conductivities less than

Table 4
Comparison of the accuracy of the fabric model and the geometric mean model

Factors	Fabric model			Geometric mean model		
Lithology	Clay	Sandstone	Carbonate	Clay	Sandstone	Carbonate
Fraction of Series Elements (*FSE*)	0.444	0.498	0.337	-	-	-
Mean of relative error $(K-K')/K$ (%)	0.01	0.01	0.01	−8.77	−4.47	−8.86
Standard deviation	9.11	11.35	9.73	10.84	8.71	8.70
Samples with error $< \pm 10\%$	85%	61%	77%	41%	71%	50%

$\pm 10\%$ are 41% for the clay group, 50% for the carbonate group, and 71% for the sandstone group. Compared with the results from the fabric model using the optimum *FSE* values, the geometric mean model produces a better prediction of the thermal conductivity for the sandstone group but gives somewhat worse predictions for the clay and carbonate groups.

These results imply that the geometric mean model is effective for the thermal conductivity of sandstone. However, this sandstone model, which is dominated by the more thermally conductive quartz mineral content, is not effective for the clay and carbonate groups because they have significant differences in rock texture and sedimentary structure which the geometric mean model may not take into account. The thermal conductivity values calculated from the geometric mean model are lower than the measured values for both the clay and the carbonate groups according to their relative error means (Figs. 9a,b,e,f and 11a,b,e,f and Table 4). As mentioned before, if the bimodel sandstone samples had been better grouped based on their mineral composition, the fabric model could potentially give much better results by using the optimum *FSE* values for the two different types of sandstones. This potential capability is important because the grain texture and sedimentary structure, including grain orientation, clay mineral structure, bedding, and porosity types, apparently have a significant influence on the thermal conductivity of rocks. The influences of grain texture and sedimentation structure on the thermal conductivity can be taken into account by adjusting the *FSE* values for different categories of rocks. From this point of view, the fabric model is generally superior to the geometric mean model.

6. Conclusions

The fabric model represents a good approach for estimating the thermal conductivity of different reservoir rocks based on the mineral composition, porosity, and temperature. The model is straight forward in application, and yields good estimates of thermal conductivity in complex fluid–rock systems; further, the model parameters are relatively easy to obtain. Mineralogical composition and volume fractions in the rock can be determined using petrographic and X-ray techniques, whereas the values of the thermal conductivity for most of the common minerals are cataloged at 25°C. The fabric model is a new approach that can make a more accurate prediction of the paleothermal conductivity of sediments and so improve our capability in basin modeling.

The selection of the optimum value for the fraction of series elements, *FSE*, in the fabric model is extremely important. This study showed that $FSE = 0.5$ is not a good choice for all rocks. This is because *FSE* depicts the way in which the mineral components are deposited and compacted into rocks. Thus, different *FSE* values should be determined for different lithologies to characterize their different grain textures and sedimentation structures. Also, for maximum accuracy, the *FSE* value must be stated with an accuracy of 10^{-3} instead of 10^{-1} to achieve the least errors in the thermal conductivities of rocks. The optimum average values of *FSE* determined in this study are about 0.444 (44.4% of components arranged in series) for water-saturated clay rocks, 0.337 for water-saturated carbonate rocks, and 0.498 for water-saturated sandstone rocks. The thermal conductivity derived from the different mixing-law models suggests that the fabric model yields

better results than the geometric mean model, largely because the fabric model is adaptable and sensitive to different lithologies.

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