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Tracking the thermal properties of the lower continental crust: Measured versus calculated thermal conductivity of high-grade metamorphic rocks (Southern Granulite Province, India)

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ABSTRACT

In this study, the bulk thermal conductivity (TC) of 26 rock samples representing different types of granulite-facies rocks, i.e., felsic, intermediate and mafic granulites, from the Southern Granulite Province, India, is measured at dry and saturated conditions with the optical-scanning method. Thermal conductivity is also calculated from modal mineralogy (determined by XRD and EPMA), applying several mixing models commonly used in thermal studies. Most rocks are fine- to medium-grained equigranular in texture. All samples are isotropic to weakly anisotropic and possess low porosities (<2%). Measured TC values range between 2.5 and 3.0 $\mathrm{W\,m^{-1}\,K^{-1}}$ for felsic granulites, between 2.5 and 3.5 $\mathrm{W\,m^{-1}\,K^{-1}}$ for intermediate granulites and between 2.4 and 2.7 $\mathrm{W\,m^{-1}\,K^{-1}}$ for mafic granulites. Considering this data and literature compilations, rocks representative for the lower continental crust typically display values between 2 and 3 $\mathrm{W\,m^{-1}\,K^{-1}}$ at ambient temperature and pressure conditions. Depending on the mixing model and the mineral TC value used in the calculations, measured and calculated bulk TC could be properly fitted. For mean values of mineral TCs, the harmonic mean provides an almost perfect fit, with a mean deviation of $-1 \pm 6\%$ (1σ). However, the implication of that correspondence would be that minerals and pores are predominantly aligned parallel, which is in apparent contrast to the texture of the rocks studied here. The geometric mean, which does not consider any layering of minerals or pores in the rock and, thus, should be in better harmony with the textural characteristics of the studied high-grade rocks, matches the measured TC data very well, if minimal minerals TCs reported in the literature are applied (mean deviation $5 \pm 8\%$). Thus, if samples appropriate for laboratory measurements (in terms of sample size or physical-chemical-mechanical condition) are not available, bulk TC of high-grade metamorphic rocks with low anisotropy and porosity could be satisfactorily good assessed from modal mineralogy, using the data sets for mineral TC applied in this study. Further work is required on the applicability of mixing models to compute TC of other rock types, e.g., of igneous and sedimentary rocks.

1. Introduction

Thermal conductivity (TC, λ) of rocks is one of the essential thermophysical parameters that govern the thermal structure of the earth. Especially the TC of granulite-facies rocks, representative of the lower continental crust, provides an important constraint on the temperature distribution of the lithosphere. Significant variation of TC in high-grade metamorphic rocks also exerts a major control on the distribution of heat in the lower crust itself. Thus, knowledge on TC of the lower crust is vital in any state-of-the-art thermal-lithosphere study.

Most thermal models are confronted with the problem that TC data for the lower crust are not available for a study area and literature-data need to be considered. Thermal conductivity is generally measured in the laboratory on core or outcrop rock samples. However, lower-crustal lithologies are only rarely exposed in surface outcrops or by drillcore, which would permit to determine TC values directly in the laboratory. In some places, probes of the lower crust are brought up to the surface as xenoliths in mafic magmas. These xenoliths, however, are generally small in size, have

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interacted with the basaltic host magma, experienced metasomatic alteration, or have already undergone surface weathering. All these features hamper or even preclude obtaining reliable TC data by laboratory measurement (cf. Förster et al., 2007).

The TC of a rock is primarily controlled by its mineralogy. Therefore, if appropriate rock samples are not available for direct laboratory measurement, TC may be alternatively assessed by indirect methods, e.g., calculated from the mineral composition of the rock. Fortunately, the size of lower-crustal xenoliths is usually sufficiently large so that their modal mineralogy can be precisely determined, for instance, by X-ray diffraction combined with electron-microprobe analysis. Even if xenoliths are metasomatically overprinted and their original mineralogical composition changed during uprise from their source, the in-situ modal mineralogy could be properly reconstructed if the mineral reactions involving the alteration species are known.

Several attempts have been made in the past to calculate the TC of rocks indirectly from its mineral composition (e.g., Birch and Clark, 1940; Beck and Beck, 1965; Horai and Baldridge, 1972; Brigaud and Vasseur, 1989; Pribnow et al., 1993; Pribnow and Umsonst, 1993; Jessop, 2013; Fuchs et al., 2013). All these approaches, however, were confronted with various shortcomings. They involved either only a limited amount of samples, did not consider all common mixing models (see below) or missed a comprehensive mineralogical/geochemical sample characterization. Calculation of rock TC from modal mineralogy is not simple and must further take into account the complexity of rock structure/texture. To tackle this problem, several petrophysical models can be applied. These models consider a rock as an n-phase system consisting of minerals and pores. They differ with regard to what they reflect, e.g. whether minerals or pores are aligned parallel or perpendicular to the direction of measurement, resulting in a TC for both directions represented by the arithmetic mean and harmonic mean, respectively. Rock TC can also be assessed considering other mixing models, e.g., the geometric mean (Lichtenecker, 1924), the Hashin–Shtrikman mean (Hashin and Shtrikman, 1962), or the effective-medium mean (Bruggeman, 1935). A comprehensive overview on such mixing models is provided by Abdulagatova et al. (2009).

The aim of the present study is two-fold. First, it examines whether the indirect determination of rock TC from modal mineralogy may serve as a reliable substitute for laboratory-measured values and what errors are inherent in such an approach. Second, it adds a set of newly measured TC values to the poor database yet existing for the lower crust, demonstrating that the range in TC of this part of the lithosphere may be enormous. In addition to the paucity in values, there are only few studies in which measured TC values for lower-crustal rocks are referred to samples that are also properly characterized petrologically (cf. Kukkonen et al., 1999). In our study, full and state-of-the-art mineralogical and geochemical data are provided for all samples.

Our study encompasses a total of 26 fresh, usually fine- to medium-grained equigranular surface rock samples, including eight felsic granulites (charnockites), ten intermediate granulites (enderbites), four mafic granulites and, for comparison, four coarser-grained amphibolite-facies ortho- and paragneisses from the Southern Granulite Province, India (Fig. 1). The sampling area represents one of the largest Precambrian granulite provinces of the world, extending over an area of ~40,000 km^2 (Gopalkrishna et al., 1986). On these samples, (i) measurements of bulk thermal conductivity were conducted using the optical-scanning method, (ii) modal mineralogy and mineral compositions were determined by X-ray diffraction (XRD) and electron-probe microanalysis (EPMA) and (iii) bulk TC values were calculated from mineral data and measured porosity applying common mixing models. Finally (iv), the best-fitting mixing model was delineated, given by the amount of deviation between measured and calculated TC.

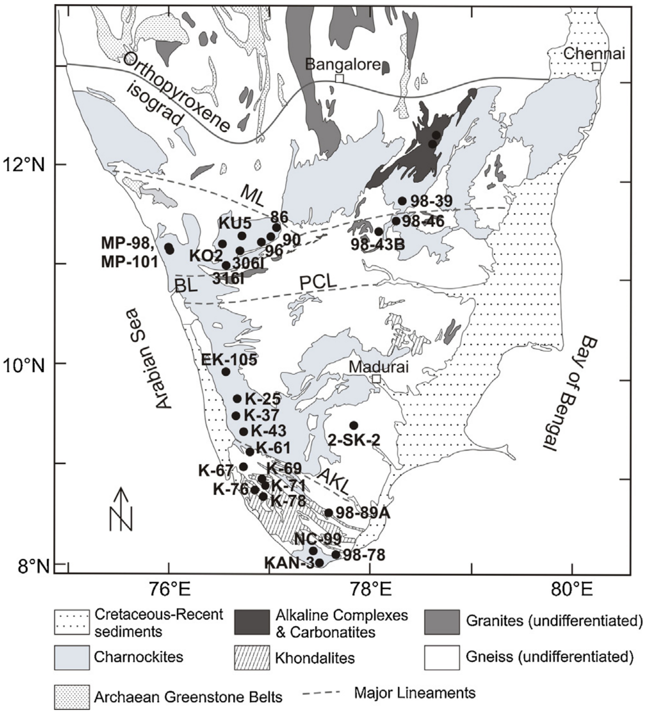

Fig. 1. Geological sketch map of the Southern Granulite Province, India (modified after Geological Map of India, 1998). Sample locations are shown by dots.

2. Analytical methods

2.1. Thermal conductivity and porosity

In principle, three analytical methods are widely in use to perform laboratory TC measurements: (i) the steady-state divided-bar method (e.g., Bullard, 1939; Birch, 1950), (ii) the transient line-source method (e.g., Carslaw and Jaeger, 1947; Jaeger, 1958) and (iii) the transient optical-scanning method (e.g., Popov et al., 1999). A comparison of these methods on amphibolite-facies metamorphic rocks revealed a satisfactorily good agreement within the limits of error (Popov et al., 1999).

In this study, TC measurements were performed with the optical-scanning method. The measurement errors, estimated from tests on standards, ranged between 1 and 3%, thus confirming previous estimates for this analytical technique (cf. Popov et al., 1999). To check for the reliability of the analytical method applied, a subset of the same samples were additionally measured for TC by the divided-bar at NGRI (Hyderabad). Both techniques yielded corresponding results within the limits of analytical error.

Measurements were conducted on sawed samples with smooth surfaces that were commonly between 5 and 9 cm in length, 4 and 6 cm in width and 4 and 6 cm in thickness. The TC was measured on both dry and water-saturated rock samples as well as along two directions which were oriented perpendicular to each other. In the situation of a gentle foliation, samples were measured parallel (λ_{PAR}) and perpendicular (λ_{PER}) to the metamorphic texture. For all samples, measurements were performed along 1–8 different scanning lines on each direction, with one scanning per line. For each direction, minimum and maximum TC values (averaged from the bulk of scanning line data) were calculated, designated as $\lambda_{\min}$ and $\lambda_{\max}$. The respective mean values are denoted as $\lambda_{\mathrm{AVERAGE}}$.