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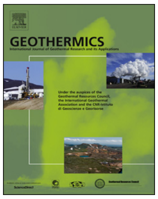

Evaluate best-mixing model for estimating thermal conductivity for granitoids from mineralogy: A case study for the granitoids of the Bundelkhand craton, central India

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ABSTRACT

Granitoid is an important part of the upper continental crust, and therefore its thermal conductivity (TC) plays an important role in understanding the lithospheric thermal structure in a region and for geotechnical or geoengineering purposes. In above context, due to the lack of TC data or absence of proper sample for its measurements, TC values are assumed which can lead to erroneous results. In such scenario, when direct measurements are not possible, TC can be estimated by indirect methods with proper precautions. An attempt is made here to arrive at the best mixing model for granitic rocks by using TC of the individual minerals and compare the deviation between the measured and calculated values. The considered mean models are: arithmetic, geometric, harmonic, effective, Voigt-Reuss-Hill and Hashin-Shtrikman along with its lower and upper bound. Studied rocks are potassic granitoid (PG), biotite granitoid (BG), sodic granitoid (GG) and gneisses (BnG) from the Bundelkhand craton, central India. Measurements of TC are done in the laboratory on 21 samples using steady-state method. Data show wide variations in TC values for granitoids (PG: 2.7 − 3.2, BG: 2.6 − 2.9, GG: 2.9 − 3.0 $\mathrm{W m^{-1} K^{-1}}$) and gneisses (2.9 − 3.7 $\mathrm{W m^{-1} K^{-1}}$). Modal mineralogy of the rocks are determined using petrological and geochemical data through modal analysis and normative (CIPW-NORM) methods. The calculated TC arrived by both the methods provide a satisfactory agreement for the harmonic mean model, showing deviation from −10.9 to 17.6% for modal analysis and −16.1 to 11.5% for NORM method. Deviations from the above methods decrease further (−23.3 to 2.8% and −27.7 to −3.1%, respectively) using minimum mineral TC. Therefore, we suggest that, in the case of non-availability of the proper sample for direct measurement, the TC of very low porous granitoids could be satisfactorily determined by assessing their modal mineralogy and considering the harmonic mean model.

1. Introduction

Thermal conductivity (TC) of rocks is an important physical property for studying the Earth's thermal field. According to Fourier's law, TC in conjunction with temperature gradient forms the basic input parameter for heat flow (q) estimation of an area, which in turn is a major input parameter in temperature modelling at shallow and deeper crustal levels. Heat flow can be expressed as

$$q = -\lambda \quad dT/dz \tag{1}$$

where λ is thermal conductivity, dT/dz is a geothermal gradient.

Thus, TC of geological formations and its spatial variations is a fundamental parameter for understanding the thermal structure of any geological setting, quantifying the thermal evolution of sedimentary basins and their hydrocarbon maturation processes, constructing the nuclear waste repository system, constructing an underground tunnel for different purposes, etc.

The thermal conductivity of Earth's material can be measured by direct and indirect methods. Direct methods are the steady-state method, transient line-source method and transient optical scanning method (Bullard, 1939; Birch, 1950; Carslaw and Jaeger, 1947; Jaeger, 1958; Popov et al., 1999). The term steady-state implies no change with time at any point within the medium. Thus, the temperature or the heat flux remains unchanged with time during heat transfer through a medium at any location, although both quantities may vary from one location to another. The term transient implies variation with time or time dependence. Thus, in transient methods, a constant heat applied to the medium and change of temperature with time is considered for calculating TC. In optical scanning method, optical character recognition is performed and produces coded signals corresponding to the

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characters identified. Although there are numerous steady-state and transient techniques available for measuring TC, the most prominent being the *divided bar*, the *needle probe* and the *optical scanning* methods. These techniques are recommended by International Society for Rock Mechanics (ISRM) for determining thermal properties of rocks in the laboratory at atmospheric pressure condition (Popov et al., 2016).

When proper samples are not available for measurements by any method discussed above, TC can be inferred from a number of indirect methods, such as, from the mineralogical composition, saturating fluids, well log correlations and correlations with other physical parameters. Among these, determinations from the mineralogical composition are well accepted as rocks are an assemblage of minerals. Thus, the TC of rock can be calculated in this method from the precise mineralogical composition of the rock and the thermal conductivities of those minerals by considering appropriate mathematical models in which minerals are assembled. In the above calculation of thermal conductivity thermal resistance caused by inter-grain contact also needs to consider which is primarily depends on the porosity and therefore becomes less effective for low porous rocks. Further, thermal resistance decreases for water saturated rocks compared to dry rocks. Thus, inter grain resistance becomes negligible for low porous rocks if measured at the saturated condition.

Mineralogical composition of rock can be determined using modal mineralogy by modal analysis, X-ray fluorescence (XRF), X-ray diffraction (XRD) and electron-probe microanalysis (EPMA) datasets. The thermal conductivity of rock-forming minerals can be found from several reported literature, e.g., Birch and Clark (1940); Beck and Beck (1965); Clarke (1969); Horai and Simmons (1969); Horai (1971); Horai and Baldridge (1972); Beck et al. (1978); Dortman (1984); Popov et al. (1987); Brigaud and Vasseur (1989); Pribnow and Umsonst (1993); Popov et al. (1998); Jessop (2013); Fuchs et al. (2013). For calculating TC of rocks, it is essential to identify an appropriate model that can provide possible mineral pattern. Commonly used mixing models are the arithmetic mean, geometric mean, harmonic mean, effective mean, Voigt-Reuss-Hill average and Hashin-Shtrikman mean along with its lower and upper bound.

During the last few decades, using the above mineral TC and mathematical models, few studies have been carried out to calculate TC of igneous, metamorphic and sedimentary rocks from their mineral composition (Horai and Baldridge, 1972; Pribnow and Umsonst, 1993; Fuchs et al., 2013; Ray et al., 2015; Zhao et al., 2016). The above studies calculate TC based on few mixing models for different rock types depicted that the various mathematical models give certain deviation from measured TC. Best models for sedimentary rocks, granulite rocks have been proposed, but for granite rocks, the best model needs to arrive.

In continents, granites/granitoid/TTG gneisses constitute the significant component of the upper crust, and their thermal conductivity values play an important role in understanding the crustal and subcrustal thermal structure. In the present study, an attempt has been made to study the difference between the measured and calculated TC of the granitoid and TTG gneisses by various mathematical models to arrive the best model for granite rocks. Here, (i) thermal conductivity is measured on 21 representative samples using steady-state divided bar method, (ii) density and porosity is determined by measuring the weight of the rock samples in air and water, (iii) thermal conductivity is calculated by an indirect method from their mineralogical compositions by using mathematical average mixing models, (iv) comparison is made between the measured and the calculated TC to identify the best mixing model for granitic rocks.The studied samples are K-feldspar rich pink potassic granitoid (PG), biotite rich granitoid (BG), mafic minerals/Na-feldspar rich grey sodic granitoid (GG) and TTG gneisses (BnG), representing more than 80% of the crust in Bundelkhand craton, central India. The mineralogical composition of the rocks is determined from petrological data using modal analysis. The mineralogical composition is also determined from chemical data obtained by X-ray fluorescence (XRF) method using NORM calculation. X-ray diffraction (XRD) and electron-probe microanalysis (EPMA) data are used to verify the major mineralogy obtained by both methods. Limitations in both the methods have been taken care during calculations.

2. Geology of the area

Representative rock samples for this study have been collected from the Bundelkhand craton, central India. Bundelkhand craton is the northernmost craton forming an integral part of Indian Precambrian shield and is bounded by central Indian tectonic zone (CITZ) against Satpura mobile belt in south and southeast, great boundary fault against Aravalli craton in west, while its northern boundary is concealed beneath the Indo-Gangetic alluvial plain (Basu, 1986, 2007; Prasad et al., 1999; Mondal et al., 2002; Saha et al., 2011). It lies approximately between 24°30′N and 26°00′N latitude and 77°30′E and 81°00′E longitude and occupies an area of about 26,000 km^2.

Major rock formations of the Bundelkhand craton are gneisses and three types of granitoid. The TTG suite of Meso-Neoarchean Bundelkhand gneissic complex (BnGC) is considered to be the oldest litho unit of this craton (Mondal et al., 2002; Singh et al., 2007). The granitoids can be broadly divided into three categories based on mineralogical, geochemical composition and textural characteristics. They are (1) K-feldspar rich pink granitoid (potassic granitoid), (2) biotite rich granitoid (biotite granitoid) and (3) mafic minerals/Na-feldspar rich grey granitoid (sodic granitoid) (Basu, 1986; Singh, 2012; Ray et al., 2016; Podugu et al., 2017). In general, the northern part of the craton is dominated by sodic granitoid; the north-central part is mainly occupied by biotite granitoid and central to southern part dominated by potassic granitoid (Basu 2010). These are I-type and evolved between granodiorite and granite (Mondal et al., 2002; Ray et al., 2016). Basu (1986) has observed that the granitoids are intruded with small scattered enclaves, mainly of banded iron formations (BIFs), meta-ultrabasics, rare quartzite's, some carbonates and calc-silicates.

The detailed work on geochronology in the Bundelkhand craton has been carried out by several workers (Sarkar et al., 1996; Mondal et al., 1998, 2002; Rao et al., 2005; Kaur et al., 2016). The oldest event took place around 3.5 Ga (Kaur et al., 2016) with the formation of TTG gneisses. Mondal et al. (2002) have reported a Pb–Pb model age of 3.3 Ga for gneisses and interpret this as defining the onset of TTG magmatism and deformation in the Bundelkhand craton. The successive events of granitoid magmatism occurred at the end of Neo-Achaean (~2.5 Ga) within the very short span of time (~50 Ma) in this craton.

In the present study, we have considered four major rocks types of Bundelkhand craton, namely, K-feldspar rich pink granitoid or potassic granitoid (PG), biotite-rich granitoid (BG), Na-feldspar rich grey granitoid or sodic granitoid (GG) and TTG gneisses (BnG). The geological map of the study area along with sample locations is shown in Fig. 1.

3. Methodology

3.1. Measurement of thermal conductivity

In the present study, a steady-state thermal conductivity meter (model QL-10™, Anter Corporation®) has been used for measuring the thermal conductivity of rock samples. Detail of the setup is given in Supplementary 1. Rock samples were broken from fresh outcrops/quarries (Fig. 2) are cored, cut and polished into cylindrical discs of diameter 2.54 cm and thickness varying between 1.0 and 2.5 cm depending on rock type and grain size. Cut surfaces of each rock disc are ground and polished until the thickness variation is less than 0.01 mm.

3.2. Measurement of density and porosity

Density is defined as mass per unit volume. The rock samples are weighed in air and then in water using a high precision balance