Thermophysical properties of rocks from the Bushveld Complex

by M.Q.W. Jones*

Synopsis

This paper presents a compilation of physical properties of rocks from the Bushveld Complex. The database consists of more than 900 measurements each of thermal conductivity and density. The data are well distributed from localities around the Complex and most rock types are well represented. Thermal conductivity and density are shown to vary widely in the ranges 1.8–4.2 W m^{-1} K^{-1} and 2600–4200 kg m^{-3} respectively. Although only 190 heat capacity measurements are available, this parameter is quite uniform for most rock types present, 800–900 J kg^{-1} K^{-1}, except for chromitite, which has a lower average, 750 J kg^{-1} K^{-1}. Rocks encountered in deep platinum mines are particularly well characterized and this has important implications for prediction of mine refrigeration requirements. The heat flux into a semi-infinite region with properties typical of the Bushveld Complex as a function of time is substantially lower than an equivalent model for the Witwatersrand Basin.

Keywords
thermophysical rock properties, platinum mines, mine cooling.

Introduction

Geothermal research provides insights into a wide variety of geological problems, including tectonic studies (Jones, 1988, 1992, 1998), maturation of oil and natural gas (Royden *et al.*, 1980), exploration for geothermal energy (*e.g.* Martinelli *et al.*, 1995), and even climatology (*e.g.* Jones *et al.*, 1999). In South Africa, the most important application is in mine engineering. South Africa leads the world in deep mining, and knowledge of virgin rock temperatures, geothermal gradients, and thermal properties of rocks is essential for planning refrigeration and ventilation requirements of deep mines (Jones, 1988; Jones and Rawlins, 2002; Rawlins *et al.*, 2002; Jones, 2003a, 2003b).

One of the most important challenges of mining is to control the environmental conditions, particularly temperature, of deep underground workings. The primary cause of elevated temperatures is heat derived from exposed rock surfaces, whose temperature is determined by the natural increase of virgin rock temperature (VRT) with depth (Rawlins *et al.*, 2002; Jones 2003a). Knowledge of VRT is therefore fundamental for calculating refrigeration requirements. Knowledge of rock thermal properties is also fundamental for refrigeration studies because (1) they determine the rate at which heat flows from the rock into underground excavations, and (2) they control the thermal gradient in strata overlying and underlying these excavations and hence their VRT (Jones, 2003a, 2003b).

Because of its long history of gold mining, which has progressively approached greater depths, the Witwatersrand Basin has been the subject of geothermal research for more than 75 years. Measurements of rock temperature and thermal conductivity dating back to 1938 (Weiss 1938; Bullard, 1939; Krige, 1939) provided the foundation for later studies and eventually an intensified collaborative research programme (from about 1980–2000) between the University of the Witwatersrand (Wits) and the Chamber of Mines Research Organisation (COMRO), and later, CSIR Mining Technology. The net product was a database of VRT, thermal gradient, and rock properties that probably surpasses any in the world (Jones, 1988, 2003a, 2003b).

In the latter period, platinum mining depths in the Bushveld Complex (to the north of the Witwatersrand Basin) increased significantly. Earlier measurements at two localities showed that the geothermal gradient in the Bushveld Complex is substantially higher than that in the Witwatersrand Basin (Carte and van Rooyen, 1969), and it was obvious that there was a need for a detailed geothermal investigation of the Complex. Subsequent research collaboration between Wits, COMRO, and other key stakeholders from industry ensued. New measurements of the geothermal gradient were made in many of the existing and potential platinum mining areas, and these measurements confirmed that the

* *School of Geosciences, University of the Witwatersrand, Johannesburg.*

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thermal gradients are high (generally 20–25 K km^{-1}) (M.Q.W. Jones, unpublished data, 2014). These data will be presented for publication elsewhere.

During the past 30 years, the number of measurements of thermal conductivity, density, and heat capacity on Bushveld rocks gradually grew and the database currently rivals that from the Witwatersrand Basin in size and coverage of rock types. It is the purpose of this paper to present a summary of the Bushveld database, characterize the thermal properties of various rock units constituting the Bushveld Complex, and discuss the implications for deep mining.

Geological background

The Bushveld Complex is an enormous igneous province occupying an area of approximately 65 000 km^2 to the north, east, and west of Pretoria (Figure 1). The Complex hosts the world's largest reserves of platinum, chromium, and vanadium, and consequently there is a vast literature. This brief summary is largely based on reviews provided by SACS (1980) and Cawthorn *et al.* (2007). For ease of reference, Table I contains a glossary of major Bushveld rock types discussed below.

The Bushveld Complex consists of coarse-grained igneous rocks with a wide range of composition from ultramafic to felsic. It is temporally, and possibly genetically, related to volcanic rocks of the Rooiberg Group (Cawthorn *et al.*, 2007) (Figure 1). However, this paper deals solely with the plutonic rocks that were intruded into the Transvaal Supergroup and older rocks 2060 Ma ago. The Complex is formally classified into three distinct units: the ultramafic to mafic Rustenburg Layered Suite and the felsic Rashoop Granophyre and Lebowa Granite Suites (Figure 2).

The average thickness of the Rustenburg Layered Suite is approximately 6 km, and it crops out in four main 'limbs'. The geology of the eastern limb (northwest to southwest of Burgersfort) and the western limb (Thabazimbi to Pretoria) is reasonably well known, whereas large parts of the southern (or Bethal) limb and northern (or Potgietersrus/Mokopane) limb are covered by younger Karoo and Waterberg strata. Different rock units can be traced for hundreds of kilometres and, although the succession is seldom complete, geophysical evidence suggests that at least the eastern and western limbs are connected at depth (Cawthorn *et al.*, 1998).

The Rustenburg Layered Suite consists of five main 'zones', which is the most convenient classification for discussing similar rocks from similar levels (Figure 2). Although specific rock types are listed below and in Table I, it should be noted that there is often a gradational change from one rock type to another. For example, there can be an almost continuous variation from anorthosite to pyroxenite and, as will be seen, this results in a gradation of thermal properties.

Table I

Glossary of major rock types in the Bushveld Complex

Rock type	Major minerals
Felsic rocks	Quartz, feldspar
Granite	Quartz, plagioclase/alkali feldspar (mica)
Granophyre	Quartz, alkali feldspar
Mafic rocks	Feldspar, pyroxene, olivine
Anorthosite	Plagioclase feldspar
Norite	Plagioclase feldspar, orthopyroxene
Gabbro	Plagioclase feldspar, clinopyroxene
Gabbronorite	Undifferentiated gabbro/norite
Diorite	Plagioclase feldspar, pyroxene, olivine
Ultramafic rocks	Pyroxene, olivine
Pyroxenite	Orthopyroxene and/or clinopyroxene
Peridotite	Olivine, pyroxene
Harzburgite	Olivine, orthopyroxene
Wehrlite	Olivine, clinopyroxene
Dunite	Olivine
Ore-bearing units	
Magnetitite layers	Magnetite
Merensky Reef	Pyroxene
Chromitite layers	Chromite (pyroxene)

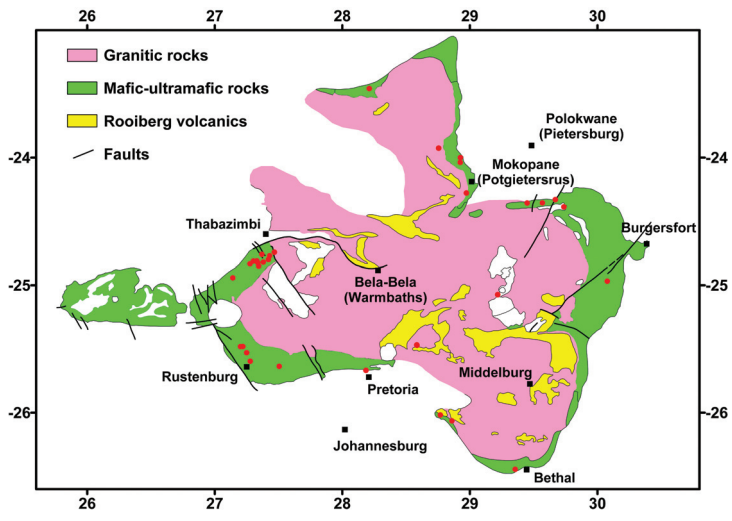


Figure 1—Suboutcrop map of the Bushveld Complex showing the distribution of major geological units after artificially removing overlying Transvaal Supergroup strata and younger Karoo Supergroup and Waterberg Group strata (after Cairncross and Dixon, 1995). Yellow, Rooiberg Group; green, Rustenburg Layered Suite; pink, Rashoop Granophyre Suite and Lebowa Granite Suite. Red dots indicate localities from which samples were collected for rock property analysis

Thermophysical properties of rocks from the Bushveld Complex

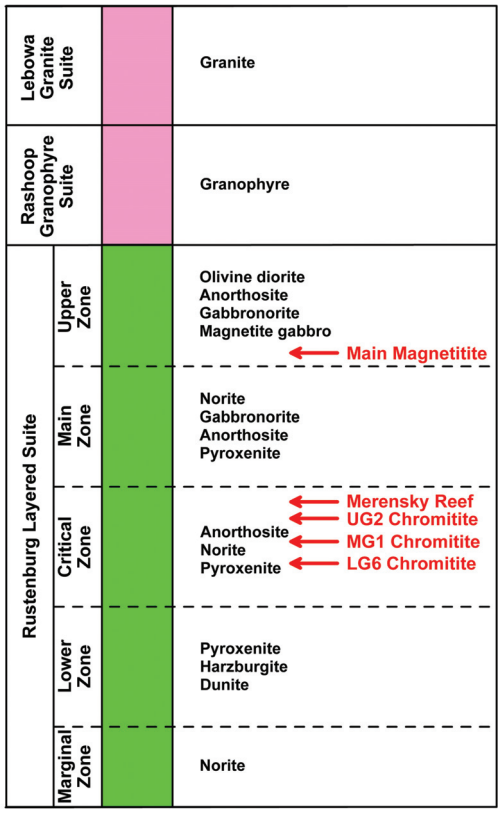


Figure 2—Generalized stratigraphic column for the Bushveld Complex indicating predominant rock types (after SACS, 1980). Red arrows schematically show the relative position of major ore-bearing layers

The lowermost 'Marginal Zone' consists predominantly of uniform, relatively fine-grained norite with minor amounts of pyroxenite. The overlying 'Lower Zone' is ultramafic in composition and dominated by pyroxenite, but includes thick layers of harzburgite with some dunite.

From a mining point of view, the 'Critical Zone' is the most important because it is the host of chromium-rich and platiniferous ores. The lower part of the Critical Zone is essentially pyroxenite with some olivine-bearing rocks, whereas the upper section is represented by cyclic layers involving pyroxenite, norite, and anorthosite. Numerous chromitite layers may be well developed in the Critical Zone, and these are divided into the Lower Group (LG1-7), Middle Group (MG1-4), and Upper Group (UG1-3). The LG6 and MG1 layers have been extensively mined for chromium. The main sources of platinum and associated platinum group elements (PGEs) are the UG2 chromitite layer and pyroxenites within the Merensky Reef (Figure 2).

The 'Main Zone' is a thick uniform sequence of norite and gabbronorite with a few layers of anorthosite and pyroxenite. It is overlain by the 'Upper Zone' in which magnetite appears as an accessory mineral in many rocks, which are predominantly anorthosite, gabbronorite, magnetite gabbro, and olivine diorite towards the top. Magnetite may accumulate in up to 24 layers, some of which exceed 2 m in thickness. Vanadium is associated with all the magnetitite layers and can reach concentrations of up to 2%. The Main Magnetite Layer in the lower part of the Upper Zone (Figure 2) is mined for vanadium.

The last stage of Bushveld magmatism involved the emplacement of large volumes of granophyric and granitic rocks of the Rashoop Granophyre Suite and the Lebowa Granite Suite, which occupy the interior of the Complex (Figure 1). Although they are often referred to collectively as 'Bushveld granite', there are significant variations in the proportions of major minerals (quartz and feldspar) as well as the content of minor mafic phases (mainly hornblende, biotite, and pyroxene). This results in subtle variations of thermal properties.

Measurement of thermophysical properties

The methods used to measure the thermophysical properties are essentially the same as those reported in this journal by Jones 10 years ago (Jones, 2003b). The reader is referred to that paper for details, and only the most salient points will be repeated here. The measured parameters are thermal conductivity (K, units W m^{-1} K^{-1}), density (ρ, kg m^{-3}), and heat capacity (C, J kg^{-1} K^{-1}). A fourth parameter, thermal diffusivity (κ, m^2 s^{-1}) is calculated from the relation $\kappa=K/C\rho$. All measurements reported here were made in the heat flow laboratory at Wits.

Thermal conductivity

Thermal conductivity measurements were made using a divided bar apparatus that is specifically designed for precise analysis of competent rocks such as those encountered in the Bushveld Complex. This is a steady-state method in which the conductivity of a rock sample is measured relative to that of a material of known conductivity (the 'substandard'). Precisely machined rock discs (30 or 38 mm in diameter and approximately 20 mm in length) and discs of the substandard are placed in the divided bar. Heat is supplied and abstracted at either end of the divided bar using temperature-controlled water circulators. When a condition of linear heat flow along the stack of discs is established, the conductivity of the sample disc relative to that of the substandard is determined by measuring the temperature gradient across each disc and applying Fourier's Law of heat conduction, $q=KdT/dx$, where q is heat flux (W m^{-2}) and dT/dx is thermal gradient (K m^{-1}). The contact resistance between discs constituting the divided bar is minimized by applying an axial pressure of 5 MPa, and radial heat loss is minimized by carefully insulating the stack. All samples were saturated with water prior to measurement and average sample temperatures were close to 25°C in all experiments. The thermal conductivity of the substandard was calibrated against gem-quality quartz cored perpendicular to the c-crystallographic axis, for which an international standard conductivity was used. The overall error in determining conductivity, including reproducibility and calibration errors, using this method is estimated to be less than 0.1 W m^{-1} K^{-1}.

Density

Most densities were determined from accurately measured masses (using a precision balance) and volumes (using a micrometer and digital vernier) of samples prepared for thermal conductivity measurement. Measurements, first dry and then saturated with water, on 30 samples across the spectrum of rocks analysed showed no significant difference (<5 kg m^{-3} on average); this is to be expected because the

porosity of the rocks is essentially zero. Repeat measurements on the same 30 specimens also yielded differences averaging at approximately 5 kg m^{-3}, and the maximum uncertainty in measuring density is estimated at 10 kg m^{-3}. The densities of damaged conductivity samples and other irregular specimens were determined from their measured masses while suspended in air and water and applying Archimedes' Principle. Measurements were made on 10 control samples using both methods and the average difference was found to be less than the above overall uncertainty.

Heat capacity

Heat capacities of samples, crushed and sieved to sand-sized grains, were determined by calorimetry using the method of mixtures. The temperature of measurement in all experiments was as close as possible to ambient temperature, but in most cases a small correction for Newtonian cooling was necessary. The uncertainty in heat capacity measurement, based on repeat measurements on 10 samples, is estimated at approximately 25 J kg^{-1} K^{-1}.

Database overview

During the past 30 years, routine thermal conductivity measurements have been made for both mine engineering applications and for tectonic studies of the Bushveld Complex. Initially, density measurements reported here were made primarily for mine refrigeration studies, but these were supplemented during the past year with measurements made on specimens originally prepared for conductivity analysis. The total number of measured values for each parameter exceeds 900.

The distribution of boreholes and mines from which samples were derived is indicated in Figure 1. Average thermal conductivities and densities of different rock types in different stratigraphic units of the Bushveld Complex are listed in Table II. It is clear that the database is representative of the Complex as a whole and that all important rock types constituting the Complex are well characterized. Conductivity and density variations are discussed in the next section. Additional detailed density measurements are available from boreholes and mines in the Complex (Cawthorn and Spies, 2003; Ashwal *et al.*, 2005; Davis *et al.*, 2007).

Heat capacity measurements were made specifically for mine refrigeration investigations. The data are summarized in Table III. Although only 190 values are available, most rock types encountered in the deep platinum mines are reasonably well represented. Fortunately, heat capacity is a relatively uniform rock parameter, and the data in Table III suffice for most purposes. Heat capacity data are discussed in the last section of this paper.

Thermal conductivity and density

Variations of thermal conductivity and density of rocks within different stratigraphic units of the Bushveld Complex are illustrated in the form of histograms and plots of conductivity *versus* density (Figures 3–11). Histograms for different rock types, identified from hand specimens, are all drawn to the same horizontal and vertical scales so that the results can be compared directly. Conductivity and density of rocks are essentially controlled by their constituent minerals (Table I), which have distinct thermal properties (Table IV). As noted previously, the distinction between different rock types is not always clear-cut, and there is continuous gradation from one rock type to another. This is particularly relevant in the Bushveld Complex, where rock density variations may reveal the relative proportions of the major rock-forming minerals (Cawthorn and Spies, 2003; Davis *et al.*, 2007). It was not possible to generate conductivity-density plots with the same horizontal (density) scale, so data for the Critical Zone and Main Zone (Figure 6a) are reproduced in all such diagrams (Figures 4, 7, 9, and 11) to facilitate comparison.

Table II

Thermal conductivity and density of rocks from the Bushveld Complex

Rock unit and type	*K*±s.d., W m^{-1} K^{-1}	N	ρ±s.d., kg m^{-3}	N
GRANITIC ROCKS				
Granite (undifferentiated)	3.43±0.41	103	2660±60	100
MAFIC ROCKS				
UPPER ZONE				
Diorite	2.17±0.07	8	3100±250	8
Anorthosite	2.09±0.08	7	2790±40	7
Gabbronorite	2.40±0.20	73	2980±120	70
Gabbronorite (magnetite-bearing)	2.34±0.24	48	3200±200	48
Pyroxenite	3.39±0.37	23	3170±70	23
Pyroxenite (magnetite-bearing)	3.35±0.15	6	3310±30	6
MAIN ZONE and CRITICAL ZONE				
Anorthosite	1.92±0.12	144	2780±40	144
Norite	2.28±0.15	360	2910±50	359
Pyroxenite	3.45±0.35	89	3190±70	89
Chromitite	2.45±0.18	16	3970±120	16
LOWER ZONE				
Pyroxenite, harzburgite, dunite	4.13±0.21	39	3280±40	39

K, thermal conductivity; ρ, density; s.d., standard deviation; N, number of observations.

Table III

Heat capacity and thermal diffusivity

Rock unit and type	*C*±s.d., J kg^{-1} K^{-1}	N	κ±s.d., 10^{-6} m^2 s^{-1}	N
MAFIC ROCKS				
MAIN ZONE and CRITICAL ZONE				
Anorthosite	820±30	36	0.83±0.04	36
Norite	840±40	46	0.95±0.09	46
Pyroxenite	870±60	82	1.27±0.16	82
Chromitite	750±50	16	0.84±0.11	16
LOWER ZONE				
Pyroxenite, harzburgite, dunite	870±20	9	1.28±0.14	9

C, heat capacity; κ, thermal diffusivity; s.d., standard deviation; N, number of observations.

Thermophysical properties of rocks from the Bushveld Complex

Lower Zone

Rocks sampled from the Lower Zone are all ultramafic, consisting essentially of pyroxene with at least small amounts of olivine. Because both of these minerals have a high thermal conductivity and density (Table IV), the respective values for the rocks are the highest in the Complex (Table II, Figures 3 and 4), with the exception of chromitite from the Critical Zone and magnetitite from the Upper Zone.

Table IV

Thermal conductivity and density of important minerals found in rocks listed in Table I (Clark, 1966; Deer, Howie, and Zussman, 1966; Horai, 1971; Cermak and Rybach, 1982)

Mineral	*K*, W m^{-1} K^{-1}	ρ, kg m^{-3}
Quartz	7.69	2650
Feldspar		
Alkali feldspar	2.31-2.49	2560-2630
Plagioclase feldspar	1.53-2.14	2620-2760
Pyroxene		
Orthopyroxene	4.16-4.47	3210-3960
Clinopyroxene	3.82-4.94	3220-3560
Olivine	3.45-5.16	3220-4390
Chromite	2.52	4800
Magnetite	5.10	5150

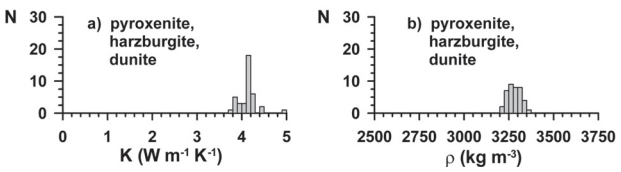


Figure 3—Histograms showing the distribution of thermal conductivity (a) and density (b) for rocks constituting the Lower Zone

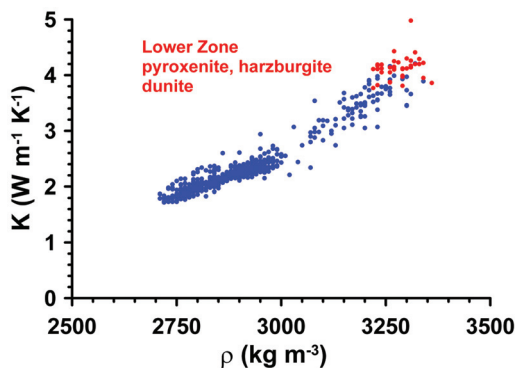


Figure 4—Thermal conductivity plotted against density for pyroxenite, harzburgite, and dunite from the Lower Zone (red dots). Blue dots indicate data for anorthosite, norite, and pyroxenite from the Critical and Main Zones (Figure 6), and are included in all similar diagrams for ease of comparison

Critical Zone and Main Zone

Thermal characterization of the Critical Zone and Main Zone (particularly its lower part) is crucial for investigations of refrigeration requirements of platinum mines and potential deep-level chromium mines. These zones are the best studied and are discussed together here for convenience. The most important rocks vary in composition from anorthosite (almost pure plagioclase feldspar) through norite and gabbro to pyroxenite (almost pure pyroxene) (Table I). Table III, the histograms (Figure 5), and the conductivity-density plot (Figure 6) show the effect of the increasing pyroxene content. Figure 6a shows that the gradation of thermal properties is not quite complete, as reflected in the paucity of data at approximately 3000 kg m^{-3}. Nor is the relationship between the parameters purely linear. Average conductivities for successive 50 kg m^{-3} density intervals suggest that a relationship is better defined by two lines, one dominated by plagioclase and the other by pyroxene (Figure 6b). This may be understood by the fact that density is controlled simply by the percentages of plagioclase and pyroxene, whereas conductivity is controlled by more or less conductive paths associated with connectivity of these minerals, as well as their relative abundance. Measuring density is quick and easy, and the correlation between conductivity and density is potentially useful for estimating conductivity where measurements of this parameter are not available.

Results for chromitite (Table II, Figure 7) are shifted substantially toward much higher density. All data are from the UG2 Reef. The data adequately characterize this important platinum-bearing horizon and serve as best estimates for Lower and Middle Group layers exploited for

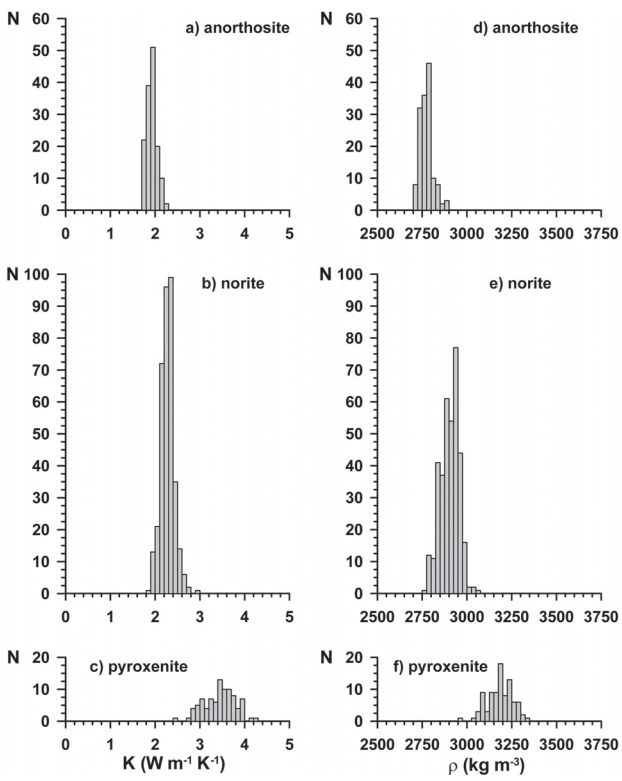


Figure 5—Histograms showing the distribution of thermal conductivity (a-c) and density (d-f) for rocks constituting the Critical and Main Zones

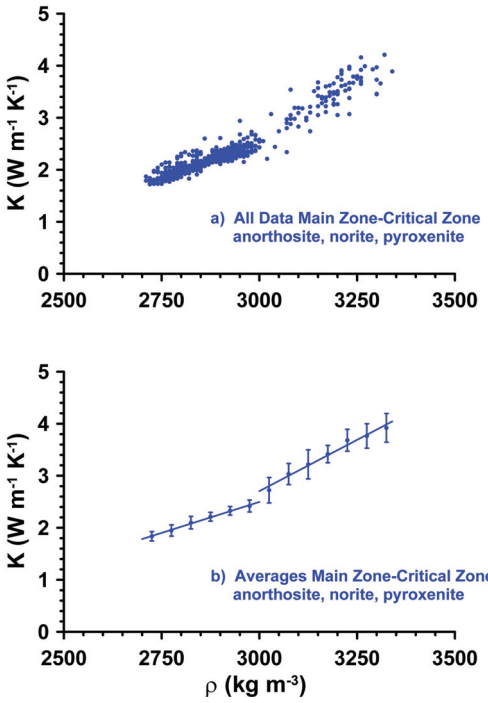


Figure 6—(a) Thermal conductivity plotted against density for individual samples of anorthosite, norite and pyroxenite from the Critical Zone and Main Zone; these data are reproduced in Figures 4, 7, 9, and 11 to facilitate comparison. (b) Average thermal conductivity and standard deviation for 50 kg m^{-3} density intervals derived from data in Figure 6a plotted against density; the two lines are least-squares fits to the averaged data for values with density less than and greater than 3000 kg m^{-3}

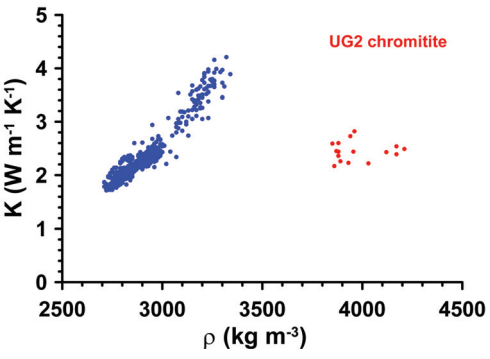


Figure 7—Thermal conductivity plotted against density for UG2 chromitite from the Critical Zone (red dots). Blue dots indicate data for anorthosite, norite, and pyroxenite from the Critical and Main Zones (Figure 6)

chromium. Few samples are known to be derived from the Merensky Reef, but this layer consists essentially of pyroxenite, and the data from the Critical and Main Zones in Table II are appropriate for mine engineering purposes.

Upper Zone

Thermal characterization of the Upper Zone is complicated by the presence of significant amounts of magnetite in many of the rocks. Most samples are norite and/or gabbro, with fewer samples of anorthosite and pyroxenite, and all data are plotted in the same histograms, the only distinction being between rocks that are apparently depleted in magnetite (Figure 8a and Figure 8c) and those that are obviously magnetite-bearing (Figure 8b and Figure 8d). Approximately half of the results fall close to the trend defined by anorthosites-pyroxenites from the Critical and Main Zones (Figure 6), but the other half suggests a different trend (Figure 9a). The latter samples are all magnetite-bearing and are displaced to higher densities as indicated by the least-squares line fitted to successive 50 kg m^{-3} density intervals for this subset of the data Figure (9b). Although magnetite has a high conductivity (Figure 9b) (Table IV), its relatively low abundance in most rocks means that the connectivity

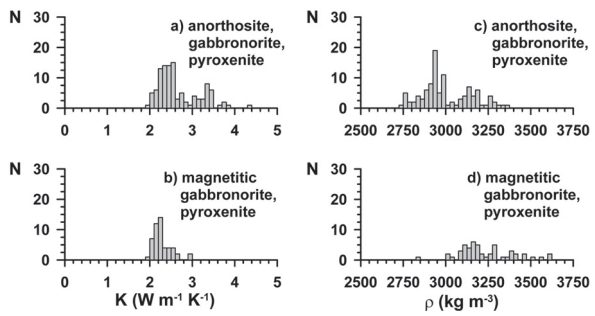


Figure 8—Histograms showing the distribution of thermal conductivity (a and b) and density (c and d) for rocks constituting the Upper Zone

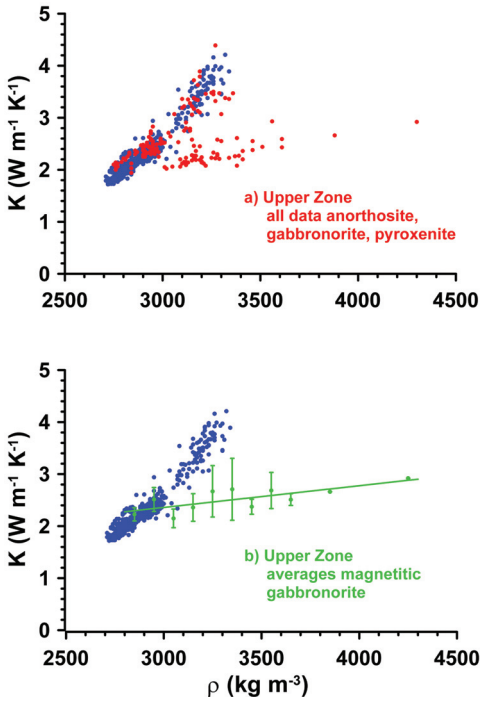


Figure 9—(a) Thermal conductivity plotted against density for all rocks from the Upper Zone (red dots). (b) Average thermal conductivity and standard deviation for 50 kg m^{-3} density intervals derived from magnetite-bearing gabbronorites and two magnetitites from the Upper Zone (green dots); the line is the least-squares fit to the averaged data. Blue dots indicate data for anorthosite, norite, and pyroxenite from the Critical and Main Zones (Figure 6)

between magnetite grains is incomplete and apparently not efficient enough to substantially enhance thermal conductivity. Density, on the other hand, is purely a function of the amount of magnetite present. Vanadium mining on the Main Magnetite Layer is shallow at present, but the data are potentially useful for engineering purposes if deeper levels are exploited in the future.

Bushveld granites and granophyres

Granitic rocks of the Rashoop Granophyre Suite and Lebowa Granite Suite have not been differentiated. Table II and Figures 10 and 11 indicate that these rocks are thermally quite distinct from the mafic and ultramafic rocks of the Rustenburg Layered Suite. The thermal parameters are typical of granites, except for a few magnetite-bearing specimens that have higher densities (Figure 11a). Although there is no strong relationship between conductivity and density in Figure 11a, a plot of average conductivity *versus* average density for different sample localities suggests a negative correlation (Figure 11b).

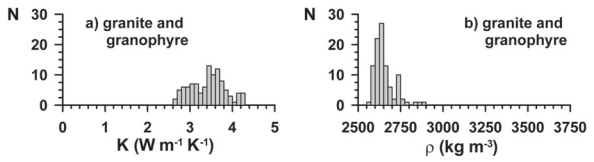


Figure 10—Histograms showing the distribution of thermal conductivity (a) and density (b) for granitic rocks from the Bushveld Complex

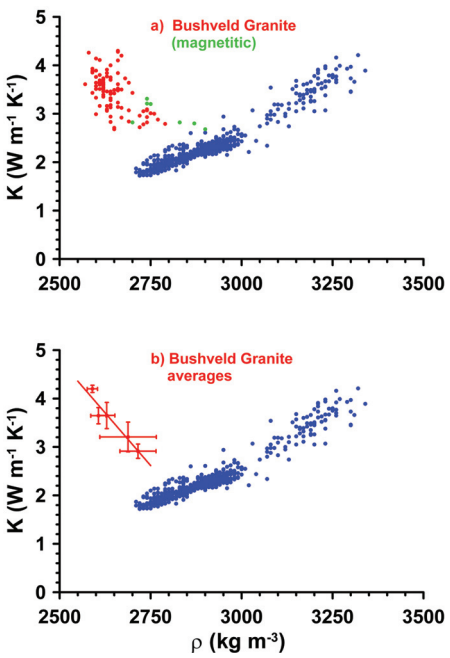


Figure 11—(a) Thermal conductivity plotted against density for granitic rocks (red dots) and magnetite-bearing granitic rocks (green dots) from the Bushveld Complex. (b) Average thermal conductivity plotted against average density for granite from different localities in the Complex (red dots); bars represent standard deviations and the red line is a least-squares fit to the averaged data. Blue dots indicate data for anorthosite, norite, and pyroxenite from the Critical and Main Zones (Figure 6)

Heat capacity and thermal diffusivity

Heat capacity measurements were made on 190 samples and results are summarized in Table III. Most of the samples were derived from the Critical Zone and lower part of the Main Zone because data on rocks from these levels is most important for applications in mine refrigeration. Although heat capacity increases with increasing pyroxene content (Table I and Table III) this effect is small, and an overall average value for the Critical and Main Zones (850 ±50 J kg^{-1} K^{-1}) will suffice (in the absence of measured values) for calculating thermal diffusivity for mine refrigeration purposes. Chromitite has a lower average heat capacity (750 J kg^{-1} K^{-1}, Table III), which should be used for calculations involving mining of the UG2 chromitite layer. The value for Main Zone pyroxenite is recommended for similar analyses involving the Merensky Reef. The calculated parameter, thermal diffusivity, varies from 0.8×10^{-6} to 1.4×10^{-6} m^2 s^{-1}.

Estimating the heat load from the country rock in underground workings is a complicated process because it depends on several factors including mine geometry, VRT, rock properties, and boundary conditions at newly exposed rock surfaces. This is beyond the scope of this paper, but the effect of thermal properties alone reported here can be illustrated by calculating the heat flux at the surface of a semi-infinite region initially at a temperature of T_i and instantaneously exposed to a constant surface temperature of T_0 at time t=0:

$$q_0(t) = \frac{(T_i - T_0)K}{\sqrt{\pi\kappa}} t^{-1/2}$$

Figure 12 shows the surface heat flux as a function of time for T_i=50°C, T_0=25°C, and various values for the thermal properties. The heat flux is up to 50% lower if the half-space is characterized by thermal parameters appropriate to the Bushveld Complex (blue) compared with an equivalent

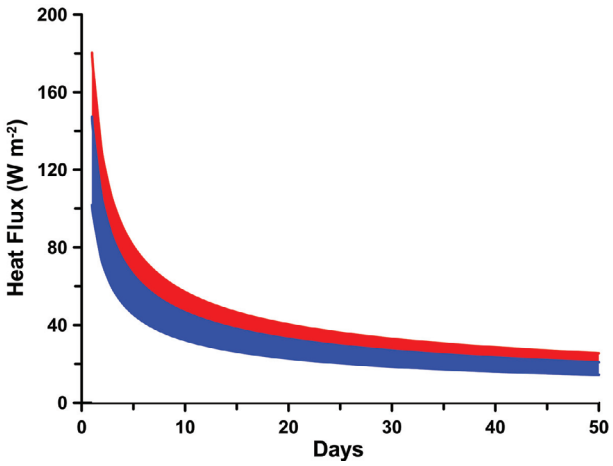


Figure 12—Heat flux as a function of time into the surface of a cooling half-space with initial temperature T_i=50°C and surface temperature T_0=25°C. Blue, calculated using thermal properties typical of the Bushveld Complex (Critical-Main Zone anorthosite, K=1.9 W m^{-1} K^{-1}, κ=0.8×10^{-6} m^2 s^{-1}; Critical-Main Zone pyroxenite, K=3.5 W m^{-1} K^{-1}, κ=1.3×10^{-6} m^2 s^{-1}). Red, calculated using thermal properties typical of rocks in the Witwatersrand Basin (Jones, 2003b) (Ventersdorp lava, K=3.5 W m^{-1} K^{-1}, κ=1.4×10^{-6} m^2 s^{-1}; Witwatersrand quartzite, K=6.4 W m^{-1} K^{-1}, κ=2.9×10^{-6} m^2 s^{-1})

situation in gold mines of the Witwatersrand Basin (red). Estimation of the controlling effect of rock properties on heat flux into underground workings obviously requires specific and in-depth calculations (C.A. Rawlins, personal communication, 2014).

Conclusions

The extensive thermophysical rock property database from the Bushveld Complex permits reliable estimation of the average thermal conductivity, density, heat capacity, and thermal diffusivity of most rock types in various stratigraphic units constituting the Complex. The results provide important inputs for calculations of the heat load on deep platinum mines and would be potentially important in chromium and vanadium mines if such mining proceeds to deeper levels. A positive correlation between conductivity and density of rocks in the Critical Zone and Main Zone may be useful as a conductivity estimator where conductivity data are not available. The high magnetite content of many rocks in the Upper Zone results in a correlation that differs from the Critical and Main Zones and the rest of the Upper Zone; the density is substantially higher but the conductivity is largely unaffected. Illustrative calculations indicate that the generally lower thermal conductivity and thermal diffusivity of rocks in Bushveld platinum mines results in a lower heat flux into underground workings compared with gold mines in the Witwatersrand Basin.

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