Thermal properties of stratified rocks from Witwatersrand gold mining areas

by M.Q.W. Jones*

Synopsis

This paper summarizes important features of a compilation of thermal properties of stratified rocks from Witwatersrand gold mining areas. The database consists of more than 1000 thermal conductivity measurements, more than 700 density measurements, and nearly 100 heat capacity measurements. Most important rock types and stratigraphic units are well represented. Heat capacity does not differ significantly from one rock type to another, and density is relatively uniform although particular rock types are characterized by distinct average values. Different rock types also have distinct thermal conductivities, but this parameter varies by a factor of four to five. Primary factors controlling the thermal properties are mineral composition, degree of metamorphism, and porosity. In addition, the temperature dependence of thermal conductivity and heat capacity of quartzite may significantly decrease the thermal diffusivity of this rock at deep mining levels.

Introduction

A knowledge of the thermal properties of rocks (thermal conductivity, density, and heat capacity) is important for mine refrigeration studies that require, for example, extrapolation of measured virgin rock temperatures (VRTs) to deeper levels and calculation of heat flux into underground workings. This is particularly relevant in the Witwatersrand gold mining areas where mining levels are expected to approach 5000 m. Fortunately, the Witwatersrand Basin is one of the better-studied regions in the world from a geothermal perspective. Several investigations conducted between the late 1930s and late 1970s, for both geodynamic reasons and mine engineering purposes, established an initial database of rock thermal properties[1-6]. In the early 1980s, a heat flow laboratory was established at the Bernard Price Institute of Geophysical Research (BPI), which resulted in routine accumulation of rock property data, and a preliminary compilation was presented by Jones[7]. Since then, substantially more observations have been made, and it is the purpose of this paper to present an up-to-date summary of the database with the view to characterizing the thermal properties of different rock types and units in Witwatersrand gold mining areas.

Geological framework

The Witwatersrand Basin is one of the oldest well-preserved stratified basins on Earth, its present-day perimeter approximately being defined by the distribution of major gold mines (Figure 1). It contains and is overlain by four Precambrian volcano-sedimentary sequences, the Dominion Group, the Witwatersrand Supergroup, the Ventersdorp Supergroup and the Transvaal Supergroup, and in the Welkom goldfields by a thin veneer of Mesozoic sediments of the Karoo Supergroup. A simplified stratigraphic column showing the relative positions of these sequences and their subdivisions, based on the classification of the South African Council for Stratigraphy[8], is provided in Figure 2. A more detailed account of the geology is given by Tankard *et al.*[9].

The floor of the basin is part of a widespread granite-greenstone basement complex that evolved between approximately 3700 and 3100 Ma (million years ago)[10]. The first major sequence deposited on this basement was the Dominion Group, which comprises up to 2 km of lava erupted 3080–3070 Ma and, locally, a zone of basal sediments[11,12].

The Dominion Group is overlain by the Witwatersrand Supergroup which is up to 7 km thick and is subdivided into the lower West Rand Group (between 2970 and 2910 Ma) and the upper, gold-bearing Central Rand Group (between 2890 and 2710 Ma)[13]. The West Rand Group consists of alternating quartzite and shale units and one lava unit, while the Central Rand Group consists almost entirely of

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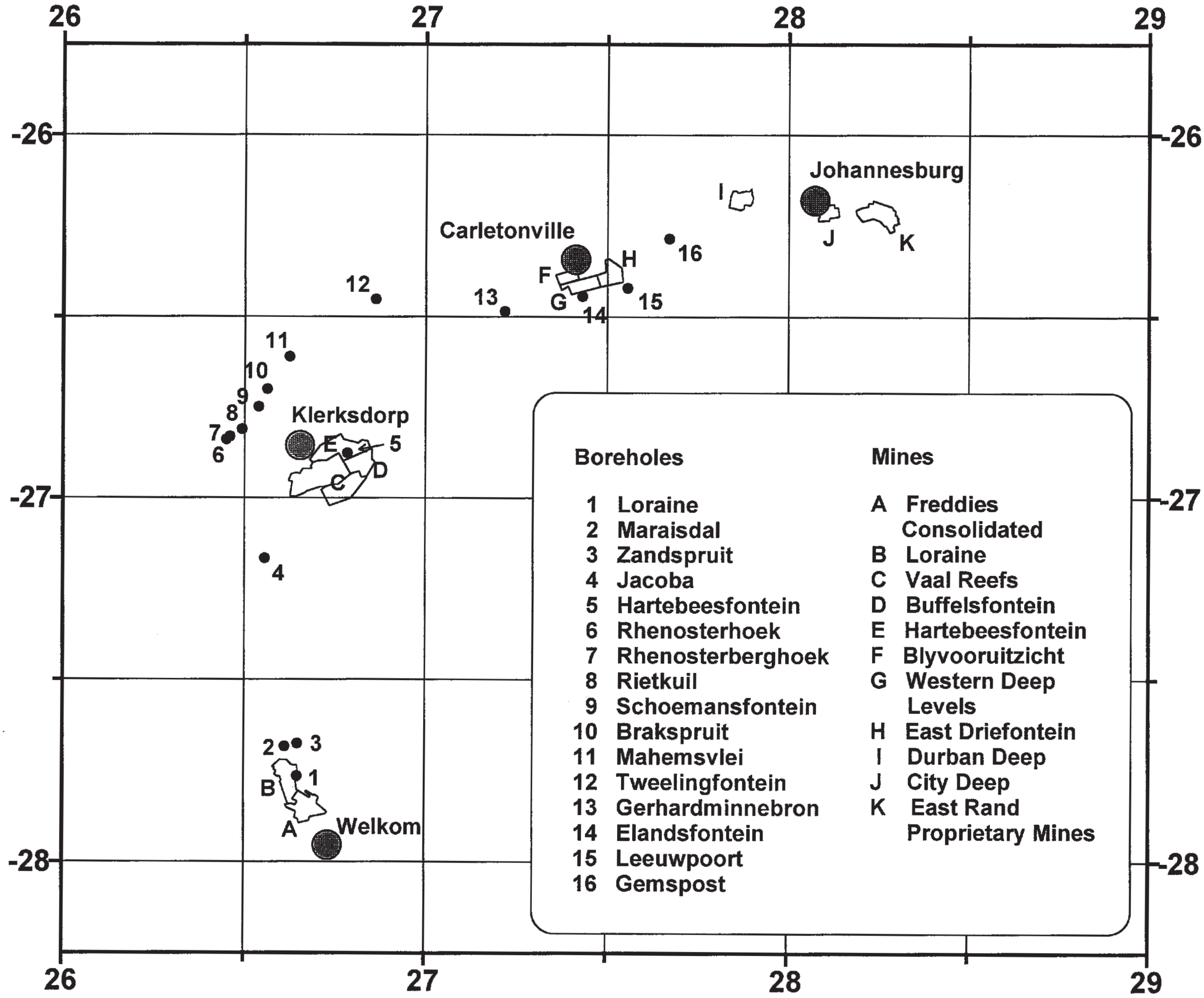

Figure 1—Locality map of Witwatersrand gold mining areas showing positions of boreholes (1–16) and mines (A–K) from which rock samples analysed for thermal conductivity, density and heat capacity were derived. Boreholes are named after farms on which they were drilled

quartzite and conglomerate, with one prominent shale unit being developed locally. In some goldfields, the Witwatersrand succession is capped by the Venterspost Formation, a thin layer of quartzite and conglomerate (the Ventersdorp Contact Reef), which has not formally been assigned to either the Witwatersrand or Ventersdorp Supergroups.

Witwatersrand sedimentation was followed by eruption of approximately 3 km of lava ~2710 Ma[11] and coeval deposition of localised, but sometimes thick, sedimentary units consisting chiefly of quartzite, siltstone and shale. This predominantly volcanic sequence comprises the Ventersdorp Supergroup, which is subdivided into three groups (Figure 2).

Deposition of the Transvaal Supergroup commenced approximately 2600 Ma with a thin layer of quartzite and shale (the Black Reef Formation), followed by up to 2 km of dolomite and subsidiary chert, shale and banded iron formation (the Chuniespoort Group, 2600-2430 Ma[14]). The overlying Pretoria Group (2350-2100 Ma[14]) is represented by a succession of chert, quartzite, siltstone and shale, capped in the region by lavas (Figure 2).

The south-east part of the basin is overlain by a layer of much younger alternating shales and sandstones of the Karoo Supergroup (~300-200 Ma). This succession covers extensive areas in the southern part of South Africa but attains thicknesses of only a few hundred metres in the Welkom goldfields.

The stratified rocks are intruded by numerous mafic dykes and sills of various ages. The oldest are diabase intrusions related to Ventersdorp volcanism and occur in Witwatersrand Supergroup strata. Intrusive rocks related to the Bushveld igneous event (~2060 Ma[15]) are common in Transvaal Supergroup strata but may also occur in older rocks. The youngest intrusives are Karoo dolerites (~180 Ma).

Methods of measurement

This section summarizes the methods used to measure thermal conductivity, density and heat capacity in the BPI heat flow laboratory. Measurements reported by other authors were made using variations of these methods and are of comparable quality. Throughout this paper the following symbols and units will be used for the thermal properties:

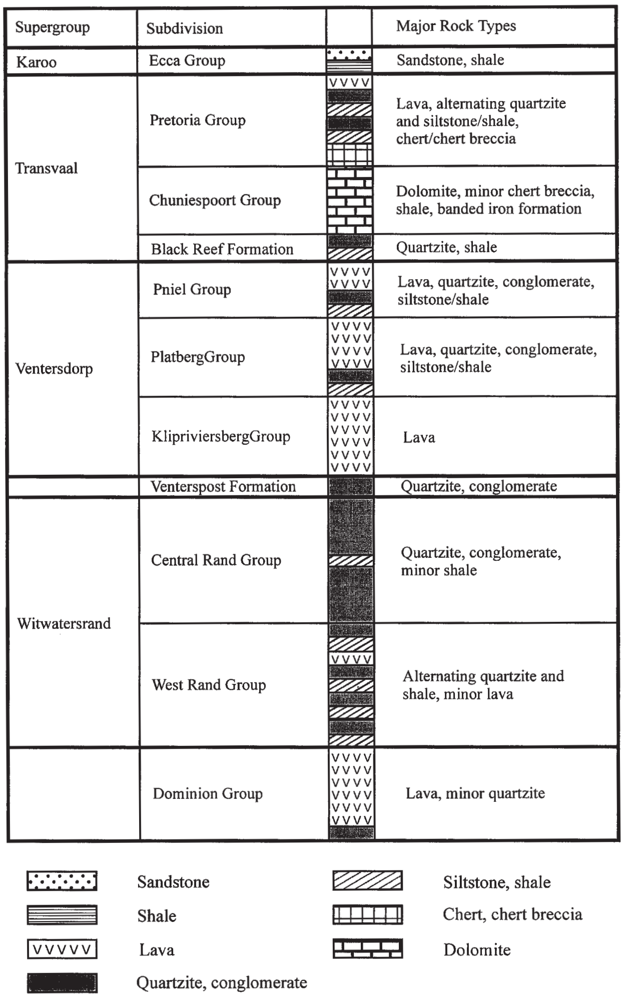

Figure 2—Schematic stratigraphic column for the Witwatersrand Basin showing relevant rock subdivisions and major rock types

K, thermal conductivity (W m^{-1} K^{-1}),
ρ, density (kg m^{-3}),
h, heat capacity (J kg^{-1} K^{-1}),
κ, thermal diffusivity (10^{-6} m^2 s^{-1}).

Thermal conductivity

Thermal conductivity measurements were made using a divided-bar apparatus illustrated in Figure 3. It is specifically designed for rapid, precise analysis of competent material of relatively low conductivity and is thus suited for rocks such as those encountered in the Witwatersrand Basin, although it can be adapted for use on rock fragments and unconsolidated material[16,17]. The divided-bar consists of two sets of discs of copper and a standard material placed on either side of the sample disc. Heat is supplied at the top and abstracted at the bottom by temperature-controlled water circulators. When equilibrium is established, the conductivity of the sample is determined relative to that of the standard from temperature gradients measured using four thermistors inserted into holes in the copper discs (T_1–T_4, Figure 3).

In determining temperature gradients across the sample and standards it is easy to correct for the thermal resistance

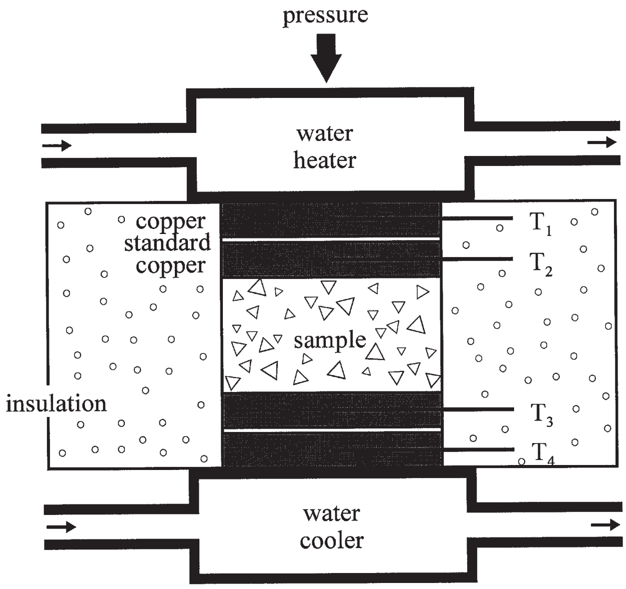

Figure 3—Cross-section of the divided-bar apparatus for measuring thermal conductivity. T_1 to T_4 represent thermistors inserted into holes drilled radially to the centres of the copper discs

of the copper discs, but care must be taken to minimize unwanted thermal contact resistances particularly at the sample-copper interfaces. This is achieved by precisely machining the samples using a lathe and toolpost grinder, coating the flat surfaces with high conductivity material, and applying an axial pressure to the divided-bar. A series of experiments on samples of uniform conductivity, but different thicknesses, showed that contact resistances were negligible under the conditions used in the laboratory[6].

In practise it is not possible to set up a condition of purely linear heat flux down the divided-bar because of radial heat losses. Errors introduced in this way are minimized by insulating the divided-bar, ensuring that the average sample temperature is close to the ambient temperature, and maximizing the diameter-to-length ratio of the assembly. The apparatus in Figure 3 uses 1 mm thick polycarbonate plastic discs as standards and approximately 20 mm thick sample discs, which is sufficient to ensure that they are representative of all but the coarsest-grained rocks. Diameters vary between 30 mm and 38 mm. Radial heat losses during experiments amounted to a few per cent, but the associated error is a fraction of this because thermal conductivity is found in terms of the average heat flow at the top and bottom of the divided-bar.

The conductivity of the polycarbonate standards was determined by calibration against samples of gem quality quartz cored perpendicular to the c-crystallographic axis for which the standard value of Ratcliffe[18] was used. All samples were saturated with water prior to measurement to simulate natural conditions and average sample temperatures were close to 25°C in all experiments. The overall error in determining the conductivity of unknowns, including calibration errors, is estimated to be less than 4 per cent.

Density

The densities of most samples were determined from the masses and volumes of samples prepared for thermal conductivity measurement. Masses were measured, after saturation with water, using a precision balance, and volumes were obtained from measurements with a micrometre and digital vernier. The densities of damaged and other irregular samples were determined from their masses measured suspended in air and water. Measurements were made on 42 control samples using both methods. The average difference between the two techniques was 5±7 kg m^{-3}. The overall error in determining density, given the precision of the measuring instruments, is estimated to be less than 0.5 per cent.

Heat capacity

Heat capacities were measured by calorimetry using the method of mixtures. Rock fragments, crushed to the consistency of sand, were heated to a constant temperature using a temperature-controlled water bath before being transferred to a copper calorimeter containing chilled water. The initial temperatures of the sample and water were pre-set in order to ensure that the final temperature of the mixture was close to ambient temperature. However, in most cases it was necessary to apply a small correction for Newtonian cooling, which necessitated making temperature observations (using a thermistor probe) for up to five minutes while stirring the sample. Heat capacities were calculated from initial and final temperatures, masses of the samples and water, and the water equivalents of the calorimeter, stirrer and thermometer probe. The error in measuring heat capacity is estimated to be less than 5 per cent.

Thermal properties

The rock property data base includes all published individual thermal conductivity, density and heat capacity measurements and those generated in the BPI heat flow laboratory since 1980. Samples were derived from boreholes and mines situated along the gold mining arc from Welkom to the East Rand (Figure 1).

Because thermal conductivity has been measured routinely both for academic reasons and applications in mine engineering, this parameter is the best determined, the total number of values exceeding 1000. Although some authors have reported density, its measurement has not been routine. However, most of the BPI conductivity samples have been preserved and several hundred density measurements were made for the purpose of this compilation; the total number exceeds 700.

Most rock types in the Witwatersrand Basin are well represented with respect to these parameters and the data are presented in the form of histograms in Figures 4–9. Each histogram includes all results for a particular rock type occurring within each of the major stratigraphic units, starting with the Dominion Group (Figure 4) and ending with the Karoo Supergroup (Figure 8), as well as for the intrusive rocks (Figure 9). Horizontal scales are kept the same throughout for ease of comparison, except that a different range is used for Karoo sediments. For the better represented rock types (Dominion lava, Witwatersrand quartzite, Ventersdorp lava and Transvaal dolomite) it was necessary to condense the vertical scales. Overall average thermal conductivities and densities are listed in Table I.

In many cases the stratigraphic positions of individual samples are known and it was possible to determine average conductivities and densities for different stratigraphic subdivisions presented in Figure 2. The results are presented below the overall averages in Table I. Most volumetrically significant units are reasonably well represented, the only exception being the West Rand Group. This group lies below the gold-bearing reefs and samples are not readily available from the goldfields. Table I is discussed in more detail in conjunction with Figures 4–9 in the following subsections.

Heat capacity measurement has not been as routine as conductivity and density measurement, but nearly 100 results are available. The data are summarized in Table II. Witwatersrand quartzites are well represented, because of their particular significance for mine cooling studies, and there are sufficient measurements on Witwatersrand conglomerates, Ventersdorp lava and pre-Karoo diabase intrusives to yield mean values. Fortunately, heat capacity is not a very variable rock parameter compared with thermal conductivity and density, the range in mean values being only ~10 per cent. It should be noted, however, that this is not always the case as shown by experience with certain rock types in the Bushveld Complex to the north of the Witwatersrand Basin.

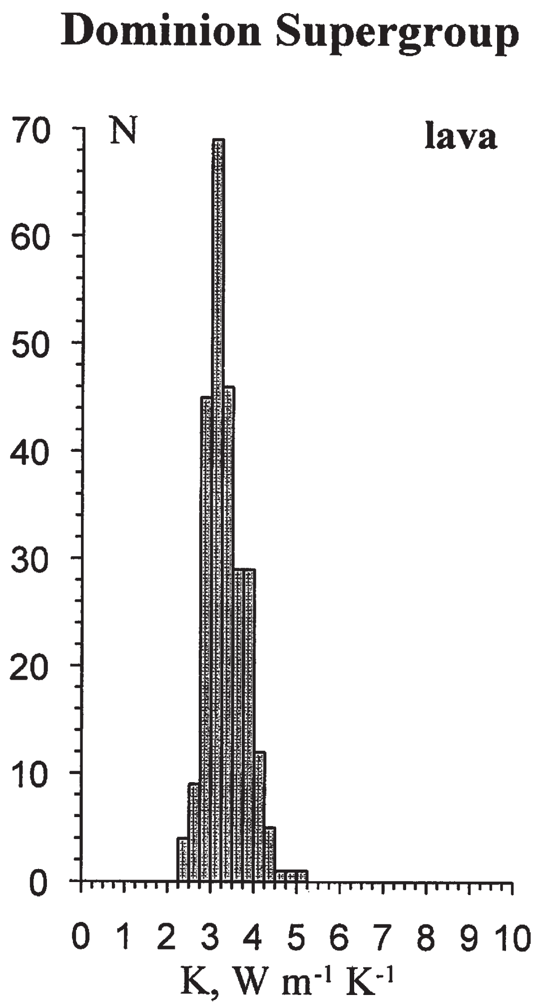

Figure 4—Histogram of thermal conductivity (K) data from Dominion Group lava

Table I

Thermal conductivity and density of Witwatersrand rocks

Rock Unit and Type		K±s.d., W m^{-1} K^{-1}		N	ρ±s.d., kg m^{-3}		N
INTRUSIVE ROCKS							
Karoo dolerite	Overall	1.99	0.13	9	2960	80	9
Pre-Karoo diabase	Overall	3.97	0.78	42	2900	80	41
	Transvaal strata	3.52	0.44	19	2870	70	18
	Witwatersrand strata	4.33	0.81	23	2920	90	23
KAROO SUPERGROUP							
Sandstone	Ecca Group	3.14	0.38	15	2380	80	15
Shale	Ecca Group	1.88	0.25	25	2540	40	25
TRANSVAAL SUPERGROUP							
Lava	Pretoria Group	3.53	0.37	21	2830	30	20
Quartzite	Overall	6.99	0.57	18	2670	20	15
	Pretoria Group	7.11	0.42	15	2670	20	14
	Black Reef Formation	6.37	1.00	3	2650		1
Siltstone, shale	Overall	3.31	0.82	55	2790	60	50
	Pretoria Group	3.34	0.76	50	2800	50	46
	Chuniespoort Group	3.41	1.85	2	2710	30	2
	Black Reef Formation	2.76	1.27	3	2790	80	2
Chert, chert breccia	Overall	6.92	0.59	19	2670	30	17
	Pretoria Group	6.79	0.61	14	2670	30	13
	Chuniespoort Group	7.27	0.37	5	2650	20	4
Dolomite	Chuniespoort Group	5.10	0.47	49	2840	20	41
VENTERSDORP SUPERGROUP							
Lava	Overall	3.46	0.56	151	2850	60	132
	Pniel Group	3.22	0.21	13	2840	20	12
	Platberg Group	3.61	0.46	27	2810	50	23
	Klipriviersberg Group	3.62	0.62	40	2880	80	40
Quartzite	Overall	5.25	0.61	26	2710	30	25
	Pniel Group	5.17	0.56	14	2700	30	13
	Platberg Group	5.49	0.68	9	2730	20	9
Siltstone, shale	Overall	4.41	1.03	14	2780	40	13
	Pniel Group	4.43	0.84	7	2760	20	6
	Platberg Group	4.40	1.26	7	2800	50	7
Venterspost Formation							
Quartzite		7.59		1	2740		1
WITWATERSRAND SUPERGROUP							
Quartzite, conglomerate	Overall	6.37	0.79	340	2690	40	308
Quartzite	Central Rand Group	6.35	0.78	312	2690	40	285
Conglomerate	Central Rand Group	6.86	0.75	24	2730	60	19
Shale	Central Rand Group	4.77	1.20	10	2790	60	6
DOMINION GROUP							
Lava	Overall	3.34	0.45	251	2780	20	5

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

Dominion Group

The study relating to the Dominion Group was aimed at determining geothermal heat flux[6,19], and there is a disproportionately large number of measurements of thermal conductivity relative to density (Table I). The conductivities of the lava samples, collected from boreholes 6–12 (Figure 1), fall in a relatively wide range, but the average is well constrained because of the large number of observations (Figure 4). Reasons for the wide spread of data for these and certain other rock units are discussed in the next section. There are no data for the sediments.

Table II

Heat capacity of Witwatersrand rocks

Rock Unit and Type	C±s.d., J kg^{-1} K^{-1}		N
INTRUSIVE ROCKS			
Pre-Karoo diabase	840	30	12
VENTERSDORP SUPERGROUP			
Lava	880	20	5
Venterspost Formation			
Quartzite	840		1
WITWATERSRAND SUPERGROUP			
Quartzite	810	40	65
Conglomerate	830	50	5
Shale	880	20	3

C, heat capacity; s.d., standard deviation; N, number of measurements.

Witwatersrand Supergroup

As noted previously, the West Rand Group has not been sampled systematically, and the four available measurements are on quartzite samples from the same horizon in the Klerksdorp goldfield. Their average conductivity (5.66±0.06 W m^{-1} K^{-1}) and density (2700±10 kg m^{-3}) fall within the range for the Central Rand Group (Table I). Quartzites and conglomerates of the Central Rand Group are, on the other hand, very well represented. There is no statistical difference between these two rock types (Table I), the latter consisting essentially of quartzite pebbles in a quartzitic matrix, and all results are plotted in the same histograms in Figure 5b. Densities fall within a relatively narrow range, but conductivities vary considerably (~4–8 W m^{-1} K^{-1}) and the histogram is skewed to low conductivity. Samples were collected from boreholes and mines in all major gold mining areas, and there are sufficient observations to determine whether there are geographic variations in these thermal parameters. Table III compares average conductivities and densities for the Welkom, Klerksdorp, Carletonville and central Witwatersrand goldfields. There are no obvious differences. A much smaller number of determinations is available for shales, but this rock type is volumetrically less

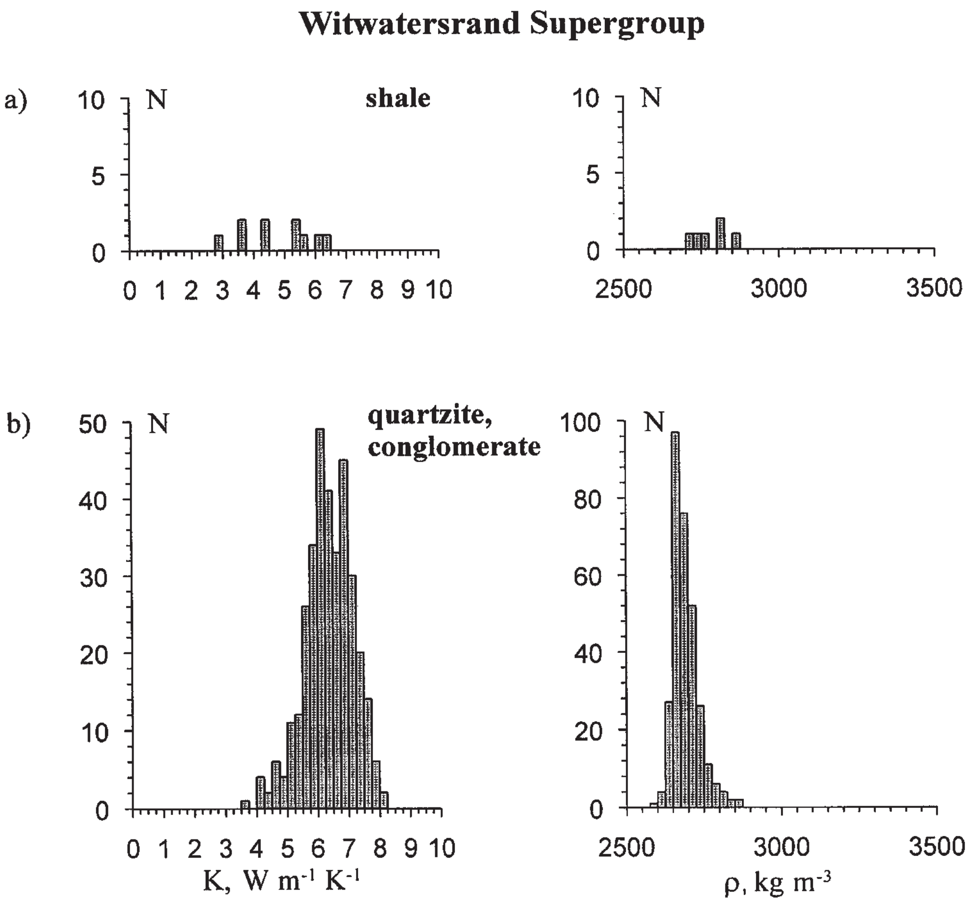

Figure 5—Histograms of thermal conductivity (K) and density (ρ) data for different rock types in the Witwatersrand Supergroup. (a) Shale (b) Quartzite and conglomerate

Table III

Thermal conductivity of Ventersdorp Lava and Witwatersrand quartzite from different mining areas

Rock Unit and Area	K±s.d., W m^{-1} K^{-1}		N
VENTERSDORP LAVA			
Central Witwatersrand	3.27	0.34	26
Carletonville	3.58	0.68	9
Klerksdorp	3.47	0.58	72
Welkom	3.53	0.61	44
WITWATERSRAND QUARTZITE			
Central Witwatersrand	6.27	0.57	78
Carletonville	6.23	1.04	63
Klerksdorp	6.39	0.79	120
Welkom	6.59	0.69	76

K, thermal conductivity; s.d., standard deviation; N, number of measurements.

important in the Central Rand Group. The average conductivity and density are lower and higher, respectively, compared with values for quartzite.

Ventersdorp Supergroup

Lava is the predominant rock type in the Ventersdorp Supergroup. There is quite a wide range of thermal conductivity and density and the conductivity histogram is skewed to high values (Figure 6c). Lavas from the Pniel Group appear to have a lower conductivity than the underlying lava units (Table I), but this is based on a relatively small sample population. Rock samples were also distributed throughout the Witwatersrand Basin, and again there is no statistical difference between average values from different goldfields (Table III). Three main types of sediment are present: quartzite, siltstone and shale. The quartzites are easily distinguishable because of their coarse grain size. Their average conductivity is substantially lower than that of quartzite from the Witwatersrand Supergroup (Table I, Figure 6a). It was not possible to clearly distinguish between siltstone and shale samples because of their fine grain size, because they are gradational, and because they are often interlayered on a scale smaller than the dimensions of conductivity samples. They have been grouped together in Figure 6b and Table I, which show that they have lower average conductivity and higher density than the quartzite. The conductivity of Ventersdorp Supergroup sediments is plotted against density in Figure 10c, which shows a gradation between low conductivity-high density shale and high conductivity-low density quartzite.

Transvaal Supergroup

The Transvaal Supergroup has the most complex stratigraphy (Figure 2), but most rock types are adequately represented, mainly by samples from boreholes 13–15 in the Carletonville goldfield and borehole 5 in the Klerksdorp goldfield. As with the Ventersdorp Supergroup, it is easy to distinguish between quartzite on the one hand and siltstone and shale on the other, but the same problems exist when attempting to categorize the latter. The histograms (Figure 7b and 7c), average values (Table I), and a plot of conductivity versus density (Figure 10b) show that the quartzites are statistically more distinct from the siltstones and shales compared with their counterparts in the Ventersdorp Supergroup. This is mainly due to the higher conductivities of the quartzites and the lower conductivities of the siltstones and shales (Table I). Chert and chert breccia have very similar properties to quartzite (Figure 7d), because this rock type consists essentially of very fine grained quartz. Dolomite (Figure 7e) is a relatively high conductivity, high-density rock, and lavas at the top of the succession have similar properties to other volcanic rocks in the basin although the ranges are substantially smaller (Figure 7a).

Karoo Supergroup

Although the Karoo Supergroup is not as important a component of the stratigraphic succession as the underlying strata, it can reach thicknesses of several hundred metres in the Welkom goldfield. Here, it is represented mainly by interlayered sandstones and shales of the Ecca Group, and rock samples were collected from borehole 3 (Figure 1). The sandstones and shales are clearly characterized by different thermal conductivity and density (Figure 8, Table I). The low conductivities result in high observed geothermal gradients in this rock unit.

Intrusive rocks

There are two main groups of pre-Karoo intrusive dykes and sills, those penetrating the Witwatersrand Supergroup and those found in the Transvaal Supergroup (informally known as 'Transvaal' diabase). Although these groups have similar densities, their average conductivities are significantly different (Table I) and there appear to be two populations in the conductivity histogram (Figure 9b). While Transvaal diabase is the product of Bushveld and possibly younger magmatic events, those occurring in the Witwatersrand succession may include younger rocks as well as those related to Ventersdorp magmatism. Without dating individual specimens it is not possible to subdivide the latter category, and the overall average thermal conductivity and density for pre-Karoo diabase are given in Table I. There are no data for Karoo-age dolerites from the Witwatersrand Basin, but measurements on samples from a borehole south-east of the basin indicate that they have a much lower thermal conductivity than the older diabases (Table I, Figure 9a).

Discussion

Of the parameters discussed in this paper, heat capacity is the least variable, the overall range of individual observations being only about 20 per cent. Density is also relatively uniform, with mean values varying by approximately 20 per cent (Table I), but different rock types have well defined averages and ranges. Thermal conductivity, on the other hand varies by a factor of four to five. Mineralogical composition has the most important controlling influence on the thermal properties of rocks, but other factors such as degree of metamorphism, porosity, anisotropy, and temperature can also be important. This section summarizes relevant aspects of these variables in relation to Witwatersrand rocks, paying particular attention to thermal conductivity.

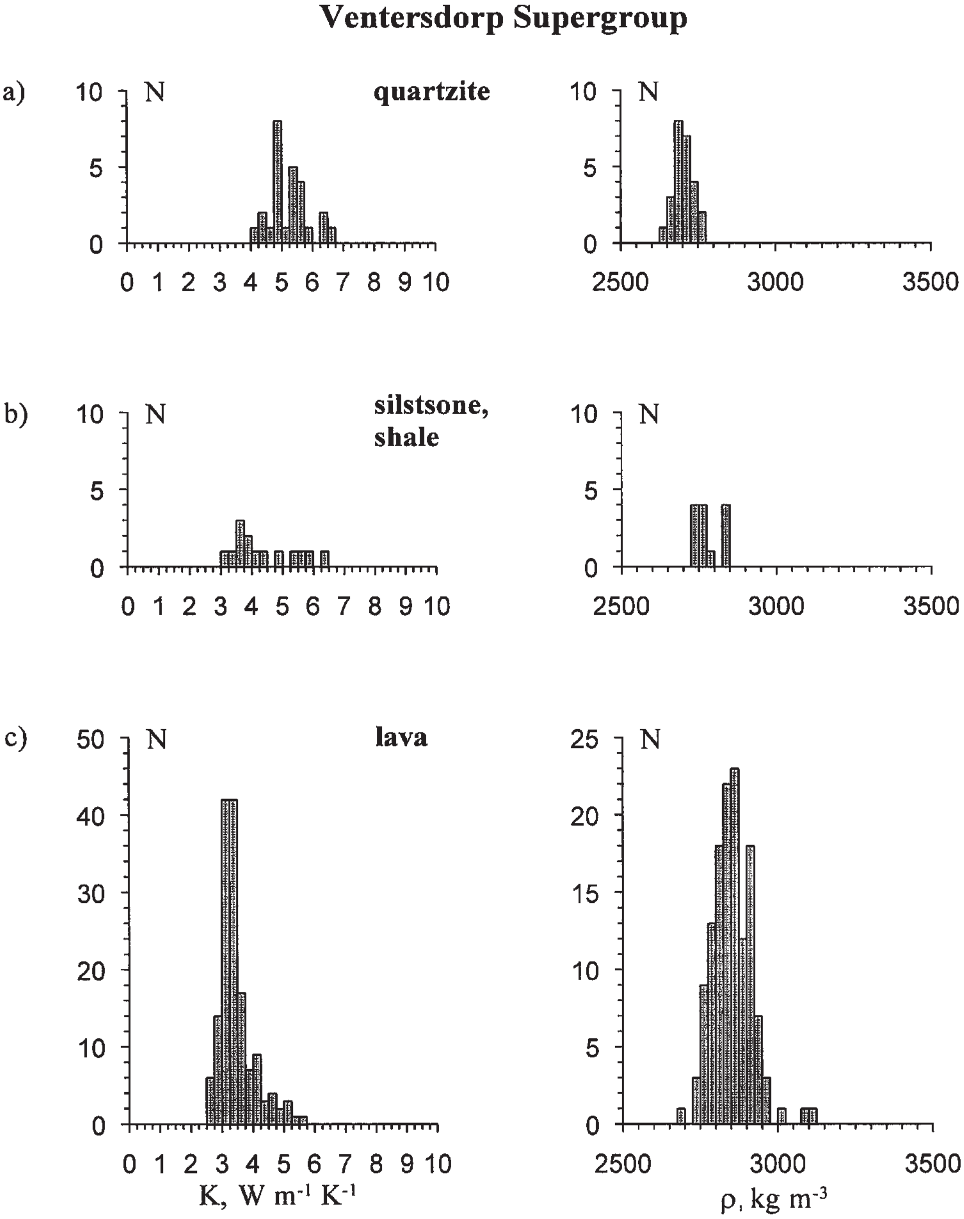

Figure 6—Histograms of thermal conductivity (K) and density (ρ) data for different rock types in the Ventersdorp Supergroup (a) Quartzite (b) Shale and siltstone (c) Lava

Table IV lists the thermal conductivities and densities of some important minerals. These include primary rock-forming minerals, the most common of which in Witwatersrand rocks are quartz, feldspar, pyroxene, hornblende and clay minerals. These minerals are present in different proportions in different rocks, and this gives rise to the range of conductivity and density. Except for the Karoo strata, most Witwatersrand rocks have undergone low-grade metamorphism during their long geological history. This may result in partial or complete alteration of the original mineralogy. For example, feldspar may be converted to epidote and sericite (fine-grained muscovite), pyroxene to chlorite and actinolite, and clay minerals to chlorite and sericite. The process generally leads to an increase in conductivity as indicated by the data for these secondary minerals in Table IV.

The Karoo dolerites are the youngest and least altered igneous rocks present. They consist essentially of feldspar and pyroxene. Because they are not altered, their conductivity and density are controlled by the primary mineral composition. Most of the diabases probably had a similar original composition, but they have been metamorphosed, probably more than once. The altered mineralogy results in a much higher conductivity compared with Karoo dolerites, but the densities do not differ much.

The volcanic rocks in the succession are referred to as 'lava' in Figure 2. This is an oversimplification because they include both lava and pyroclastic material, and the composition is variable. Lavas in the Transvaal Supergroup are mainly basalt (feldspar+pyroxene) and andesite (feldspar+hornblende+pyroxene), and their mineralogy leads to a relatively limited range of conductivity (Figure 7a). However, Ventersdorp lava and Dominion lava range from rocks of these compositions to felsic rhyolites and dacites

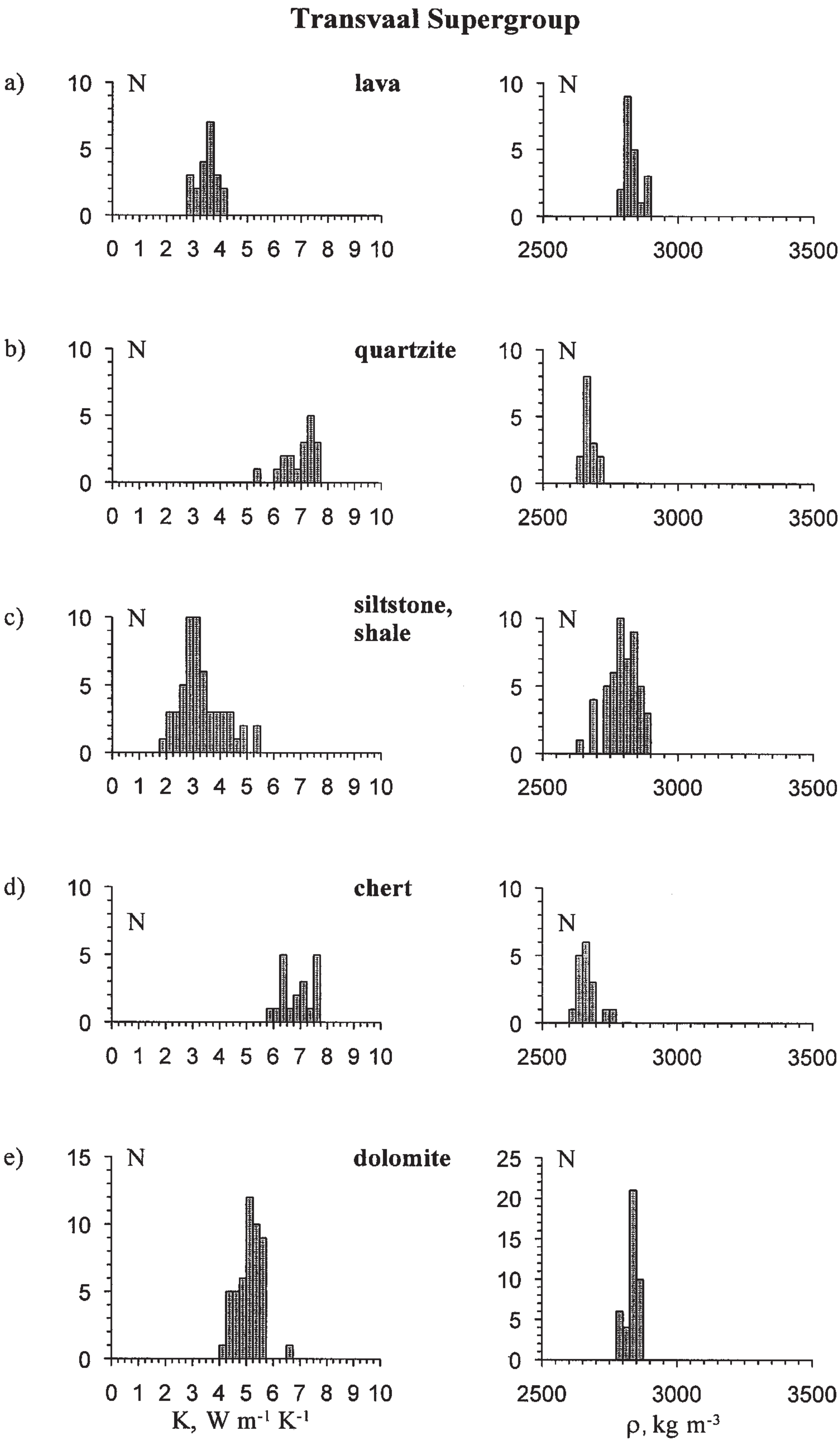

Figure 7—Histograms of thermal conductivity (K) and density (ρ) data for different rock types in the Transvaal Supergroup (a) Lava (b) Quartzite (c) Shale and siltstone (d) Chert and chert breccia (e) Dolomite

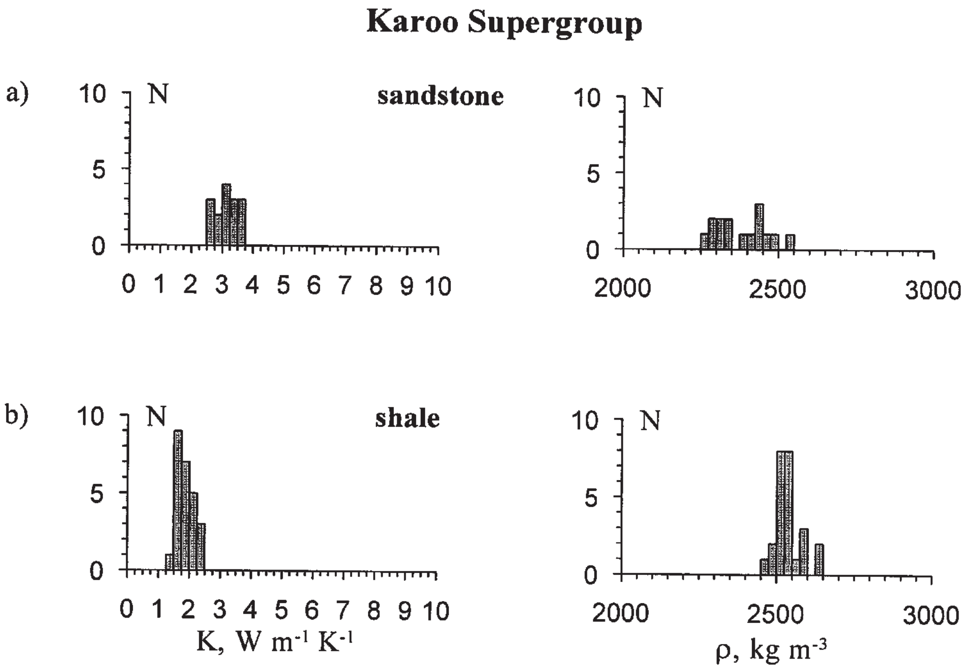

Figure 8—Histograms of thermal conductivity (K) and density (ρ) data for rocks from the Karoo Supergroup (a) Sandstone (b) Shale

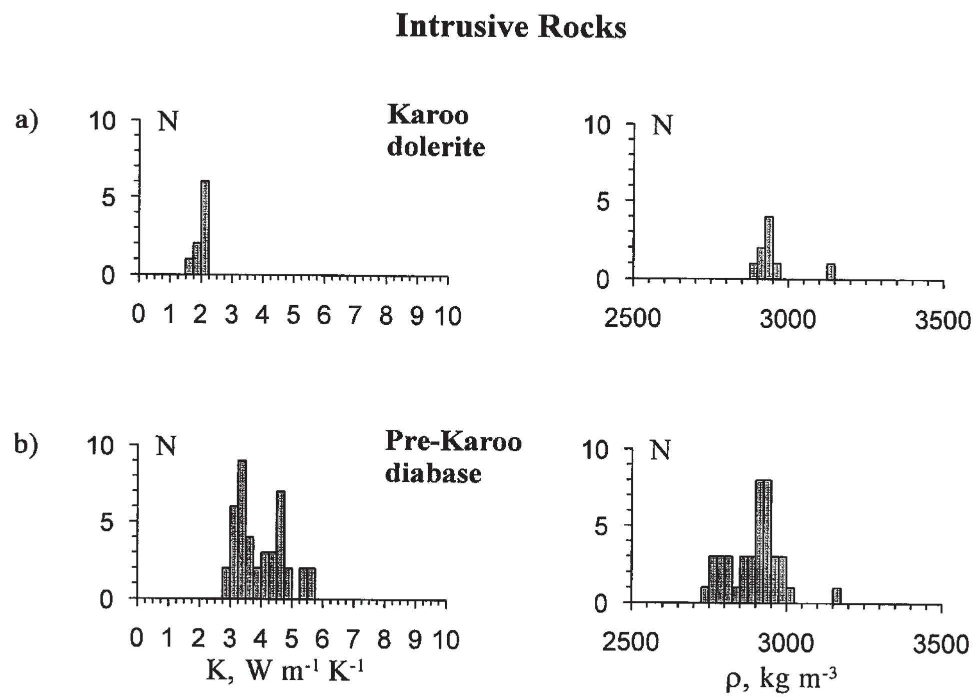

Figure 9—Histograms of thermal conductivity (K) and density (ρ) data for intrusive rocks (a) Karoo dolerite (b) Pre-Karoo diabase

(both essentially feldspar+quartz) and the conductivity range is substantially greater. Besides being metamorphosed and sometimes silicified, the volcanic rocks commonly contain amygdales of quartz, calcite and chlorite. Both phenomena contribute to some of the very high conductivities (Figures 4 and 6c).

Of the sedimentary rocks in the succession, chert and dolomite are recrystallized chemical deposits. The chert and chert breccia consist essentially of extremely fine-grained quartz resulting in very high conductivity. The Chuniespoort Group consists primarily of dolomite, which has a relatively high conductivity and density (Table IV), but the dolomite is often mixed with limestone (which is rich in calcite) and chert, and this gives rise to a substantial range in conductivity (Figure 7e).

The Karoo sediments consist of alternating shales and sandstones. Like the dolerites, they are young and unmetamorphosed. The shales are fine-grained rocks

Table IV

Thermal conductivity and density of some rock-forming minerals (after Clark[22], Horai[23], Cermak and Rybach[24])

Mineral	K, W m^{-1} K^{-1}	ρ, kg m^{-3}
Quartz		
Quartz (random)	7.69	2650
Quartz (⊥c-axis)	6.50	2650
Quartz (//c-axis)	11.30	2650
Feldspar		
Alkali feldspar	2.31-2.49	2560-2580
Plagioclase feldspar	1.53-2.14	2620-2770
Pyroxene		
Orthopyroxene	4.16-4.47	3270-3370
Clinopyroxene	3.82-4.94	3280-3330
Amphibole		
Hornblende	2.81	3180
Actinolite	3.48	3060
Olivine	3.45-5.16	3240-3770
Mica		
Muscovite	2.32	2850
Biotite	2.02	2980
Chlorite	5.15	2760
Epidote	2.83	3290
Carbonates		
Calcite	3.59	2720
Dolomite	5.51	2860
Clay	1.2-2.2	2200

K, thermal conductivity; ρ, density.

consisting of clay minerals and minor quartz, feldspar, muscovite and carbonaceous material cemented with silica. These are the lowest conductivity rocks in the succession. The sandstones are much coarser grained and consist of quartz and feldspar with minor muscovite embedded in a silica matrix, and they have substantially higher conductivities. Unlike most other rocks in the succession, the Karoo sediments are porous, and this has implications for thermal conductivity and density. The effect was investigated in the laboratory by making measurements on dry as well as water-saturated samples. The shales had porosities ranging up to 12 per cent, and the difference between wet and dry conductivity and density were 0.46±0.09 W m^{-1} K^{-1} and 90±40 kg m^{-3} respectively (25 measurements). The sandstones usually had higher porosities, the maximum value being 22 per cent, and the corresponding differences were 1.01±0.27 W m^{-1} K^{-1} and 140±50 kg m^{-3} (15 measurements). *In situ*, the pore spaces are filled with groundwater, and it is therefore important to ensure that samples are saturated with water before laboratory measurements are made. Finally, it is worth noting that there is a gradation between shales and sandstones that is reflected in the conductivity and density data (Figure 10a).

Shales and siltstones in the Transvaal, Ventersdorp and Witwatersrand Supergroups are much older than their Karoo counterparts and their original mineralogy has largely been replaced with higher conductivity secondary minerals. There is an evident progression from very low conductivity, young and unaltered Karoo shales to high conductivity, ancient and highly altered Witwatersrand shales (Table I). Figure 10 shows that there is a gradation in thermal properties from shale and siltstone to quartzite, and many of the higher conductivity siltstones could probably be better described as fine-grained quartzites.

Quartzites in the Witwatersrand Basin are essentially metamorphosed and recrystallized sandstones. The major constituent mineral is quartz, but accessory minerals, including feldspar, chlorite, calcite and sericite, may be present in various amounts. Specimens from the Transvaal Supergroup are mostly pure quartzite and have high conductivities, whereas those from the Ventersdorp Supergroup are quite feldspathic and have correspondingly lower conductivities. Although the average conductivity of Witwatersrand quartzite is similar to that for the Transvaal Supergroup, there is a large range (3.72–8.21 W m^{-1} K^{-1}). Petrographic analyses undertaken by Bullard[1], Mossop and Gafner[2] and Carte[3] on a number of samples showed that thermal conductivity is directly related to purity. Specimens containing significant amounts of the accessory minerals, which have lower conductivities than quartz (Table IV), were shown to have lower conductivities.

Two other factors that potentially affect the thermal conductivity of Witwatersrand quartzite, and which may have important implications for mine refrigeration studies, are anisotropy and temperature dependence of conductivity. Quartz is a highly anisotropic mineral, the conductivity parallel to the c-crystallographic axis being nearly twice that perpendicular to the c-axis (Table IV). A preferred orientation of crystals in rock masses would result in greater heat flux in the direction in which the c-axis is aligned. The highest observed conductivity for Witwatersrand quartzite is not much greater than that for an aggregate of randomly orientated quartz grains (Table IV), and measurements on 10 samples of quartzite cored parallel to and perpendicular to the bedding plane did not reveal any statistical difference. This suggests that, in general, the quartz grains are randomly orientated in the rock.

The temperature dependence of the thermal conductivity of most rocks in the Earth's crust may be represented by $K_T=K_0/(1+\alpha T)$ where K_0 is conductivity at 0°C, T is temperature and α is a constant[24]. The conductivity of rocks consisting mainly of feldspar and mafic minerals like pyroxene tends to be relatively constant, but the conductivity of quartz-rich rock decreases significantly with temperature. Although not much experimental work has been done on pure quartzite, one set of observations shows a decrease of conductivity from 6.2 W m^{-1} K^{-1} at 0°C to 5.2 W m^{-1} K^{-1} at 100°C[24]. While the variation of density is negligible over this temperature range, a separate experiment on quartzite indicates an increase in heat capacity from 700 J kg^{-1} K^{-1} at 0°C to 830 J kg^{-1} K^{-1} at 100°C[24]. All the thermal property measurements reported in this paper were made at room temperature (~25°C), whereas VRTs in the deepest mines can be expected to approach 75°C. This implies that measured conductivity values for Witwatersrand quartzite may be up to 8 per cent higher than in situ values, that measured heat capacities may be up to 10 per cent lower than *in situ*, and that the thermal diffusivity (derived from $\kappa=K/\rho C$) may be over-estimated by up to 18 per cent. It may be necessary to take this into account when calculating heat loads on deep mine workings and, preferably, to make measurements on specimens of Witwatersrand quartzite at elevated temperatures.

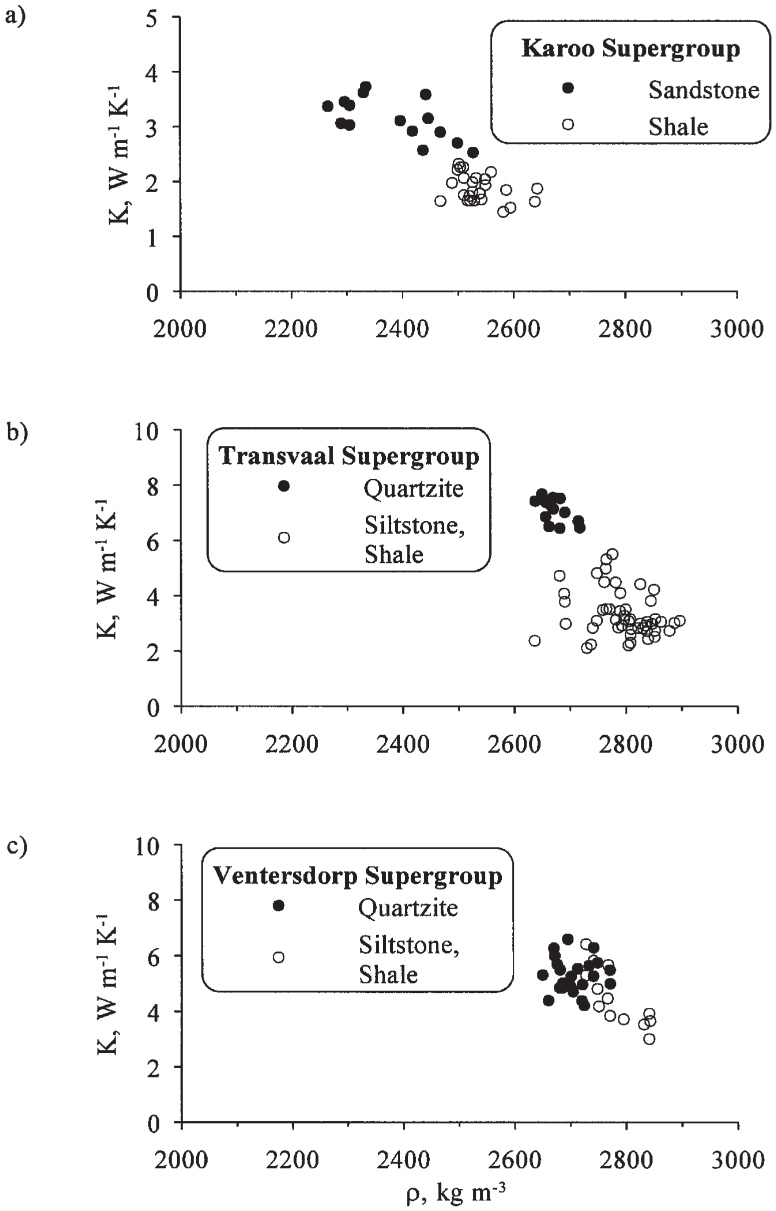

Figure 10—Plot of thermal conductivity versus density for shales and sandstones of the Karoo Supergroup (a), and shales, siltstones and quartzites from the Transvaal Supergroup (b) and Ventersdorp Supergroup (c)

Conclusions

The large database of thermal conductivity, density and heat capacity now available for rocks from the Witwatersrand Basin permits reliable estimates for average thermal properties of most rock types occurring in different stratigraphic units within and overlying the basin. Heat capacity does not vary much from one rock type to another, but additional measurements should be made in order to obtain a more complete coverage. Although density is relatively uniform, different rock types are characterized by distinctly different mean values and have well-defined ranges. Thermal conductivity is the most variable parameter, changing by a factor of ~4, but different rock types have distinct mean values and standard deviations. The most important factors controlling the thermal properties, particularly thermal conductivity, are mineral composition, degree of metamorphism and porosity. The temperature dependence of thermal conductivity and heat capacity of Witwatersrand quartzite may result in significant over-estimation of the thermal diffusivity of this rock in very deep gold mines.

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I am indebted to numerous mine engineers and geologists who provided rock samples over a period of many years. P.J. Hancox assisted in classifying rock samples in the BPI collection. This manuscript was reviewed by C.R. Annhaeusser and L.D. Ashwal. Many of the measurements were made during the 1980s under contract to the Chamber of Mines Research Organization. Additional measurements and this compilation were made as part of a project supported by the DeepMine Collaborative Research Programme.

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Murray & Roberts make safety a priority with half a million hours lost-time, injury-free manhours on furnace project*

Murray & Roberts has achieved a significant safety milestone of 500 000 hours lost-time, injury-free on the Anglo Platinum Slag Cleaning Furnace project at the Waterval smelter. The project is being implemented as an EPCM contract in a joint venture with Murray & Roberts and Pyromet Technologies.

Says Murray & Roberts project manager, Alan Wingrove 'The safety milestone is a significant achievement for the project which is approximately 70% complete. Safety is a priority for Murray & Roberts and the slag cleaning furnace achievement within a 'brownfield' environment demonstrates the high standards and construction management disciplines that are adhered to on any given project. We are proud of having reached the milestone and intend to complete the project injury free early in 2003.'

It is regretted that one fatal incident has occurred on the project to date; the exact cause of death is yet to be determined.

The primary function of the 30 MVA slag cleaning furnace is to process granulated slag from the new Ausmelt converter plant at Waterval to further improve the recovery of platinum values. Interestingly, the furnace has been designed by Pyromet Technologies with the flexibility to handle a variety of other feed streams, including concentrates, reverts and molten matte or slag from the Pierce-Smith converters. This flexibility will provide Waterval with reserve smelting capacity. Particularly important is the ability of the furnace to smelt concentrates containing the chromite found in the UG2 concentrates. ◆

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42 Parties now implementing Kimberley process certification scheme since 1 January launch*

The world-wide Chairman of the Kimberley Process, Abbey Chikane, recently confirmed that the Kimberley Process Certification Scheme (KPCS), which was launched successfully with 20 participants on 1 January 2003, is making excellent progress. A further 22 of the parties have implemented the Scheme thus bringing the total number of participants to 42 as at 31 January.

This rate of implementation, which has effectively doubled in just over four weeks since the launch, is expected to continue with a further seven to ten new countries coming on board in the next month.

This early success can be attributed to many factors that have helped establish the credentials of the Kimberley Process. These include, among others, the United Nations General Assembly approving the Kimberley Process and the United Nations Security Council passing a resolution in April 2000 which welcomed the proposal that led to the adoption of the Interlaken Declaration of 5 November 2002 about the Kimberley Process Certification Scheme for Rough Diamonds.

The UN Security Council tabled a further resolution on 27 January 2003 which strongly supported the KPCS, applauded the system of self-regulation and encouraged participants to resolve any outstanding issues so that there would be the widest possible participation in this essential Scheme.

In the light of this, certain interim measures were put in place on 1 February 2003 in order to fulfil the KPCS mandate, and in order to accommodate the unique national procedures of participating states in passing legislation and fulfilling other administrative requirements of the KPCS.

Abbey Chikane, Chairman of the Kimberley Process comments, 'We felt that it was essential to not discriminate against any of our colleagues which could not comply with all of the KPSC conditions straight away'

'We did not want to penalize any of the interested parties and these interim measures were put in place to enable those countries to participate in the Scheme as early as possible.'

He continues, 'This period of tolerance will continue until the end of April 2003 after the first Plenary Session of 2003 will have taken place.'

As Chairman of the Kimberley Process, Chikane, having carefully examined information provided so far and following intensive consultations with many of the KPCS colleagues has drawn the following conclusions :

A number of parties could be considered to have fulfilled all or most of the conditions to qualify as participant, as defined in Section I of the Kimberley Process Certification Scheme document adopted at Interlaken in November 2002.

These 42 parties are: Angola, Armenia, Australia, Belarus, Botswana, Burkina Faso, Canada, Central African Republic, Côte D'Ivoire, Democratic Republic of Congo, European Community, Gabon, Ghana, Guinea, Guyana, India, Israel, Japan, Republic of Korea, Laos, Lebanon, Lesotho, Malta, Mauritius, Mexico, Namibia, People's Republic of China, Philippines, Russia, Sierra Leone, South Africa, Sri Lanka, Swaziland, Switzerland, Tanzania, Thailand, Togo, Ukraine, United Arab Emirates, United States of America, Vietnam and Zimbabwe

A further 10, Algeria, Brazil, Cyprus, Czech Republic, Hungary, North Korea, Norway, Romania and Venezuela having recently informed the Chair of their intention to become participants, have also been required to ensure that all rough diamonds exported from their territories are accompanied by a duly validated temporary Kimberley Process Certificate.

In line with the KPCS agreement, all parties are required to ensure that no shipment of rough diamonds is imported from or exported to a non-Participant.

The KPCS document also set out procedures whereby issues regarding the implementation could be raised and addressed through the Chair, who would then inform all Participants without delay about the said concern and enter into a dialogue on how to address the matter.

Kimberley Process Chairman, Abbey Chikane comments, 'As much as we are excited at the excellent progress being made by participants, we do not want the Certification process to interfere or disrupt the legitimate global diamond trading industry'

'Nonetheless we believe that this rate of implementation indicates that the Certification Scheme is well advanced,' he concludes.

South Africa hosts the first Plenary Session of the Process this year during the latter part of April at the Sandton Convention Centre in Johannesburg. Representatives of the 56 countries participating in the Kimberley Process are expected to attend. ◆

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