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Virgin rock temperatures and geothermal gradients in the Bushveld Complex

by M.Q.W. Jones

Synopsis

Knowledge of virgin rock temperature (VRT) is essential for planning refrigeration and ventilation requirements of deep mines. Geothermal studies in the goldfields of the Witwatersrand have been in progress for approximately 80 years, with the result that a very extensive rock temperature database is available. However, it is only in the last three decades that deep-level platinum mining in the Bushveld Complex, north of the Witwatersrand Basin, has made mine refrigeration an important issue. This paper presents temperature profiles in 31 boreholes in the Bushveld Complex that were surveyed as part of a project, conducted between 1985 and 2005, aimed at establishing the geothermal characteristics of the Complex. Most of the boreholes are located in platinum mining areas or prospects situated around the perimeter of the Complex. The geothermal gradient in rocks of the Main Zone of the Complex, which immediately overlie the platinum reefs, is remarkably constant at 20.7±1.3 K/km. Data from the Upper Zone and the Bushveld granites yield lower gradients, 16.5±1.1 K/km and 16.4±2.4 K/km respectively. Geothermal gradients in the Bushveld Complex are approximately double the thermal gradients in the Witwatersrand. The geothermal heat flux in the platinum mining areas, calculated from the thermal gradients and thermal conductivity data measured on samples of borehole core, is also remarkably uniform at 45±4 mW/m^2; this is somewhat less than the average for Witwatersrand gold mining areas, 51±6 mW/m^2. The main reason for the higher gradients in the Bushveld Complex is the low thermal conductivity of the rocks. Bottom-hole temperature measurements in boreholes in the Northam mining area of the Complex yield the highest virgin rock temperatures (up to 70°C at 2.2 km depth). This is 30°C hotter than the temperature at the same depth in mines in the Carletonville area of the Witwatersrand Basin. The surface temperature data and heat flow data, together with an extensive thermal conductivity database, make it possible to predict VRTs in new platinum mining areas as well as chromium and vanadium mines if such mining proceeds to substantial depths.

Keywords
Bushveld Complex, platinum mines, virgin rock temperature, geothermal gradient, heat flux.

Introduction

South Africa is endowed with an enormous mineral wealth, with the result that mining is one of the main pillars of the economy. Advances in technology in the last five decades have permitted mining at increasingly deeper levels. Increased mining depth means an increase in virgin rock temperature (VRT), which results in increased heat loads on underground workings (*e.g.* Rawlins, Phillips and Jones, 2002; Jones, 2003a). This is particularly relevant in the goldfields of the Witwatersrand, where mining approaches 4 km in depth, and in the Bushveld Complex, where platinum mines exceed 2 km depth. Because it is necessary to control the working environment, mine refrigeration and ventilation are important considerations when planning such deep-level mining. This planning requires knowledge of the VRT as well as the thermal properties of the rocks surrounding underground workings.

Gold has been mined in the Witwatersrand Basin (Figure 1) for more than 100 years, and geothermal research has been conducted for approximately 80 years. The earliest rock temperature studies (Weiss, 1938; Bullard, 1939; Krige, 1939) showed that the geothermal gradients are relatively low in the Witwatersrand. This has been confirmed by routine VRT measurements made in mines since 1950 down to maximum rock-breaking depth, where the VRT exceeds 65°C (Jones, 2003a). In the 1980s a detailed thermal investigation of the Witwatersrand Basin was conducted by the University of the Witwatersrand (Wits) in collaboration with the Chamber of Mines Research Organization (COMRO, now CSIR Mining Technology), and major mining companies. This resulted in an extensive compilation of VRT data in the basin and thermophysical properties of the main rock types. It also allowed for calculation of numerous determinations of the heat flux through the Earth's crust. Details of the results are reported by Jones (1988, 2003a, 2003b).

During the Witwatersrand project, platinum mining in the Bushveld Complex north of the Witwatersrand Basin (Figures 1 and 2) was increasing in depth and it became obvious that a similar investigation of the Complex was necessary. The importance of this was made clear by two early measurements that indicated that the geothermal gradients were approximately

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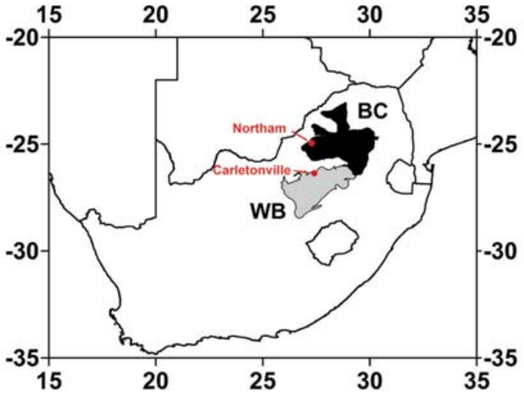

Figure 1—Locality of the Bushveld Complex (BC, black) and Witwatersrand Basin (WB, grey). The positions of mines in the Northam and Carletonville areas are also shown (in red)

double those in the Witwatersrand Basin (Carte and van Rooyen, 1969). The ensuing collaborative research project between Wits, COMRO, the Geological Survey of South Africa (now the Council for Geoscience) and major mining houses resulted in an extensive database constituting rock temperature measurements in boreholes distributed in the main mining areas, nearly 1000 measurements of the thermal properties of Bushveld rocks and 31 new values for the heat flux through the Earth's crust. The latter two aspects of the project have been reported on in detail by Jones (2015, 2017).

This paper focuses on rock temperatures and geothermal gradients. It reports on temperature measurements made in boreholes situated in the main platinum mining areas as well as some in the interior of the Bushveld Complex. It discusses relevant aspects of thermal conductivity measurements on Bushveld rocks and determinations of heat flux. It provides a comparison with geothermal data from the Witwatersrand Basin and shows how the VRT in unexplored regions of the Complex can be estimated from existing geothermal data. This has implications for mine refrigeration studies for new platinum mines as well as future chromium and vanadium mines if they should become deeper.

Geological background

The geological terrain in which the Bushveld Complex is located is known as the Kaapvaal Craton. This Archaean cratonic nucleus, represented by basement granitic rocks and greenstone belts, developed between 3700 and 2650 Ma ago (Eglington and Armstrong, 2004), by which time it had largely stabilized. During this period, and subsequently, relatively undeformed stratified basins formed on the craton. The stratigraphy of these basins is shown in Figure 3. The oldest, the Witwatersrand Basin (Figure 1), hosts the largely volcanic Dominion Group (ca. 3100 Ma) (Marsh, 2007), overlain by the largely sedimentary Witwatersrand Supergroup (3000–2700 Ma) (McCarthy, 2007), and followed by the largely volcanic Ventersdorp Supergroup (2700 Ma) (van der Westhuizen, de Bruijn, and Meintjies, 2007). Subsequent deposition of platform strata of the Transvaal Supergroup (2650–2200 Ma) (Erikkson, Altermann and Hartzer, 2007) occurred in the Transvaal Basin, which overlies the Witwatersrand Basin and an extensive area of Archaean basement rocks further north. The next important geological event to affect this part of the Kaapvaal Craton was extrusion of the Rooiberg Group ca. 2070 Ma (Buchanan, 2007) and emplacement of plutonic rocks of the Bushveld Complex into the northern part of the Transvaal Basin at 2060 Ma (Figures 1 and 2) (Zeh *et al.*, 2015; Mungall, Kamo and McQuade, 2016). Parts of the Witwatersrand Basin and the southern Bushveld Complex are covered by sedimentary rocks of the 300–200 Ma old Karoo Supergroup (Johnson *et al.*, 2007).

The geology of the Bushveld Complex is shown in Figure 4, which is a sub-outcrop map showing the surface and inferred subsurface distribution of the main rock units below the Karoo cover (after Cairncross and Dixon, 1995). A simplified stratigraphic column of the Complex is shown in the right side of Figure 3.

The Bushveld Complex is a huge igneous province that occupies an area of more than 65 000 km^2 (Cawthorn *et al.*, 2007). There are two main subdivisions, a lower, older mafic to ultramafic phase, known as the Rustenburg Layered Suite, and a younger, upper granitic phase comprising the Rashoop Granophyre Suite and the Lebowa Granite Suite, usually referred to collectively as 'Bushveld granite' (Figures 3 and 4). The Rustenburg Layered Suite occurs in four main lobes (Figures 2 and 4). The western lobe extends from Pretoria to Thabazimbi, the northern lobe is mainly north of Mokopane, the eastern lobe from Zebediela to Stoffberg and the southern lobe (which is hidden by Karoo cover) extending as far south as Bethal.

Stratigraphically, the Rustenburg Layered Suite is conveniently divided into five zones (Figure 3). The Marginal Zone consists mainly of norite with some pyroxenite. The Lower Zone is ultramafic, dominated by pyroxenite, harzburgite, and dunite. The lower part of the Critical Zone is essentially pyroxenite, whereas the upper part is represented by cyclic layers of pyroxenite, norite and anorthosite. The Main Zone is predominantly norite and gabbro, with some layers of anorthosite and pyroxenite. The Upper Zone shows

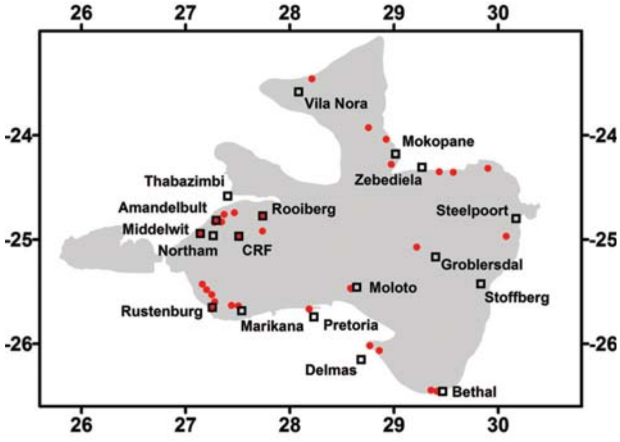

Figure 2—Outline of the outcrop and suboutcrop of the Bushveld Complex showing borehole localities (red dots) in relation to major localities mentioned in the text (hollow black squares). CRF: Crocodile River Fragment

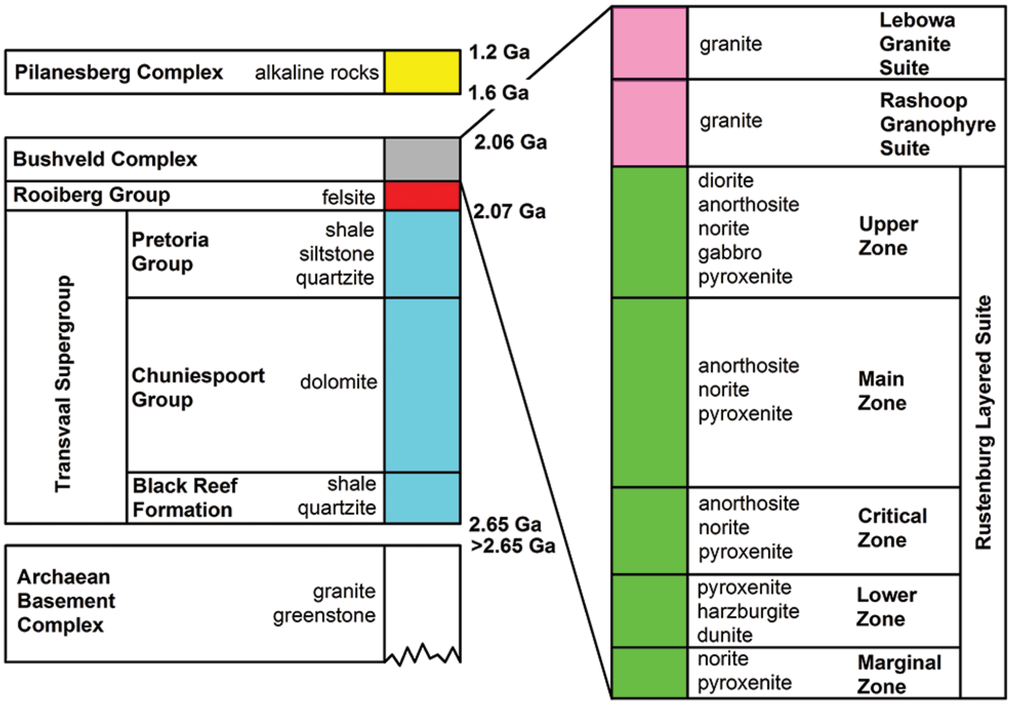

Figure 3—Simplified chronostratigraphic succession of the central part of the Kaapvaal Craton (left) and a more detailed subdivision of the Bushveld Complex (right) (after Jones, 2017). Ages are in Ga, which is equivalent to 1000 Ma

more variation in rock type and includes diorite, anorthosite, norite, gabbro and pyroxenite. The Bushveld granites intruded above this sequence.

The Bushveld Complex hosts the world's largest reserves of platinum (and associated platinum group elements), chromium and vanadium (Cawthorn *et al.*, 2007). The main units mined for platinum are the UG2 (Upper Group 2) chromitite layer and the Merensky Reef, which occur in the upper part of the Critical Zone in the eastern and western limbs of the Complex, and the Platreef in the northern limb. Because of its economic value, platinum mining of the UG2 and Merensky reefs now approaches depths of 2 km, which necessitates mine refrigeration. Current mining of the Platreef is by opencast methods, but underground mines are in the development stage. The main units mined for chromium are the LG6 and MG1 (Lower and Middle Group) chromitite layers, which occur deeper (stratigraphically) in the Critical Zone than the UG2 and Merensky Reef. Chromium mines are currently relatively shallow, but if mining proceeds deeper in the future, refrigeration will be required. Vanadium deposits are associated with magnetite-rich layers near the base of the Upper Zone in the eastern, northern, and western limbs of the Complex. Vanadium mines are also opencast at present but could go underground in the future.

Virgin rock temperatures and geothermal gradients

In addition to early borehole temperature measurements in the Witwatersrand Basin, most mining companies have conducted VRT measurements in mine workings since 1950. These data were collated by COMRO and the database provided valuable information regarding the depth to various isotherms in the Witwatersrand gold mining arc (Jones, 1988, 2003a). Although individual mining companies have made in-house VRT measurements in Bushveld mines, there is no similar coordinated VRT database for the Bushveld Complex. One of the main objectives of this investigation was to measure temperatures in exploration boreholes around the Complex in order to provide reliable estimates of the geothermal gradient for mines in the Complex. The methods of measurement and the results are described below.

Borehole temperature measurement

Temperature measurements were made in 31 boreholes (Table I) using electronic temperature probes attached to a cable and lowered by a portable winch. The temperature probes are similar to those described by Jones (1987, 1988). The sensor was either a thermistor or temperature transducer; both devices can detect temperature fluctuations of as little as 0.001 K, and calibration experiments ensured that absolute temperatures were accurate to within 0.01 K. The temperature at each depth was recorded after the probes had been held at the depth for two minutes, which is more than sufficient time for the probes to reach equilibrium. Temperatures were recorded at 10 m or 20 m depth intervals while the probes were being lowered. Depths were recorded using a calibrated depth counter attached to a pulley, over which the cable ran, and are estimated to be accurate to within 10 cm. Thermal gradients between successive temperature measurements were calculated from the field measurements.

Many of the boreholes are located in the platinum mining areas situated around the periphery of the Bushveld Complex, but there are some in the interior of the Complex (Figure 4, Table I). They are named after the original farms on which they are located and can be identified from their serial numbers, which appear in Tables I and II. All boreholes were

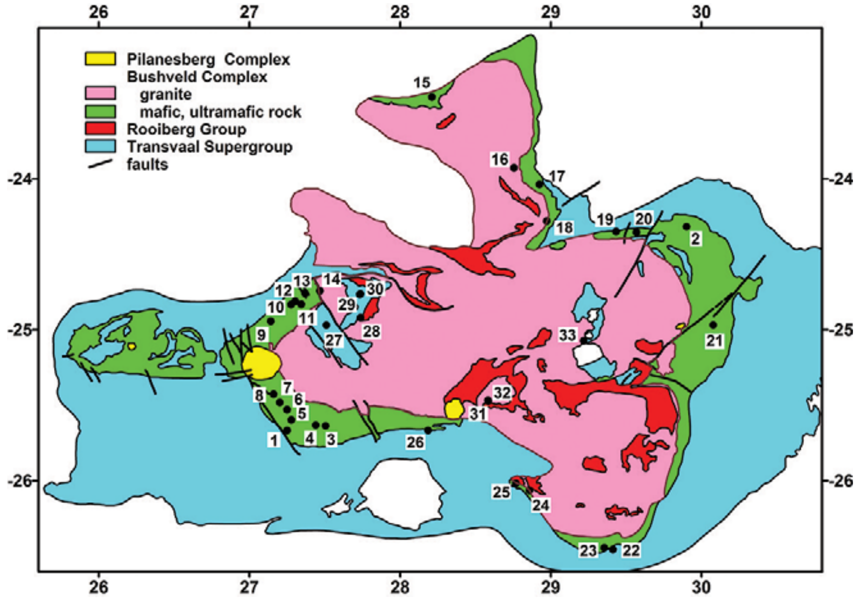

Figure 4—Geological map of the Bushveld Complex and surrounding areas constructed from outcrop maps and inferred suboutcrop maps derived by stripping off the younger Karoo cover (after Cairncross and Dixon, 1995). Dots represent boreholes, and numbers refer to the site number listed in column 2 of Tables I and II

Table I

Localities of boreholes in the Bushveld Complex and main stratigraphic units penetrated

Site name	No.	Latitude	Longitude	Elev. (m)	Stratigraphic Unit	Area
Rustenburg*	1	-25.667	27.250	1160	Main Zone	Rustenburg
Umkoanesstad*	2	-24.313	29.900	832	Main Zone	Umkoanesstad
Schaapkraal SK2	3	-25.636	27.505	1120	Main Zone	Marikana
Schaapkraal SK1	4	-25.632	27.440	1125	Main Zone	Marikana
Reinkoyalskraal RK1	5	-25.596	27.278	1096	Main Zone	Rustenburg
Vlakfontein VLF1	6	-25.529	27.250	1127	Main Zone	Rustenburg
Doornspruit DS1	7	-25.481	27.201	1071	Main Zone	Rustenburg
Goedgedacht GG1	8	-25.427	27.160	1072	Main Zone	Rustenburg
Nooitgedacht NG1	9	-24.942	27.141	1005	Lower Zone	Middelwit
Elandsfontein EL1	10	-24.833	27.276	960	Main Zone	Amandelbult
Schildpadnek SKN1	11	-24.811	27.303	935	Main Zone	Amandelbult
Elandskuil EK1	12	-24.759	27.369	959	Main Zone	Amandelbult
Zondereinde ZE1	13	-24.831	27.344	977	Main Zone	Northam
Paddafontein PAD1	14	-24.742	27.467	941	Bushveld granite	Northam
Wemmersvlei WEM1	15	-23.413	28.241	994	Main Zone	Vila Nora
Bellevue BV1	16	-23.926	28.755	980	Bushveld granite, Upper Zone	Mokopane
Rietfontein RTN1	17	-24.038	28.924	1097	Main Zone	Mokopane
Moorddrift M1	18	-24.278	28.973	1064	Main Zone	Mokopane
Kafferkraal KF1	19	-24.350	29.433	1010	Main Zone	Zebediela
Doornvlei DV1	20	-24.355	29.568	913	Main Zone	Zebediela
Dwarsrivier DWR1	21	-24.968	30.077	986	Main Zone	Steelpoort
Rustfontein RUS1	22	-26.455	29.412	1654	Upper Zone	Bethal
Palmietfontein PF1	23	-26.444	29.355	1593	Upper Zone	Bethal
Boschpoort BP1	24	-26.064	28.858	1501	Upper Zone	Delmas
Dwarsfontein DW1	25	-26.018	28.768	1542	Upper Zone	Delmas
Onderstepoort OP1	26	-25.669	28.183	1230	Upper Zone	Pretoria
Wachteenbeetje WB1	27	-24.969	27.510	981	Pretoria Group	Crocodile R. Inlier
Leeuwpoort LP1	28	-24.919	27.737	1110	Pretoria Group	Rooiberg
Olievenbosch OB1	29	-24.766	27.732	1140	Pretoria Group	Rooiberg
Olievenbosch OB2	30	-24.763	27.736	1138	Transvaal Supergroup	Rooiberg
Varkfontein VF1	31	-25.467	28.583	1230	Bushveld granite, Upper Zone	Moloto
Fairfield FF1	32	-25.471	28.585	1227	Bushveld granite, Upper Zone	Moloto
Loskop North LKN1	33	-25.073	29.218	975	Bushveld granite	Groblersdal

*Published values (Carte and van Rooyen , 1969)

Table II

Geothermal gradients in boreholes in the Bushveld Complex and main rock types in which they were measured

Site name	No.	Depth range (m)	Thermal gradient (K/km)		Main rock types
			dT/dx	N_T	
Rustenburg*	1	150–1070	19.3–24.5	19	norite, anorthosite
Umkoanesstad*	2	150–610	21.2	14	norite, gabbro
Schaapkraal SK2	3	120–780	20.4	34	norite, anorthosite
Schaapkraal SK1	4	120–320	21.1	11	norite, anorthosite
Reinkoyalskraal RK1	5	80–580	20.8	26	norite
Vlakfontein VLF1	6	100–640	22.2	28	norite
Doornspruit DS1	7	140–580	21.4	23	norite
Goedgedacht GG1	8	100–680	22.2	30	norite
Nooitgedacht NG1	9	60–760	16.0	36	pyroxenite, dunite
Elandsfontein EL1	10	200–380	19.9	10	norite, anorthosite
Schildpadnek SKN1	11	160–320	20.2	9	norite, anorthosite
Elandskuil EK1	12	120–300	21.1	10	norite, anorthosite
Zondereinde ZE1	13	200–540	20.2	18	norite, anorthosite
Paddafontein PAD1	14	60–740	17.1	35	granite
Wemmersvlei WEM1	15	500–800	22.6	15	anorthosite, norite
Bellevue BV1	16	160–780	9.4–15.4	32	granite, diorite, gabbro
Rietfontein RTN1	17	140–700	20.9	29	norite
Moorddrift M1	18	220–780	18.2	29	norite
Kafferkraal KF1	19	140–800	17.7	34	norite, anorthosite
Doornvlei DV1	20	140–780	19.9	33	norite, anorthosite
Dwarsrivier DWR1#	21	120–236	21.2	7	anorthosite, norite
Rustfontein RUS1	22	200–480	16.3	15	gabbro, norite, anorthosite
Palmietfontein PF1	23	200–700	14.2–17.6	25	gabbro, hornfels, pyroxenite
Boschpoort BP1	24	200–440	16.4	15	gabbro
Dwarsfontein DW1	25	120–600	14.9	25	pyroxenite, gabbro
Onderstepoort OP1	26	220–620	18.0	21	gabbro, pyroxenite
Wachteenbeetje WB1	27	59–742	17.6	35	shale, siltstone, quartzite
Leeuwpoort LP1	28	210–260	20.4	6	shale, arkose
Olievenbosch OB1	29	140–270	20.4	8	shale, arkose
Olievenbosch OB2	30	160–380	18.8	12	shale, arkose
Varkfontein VF1	31	160–393	17.9	13	granite, gabbro
Fairfield FF1	32	160–800	13.7–17.7	33	granite, gabbro
Loskop North LKN1	33	50–220	18.3	18	granite

dT/dx, thermal gradient; N_T, number of temperature measurements; *published values (Carte and van Rooyen, 1969); #thermal gradient after topographic correction

vertical except for Wachteenbeetje WB1 (Table I), in which case depths were adjusted for borehole inclination. Surveys were conducted sufficiently long after the cessation of drilling so that transients associated with drilling were negligible. The relief surrounding the boreholes is low and only one measurement, Dwarsrivier DWR1 (Table I), required a topographic correction, which was achieved using the method of Jeffreys (1937); tests on two other boreholes with the next most severe surrounding topography yielded corrections less than 1% of the measured thermal gradient. The boreholes penetrated impermeable rock but some underground water flows, associated with fracture systems, were evident in a few boreholes; none of these results were used for the main data compilation described below. In most cases lateral heat conduction due to horizontal thermal conductivity contrasts was considered to be negligible, but see below for a discussion of data from boreholes Nooitgedacht NG1 and Paddafontein PAD1 (Table I).

Results

Table I lists borehole localities, elevations, the main stratigraphic units in which temperatures were measured and the areas where the boreholes are located. Table II gives depth ranges displaying linear temperature profiles, average thermal gradients for these depths and the main rock types in which measurements were made.

Borehole positions are shown in Figure 4. Borehole numbers refer to column 2 of Tables I and II. The results of temperature measurements as functions of depth are shown in Figure 5. The latter results are arranged in stratigraphic order, with those in the uppermost rocks being presented first and those in the oldest rocks appearing last. The data in Figure 5 are colour-coded so that results from individual boreholes are evident. The geographic region in which the boreholes occur is indicated in Figure 2. The vertical bars on the temperature axes of Figure 5 indicate the temperature minimum relative to which the borehole data are plotted. Figures 5a and 5b present temperature profiles in Bushveld granite and the Upper Zone of the Complex, respectively. The data from the Main Zone (Figures 5c and 5d) are most relevant to this paper; they are arranged in clockwise order from Marikana through the western and northern limbs of the Complex to the Steelpoort region (Figure 3). Data from one borehole from the Lower Zone are given in Figure 5e. Figure 5f shows results from Transvaal Supergroup and Rooiberg Group lithological units occurring in geological inliers, or fragments, in the interior of the Complex (Figure 4).

The uppermost 100–200 m sections of many boreholes are characterized by a systematic concave temperature curve. This phenomenon is common in South Africa and elsewhere and is caused by increases in ground surface temperature of

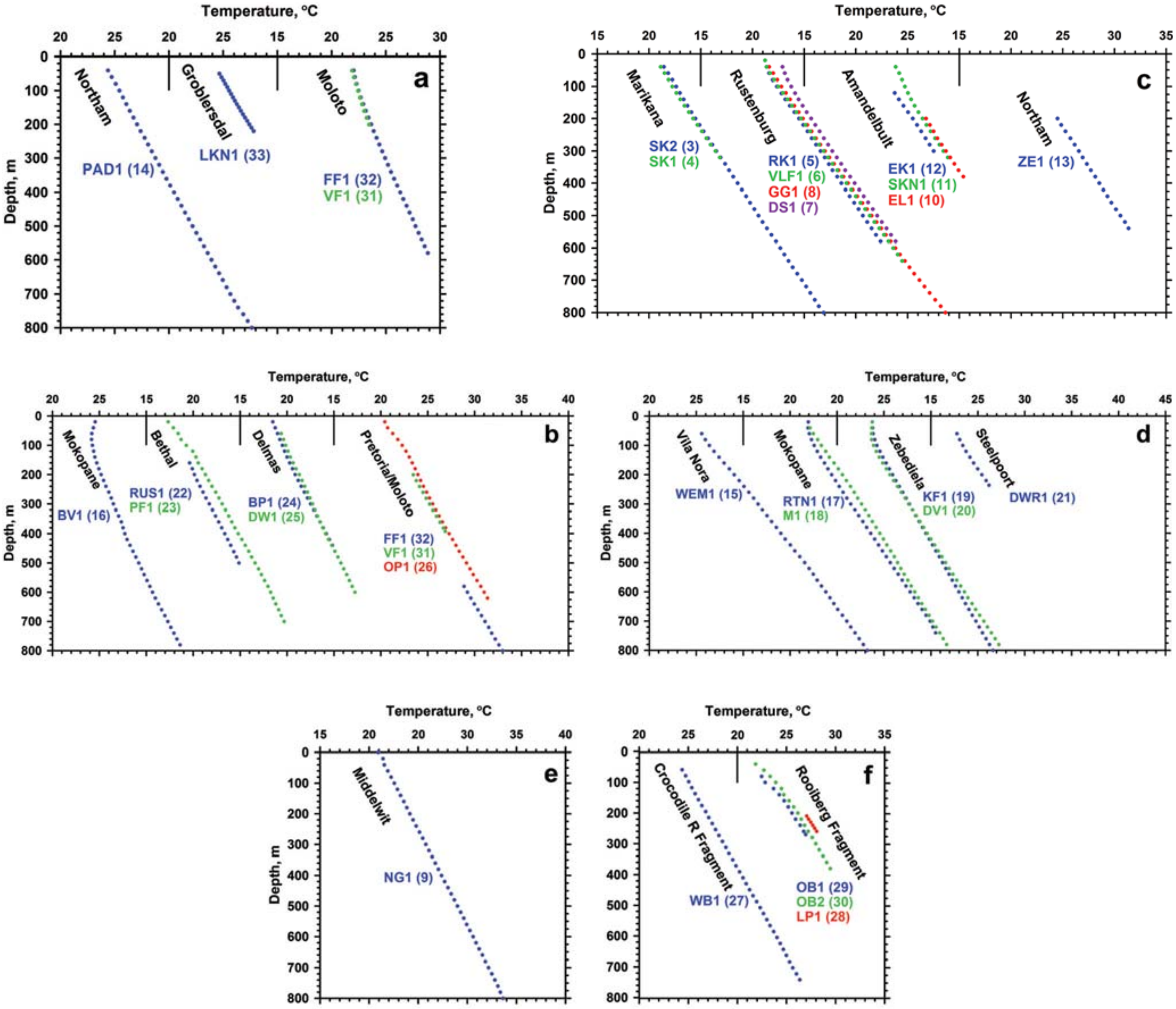

Figure 5–Temperature *versus* depth profiles for boreholes in the Bushveld Complex in the following order: (a) Bushveld granite, (b) Upper Zone, (c) and (d) Main Zone and upper Critical Zone, (e) Lower Zone and (f) fragments of pre-Bushveld rocks occurring in the interior of the Complex. Data from the Main–Critical Zones (c and d) are arranged in clockwise order from Marikana to Steelpoort. In order to conserve space, the temperature axes are arranged into 'boxes', the top boundaries of which are indicated by long vertical bars on the temperature axes; borehole temperatures are plotted relative to the top left value shown in each box. The area in which the boreholes occur is indicated diagonally in the top left hand corner of each box (see Figure 2 for area localities). Where there is more than one borehole in a particular area, the borehole data are colour-coded, as are the serial numbers. Borehole serial numbers (*e.g.* PAD1) and borehole numbers in parentheses (*e.g.* 14) are those listed in columns 1 and 2 of Tables I and II. Boreholes in the Moloto area pass through Bushveld granite and Upper Zone gabbro and these data are split between Figures 5a and 5b

1–2°C during the last 200 years (Tyson *et al.*, 1998; Jones, Tyson, and Cooper, 1999). Data showing such curvature was not used in the analyses. Below the curved zone, most boreholes display linear temperature profiles where the temperature data was obtained in a uniform rock type.

Discussion

Geothermal gradients in the Bushveld Complex

The thermal gradients listed in Table II are least-squares fits to the temperature *versus* depth data in the specified depth intervals. A range of gradients is given in cases where boreholes pass through variable lithologies with different thermal conductivities. The data confirm the early results of Carte and van Rooyen (1969), which indicated that the thermal gradient in the Bushveld Complex is relatively high.

Because of the great depth of some platinum mines, geothermal gradients above these mines are most pertinent. The gradient in individual boreholes, or range of values if more than one borehole was used, for different segments of the platinum mining areas or prospects around the perimeter of the Bushveld Complex are listed in Table III. In most cases the measurements were made in rocks constituting the Main and upper Critical Zones of the Complex, which overlie the main platinum reefs. The thermal gradient is remarkably uniform and averages at 20.7±1.3 K/km.

There is also a significant change vertically in the thermal gradient within the Bushveld Complex (Table IV). One

Table III

Geothermal gradients and heat flow in platinum mining areas of the Bushveld Complex (after Jones, 2017)

Area	dT/dx (K/km)	q_0 (mW/m²)
Marikana	20.4–21.1	44–48
Rustenburg	19.3–24.5	46–51
Amandelbult	19.9–21.2	41–44
Northam	20.2	45
Vila Nora	22.6	42
Mokopane	18.2–20.9	43–47
Zebediela	17.7–19.9	40–44
Umkoanesstad	21.2	47
Steelpoort	21.2	43

dT/dx, thermal gradient; q_0, heat flow

measurement in the Lower Zone yielded a gradient of 16.0 K/km (NG1). Eight measurements in the Upper Zone yielded 16.5±1.1 K/km, and three in Bushveld granite yielded 16.3±2.4 K/km.

Thermal conductivity and heat flow

Jones (2015) recently reported on thermal conductivity measurements of more than 900 samples of all major rock types constituting the Bushveld Complex. Average values are listed in Table V. This table also summarizes results of measurements on more than 1000 samples of rocks from the Witwatersrand area (Jones, 2003b). As such, this table represents an almost complete 'thermal conductivity stratigraphy' of the rock groups represented in Figure 3. An important aspect of the data is that many rocks in the Bushveld Complex have conductivities that are one-third to one-half of the conductivity of strata in the Witwatersrand Basin and the overlying Transvaal Supergroup. This has important implications for understanding the geothermal gradients in the two regions.

Jones (2017) combined the borehole temperature data with the thermal conductivity data to make 31 new estimates of the heat flux through the Earth's crust within the Bushveld Complex. Table III lists individual heat flow values including two results previously published by Carte and van Rooyen (1969), or a range of values if more than one measurement is available, for different segments of the platinum mining areas around the perimeter of the Complex. These exclude two exceptionally high values – 66 mW/m² for Nooitgedact NG1, which is located in relatively high conductivity rocks of the Lower Zone, and 62 mW/m² for Paddafontein PAD1, which is located in relatively high conductivity Bushveld granite. In both cases the high heat flow can be attributed to heat refraction due to a lateral conductivity contrast with the surrounding rock (Jones, 2017). The overall average for the rest of the data from the perimeter of the complex is tightly constrained at 45±4 mW/m² (24 values) (Jones, 2017). The few measurements in the interior of the Complex are in pre-Bushveld inliers or Bushveld granite and yield an average heat flow of 51±7 mW/m² (seven values); the higher heat flow can probably be attributed to enhanced radioactive heat generated by the decay of uranium, thorium, and potassium in the Bushveld granites, which occupy the interior of the Complex (Jones, 2017). The heat flux from the platinum mining areas is actually lower than that from the Witwatersrand goldfields (51±6 mW/m² (81 values), (Jones, 1988).

Comparison with Witwatersrand Basin and younger stratified rocks

Average values for the thermal gradient of rocks occupying the Witwatersrand Basin and the Transvaal Basin, the intrusive Bushveld Complex, and the younger Karoo sedimentary cover are listed in Table IV. There is an obvious relationship between thermal gradient, rock type, and position in the stratigraphic column (Figure 1). Fourier's Law of heat conduction, which can be written as:

$$\frac{dT}{dx} = -\frac{q_0}{K}$$

states that thermal gradient (dT/dx) is inversely proportional to thermal conductivity (K) and proportional to surface heat flow (q_0) at a particular locality. In most cases, variation of thermal conductivity is the dominant cause of the differences in thermal gradient.

One exception is the thermal gradient in the Dominion Group (Table IV). The boreholes from which the average gradient in this unit was derived are situated on the northwest margin of the Witwatersrand Basin, where the heat flow is amongst the lowest in the world, 33±2 mW/m² (seven values) (Jones, 1988). Quartzites in the Witwatersrand Supergroup and dolomites in the Transvaal Supergroup have relatively high conductivities (6.4 and 5.1 W/mK respectively, Table V) and concomitantly low thermal gradients. The thermal gradient in Ventersdorp lava is higher than in the quartzites and dolomites because of its

Table IV

Mean geothermal gradients in rock units above the main gold mining areas of the Witwatersrand Basin and platinum mining areas of the Bushveld Complex

Rock unit/sub-unit	Rock type	dT/dx±s.d. (K/km)
KAROO SUPERGROUP		
Ecca Group	sandstone, shale*	25.3±5.1
BUSHVELD COMPLEX		
Bushveld granite	granite	16.3±2.4
Upper Zone	gabbro, norite	16.5±1.1
Main–Critical Zone	norite, anorthosite	20.7±1.3
Lower Zone	dunite	16.0
TRANSVAAL SUPERGROUP		
Chuniespoort Group	dolomite*	8.8±1.6
VENTERSDORP SUPERGROUP	lava*	14.5±1.6
WITWATRSRAND SUPERGROUP		
Central Rand Group	quartzite*	9.3±1.0
DOMINION GROUP	lava#	9.8±0.8

dT/dx, mean thermal gradient; s.d., standard deviation;*Jones (2003a); #Jones (1988) lower conductivity (3.4 W/mK, Table V). As discussed below, the high thermal gradients in rocks of the Bushveld Complex are associated with the low conductivities of the most predominant rock types. The highest thermal gradients occur in the young, low-conductivity rocks of the Karoo cover (Table IV).

The thermal gradients in Bushveld rocks and particularly those of the Main Zone, which overlie the main platinum mining horizons, are double those for rocks overlying the Witwatersrand goldfields. This means that the VRT must be higher. The difference in thermal regime is clearly illustrated in Figure 6, which compares actual VRT data from the Carletonville area (where the deepest gold mines in the Witwatersrand Basin occur) (Jones, 2003a) with VRT data from the Northam area (which hosts the deepest platinum mines in the Bushveld Complex) (Jones, 2017). The latter data-set comprises bottom-hole temperature measurements from deep exploration boreholes northeast of Northam, which were deemed to be too disturbed by underground water flow to yield reliable thermal gradients, as well as bottom-hole temperatures measured in boreholes listed under Northam and Amandelbult in Table II. The maximum VRT in the Northam area is 70°C at a depth of 2.2 km. This is 30°C hotter than gold mines at equivalent depths in the Carletonville area. As indicated in the previous two subsections, this difference cannot be attributed to an enhanced heat flux in the platinum mining areas, which is lower than that in the gold mining areas. The difference is due to both a higher surface temperature and steeper gradient at Northam compared with Carletonville. The extrapolated surface temperature at Northam is 21.6°C compared with

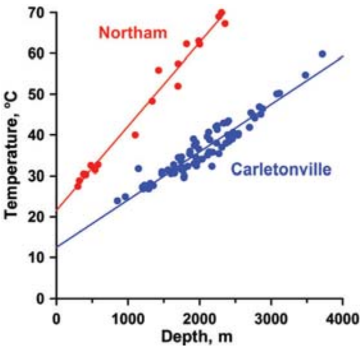

Figure 6—Bottom-hole temperature data from boreholes north and northeast of Northam in the Bushveld Complex, and virgin rock temperature data from the Carletonville area (after Jones, 2003a) in the Witwatersrand Basin. The least-squares regression line for the Northam data is *T*=21.6+20.5*x*, and for the Carletonville area *T*=12.5+11.7*x*

Table V

Thermal conductivity of major rock types occurring above the platinum mining areas of the Bushveld Complex and gold mining areas of the Witwatersrand Basin (Jones, 1988, 2003b, 2015, unpublished data)

Rock unit/sub-unit	Rock type	*K*±s.d. (W/mK)	Range (W/mK)	N_K
KAROO SUPERGROUP				
Ecca Group	sandstone	3.43±0.68	1.80–4.78	69
	shale	2.02±0.46	0.81–2.96	118
	coal	0.42±0.10	0.24–0.71	49
BUSHVELD COMPLEX				
Bushveld granite	granite	3.43±0.41	2.68–4.00	103
Upper Zone	diorite	2.17±0.07	2.04–2.27	8
	anorthosite	2.09±0.08	2.00–2.22	7
	gabbro, ferrogabbro	2.39±0.22	1.94–3.07	122
	pyroxenite	3.38±0.33	2.40–4.39	29
Main-Critical Zone	anorthosite	1.92±0.12	1.72–2.25	144
	norite	2.28±0.15	1.86–2.94	360
	pyroxenite	3.45±0.35	2.41–4.21	89
	chromitite	2.45±0.18	2.17–2.90	16
Lower Zone	pyroxenite, dunite, harzburgite	4.13±0.21	2.56–4.98	39
TRANSVAAL SUPERGROUP				
Pretoria Group	lava	3.53±0.37	2.90–4.25	21
	quartzite, chert	6.96±0.54	5.77–7.71	29
	siltstone	4.09±0.69	3.07–5.50	19
	shale	2.57±0.34	1.90–3.14	28
Chuniespoort Group	dolomite	5.09±0.63	3.19–7.53	57
VENTERSDORP SUPERGROUP				
	lava	3.41±0.47	2.59–5.06	153
	quartzite, conglomerate	5.20±0.68	3.71–6.59	34
	shale	3.58±0.32	3.01–3.92	5
WITWATRSRAND SUPERGROUP				
Central Rand Group	quartzite, conglomerate	6.38±0.79	3.72–8.21	336
	shale	4.77±1.20	2.76–6.38	10
DOMINION GROUP				
	lava	3.34±0.45	2.28–5.09	251

K, mean thermal conductivity (except when referring to kelvin in units of measure); s.d., standard deviation; N_K, number of conductivity measurements.

12.5°C at Carletonville. The reason for this is that Northam is at a lower elevation (1020 m amsl) and latitude (24.95°S) compared with Carletonville (1630 m amsl and 26.40°S). The steeper thermal gradient at Northam (20.5 K/km) compared with Carletonville (11.7 K/km) is largely due to the difference in the thermal conductivities of the rocks in these regions.

Prediction of VRT

Although there is no substitute for making VRT measurements, reasonably accurate predictions for new prospective mining areas can be made from the data presented in this paper. The mafic rocks of the Bushveld Complex contain very low concentrations of the heat-producing elements uranium, thorium and potassium (Jones, 2017), so the most simple expression for the temperature as a function of depth is given by the following equation:

$$T(x)=T_0+q_0\int_0^x \frac{1}{K(x)}dx$$

The surface heat flow in the platinum mining areas (q_0) is tightly constrained at 45±4 mW/m^2. The surface temperature (T_0) depends on latitude and altitude, as shown in Figure 7. The local surface temperature lapse rate as a function of elevation is –7.4 K/km, and as a function of latitude –1.9 K per degree. It should be noted that the surface temperatures in these diagrams were obtained by upward extrapolation of temperature-depth data from the deeper linear sections of borehole temperature profiles. These temperatures are higher than mean annual air temperatures because the rainy period in the Bushveld is during the summer, when more heat is transferred into the ground. The thermal conductivities of all important rock types occurring in the Complex are well established, so estimates of thermal conductivity as a function of depth, $K(x)$, can be made provided the stratigraphy is known. Evaluation of the integral then becomes trivial. However, it should be noted that this calculation assumes that the heat flux is linear and vertical. Local horizontal changes in thermal conductivity can lead to a significant component of lateral heat transfer, in which case two-dimensional modelling (Jones, 2003a) would be required. Also, heat may be transferred locally by underground flow of water, which can disturb VRTs appreciably. This is a major issue where mines occur along deep-seated fracture zones in the Earth's crust. Northam is an example. Measured temperature profiles and derived thermal gradients in some boreholes in the Northam area (Figure 8) show clear disturbance by underground water flow, represented by spikes in the temperature profiles and temperature variations that cannot be related to variation of rock type. The temperature profiles in these boreholes are not suitable for establishing geothermal gradients, but their bottom-hole temperatures are useful for establishing the general VRT trend shown in Figure 7.

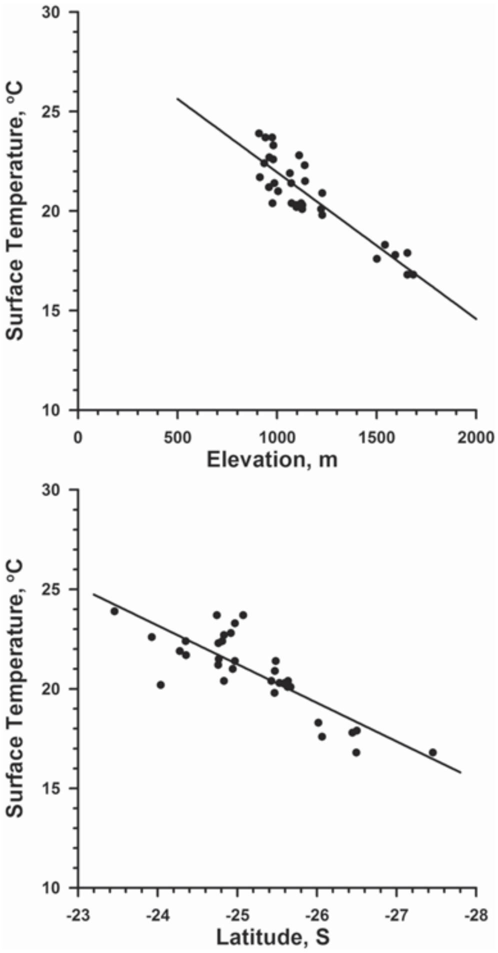

Figure 7—Surface temperature in the Bushveld Complex (extrapolated from the temperature-depth profiles in boreholes, see text) plotted against elevation above mean sea level (a) and latitude (b)

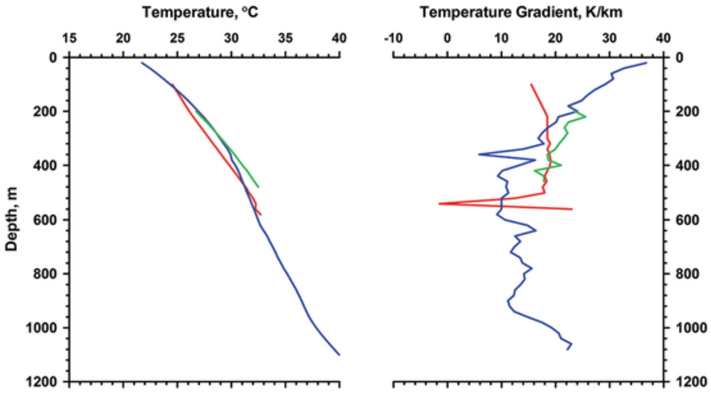

Figure 8—Temperature profiles (left) and geothermal gradients (right) in three boreholes in the Northam area that are disturbed by underground water flow

Conclusions

Geothermal gradients in the platinum mining areas of the Bushveld Complex (17.7–24.5 K/km) are approximately double the gradients in rocks overlying gold reefs of the Witwatersrand Basin (9.6–12.9 K/km). The geothermal heat flux in platinum mining areas of the Bushveld Complex (45 mW/m^2) is lower than that in the Witwatersrand goldfields (51 mW/m^2). The main reason for the high thermal gradients in the Complex is the relatively low thermal conductivity of the constituent rocks compared with the Witwatersrand Basin. The VRT in the Northam area, the deepest area investigated in the Bushveld Complex, is as much as 30°C higher than the VRT at equivalent depths in the Carletonville area, where the deepest gold mining takes place; this is due both to elevated surface temperatures and thermal gradients in the Bushveld. The Bushveld thermal gradient, heat flux and thermal conductivity database make it possible to predict the VRT in new potential mining areas for platinum and other ores that may be extracted from the Bushveld Complex.

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