



European Geosciences Union General Assembly 2016, EGU  
Division Energy, Resources & Environment, ERE

# Geothermal energy from the Main Karoo Basin (South Africa): An outcrop analogue study of Permian sandstone reservoir formations

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## Abstract

The geothermal potential of the Main Karoo Basin has not been addressed in the past. A first assessment of Permian sandstone formations in the Eastern Cape Province, including down-hole temperature data from deep boreholes, and evaluation of groundwater temperature and heat flow values from literature leads to 3130 TWh (11.3 EJ) of power generation potential within the central and southern parts of the basin. The low permeability lithotypes may be operated as enhanced geothermal systems (EGS), depending on the fracture porosity in the deeper subsurface. In some areas auto-convective thermal water circulation might be expected and direct heat use becomes reasonable.

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Peer-review under responsibility of the organizing committee of the General Assembly of the European Geosciences Union (EGU)

*Keywords:* Geothermal potential; renewable energy; thermophysical rock properties; Karoo Basin; South Africa

## 1. Introduction

To date, in South Africa geothermal energy has not been addressed or included into any renewable energy scheme. The continent's geothermal resources are basically concentrated in the Red Sea Valley and the East African Rift System. Kenya is the principal exploiter of geothermal energy in Africa with 45 MWe and some direct heat use. Ethiopia is the only other African country producing electricity from geothermal heat at this time. However, Algeria

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and Tunisia obtain some direct heat from geothermal sources [1]. A deep sedimentary basin such as the Karoo of South Africa may prove successful in supplying additional energy to the planned renewable energy mix of solar, wind and hydroelectric power. This study presents petro- and thermophysical rock properties of potential Permian sandstone reservoir formations. A first estimation of the geothermal resource potential was performed for the central and southern basin by quantifying the heat in place. The initial data may be added as attributes into 3D reservoir models, identifying further target formations for geothermal energy utilization.

## 2. Geological setting

The Main Karoo Basin (Fig. 1) forms part of a series of basins that developed through subduction, compression, collision, and terrane accretion along the southern margin of Gondwana [2], depocentres filled between the Pennsylvanian and Middle Jurassic. Their economic significance in terms of energy resources ranges from coal and coal bed methane to shale gas, uranium and geothermal energy [3]. Heat flow measurements in South Africa exist for the central part of the Kaapvaal Craton, across the Witwatersrand Basin, and the surrounding mobile belts [4]. Heat flow in the mobile belts is generally higher than in the craton with maximum values recorded from the Karoo Basin. A number of hot springs are found in South Africa with varying surface water temperatures ranging from 26–67°C [5]. Groundwater occurrence and movement in the basin are governed by its layer-cake stratigraphy, the historical stress conditions and the abundant dolerite intrusions. The complex geometry of the shallow aquifers is due to distinct bedding-parallel fracturing, microporosity of the rock mass, and the limited storage of small-aperture fractures requiring water storage within the primary porosity [6]. Sandstones typically have very low porosities and permeabilities, contributing to aquifers being highly anisotropic. This was exacerbated by the extrusion of the Drakensberg lavas, resulting in slight metamorphism as overburden pressures and temperatures increased. Following extrusion of the Drakensberg lavas, the groundwater possibly became mineralised, resulting in further reduction of porosity and permeability [6]. Horizontal fracturing is partly ascribed to the intrusion of dolerites which likely increased this fracturing [7-9]. Information is not readily available regarding the deep Karoo aquifer systems [10].

The studied Ripon Formation is generally 600–700 m thick but increases in thickness to over 1000 m in the southeastern part of the basin and rapidly wedges out northwards [11]. It is composed of poorly-sorted medium- to fine-grained sandstones, alternating with siltstones and shales, and occurring at depths between 1000 and 3500 m in the southern part of the Karoo Basin.

## 3. Material and methods

This study is based on an integrated analysis of petro- and thermophysical data from the Permian Ripon Formation exposed along road cuts of the Ecca Pass north of Grahamstown (Fig. 2a,b). 76 samples were collected, covering all lithologies from very fine to medium-grained sandstone (Fig. 2c-e). Measurements of skeletal density (helium pycnometer AccuPyc 1330) and envelope density (DryFlo pycnometer GeoPyc 1360) allowed the calculation of total porosity. Permeability measurements were conducted using a gas pressure columnar-permeameter [12]. All samples were dried overnight in a conventional oven at 105°C before the measurements. For the determination of the dry bulk thermal conductivity  $\lambda$  and dry bulk thermal diffusivity  $\alpha$ , the Optical Scanning Method was applied [13] using a Thermal Conductivity Scanner. By incorporating the bulk density  $\rho_b$ , the specific heat capacity is calculated by using Eq. (1):

$$c_p = \frac{\lambda}{\alpha \cdot \rho_b} \quad (1)$$

Information on the geothermal gradient in the southern Karoo Basin is based on down-hole temperature data from two deep research boreholes recently drilled in the Eastern and Western Cape provinces [14,15].

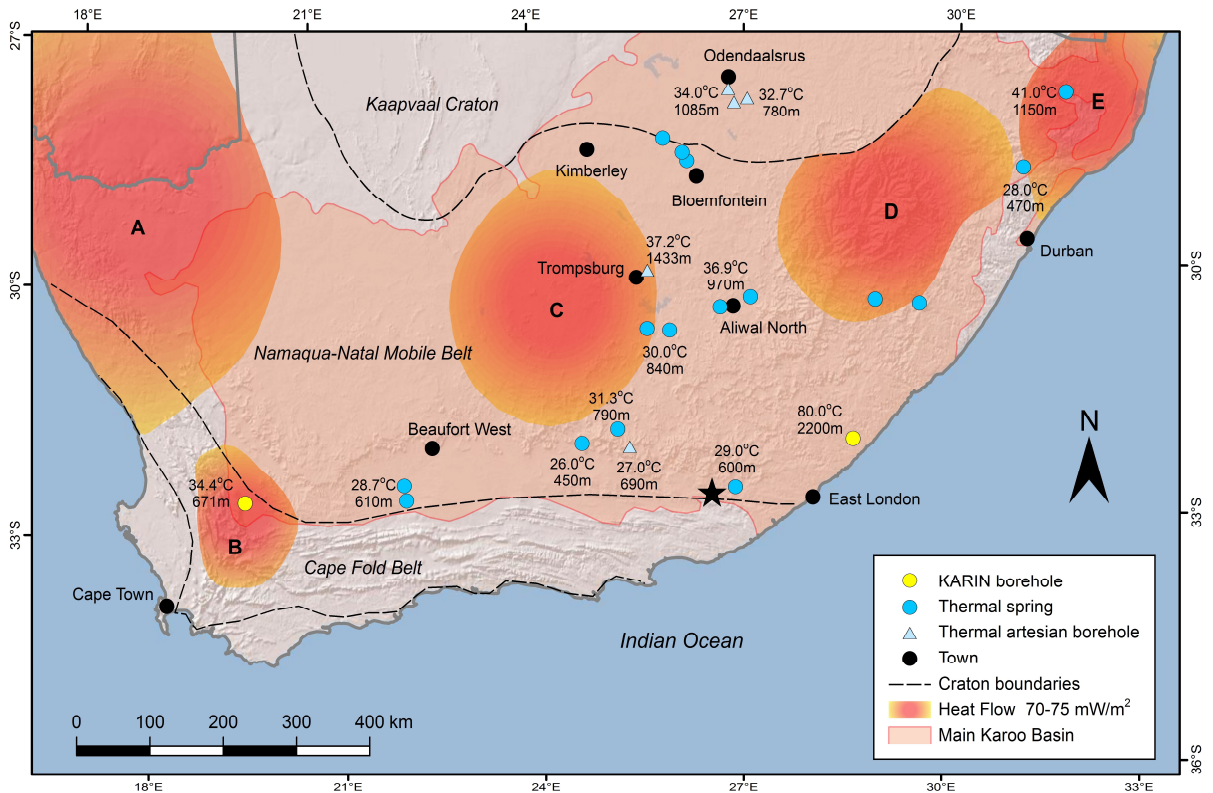


Fig. 1. Geothermal resource base map of the Karoo Basin highlighting areas (A-E) of elevated heat flow ( $70\text{--}75\text{ mW/m}^2$ ), location of thermal springs and thermal artesianian boreholes with measured surface water temperatures ( $^{\circ}\text{C}$ ) and depth of origin (m), and location of KARIN boreholes KZF-1 (northeast of Cape Town, Western Cape, area B) and KWV-1 (northeast of East London, Eastern Cape) with measured down-hole temperatures at 671 m and 2200 m depth, respectively. Data compiled from Jones [6], Steyl et al. [5], De Kock et al. [14, 15], and Bird et al. [16]. Star marks the studied Ecca Pass in the southern Karoo Basin, Eastern Cape Province.

The geothermal resource base map (Fig. 1) was created using the ESRI ArcGIS 10.0 GIS software package with data from Jones [6], Steyl et al. [5], De Kock et al. [14,15], and Bird et al. [16], highlighting areas of elevated heat flow (A-E) and locations of thermal springs, thermal artesianian boreholes, and KARIN boreholes. The relief base map with a resolution of 90 m was added from the ARCGIS online server ([http://goto.arcgisonline.com/maps/World\\_Shaded\\_Relief](http://goto.arcgisonline.com/maps/World_Shaded_Relief)). The outlines of South Africa and the Karoo Basin were digitized from Johnson et al. [11]. The areal extend of the areas of elevated heat flow was calculated using the algorithm within the polygon feature tool of ArcGIS 10.0.

## 4. Results

### 4.1. Lithology and petrography

The Permian Ripon Formation contains three distinct sandstone lithologies: (1) very fine-grained, (2) fine-grained, and (3) medium-grained. Lithic arkoses are the dominant rock type. The very fine-grained sandstones vary in colour from light-brown to grey when fresh and light brown to rusty red when weathered. They are laminated with laminae ranging in thickness from millimetres up to 5 cm and contain abundant plant debris. In thin sections, poorly sorted, rounded to sub-rounded quartz and feldspar grains are identified in a matrix of dark organic matter and clay-sized particles (Fig. 2e). The fine-grained sandstones are predominantly brownish-grey to dark grey when fresh and rusty red when weathered, containing abundant plant debris. In thin sections, poorly sorted and well-

sub-rounded quartz, feldspar, and lithic fragments in a matrix of clay-sized particles and organic matter (Fig. 2e) is observed. Quartz and feldspar grains comprise 45%, lithic fragments 5%, and 50% is occupied by the matrix.

The medium-grained sandstones range in colour from grey to greenish-grey and brown, and are weathering to light grey and dark brown. This lithology is massive with fining-upwards units ranging in thickness from 20 cm to several meters. In thin sections, poor sorting and very well rounded to sub-rounded grains of varying size are observed. The grains consist of internally fractured, monocrystalline, undulatory quartz, twinned and zoned feldspar, chert particles, lithic fragments containing altered feldspar, glauconite, elongated biotite (locally replaced by limonite), and organic particles in a yellow-brown matrix. Iron oxides (hematite) are present in organic-rich sections. A common variation of the medium-grained, grey sandstone is the spotted sandstone (Fig. 2d), intermittently inter-bedded with the grey sandstone in certain localities (Fig. 2c). In thin sections, moderately to well-sorted quartz and feldspar grains that are grain-supported with line contacts, are recognized. Grains are angular to sub-rounded and internal fracturing of quartz grains is not as pervasive as observed in samples of non-spotted sandstone but microfissures between grains are prevalent (Fig. 2f).

#### 4.2. Petro- and thermophysical rock properties

Petro- and thermophysical properties of the Ripon Formation sandstones are provided in Table 1. The very fine-grained sandstones range in porosity from 0.02–1.44% with a mean of 0.73%. Their permeabilities range from  $8.09 \cdot 10^{-17}$ – $9.22 \cdot 10^{-17}$  m<sup>2</sup> (mean  $8.65 \cdot 10^{-17}$  m<sup>2</sup>), mean density is 2680 kg/m<sup>3</sup>. The fine-grained sandstones range in porosity from 0.94–1.08% with a mean of 1.01%. The permeabilities range from  $1.12 \cdot 10^{-17}$ – $1.37 \cdot 10^{-17}$  m<sup>2</sup> (mean value of  $1.25 \cdot 10^{-17}$  m<sup>2</sup>), mean density is 2660 kg/m<sup>3</sup>. The medium-grained sandstones range in porosity from 0.00–3.7% with a mean of 0.5%. Their permeability ranges from  $7.21 \cdot 10^{-18}$ – $9.94 \cdot 10^{-17}$  m<sup>2</sup> with a mean of  $4.59 \cdot 10^{-17}$  m<sup>2</sup>, mean density is 2670 kg/m<sup>3</sup>.

Table 1. Petro- and thermophysical properties of the Ripon Formation sandstones, and calculated values of specific heat capacity.

Lithology	Number of Measurements	Density [kg/m <sup>3</sup> ]	Porosity [%]	Permeability [m <sup>2</sup> ]	Thermal conductivity [W/(m·K)]	Thermal diffusivity [m <sup>2</sup> /s]	Specific heat capacity [kJ/(kg·K)]
Very fine-grained sandstone	20	2680-2690 (mean 2680)	0.02-1.44 (mean 0.73)	$8.09 \cdot 10^{-17}$ – $9.22 \cdot 10^{-17}$ (mean $8.66 \cdot 10^{-17}$ )	2.78-3.20 (mean 2.98)	1.15-1.64 (mean 1.39)	0.73-0.91 (mean 0.81)
Fine-grained sandstone	25	2650-2670 (mean 2660)	0.94-1.08 (mean 1.01)	$1.12 \cdot 10^{-17}$ – $1.37 \cdot 10^{-17}$ (mean $1.25 \cdot 10^{-17}$ )	2.45-2.95 (mean 2.69)	0.95-1.37 (mean 1.12)	0.82-0.98 (mean 0.91)
Medium-grained sandstone	31	2630-2730 (mean 2670)	0-3.70 (mean 1.10)	$7.21 \cdot 10^{-18}$ – $9.94 \cdot 10^{-17}$ (mean $4.59 \cdot 10^{-17}$ )	2.38-3.09 (mean 2.79)	0.90-1.40 (mean 1.17)	0.84-1.03 (mean 0.91)

The thermal conductivity of the very fine-grained sandstones ranges from 2.78–3.20 W/(m·K) with a mean of 2.98 W/(m·K). The fine-grained sandstones exhibit thermal conductivities ranging from 2.45–2.95 W/(m·K) with a mean of 2.69 W/(m·K), and the thermal conductivity of the medium-grained sandstones ranges from 2.38–3.09 W/(m·K) with a mean of 2.79 W/(m·K). The thermal diffusivity of the very fine-grained sandstones ranges from 1.15–1.64 (m<sup>2</sup>/s) with a mean of 1.39 (m<sup>2</sup>/s). The fine-grained sandstones exhibit values ranging from 0.95–1.37 (m<sup>2</sup>/s) with a mean of 1.12 (m<sup>2</sup>/s), and the thermal diffusivity of the medium-grained sandstones ranges from 0.90–1.40 (m<sup>2</sup>/s) with a mean of 1.17 (m<sup>2</sup>/s). Specific heat capacity is calculated by using Eq. (1) and shows a mean value of 0.876 kJ/(kg·K) for the clastic rocks of the Ripon Formation.

### 4.3. Geothermal gradient

Down-hole temperature data from deep boreholes (KZF-1, KWV-1) recently drilled in the southern Karoo Basin (Eastern and Western Cape provinces; Fig. 1) provided information on the geothermal gradient. In both areas a moderately elevated geothermal gradient is observed. Temperatures of 80°C at 2200 m depth recorded from borehole KWV-1 indicate a geothermal gradient of 28.2°C/km in the Willowvale area northeast of East London (Eastern Cape). Temperatures of 34.4°C at 671 m recorded from borehole KZF-1 indicate a geothermal gradient of 24.5°C/km in the Ceres area (Western Cape). Reservoir temperatures (reservoir depth 3500 m) of 104°C to 117°C are thus expected in the southern Karoo Basin.

### 4.4. Volumetric calculation of potential exploration areas

Available literature data [6] describing areas of elevated heat flow within the Karoo Basin (Fig. 1) were integrated into a geographical information system for areal and volumetric calculation of potential exploration areas (A-E). Most of the areas (A, C, D) with elevated heat flow within the Namaqua-Natal Mobile Belt are related to the occurrence of young (94 Ma and younger) kimberlites [17], area B represents the syntaxis of the Cape Fold Belt [18], and area E builds the southernmost extension of the East African rift system [19]. The area that was found most suitable for further investigation with respect to geothermal energy exploration is the area west of Trompsburg, Free State (C). In this area, a thickness of 650 m can be expected for the Ripon Formation. Together with the areal extent (74,853.79 km<sup>2</sup>) of this area of elevated heat flow a volume of 48,654.96 km<sup>3</sup> can be calculated for this potential geothermal exploration area.

### 4.5. Heat in place

The approach by Muffler and Cataldi [20] allows a direct calculation of the heat in place for each stratigraphic unit that is hotter than 60°C by using Eq. (2) and may enable a detailed regional quantification.

$$E_{th} = c_r \cdot \rho_r \cdot V \cdot (T_r - T_s) \quad (2)$$

where  $E_{th}$  is heat in place [J],  $c_r$  the specific heat capacity of the reservoir rock [kJ/(kg·K)],  $\rho_r$  the density of the reservoir rock [kg/m<sup>3</sup>],  $V$  the reservoir volume [m<sup>3</sup>],  $T_r$  the reservoir temperature [°C] and  $T_s$  the average ground surface temperature [°C], respectively. Reservoir porosity and heat stored in reservoir fluids can be neglected due to errors of less than 5% for regional scale studies [20] if porosity is lower than 20%. With the available data of a mean specific heat capacity  $c_r$  of 0.876 kJ/(kg·K) for the clastic rocks (Table 1), a mean density  $\rho_r$  of 2670 kg/m<sup>3</sup> (Table 1), a reservoir volume of 48,654,963,387,483.10 m<sup>3</sup>, and a temperature difference for the minimum and maximum geothermal gradient ( $T_r - T_s$ ; 104–18°C and 117–18°C, respectively), a preliminary estimation of the geothermal resource potential suggests a minimum of 2719 TWh (9.8 EJ) and a maximum of 3130 TWh (11.3 EJ) of heat in place.

## 5. Discussion

Permian clastic successions are widespread in the southern and southwestern parts of the Karoo Basin [11] and petro- and thermophysical rock properties of the Ripon sandstones show a potential of this formation for utilization of deep geothermal energy. Applying the thermofacies concept [21], the low permeability sandstones represent petrothermal systems that can be exploited and used for electricity production by means of hydraulic stimulation as an enhanced geothermal system (EGS). On the other hand, depending on (1) the degree of fracturing and the occurrence of dykes and sills within the deeper part of the basin and (2) the degree of water saturation of the rocks [c.f. 22], the sandstones could represent transitional or hydrothermal systems, respectively. The influence of dykes and sills to permeability enhancement was studied by Senger et al. [23] and demonstrates the potential for fluid flow channelling along the intrusion-host rock interfaces. Furthermore, the deep aquifers in the Trompsburg area where hot springs exist would be suitable for electricity production in a binary geothermal power plant. Following the

volumetric approach of Muffler and Cataldi [20] leads to a first assessment of the geothermal resource potential by quantifying the heat in place. This simplistic approach is especially suitable for scenarios with few data points [e.g., 24] and provides the first information for potential resource areas that are so far not well studied. At a later stage and with more extensive data sets, more rigorous calculations such as a Riemann-sum approach or the volumetric-probabilistic methods currently utilized by the U.S. Geological Survey [25] can be applied. In a next step, the recoverable thermal energy, considering recovery factors suitable for low porosity rocks, and additionally the recoverable electrical energy can be reported for an identified resource as outlined in Limberger et al. [26]. Techno-economic feasibility has recently been performed for a geothermal resource assessment of Permian Rotliegend formations in the Netherlands suitable for direct heat production, distinguishing between heat in place (HIP), potential recoverable heat (PRH) and technical potential (PRH/30 yr), and recoverable heat (RH). Following Van Wees et al. [27] the recoverable heat (RH) is about 33% of the HIP and the technical lifetime of a doublet system is 30 years. Consequently, the maximum yearly RH, unconstrained by economics, is PRH/30. Prospective geothermal resources located in the central and southern parts of the Karoo Basin reveal maximum 3130 TWh (11.3 EJ) HIP, which might lead to about 1043 TWh (3.7 EJ) RH. However, to obtain a basin-wide overview of the resource potential in terms of recoverable geothermal energy, a progressive filtering approach from total heat content of different reservoirs (HIP) via the heat that can potentially be recovered (PRH) to geothermal potential maps taking into account a techno-economic performance evaluation (RH) has to be conducted. Potential reservoirs may also include sandstone formations overlying the Ripon Formation, representing the deepest clastic rocks of the Karoo sequence. Hence, the resource potential of the entire basin is seen much higher as indicated by the estimation presented here. Recently drilled deep research boreholes provided information on the moderately elevated geothermal gradients in the southern Karoo Basin. For future studies, the southern part of the Karoo Basin where the Ripon Formation can be found at depths of >3000 m is thus seen as key area with regard to future geothermal research. Here, with geothermal gradients ranging from 24.5°C/km to 28.2°C/km at 3500 m depth, reservoir temperatures of 104°C to 117°C can be assumed. A first assessment of the geothermal potential of the Karoo Basin is based on a limited data set and has to be seen as a first attempt to evaluate possible target formations and areas within a basin of 700,000 km<sup>2</sup> with a basin fill of more than 5000 m of siliciclastic rocks. However, a comprehensive compilation of existing geological data and the generation of an initial data set of thermophysical rock properties identified the Permian Ripon sandstones as an EGS candidate. The knowledge of thermal conductivities is seen as a vital parameter for upscaling [28] in a later stage of geothermal exploration and reservoir modelling. Further studies on the geothermal potential of the Karoo Basin within the research programme KARIN (Karoo Research Initiative), including drill core and seismic data analyses, and reservoir modelling of potential target formations, will provide more detailed information on the actual extent and quality of the resource. Based on a first 3D structural model of the areas identified here and information on the hydraulic and hydrochemical properties of the reservoir fluids from deep boreholes, we aim to provide a more precise estimation of the geothermal potential from ongoing research.

## 6. Conclusions

A first assessment of the geothermal potential of the Main Karoo Basin based on petro- and thermophysical data from outcrop analogues of clastic series in the Eastern Cape Province, including down-hole temperature data from deep research boreholes, and evaluation of groundwater temperature and heat flow values from literature identifies the Permian Ripon Formation as an EGS candidate. A first estimation of 3130 TWh (11.3 EJ) of theoretical capacity of power generation within the central and southern parts of the basin shows the potential for future geothermal energy utilization. The low matrix permeability of the studied lithotypes may be enhanced by (1) joint and fracture systems, and (2) dykes and sills with a potential for fluid flow-channelling along the intrusion-host rock interfaces.

The present study demonstrates the need for investigation of the Karoo's deep aquifer systems to gain a reliable data set for reservoir modelling and to better understand the reservoir system for future geothermal utilization. This is seen as a key research topic to be addressed in the context of South Africa's future sustainable energy supply.





Fig. 2. Ripon Formation sandstones exposed along the Ecce Pass (Eastern Cape Province, South Africa, 33° 12' 58.63" S, 26° 37' 38.05" E). **a**: Outcrops along the road R67 north of Grahamstown. **b**: Thinly to thickly bedded sandstone sequences with two dominant joint orientations (242/53 and 143/73). **c**: 20 cm thick spotted sandstone layer within fine- to medium-grained sandstone. **d**: Jointed, medium-grained spotted sandstone. **e**: Fine-grained sandstone (1) with organic-rich layer (2) overlain by very fine-grained sandstone (3). **f**: Equigranular, well-sorted, angular to sub-rounded quartz and feldspar grains with prevalent inter-granular microfissures in spotted sandstone (arrows mark microfissures).

## Acknowledgements

This work is a pilot study on the geothermal potential of the Karoo Basin funded by the DST-NRF Centre of Excellence for Integrated Mineral and Energy Resource Analysis CIMERA and the Karoo Research Initiative KARIN.

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