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Exploration into the potential for a low-enthalpy geothermal power plant in Cape fold belt

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ABSTRACT

South Africa has long been dependent on coal and other fossil fuels for cheap electricity generation. While there has been an increase in utilising renewable energy over the last two decades, the main focus has been on solar and wind, which are intermittent, with geothermal energy not even considered. With advances in technology that harness geothermal energy, geothermal resources as low as 85 °C have been reported attainable when using low-enthalpy technologies as such binary systems. This makes geothermal energy a reality for regions in South Africa where moderately high geothermal gradients exist.

The initial high level assessment of the geothermal potential of the Cape Fold Belt region was done through accessing eight hot springs found to have the highest temperature from previous studies. Temperature measurements were taken as close to the source as possible as well as collection of water samples for ICP-AES analysis for major cations. The cation concentrations from the ICP-AES analysis (completed with the Thermo ICap 6200 ICP-AES) allowed for geothermometry calculations to be conducted which gave the minimum temperature estimates of the reservoirs of each hot spring. Both the surface temperature measurements and the estimates of the reservoir temperature resulted in two locations that were in the top three for both measurements. These two locations were Calitzdorp and Caledon, having water temperatures of 47 °C and 45 °C at surface and estimates of the reservoir temperatures of 117 °C ± 13 °C and 108 °C ± 21 °C respectively.

The hydro-geological analysis of the Oudtshoorn region, where the Calitzdorp hot spring is located, was conducted using published geophysical data in the form of magneto-telluric (MT) survey that was carried out in 2005 by the Agulhas-Karoo Geoscience Transect project. The MT data was presented in a paper by Weckmann et al. (2012) as a cross sectional profile from Mossel Bay to Prince Albert to a depth of 30 km, where a large region of low resistivity was found below the Oudtshoorn basin. The Calitzdorp hot spring is positioned at the surface above this region. The geological cross sections and regional interpretation presented in this study infers that a major syncline of the Cape Supergroup exists below the basin, potentially as deep as 10 km, and covers the low resistivity area shown in the MT profile. This led to the inference that the large region of low resistivity is most probably due to a large water reservoir. This potential reservoir is about 40 km in length with a depth of 2.5 km–7 km at its thickest, tapering out towards the edges.

The depth to the top of the potential reservoir and the estimated reservoir temperature from the geothermometry results in a geothermal gradient of 39 °C/km ± 4.3 °C/km. Thus Calitzdorp was identified as a promising location for further exploration, ideally deep boreholes or more geophysical surveys, to validate the existence of a reservoir and take down-hole temperature measurements. The depth and size of this potential reservoir would make it a favourable candidate for a pilot low-enthalpy geothermal power plant within the Cape Fold Belt and South Africa.

1. Introduction

South Africa has largely relied on generating electricity from coal due to the large coal reserves found within the country which allow for a very cheap form of electricity generation. The agreement in the international community to lower greenhouse gas emissions (Kyoto 2010) by reducing the use of fossil fuels has forced governments to start implementing electricity generation using alternative energy resources. Within South Africa, renewable power plants have been developed effectively through partnerships with private investment. The majority of

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electricity generated from renewable resources in South Africa has been around hydroelectric and nuclear although nuclear is seen as an alternative energy (to fossil fuels) rather than renewable. While there has been a steady increase in the percentage contribution from solar and wind, helped by the fact that the technology has improved drastically in efficiency, South Africa has left geothermal energy out of the equation altogether. While generation of electricity from hydroelectric resources is the most efficient of the renewable resources and has negligible greenhouse gas emissions, the water scarcity of the country limits the potential of this energy source. Solar and wind are making increasingly significant contributions however they are limited by the intermittent nature of this resource and efficiency of the technology. Also the increased contribution from solar and wind energy has not been reflected in a percentage increase of the overall power generation mix largely due to the increased demand keeping in mind electricity is still not supplied to the whole population.

Although geothermal resources within South Africa is largely believed to be too low for harnessing electricity, with the development of binary systems the potential for harnessing electricity from low geothermal resources has become a possibility and could result in a significant contribution to South Africa's electricity capacity. Geothermal energy has very little environmental impact with the ability to supply constant energy required for base load electricity generation. Although prospects for geothermal energy within South Africa would rely on low-enthalpy resources, the current technology has made this resource feasible and, with sustainable utilisation, can contribute a significant amount of electricity to the growing need within South Africa for decades to come, especially to the capacity of renewable energy needed to replace fossil fuels.

Over the last decade there has been an increasing interest and argument for geothermal energy in the country, evident by the recent investigations and papers published [Tshibalo et al., 2010; Dhansay et al., 2014; Campbell et al., 2016a,ba and Campbell et al., 2016a,bb; Johnson and Fourie, 2016; Fourie and Johnson, 2017; Dhansay et al., 2017]. Dhansay et al. (2017) highlighted multiple regions around the country which have elevated heat flow measurements based on historical down-borehole temperature measurements and mining activities. One such region falls over the Cape Fold Belt which was the area explored in this study. Dhansay et al. (2014) discussed the geothermal potential of a location in Limpopo province, showing the cost of electricity generated by geothermal energy was higher than coal generated electricity. However this was before the government implemented a structure of subsidising renewable energy costs, through the Independent Power Producer Procurement Programme (IPPPP) and Renewable Energy Feed-In Tariff (REFIT), which has brought down the cost of electricity generated by solar and wind energy by 71 % and 46 % respectively. With these subsidies and understanding that geothermal energy is an unending energy resource, with correct management, a lower cost would be calculated for the cost of electricity and possibly one comparable to coal generated electricity.

2. Methodology

Sampling was conducted at the eight hot springs around the Cape Fold Belt shown to be the hottest from previous studies (Kent, 1949; Diamond and Harris, 2000; Tshibalo et al., 2010; Boekstein, 2012; and Olivier and Jonker, 2013). The water temperature, electronic conductivity (EC), total dissolved solids (TDS) and pH measurements were taken during this process of collecting water samples for later laboratory analysis. A Hanna multimeter (model no. HI98131) was used to record the EC, TDS and pH levels of the water. An electronic thermometer was used to measure the temperature which had a range of below zero to over one hundred degrees Celsius. The multimeter was calibrated prior to each sampling point and both instruments were rinsed and appropriately stored after each sample was measured. Filtering and acidified storage of each sample was not deemed necessary by the laboratory based on the cations analysed for and process used. ICP-AES analysis was conducted using simultaneous analysis in a Thermo ICap 6200 ICP-AES machine. The analysis on the water samples to obtain the concentration of selected major cations in the spring water. The selected cations analysed for were sodium, potassium, magnesium, calcium and silicon. Stochiometric conversions were required to calculate the concentration of silica (SiO_2) from the concentration of silicon.

Geothermometry is a well established geothermal exploration tool that was used in this study and was developed to estimate the temperature of the underground water reservoir which supplies the hot spring [Fournier and Truesdell, 1973; Fournier et al. 1974; Fournier, 1977; Ellis, 1979; Fournier and Potter, 1979; Nieva and Nieva, 1987; Giggenbach, 1988; Kharaka and Mariner, 1989; Verma, 2000; Arnórsson, 2000]. There are various types of geothermometers and each was developed to use the concentration of certain cations from the water flowing from the hot spring. While most were developed using common rock forming minerals (like silica, sodium, magnesium, potassium and calcium) some used uncommon minerals applicable to certain geological formations. Thus based off the largely sedimentary geology of the Cape Fold Belt, five main cations were used in various combinations. Twenty equations from thirteen different papers were used in this study [Fournier and Truesdell, 1973; Fournier, 1977, 1979; Fournier and Potter, 1979, 1982; Arnórsson, 1983; Nieva and Nieva, 1987; Giggenbach, 1988; Kharaka and Mariner, 1989; Verma and Santoyo, 1997; Verma, 2000; Arnórsson, 2000]. Such equations were derived from the theory behind thermodynamics of mineral(s)-water equilibria and used the concentration of dissolved silica, sodium, potassium, magnesium and calcium. All the geothermometry equations, with the relevant authors cited, can be found in the supplementary file.

The temperature measurements as well as the estimated temperature of the reservoirs were used to identify regions with high potential for the required geothermal gradient which would warrant further exploration. The plan to conduct geophysical surveys or deep borehole drilling to assess the hydro-geological setup present was not executed due to the constraint of limited funding and unavailable equipment. Thus new geophysical testing was not possible as part of this study, however published data was found for a high potential region which was close to the Calitzdorp Spa. This data allowed for the in-depth/subsurface analysis of a location with high potential based on the evidence collected at hot springs. This location was then evaluated as a potential location for a geothermal power plant operated as a low enthalpy system.

3. Results and discussion

3.1. In-field temperature measurements

The water temperature measurements were used as a preliminary indicator of the geothermal energy. Other physiochemical parameters such as pH, electric conductivity and total dissolved solids were measured and can be seen in the supplementary file. The water temperatures measured in this study were slightly lower than measurements found in literature at most locations. A variation in temperature between hot springs as well as at each hot spring over different seasons and years can be anticipated with various factors that can contribute to this. Diamond and Harris (2000) attributed the variation between hot springs to the different flow rates measured at each hot spring, proposing that the lower flow rate allowed for more heat loss during the path of ascent from the underground reservoir. From the in-field temperature measurements, the highest temperature was from Brandvlei with the next three, within 3 degrees of each other, being Calitzdorp, Caledon and Goudini. With consideration of the past temperature measurements, Brandvlei was the highest by around 10 °C from the next highest in all studies (Table 1).

With the aim of further exploring a prospective location for a geothermal resource, based on the temperature analysis discussed above,

Table 1
Temperature measurements from literature in form of mean and standard deviation compared to measurements in current study. Literature consulted for temperature measurements was Kent (1949); Diamond and Harris (2000), Tsibalo et al. (2010), Boekstein (2012) and Olivier and Jonker (2013).

Location	Latitude	Longitude	Altitude (meters a.s.l.)	Temperature (°C)	
				Current Investigation	Measurements from Literature
Brandvlei	33°43′55.57″S	19°24′47.04″E	219	58	62.4 ± 3.1
Calitzdorp	33°39′37.64″S	21°46′25.20″E	192	47	47.5 ± 4.7
Caledon	34°13′29.19″S	19°26′24.66″E	311	45	49.8 ± 1.8
Goudini	33°40′1.38″S	19°15′55.89″E	264	45	41.0 ± 1.9
Citrusdal	32°44′26.37″S	19° 2′4.43″E	313	41	44.7 ± 3.9
Warmwaterberg	33°45′58.15″S	20°53′53.71″E	505	41	43.4 ± 1.9
Avalon Springs, Montagu	33°45′58.74″S	20° 7′0.98″E	262	38	43.0 ± 1.6
Baden Resort, Montagu	33°42′17.00″S	20° 7′19.85″E	343	36	38.5 ± 0.7

Brandvlei hot spring was the most prominent option for further exploration and a possible pilot geothermal plant, with Calitzdorp and Caledon strong alternative options.

3.2. Estimated temperatures from Geothermometers

The concentrations of the selected major cations were used in the relevant geothermometer equations to calculate the estimated temperature of the underground reservoirs. The laboratory reported concentrations can be seen in the supplementary file as well as the equations for all twenty geothermometers as well as the estimated temperatures. The estimated temperatures calculated from all of the different geothermometers fell over a large range, not allowing for any one temperature bracket to be confidently used at any of the locations. A process of elimination was conducted to arrive at selection of geothermometers using various reasoning which resulted in a narrower bracket of estimated temperatures.

Initially the geothermometers were assessed based on rationally determined upper and lower limits for the calculated temperature estimates within the context of this study. The limits chosen could impact on the validity of the eventual temperature estimates used, however these limits were not a set on arbitrary numbers but rather logically determined from two relevant values within the context of this study; the first lower bound was that the estimated temperature of the reservoir could not be lower than the measured temperature of the water at surface, and the second upper bound was based on the generally accepted understanding that this region of study has low geothermal gradient (between 20 °C/km and 45 °C/km) and thus the temperatures at depth would not be above 250 °C. The latter also assumed that the reservoirs of each hot spring were not deeper than 5 km, lending to the purpose of harnessing geothermal energy which at any further depth would not be economically viable for further development. Thus the eight geothermometers considered further were the chalcedony based Silica geothermometer by Fournier (1977) and the quartz based Silica geothermometer by Fournier (1977); Fournier and Potter (1982), Arnòrsson (2000) and Verma (2000) as well as the Na-K-Ca geothermometers by Fournier and Truesdell (1973) and Kharaka and Mariner (1989), and the Na-K-Mg geothermometers by Nieva and Nieva (1987). The effect of processing the irrelevant geothermometers out is shown in the Fig. 1 below.

These eight geothermometers were further evaluated and compared in order to find a concise range that allowed for an estimated temperature to be used for each location. The quartz based silica geothermometers by Fournier (1977) was deemed the most reliable given the geology of the area being mainly quartz-heavy sedimentary rocks, the reliability shown in literature studies and the wide usage by other researcher into potential geothermal areas. The three ionic exchange geothermometers left were then compared to the five silica geothermometers to find an overlapping range. The evaluation of the eight estimated temperatures left within reasonable range eventually reached a selection of specific silica based geothermometers and specific Na-K-Ca geothermometers within a similar range of estimated temperatures; namely the quartz based silica geothermometers by Fournier (1977) and Verma (2000) as well as the Na-K-Ca geothermometer by Kharaka and Mariner (1989) and Fournier and Truesdell (1973). A band of estimated temperatures allowed for agreement between the different types of geothermometers and this agreement implied that the overlap gave a reliable estimate of the approximate reservoir temperatures at each location.

The temperature estimates of the four selected geothermometers are shown below in Fig. 2 with the measured in-field temperatures of each sampling location. The statistical mean, with margins of uncertainty, were calculated from the four temperature estimates to find the minimum temperature estimate of the hot spring reservoir. There were three locations where the estimated reservoir temperature was above 100 °C, which were Calitzdorp, Warmwaterberg and Caledon. These locations were estimated at 117 °C ± 13 °C, 112 °C ± 12 °C and 108 °C ± 21 °C respectively. With the threshold temperature for binary systems being 85 °C, these reservoirs could be considered for further exploration as geothermal sites.

3.3. Interpretation of MT data with the geology

The geophysical data used was in the form of magneto-telluric survey presented and discussed by Weckmann et al. (2012). This data was used for a more in-depth analysis of the geothermal potential and the hydro-geological setup of the region of Oudtshoorn which is where the Calitzdorp hot spring was found. Due to the Calitzdorp hot spring being around 27 km west of the line along which the MT survey was conducted, the geological structure was analysed to establish relevance between the two sites. The geological cross sections presented here were created and interpreted in this study and were not cited from other research. The geological history of the region was such that the formation of the Cape Supergroup, and the subsequent deformation, created an east-west continuity noted by the strike of the contacts, the direction of the fold axes and major faults being predominantly east-west. The Calitzdorp hot spring is located on the south-western edge of the Oudtshoorn basin and at the point along a minor fault which is the lowest point in altitude it surfaces at. With the MT survey going directly through the basin, the geology around and underlying the basin was the main focus. Two geological cross sections were drawn along the MT survey line and a parallel line through the Calitzdorp hot spring. The main geological structure that shows continuity between these two cross sections and establishes relevance of the MT survey is the major syncline below the Oudtshoorn basin. The interpretation of the inversion profile of the magneto-telluric data was done by both direct connections to the surface geology as well as assessment with regards to the geological cross section 1. Subsequent inferences were then made about the Calitzdorp hot spring by extrapolation to cross section 2 based on the continuity and relevance established between the two geological profiles.

Weckmann et al. (2012) made inferences from just the surface

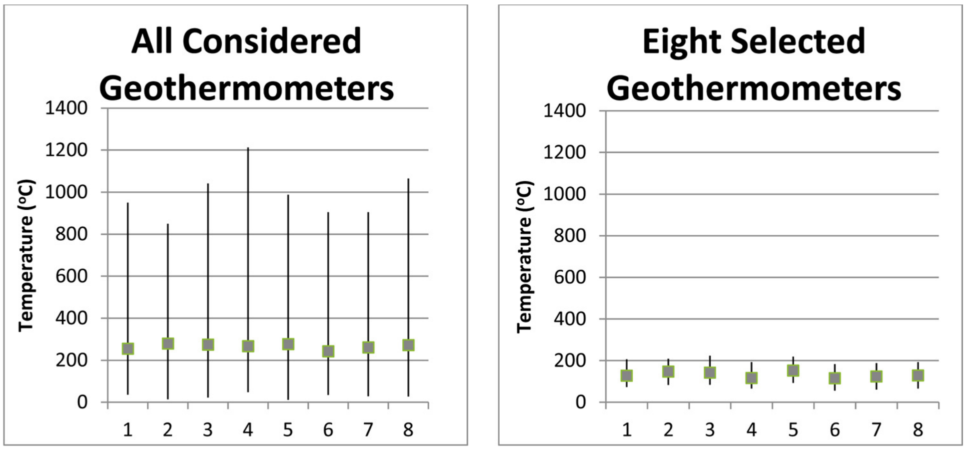

Fig. 1. Scatter plots showing the difference in the ranges of estimated temperature between all and selected geothermometers at each sampling location. Locations are as follows; 1 Brandvlei, 2 Calitzdorp, 3 Caledon, 4 Goudini, 5 Warmwaterberg, 6 Citrusdal, 7 Baden Resort, 8 Avalon Springs. Each line starts at the minimum temperature estimate and ends at the maximum temperature estimate with the average marked as a point along the line. The estimated temperatures used for each graph can be found in page 2 of the supplementary file.

geology and regional structure features while this study also incorporated the most probable underlying geological structure through the cross sections drawn. The interpretation from Weckmann et al. (2012) was discussed here to highlight some important points that agreed with what was found from the cross sections. Based off the figure generated by Weckmann et al. (2012), the bodies of notably high and notably low resistivity were linked to the surface geology by displaying the MT profile in line with a geological map, with MT survey shown as a red line on the geology map, as seen in Fig. 3 (the geological map in Fig. 4(a) taken from the 1:250 000 geological map 3322, Oudtshoorn. Geoscience Council, Pretoria, RSA). The geological map had basic regional structural details shown, such as major folds and faults, which was taken into account when interpreting the boundaries and shapes of bodies of resistivity in terms of geological boundaries and structures. Arrows were drawn from geological contacts or significant features down to the top of the MT profile to show the coverage of the surface geology on the profile. This helped with linking certain bodies of resistivity or conductivity to certain geological formations, for example the Kango Group can be confidently linked to the highly resistive body that extended southwards below the surface as it tapers out. This linkage between the resistive wedge and the Kango Group rocks agreed with the cross section in that the body is defined by two listric faults to the north and south that both curve from steep to shallow gradients to the south.

Of particular interest was the large body of low resistivity (or high conductivity) below the Oudtshoorn basin. Weckmann et al. (2012) discussed this large conductive body found to underlie the Oudtshoorn basin and gave two possible explanations for the size and strength of the signal received. The first explanation suggested that the conductivity was attributed to a large region of mineralised phases within the Namaqua-Natal basement such as sulphides or ore-deposits. While they state this was fairly common within parts of this meso-proterozoic crystalline Supergroup, mineralisation has not been commonly found in the lower parts of the Namaqua-Natal Supergroup and based on the structure put forward in their model the basement (i.e. assigned at the contact with the bottom of the Cape Supergroup) was fairly shallow and as such most of the conductivity would be throughout the whole basement rock. Thus this explanation was deemed a less likely one. Also the underlying geology of the Cape Fold Belt is not well mapped and there is some speculation on whether the Namaqua-Natal Supergroup exists under the Cape Supergroup this far south from the Kaapvaal craton. The second, and more likely, explanation put forward by them was a saline reservoir, most probably within the Table Mountain Group sandstones and the basement rocks. The second explanation agreed with the cross section and structure put forward in this study; however Cross Section 1, in Fig. 5(b) below, shows the TMG sandstones going beyond 10 km in depth and covering most of the area of the conductive body. Further evidence for a deep underground reservoir was noted in the mention of “Warmbad” location by Weckmann et al. (2012). This “Warmbad” village, as it was described, was found to be less than 1 km

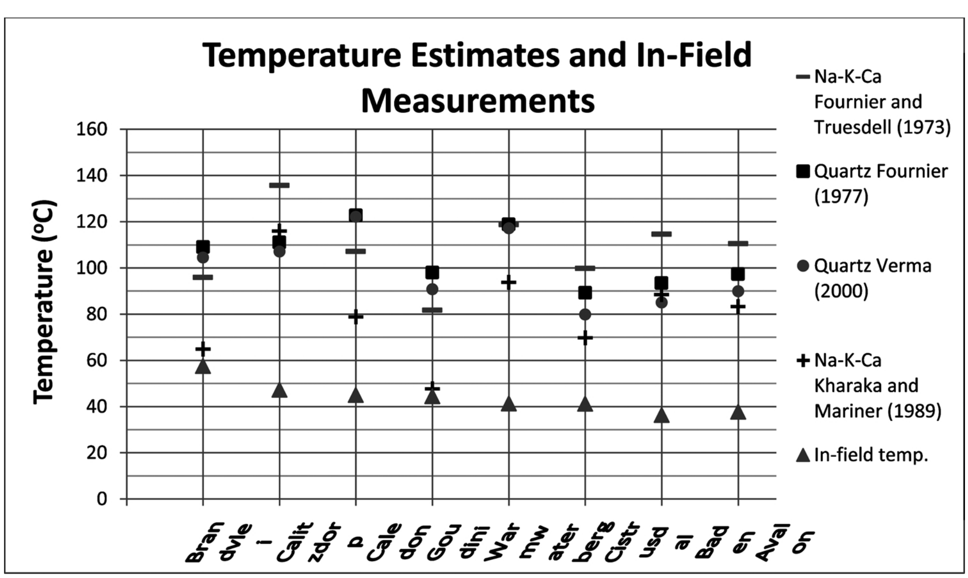

Fig. 2. The temperature estimates of the selected geothermometers shown in decreasing order of in-field temperature measurements.

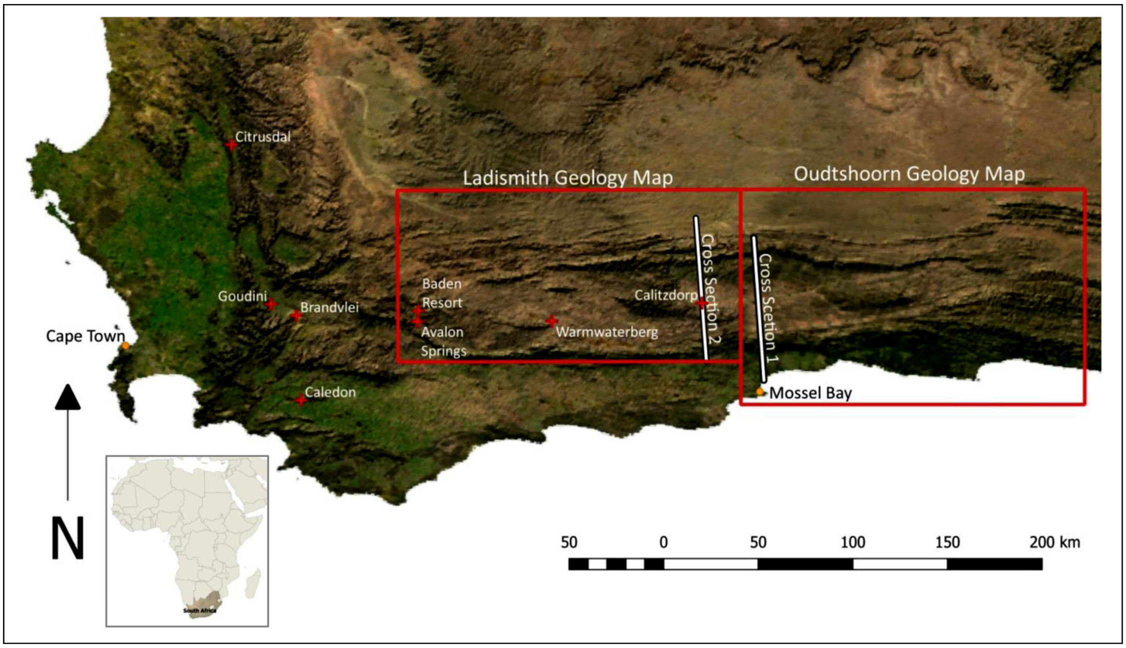

Fig. 3. Regional map showing the locations of the hot springs, the cross sections and the areas covered by each of the two geological maps used. Reference map showing the location of South Africa as a basic outline of Africa (in grey).

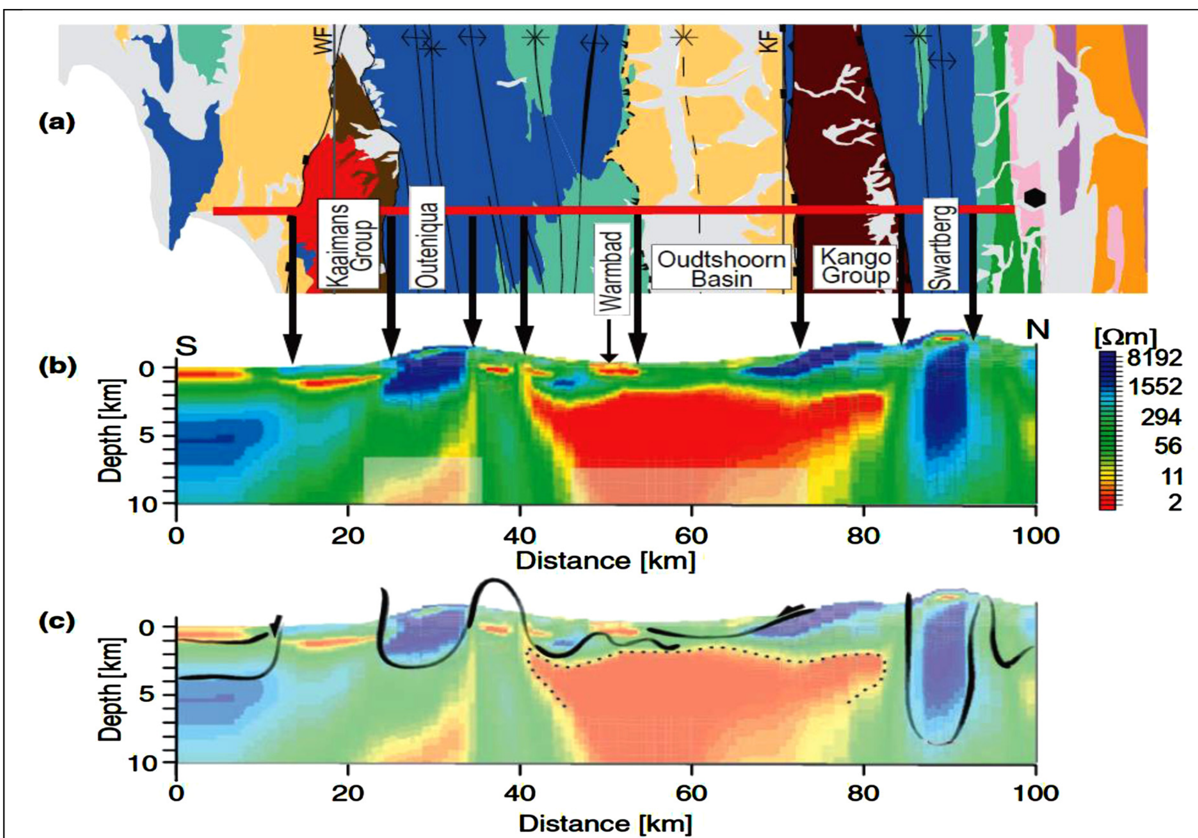

Fig. 4. Figure showing the (a) geological map in aerial view lined up with the (b) MT profile shown in cross-sectional view corresponding to the red line on the geological map. The geological map in (a) adapted from the Oudtshoorn geological map [Geoscience Council, 1979]. (c) The second MT profile shows the inferred geological formation boundaries and structural features as seen by Weckmann et al. (2012).

from Calitzdorp Spa hot spring sampled in this study and named so (translated to 'warm bath' from Afrikaans) due to the hot spring located there.

The main insight shown by the cross section was the complex shape of the Cape Supergroup from relatively shallow at the Outeniqua Mountains to depth below the Oudtshoorn basin; the progression was from a combination of multiple small folds generally getting deeper towards the north, to the major anticline at the start of the basin that

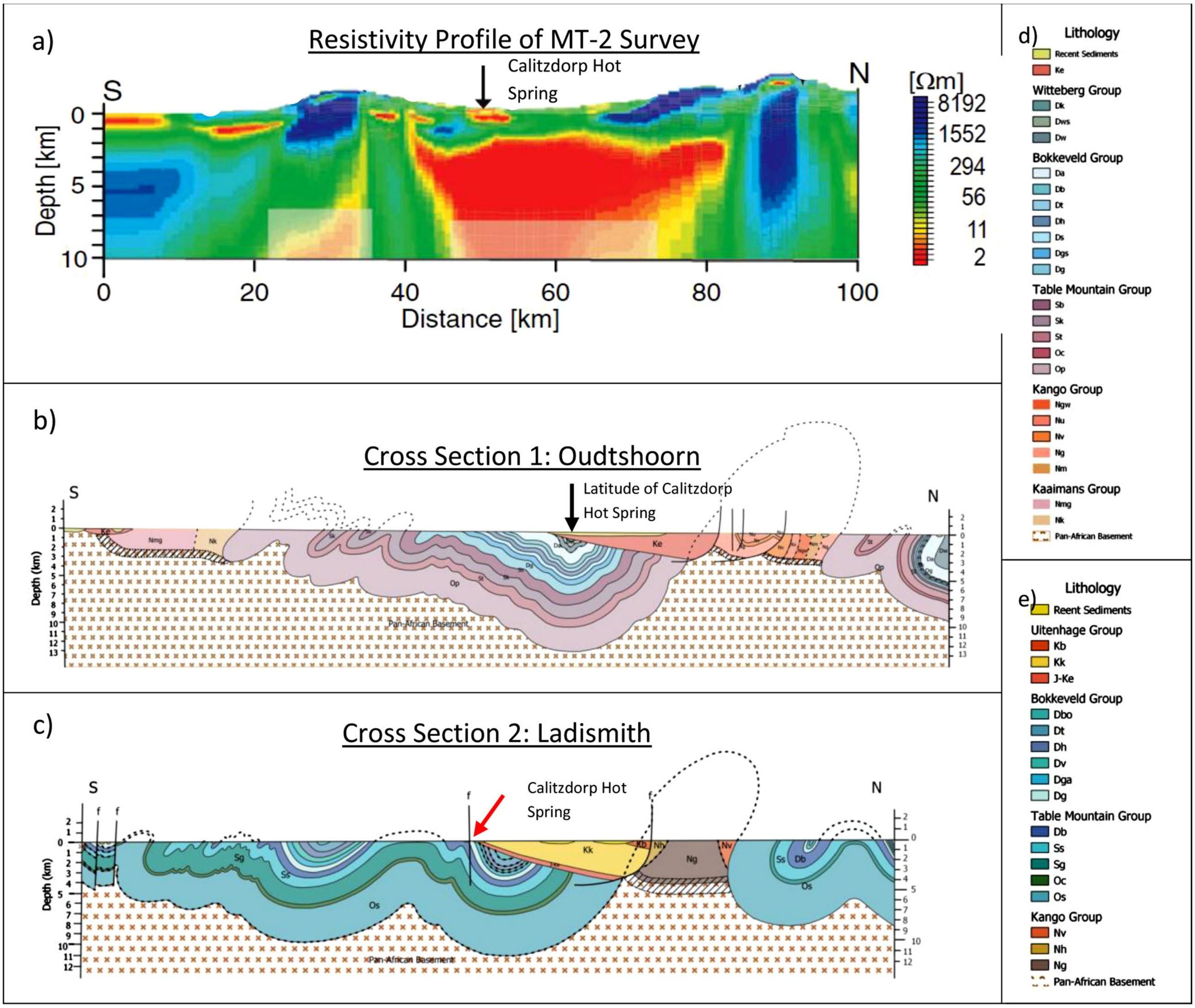

Fig. 5. Figure showing (a) the inversion profile of MT-2 survey above (b) Geological Cross Section 1 along the same physical line for direct comparison. (c) Geological Cross Section 2 through the Calitzdorp hot spring where the hot spring was indicated by a red arrow at the fault. The latitude of the Calitzdorp hot spring was indicated in both (a) and (b) profiles to provide a reference point since the two cross sections was 27km apart. The legend for the geological formations for Cross Section 1 and Cross Section 2 were shown in (d) and (e) respectively due to the difference in the colours and labels of the published Oudtshoorn and Ladismith geological maps respectively [Council for Geoscience, 1979; Council for Geoscience, 1991].

was subsiding to the west and then the prominent syncline that was easterly dipping and underlying the basin. The westerly anticline results in the large exposure at surface of the top layer of Bokkeveld Group (formation “Da”) next to the basin as well as the shallow dip angles throughout the exposed Bokkeveld formations next to the basin. This anticline was interpreted as subsiding but still distorting the syncline by creating a steeper southern limb of the syncline. This shape produces a favourable layout of the TMG sandstones in reference to the conductive body, although does not perfectly cover the extent of the conductive body. However with the understanding that the TMG sandstones are known to have strong secondary permeability, this cross section presents a very reasonable setup for the potential reservoir at depth. It is also interesting to note that the southern boundary aligns with the apex of a syncline in the “St” group and the northern boundary follows a similar shape to how the Cape Supergroup unconformably sits below the Oudtshoorn basin and would be steeply dipping south to form part of the anticline.

Above the large conductive body, as seen in Fig. 5(a), there is a smaller highly conductive body at the surface at the same latitude of the Calitzdorp hot spring. It is stated as the same latitude because the MT survey ran along a line that lies 27 km east from the Calitzdorp hot spring. This shallower body could be the reservoir supplying the hot spring and considering the top of the aquifer at a depth of 0.75 km with an increase of ca. 30 °C above the surface temperature there would be a fairly high geothermal gradient. There was no link indicated from the MT survey however there could be a link to the larger conductive body. This emphasises the advantage that would come from further MT surveys run parallel to this one. These parallel MT surveys could provide a better understanding of the 3-dimensional nature of these conductive bodies and determine whether they were connected and form one very large reservoir or were separate systems. And if the large conductive body does indicate a reservoir between 3 km and 7 km in depth, it would both have a substantially large volume to work with as well as almost definitely be hot enough for a low enthalpy geothermal power plant.

Since there was limited knowledge of the basement rock, the bottom of formations of the Kango and Kaaimans Group were shaded to indicate the progression with depth is unknown and cannot be interpreted with any certainty into the Pan-African basement, in Fig. 5(b) and (c). The dashed lines along contacts (below ground level) were also used to indicate uncertainty of how those contacts progressed with depth. The dashed lines (above ground level) were extrapolations of the formations based on the interpreted structure with these lines were perceived as the contacts before erosion of such formations occurred. The sudden change in the dashed line over the Kango Group indicates the movement that would have occurred from the two major normal faults that created the wedge.

Although not determined with any certainty, the strong potential of a large reservoir below the Oudtshoorn basin was inferred from the data presented and warranted further discussion of the geothermal implications if such is a reality. Thus the geothermal properties were analysed with regards to the data and estimates given to substantial the potential and then explored the possibility of a pilot geothermal power plant in that region together with the projected effects and concerns.

3.4. Geothermal implications of a reservoir below Oudtshoorn Basin

One of the most important properties of the geothermal potential of a region to consider was the geothermal gradient. The geothermal gradient was estimated as the change in temperature, from a temperature at depth to the local mean annual air temperature at surface of 19 °C, over the given depth. With the available data, inferences were first made about the hydrological setup of the Calitzdorp hot spring with regards to the two conductive bodies found directly below it. For the purposes of this discussion, the two conductive bodies were referred to as the small reservoir and the large reservoir, being the small shallow body within the first kilometre below the hot spring and the very large deeper body being from 3 km to 7 km below the surface respectively. They were assumed to be aquifers from this point on, even though it was acknowledged that further evidence was needed to substantiate this claim. Establishing and discussing the hydrological setup, in the possible variations, was necessary together with the measured and estimated temperatures in order to postulate reasonable geothermal gradients depending on the setup.

The MT profile and regional geological structures lead to three reasonable possibilities in terms of hydrological setup that supplied the Calitzdorp hot spring and the potential link to the small and large reservoirs. The first possibility was that the hot spring is not connected to either of the reservoirs and has a completely different setup below it. Although possible, this was deemed highly unlikely due to the continuity established from the regional geological trends and the cross sections drawn discussed in the previous chapter. The second possibility was that the shallower small reservoir acts as the aquifer of the hot spring and travels to the surface through a fault but is not connected to the deeper large reservoir. This would put the minimum temperature estimate of the reservoir of 117 °C ± 13 °C at a very unrealistic possibility due to the depth of 0.75 km. The measured temperature of 47 °C would have to be applied as the reservoir temperature which would result in a geothermal gradient of ca. 37 °C/km. The third possibility was deemed the most likely and involved the deeper, large reservoir acting as a primary reservoir with the shallower smaller reservoir acting as a shallower aquifer which the water temporarily collects at before rising to the hot spring. This would make the minimum estimated temperature of the reservoir at 117 °C ± 13 °C to be reasonable, and at a depth of 2.5 km, result in a geothermal gradient of 39.2 °C/km ± 4.3 °C/km.

Previous studies on the hot springs of the Cape Fold Belt have been conducted by Diamond (1997) with various points of agreement and differences. The hypotheses presented in this study of secondary porosity in the Table Mountain Group Sandstones as well as potentially having a higher and a lower aquifer was in agreement with Diamond (1997). However the geothermal gradient, estimated in this study from the geothermometry calculations and geological cross sections, was approximately double the gradient presented in Diamond (1997). While there was a large difference, the focus of Diamond (1997) was the isotope analysis and associated movement of meteoric water with regards to recharge of the hot spring. The figures used by Diamond for estimating the geothermal gradient was based off rough estimations from previous studies with a much shallower estimation of depth to the aquifers. Whereas when compared to the indepth study done by Dhansay et al. (2017), which focused on geothermal potential specifically, the geothermal gradient of the study area was estimated at 35 − 40 °C/km and this was in agreement with the 37–39.2 °C/km estimated in this study.

The volume and recharge rate of the reservoir accessed for a geothermal power plant are important factors to be assessed for the successful and long term operation of the plant as well as the impact to surrounding activities, especially when large scale operations which involve multiple power plants accessing the same reservoir. The volumes calculated for the small and large reservoirs are admittedly tentative as the east-west dimensions of the reservoir is unknown and even the assumption that the areas shown as conductive bodies are due to saline water will still need to be confirmed. For this reason the dimension in the east-west direction has been taken at 1 km even though the Calitzdorp hot spring is ca. 27 km away from the line of the MT survey. The porosity of the rock was conservatively taken as 1% based on the studies done by Lin (2007) on the fractured TMG sandstones as well as Campbell et al., 2016a,b on the core from borehole KWV-01 in Willowvale area, Eastern Cape as part of the KARIN project, even though this formation was from the Karoo Supergroup. The small reservoir was estimated at 1.44 km^3 which, at a porosity of 1%, results in a water volume of 1.44×10^{10} litres. The large reservoir was estimated at 161.4 km^3 which, at a porosity of 1%, results in a water volume of 1.61×10^{12} litres. A relevant comparison was taken of the total volume of the major dams that supply the greater Cape Town area which has a capacity of 8.98×10^{11} litres, with the single largest dam having a capacity of 4.80×10^{11} litres. When compared to the study by Jia (2007), the estimated capacity of the one large aquifer in this study was approximately 50 times larger (1.61×10^{12} litres) than the estimated total capacity of the Table Mountain Group Sandstones aquifers (estimated capacity up to 3.3×10^{10} litres). However the estimation of the overall hydro-geological structure by Jia (2007) was completed with admitted uncertainty, especially with regards to the depth of important geological formations.

While the geothermal power plant would be designed with a production well for extraction of water and a re-injection well to return the water after use, a change in volume of the reservoir could be experienced and thus affecting existing out-flow of the hot spring. Change in the volume of the reservoir depends on the flow rate in to the reservoir, also known as recharge rate, and the flow rate out of the reservoir. The current state of the large reservoir can be seen as in a natural equilibrium because natural factors control the rate of flow in and out and, as far as is known, no man-made boreholes have been drilled to that depth to extract water out of the reservoir or inject into the reservoir. This equilibrium does not mean that the flow rates and volume are in a constant state but rather that any changes are slow and due to change in the natural factors. The main affect experienced in this natural equilibrium would be during the initial stages of power plant operations where water is extracted to fill the system before enough water allows for re-injection and thereafter able to reach a similar state of equilibrium as before. The volume used by one pilot power plant would be negligible when considering volume estimates mentioned above however the volume used by multiple power plants extracting water from the same geothermal reservoir becomes significant and can affect surrounding activities, although the initiation of multiple plants would be phased and not done all at once.

3.5. Pilot geothermal power plant near Calitzdorp

The proposal of a pilot geothermal power plant constructed close to the Calitzdorp hot spring was then considered with an estimated installed capacity of such ca. 1 MW_e following the example of the pilot

Enhanced Geothermal System (EGS) plant built in Soultz, France. This pilot plant would be more appropriately designated to supply electricity to the town of Calitzdorp rather than Oudtshoorn. This was owing to the size of each town and the estimation by Eskom, the national electricity supplier, that 1 MW would be able to support 650 households. According to the 2011 national census, the town of Calitzdorp has a population of ca. 4 200 people and a household count of ca. 1 000 compared to a population of ca. 61 500 people and household count of ca. 21 900 in Oudtshoorn.

Two important factors to consider with any new construction and energy extraction are the environmental and socio-economic factors. Drilling has commonly been seen as non-environmentally friendly and has many negative associations. This has largely been due to the fact that drilling is often done by mining or oil and gas companies where the procedure to extract those commodities may have largely negative impacts on the environment. There are the negative impacts of acid-mine drainage, potential water contamination by oil or gas, potential seismicity of abandoned mine shafts, destruction of vegetation (however temporary) from open cast mining, air pollution from various processes, and the controversial hydraulic fracturing for natural gasses. However geothermal energy extraction using a number of boreholes, thus limited excavation of earth, as well as a relatively small footprint/physical land area use taken up by the actual power plant, especially compared to other types of power plants. The indirect impact on the environment is positive as geothermal energy is a clean and renewable source of energy, thus lowering the need for fossil fuel based energy production. The aspect of water use is also an important environmental concern, especially with the agricultural land use in the region. The current standard for geothermal power plants is to re-inject the water used by the process and thus creates a closed loop where a negligible amount of water is removed from the system if any. Also a binary ORC system means only the heat is extracted from the water but otherwise the water stays as is from extraction to re-injection. Thus concern of contamination of water or loss of water would be unfounded. The socio-economic impact would be positive in that construction would create temporary jobs while the maintenance and operation of this plant would create long term jobs. If the electricity is generated at a competitive price, the indirect lowering of electricity costs would help the economy. The long term impact of further geothermal power plants should also be considered in that electricity could be generated for other towns and, given a well designed system, could help to power a town like Oudtshoorn or even bigger. With the research into the geothermal potential within areas of Limpopo and the suspected geothermal potential in the Northern Cape, this larger contribution to the national electricity grid should be seen as plausible.

Lukawski et al. (2014) conducted a comprehensive study on the total cost of drilling and completion of geothermal wells and presented the cost distributions in four depths. The four depths were 2.4 km, 3 km, 3.7 km and 4.6 km and fall into a range of which 70 % of EGS systems fall into, according to this study. The study considered the various components of drilling boreholes and identified the most important variables that influence the total cost. The variables were quantified into measurable intervals such as length of drilling (feet) or period of time (per hour or per day). The distribution of each variable was also analysed, given enough data, to better substantiate the distribution for the total cost of drilling and completion of a geothermal well to a given depth. The study used data from completed geothermal wells in the Western United States as well as data produced from wells designed in a program, called ‘WellCost Lite’, for the study. The dataset of actual wells completed was limited to the timeframe of 2009–2013 to give more recent and relevant costs of the various components. While it is recognised that the study does not take into account the different types of lithology as well as using pricing from the USA, the influence of each component as well as the relative cost and risk of drilling over various depths was well analysed and reasoned. Thus given that the top of the large reservoir below Oudtshoorn sits at ca. 2.25 km below the surface based on the MT profile, a cautious depth of 3 km would be considered. According to Lukawski et al. (2014), the average estimated cost would be US$ 8.12 million. This was considered quite a substantial study on the total drilling cost and would be seen as a very realistic value even with delays or complications.

Considering the fact that geothermal energy is renewable and the lifespan of a power plant is entirely dependent on the maintenance, with a significant amount of geothermal plants having been run for more than three decades, this cost estimate is fairly low. Thus with a positive indirect impact on the environment, a positive socio-economic value and a fairly reasonable cost of drilling, the construction of pilot low-enthalpy geothermal power plant was deemed achievable and realistic, developing the much needed renewable energy production within the country.

4. Conclusions

The findings and the inferences of this investigation has lead to two main conclusions within the scope of geothermal energy potential in the Cape Fold Belt. Firstly there were two locations, Calitzdorp and Caledon, within the Cape Fold Belt that show high potential for geothermal potential, warranting further investigation, which was qualified by the temperature measurements of water from the springs and the temperature estimates from the geothermometry calculations. Secondly there was a strong indication that there is a large reservoir at an ideal depth below the Oudtshoorn basin, close to the Calitzdorp hot spring, which if present would provide enough heat energy for a low-enthalpy geothermal power plant.

The interpretation of the geology in the form of cross sections aided in validating the possibility of a reservoir existing at that depth and placed the potential reservoir largely within the Cape Supergroup rocks, mainly the Table Mountain Group sandstones. The volume was approximated at 1.6×10^{12} litres (or 1600 million cubic metres) given the dimensions from the MT profile, with only 1 km used for the unknown parameter, and a porosity of 1% of that volume of rock.

The depth of the potential reservoir below the Oudtshoorn basin would make it a highly favourable candidate for a pilot low enthalpy geothermal plant, with the depth being both within economic limits of 5 km and deep enough for a high enough temperature given a moderate to elevated geothermal gradient. Based off the geothermometry calculations and the estimated depth of the reservoir at 2.5 km, a geothermal gradient in the Oudtshoorn region was estimated at ca. 39 °C/km ± 4.3 °C/km. The estimated minimum temperature of the reservoir was 117 °C ± 13 °C, averaged from the four chosen geothermometer equations, which would be hot enough for a binary system setup for a low-enthalpy power plant. The outcome of operating a pilot geothermal power plant in that region would be that the electricity demand be met for most of the town of Calitzdorp. Following success of that pilot plant, increase in generation capacity could be achieved by increasing the number of geothermal power plants powered from the same reservoir, which could potentially meet the demand of a bigger town like Oudtshoorn. The overall impact on both the environmental and socio-economic aspects of the region would be positive with the expanse of the renewable energy sector in South Africa being the main achievement.

5. Recommendations

The findings of this study support the prospect that the required geothermal gradient and deep reservoir are present to facilitate electricity production from geothermal energy in the Oudtshoorn region. It is therefore recommended that further exploration is conducted into the Oudtshoorn basin; either by indirect methods of geophysical surveys like reflection seismic surveys and magnet-telluric surveys or by direct exploration such as deep boreholes, to 3 km or 4 km, where temperature measurements at depth can be taken. This would be aimed at gathering data to validate whether there is a large reservoir below the Oudtshoorn basin from about 3 km depth and to ascertain what the temperature of the water is if the reservoir exists. Exploration in this area can also build into the understanding of the lithology and structure of the Cape Fold Belt as well as determine how deep the Cape Supergroup goes and what lies below the Cape Supergroup in different locations.

Furthermore the Caledon hot spring was determined to be a promising location for geothermal energy from both the water temperature measurements at surface and the geothermometry estimations. This region would also benefit from in-depth geophysical surveys or deep boreholes to ascertain the hydro-geological setup and the geothermal potential. The other two locations that would be recommended for further exploration are Brandvlei and Warmwaterberg, as the former location had a significantly high water temperature at surface and high flow rate, and the latter had a high estimated reservoir temperature calculated from the geothermometry equations.

CRediT authorship contribution statement

J.W. Martin: Writing - original draft, Conceptualization, Methodology, Investigation, Visualization, Formal analysis, Project administration. **L. Croukamp:** Supervision, Writing - review & editing, Conceptualization, Funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

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