Exploration into the Potential for a Low-Enthalpy Geothermal Power Plant in the Cape Fold Belt

by

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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, while geothermal energy is not considered by the main power producer Eskom or private energy producers and only limited research has been done by academics. With advances in technology that harness geothermal energy from a wider range of temperatures, 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; making sure the geothermal gradient is high enough to obtain necessary heat energy from 3-4km depth.

The initial high level assessment of the geothermal potential of the Cape Fold Belt region was done through accessing seven hot springs found to have the highest temperature from previous studies. Temperature measurements, amongst other parameters, 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 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 surface measurements of 47°C and 45°C and estimates of the reservoir temperatures of 117°C ±13°C and 108°C ±21°C respectively.

The analysis of the Oudtshoorn region, where the Calitzdorp hot spring is located, was conducted using published geophysical data in the form of a 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 30km, 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 10km, and covers the low resistivity area from 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 40km in length with a depth of 2.5km to 7km 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.

Opsomming

Suid-Afrika is al lank afhanklik van steenkool en ander fossielbrandstowwe vir goedkoop kragopwekking. Hoewel die benutting van hernubare energiebronne vir kragopwekking toegeneem het in die afgelope twintig jaar, is die klem deurentyd op son- en windkrag, wat nie-deurlopend is, sonder enige oorweging van geortermiese energie. Geotermiese bronne by 85°C is al as haalbaar gerapporteer wanneer lae-energie strategieë soos binêre sisteme aangewend word. Gevolglik kan geotermiese energie potensiaal inhou vir Suid-Afrika met matige geotermiese gradiënte wat voorkom in sekere dele van die land met die voorbehoud dat dit hoog genoeg is om geo-vloeistof vanaf 'n diepte van 3-4km te verkry.

Die aanvanklike hoëvlak evaluering van die geotermiese potensiaal vir die 'Cape Fold Belt' streek is gedoen deur sewe warmwaterbronne, wat in vorige studies as dié met die hoogste temperatuur uitgewys is, te assesseer. Lesings vir temperatuur en ander parameters, sowel as watermonsters vir 'ICP-AES' analise van die belangrikste katione, is so naby as moontlik aan die bron geneem. Die katione konsentrasies vanaf die 'ICP-AES' analise is gebruik om geotermometriese berekeninge te doen, sodat die minimum temperatuur beramings vir die reservoirs van elke warmwaterbron verkry kon word. Ná die verkryging van die oppervlak temperatuurlesings en die beramings van die reservoir temperatuur is twee liggings verkry wat in die top drie vir beide metings was. Hierdie twee liggings, nl. Calitzdorp en Caledon, het oppervlak temperatuurlesings van 47°C en 45°C en beramings van reservoir temperature van 117°C ±13°C en 108°C ±21°C, onderskeidelik, gehad.

Die analise van die Oudsthoorn streek, waar the Calitzdorp warmwaterbron is geleë is, is uitgevoer met behulp van gepubliseerde geofisiese data in die vorm van 'n 'magneto-telluric' (MT) opname. Hierdie opname was uitgevoer in 2005 deur die Agulhas-Karoo Geoscience Transect projek. Die MT data is gepubliseer in 'n artikel deur Weckmann et al. (2012) as 'n deursnitprofiel vanaf Mosselbaai tot Prins Albert tot 'n diepte van nagenoeg 30km, waar 'n groot area van lae resistiwiteit gevind was onder die Oudtshoorn vallei. Die Calitzdorp warmwaterbron is geleë by die oppervlak bokant hierdie area. Die geologiese deursnitte en streekswye interpretasie aangebied in hierdie studie het tot die interpretasie gekom dat 'n groot sinklien van die Kaapse Supergroep onder hierdie vallei bestaan, wat moontlik tot 'n diepte van 10km strek en die area van lae resistiwiteit, getoon in die MT profiel, behels. Gevolglik was die afleiding gemaak dat die groot area van lae resistiwiteit as gevolg van 'n groot water reservoir is. Hierdie reservoir is omtrent 40km lank met 'n diepte van 2.5km tot 7km in die middel en wat sywaarts afneem.

Die diepte tot die bokant van die reservoir en die beramings van reservoir temperature het 'n geotermiese gradient van 39°C/km ±4.3°C/km tot gevolg. Calitzdorp is dus as 'n belowende ligging bestempel vir verdere ondersoek, byvoorbeeld addisionele geofisiese opnames of diep boorgate, om die bestaan van 'n reservoir onder die Oudtshoorn vallei te bevestig en om lesings vir temperatuur met diepte te versamel. As gevolg

van die diepte en grootte van hierdie potensiële reservoir kan dit as ‘n ideale kandidaat dien vir ‘n loodsprojek in die ‘Cape Fold Belt’ en Suid-Afrika, in die vorm van ‘n lae-entalpie geotermiese kragsentrale.

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1. Introduction

1.1. Background

Geothermal energy is a vastly untapped renewable energy resource globally that lies within the earth's crust which was first discovered early in the 20th century and since has been harnessed in some areas for direct use (i.e. central heating) and indirect use (i.e. generation of electricity). When compared to other renewable energy resources, it has had a slow rate of implementation if one considers that favourable aspects of geothermal energy such as it being a constant source of energy, unlike solar and wind which are intermittent, and having the potential for large capacity electricity generation at locations with high geothermal gradients. The first power plant that generated electricity from geothermal energy began operation in 1904 found in the Italian region of Larderello paving the way for other countries to investigate and construct geothermal power plants. A few of the countries that have developed major generation capacity from geothermal energy are the United States of America, Iceland, the Philippines, Indonesia, Turkey and Kenya. The U.S.A. has one of the largest commercial geothermal power plants for electricity generation located in 'The Geysers' of California and was built in the 1960s. Bertani's estimation in 2010 of the global installed capacity was 10.7 GW_e which is small when compared to Stefánsson's estimation of the potential capacity of 240 GW_e [Bertini, 2010; Stefánsson, 2005; Axelsson, 2012].

In Africa there are only two countries that have geothermal power plants, Kenya and Ethiopia, while two other countries, Tunisia and Algeria, harness geothermal energy for direct uses [Omenda & Simiyu, 2015; Merem, E. C. et al., 2019; Godinho & Eberhard, 2019]. Kenya has an estimated 630MW_e of installed electricity generation and is an example to other countries along the East African Rift Valley of the potential resource available to them. Kombe and Muguthu (2018) reported that a further seven countries were in the process of investigating geothermal energy for electricity production; namely Eritrea, Djibouti, Uganda, Rwanda, Tanzania, Malawi and Zambia. While the geothermal resources along the East African Rift Valley are mainly high temperature resources, a number of countries from around the world were discussed in literature that have investigated and constructed geothermal power plants based in low temperature resources [Xu et al., 2018]. Those low temperature resources are anticipated to be similar to the resource potential in South Africa. Recent developments in geothermal technology, in the form of binary systems, have made geothermal energy relevant to South Africa when previously prospects were unrealistic. These binary systems are used within low enthalpy geothermal power plant which has allowed for low temperature resources to be harnessed. This technology can operate with a geofluid having a temperature within the range of 85°C to 170°C [Saeid et al., 2014; Tomaszewska et al., 2018].

1.2. Problem Statement

Geothermal potential in South Africa is still viewed as being too low for electricity production even though there have been advances in the technology that can now make it possible to harness electricity from low temperature resources. The commercial development of renewable energy in South Africa has not considered geothermal energy for this reason. However this energy resource has favourable aspects such as being a continuous energy resource for base load supply as well as being a virtually indispensible resource that is not climate dependant. This is contrasted with solar and wind energy which is intermittent and climate dependant. While some research, driven by academics, has been done into the geothermal resources available in the country, the national energy supplier, Eskom, has indicated no interest in investigating or including this energy resource in trying to meet the demand of the country.

Eskom has largely relied on generating electricity from coal due to the large coal reserves found within the country allowing a very cheap form of electricity. 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. The main two alternative energy resources developed first were hydroelectric and nuclear energy as they can generate large amounts of electricity for each power plant built. Also the technology has been around for a long time. Hydroelectric energy is limited within the country due to the water scarcity. Nuclear power has a risk of highly severe consequences in the case of a failure which has hindered widespread endorsement. Within South Africa, renewable power plants have been developed effectively through partnerships with private investment. While there has been a steady increase development of solar and wind power plants, helped by the fact that the technology has improved drastically in efficiency, South Africa has left geothermal energy out of the equation altogether. Solar and wind are receiving increasingly greater development however their effectiveness is limited by the intermittent nature of this resource and efficiency of the technology. Unfortunately the percentage contribution to the power grid by renewable energy has been hampered due to the increased demand to newly supplied parts of the country. It was recently announced that there would be an increase in the electricity generation from nuclear. This would be achieved by the construction of two new plants together with the restoration of the existing Koeberg Power Plant.

1.3. Motivation for Research

Although geothermal potential 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 geothermal energy has become a possibility and could result in a significant contribution to South Africa's electricity capacity. The case for investigating geothermal energy within the country should be more of a consideration and while the estimated potential may not be comparable to coal generation by itself, it can contribute to the collective capacity of electricity generation from renewable resources. 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 and well managed utilisation, thus can contribute a significant amount of electricity to the growing need within South Africa for decades to come, especially increasing the ability of renewable energy to replace fossil fuels.

1.4. Goals and Objectives

The main goal of this research study was to investigate the potential of using geothermal energy in the Cape Fold Belt for electricity production. The Cape Fold Belt region was one of the areas identified as having elevated heat flow measurements in the country by Dhansay et al. (2014) and this investigation follows a recommendation made in a paper by Dhansay et al. (2017).

The goal of this study was designed to be addressed by five objectives which are as follows:

- Conduct a high level assessment of the Cape Fold Belt region by targeting the main hot springs found within the region
- Narrow the study to a select number of locations based off the data collected and analysed from the hot springs
- Review published geophysical survey data that allows for the assessment of the hydrological system within 5km of the surface (specifically below the hot spring of the chosen area)
- Investigate whether a reservoir exists at depth that is suitable for operating a geothermal power plant
- If a location holds a high enough geothermal gradient and/or a suitable deep reservoir, to conduct a basic assessment of the impact of a pilot geothermal power plant in the region

1.5. Report Layout

The report layout is in the following manner:

- Chapter 1 introduces the subject of geothermal energy and provided the background and motivation for conducting this research within South Africa.
- Chapter 2 review the literature published on geothermal energy in the worldwide context, the geological setting of the country, the various exploration methods considered for this study and ending with the recent research conducted into geothermal energy within South Africa specifically.
- Chapter 3 presents the method used to achieve the goals and objectives of this study.
- Chapter 4 discusses the results obtained from the field measurements and lab analyses conducted. The geothermometry calculations are also presented and processing those results are discussed.

And lastly an interpretation of the geological structure is presented to aid in the analysis of the geophysical data used.

- Chapter 5 contains the discussion of the results and estimations obtained, and consider the inferences that could be proposed from those results and observations. A potential reservoir below the Oudtshoorn basin is then discussed with regards to the implications of a geothermal power plant setup.
- Chapter 6 concludes the findings and potential developed from the discussion and provides recommendations to further investigate and validate the geothermal potential within the proposed locations.

2. Geothermal Literature Review

2.1. Worldwide Operational Status of Geothermal Power Plants

Geothermal Energy is a renewable energy resource which has been successfully used to generate electricity, and also used in various ways for direct heating (also known as thermal energy use), in different parts of the world for many decades [Axelsson, 2012]. One of the earliest and currently most established geothermal resources harnessed for electricity production has been the Geysers geothermal field within the Mayacamas Mountains of California in the United States of America. The geothermal resource accessed in the Geysers is considered a high temperature system. The overall power generation is consists of 22 small to medium sized power plants that all contribute to an overall electrical power output of 1517MW$_e$. This constitutes just under half of the USA's 3200MW$_e$ of total electricity generated by geothermal energy. The other states within the USA which have incorporated geothermal energy into their electricity generation are Utah, Nevada and Hawaii. The Desert Peak geothermal field, found in Nevada, was a region previously identified with a geothermal resource big enough for electrical generation. In 2002 a project was initiated to develop an enhanced geothermal system (EGS) in order to construct and operate a 2-5MW$_e$ power plant. An enhanced geothermal system is where the permeability of a geothermal reservoir is mechanically or chemically enhanced to allow for sufficient flow rate of the geothermal fluid. Yao et al. (2018) uses the Desert Peak geothermal project as a case study in a paper which was aimed at developing a 3D model of a geothermal resource. The geothermal fluid was reported at an average of 210^{o}C, a high temperature resource, where the geothermal reservoir was located between ca. 1.2km to ca. 1.6km below ground level.

Another country to have significantly developed the geothermal resources available is Iceland and is considered a world leader in their initiative to fully develop their renewable resources to a position where no fossil fuels are used. Although a small country by size and population, all of the electricity used by the country is generated by renewable energy, three quarters by hydro-electric power and the other quarter by geothermal energy. Iceland has a very unique geological and hydrological setting which allows for an especially large potential for hydro-electric and geothermal electricity generation. This power output not only meets the demand of sustaining the general societal and residential needs but also allows for a large aluminium industry which is a major export of the country. Another remarkable aspect of this electricity generation setup is that the cost of electricity in Iceland is approximately one third of the cost in the UK, which uses a mix of renewable energy (between 20% and 37%), nuclear energy (fairly constant at 21%) and energy from fossil fuels (between 47% and 57%; variation to account for the fluctuation in renewable generation) with a small percentage of energy imported [Stolworthy, 2014]. This is significant as renewable energy is often considered more expensive than an energy generation mix that largely comprised of fossil fuels. This is often skewed by the fact that the high capital cost for investigating and constructing renewable power plants is designed to be repaid over a relatively short period of time. This then negates the advantage of renewable energy having that long term life span with only maintenance largely determining the main cost. However using a reasonable (longer) timeline will give a competitive pricing for consumers as renewable energy has a virtually endless supply with the main long term costs coming from maintenance which, when managed correctly, would not be exorbitant. Nesjavellir power plant in Iceland is one of the high temperature geothermal power plants which has been in use since 1990 and produces a mix of electricity generated power as well as direct thermal heating. It produces approximately 120MW_e of electricity and 300MW_t of thermal energy [Axelsson, 2012]. An example of direct thermal use in Iceland is in the heating of greenhouses which allows for the production of certain food which otherwise would not be possible in the cold climate of Iceland.

The African continent by and large is considered a tectonically stable land mass, except for the East African Rift Valley which traverses south-southwest from the Red sea through multiple countries and is ca. 6400km in length and 30-70km in width. The East African Rift valley is a large tectonically active linear region that is essentially a newly developing divergent mid ocean ridge (plate boundary) where the crust is thinning and subsequently a significantly high geothermal gradient developing. This results in a number for countries with significant geothermal potential. While there have been many countries that have recently invested in exploration or pilot plants to harness geothermal energy, only two countries are currently generating electricity from geothermal energy; namely Kenya and Ethiopia. The other countries that have started investigating geothermal potential are Eritrea, Djibouti, Uganda, Rwanda, Tanzania, Malawi and Zambia [Kombe and Muguthu, 2018]. One such country which has already vastly developed the geothermal resources available is Kenya and is the leader in electricity generation from geothermal energy in Africa [Merem et al., 2019 and George et al., 2019]. Kenya currently produces 630MW_e of electricity from geothermal energy alone, which meets 47% of the country's electricity demand [George et al., 2019]. The Olkaria power plant is one of the major geothermal plants in Kenya [George et al., 2019]. Axelsson (2012) discusses how Olkaria consists of 3 generation plants (each with a turbine) which is fed by 20 production wells. The reported depth of the production wells are in the range of 2.2km to 3km. Merem et al. (2019) reports that the capacity of Olkaria power plant has recently been expanded by the installation of two new units. There is also direct use of geothermal energy in Kenya, one example being the cultivation of flowers at the Oserian Farm. The geothermal energy at Oserian Farm produces 2.5 MW_e of electricity used for general use and farming and also incorporates the pumping of geothermal fluid for direct heating of the greenhouses to promote plant growth as well as the extraction of CO_2 gas from the geothermal fluid for the promotion of photosynthesis [Merem et al., 2019].

While many countries around the world have started using geothermal energy, further examples of geothermal power plants mentioned below are found in France, Japan and China. An enhanced geothermal system has been developed at Soultz in France with a binary power plant used to generate electricity

[Hooijkaas et al., 2006; Radilla et al., 2012; Schill et al., 2017]. The two production wells were drilled to a depth of 5km with a third 5km deep borehole and the pilot 3.6km deep borehole, originally used for exploration, which are now both used as re-injection wells [Genter et al., 2010]. The reservoir temperature was measured at 200^{o}C at 5km below ground level however the production wells report a temperature between 150 and 160^{o}C during electricity generation. The power plant currently produces ca. 1.5MW$_{e}$ of electricity and has been demarcated for a higher capacity. Based on the temperature measurement of 200^{o}C at 5km depth, the average geothermal gradient would be 40^{o}C/km, which would be considered low in world standards but just high enough to be potentially economically viable for low-enthalpy geothermal energy. Recent studies have identified locations within the Cape Fold Belt as potentially having elevated geothermal gradients compared to the rest of South Africa. These geothermal gradients could be as high as 40^{o}C/km, although further investigations need to be conducted to substantiate this, and with boreholes drilled to depths of 4km to 5km, it may be possible to harness geothermal energy [Dhansay et al., 2017]. The Soultz geothermal power plant is a key example for the use of both a binary system power plant and 5km deep boreholes that are envisioned to be required for harnessing any geothermal energy found in the Cape Fold Belt [Radilla et al., 2012; Schill et al., 2017]. Matsukawa geothermal power plant in Japan produces ca. 23MW$_{e}$ of electricity and has been in use since 1966 [Axelsson, 2012]. Xu et al. (2018) analysed the feasibility of enhanced geothermal systems (EGS) with the proposal of horizontal wells for extraction and injection of geothermal fluids. Xu et al. (2018) mentions ten operational EGS sites, of which Desert Peak and Geysers, USA, and Soultz, France, which have been discussed above with the others being Ogachi and Hijiori in Japan, Fenton Hill and Raft River in USA, Rosemanows in UK, Gross Schoenebeck in Germany, and Cooper Basin in Australia. According to Xu et al. (2018), none of these power plants are commercially viable due to the cost of enhancing the permeability of the reservoir to a sufficient flow rate for electricity production.

2.2. Development of Electricity Generation by Geothermal Energy

Geothermal power plants started as systems that generated electricity directly from very high enthalpy (i.e. temperatures that are >200^{o}C) geothermal fluids, or geofluids, from the ground. This was essentially a system that captured the steam released from the ground and redirected it through a conventional steam turbine system to generate electricity. Over time the technology has developed to the point of being able to utilise low enthalpy resources that have temperatures as low as 85^{o}C for electricity generation. There have been various divisions made throughout literature of the grading of geothermal resources based on the enthalpy of the geofluid, which is roughly equivalent to the temperature of the resource; however the terminology and divisions of geothermal resources have not been completely agreed upon or standardised. The use of standardised divisions would help professionals, both in the field and those associated with geothermal work, to have a means of easy communication without having to delve into the details of each site. As expected the terminology should be able to convey the economic potential from the heat energy available as well as relate to the technology that would best optimise the extraction of that heat energy in generating electricity, i.e. the division relating to the highest temperature bracket should imply the highest electricity capacity generated using conventional steam turbines. In this thesis, the resources have been distinguished based on the temperature ranges that give optimal power to each of the current broad technologies used to generate electricity; namely dry steam system, flash steam system and binary cycle system [Dickson and Fanelli, 2005]. Although there may be overlap in the possible temperatures each technology can utilise, one will have to consider which technology is best (and most feasible) to generate electricity with the given resource and use the corresponding division. This consideration should take into account possible drop in temperature and/or pressure of the geothermal resource once extraction, and possibly re-injection, begins [Axelsson, 2012]. These three systems differ from an Enhanced Geothermal System (EGS) discussed in this thesis. The three systems (dry steam, flash steam and binary cycle) for electricity generation refer to a specific technology and operation for the heat extraction of heat for different geothermal resources. Whereas an Enhanced Geothermal System refers to the artificial improvement (by hydraulic fracturing) of the permeability of a rock formation at depth in order to create a pathway to pass water through for geothermal energy.

Binary systems can harness electricity from geothermal fluids at temperatures between 85^{o}C and 170^{o}C. This is done with the utilisation of a secondary fluid in a system called an Organic Rankine Cycle. The most important criteria of the secondary fluid is that it must have a much lower boiling point than the geofluid (i.e. the hot water from the ground), and thus is typically an organic compound such as n-pentane which has a boiling point of 36.1^{o}C [Dickson and Fanelli, 2005]. A heat exchanger allows the transfer of heat from the geofluid to the secondary fluid, causing the secondary fluid to flash into its gaseous form. This gaseous form, under high pressure, travels through a pressure-controlled pipeline to then power the turbine and generate electricity. The secondary fluid is then condensed and returned back to the heat exchanger. An advantage that has been noted of this system is that each fluid is contained within a different closed loop which means there is no release of any vapours or gasses into the atmosphere [Dickson and Fanelli, 2005].

Flash steam and dry steam systems utilise conventional steam turbines and operate off the medium to high enthalpy geofluids. The former utilise temperatures between 160^{o}C and 220^{o}C [Michaelides, 2012] whereas the latter can operate with temperatures above 150^{o}C, although typically temperatures of above 200^{o}C are used. The main difference between these two systems is that a dry steam system has virtually no water droplets present whereas the flash steam system has a mix of water droplets and water vapour, even though it is above the boiling point temperature. Thus for the dry steam system the whole system can be designed to harness dry steam and not worry about water in liquid form whereas flash steam system has stages to account for the separation of the water vapour from the liquid water. The geothermal resources required for these systems to be feasible are generally found in regions with high geothermal gradients; i.e. regions of high tectonic activity along plate boundaries, which are commonly found close to regions of active volcanoes or earthquakes. Although there are ancient tectonic plate boundaries within Southern Africa, they have been stable for millions of years and very little tectonic activity is expected within Southern Africa in the next significant geological time period.

2.3. Influence of the Geological Setting on Geothermal Energy

A potential geothermal resource depends on the geothermal gradient which is the rate at which the temperature increases with increasing depth from the surface. The geothermal gradient largely depends on the geological setting which varies greatly throughout the world. Geothermal gradients can be anywhere from 10^{o}C/km to 200^{o}C/km or more. Generally the geothermal gradient is higher in areas where there is tectonic activity. This relationship between the tectonic activity and the geothermal gradient of a region will be explained fully in the following paragraphs. Although the lack of tectonic activity in, or rather the tectonic stability of, Southern Africa has been the main reason for the lack of geothermal exploration in the past, recent developments in the geothermal technology has allowed the prospect of harnessing the low temperature geothermal resource potentially present in South Africa. Consequently binary systems will be the anticipated system required when proposing electricity generation in this thesis.

The earth is divided into three layers, namely the crust, the mantle and the core, based on their different physical states and compositions [Dickson and Fanelli, 2005]. The core is the innermost layer of the earth and has a radius of approximately 3400km and a temperature at the centre of approximately 6000^{o}C at the centre [Dickson and Fanelli, 2005]. The mantle is the middle layer and is approximately 2900km thick and is made of rock in a plastic state due to the temperature and pressure conditions [Dickson and Fanelli, 2005]. This plastic state within the mantle does increase in viscosity (i.e. become more solid) when moving away from the core due to the decrease in temperature and pressure. Consequently the upper portion of the mantle behaves quite rigidly and essentially a top layer is attached to tectonic crust above it with the thickness of this top layer varying with geological setting and tectonic history [Tankard et al., 2009]. The combination of upper mantle and crust is also referred to as the lithosphere. The temperature across the lithosphere rapidly decreases from a few thousand degrees Celsius (in the plastic section of the mantle) to the ambient temperature at surface. Thus the thickness of the lithosphere is a major contributor to the geothermal gradient.

The crust is the outer most layer of the earth and can be very thin (6-10km thick) to very thick (20-50km thick) however the latter is continental crust and when including the rigid mantle can be 150km thick or thicker (i.e. lithosphere). The plastic, malleable, rock of the mantle is theorised to move under convection on the lithospheric melt and power the mechanism known as plate tectonics. Tectonic plates consist of segments of lithosphere which move in different directions relative to each other and thus different types of contacts, or plate boundaries, exist. The thinnest sections of the crust is at divergent plate boundaries most commonly found along the ocean floor (mid ocean ridge) whereas the thickest is under convergent plate boundaries that are areas of mountain building or orogenous zones (high mountain ranges) present today. There are two main types of crust based on the composition which results in different physical properties such as density; namely continental crust and oceanic crust. Continental crust has a lower density than oceanic crust and thus the oceanic crust would sink, or be subducted, more readily than the continental crust when these two types of crust collide at a convergent plate boundary. On the other hand when continental crust collides with continental crust, various outcomes can occur, including subduction of one or deformation of both as the underlying tectonic forces push them together. The latter outcome, in many instances, has resulted in the accumulation of continental crust into larger bodies over the geological time scale. This accumulation of continental crust has resulted in large, stable bodies called Cratons which, over time and through various geological processes, have cooled down and became stable and rigid. These ancient bodies of rock typically have lower heat conductivity due to their physical state and chemical composition. South Africa is considered tectonically stable due to the lack of tectonic activity and the Kaapvaal Craton, which underlies the central and northern regions of the country, is the result of that lack of tectonic activity.

2.4. Geological Setting of South Africa

The geology of South Africa is largely deposited on the Kaapvaal Craton with a number of younger geological formations juxtaposed which, when studied with observable geological structures, indicates the various events which have developed into the current geological setting. Active convergent plate boundaries are often marked by volcanic activity due to the increase in elements that allow melting of rocks (i.e. magma production) as well as faults that form from the enormous compressional forces. The geothermal gradient is higher at plate boundaries due to thinner crust (closer to the hot mantle) or the presence of magma at shallower depths in the crust. In the case of the very old tectonic boundaries present in South Africa, convergence occurred in three regions of Southern Africa at different times and these areas are of interest with regards to potential geothermal energy. The one region is found in the northern most part of South Africa and is referred to as the Limpopo Mobile Belt. This mobile belt was formed around 2700 Ma (million years ago) during the collision of the Kaapvaal Craton and the Zimbabwe Craton to form the Kalahari Craton, which was part of the larger Gondwana supercontinent. The collision would have essentially formed a mountain range due to the amalgamation and deformation of the two sides being continental crust. The uplift of this region of crust and a significant amount of erosion has reduced that topography over the last 2700 Ma, exposing the roots of this ancient convergent mountain range through the current Limpopo River running through this area. Thus there is potentially a thinner lithosphere than expected there, especially when compared to the old thick Kaapvaal craton which reaches a significant distance into the mantle. This current state of the Limpopo Mobile Belt with a potentially thinner lithospheric crust as well as a network of faults and old joints would allow for both a high enough geothermal gradient and movement of fluid from significant depths. The other factor is rock formed during the collision that could contain radiogenic elements. A high concentration of these elements could contribute a significant amount of heat to the crust and is the second potential reason for a high enough geothermal gradient in the region. The Namaqua-Natal Metamorphic province (also referred to as Namaqua-Natal Mobile Belt) is also of interest and formed during a convergent plate event along the southern boundary of the Kaapvaal craton around 1100 Ma. The metamorphic province formed due to the intruding magma which caused low grade metamorphism to occur as well as the emplacement of intrusive rocks. Similar to the Limpopo Mobile Belt, the Namaqua-Natal Metamorphic province has a higher concentration of radiogenic isotopes due to its composition. The other region of interest is the Cape Fold Belt which was formed as a result of the compression experienced by the Cape Supergroup during the formation of a subduction zone along the southern boundary of the Gondwana supercontinent 280 Ma to 235 Ma [Compton, 2004; Weckmann et al., 2012]. The sediments of the Cape Supergroup were deposited between 550 Ma and 330 Ma in the Agulhas Sea which was located in a rift valley which formed between the Falkland plateau in the south and the African plate in the north. The closure of the rift valley was a result of northwards movement of the Falkland plateau driven by a subduction zone that formed on its southern border. This resulted in the compression of area where the Cape Supergroup was found, causing major folding and faulting of that younger sedimentary rocks as well as structural deformation to the underlying Namaqua-Natal rocks [Compton, 2004]. This compression resulted in a massive mountain range, similar to that of the Himalayas, with the Cape Fold Belt situated on the northern slopes of this mountain range [Compton, 2004]. The subsequent breakup of the Gondwana supercontinent, around 180 Ma, promoted the erosion of this mountain range with only the Cape Fold Belt as the remnants found along the coast of the African plate. This past tectonic activity left multiple faults and joints within the somewhat impermeable sedimentary rocks of the Cape Supergroup especially with the intense, and some cases overturned, folding that caused tight folds. These faults and joints promoted secondary permeability and thus allow the movement of fluid and formation of aquifers/reservoirs.

Geothermal energy essentially is heat energy transported to the surface from some depth in the crust via a fluid (water), with varying amounts of dissolved compounds, which is what has previously been referred to as geothermal fluid or geofluid. This geofluid is heated while passing through the host rock formations at depth which are in the order of hundreds of metres to kilometres deep. It travels to the surface, through natural faults or manmade boreholes, producing a water source at significantly higher temperatures than the present ambient conditions. Some literature arbitrarily defines a hot spring as 18^{o}C above the ambient temperature. In general, the temperatures of hot springs can range from 30^{o}C to over 100^{o}C, and move into supercritical temperatures, above around 200^{o}C, where dry steam is released. The geology of the area therefore has large influence over any potential geothermal resource, as the geofluids needs a suitable rock formation (i.e. having primary or secondary permeability) at the necessary temperature (i.e. a certain depth given the geothermal gradient of the area) and a sizeable pathway to reach the surface without significant loss in temperature or volume though other pathways. Thus there are many lines of evidence to support the potential of a geothermal resource, including the assessment of the geothermal gradient (e.g. measurements of down-hole temperatures in boreholes), the analysis of the geological setting and structure (to find suitable host rock formations), and the analysis of natural spring water (e.g. temperature measurement at surface or estimation of temperature at depth via chemical composition).

2.5. Methods of Geothermal Exploration

Exploration of geothermal resources has expanded to include many different geophysical methods besides direct methods such as borehole drilling [Aretouyap et al., 2016]. Conventionally deep borehole drilling allowed for the collection of temperature and pressure measurements at in-situ depths as well as the evidence of water at depth. Although drilling boreholes can obtain the most direct evidence of geothermal resources, it has a significantly high cost attached to it and requires specialised drilling rigs and high levels of expertise. Thus it is a large cost and risk to all parties involved. Consequently other techniques have been developed or adopted from other industries, like the oil and gas industry, to help identify potential geothermal resources. Data from these other methods can allow for targeted borehole drilling in areas with a certain level of probability which lowers the risk and is aimed at obtaining more accurate evidence to increase confidence. These other geophysical methods include surface heat flow measurements, magneto-telluric surveys, seismic reflection surveys, Landsat imagery and airborne magnetic surveys amongst others [Nyabeze & Gwavava, 2016]. Many of the above mentioned techniques are designed to map out the geological structure with depth. The geological structure is important in finding geothermal prospects due to the dependence on a permeable host rock that is enclosed by impermeable layers to create an aquifer. Threshold permeability is required so that a sufficient rate of flow is reached in order to allow for circulation of a certain volume while maintaining a high enough temperature. While in most cases these other methods are less costly than drilling, some can still have significant costs, especially when increasing the depth of exploration into the order of kilometres. One advantage is that they are less intrusive methods, meaning the data is inferred rather than based on physical rock brought up from that depth.

2.5.1. Heat Flow Measurements

The measurement of heat flow refers to the net terrestrial heat radiated from the earth’s surface. It can be calculated using measurements of down-hole temperatures and the calculated thermal conductivity of in-situ rock formations found during the drilling of that borehole. Boreholes have been drilled across the country by mining or oil and gas companies which have been used in literature by calculating heat flow measurements or thermal conductivity across the country using that data [Bouwer, 1954; Carte, 1955; Carte and Van Rooyen, 1969; Chapman and Pollack,1977; Jones, 1992a; Jones, 1992b]. Figure 2-1 shows the data that has been compiled and processed by Dhansay et al. (2014) into a map which shows a contoured map of higher and lower heat flow areas. A general low heat flow was noted from the majority of the country’s surface, centred over the Kaapvaal craton, however slightly higher measurements can be seen in certain regions around the Kaapvaal craton. One such region is a latitudinal band in the south that aligns with the Cape Fold Belt and the Namaqua-Natal Mobile Belt. In this area there are regions of higher release of heat from the ground which corresponds to higher geothermal gradients.

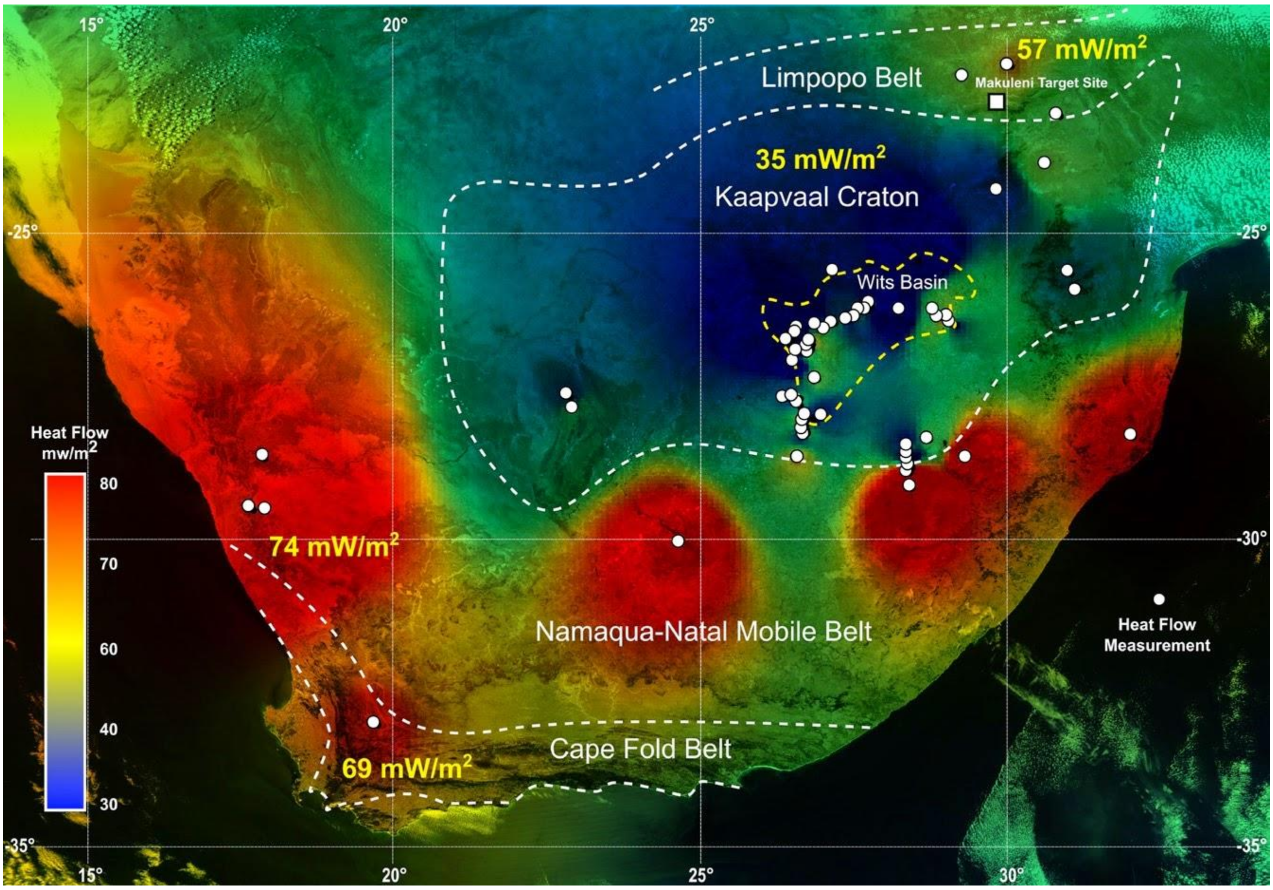


Figure 2-1: Heat Flow Map of South Africa compiled from data of various sources, including Jones (1987), and processed by T. Dhansay et al. (2014).

There are three main causes for heat flow in the crust, namely magma intrusion/emplacement, a thinner crust (i.e. mantle closer to the surface) or radiogenic heat produced. Radiogenic isotopes, such as uranium, thorium or potassium, can be present in high enough concentrations due to the composition of the rock crystallised there and can generate a significant amount of heat within the crust, known as latent heat. Magma intrusion/emplacement increases the geothermal gradient above what is expected due to the release of heat from the magma, being at much higher temperatures, into the rock around it as it cools and crystallises. As mentioned previously, magma is generally present at tectonically active plate boundaries and would not be the case in the South African context. A thinner crust, as discussed previously, means the hot mantle is closer to the surface and thus the geothermal gradient would be higher. The elevated heat flows mentioned above is evidence that there are higher geothermal gradients in those areas despite the source; however a thinner crust in these areas may be a better prospect to investigate for geothermal resources than latent heat energy.

2.5.2. Geothermometry

Geothermometry is the estimation of the water temperature when the indicator constituent, tested for within the water, was in equilibrium with the minerals of the host rock [Fournier, 1977]. Geothermometry relies on the assumption that the respective indicator constituent is dissolved or exchanged out of the minerals of the rock when the water and rock are in contact. The indicator constituent chosen is an isotope, an element in ionic form or a compound that is relevant to the geological composition of the underground reservoir. There have been a number of geothermometers developed characterised by the isotopes, ions or compounds used. They can be split into the different chemical reaction mechanisms used; namely mineral solubility, ionic exchange, solute reactions and isotope exchange [Ellis, 1979]. A number of studies have been done using the different geothermometers with direct comparisons to temperature measurements at depth, testing the reliability of the estimation and the limitations of this method in different conditions [Fournier and Truesdell, 1973; Fournier, 1977; Fournier and Potter, 1979; Nieva and Nieva, 1987; Giggenbach & Soto, 1922; Dulanya et al., 2010]. There have also been subsequent studies that compare different geothermometers to validate the agreement [Wishart, 2015; Wang et al., 2015; Chenaker et al., 2018; Rezaei et al., 2019]. It is generally accepted that geothermometers should be used with caution and estimations are best made using various geothermometers with the results being in some agreeable range which increases confidence.

The theory of geothermometry is built on three main assumptions which need to be present in order for one to use this method successfully [Fournier et al 1974; Ellis, 1979]. Firstly the element or compound which is used in the calculation needs to be present within the mineralogy of the host rock and readily available to form secondary compounds or dissolved ions. Secondly, the time needed for the reaction to equilibrate should be less than the time the water is present at the depth of interest. Thirdly, the rate of the reverse reaction should be slow enough such that the time it takes for the water to move to the surface does not allow re-equilibration to occur. Furthermore one must consider that the there are various factors that can affect the required concentrations while the water moves from the host rock at depth to the surface. One such factor is any shallower aquifers or faults supplying water into the ascending flow of water. This would change one or more of the concentrations used in the calculations, either giving a higher or lower temperature estimate than is actually present at depth. Another consideration is the precipitation of minerals out of the water as it cools during the ascent to the surface [Nieva and Nieva, 1987]. However this is more common when it comes to high temperature systems as a high level of salinity is common and oversaturation is more easily reached in these systems [Nieva and Nieva, 1987]. Thus this factor is not deemed applicable to this study due to the geothermal systems studied being the low temperature systems. Another consideration was the loss of water due to steam generation during ascending [Fournier, 1977]. This factor is only considered in certain geothermometers based on the significance of its affect; for example it is necessary for silica but not for Na-K geothermometers [Fournier and Truesdell, 1973]. In this study only the silica geothermometer by Fournier (1977) accounts for steam loss. This loss due to steam would change the concentration tested for provided the temperature of the water is high enough to produce significant amounts of steam.

2.5.2.1. Silica Geothermometers

One of the geothermometers that was commonly used for a long time was the silica geothermometer which falls into the mineral solubility type [Ellis, 1979]. This geothermometer was noted as very suitable for geothermal exploration application as the most abundant mineral in rocks is silicate tetrahedrons (SiO_4) which can dissolve into the water as a silica compound (SiO_2) [Fournier, 1977]. The equilibrium between the dissolved silica in the water and the silicate tetrahedrons in the rock in theory will depend on the temperature [Fournier, 1977]. This allows one to calculate the temperature the water was at in the host rock at depth once the concentration of the silica is known. The quartz geothermometer is stated as optimal at high temperatures, a range of 150-225^{o}C given by Fournier (1977), but generally accepted as accurate for systems higher than 180^{o}C [Ellis, 1979]. For lower temperature systems (<180^{o}C) other forms of silica dictate the silica concentration, namely chalcedony, cristobalite and amorphous silica, and these have been calibrated to decreasing brackets of lower temperature systems [Ellis and Mahon, 1977; Fournier, 1977]. Due to the unknown temperature range of the systems studied, the two forms of silica geothermometers that were used are the chalcedony and quartz geothermometers to allow for temperatures up to 160^{o}C, however likely or unlikely it is, with the respective equations are shown below:

<u>Equation 1</u>: Chalcedony geothermometer by Fournier [1977]

$$T\ (°C) = \left(\frac{1032}{4.69 - \log{[SiO_2]}}\right) - 273.15$$

<u>Equation 2</u>: Quartz geothermometer by Fournier [1977]

$$T\ (°C) = \left(\frac{1309}{5.19 - \log{[SiO_2]}}\right) - 273.15$$

Fournier (1977) has shown that steam loss can be taken into account with temperatures over 100^{o}C with an adaption of the above equation. The maximum steam loss is taken into account and shown in following equation:

<u>Equation 3</u>: Quartz geothermometer corrected for steam loss by Fournier [1977]

$$T\ (°C) = \left(\frac{1522}{5.75 - \log{[SiO_2]}}\right) - 273.15$$

2.5.2.2. Ionic Exchange Geothermometers

There are multiple ionic exchange geothermometers that have been developed empirically through the decades. One of the first geothermometers developed was the sodium-potassium (Na-K) geothermometer due to various common rock forming minerals that contain both elements, the ionic exchange reactions that commonly occur between these elements and the high solubility of these elements in water. It has been noted that the Na-K geothermometer was calibrated at high temperature conditions and has an optimal range of 180-350°C [Ellis, 1970; Nieva and Nieva, 1987; Giggenbach, 1988]. A variation of this ionic exchange was then developed for high calcium lower temperature springs which included calcium cation (Ca^{2+}) concentrations into the equation and this resulted in more reliable estimations below 180°C [Fournier and Truesdell, 1973]. The Na-K-Ca geothermometer is shown below in Equation 4 and within the equation there is a variation that allows for considering temperatures below 100°C, as opposed to the temperature range of 100°C-180°C which it can also work for. The Na-K-Ca geothermometer relies on the ion exchange between K-feldspar and Na-feldspar, with Ca^{+} ion participates as part of this substitution reaction in nature [Fournier and Truesdell, 1973].

Equation 4: The Na-K-Ca geothermometer by Fournier and Truesdell [1973]

$$T_{Na-K-Ca}\ (°C) = \left(\frac{1647}{\log\left\{\frac{[Na]}{[K]}\right\} + \beta * (\log\left\{\frac{\sqrt{[Ca]}}{[Na]}\right\} + 2.06) + 2.47} \right) - 273.15$$

Where: β = 4/3 for {√[Ca] / [Na]} > 1 and if water temperature ($T_{4/3}$) is <100°C

β = 1/3 for {√[Ca] / [Na]} < 1 or if ($T_{4/3}$) is >100°C

Multiple revisions of the Na-K-Ca geothermometer and subsequent developments were found in the literature since the first development of this equation from Fournier and Truesdell [1972]. Fournier and Potter [1979] revised the above equation with the inclusion of magnesium, within an addition parameter 'R', to correct for low temperature reservoir estimates that are above 70°C (while still being below 100°C) and the required ration of Mg to the sum of Mg, Ca and K as seen below:

Equation 5: The R-value for the Mg correction of the Na-K-Ca geothermometer by Fournier and Potter [1979]

$$R = \left(\frac{[Mg]}{[Mg] + [Ca] + [K]}\right) * 100$$

Equation 6: The change in temperature for the Mg corrected Na-K-Ca geothermometer by Fournier and Potter [1979]

$$\Delta T\ (°C) = 10.66 - 4.7415 * R + 325.87 * (\log(R))^2 - 1.032x10^5 * \frac{(\log(R))^2}{T} - 1.968x10^7 * (\log(R))^2/T^2 + 1.605x10^7 * (\log(R))^3/T^2$$

Provided $T_{Na\text{-}K\text{-}Ca}$ > 70°C and the R < 50 as stated in Fournier and Potter (1979) and where 'T' is $T_{Na\text{-}K\text{-}Ca}$ from Fournier and Truesdell (1973) in Equation 4.

Equation 7: The temperature correction for the Mg corrected Na-K-Ca geothermometer by Fournier and Potter [1979]

$$T_{Corrected}\ (°C) = T_{Na-K-Ca} - \Delta T$$

Provided 'ΔT' is not negative and the '$T_{Corrected}$' is not negative.

Nieva and Nieva (1987) and Giggenbach (1988) both reviewed the various multi-cation geothermometers that were developed and in use at the time. These papers aimed to evaluate and develop this method of temperature estimation and in both cases present multiple equations to use in conjunction with an assessment of the system under study, choosing the appropriate equations to be used. While these geothermometers presented may have relevance to this study, it is noted that they rely more on magnesium than the previous ionic exchange equations, which in the geological setting of this study may not be appropriate. However the equations presented in the two papers were still included in this study and thereafter evaluated based on the whether the resultant temperature estimations were realistic.

Nieva and Nieva (1987) developed a flow diagram of criteria and equations named the Cation Composition Geothermometer which was intended for prospecting geothermal resources over any temperature range. A literature-based dataset was used, encompassing over one hundred sampling points, that had both the cation concentrations of the four supposed major cations (from Fournier and Truesdell, 1973) as well as the measured (or estimated) reservoir temperatures; in the case of estimated temperatures, silica geothermometers were used. Both the cation concentrations and the reservoir temperatures were necessary for the analysis and development of the best-fit logarithmic equations to give confidence of the resultant equation. Sub-divisions were made between different temperature systems based on criteria in the form of cation ratios as this allowed for different geological systems as well as the different reactions that dominate over certain temperature ranges, e.g. Na-K exchange reaction which is dominant in high temperature systems or the distinctive circumstance of a high magnesium system. The equations found from best-fit logarithmic lines were evaluated based on root mean square of the difference between the measured/estimated reservoir temperatures and the calculated reservoir temperatures and this was intended to give an estimation of the error of the best-fit equation. The calculated error value allowed for the evaluation of the equations using real data as well as the substantiation of the sub-groups made. The divisions were made in the form of either total salinity ratios or a ratio of two potentially dominant cations. The flow diagram developed allowed the use of the cation concentrations of a study to reach a certain equation which is most likely to be the appropriate equation for temperature estimation of the intended reservoir. Following the flow diagram, with use of the cation concentrations from this study, the appropriate equation was shown below as Equation 8.

Equation 8: The Na-K-Mg geothermometer by Nieva and Nieva [1987]

$$T\ (°C) = \left(\frac{11\ 140}{6 * \log\left\{\frac{[Na]}{[K]}\right\} + \log\left\{\frac{[Mg]}{[Na]^2}\right\} + 18.30} \right) - 273.15$$

Given that the all the samples in this study failed the first of the following criteria, passed the second and failed the third criteria to reach the above equation:

- TMEQ > 8.0 and %Mg ≤ 3.5 (where TMEQ = [Na]+[K]+[Ca]+[Mg]
- √[Mg]/[Na] ≥ 1.7 and %Mg = {[Mg]/TMEQ}*100)
- √[Ca]/[Na] > 2.6

Giggenbach (1988) reviewed a range of multiple-cation geothermometers by discussing the respective geochemical reactions together with the reaction rates and temperature dependence, specifically focusing on three relationships between Na^+, K^+ and Mg^{2+}. It was noted that Na-K relationship showed a better equilibration at high temperatures and had a low rate of reaction while the K-Mg relationship was better reflective of low temperature systems and had a higher rate of reaction. Uncertainties were discussed in the application of these two relationships as geothermometers due to empirical data from acidic immature (non-equilibrated) water samples overlapping with water samples that were well equilibrated. This emphasises the empirical nature of these geothermometers and highlights the caution with which they should be used. The relationship of Na-Mg was discussed as a marker to distinguish between equilibrated and non-equilibrated water samples but could not be used as a geothermometer itself. This is because the relationship is dependent on albite as the main rock forming mineral and at low temperatures it is unlikely to reach a state of equilibrium. Thus the K-Mg relationship was considered as a geothermometer for this study and is shown below as Equation 9.

Equation 9: The K-Mg geothermometer by Giggenbach [1988]

$$T\ (°C) = \left(\frac{4410}{14 - \log\{ [K]^2 / [Mg] \}} \right) - 273.15$$

Whereas the Na-K and Na-Mg equations were not deemed appropriate but are shown below as Equation 10 and Equation 11 respectively.

Equation 10: The Na-K geothermometer by Giggenbach [1988]

$$T\ (°C) = \left(\frac{1390}{1.75 - \log\{ [Na] / [K] \}} \right) - 273.15$$

Equation 11: The Na-Mg geothermometer by Giggenbach [1988]

$$T\ (°C) = \left(\frac{1630}{10.5 - \log\{ [Na]^2 / [Mg] \}} \right) - 273.15$$

The silica and Na-K-Ca geothermometers were deemed the most suitable for the chosen area of research as the geology of the Cape Fold Belt and underlying stratigraphy was mainly either Cape Supergroup or the underlying Namaqua-Natal basement, of which both were abundant in silicate minerals as well as the various feldspars and other rocks containing above mentioned minerals. All the above mentioned geothermometers had been included in this study despite certain ones being deemed more appropriate. This was to allow for a comparison of estimated temperatures from the data of this study. Thereafter the suitability and relevance of each geothermometer will be discussed. **Table 2-1** below shows the rest of the main eight geothermometers considered applicable to this thesis. However Appendix B does shows a complete list of all the geothermometers researched as well as the temperature estimated using the corresponding cation concentrations.

Geothermometer	Equation	Author
Na-K	$T\ (°C) = \left(\frac{1217}{1.483 + \log\left\{\frac{[Na]}{[K]}\right\}} \right) - 273.15$	Fournier (1979)
Na-K-Ca	$T\ (°C) = \left(\frac{1120}{\log\left\{\frac{[Na]}{[K]}\right\} + \frac{1}{3} * \{\log\left\{\frac{\sqrt{[Ca]}}{[Na]}\right\} + 2.06\} + 1.32} \right) - 273.15$	Kharaka and Mariner (1989)
Quartz	$T\ (°C) = 42.198 + 0.28831 * [SiO_2] - 3.6686x10^{-4} * [SiO_2]^2 + 3.1665x10^{-7} * [SiO_2]^3 + 77.034 * \log[SiO_2]$	Fournier and Potter (1982)
Quartz	$T\ (°C) = 55.3 + 0.36598 * [SiO_2] - 5.3954x10^{-4} * [SiO_2]^2 + 5.5132x10^{-7} * [SiO_2]^3 + 74.36 * \log[SiO_2]$	Arnórsson (2000)
Quartz	$T\ (°C) = \left(\frac{1175.7}{4.88 - \log[SiO_2]} \right) - 273.15$	Verma (2000)

Table 2-1: Equations of other main geothermometers considered in this study with the respective authors noted.

2.5.3. Magneto-Telluric Surveys

A magneto-telluric survey is a geophysical method used to map electrical resistivity at the targeted depth and is aimed at understanding the geological structure and finding potential aquifers. The technique was originally developed about 60 years ago for the oil and gas industry and still commonly used in that field as well as for geothermal exploration, mining exploration and within academia. As the name suggests, this technique makes use of electric and magnetic waves and more specifically records the strength of each at a certain location with the resultant signals giving a measure of resistivity. The resistivity can then be used to infer basic structural components or identify formations with certain minerals present or even aquifers with high salinity. Solar wind energy interacts with the earth's magnetic field and produces variations in the magnetic field which induces electric current in the subsurface [Fourie and Johnson, 2017]. Although rock formations may have different electrical conductivities to allow for the distinguishing between layers or bodies, the main aim is detection of liquid at depth. The presence of a liquid is indicated by a significantly lower resistivity, or relative higher conductivity, due to the high salinity or increased dissolved salts present in the hot water at depth [Kana et al., 2015; Chen et al., 2009].

The equipment generally consists of five devices, three that record the magnetic field strength and two for the electric current strength. The magnetic field is recorded in three orthogonal directions while the electric field is recorded in two horizontal and perpendicular directions. Collecting data over a line of locations allows for the data to be processed into a cross section through the ground to a certain depth. Theoretically magneto-telluric surveys can be done anywhere from 300m deep to 10km deep [Kana et al., 2015]. Sets of equipment can be used for specific ranges depending on the calibration and sensitivity. The targeted depth is a calculated estimation based on the relationship between the frequency the devices record at and the resistivity that is recorded. The resistivity and the estimated depth are calculated using Equation 12 and Equation 13 respectively.

Equation 12: Equation to calculate resistivity from frequency used and signals received from Kana et al. [2015]

$$\rho = \frac{|Ex|^2}{5 \times f\, x\, |Hy|^2}$$

Equation 13: Equation to estimate the depth of the electromagnetic data from Kana et al. [2015]

$$\delta = 503 \times \sqrt{\frac{\rho}{f}}$$

Where *'Ex'* is the electric field strength in x-direction (in milli volt), *'Hy'* is the magnetic field strength in the y-direction (in gammas), *'f'* is the frequency the devices are set to (in Hertz), *'ρ'* is the resistivity measured (in 'ohm.metres') and 'δ' is the estimated depth of testing (in metres) [Kana et al., 2015].

The use of MT surveys within South Africa has been very limited, especially over the Cape Fold Belt. However a project, called the Agulhas-Karoo Geoscience Transect (AKGT), was funded by the Council for Geoscience as well as a collaboration of German and South African academics, the collaboration called *Inkaba yeAfrica*, and involved multiple geophysical surveys over more than 500km and surveyed over 3 years [Branch et al., 2013]. One of the main focuses was the study of the Beattie Magnetic Anomaly which is the largest single magnetic anomaly in the world and spans 1000km in the Karoo basin [Weckmann et al., 2006]. The project consisted of four magneto-telluric surveys stretching from the coast to the edge of the Kaapvaal craton, with the second MT survey (MT-2) spanning from Mossel Bay to Prince Albert [Branch et al., 2013]. This MT-2 survey was identified as applicable and relevant to this study as the one sampling location (Calitzdorp Hot Spring) was only ca. 27km from the line.

Weckmann et al. (2012) discusses the results of this MT-2 survey in relation to the Cape Fold Belt and highlights specific structural features that can be inferred from the surface geology and the resistivity signals. The results and discussion of the paper by Weckmann et al. (2012) will be drawn upon in later chapters of this thesis due to its relevance in both proximity as well as similar geology. Below is Figure 2-2 which shows the line of MT-2 as well as the Calitzdorp Hot Spring that formed part of the initial investigation of this thesis.

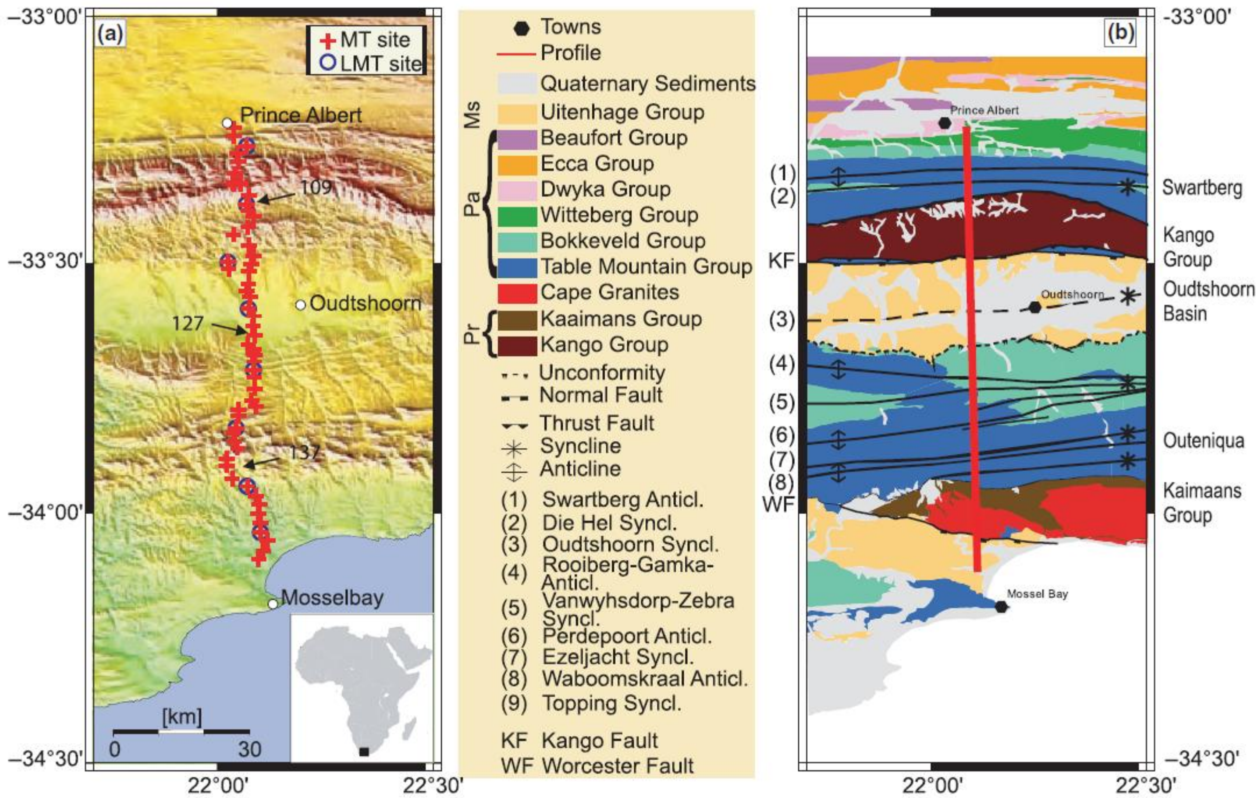


Figure 2-2: Map taken from Weckmann et al. (2012) showing the locations of each MT sampling point that make up the MT-2 line survey as well as the geology of the region and where the line survey runs.

2.5.4. Seismic Reflection Surveys

Seismic tomography was initially developed for the oil and gas industry to find potential oil or gas reserves but also has application in geothermal exploration. The aim of this technique is to map out the geological structure as well as see evidence of liquid which could be the commodity of interest. In general seismic geophysical equipment records seismic waves that are either generated artificially or naturally and is used to help find geological formations and structures or locate the epicentre of an earthquake. Seismic waves move through different rock formations at different speeds depending on their density as well as being reflected, refracted or diffracted at boundaries. The outcome is that boundaries between different formations become evident once the data is processed. Another key aspect of how seismic waves interact with substances as they travel through the ground is that certain types of waves cannot be transmitted through liquids and this can indicate where liquid commodities are potentially present.

A seismic reflection survey uses devices called geophones to receive the seismic wave energy. The source of the seismic wave is usually artificial and common instruments used are vibroseis, a mechanised hammer or controlled explosions, all of which generate a sudden impact or shock in the ground with a certain amount of energy to produce a seismic wave from the desired location. Usually multiple geophones are used in a configuration (a line or grid) with certain spacing, from each other and the source, which helps to correlate the signal received to each boundary.

In the case of geothermal exploration, seismic reflections can be used to analyse the geological structure in order to find potential aquifers. This technique has the limitation of decreasing clarity with increasing depth due to progressively more interference from other waves as well as the energy absorbed when passing through boundaries. This interference is lowered when targeting deeper layers because the receivers are spaced at larger distances and this results in less overlap with reflected waves while the receivers are still at the correct location to detect those waves reflected from boundaries at larger depths. The range of depths that are detectable is determined by the level of clarity and attributed to the various factors; namely the source of the seismic waves (and its energy), the geology present, and the sensitivity and accuracy of the receiver technology amongst others.

2.6. Geological Exploration in South Africa

Various projects have been conducted in South Africa that involve geological exploration methods aimed at various outcomes, but most do not have geothermal exploration as a main outcome. Geological exploration has been discussed here as relevant insights can be drawn for assessing geothermal potential in a region. Most of these projects have been commercially driven by the mining and the oil and gas industries, specifically with the rich mineral deposits that have been exploited in the northern interior region. The above mentioned seismic reflection surveys are used readily by the oil and gas industry for stratigraphic analysis and detection of oil or gas reserves. The mining industry makes use of various geophysical methods, like magnetic or gravity surveys, as well as drilling to obtain primary samples that can be used for confirmation of inferred data as well as for chemical analysis. A considerable amount of exploration boreholes have also been drilled which allow for valuable information from depth that would otherwise be inferred from geophysical methods.

SOEKOR (Pty) Ltd. was the national oil company of South Africa before it underwent a merger in 2002 to form PetroSA [petrosa.co.za]. The SOEKOR drilling project was conducted by SOEKOR (Pty) Ltd. in South Africa over the 1960's and 1970's which consisted of nine wells drilled across the Karoo Basin. This project took multiple data measurements with depth, which in most cases included temperature measurements with depth. The project was aimed at finding oil and gas reserves, with some evidence found of potential gas however it was not deemed as commercially viable project. The data from the boreholes is not currently available to the public however some of the data has been used by academics in the past, some of which is available through published literature, for example the thermal conductivity measurements by Jones (1992a).

The Council for Geoscience (CGS), together with academics from Keele University in UK and from six major South African universities, completed a multi-site project called the Karoo Research Initiative (KARIN) which was run in 2015 with the reports published in 2016 [de Kock et al., 2016a]. This project consisted of two deep boreholes drilled primarily exploring the prospect of shale gas in the Karoo Supergroup, however data that was collected has been analysed for assessing geothermal potential [de Kock et al., 2016b; Campbell et al., 2016a; Campbell et al., 2016b]. The Whitehill and Prince Albert formations of the Ecca Group have been theorised to contain high enough organic matter, with the appropriate conditions, to produce shale gas. Thus each borehole was terminated a short distance into the next geological strata called the Dwyka Group [de Kock et al., 2016a].

The two sites were approximately 800km apart (east to west) with both being on the southern edge of the Karoo Basin; the first borehole (KFZ-01) was in the Tankwa Karoo near Ceres, Western Cape and the second borehole (KWV-01) was near Willowvale in the Eastern Cape [de Kock et al., 2016b]. Borehole KFZ-01 (32°50’30.43”S 19°49’3.02”E) was drilled to 671m deep and showed the complex geology of the southern part of the basin, including the duplication of geological strata (in the Ecca group) by folding [de Kock et al., 2016a]. Importantly there was water encountered at three points during the drilling. These points occurred at depths of 560m, 625-626m and 668-671m which implied that aquifers could exist at further depths for geothermal prospects [de Kock et al., 2016b]. The water temperature measured at depth was between 33.7°C and 36.6°C. With water samples from the surface sources measuring at 15-20°C, the increase in temperature to the given depth results in a rough estimated geothermal gradient of between 25 to 35°C/km. This range is slightly higher than expected which supports the proposal of geothermal exploration. Borehole KWV-01 (32°14’41”S 28°35’08”E) was drilled to a depth of 2353.48m in an area known to have pervasive dolerite intrusions [de Kock et al., 2016a]. The significantly greater depth of the targeted formations was due to some of the formations of the Karoo Supergroup being thicker as well as dolerite intruding horizontally which adds to the stratigraphy. In relation to potentially harnessing geothermal energy, intrusions can help increase fluid pathways and effectively increase the permeability of the formation [Campbell et al., 2016a; Campbell et al., 2016b]. In this case it has also increased the depth of the sedimentary formations of the Karoo Supergroup, and concluding from borehole KFZ-01 that the Ecca Group has suitable formations (sandstone and shale layers) to serve as deep aquifers, this would allow for possible aquifers at the correct temperature (i.e. relevant depth for geothermal gradient) for a geothermal resource to be developed. However there was no water encountered at depth within borehole KWV-01 which can be attributed to the location with reference to the geological structure and the regional rainfall.

An analysis of the isotopes done on the Western Cape hot springs showed that the water, from multiple springs each having different source depths, were recharged by meteoric sources [R. Diamond and C. Harris, 2001]. Thus with regards to suitable recharge of deep aquifers, rainfall is required to occur in a certain location, usually inland for South African context, in order to infiltrate the geology and move deep into the crust.

2.7. Study of the Hot Springs in South Africa

Hot springs are a natural release of heat energy from deep in the crust through the discharge of hot water or steam at the surface, i.e. the release of geothermal energy. Natural hot springs are a good basis to work from when considering geothermal energy as they have two key factors present for harnessing the geothermal resource if the resource is commercially viable; the first being a significantly sized reservoir at a depth where the water is heated to a substantial temperature, and the second being the geological structure of the region to direct the water both through the reservoir for heating and from the reservoir to the surface without significant loss of volume or heat. Hot springs have historically been the first indicators of a geothermal resource that could be utilized for either indirect use (electricity generation) or direct use (e.g. general heating, etc.). In South Africa, there is an unexpectedly large number of hot springs around the country, and literature reports 87 thermal springs of which 29 are in direct use for leisure type resorts with a map showing many of the locations in Figure 2-3 below [Diamond and Harris, 2000; Tshibalo et al., 2010]. There are a number of hot springs that have been correlated to certain geological settings, with a few that seem more randomly placed. One such geological setting was the Cape Fold Belt which has over ten identified hot springs [Diamond and Harris, 2000]. Another two areas easily identified in the map below are the Limpopo Mobile Belt in the north of the country as well as the eastern shoulder of the country which has eastern edge of the Namaqua-Natal Metamorphic Province [Dhansay et al., 2017]. The northern cluster shows more than 14 thermal springs and the eastern group is more a north-south line with both groupings in areas with a high density of tectonic structures. The hot springs in the Cape Fold Belt have been the chosen area of study for this research project and within that the seven hot springs with the highest recorded temperatures, as found in the literature, were focused on.

Diamond and Harris (2000) analysed the hot springs of the Western Cape and aimed to determine the origin of the water from the hot springs by isotope analysis. The results confirmed findings from previous literature that the recharge of the hot springs was meteoric in origin. Diamond and Harris (2000) sampled four of the hot springs monthly for eight months, all four included in this study, which gave reliable temperature data useful for this study as well as concluding that seasonal variation did not influence the isotope values. The latter conclusion was attributed to the reservoir of each hot spring having a significant volume such that the seasonal variation in isotope value did not significantly change the overall isotope value within the aquifer.

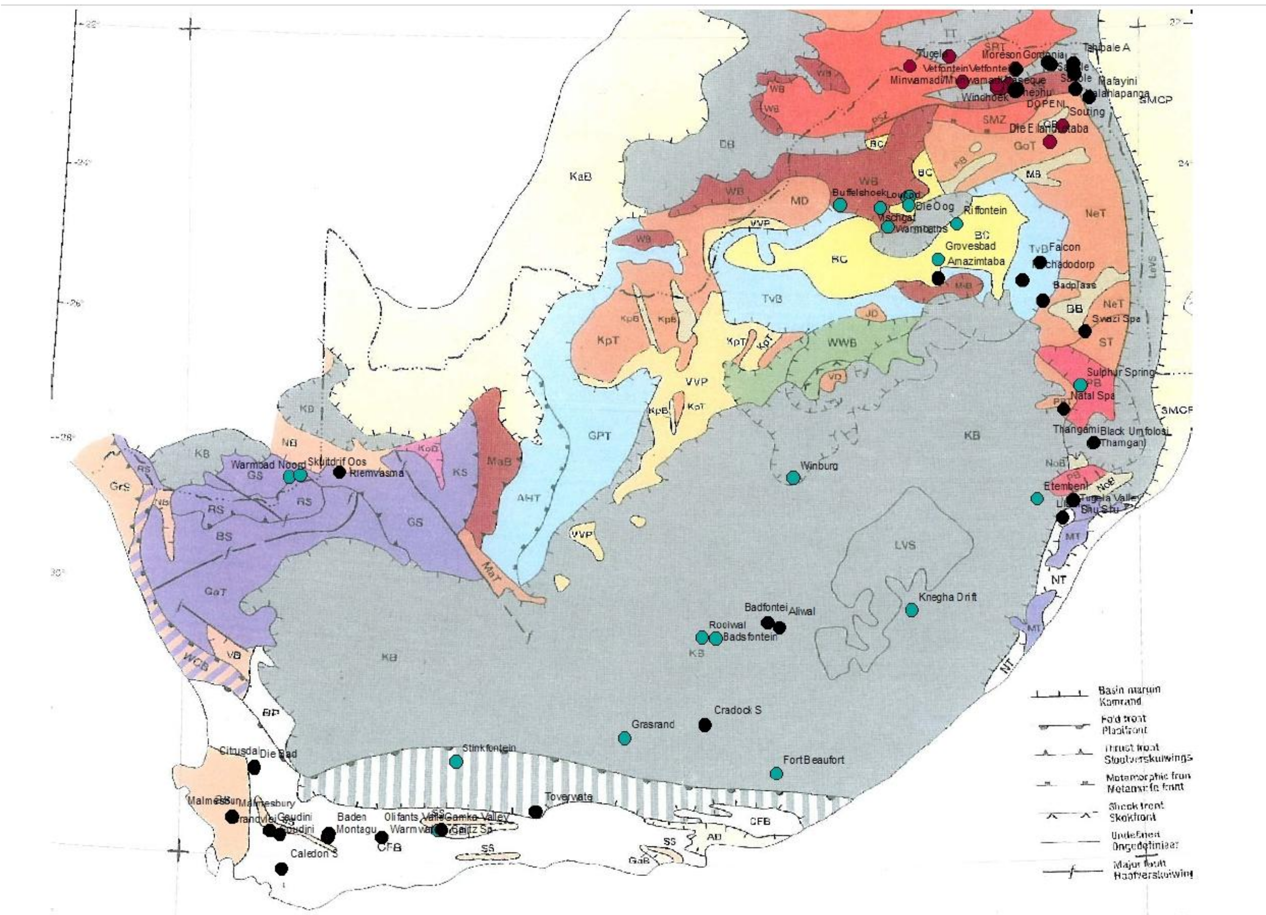


Figure 2-3: Map of South Africa from Tshibalo et al. (2010) showing the location of the hot springs.

Tshibalo et al. (2010) gave an overview of the geothermal potential in South Africa and highlights the thermal springs as good indicators of geothermal energy. A list of thirty one thermal springs was given with temperature readings, pH measurements and recorded minerals present. These are assumed to be compiled from pervious literature where the only reference made was to Kent (1916) for the list of minerals. This thesis was a useful resource in this study for both historical temperature measurements of hot springs as well as substantial list of hot springs in South Africa with their relative locations. The paper also highlighted the scarce historical investigation into geothermal and the lack of planned time and resources dedicated to this area of potential energy.

2.8. Geothermal Research in South Africa

Over the last decade there have been increasingly more research projects and papers discussing geothermal potential within South Africa and further investigations into certain areas that seem likely to have geothermal potential given the available data and geological understanding of the country [Tshibalo et al., 2010; Dhansay et al., 2014; Campbell et al., 2016a and 2016b; Johnson and Fourie, 2016; Fourie and Johnson, 2017; Dhansay et al., 2017]. Researchers have re-evaluated geothermal energy given the advances in geothermal technology and the pressure on the country to reduce greenhouse gas emissions [Johnson and Fourie, 2016; Dhansay et al., 2017]. Geothermal energy could also help alleviate the energy constraint experienced by the electricity supplier, Eskom, to meet the basic electricity demand countrywide. The amount of data on potential geothermal resources in the country as well as the feasibility to produce electricity is still scarce and needs significantly more research [Dhansay et al., 2014]. A conference paper written (by Tshibalo, Olivier and Venter) in 2010 titled the "South African Geothermal Country Update (2005-2009)" provides a basic understanding of how there had been virtually no time or resources put directly into geothermal exploration [Tshibalo et al., 2010]. The report highlights the fact that South Africa, in 2004, generated 89% of its electricity from fossil fuels (68.2% from coal, 19.4% from crude oil and 1.6% from gas), compared to 8.1% which was generated from renewable and 2.8% from nuclear. These percentages have changed slightly, with coal generation increasing to 72.1%, attributed to the construction and operation of two big coal power plants, while nuclear power contributes 6.9% as of February 2016. Multiple solar and wind farms have been constructed that have considerably increased the electricity capacity that renewables have contributed however still contributes a similar percentage. The paper reviewed the vast number of thermal springs present in the country with the majority in the Limpopo province as well as along the Cape Fold Belt in the Western province and concludes that research into geothermal potential is warranted.

A feasibility study of an Enhanced Geothermal System (EGS) has been investigated in the Vhembe District in the Limpopo province. This study considered the overall cost of exploration, installation, operation and long term (30 years) maintenance and was completed by T. Dhansay, M. De Wit and A. Patt in 2014. This study considered the geothermal energy generated from radiogenic heat available in the crust. This radiogenic heat energy is produced from radioactive decay of a high concentration of radiogenic isotopes such as uranium, thorium and potassium. These isotopes are generally found in felsic rocks that are emplaced during intrusive or extrusive geological events. In the South African context, this occurred in the Limpopo Mobile Belt during the orogenic collision of the Kaapvaal and Zimbabwe cratons which started around 3200 Ma and reached its peak at around 2000 Ma. Dhansay et al. (2014) found that there are potential areas in this mobile belt that would be a suitable position for harnessing low-enthalpy geothermal resources through an EGS setup. Overall it was concluded that more data acquisition needs to take place on a national scale, and the high initial cost of installation would need to be offset by the government tax incentives in order for geothermal energy to become feasible. In a more recent paper, Dhansay et al. (2017) discussed the geothermal potential on a national scale and used various types of data to construct an estimated geothermal gradient contoured map of the country, as shown below Figure 2-4. The map clearly shows areas where high estimated geothermal gradients exist, high enough for low enthalpy power plants. Dhansay et al. (2017) also explained how the government had implemented the Independent Power Producer Procurement Programme (IPPPP) and Renewable Energy Feed-In Tariff (REFIT) which brought down the cost of electricity generated by solar and wind energy by 71% and 46% respectively. These governmental incentives could also bring down the cost of electricity generated from geothermal power plants and could possibly bring it low enough to be competitive with coal generated electricity [Dhansay et al., 2017]. Keeping in mind the example of the lower cost of electricity in Iceland compared with that of the UK, discussed at the start of this literature review, having a competitive costing from renewable energy, especially geothermal energy, is both realistic and inevitable. This current study aimed to address the need for data acquisition within the country by conducting a high level investigation of the Cape Fold Belt and then planned to focus in on selected areas with more substantial geophysical testing and investigation.

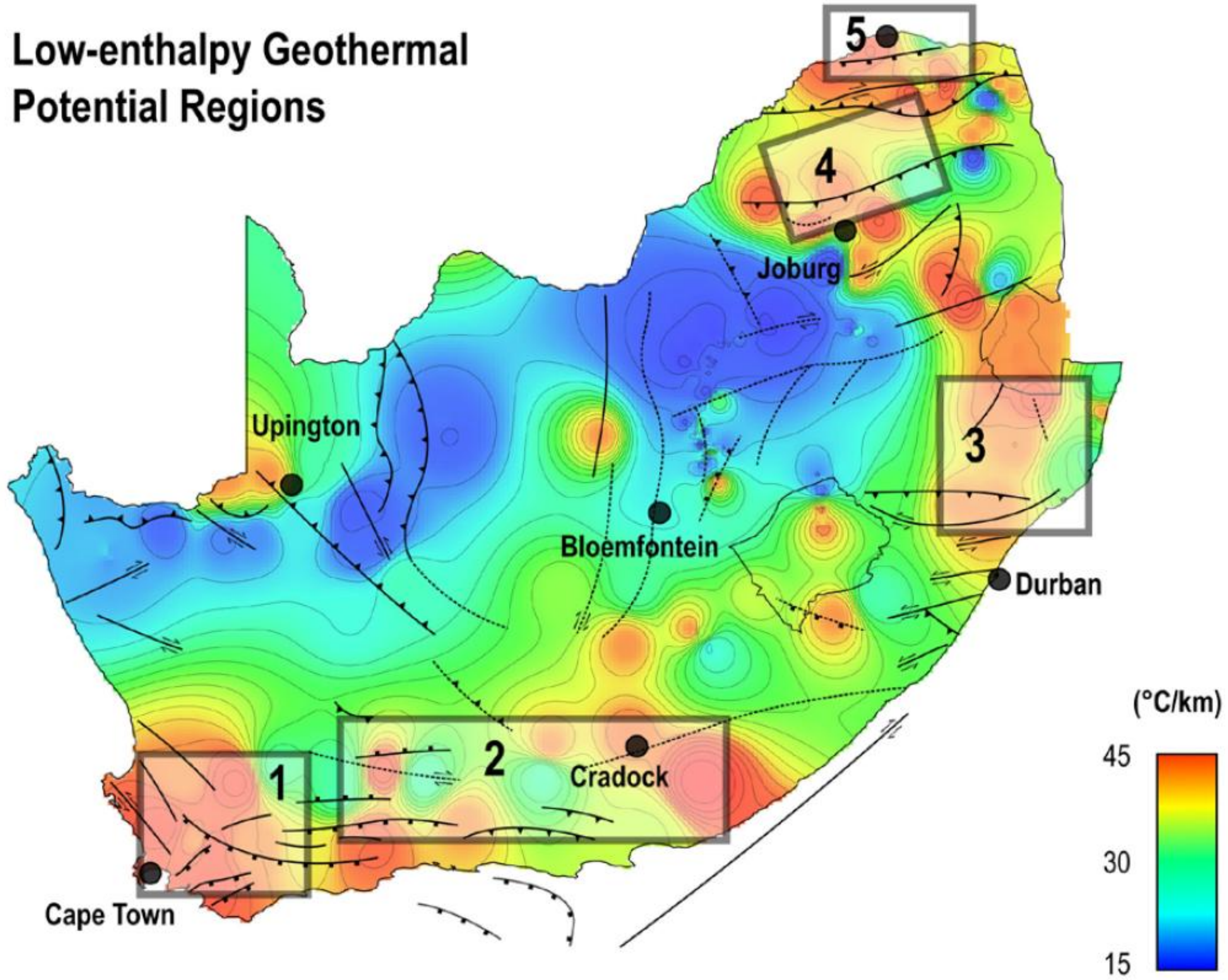


Figure 2-4: Map of South Africa contoured by estimated geothermal gradient with potential low-enthalpy geothermal regions sectioned off by Dhansay et al. (2017).

A more recent review of the country's geothermal potential was discussed in a paper titled "Exploration of South Africa's Geothermal Resources" written by D. Johnson and C.J.S. Fourie in 2016. The evidence presented implied that there was geothermal potential in regions mentioned earlier based on the heat flow measurements; namely Limpopo Mobile Belt, the Namaqua-Natal Metamorphic province and Cape Fold Belt [Johnson and Fourie, 2016]. Magnetic surveying, magneto-telluric surveying, seismic reflection and seismology were four geophysical methods highlighted as substantial analytical methods of geothermal potential [Johnson and Fourie, 2016]. These four geophysical methods were discussed; explaining how each could contribute data to the overall information needed and would allow for the assessment of a region with regards to the different factors needed in a geothermal resource [Johnson and Fourie, 2016]. It is stated that a better analysis of the deep geological structure can be drawn when a study involves two or more geophysical methods as one can help confirm or clarify the data from another [Johnson and Fourie, 2016].

Another research project linked to geothermal exploration was an analysis of existing data of the Aliwal North hot springs and the surrounding area [Fourie and Johnson, 2017]. The analysis was motivated by the presence of natural hot springs and a general understanding of a suitable regional geology, which is the boundary between the Kaapvaal Craton and the Namaqua-Natal Mobile Belt. The analysis completed by C.J.S. Fourie and D. Johnson in 2017 used data from multiple geophysical exploration methods in order to analyse the local geological structure of the subsurface around the hot springs, exploration methods such as Landsat imagery and airborne magnetic surveying. The airborne magnetic survey revealed a vast number of faults throughout the area with two prevalent dykes, one in the north-south direction and the other in east-west direction [Fourie and Johnson, 2017]. Furthermore two ring dykes were shown to be part of the subsurface structure around Aliwal North [Fourie and Johnson, 2017]. The Landsat data helped to confirm the structures found in the airborne magnetic survey. In terms of geothermal prospects, these intrusions and faults are favourable when considering fluid movement and secondary permeability [Fourie and Johnson, 2017]. To ascertain whether a potential geothermal aquifer would be present would require further investigation where seismic surveying and magneto-telluric testing was recommended. This thesis gives a good example of where a seismic survey and a magneto-telluric survey have been completed over the same line in the Cape Fold Belt [seismic data from Council for Geoscience and MT survey from Branch, (2013). This allows one to line up the two sets of data and infer geological structures from the seismic survey to areas of low resistivity in the magneto-telluric survey and find potential aquifers and fluid conduits [Weckmann et al., 2012]. These geophysical methods can give an indication of groundwater at depths of a few kilometres, or suitable rock formation to act as an aquifer and relevant geological structures that need to be taken into account.

A paper written by S. Campbell et al. (2016b) discusses the data collected from the KARIN deep boreholes mentioned above in reference to geothermal potential of the Karoo Basin. The Ripon formation, part of the Ecca group, was identified as an appropriate formation within the Karoo basin to be assessed as a potential aquifer and to serve as a geothermal reservoir [Campbell et al., 2016b]. The analysis of the thermal properties (i.e. thermal conductivity, thermal diffusivity and heat capacity) as well as the physical properties with regards to water mobility (i.e. density, porosity and permeability) was conducted on the core samples of the sandstones from the Ripon formation. The permeability was calculated to be low however it was deemed plausible that the intrusive dolerites could increase the fluid movement at depth along intrusion-host rock interfaces [Campbell et al., 2016b]. An estimation of a geothermal gradient of between 24.5^{o}C/km and 28.2^{o}C/km was calculated from the data of boreholes KFZ-01 and KWV-01 [Campbell et al., 2016a]. This gives a geothermal reservoir temperature of between 104 and 117^{o}C at an assumed depth of 3.5km. With the area of the Karoo Basin estimated at 700 000km^2 and the southern edge estimated to reach 5km in depth, there is thought to be significant geothermal potential using low enthalpy power plants [Campbell et al., 2016a]. An estimation of the geothermal resource potential (or heat in place) of the central to southern Karoo basin was calculated between 2719 TWh and 3130 TWh [Campbell et al., 2016b]. Together with a recoverability rate of 33%, approximately 1043 TWh of recoverable heat (RH) was estimated that can be harnessed as geothermal energy [Campbell et al., 2016a]. As stated earlier, this would be heavily reliant on a suitable geothermal reservoir at the correct temperature as well as multiple locations along the southern Karoo basin having multiple power plants in order to harness the majority of that 1043TWh of energy estimated.

The Council for Geoscience started a new project in 2018, similar to KARIN discussed above, which T. Dhansay is working on and was titled the "Karoo Deep Drilling and Geo-Environmental Baseline Programme". The project had multiple phases planned, currently in starting the magneto-telluric survey phase, and aimed to address multiple areas of research, one such area being geothermal potential within the study area of Beaufort West and thus the southern Karoo Basin at large. The magneto-telluric data, the stratigraphy, the down borehole temperature measurements as well as the depth of any water horizons will be of great interest to understanding the geothermal gradient and geothermal potential of the southern Karoo Basin. Following the recommendations from Dhansay et al. (2017), this research project focuses in on the Cape Fold Belt (which covers block 1 and 2), aiming to identify the most promising location(s) of the region and assess whether further exploration is warranted.

3. Methodology

The fieldwork was designed to consist of two rounds of investigation. The first was a high level, low cost investigation focusing on the water properties of the hot springs along the Cape Fold Belt of the Western Cape and what could be inferred about each area in terms of geothermal potential. These hot springs were targeted as they were seen as suitable markers for potential geothermal reservoirs with relevant geological structures to allow water movement to the surface. This was where the physiochemical properties were measured at the source or closest point that was accessible and the samples were collected for chemical analysis and later geothermometry calculations. The first round was aimed to give an approximate geothermal potential of each location and therefore direct which locations were best to investigate further.

The second round was a focused investigation using geophysical methods which are highly expensive and require high level of expertise, thus only to be conducted over one or two locations, with the aim to give supplementary data with depth. Unfortunately a lack of time, funding and availability of equipment meant that the desired geophysical surveys were not possible within this study. However data collected in November 2005, and later discussed in a paper by Weckmann et al. (2012), covered an area of close proximity, and with similar geology, to one of the locations which showed high potential in the first round. This data was regarded as sufficient data to complete this study and further analyse this area as a potential geothermal resource. Thus the methodology of the second round will be brief description of the steps taken by Weckmann et al. in collecting the geophysical data.

3.1. Water Samples and Physiochemical Data

The initial data collection consisted of testing the physiochemical features of the water as well as collecting water samples for chemical analysis. The physiochemical features measured were temperature, pH, electric conductivity (EC), and total dissolved solids (TDS). The temperature gave an initial indication of the heat energy potential of the reservoir of each hot spring and was deemed a more reliable parameter to use than the temperature estimates with regards to the geothermal potential. The EC and TDS indicated the approximate level of the overall dissolved salts concentration in the water as well as the potential susceptibility to the magneto-telluric testing. The chemical analysis was aimed at obtaining the concentrations of the major cations for the geothermometry calculations. The sodium, potassium, calcium, magnesium and silicon concentrations were analysed using Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) analysis. This combination of cations allows for the various ionic exchange and silica geothermometers to be calculated.

The sampling procedure was kept consistent and in line with best practise for all samples to maintain reliability and limit any contamination or error as outlined in “Volume 2: Sampling Guide” by the Department of Water Affairs (DWA), South Africa (2000) and in “Chapter 5: Field Work and Sampling” by the World Health Organisation (1996). Photos were taken of each extraction point and can be found in

Appendix A. The pH and the EC/TDS meters of the Hanna HI98131 portable device were calibrated prior to sampling at each location even though specified calibration period was only once a day. Calibration was done with the calibration liquid specified by the manufacturer. The device was rinsed off with cleaning solution after each sample was taken and stored with the specified storage solution. The spring water was allowed to run for a few minutes (if piped) before the sampling cup was rinsed with water from the hot spring and then filled with enough liquid to cover all the sensors of the Hanna HI98131; the EC, TDS and pH measurements were recorded once stability was reached. A separate electronic thermometer was then used to measure the temperature of the sample, in most cases measured directly from the hot spring where possible. A separate thermometer was necessary as the Hanna HI98131 had a temperature limit of 60^{o}C, which only one of the hot springs has been previously recorded above, however it was deemed more accurate if the temperatures measured were not close to the limit of the equipment. Generally there is an effect on the pH, EC and TDS measurements by an increase in temperature; pH level decreasing slightly and EC/TDS increasing slightly. However the Hanna device has an automatic compensation mechanism for the temperature effect when recording the pH, EC and TDS levels. With no temperature measurements above 60^{o}C, the other measurements would be correctly compensated for. The 15ml sampling vial was then rinsed with water from the hot spring and filled to the top and sealed with no air bubbles. The water samples were then stored in a cooler box with ice brinks to maintain a cool stable temperature during transport. A blank sample of de-ionised water was the first sample collected and transported with the samples to gauge the QA/QC of the entire sampling process; from collection to transport to the laboratory handling and analysis procedure.

The physiochemical testing and sample collection was done at the source or as close to the source as possible. The proximity to the source and the infrastructure built to collect and direct the hot spring water was noted during the collection. Also noted was the rate of flow, any significant distinction in the colour of the water or significant amount of sediment in the water. Most of the hot springs had clear water with no observable sediment in the either collection pools or in the sampling vials. For the majority of the hot springs, the closest point to the source was between 5m to 50m away and samples were collected from a tap along the piped system. This was due to all, but one, of the hot springs currently used for commercial purposes. From what could be estimated, the majority of the hot springs had a flow rate larger than 5 ℓ/s and thus the heat lost (over those 5-50 metres) from the source was deemed negligible. While the iron concentration could be effected by the water travelling through the piped system, this was deemed negligible, especially at the high flow rate of the water. Precipitation of the cations could occur on the inside of the piped system, however this would be a very slow process and would not have a significant effect on the cation concentrations measured for. Table 3-1 below shows the list of hot springs, their current use and all other notes mentioned above made during collection.

Table 3-1: Observations of hot springs during water sampling

Name of Facility	Location	Current Use	Sampling Point and Water System	Additional Notes
Calitzdorp Spa	Calitzdorp	Commercial Resort	Spring water piped or collected in large well. Sampled from large well at entrance to resort. Water pumped from there up to facilities.	Collection well of hot spring water at bottom of valley and close to river. Flow rate could not be assessed. Water was slightly murky (probably due to open collection well).
Caledon Casino, Hotel and Spa	Caledon	Commercial Resort	Sampled from pipe outlet that was directly above the spring point in the ground. Water flowed out into a series of pools open to the ambient conditions.	Sampling point was relatively high on a slope. Flow rate was noted as very high.
Warmwaterberg Spa	Barrydale	Commercial Resort	Sampled from a tap approximately 50m from the extraction point. Extraction point could not be accessed. However the water was piped at a fast rate and the distance negligible.	Extraction point was relatively high on a slope (above the resort). Flow rate was noted as very high. Water was a bit murky in bathing pools.
Avalon Springs	Montagu	Commercial Resort	Sampled at a tap piped 5m metres from the borehole. Borehole was drilled to 90m below the ground surface at a point located on a spur which was relatively elevated compared to the surrounding landscape.	Borehole located at relatively high elevation. Assumed that the manmade (borehole) control allowed access to aquifer of hot spring water, and not a geological structure. Flow rate seemed fairly high.
Baden Resort	Montagu	Commercial Resort	Sampled from a tap piped about 10m from extraction point. The extraction point was covered and piped, located about halfway up the slope.	It was reported that there were multiple release points of hot spring water in the vicinity; one example pointed out was about 5m from the extraction point of the sampled hot spring. Flow rate could not be assessed.
Brandvlei Correctional Services	Close to Rawsonville	Spring not in use – on property of Governmental Correctional Facility	Sampled from pipe out ground about 5m from extraction point. Water flows along channel into a series of two large pools before being pumped into the vlei.	Extraction point on a slope at relatively high elevation to surrounding landscape.

Table 3-2: Continued observations of hot springs during water sampling

Name of Facility	Location	Current Use	Sampling Point and Water System	Additional Notes
Goudini Spa	Rawsonville	Commercial Resort	Sampled from a tap directly above a large collection well (about 2m above). From the collection well the water is pumped throughout the resort.	No significant elevation of collection point. Flow rate could not be assessed. Geological outcrops gave evidence of significant folding around the resort with the break in the hillside possibly due to a fault running though where the resort was located.
The Baths	Citrusdal	Commercial Resort	Sampled directly from source, i.e. where hot spring water flows from rock out the ground. Sampling point was contained within an enclosed room and thereafter was collected before being pumped around the resort.	Source is relatively elevated within the valley where the resort is found. Flow rate was low to medium from observations. Geological outcrops gave evidence of a fault through the valley (orthogonal to regional cape folding).

3.2. Geophysical Data

The second round of the investigation focused on geophysical survey data to analyse the geological structure and thus to better assess the geothermal gradient and identify potential reservoirs. This is important as the surface physiochemical data as well as the reservoir temperature estimates, from the geothermometer calculations, needed to be evaluated against the depth to the reservoir in order to establish a geothermal gradient amongst other important factors. Based on the results from the first round, the hot springs at Brandvlei and Calitzdorp were chosen as areas with the highest potential for geothermal resources due to the highest temperatures measured at these locations. Due to the existing geophysical data (taken from literature) being in proximity to Calitzdorp hot spring, this was the location selected for further analysis.

As mentioned above, the geophysical survey data, which is discussed in later chapters, was a magneto-telluric survey collected as part of the Agulhas-Karoo Geoscience Transect (AKGT) conducted over 2003 to 2006. The project consisted of four line surveys, with the one discussed in this thesis named MT-2. The other three line surveys continued on into the interior of the country to cover the Karoo basin and onto the edge of the Kaapvaal Craton, thus were not relevant to this study. The AKGT project as a whole was aimed at analysing the Beattie Magnetic Anomaly, however the data has since been deemed useful for analysing the geology of the Karoo Basin as well as the Cape Fold Belt. It has been pointed out in multiple papers that there is a lack of data with depth when it comes to the Cape Fold Belt, especially with regards to geophysical data which can be used for better understanding the complex structural geology [Booth, 2009; Mielke and de Witt, 2009; Weckmann et al., 2012].

The data for MT-2 was collected along a line survey, from Mossel Bay to Prince Albert, where it passed ca. 27km away from the Calitzdorp sampling point at its closest point. The close proximity as well as the similar geology allowed the use of this data in direct relevance to the aim of this study; i.e. the geothermal potential of the Calitzdorp Spa. The paper by Weckmann et al. (2102) notes the location "Warmbad" which was actually the same location as the Calitzdorp Spa. The survey ran perpendicular to the general strike of the contacts and structural features (such as folds and faults) such that a cross sectional profile through all the major formations and features of the Cape Fold Belt can be seen and thus a better understanding of the geological structure can be interpreted. As explained by Weckmann et al. (2012), the line survey consisted of 52 stations that were spaced at ca. 2km intervals, seen in Figure 3-1 below. "*Electric and magnetic field variations (1 kHz-1 mHz) were measured using S.P.A.M. MkIII and CASTLE instruments, Metronix induction coils and Ag/AgCl and processed according to Ritter et al. (1998) and Weckmann et al. (2005)*" [Weckmann et al., 2012].

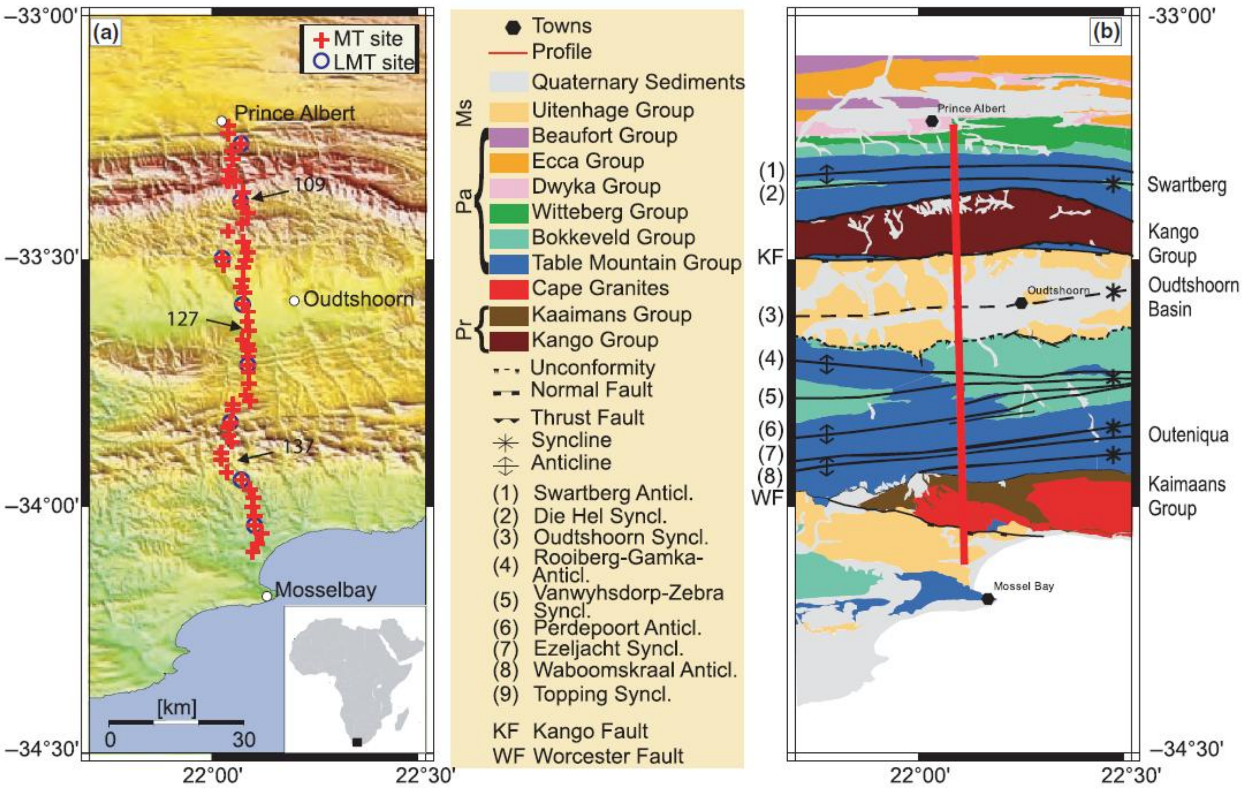


Figure 3-1: Map showing station locations of magneto-telluric survey conducted in proximity to Calitzdorp hot spring.

4. Results and Calculations

4.1. In-field Water Parameter Measurements

The in-field measurements shown in Table 4-1 were completed with the collection of water samples for major cation analysis by means of ICP-AES. The temperature measurements showed that only two locations were lower than 40°C, with four that were between 40°C and 50°C and only one location that measured above 50°C. The location measured over 50°C was the Brandvlei hot spring and has historically been the hottest natural spring in the Cape Fold Belt according to the literature [Kent, 1949; Diamond and Harris, 2000; Tshibalo et al., 2010]. The highest temperature measured there was 64°C (Diamond and Harris, 2000) which is notably higher than the current measurement of 57.6°C.

The accompanying measurements of pH, electric conductivity (EC) and total dissolved solids (TDS) were all within expected ranges. The pH of the samples show that the hot springs were all slightly acidic to neutral, ranging from 5.58 to 7.11, which would fall into the normal range of meteoric water. The slight acidity could also be slightly influenced by any interactions with minerals in the host rock of the underground reservoir however no significant interaction was inferred. Generally the EC and TDS levels in water follow a similar trend but are not directly correlated. EC ranged from 0.10 mS to 0.37mS and TDS ranged from 50ppm to 210ppm. Both were within the expected ranges for natural spring water. The highest values for each parameter was recorded in sample HS2 from Caledon but were still considered reasonable measurements.

Table 4-1: In-field measurements of hot springs along Cape Fold Belt.

Location	Sample ID	Temperature (°C)	pH	EC (mS)	TDS (ppm)
Calitzdorp	**HS1**	47.3	6.51	0.26	130
Caledon Spa	**HS2**	45	6.23	0.37	210
Test Blank	**HS3**	20.4	5.64	0	0
Warmwaterberg	**HS4**	41.4	6.62	0.21	110
Baden Resort	**HS5**	36.4	6.02	0.13	70
Avalon Springs	**HS6**	37.8	7.11	0.19	100
Brandvlei	**HS7**	57.6	5.80	0.13	60
Goudini Spa	**HS8**	44.5	6.07	0.19	110
Citrusdal	**HS9**	41.2	5.58	0.10	50

Sample HS3 was included to ascertain the QA/QC of the whole sample collection procedure from sample collection to transport to the lab procedure during analysis. The water used in HS3 was de-ionised water, processed through reverse osmosis, and used as a standard in most laboratory procedures. As can be seen in Table 4-1, the EC and TDS values were zero as expected.

4.2. Results of Major Cation Analysis

The water samples were analysed at the Central Analytical Facility at Stellenbosch University. The analysis was done using an Inductively Coupled Plasma - Atomic Emission Spectroscopy (ICP-AES) machine. Only selected major cations were analysed for as these were chosen specifically for the geothermometry calculations intended for this study. The results can be seen in Table 4-2 as presented in the lab report however the location corresponding to the sample ID have subsequently been included for ease of reference. The original lab report is shown in Appendix B. All results were reported above a detection level of 0.1mg/l (or ppm) with the exception of iron which had a detection level of 0.05mg/l. All the concentrations of the blank sample (HS3) were reported below the level of detection (LOD). The blank sample successfully showed reliability in the analysis and lack of contamination or compromise within the sampling procedure and thus fulfilled its purpose in the assessment of QA/QC of the methodology and will not be included in any further comparisons, calculations or discussions.

Table 4-2: Concentrations of major cations from water samples of hot springs.

Sample ID	Cation	Ca	Fe	K	Mg	Na	Si
	Unit	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
	LOD	0.1	0.05	0.1	0.1	0.1	0.1
	% Recovery	108.4	108.5	105.1	108.7	101.4	101.16
HS1	Calitzdorp	10.22	2.83	10.6	4.62	16.49	18.7
HS2	Caledon Spa	7.51	3.07	5.07	3.20	16.77	24.6
HS3	Test Blank	< LOD	< LOD	< LOD	< LOD	< LOD	< LOD
HS4	Warmwaterberg	15.72	0.72	9.15	2.74	21.69	22.5
HS5	Baden Resort	3.24	< LOD	2.90	2.01	6.68	12.1
HS6	Avalon Springs	12.28	< LOD	3.84	2.96	8.56	13.4
HS7	Brandvlei	3.02	< LOD	1.98	1.94	8.14	17.9
HS8	Goudini Spa	6.21	< LOD	0.92	1.64	3.97	13.6
HS9	Citrusdal	2.34	< LOD	1.98	1.91	7.35	10.8

The cation with the highest concentration in all cases was silicon (Si) which was expected given the geology of the Cape Fold Belt being mainly sedimentary. This highlighted the relevance of using the silica geothermometry in the following sections. The concentration of silicon ranged from 10.81mg/l to 24.56mg/l. Sodium (Na) ranged from 4.0mg/l to 21.7mg/l and was the second highest cation concentration in all samples, with calcium next highest, with one exception. The exception was the sample taken from Goudini Spa (HS8) where this was reversed, i.e. calcium was second highest and sodium was third highest in sample HS8. Calcium ranged from 2.34mg/l to 15.72mg/l. Also in the case of Calitzdorp, the potassium (K) is slightly higher than calcium. For the rest of cations in the samples, potassium was the fourth highest concentration tested for and ranged from 0.92mg/l to 10.60mg/l. The concentration of magnesium (Mg) ranged from 1.64mg/l to 4.6mg/l and iron (Fe) ranged from below level of detection to 3.07mg/l. Although iron was not used for any of the geothermometry calculations, it was included as a cation of interest when considering water quality.

4.3. Calculation of Geothermometers

The estimated temperatures calculated from the geothermometers were calculated as minimum temperatures of the reservoir supplying the hot springs. While 20 geothermometer equations were considered, only certain geothermometers were deemed relevant and applicable. The temperature estimates from most of the geothermometers are discussed below, with the respective authors, and thereafter the method of selection is discussed. The calculations followed the equations shown and explained in the literature review (Chapter 2). The ionic exchange geothermometers have been split up into Na-K geothermometers and other ionic exchange geothermometers. The other ionic exchange geothermometers comprise those that have been adapted from the Na-K geothermometer which mainly focuses on the Na-K-Ca geothermometer with some that also include Mg.

The unit of concentration required for the ionic exchange calculations were molal units (mol/kg) as specified by the relevant literature. This required conversion from units given by the lab report (mg/l) using the respective molar masses. It was assumed that 1.00kg/l could be used for water (the solvent for purposes of molal units) and that no significant difference would be made in factoring out the cation masses or the change in density due to a change in temperature of the sample during analysis. For the silica based calculations, the silicon cation concentration (given in mg/l) was converted to equivalent silica cation concentration (in mg/l). Since the lab reported on the concentration of silicon (Si) and the concentration needed for geothermometry was for the silica (SiO_2), the oxygen component was included through stiochiometric equations. This was done by finding the number of moles of silicon, then multiplying by two to get the equivalent number of moles of oxygen and finally summing together the mass of silicon (mg), given by number of moles multiplied by the molar mass, and similarly the mass of oxygen. The calculated concentrations are shown in Table 4-3 below.

Table 4-3: Concentrations converted to the required units.

Cations	Ca^{2+}	K^+	Mg^{2+}	Na^+	Si^{4+}		O^{2-}	SiO_2
Units	mol/kg	mol/kg	mol/kg	mol/kg	mg/l	mmol/l	mmol/l	mg/l
Calitzdorp	2.55×10^{-4}	2.71×10^{-4}	1.90×10^{-4}	7.17×10^{-4}	18.7	0.67	1.33	61.44
Caledon	1.87×10^{-4}	1.30×10^{-4}	1.32×10^{-4}	7.29×10^{-4}	24.6	0.87	1.75	80.52
Warmwaterberg	3.92×10^{-4}	2.34×10^{-4}	1.13×10^{-4}	9.43×10^{-4}	22.5	0.80	1.60	73.74
Baden	8.08×10^{-5}	7.41×10^{-5}	8.27×10^{-5}	2.91×10^{-4}	12.1	0.43	0.86	39.61
Avalon	3.06×10^{-4}	9.82×10^{-5}	1.22×10^{-4}	3.72×10^{-4}	13.4	0.48	0.95	43.87
Brandvlei	7.53×10^{-5}	5.07×10^{-5}	7.98×10^{-5}	3.54×10^{-4}	17.9	0.64	1.27	58.52
Goudini	1.55×10^{-4}	2.36×10^{-5}	6.74×10^{-5}	1.73×10^{-4}	13.6	0.48	0.97	44.59
Citrusdal	5.84×10^{-5}	5.06×10^{-5}	7.87×10^{-5}	3.20×10^{-4}	10.8	0.38	0.77	35.44

4.3.1. The Na-K Geothermometers

Although the literature has shown that the Na-K geothermometer as most applicable to high temperature systems, these equations were still included to check if the resultant estimated temperatures were within a realistic range considering the circumstances. The most commonly used Na-K geothermometer found in literature was Fournier's 1979 revision of his own work founded by empirical data in 1966. Subsequently multiple equations have been derived from revisions of Fournier's work or other empirical studies; and various examples are Arnórsson et al. (1983), Nieva and Nieva (1987), Giggenbach (1988), Verma and Santoya (1997) and Arnórsson (2000). All of these equations resulted in very high estimates (250°C to 1000°C), which were deemed unrealistic in the Cape Fold Belt setting, since these temperatures are more likely to occur in regions of high tectonic activity within a few kilometres of the surface.

The range of temperatures estimated by the Na-K geothermometers (shown below in Figure 4-1) were as follows: 245°C to 366°C for Fournier (1979), 287°C to 387°C for Nieva and Nieva (1987), 295°C to 470°C for Arnórsson (2000) and 619°C to 972°C for Giggenbach (1988). The analysis and applicability of these temperature estimates are discussed in the next chapter however it was easily distinguished that those estimates were significantly higher than the other geothermometers.

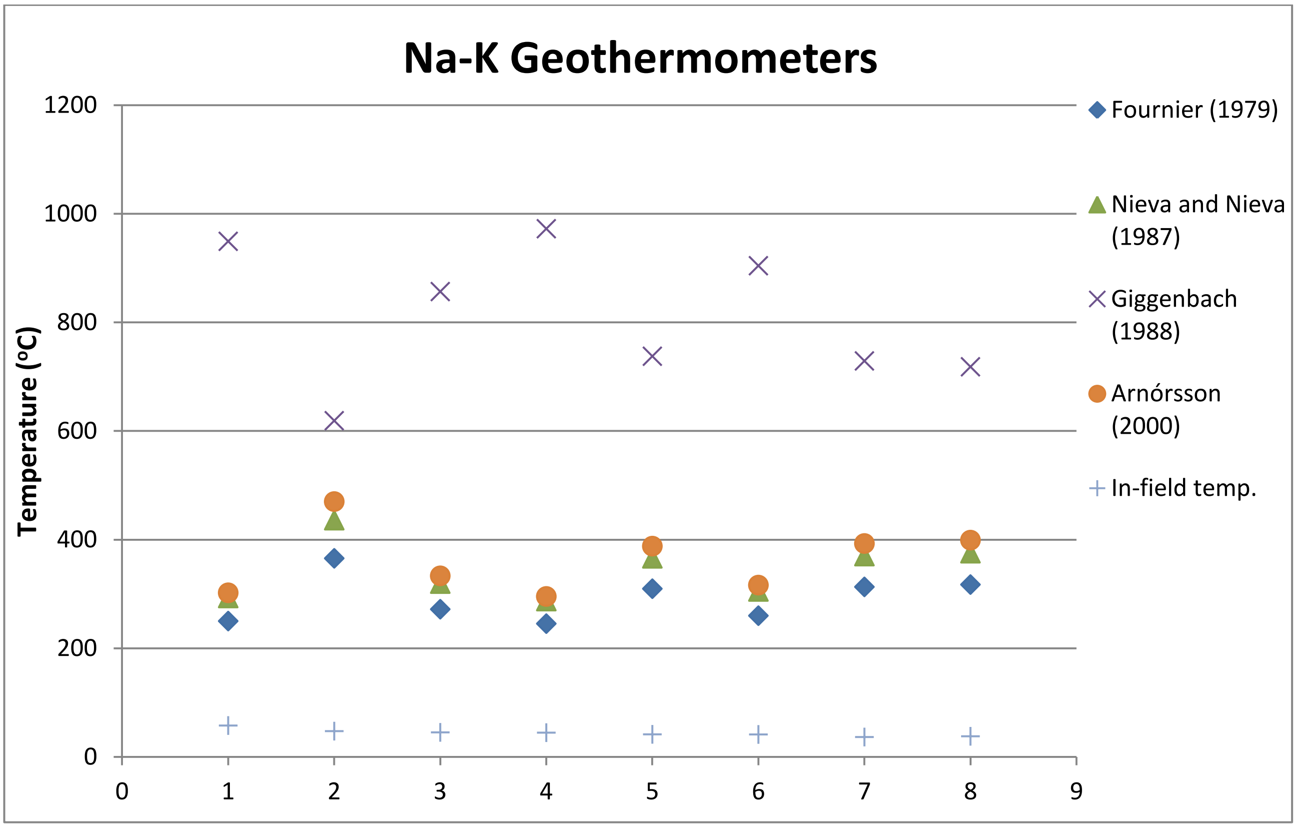


Figure 4-1: The estimated temperature of the Na-K geothermometers at each sampling location. Locations are as follows; 1 Brandvlei, 2 Calitzdorp, 3 Caledon, 4 Goudini, 5 Warmwaterberg, 6 Citrusdal, 7 Baden Resort, and 8 Avalon Springs. The in-field temperature is included as a reference point.

4.3.2. Other Ionic Exchange Geothermometers

The development of the Na-K geothermometers to include calcium or magnesium allowed for study of lower temperature geothermal systems. This was originally found by Fournier and Truesdell (1973) however a revision by Kharaka and Mariner (1989) was found to be useful for this study. Due to the use of geothermometry being highly dependent on the geology, the Na-K-Ca geothermometer corrected with Mg by Fournier and Potter (1979) has not proven applicable to this study.

The estimated temperatures calculated for the following ionic geothermometers can be viewed in the graph below (Figure 4-2). The Na-K-Ca geothermometers ranged from 82°C to 136°C for Fournier and Truesdell (1973), and 48°C to 116°C for Kharaka and Mariner (1989). The Na-K-Mg geothermometer of Nieva and Nieva (1987) resulted in estimated temperatures within a range of 142°C to 203°C. The Mg corrected Na-K-Ca geothermometer by Fournier and Potter (1979) ranged from 792°C to 1212°C. During the calculations of the Mg corrected Na-K-Ca geothermometer, the 'ΔT' calculated was negative, and as a result was established as inappropriate for this study (as stated by the authors). The K-Mg geothermometer by Giggenbach (1988) produced unrealistically low estimates of 12°C to 48°C. The temperature estimates from Giggenbach (1988) were also deemed unrealistic due to some of the estimates being lower than the surface temperature measurements of the respective springs.

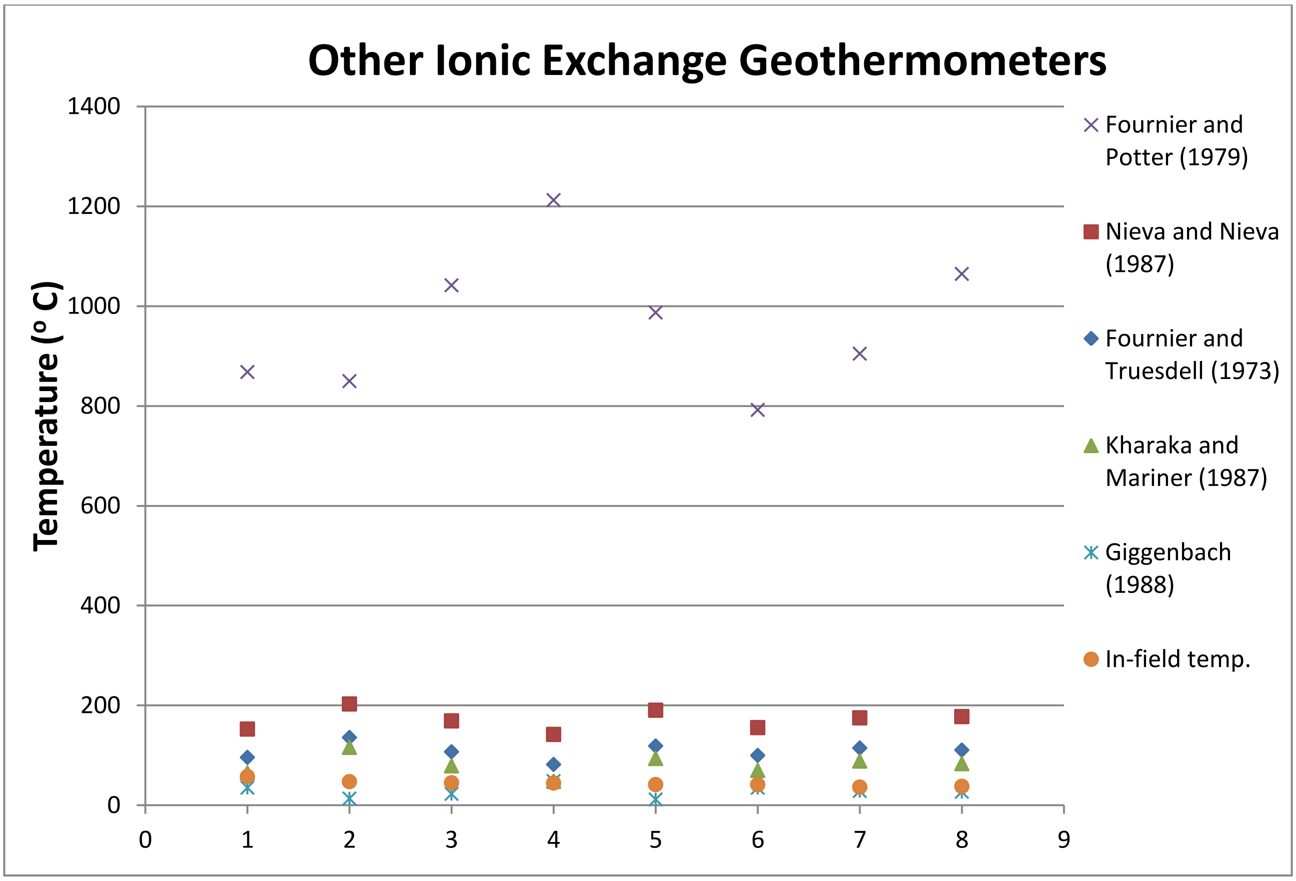


Figure 4-2: The estimated temperature of the other ionic geothermometers at each sampling location. Locations are as follows; 1 Brandvlei, 2 Calitzdorp, 3 Caledon, 4 Goudini, 5 Warmwaterberg, 6 Citrusdal, 7 Baden Resort, and 8 Avalon Springs. The in-field temperature is included as a reference point.

4.3.3. The Silica Geothermometers

The equations empirically found by Fournier (1977) have been widely used, for a large range of temperatures, and proven to be reliable provided the correct form of silica is considered for the system being studied. Verma and Santoyo (1997) critically evaluate Fournier's silica geothermometer amongst others and used statistical methods to correct for errors and outliers. The equation was further developed by Verma (2000) and deemed relevant to this study. The quartz based silica geothermometers from Fournier and Potter (1982) and Arnȯrsson (2000) were also considered.

The estimated temperatures of the silica geothermometers was presented in a graph below (Figure 4-3). Of the silica geothermometers, the quartz based equations fell into two ranges of similar values, a higher grouping around 200°C and a lower grouping around 100°C, with the chalcedony based geothermometer slightly lower than the latter quartz based range. The estimates from the chalcedony geothermometer ranged from 55°C to 98°C where as the lower grouping of two quartz-based geothermometers from Fournier (1977) and Verma (2000) ranged within 80°C and 125°C, each location within a ±5°C margin. The higher grouping from Fournier and Potter (1982) and Arnȯrsson (2000) fell in the range of 171°C and 223°C, each location within a ±7°C margin.

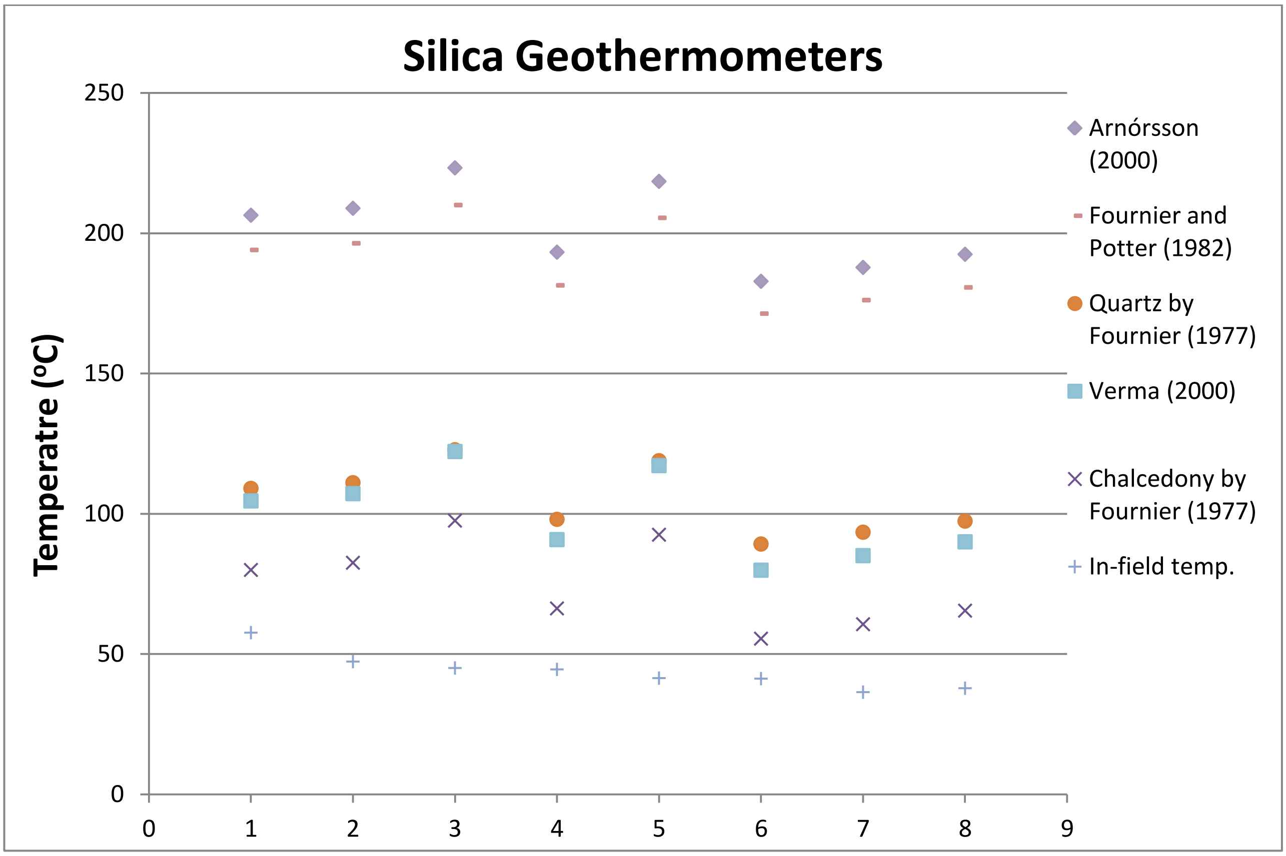


Figure 4-3: The estimated temperature of the silica based geothermometers at each sampling location. Locations are as follows; 1 Brandvlei, 2 Calitzdorp, 3 Caledon, 4 Goudini, 5 Warmwaterberg, 6 Citrusdal, 7 Baden Resort, and 8 Avalon Springs. The in-field temperature is included as a reference point.

4.3.4. Determination of the Most Reliable Set of Geothermometers for this Study

A selection of geothermometers was established from the multitude of geothermometers found in thirteen different published articles that were potentially applicable to this study. The various temperature estimates calculated from all the geothermometers covered such a large range which would not allow any one temperature estimate to be taken with any confidence. A narrow set of temperature estimates was necessary for a more concise temperature range in order to apply an estimated temperature at a location with reasonable confidence. The initial process filtered the twenty geothermometers considered down to eight which were shown as the "selected geothermometers" in the Figure 4-4 below. This figure is to illustrate the vast difference in range obtained by the initial filtering process. Appendix C shows a complete table of the estimated temperatures for all 20 geothermometers considered with some intermediate terms included which were necessary for certain calculations. There were three geothermometers that resulted in temperatures below zero degrees Celsius; the Na-Mg geothermometer by Giggenbach (1988) and two silica based geothermometers by Fournier (1977). The Na-Mg geothermometer was extrapolated from the chemical relationship between the K-Na and K-Mg geothermometers, however its reliability as a geothermometer is much lower and is discussed as being highly sensitive to mixing with non-equilibrated water. The amorphous silica and beta cristobalite silica geothermometers by Fournier (1977) were discussed as being applicable to systems where that type of silica was in majority abundance. This is especially common in very low temperature systems.

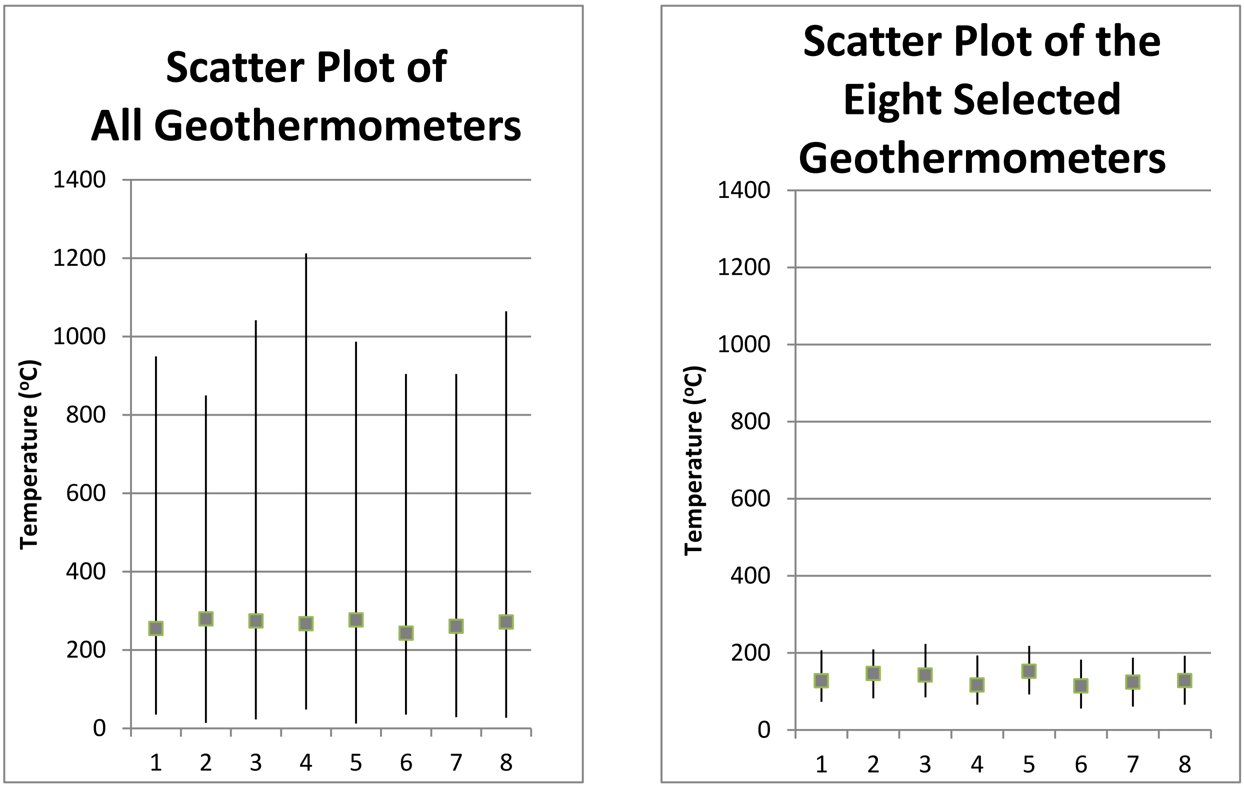


Figure 4-4: Scatter plots showing the difference in the ranges of estimated temperature between all and selected geothermometers at each sampling location. Locations are as follows; 1 Brandvlei, 2 Calitzdorp, 3 Caledon, 4 Goudini, 5 Warmwaterberg, 6 Citrusdal, 7 Baden Resort, and 8 Avalon Springs. Each line starts at the minimum temperature estimate and ends at the maximum temperature estimate with the average marked as a point along the line.

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 lower bound was the estimated temperature of the reservoir which could not be lower than the measured temperature of the water at surface, and the upper bound was based on the generally accepted understanding that this region of study has a low geothermal gradient (between 20°C/km and 45°C/km) and 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 5km, 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), Arnȯrsson (2000) and Verma (2000) were considered 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).

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, 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. It was found that many geothermometers were empirically based and thus heavily influenced by the geology of the study area, resulting in the various ionic exchange geothermometers each having a high potential for irrelevance.

Table 4-4: Estimated minimum temperatures calculated using selected geothermometers found in literature.

Geotherm-ometer Author	**Estimated Minimum Temperature of Geothermal Reservoir (^{o}C)**							
	Brandvlei	**Calitzdorp**	**Caledon**	**Goudini**	**Warm-waterberg**	**Citrusdal**	**Baden**	**Avalon**
Na-K-Ca Fournier and Truesdell (1973)	96	136	107	82	119	100	115	111
Na-K-Ca Kharaka and Mariner (1989)	65	116	79	48	94	70	88	83
Na-K-Mg Nieva and Nieva (1987)	153	203	169	142	190	156	175	178
Chalcedony Fournier (1977)	80	83	98	66	93	55	61	65
Quartz (Max. Steam loss) Fournier (1977)	109	111	123	98	119	89	93	97
Quartz Fournier and Potter (1982)	194	196	210	181	205	171	176	181
Quartz Arnórsson (2000)	206	209	223	193	218	183	188	192
Quartz Verma (2000)	105	107	122	91	117	80	85	90

With two types of silica based geothermometers still under consideration, chalcedony and quartz, an assessment on which type was most probable in the sampled locations was necessary as only one type could be the dominant silica present. Agreement with the ionic exchange geothermometers was used as the determining factor between which of the two types were to be used. While the quartz geothermometers of Fournier and Potter (1982) and Arnórsson (2000) agreed loosely with Nieva and Nieva (1988), the quartz geothermometers of Fournier (1977) and Verma (2000) and the chalcedony geothermometer of Fournier (1977) were closest to the Na-K-Ca geothermometers of Fournier and Truesdell (1973) and Kharaka and Mariner (1989). The chalcedony geothermometer did agree with the latter two Na-K-Ca geothermometers within $^{-}\pm 25^{o}$C however the two lower quartz geothermometers were in much closer agreement (within $\pm 13^{o}$C). Thus the chalcedony geothermometer was no longer considered in this study.

Of the seven geothermometers left, the estimated temperatures were found to group into two ranges. The upper grouping consisted of three temperature estimates with one ionic exchange geothermometer and two silica geothermometers whereas the lower grouping had two of each type of geothermometer. The agreement between different types inferred reliability of the temperature estimate, and with the lower grouping consisting of four geothermometers of two different types, it was chosen as the more reliable set of temperature estimates for this study.

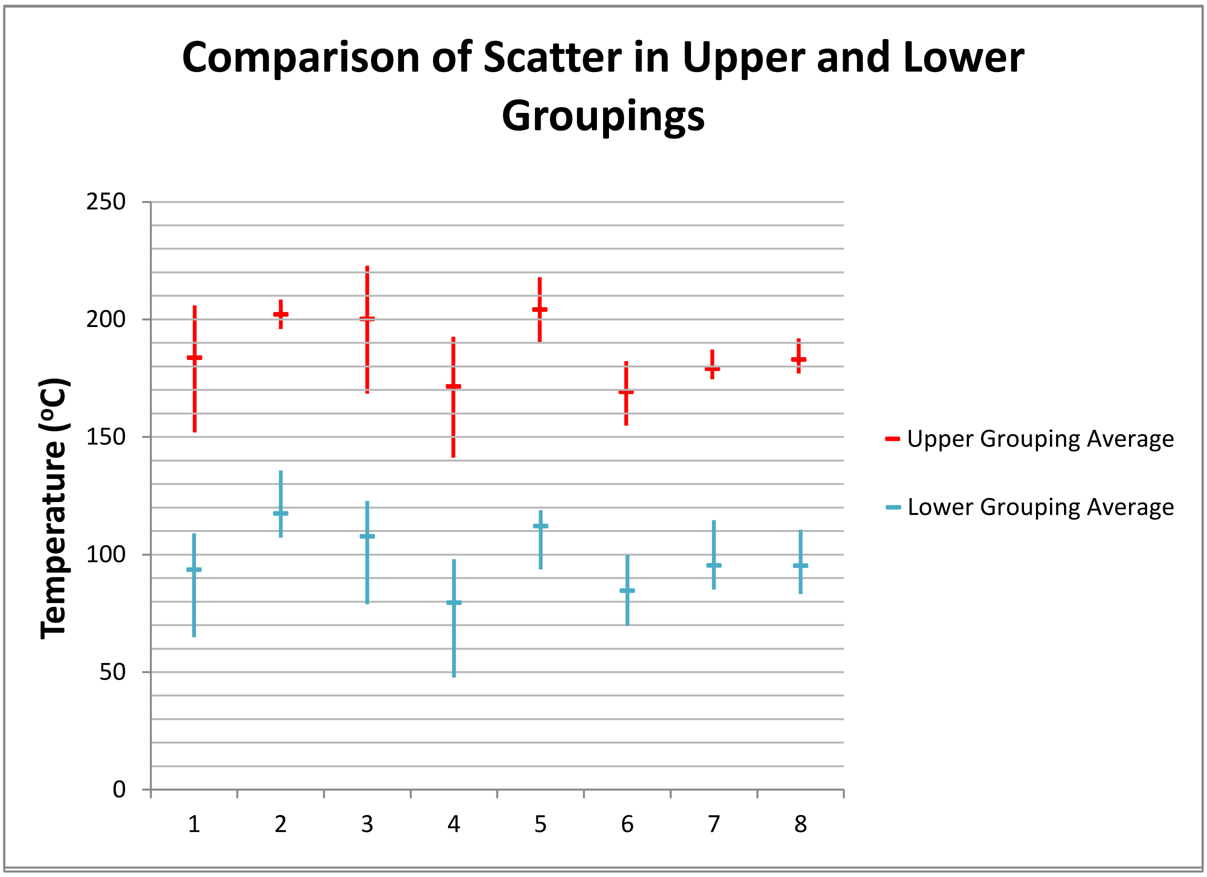
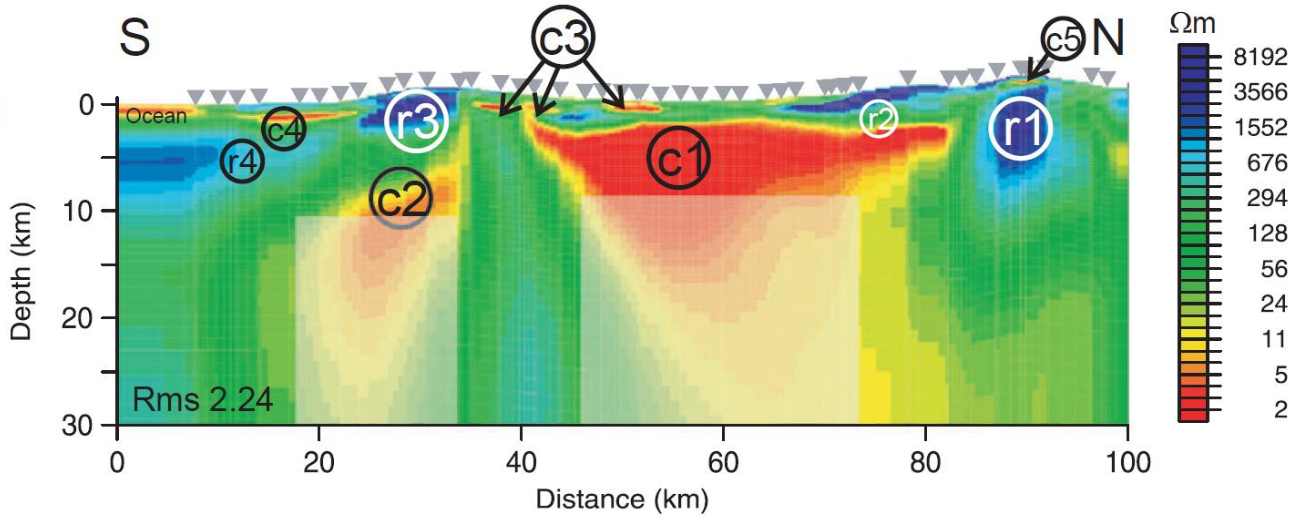


Figure 4-5: Scatter plots showing the range of estimated temperatures for two groupings of estimated temperatures at each sampling location. Locations are as follows; 1 Brandvlei, 2 Calitzdorp, 3 Caledon, 4 Goudini, 5 Warmwaterberg, 6 Citrusdal, 7 Baden Resort, 8 Avalon Springs. Each line starts at the minimum and ends at the maximum temperature estimate with the average marked as a point along the line for each of the two groupings. The upper grouping consisted of the Na-K-Mg geothermometer by Nieva and Nieva (1987), quartz based silica geothermometers by Fournier and Potter (1982) and Arnórsson (2000). The lower grouping consisted of Na-K-Ca geothermometers by Fournier and Truesdell (1973), and Kharaka and Mariner (1989) as well as the quartz based silica geothermometers by Fournier (1977) and Verma (2000).

4.4. Inversion Models from Geophysical Data

Weckmann et al. (2012) processed the magneto-telluric data, collected over the 100km line from Mossel Bay to Prince Albert, by means of inversion and produced a cross sectional profile up to 30km in depth and covering 100km between Mossel Bay and Prince Albert (shown in Figure 4-6 below). This profile showed the resistivity of the underlying rocks with depth. Due to the interference by strong shallow signals (noted as c1 and c2), only a depth of ca. 10km was taken with confidence and analysed with regards to the geological structure. There were a number of distinct areas of low and high resistivity within the profile. Weckmann et al. (2012) labelled the areas of high resistivity r1-r4 and the areas of low resistivity were referred to as conductive bodies and were labelled c1-c5 on the profile.



<u>Figure 4-6</u>: The full profile of MT-2 sourced from Weckmann et al. (2012). This profile shows the relative resistivity with depth along a line survey from Mossel Bay to Prince Albert, ca. 100km along the surface from south to north respectively. The grey arrows along the surface demarcate the approximate location of each data collection point. The labels 'r1-r4' and 'c1-c5' were placed by the original author and have been utilised in this study in a similar way to the source article.

While the same labels have been used as Weckmann et al. (2012), new descriptions have been given to the shapes of low and high resistivity for the purpose of this thesis. The areas of high conductivity ranged in size and shape however could be split into the larger bodies of c1 and c2 compared to the very thin and shallow bodies of c3, c4 and c5. The area indicated as c1 was significantly large in both length and depth and, although the deeper boundary was not defined with confidence, it covered a length of approximately 40km and a depth of about 7km, excluding the undefined tail that was conservatively disregarded. The upper boundary of c1 was well defined and could be indicative of a geological boundary, especially with the parallel trend of the bottom boundaries of r2 and c3. The southern boundary of c1 had a northwards dip and extended almost to the surface where as the northern boundary had an abrupt boundary with a steep dip towards the south. Similarly c2 covered a depth of about 7km however the shape was less laterally extensive and formed a wedge shape. The northern boundary followed a steeply southwards dipping plane and appeared to extend to the surface similar to the southern edge of c1. The other conductive bodies were up to a kilometre thick and up to 10km in length, all within 3km of the surface. The three conductive bodies labelled as c3 were in close proximity to c1 and c2, and with another survey to collect data towards the east or west of this profile, it would be determined if there is a link between these bodies. While only noted as the ocean, this conductive body in the south had a strong conductive signal with a thin horizontal shape.

The size and shape of the signals of resistivity varied quite substantially throughout the profile, with only two of them that extended to the surface. The body labelled r1 had significant depth with a shorter lateral extent. The top boundary had a gently dipping southwards boundary where as the northern and southern boundaries were both steeply dipping towards the south. The resistive body of r2 was relatively shallow and extended over a significant length of the surface. The very thin resistive body at surface (above c5) could be the northern extension of r2 however the gap of ca. 2km in the signal was deemed significant enough to be a separate body. The shape of r2 tapered towards the south with the bottom boundary gently dipping to the south (in the northern part) and gradually became horizontal in the south. Similarly r3 extended to the surface and had a greater length than depth. The northern boundary was steeply dipping to the south, in a similar trend to the surface extension of body c2. The resistive body r4 was relatively horizontal and constant in shape laterally. The body was about 3 - 5km thick with an undetermined length as it appeared to continue under the ocean. The unlabelled resistive body between c1 and c3 was a small but strong signal and appears sandwiched between those conductive layers.

4.5. Regional Geological Structure

The regional geology was important to analyse in the overall assessment of geothermal potential in the region as well as to establish relevance between the MT survey and the Calitzdorp hot spring. The geology was analysed by understanding the three dimensional structure of the geological formations through studying the published geological maps and then constructing the two cross sections presented in this thesis. The discussion of the main features from the geological maps and two cross sections was used to show how the geology has continuity from east to west, mainly due to the formation and subsequent deformation of the Cape Supergroup in this region. The geology of the region had extensive folding, with some faulting, particularly in the Cape Supergroup rocks, with both major and minor folding present. Each of the 1:250 000 geological maps of the Oudtshoorn and Ladismith regions (published by the Council for Geoscience, formerly known as the Geological Survey, in 1979 and 1991 respectively) were used to draw the geological cross-sections along the same line of the MT-2 survey and along a parallel line through the location of the hot spring respectively. The area covering the Cape Fold Belt area was shown within the blue box below in Figure 4-7 with the red boxes outlining the area of the Oudtshoorn and Ladismith geological maps used. These two maps were then shown below in Figure 4-8 and Figure 4-9 respectively, showing lines for each cross section, drawn from south to north, which allowed direct comparison with the MT-2 profile shown above.

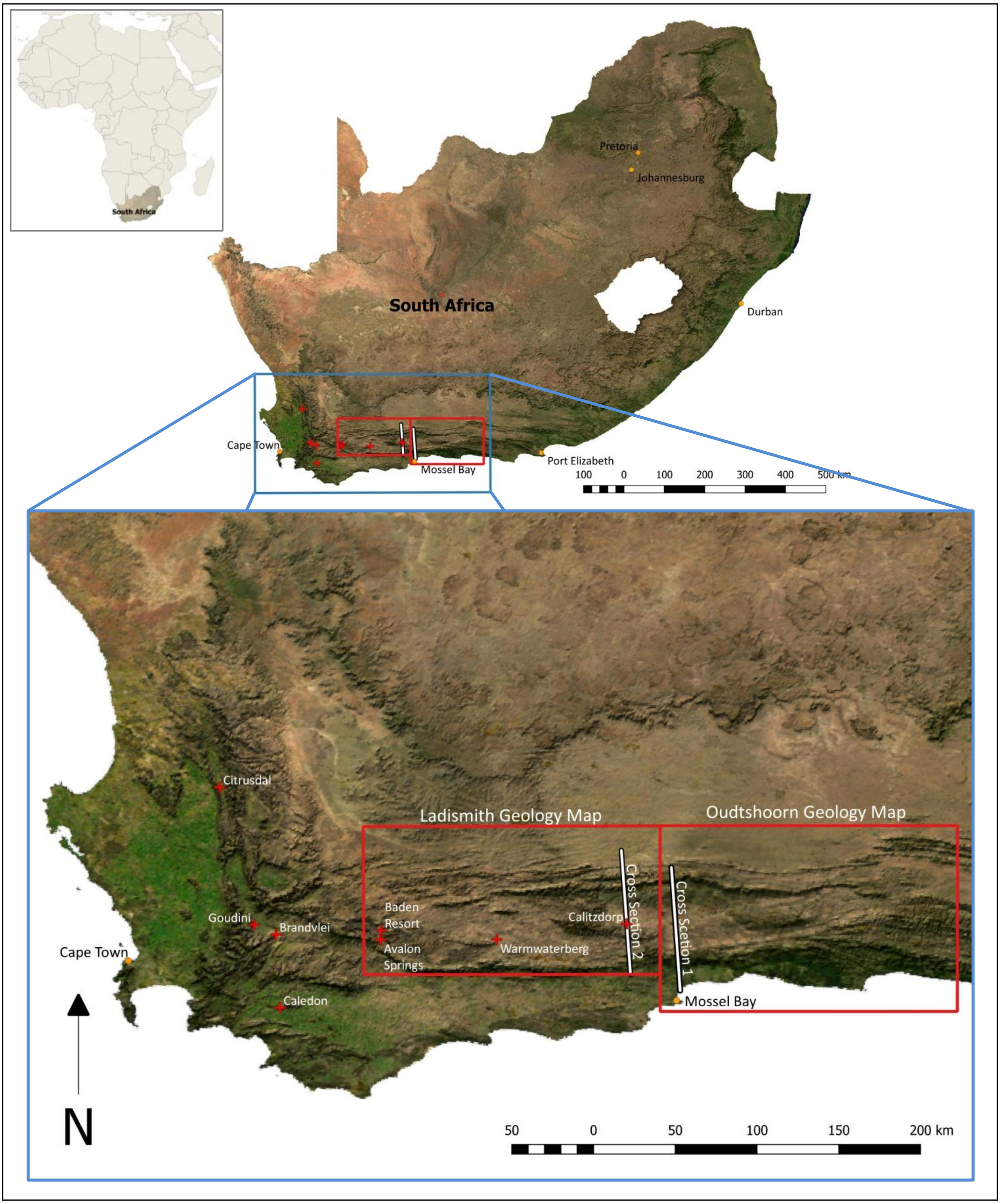


Figure 4-7: Regional map (within the blue box) showing the locations of the hot springs, the cross sections and the areas covered by each of the two geological maps used. Reference maps are shown above in the form of a cropped satellite image of South Africa as well as a basic outline of Africa (in grey).

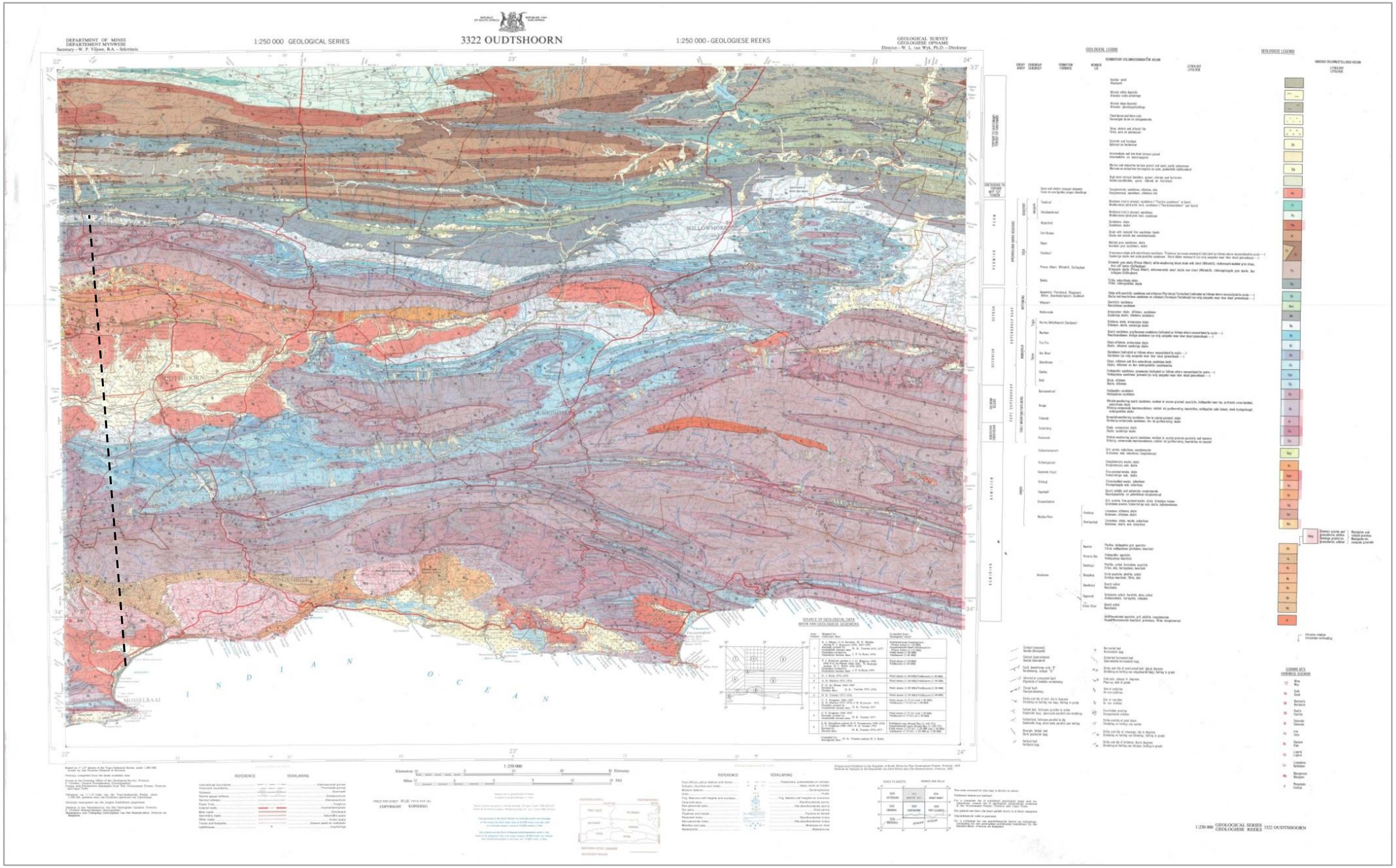
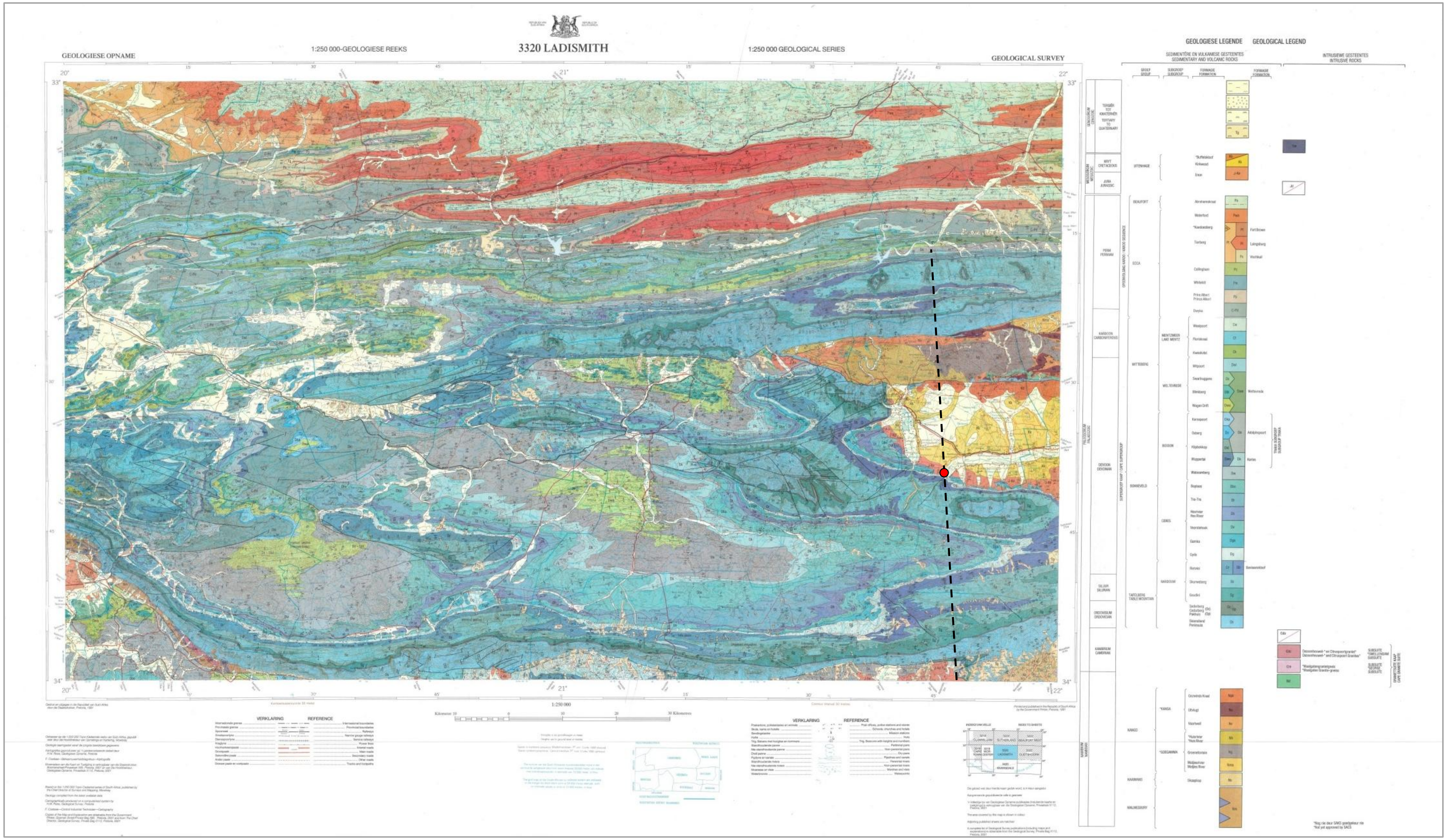


Figure 4-8: The 1:250 000 geological map of Oudtshoorn, as published by the Council for Geoscience of South Africa, with the addition of the dashed line to indicate both the MT-2 survey line as well as the line over which cross section 1 was taken.



<u>Figure 4-9</u>: The 1:250 000 geological map of Ladismith, as published by the Council for Geoscience of South Africa, with the addition of the dashed line to indicate the line over which cross section 1 was taken and a red circle to indicate the location of the Calitzdorp hot spring.

One of the main features of this region was the Oudtshoorn basin that was formed due to a listric normal fault that has an east-west strike with the hanging wall to the south. This resulted in a depression in which relatively young Jurassic-Cretaceous sediments of the Uitenhage Group (which includes the Enon Formation) formed as well as overlying deposition of more recent sediments [Muir et al., 2017]. These young rocks were surrounded by the Cape Supergroup to the south and by the much older Kango formations to the north. Due to the exposed Kango rock formations, where the well-known Kango caves tourist attraction is located, this normal fault was named the Kango fault and has a length of ca. 270km. The main deposition of younger formations which make up the basin was ca. 80km from east to west with two smaller portions of the Jurassic-Cretaceous rocks of 40km and 25km to the east. The other major feature was the Kaaimans group formations exposed in the south around George. These Namibian aged rocks were some of the oldest in the region and theorised to form the Pan-African basement.

Around these two lenses lie the Cape Supergroup formations, where the oldest group is made up of sandstones and named the Table Mountain Group (TMG). This was overlain by the Bokkeveld Group and then the youngest group of the Cape Supergroup named the Witteberg Group. The TMG was highly resistive to weathering and thus formed most of the high relief features in this region where as the Bokkeveld Group was easily weathered and eroded, thus forming most of the valleys. The Witteberg Group was also fairly resistive to weathering and erosion and forms some of the high relief but was less exposed due to the thinner extent of the formations and the overall major structural folding. The formations of the Witteberg Group were mostly exposed along the northern edge of the Cape Fold Belt just before one navigates into the overlying Karoo Supergroup formations. From the MT survey, the large conductive body below the Oudtshoorn basin was of particular interest together with the structural features around the Calitzdorp hot spring that could direct hydrological flow to the surface. Thus the main focus was on the TMG and the Bokkeveld Group, as these surround the Oudtshoorn basin with the TMG theorised to have secondary permeability which could allow the formation of a deep aquifer. While the Kango formation is only theorised to go to a depth of about 3km, cavities are known to form in these dolomite rock and if actual depth of the basin is greater, this formation could contribute to the aquifer system of this region.

The two cross sectional profiles through the MT-2 line and the hot spring gave a comprehensive picture of the major geological structure of the area, especially the folding of the Cape Supergroup. With the nature of such an extensively folded region, the main focus was the overall structure, primarily ensuring the major folding was accurately interpreted. Thus not all of the secondary folding was shown. Another consideration in the interpretation of the geological structure was the extent and plunge of the anticlines and synclines. Synclines and anticlines can vary in the east-west direction as well as the steepness of the plunge of the fold axis. With the overall east-west trend of contacts in the Cape Supergroup, the axes of the synclines and anticlines were parallel to this and the plunge of these axes was towards either the east or the west. The two cross sections show the relative movement of certain major synclines and anticlines over a distance of the ca. 27km between the two profiles. The cross section profiles cover between 80 and 100km over the surface and with the topography reaching a maximum of 1.8km, the relief appears almost flat. While the topography was useful in attributing more resistive formations by exposure at high relief and more erosive formations by exposure in the valleys, the scale of the cross sections rendered the change in topography virtually inconceivable without vertical exaggeration. Vertical exaggeration was not used in the cross sections presented here as it distorts the dip and vertical thickness of the layers, making interpretation of the underlying structure difficult.

The cross section along the MT-2 survey line was labelled CS1 and was located east of the Calitzdorp hot spring, i.e. the other cross section (CS2). CS1 was shown in Figure 4-10 below and was drawn from the coastline in the south at Mossel Bay to a point just south of the town of Prince Albert. The highly folded deformation of the Cape Supergroup became very apparent through the cross section, with some folds being very tight and overturned, and an overall trend was noted of the group of formations reaching greater depths when moving towards the north. This trend aligned with the generally understanding that the Cape Supergroup was formed on the southern edge of the African plate and was formed as north dipping flat sedimentary beds before experiencing intense deformation through folding and faulting.

There are two major faults noted in CS1, both normal listric faults, with both having a southern hanging wall downthrown along a shear zone that is theorised to go from sub-vertical at the surface to sub-horizontal at depth. These two listric faults are located to the north of the Oudtshoorn Basin and in close proximity to each other. The two major listric faults being in close proximity were theorised to join at depth to create a wedge shaped half graben which moved downwards as well as rotated slightly along that curved shear zone. It must be highlighted that there are two smaller faults in between these listric faults that are small in the horizontal extent and go to relatively shallow depths compared to the major listric faults. Of these two smaller faults, the northern one was a normal fault and the southern one was an oblique fault. These two smaller faults intersect at an acute angle towards the west and together with another small intersecting fault to the east form a smaller half graben. This half graben was bordered by oblique faults on the east and west with rotational downwards movement of the northern part of the half graben. These two smaller faults have been shown on the cross section even though the relative displacement of ground was minimal.

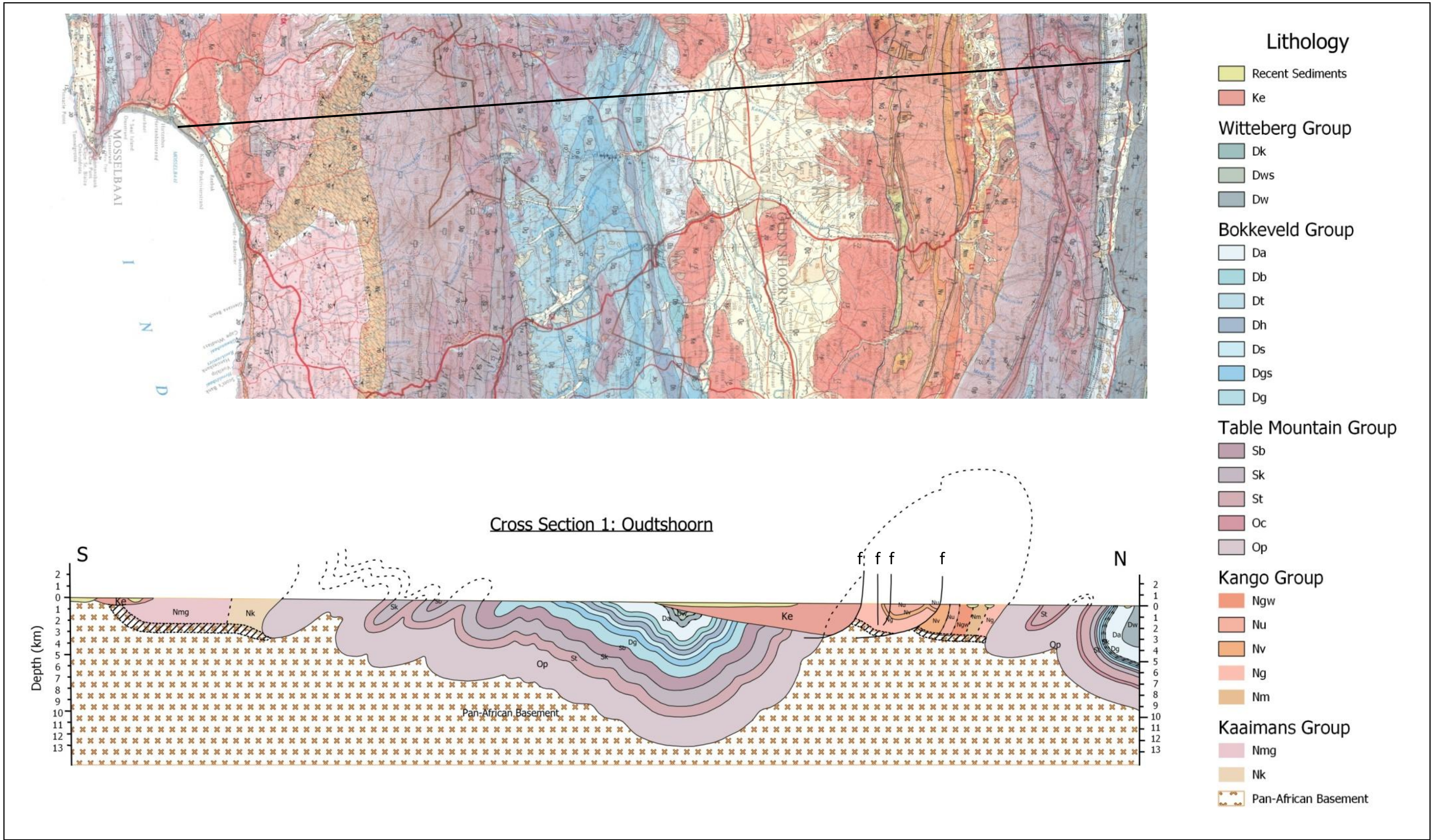


Figure 4-10: Cross section 1 shown parallel to a portion of the Oudtshoorn geological map used with a black line indicating where the cross section was drawn over. The cross section has dashed lines to indicate the extrapolated contacts either above or below the ground. The shaded areas below the Kango Group and Kaaimans Group indicate the uncertainty of the continuation of these formations with depth.

The two major listric faults have resulted in three main changes to the geology; namely the space formed in the Oudtshoorn basin where the Jurassic-Cretaceous formations of the Uitenhage Group formed, the removal through weathering and erosion of the major anticline of Cape Supergroup due to the faults creating preferential points for weathering, particularly in the highly resistive TMS group, and lastly the resultant exposure of the very old underlying Kango formations. It must be noted that the Cape Supergroup overlies the Kango formations unconformably and, with minimal surface exposure of the Kango group, the contacts between the formations were difficult to define with depth. This was similar to the Kaaimans group in the south which is theorised to form the Pan-African basement.

The Oudtshoorn basin forms a wedge shape basin of sedimentary formations that unconformably overlies the Cape Supergroup with the basin shallow in the southern edge to deep at the northern edge due to maximum movement along the listric fault. The major syncline below the Oudtshoorn basin was inferred based off three observations from the geological maps. The first and main observation was the synclinal structure evident in the Ladismith geological map (Figure 4-9) on the south western edge of the basin with an easterly plunge below the basin. The second observation was that the formations that comprise the southern section of this syncline continue along the southern edge of the basin all the way through both cross sections to the south-eastern edge of the basin. Most notably the upper most formation of the Bokkeveld Group (denoted “Da”) had a fairly large exposure at the surface of CS1. This could be attributed to secondary folding which can increase surface exposure and thus the apparent thickness. The third observation was the slivers of the lower most formation of the TMG found on both the northern and southern side of the southernmost listric fault. The slivers on the northern side were seen sporadically in the Oudtshoorn map and more continuously on the Ladismith map. The slivers on the southern side of the fault can be seen on the western part of the basin in the Ladismith map. The slivers of TMG on both sides of the fault line also inferred that the fault could have developed along the lower boundary of the TMG, with the boundary of unconformity being a plane of weakness when extensional forces were experienced in this region.

The second cross section (CS2) was drawn along a parallel line ca. 27km west of CS1 and directly through the Calitzdorp hot spring, as seen in Figure 4-11. The profile of CS2 started and ended slightly to the north when compared to the profile of CS1 which was due to the Ladismith map ending at 34°00’ south compared to the Oudtshoorn geological map which was extended down to 34°15’ to include the coastline. Thus the profile of CS2 showed none of the Pan-African basement of Kaaimans Group in the south. In CS2 the Oudtshoorn basin had the same mechanism and shape as in CS1, forming from a normal listric fault with the hanging wall in the south. It was noticeable that there was only one fault at the northern edge of the basin and none in the Kango Group in this profile, however this was not pivotal to this study as the main focus was the geology below the Oudtshoorn basin.

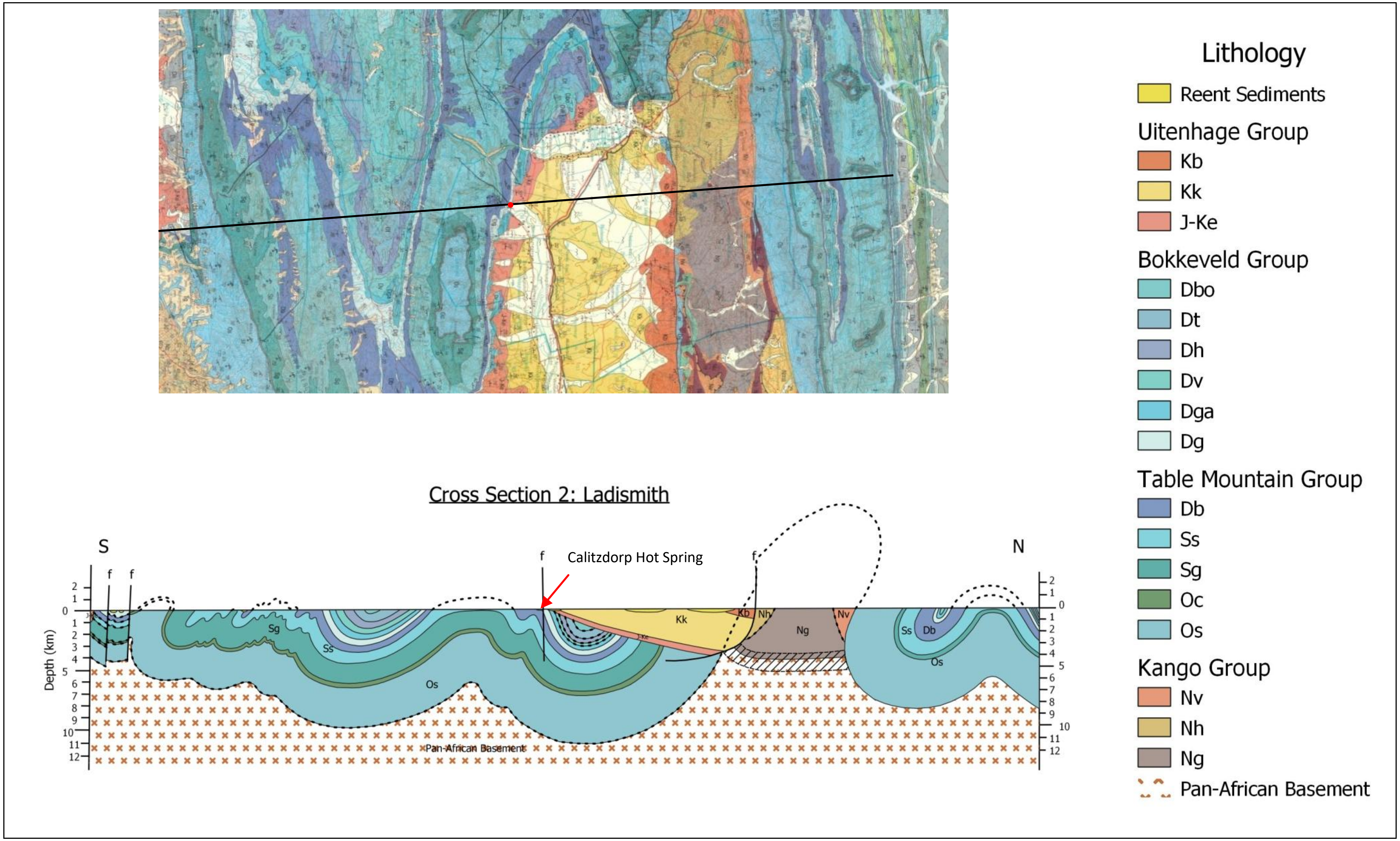


Figure 4-11: Cross section 2 shown parallel to a portion of the Ladismith geological map used with a black line indicating where the cross section was drawn over. The Calitzdorp hot spring is indicated by the red spot and red arrow in the geological map and cross section respectively. Note that the hot spring is located on a fault.

The geology within the basin was split up into three different formations from the Jurassic-Cretaceous era instead of just one, with recent sediments deposited over this, however this did not change the interpretation of this basin as a wedge shape with the thickest part of the wedge proximal to the fault in the north. However it was noted that this cross section runs close to the western edge of the basin and, assuming that the basin would thin out to the western edge, the depth of the basin would be interpreted as becoming shallower to the west. Most literature estimates the depth of the basin as up to 3km at the maximum point however the true shape and depth of the Oudtshoorn basin has not been properly mapped as no boreholes have been drilled to depth in different sections to analyse this aspect of the basin.

One of the main features of this cross section was the fault that intercepts just off the southern edge of the Oudtshoorn basin, where the Calitzdorp hot spring was located. There was minimal evidence of this fault resulting in vertical or horizontal displacement of the geology around it in the geological map and as such appears as a sub-vertical line in the cross section. It was interpreted as reaching the middle formation (the Goudini formation denoted as 'Sg') of the TMG, however this was presented as just one possibility, with another strong possibility where it reaches the lowermost formation (the Peninsula formation denoted as 'Os') of the TMG. Following the same reasoning as above, a major syncline was drawn under the basin with a major anticline extrapolated to go over the exposed Kango Group to the north of the basin. Due to the syncline plunging towards the east the bottom of the syncline, denoted here as the bottom of the TMG, did not reach as great a depth as in CS1. The other major feature of this profile was the major syncline to the south of the above mentioned syncline. This syncline had a tighter fold hinge and the axes plunged to the west steeply, resulting in this syncline not being evident in CS1. The overall trend of the Cape Supergroup was similar to CS1 in that, while intense folding was evident, there was a general dip of the Cape Supergroup to the north, due to the lowermost formation exposed in the south with the uppermost formations being overlain by the younger Karoo Supergroup in the north.

Analysis of the regional geological structure was necessary as the hot spring sampled was ca. 27km away from the MT line survey. Thus the continuity of the major geological features was established between these two profiles and resulted in the MT survey being deemed relevant and useful. Generally an understanding of the underlying rock structure can help to identify an appropriate rock formation to target based on favourable properties such as permeability and depth.

5. Discussion

The evidence collected during sampling as well as the data found in the literature was used to identify and evaluate a potential location for a feasible geothermal power plant operated as a low enthalpy system. Due to the constraint of limited funding and resources new geophysical testing was not possible as part of this study, and so published data was found for the region around Calitzdorp Spa. This data allowed for the in-depth/subsurface analysis of one of the promising locations based on the evidence collected at hot springs. This directed the study onto Calitzdorp Spa, which had the second highest potential in terms of measured in-field temperatures. The temperature estimate of the reservoir, from the geothermometry calculations, and the geophysical data, from the magneto-telluric survey, were promising for Calitzdorp which substantiated the decision. These points are further discussed in this chapter as well as the implications of a sufficient geothermal resource present and the construction of a pilot power plant, assuming further exploration beyond this study confirm the inferences made from the data.

5.1. In-field Temperature Measurements

The water temperature measurements were used as a preliminary indicator of the geothermal energy. 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 a number of different 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. Whereas the variation between seasons can be attributed to two possible factors such as rainfall, both seasonally as well as comparing seasons over different years, and air temperature variations. The main focus of the paper by Diamond and Harris (2000) was the origin of the water of the hot springs through isotope analysis and they concluded that the water of all the hot springs in the Cape Fold Belt had a meteoric origin. Since the underground reservoirs of the hot springs can be taken to be recharged by rain water, rainfall can directly influence the flow rate of water into the reservoir, and therefore influence the flow rate through and out of these reservoirs. Flow rate directly influences the temperature to which the water is heated as the longer the water stays in contact with the hot rock, the more likely it will be heated to the same temperature as the rock before leaving the reservoir. Air temperature is a more indirect factor, with much less impact, as the geothermal gradient is determined as the increase of the temperature of the ground from air temperature at surface to the temperature of the rock at the depth of the reservoir. Due to the seasonal and annual variation, both the literature temperature measurements and the current temperature measurements have been considered during this analysis.

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. Diamond and Harris (2000) conducted a few visits to majority of the hot springs in their study while monthly visits were conducted at Brandvlei, Calitzdorp and Citrusdal. The measurements based on monthly visits could be taken with confidence. Diamond and Harris (2000) showed that Brandvlei, Calitzdorp and Caledon were the only locations above 50°C. With the aim of further exploring a prospective location for a geothermal resource, based on the temperature analysis discussed above, Brandvlei hot spring was the most prominent option for further exploration and a possible pilot geothermal plant, with Calitzdorp and Caledon strong alternative options.

Table 5-1: Temperature measurements from literature compared to measurements in current study.

Location	Temperature (°C)			
	Diamond & Harris (2000)	Tshibalo et al. (2010)	Boekstein (2012)	Current Investigation
Brandvlei	64	64	57	58
Calitzdorp	52	43	44	47
Caledon	53	49	49	45
Goudini	39	40	43	45
Citrusdal	43	51	41	41
Warmwaterberg	44	43	41	41
Avalon Springs, Montagu	45	43	41	38
Baden Resort, Montagu	38	-	39	36

5.2. Estimated Temperatures from Geothermometers

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 evaluation was conducted to arrive at selection of geothermometers using various reasoning which resulted in a narrower bracket of estimated temperatures, as explained in the results and calculations section (Chapter 4). Certain geothermometers were unrealistically high, those being above 250°C, which would translate into either a depth that is beyond current drilling limits (>10km) and economical limits (>5km), or a geothermal gradient much higher than the literature and the current general consensus of the low geothermal potential in the region. The bottom of the crust has been estimated to lie in the range of 500 to 1000°C and a depth of 20km to 50km and thus estimated temperatures above 600°C was deemed highly unrealistic when expected at 5km in depth. Certain geothermometers were below the in-field measured temperatures and thus were also removed from consideration; namely the cristobalite and amorphous silica geothermometers by Fournier (1977) and the ionic exchange geothermometers by Giggenbach (1988).

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. There was a noticeable variation in the relative position between the different geothermometers at each location. This difference in relative position was attributed the interaction of the water with different formations due to the hydro-geological setup with regards to the reservoir and the pathway differing between different hot springs. This was a reasonable assumption as the hot springs were found at the surface to be either in the Bokkeveld group, in the Table Mountain Sandstones or close to the contact of both as well as the formations varying in thickness and the potential of interaction with the Pan-African basement, the Cape Granite Suite or even more recent sedimentary deposits from the Jurassic-Cretaceous time. These variables allowed for a variety of possible hydro-geological configurations even to similar depths.

The temperature estimates of the four selected geothermometers are shown below in Figure 5-1 with the measured in-field temperatures of each sampling location. The average was taken of 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^{o}C, which were Calitzdorp, Warmwaterberg and Caledon. These locations were estimated at 117^{o}C ±13^{o}C, 112^{o}C ±12^{o}C and 108^{o}C ±21^{o}C respectively. With the threshold temperature for binary systems being 85^{o}C, these reservoirs could be considered for further exploration as geothermal sites.

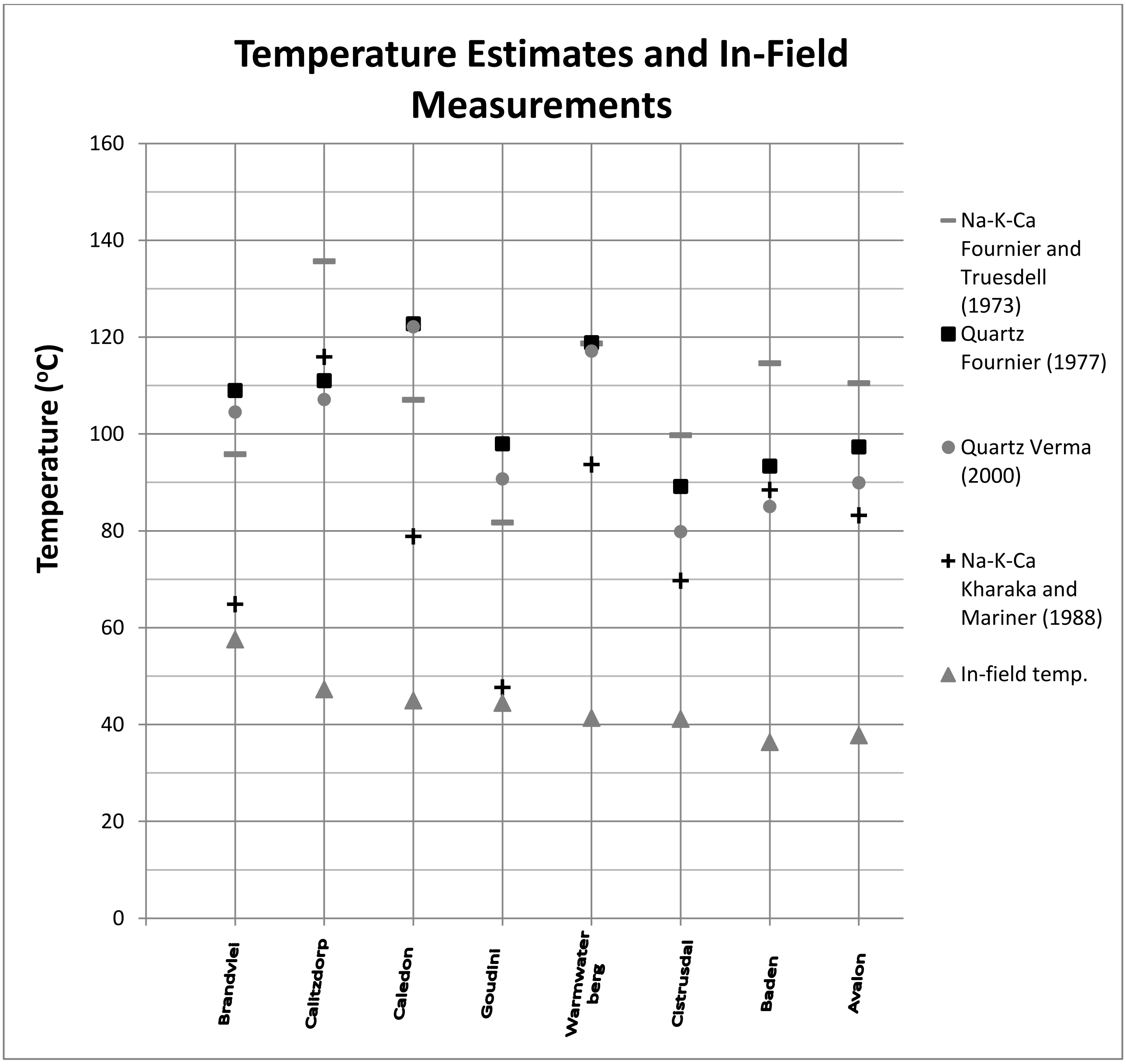


Figure 5-1: The temperature estimates of the selected geothermometers shown in decreasing order of in-field temperature measurements.

An estimated temperature of ca. 117°C ±13°C was obtained for Calitzdorp hot spring. With an annual surface temperature of 19°C in the region of Oudtshoorn, the increase in temperature was 98°C which would indicate a depth to reservoir of 4km with a conservative 25°C/km geothermal gradient assumed. If an elevated geothermal gradient of 40°C/km is assumed, then a depth of ca. 2.5km is obtained. However, instead of using approximations and assumptions for both the depth and the geothermal gradient, the geophysical data, together with the geology, gave insight into the depth and positioning of the potential reservoir. This analysis was discussed in the following subsection together with the MT survey data.

5.3. Interpretation of MT Data with the Geology

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 in geological structures and relevance established in the previous chapter of results and calculations (Chapter 4.5). It must be stated that while the resistivity can be directly influenced by different minerals of certain formations, in the form of more or less resistive minerals, formations containing such minerals directly influencing resistivity were not known to be present in this regional setting, especially for less resistive (or more conductive) minerals like iron-based minerals. Rather inferences were made about conductive bodies based off indirect influences on resistivity, like saline water contained within permeable formations or lack thereof due to highly impervious formations, and the latter used to draw a relation to certain formations of this geological setting.

In the interpretation done by Weckmann et al. (2012), inferences were made using the surface geology and regional structure features however this study additionally interpreted the most probable underlying geological structure by incorporating the cross sections constructed. The geological structures drawn in the cross sections were seen as most probable but not conclusive as a few assumptions were made to construct the cross sections from the mapped surface geology. These assumptions included a constant thickness of formations, use of dip angles within 5km away from the line of the cross section, assumed depth of the Oudtshoorn basin and the Uitenhage Group, and no detachment of formations along contacts at depth. These assumptions were very reasonable and the cross sections fall well within the generally accepted understanding of the structure of the regional geology.

The interpretation from Weckmann et al. (2012) was discussed 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 the MT survey shown as a red line on the geology map, as seen in Figure 5-2. The geological map had basic regional structural details shown, such as 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.

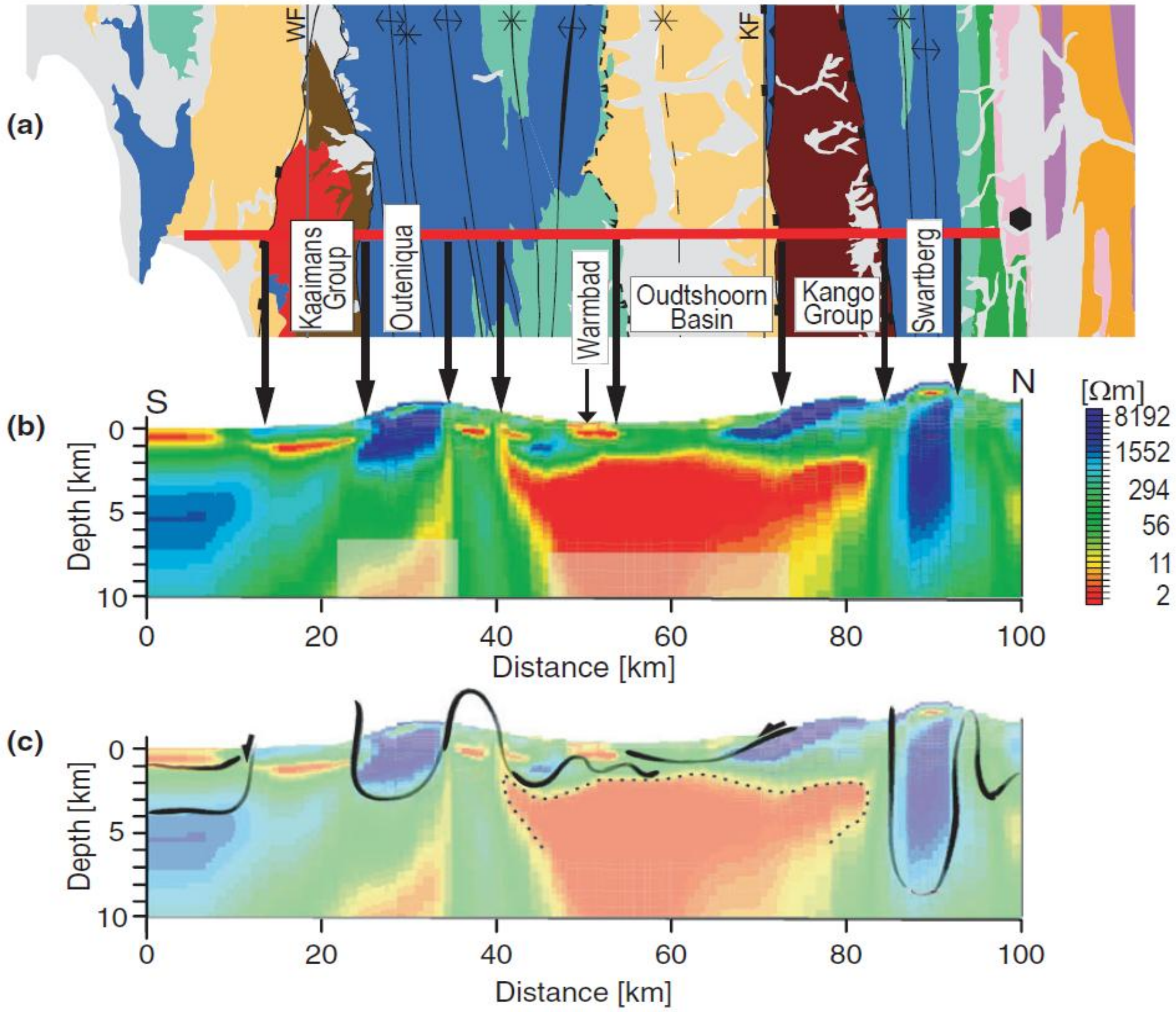


Figure 5-2: Figure, taken directly from Weckmann et al. (2012) showing the (a) geological map in aerial view lined up with the (b) MT profile shown in cross-sectional view corresponding to the red line on the geological map. (c) The second MT profile shows the inferred geological formation boundaries and structural features as interpreted by Weckmann et al. (2012).

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 Figure 5-3 below, shows the TMG sandstones going beyond 10km 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 1km 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 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 it 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.

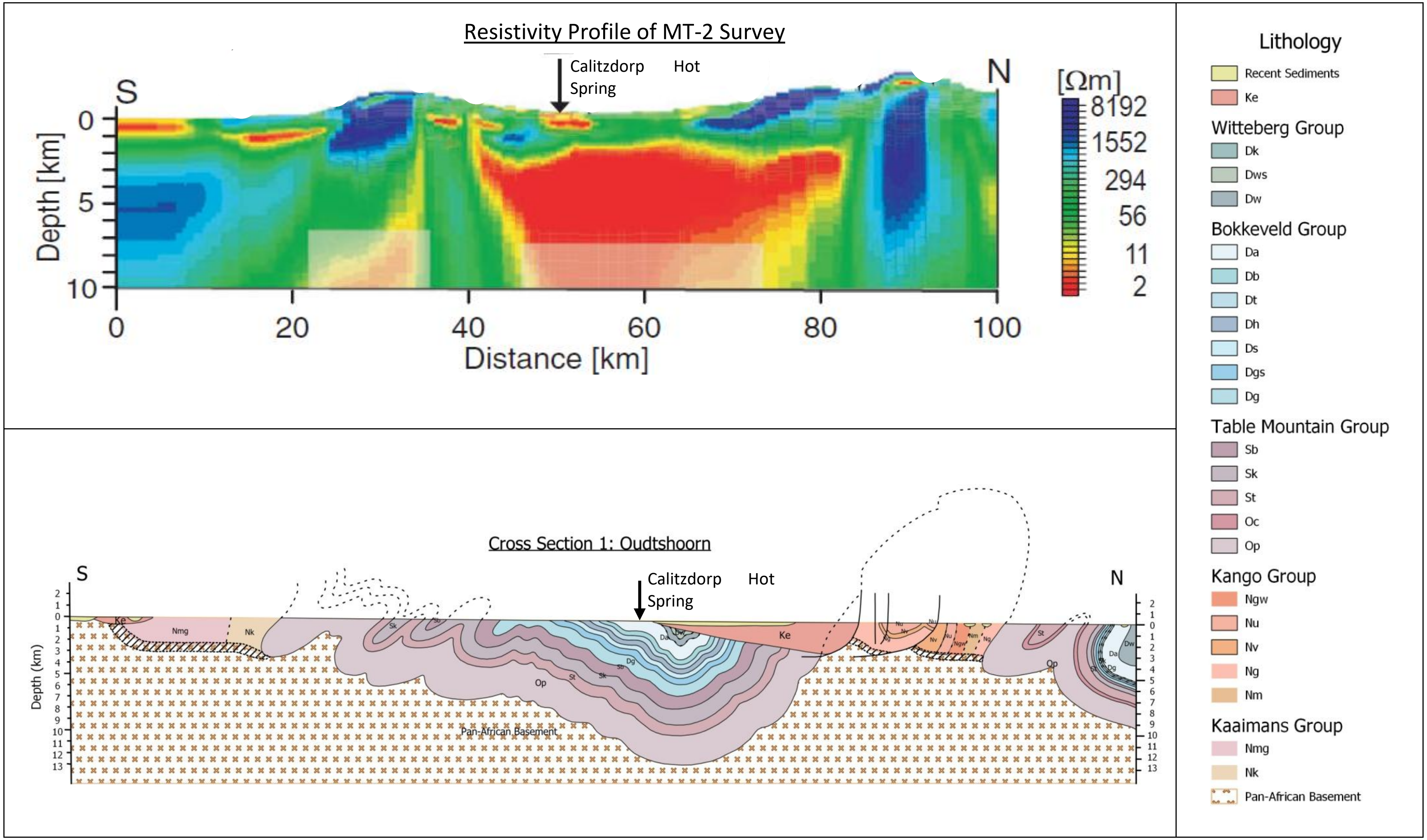


Figure 5-3: MT-2 survey displayed above Cross Section 1 along the same profile for direct comparison. The cross section was constructed with no vertical exaggeration however the MT survey has a vertical exaggeration of about 2 and must be kept in mind when comparing these two profiles. Calitzdorp hot spring was indicated in both profiles to provide a reference point.

Above the large conductive body, 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 27km east from the Calitzdorp hot spring. This shallower body could be the reservoir supplying the hot spring, although being at 0.75km depth and being ca. 30^{o}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 underlines 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 3km and 7km 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. 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. The subchapters following this then took these geothermal properties and then explored the possibility of a pilot geothermal power plant in that region together with the projected effects and concerns.

5.4. 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 annual air temperature at surface of 19^{o}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 3km to 7km 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 with certainty. 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 supplies 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^{o}C ±13^{o}C at a very unrealistic possibility due to the depth of 0.75km. If the estimated temperature of 117^{o}C ±13^{o}C was used to the depth of 0.75km, the resultant geothermal gradient would be ca. 156^{o}C/km ±17.3^{o}C/km which was deemed highly likely in this setting. 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^{o}C ±13^{o}C to be reasonable, and at a depth of 3km, result in a geothermal gradient of 39^{o}C/km ±4.3^{o}C/km.

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 is admittedly tentative as the east-west dimensions of the reservoir is unknown and even the assumption of that the area shown as the conductive bodies is fully due to saline water does still need to be confirmed [Blake et al., 2010]. For this reason the dimension in the east-west direction has been taken at 1km even though the Calitzdorp hot spring is ca. 27km away from the line of the MT survey. Estimates of the volume of the reservoirs were conducted from the MT profile with the conservative assumption that the dimension into the page (or East-West) was taken as 1km. In the estimation of the water volume of the reservoir, a porosity of the aquifer rock was conservatively estimated at 1% based on previous measurements done by Campbell (2016a). Campbell (2016a) measured the porosity of rocks collected from borehole KWV-01, which was drilled to 2.3km in depth, during the KARIN project and found the porosity of those rocks from the Karoo Supergroup to be ca. 1%. This was assumed as reasonable as borehole KWV-01 was drilled in close proximity to the Cape Fold Belt and the rocks tested were collected from substantial depth, providing a representative sample of rock in similar physical conditions. The small reservoir was estimated at 1.44km^3 which, at a porosity of 1%, results in a water volume of 1.44x10^{10} litres. The large reservoir was estimated at 161.4km^3 which, at a porosity of 1%, results in a water volume of $1.61x10^{12}$ 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 $8.98x10^{11}$ litres, with the single largest dam having a capacity of $4.80x10^{11}$ litres. The large reservoir has a larger volume keeping in mind that the calculation was conservative in both porosity of 1% and the east-west dimension of 1km.

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 could affect the current out-flow of the hot spring. Change in the volume of the reservoir depends on the flow rate into the reservoir, also known as recharge rate, and the flow rate out of the reservoir. The current state of 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. These natural factors or controls would be rainfall as the main process of recharge, and the hydro-geological setup and structures which direct the pathway of the water and control the rate of flow out of the reservoir by means of the size of shear zones of faults or primary and secondary permeability of the rock formations and shear zones. The latter control (of hydro-geological setup) would only change due to geological processes (i.e. tectonic movement) and thus would be assumed as constant in our lifetime, unless artificially altered through hydraulic fracturing. While rainfall in this area was not particularly high, reported at $172ml/m^2$, it does have the advantage of receiving year round rainfall; winter rain from the cold fronts as well as some summer rains due to convection rainfall.

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 water used by the power plant would be the hot water extracted and directed to the heat exchangers. The cooled water would then be directed from the heat exchangers and into the re-injection wells and down into the reservoir. 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.

5.5. Pilot Geothermal Power Plant near Calitzdorp

The proposal of a pilot geothermal power plant constructed close to the Calitzdorp hot spring was then considered and discussed. It is acknowledged that further exploration would need to be conducted to confirm the inferred large reservoir below Oudtshoorn Basin and to better understand the regional hydro-geological structure before such plans could be initiated. The estimated installed capacity of such a pilot plant would be ca. 1MW_e following the example of the pilot EGS plant built in Soultz, France [Radilla et al., 2012; Schill et al., 2017]. 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 1MW 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 low amount of water is removed from the system. Also a binary ORC system means only the heat is extracted from the water but otherwise the water is not altered or changed from extraction to re-injection, as discussed in the literature review (Chapter 2). Thus contamination of water would be highly unlikely. 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 areas of the Limpopo and the potential suspected in the Northern Cape, this is not an unrealistic notion.

With the high potential of a large reservoir at depth established and the overall positive effect of a geothermal power plant discussed, a brief presentation of the cost of drilling and construction of a pilot geothermal power plant was then considered as an extension into this possibility [Yost et al., 2015]. Lukawski et al. (2014) conducted a comprehensive study on the total cost of drilling and completion of geothermal wells and thus was used in this consideration of the drilling and construction costs. The study presented the cost distributions in four depths which were 2.4km, 3km, 3.7km and 4.6km 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 to 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. 2.25km below the surface based on the MT profile, a cautious depth of 3km would be considered. According to Lukawski et al. (2014), the average estimated cost would be US$ 8.12 million with a lower 10% probability of US$ 7.33 million and an upper 90% probability of US$ 9.14 million. This was considered quite a substantial study on drilling cost and would be seen as a very realistic value for the cost to drill to 3km and construct a pilot geothermal power plant.

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.

6. Conclusions and Recommendations

The findings and the inferences of this investigation has led 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.

6.1. Conclusions from Preliminary Assessment

The overall assessment of the geothermal potential within the Cape Fold Belt centred on the seven main hot springs previously noted as the hottest in the specified region, with these as preliminary sources for data collection. That data allowed the assessment of which location(s) showed the most potential to continue with a more comprehensive analysis. Sampling hot springs was a choice based on three rationales; the first was that a hot spring generally has a water source with an elevated temperature which infers an elevated geothermal gradient and an aquifer located at some depth, the second was the ease of analysis of water from a potentially deep aquifer, and the third was that an already established deep aquifer would result in a water source available to operate a geothermal power plant from as well as the host rock possessing a high enough permeability. The latter could potentially lower the cost of construction as hydraulic fracturing would not be necessary, which is commonly referred to as an enhanced geothermal system (EGS). In order to gain some insight into the temperature of the water at depth, temperatures were calculated from the concentrations of major cations analysed for by using the selected geothermometry equations. These estimations were considered the minimum temperature of the water in each reservoir. The two locations presented as most promising for further analysis were Calitzdorp, with a temperature measurement of the water from the spring of 47°C and an estimated reservoir temperature of 117°C ±13°C, and Caledon, with a temperature measurement of the water from the spring of 45°C and an estimated reservoir temperature of 108°C ±21°C.

6.2. Conclusions from Focused Evaluation

Geophysical survey methods and deep boreholes were envisioned for the collection of data with depth to further assess any promising locations from the hot spring assessment. However due to the limitations of funding and the lack of availability of the necessary equipment, primary data was not collected and already published data was used. This dependence on published data directed the study to one location, Calitzdorp hot spring, which was identified as one of the promising locations from the preliminary assessment. This data, in the form of a magneto-telluric survey, was conducted in 2005 by the Agulhas-Karoo Geoscience Transect (AKGT) project while the data was processed and presented by Weckmann et al. (2012). Together with an interpretation of the geology of the region from the Oudtshoorn and Ladismith geological maps published by the Council for Geoscience of South Africa, a thorough assessment of this region was conducted in terms of the geothermal potential and the hydro-geological setup present.

While no definitive statements could be made without further confirmation from deep boreholes drilled, it was inferred that there is a large reservoir present at depth in the Calitzdorp/Oudtshoorn region from the magneto-telluric data published by Weckmann et al. (2012). The MT data showed a region within the rock with a low resistivity (or high conductivity) that was interpreted as a water reservoir which covered a 4km depth at its maximum, from 3km to as far as 7km below the surface. 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. It has been well established that the significant deformation of this TMG has resulted in secondary permeability and, in other locations, has allowed for the development of reservoir(s) or water movement through the rock formations. The volume of the potential reservoir was estimated from the MT profile and was regarded as a substantial volume. The volume was approximated at 1.6×10^{12} litres (or 1600 million cubic metres) given the dimensions from the MT profile, with only 1km used for the unknown parameter, and a porosity of 1% of that volume of rock.

6.3. A Potential Geothermal Resource and the Implications

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 5km and deep enough for a high enough temperature given a moderate to elevated geothermal gradient. Based on the geothermometry calculations and the estimated depth of the reservoir at 2.5km, a geothermal gradient in the Oudtshoorn region was estimated at ca. 39.2°C/km, which is within the upper limits of previous estimations in this region. 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 approximately half of the households 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 expand to cover some of 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.

6.4. Recommendations for Future Research

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 3km or 4km, where temperature measurements at depth can be taken. This would be aimed at gathering data to validate whether a large reservoir below the Oudtshoorn basin from about 3km depth exists and if so, to ascertain what the temperature of the water is. Deep borehole drilling would be mainly commercially driven, with the geothermal energy prospect and another prospect being a water source for agricultural or governmental use. Geophysical exploration in this area would be academically driven and aimed to build into the understanding of the lithology and structure of the Cape Fold Belt as well as determine how deep the Cape Supergroup extends and what lies below the Cape Supergroup in different locations. Deep borehole drilling would be on the order of millions of rands which is why the commercial sector would be the main agent whereas geophysical exploration can range from tens of thousands to millions of rands depending where one can source the equipment from and how much the equipment costs to operate.

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 an 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. Another research opportunity would be a sensitivity study conducted on the assumptions made in section 4.3 around unit conversion and how it impacts the geothermometer estimations.

Geothermal energy within South Africa should be looked at as a genuine option to help address the need to move away from fossil fuels. The technology to harness low temperature geothermal resources, developed in the last decade, has now made geothermal energy accessible to regions previously overlooked due to their tectonic stability. South Africa has the expertise and resources to at minimum investigate the geothermal potential via low-enthalpy binary systems, before dismissing it. The need to lower the use and dependence on fossil fuels grows each year and this can only be achieved by developing the renewable energy sector. Geothermal energy is a continuous and long term energy resource resulting in a big advantage over other renewable energy resources in the long term, making it a favourable energy resource to utilise if possible. Currently it may be economically advantageous to utilise the cheap fossil fuels available, especially being a developing nation, but the cost of addressing the effects of global warming in the future may render those economic gains negligible.

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Appendices

Appendix A

Collection pool at Calitzdorp Hot Spring where water sample was collected.

Caledon Hot Spring sample collected from pipe at top right which was closest accessible point to source.

Warmwaterberg Hot Spring sample collected from tap in roman style bath.

Baden Resort Hot Spring (Montagu) sample collected in roman style bath.

Avalon Springs (Montagu) sample collected from tap with hot spring water collected in well below.

Brandvlei Hot Spring sample collected from pipe at surface level (flowing water in foreground of photo)

Goudini Hot Spring sample collected from pipe at surface level.

Citrusdal Hot Spring sample collected from natural water flow from rock (bottom right of photo).

Appendix B

Full Lab Report as received from the Central Analytical Facility at Stellenbosch University.

	Ca	Fe	K	Mg	Na	P	Si
	mg/l	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**	**mg/l**
LOD	**0.1**	**0.05**	**0.1**	**0.1**	**0.1**	**0.1**	**0.1**
% Recovery	**108.4**	**108.5**	**105.1**	**108.7**	**101.4**	**103.7**	**101.16**
Johnathan HS1	10.22	2.83	10.6	4.62	16.49	0.2011	18.7
Johnathan HS2	7.508	3.07	5.067	3.197	16.77	0.191	24.6
Johnathan HS3	0.01	< LOD	< LOD	0.00	< LOD	< LOD	< LOD
Johnathan HS4	15.72	0.72	9.15	2.74	21.69	< LOD	22.5
Johnathan HS5	3.24	< LOD	2.90	2.01	6.68	0.18	12.1
Johnathan HS6	12.28	< LOD	3.84	2.96	8.56	0.18	13.4
Johnathan HS7	3.02	< LOD	1.98	1.94	8.14	0.21	17.9
Johnathan HS8	6.21	< LOD	0.92	1.64	3.97	0.24	13.6
Johnathan HS9	2.34	< LOD	1.98	1.91	7.35	0.19	10.8

Appendix C

Geothermometer	Author	Estimated Reservoir Temperature (°C)							
		Brandvlei	Calitzdorp	Caledon	Goudini	Warmwater -berg	Citrusdal	Baden	Avalon
Na-K	**Fournier (1979)**	250	366	272	245	310	260	313	317
	Arnórsson et al (1983)	246	349	265	241	299	255	302	306
	Nieva and Nieva (1987)	293	436	319	287	366	305	370	375
	Giggenbach (1988)	949	619	857	972	738	904	729	718
	Verma and Santoya (1997)	251	359	272	247	307	261	310	314
	Arnórsson (2000)	302	470	333	295	388	316	393	399
Na-K-Ca	**Log (Ca^0.5/Na)***	1	1	1	2	1	1	1	2
	Fournier and Truesdell (1973)	96	136	107	82	119	100	115	111
	R value*	31	19	23	25	12	33	27	19
	delta T*	-772	-714	-934	-1131	-868	-692	-790	-954
	Fournier and Potter (1979)	868	850	1042	1212	987	792	905	1064
	Kharaka and Mariner (1989)	65	116	79	48	94	70	88	83
Na-K-Mg	**Nieva and Nieva (1987)**	153	203	169	142	190	156	175	178
K-Mg	**Giggenbach (1988)**	35	13	23	48	12	35	28	27
Na-Mg		-91	-86	-83	-102	-76	-93	-95	-94
Amorphous Silica	**Fournier (1977)**	-8	-6	6	-19	2	-27	-23	-19
Beta Cristobalite	**Fournier (1977)**	12	14	27	0	22	-9	-5	-1
Alpha Cristobalite	**Fournier (1977)**	59	61	75	46	70	36	41	46
Chalcedony	**Fournier (1977)**	80	83	98	66	93	55	61	65
Quartz (No Steam loss)	**Fournier (1977)**	109	112	125	97	121	86	91	96
Quartz	**Fournier (1977)**	109	111	123	98	119	89	93	97
	Fournier and Potter (1982)	194	196	210	181	205	171	176	181
	Arnórsson (1983)	216	218	231	204	227	194	199	204
	Arnórsson (2000)	206	209	223	193	218	183	188	192
	Verma (2000)	105	107	122	91	117	80	85	90
In-field temperature measurements (°C)		57.6	47.3	45	44.5	41.4	41.2	36.4	37.8

*these values are not temperature values but rather values used to calculate the temperatures in the row below. In the case of 'delta T', this is a change in temperature value applied to 'Fournier and Truesdell' to result in the temperature estimate of 'Fournier and Potter'.