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STATUS OF GEOTHERMAL EXPLORATION AND DEVELOPMENT IN SELECTED AFRICAN COUNTRIES

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ABSTRACT

Africa continent has abundant geothermal resources that span the range from low temperature through medium to high enthalpy resources. The countries of the Eastern African Rift System from Eritrea in the North to Tanzania in the South are known to host many high temperature resources that are volcano hosted and being developed for power generation and other applications. The other countries largely have low to medium temperature geothermal systems. In this paper, we provide occurrence, geological setting and utilization in selected representative countries that include: in North Africa Algeria and Egypt; West Africa Nigeria; Southern Africa represented by Namibia and South Africa; Central Africa by the Sudan, South Sudan and The Democratic Republic of the Congo; and Somalia in the horn of Africa. Results of the review indicate that the countries have significant resources that can be used for some electricity generation while a lot of the resources can be developed for direct applications. Current utilization in most of the countries considered is recreation, tourism and agriculture. A huge potential remains untapped and which can have significant socio-economic impact on the community.

1. INTRODUCTION

This review covers selected countries in Africa where known geothermal resources have been identified or are currently under low-level utilization, but the countries have desire for expansion and development of new utilization schemes. Most of the countries discussed have had only little or no exploration undertaken while some have some form of utilization, but the potential for growth is large and untapped. The summary includes Algeria, DR Congo, Egypt, Namibia, Nigeria, Somalia, South Africa, South Sudan, and the Sudan. All these countries do not have electricity generation plants but do have some low-level direct utilization mainly in the form of hot baths and some greenhouses. This paper reviews the geothermal occurrences and controlling geologic features, current status of knowledge and development status, and suggests what could be done in the short and medium term to move the geothermal projects forward.

2. GEOLOGY AND GEOTHERMAL RESOURCES IN SELECTED AFRICAN COUNTRIES

A brief description of the geological setting, geothermal manifestations and utilization is covered for the following selected African countries: Algeria, Democratic Republic of the Congo, Egypt, Namibia, Nigeria, Somalia, South Africa, South Sudan, and the Sudan.

2.1 Algeria

The People's Democratic Republic of Algeria is located in Northern Africa and occupies part of the Atlas Mountains on the Mediterranean Sea, the Sahara plans in the Central and South and Al Hoggar mountain range in the South (Figure 1). The climate is largely desert but with cooler winter seasons.

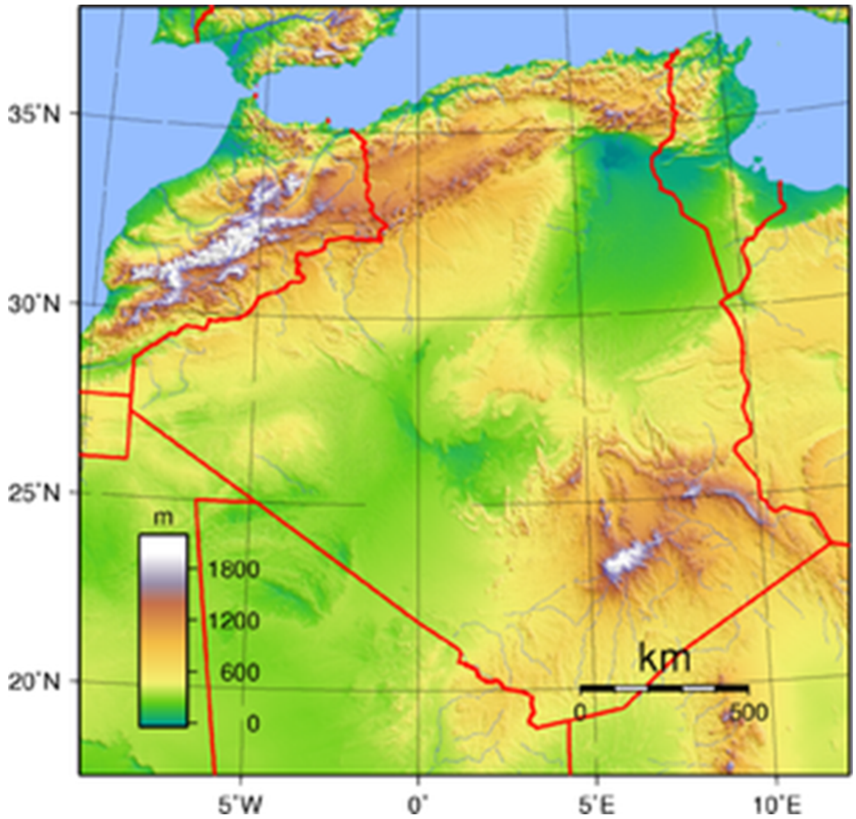

FIGURE 1: Physiographic map of Algeria

2.1.1 General geology of Algeria

The Atlas mountain range was formed during three subsequent phases of Earth's geology. The first tectonic deformation phase involves only the part of the mountain range called the Anti-Atlas, which was formed in the Paleozoic Era (~300 million years ago) as the result of continental collisions between North America, Europe and Africa.

The Anti-Atlas Mountains are believed to have originally been formed when Africa and America collided. A second phase took place during the Mesozoic Era (before ~66 My). It consisted of a widespread extension of the Earth's crust that rifted and separated the continents mentioned above. This extension was responsible for the formation of many thick intracontinental sedimentary basins including the present Atlas. Most of the rocks forming the surface of the present High Atlas were deposited under the ocean at that time (Figure 2). Finally, in the Paleogene and Neogene Periods (~66 million to ~1.8 million years ago), the mountain chains that today constitute the Atlas were uplifted, as the land masses of Europe and Africa collided at the Southern end of the Iberian Peninsula. The mountains are primarily composed of metamorphic rock approximately 2 billion years old, although there are areas where more recent volcanic rocks are exposed. In between the Atlas and the Hoggar mountains is the Sahara desert dominated by sand dunes and dry plateaus (Ait Ouali et al., 2021).

2.1.2 Geothermal occurrences

The areas of geothermal manifestations in Algeria follow the geological setting with most activities occurring within the Atlas mountain range and in the South highlands as well as the Sahara basin regions (Figure 3). The Jurassic limestones of the Algerian North, which constitute important geothermal reservoirs, give rise to more than five hot springs located mostly in the NE and NW regions of the country. These sources have temperatures above 40°C up to 80°C. Generally, the pH of the thermal waters ranges from 6.4 to 7.5 and generally flow rate is between 3 and 20 l/s. In the North, in part including the Saharan Atlas to the sea, occur more than 200 hot springs (Saibi, 2015; Fekraoui and Abouriche, 1995). The water temperature at these springs varies between 22°C and 98°C.

The discharge points of the hot springs are strongly controlled by structures. In the Atlas region and the Hoggar Mountains, the geothermal model is that of deep circulation along the fracture planes which then results in conductive heating of the ground waters which rises by buoyancy to the surface. In the Southern plateaus, it is postulated that the heat sources are the radiogenic basement rocks underlying the sedimentary basins. The sediments form an insulating blanket of cap rock (Figure 4).

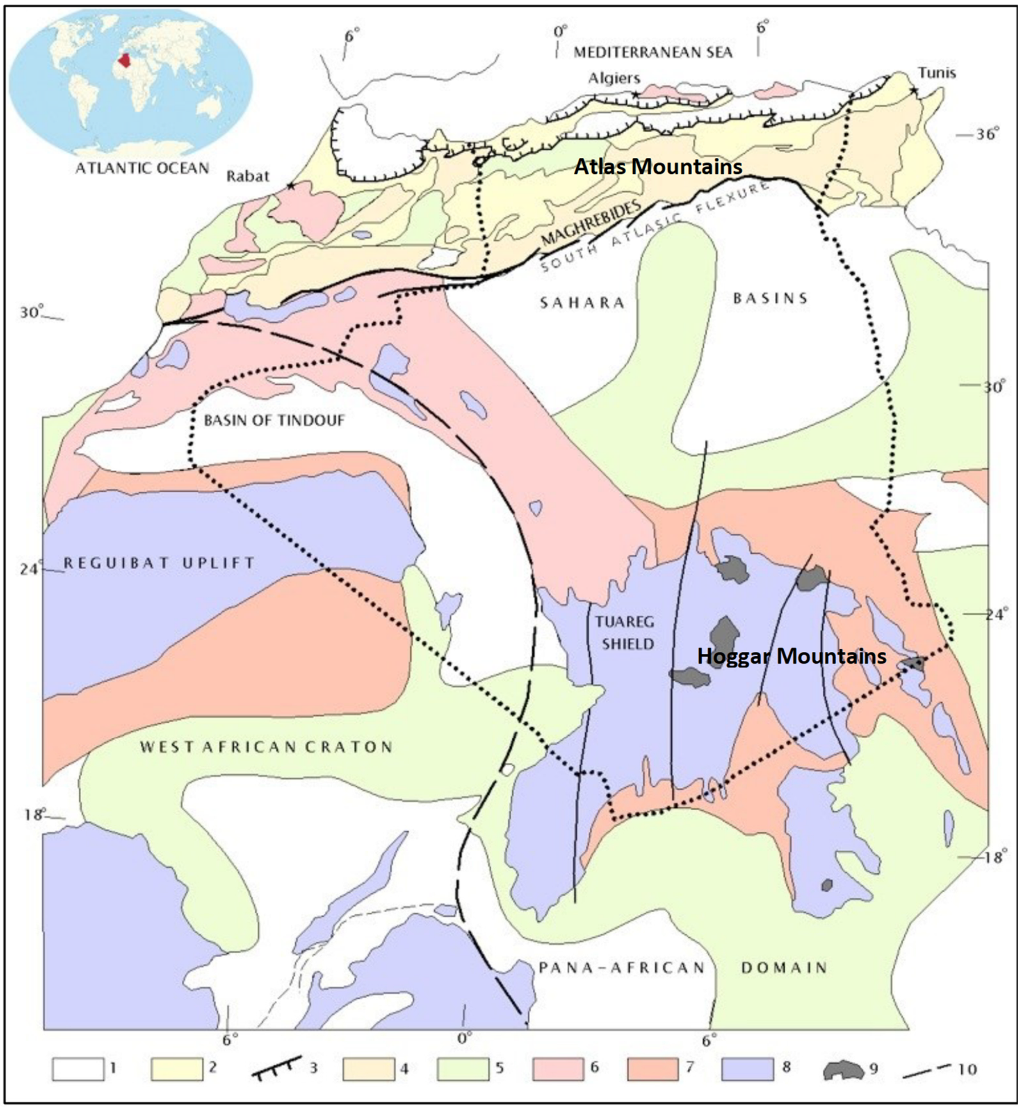

FIGURE 2: Major geotectonics units of Algeria (Ait Ouali et al., 2021)

2.1.3 Uses of geothermal energy in Algeria

Balneotherapy and greenhouse heating are the most common uses of geothermal resources in Algeria. Others are fish farming as well as farming of crustaceans, but the use is at relatively small to moderate scales. As a natural energy source, geothermal energy is not harmful to humans and their environment. Geothermal water is also known for its benefits and is particularly used in spas to treat rheumatism. Hydrotherapy was one of the first applications of geothermal energy during antiquity, recognized for its health qualities. Today, it remains an excellent natural option for thermal cures. The country has more than two hundred hot springs distributed throughout the Northern region of Algeria. About one-third have temperatures above 45°C. There are sources at high temperatures of the order of 98°C in Guelma, which could be evaluated for electricity generation.

As many as 200 thermal springs have been inventoried across the country. Over 80 spas or "Hammam" are operated across the country (Figure 5), including five major national, with each source including therapeutic advantages. Spas are requested by the Algerian population for various therapeutic treatments (rheumatism, dermatology). A heat-pump project was installed in a primary school in Saida

(NW-Algeria) for heating and cooling purposes. A thermal water of 46°C with a flow rate of 25 m^3/h was used for this project. A similar project is planned in Khenchla (NE-Algeria) and a binary-cycle geothermal power plant is also planned in Guelma (NE-Algeria). Other projects under development in the Sahara include fish farming and greenhouses using geothermal waters at about 60°C.

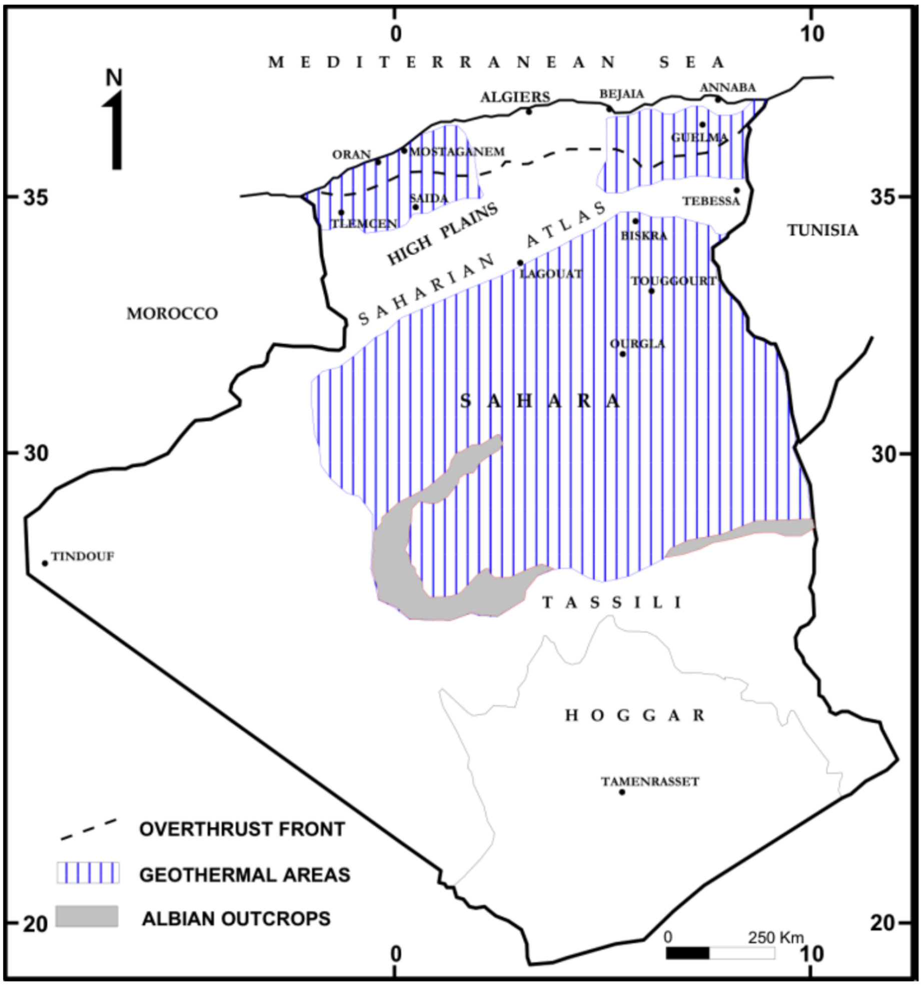

FIGURE 3: Map of Algeria showing hot springs locations (Saibi, 2015)

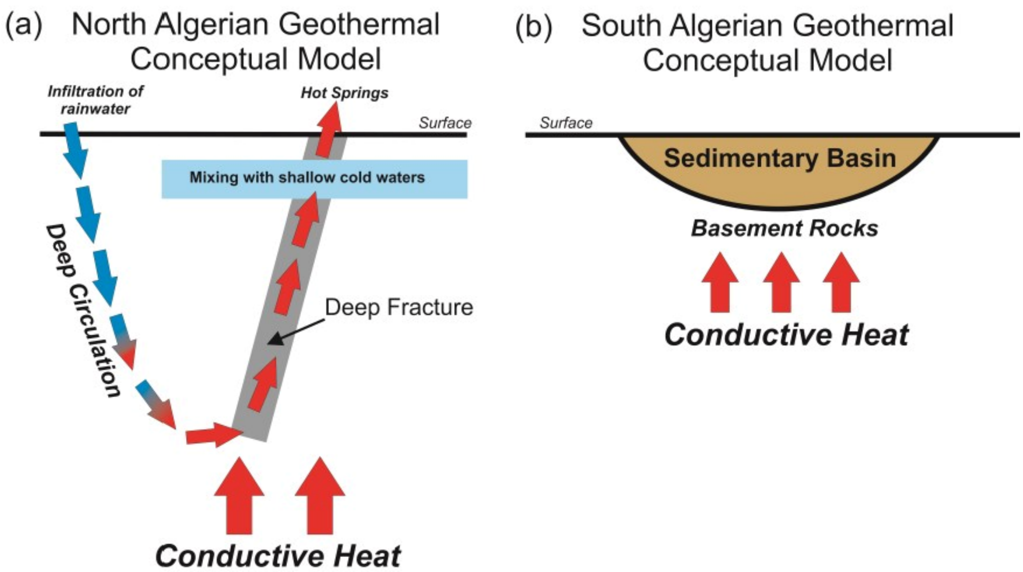

FIGURE 4: Conceptual models for the Algerian geothermal systems (Saibi, 2015)

FIGURE 5: Hammam Essalihine in Algeria

2.2 The Democratic Republic of Congo

DR Congo (DRC) is the second largest country in Africa with a surface area of about 2.345 million km² and a population of more than 100 million. The country transects different geographic regions from the equatorial forest in the Central part to the Atlantic coast to the West (Figure 6).

FIGURE 6: Geographic map of the Democratic Republic of Congo

2.2.1 Geologic setting

The country spans the Congo Craton: a stable section of ancient continental crust, deformed and influenced by several different mountain building orogeny events, sedimentation, volcanism and the geologically recent effects of the East Africa Rift System (EARS) in the East. The Eastern part of the country is dominated by Precambrian and younger rocks and sediments. The area also experienced extensive faulting and fracturing associated with the tectonics of the Western Branch of the East African Rift system. The Northeast part of the country is also tectonically active with some of the world's most active volcanoes, named Nyiragongo. Volcanism started 12 Ma at Virunga and has continued to the present time (Odhipio et al., 2020; Figure 7).

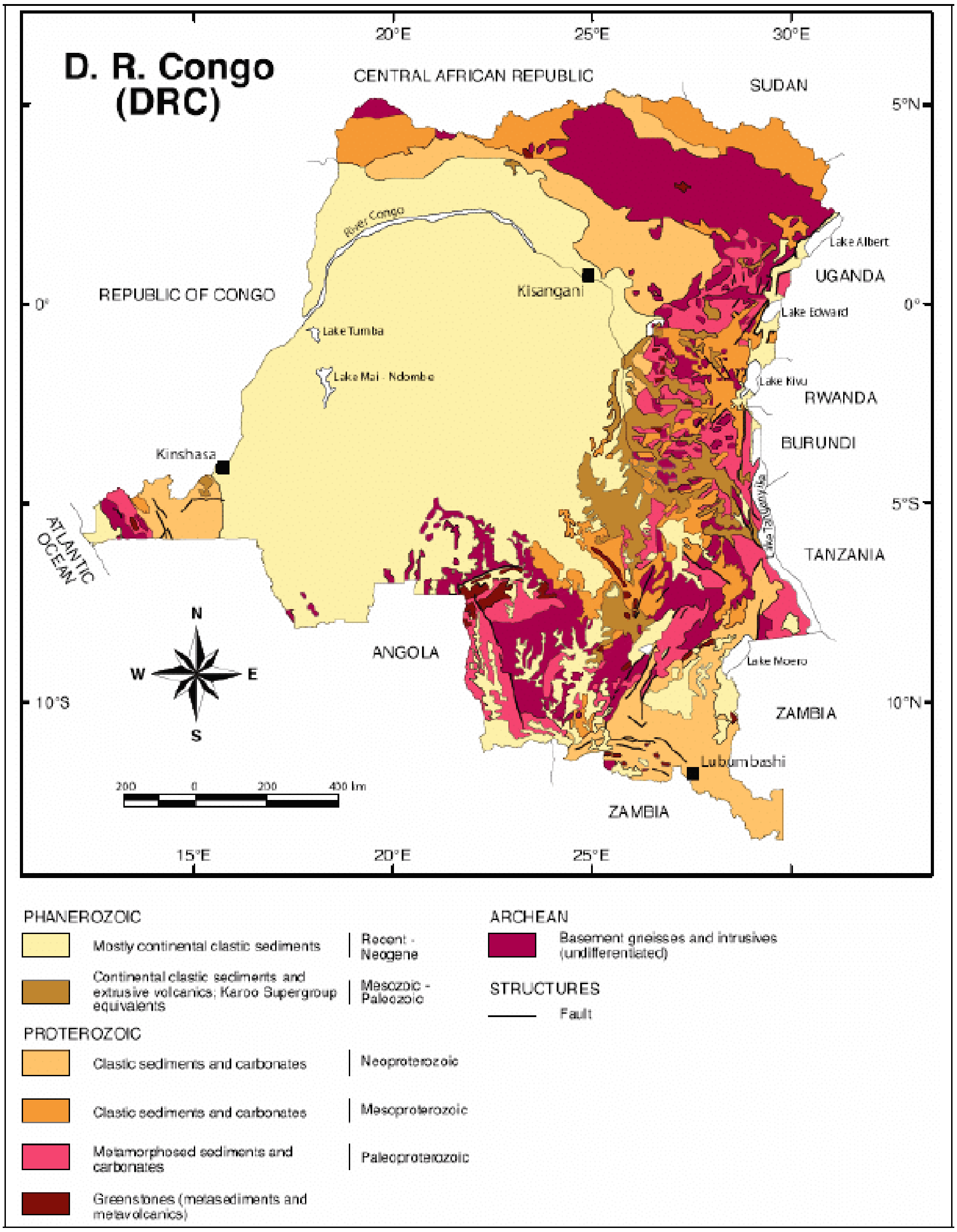

FIGURE 7: Geological map of DR Congo (Kasay, 2018)

The high Mitumba Mountains region of Eastern DRC is part of the "African Superswell" which has undergone the most thermal uplift. The Ubendian basement terrain reaches 3,200 m elevation along the Western Rift margin on the Western side of Northern Tanganyika Lake (Makuku, 2019; Kipata et al., 2013). This is the highest standing basement terrain of Africa attributed to thermal uplift. Between Bukavu city and Kalemie area, about 400 km, the Western Rift exhibits a complex structural pattern where faults of its three arms interact: the Lake Kivu rift zone as North-Eastern termination of the rift branch at the Aswa shear zone in Uganda; the Tanganyika-Rukwa-Malawi (TRM) Rift zone which trends NW-SE to NNW-SSE as South-Eastern arm, the Northern L, Tanganyika basins and links the above two rift arms and the Ruzizi rift zone, a N-S oriented structure which host the Ruzizi River and serves as linking of the two rifts.

2.2.2 Geothermal activity

Geothermal manifestations occur in many areas within and near Virunga volcanic field and further South within the faulted Precambrian formations in Katanga province (Figure 8). The DRC geothermal areas are mostly located in three axes: Kahuzi-Biega area, Virunga volcanic field, and Rwenzori area with some small areas in the country. These areas are prioritized since they fall within volcanic and tectonic regions of good permeability and heat flow. The South Kivu geothermal prospect is located in the Kahuzi-Biega volcanic field between Lake Tanganyika and Lake Kivu and area around Bukavu town (Makuku, 2019; Figure 8). The geology is dominated by basaltic flows and craters overlying granitic and gneissic rock. The age of the volcanic activity has been estimated at Pleistocene to Holocene. Geothermal surface manifestations are typically hot springs. The hot springs and hot grounds are strongly controlled by the fault structures. The largest hot springs in the NE include the Mayi ya Moto with measured temperatures of 94-100°C. In the South Kivu region, the hottest springs are Kankule and Mahyuza which discharge at 65-72°C and Kiabukwa in Katanga at more than 90°C (Odhipio et al., 2020; Kambale Kavyavu and Makabu Kayembe, 2020).

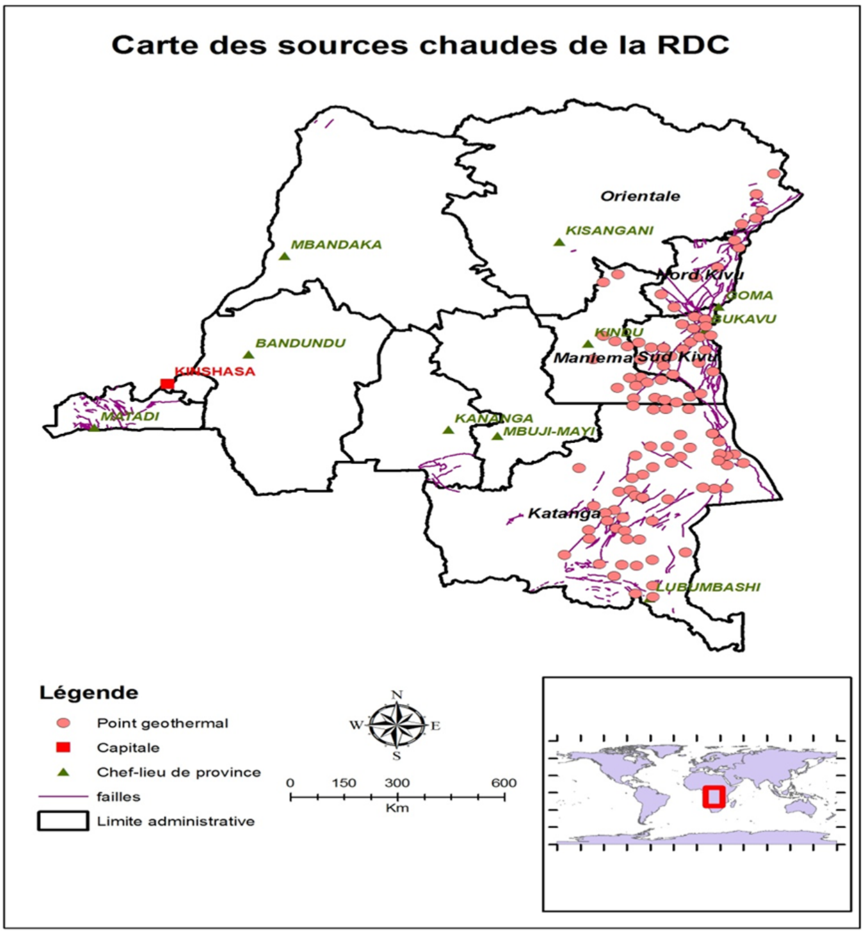

FIGURE 8: Map of DRC showing the locations of geothermal manifestations (Mukandala and Mahinda, 2020)

2.2.3 Geothermal utilization in DRC

Kiabukwa hot spring within the Upemba rift in Southeast DRC is probably the largest hot spring in the area. In 1952, a 0.25 MWe binary plant was installed to supply electricity to a tin mine (Figure 9). The plant was developed by Société d'Exploitation et de Recherches Minières au Katanga (Sermikat) to supply power for their tin mining operations in Katanga (White, 2021). The characteristics of the fluid flow and power output are as follows: 139 t/hr at 91°C to 243 t/h at 93°C generating between 220-275 kW at maximum capacity. The plant was de-commissioned about 1960 (White, 2021). There is no current commercial utilization of geothermal resources in DRC (Makuku, 2019).

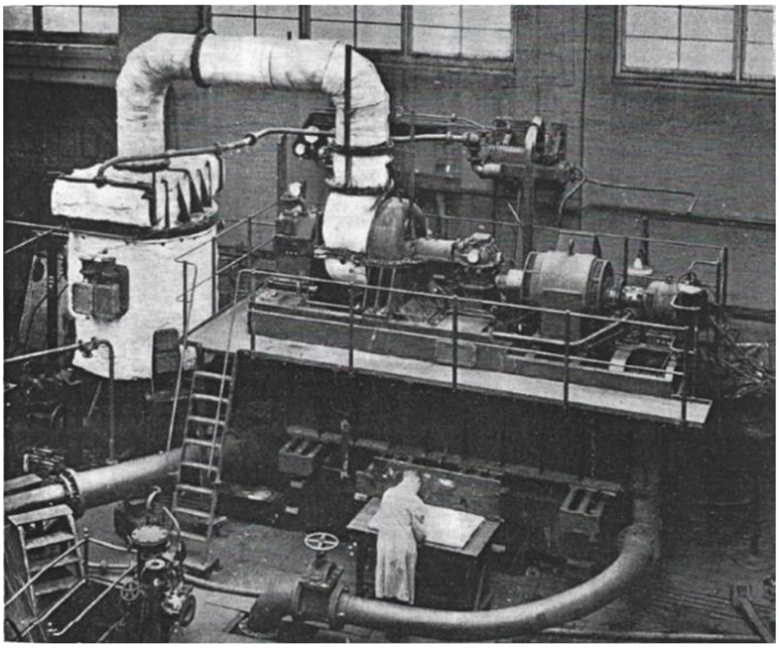

FIGURE 9: View of the main Kiabukwa plant during trials at Belliss and Morcom's works. Evaporator capped with the superheater is on the left, turbine, gearbox and alternator are fixed on top of the condenser, air pump is mounted on the wall behind the alternator (White, 2021).

2.3 Egypt

Egypt is located at the Northeast corner of Africa and with an extension in the Sinai Peninsula. It is bordered by the Mediterranean Sea to the North, the Gaza Strip of Palestine and Israel to the Northeast, the Red Sea to the East, Sudan to the South, and Libya to the West (Figure 10). Egypt's present energy strategy aims at increasing the share of renewable energy to 20 percent of Egypt's energy mix by 2020. Egypt's demand for electricity is growing rapidly (an annual rate of increase from 1,500 to 2,000 MWe and with time alternative sources of power supply become more urgent.

FIGURE 10: Map of the Arab Republic of Egypt

2.3.1 Geological setting

The geology of Egypt includes rocks from Archaean – early Proterozoic times onwards. These oldest rocks are found as inliers in Egypt's Western Desert. In contrast, the rocks of the Eastern Desert are largely late Proterozoic in age (Figure 11). Throughout the country this older basement is overlain by Palaeozoic sedimentary rocks dominated by limestones and sandstones. Cretaceous rocks occur commonly whilst sediments indicative of repeated marine transgression and regression are characteristic of the Cenozoic Era. Egypt is surrounded by three active tectonic plate boundaries: the African-Eurasian plate boundary, the Gulf of Suez-Red Sea plate boundary, and the Gulf of Aqaba-Dead Sea Transform Fault. Geothermal manifestations closely follow the structural features.

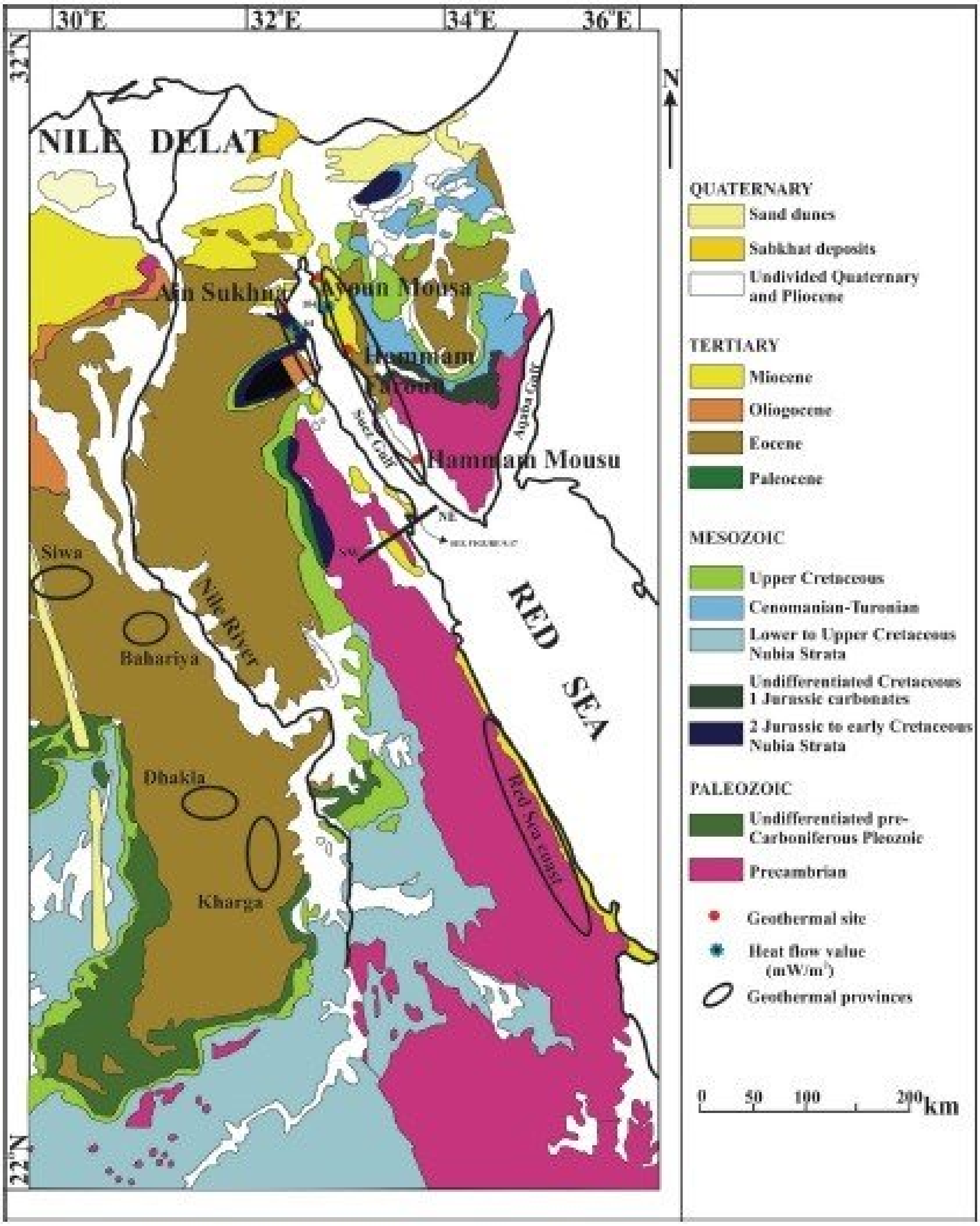

FIGURE 11: Geological map of Egypt showing areas of geothermal manifestations

2.3.2 Geothermal occurrences

The majority of geothermal resources of Egypt are located along the Gulf of Suez and Red Sea with a surface temperature range of 40-76°C. Temperature measurements from oil and gas wells in Egypt recorded high geothermal gradients of more than 45°C and heat flow of more than 120 mW/m^2 along the Red Rea (Figure 12). Some hot springs have a flow temperature of up to 76°C. The fracture and faulting systems associated with the tectonic activity of the Red Sea and Gulf of Suez provide a continuous supply of heat energy to the deep circulated fluids resulting in the high heat flow recorded in the area. The heat sources are attributed to high heat-generating rocks of granitic composition in the Eastern desert region (Chandrasekharam et al., 2016; 2018). Hammam Faraun geothermal spring is the best example with geothermal reserve of 12.4 MWt from a spring discharging at 71-76°C.

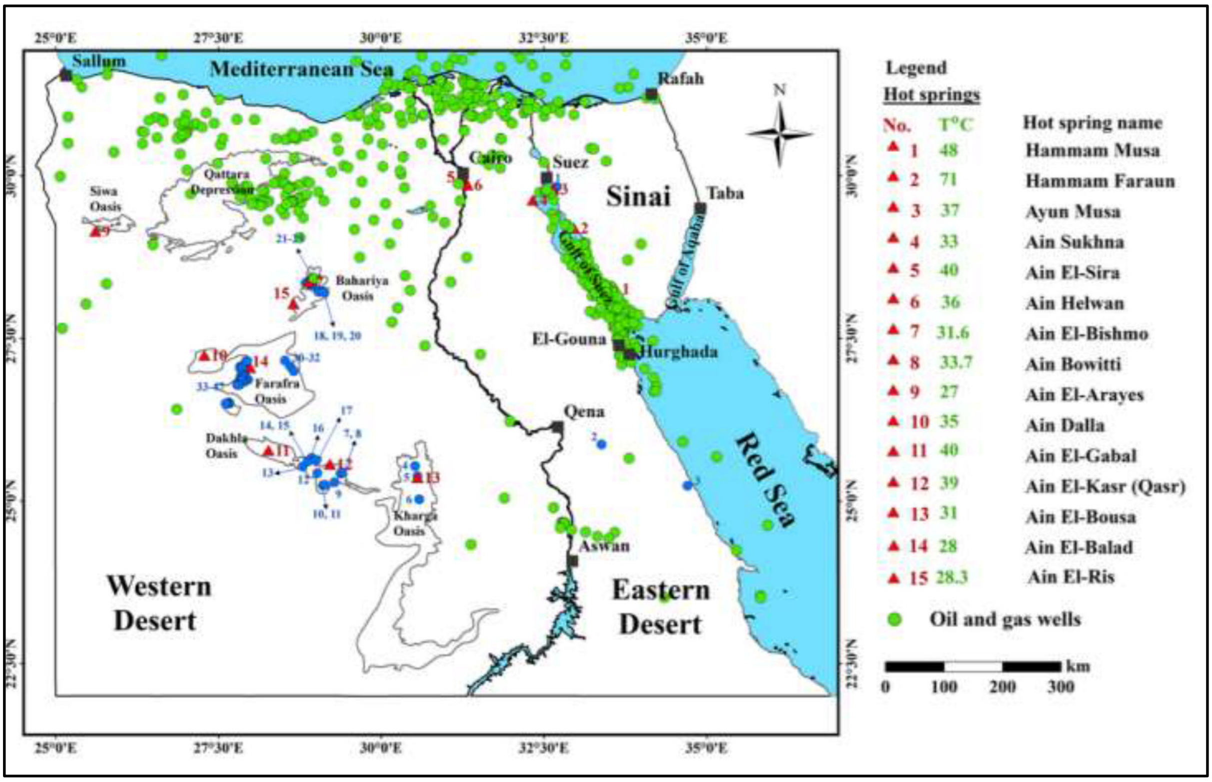

FIGURE 12: Location of different hot springs in Egypt with surface temperature indicated (Kortam et al., 2022)

Some other geothermal areas are found in the Western desert of Egypt, close to the Oasis of Baharia and Dakhla. There are also locations where hot water is produced from some deep artesian wells with a temperature range of 35-45°C. Some other thermal springs (up to 35°C) enriched with sulphur are located 25 km South of Cairo close to Helwan city and are structurally controlled and flowing naturally from the Nubia Sandstone (Lashin, 2020).

2.3.3 Utilization of geothermal resources in Egypt

Direct utilization of thermal waters in ancient Egypt goes back thousands of years, with Egyptians using warm water from hot spring for domestic uses. The wealthy developed warm ponds for swimming and medical purposes, as was recorded by some papyrus documents discovered in the Western desert. Some direct low-grade geothermal applications are now in use in Egypt, in the form of district heating, fish farming, agricultural applications and green houses. Some swimming pools have been constructed along the Eastern coast of the Gulf of Suez. These thermal pools mainly used for touristic and medical purposes are commonly known as Hammams. The majority of the green houses in the Western desert of Egypt (Baharia and Dakhla oases), use thermal waters. District heating is also used in the winter. A total of 12 sites report the use of geothermal energy, 7 sites using it for bathing and swimming, and 5 sites for other uses (cooking). The estimated use is 44 MWt and 152.9 TJ/yr (Lund and Toth, 2021).

2.4 Namibia

Namibia is situated in Southern Africa and has a population of approximately 2.3 million people (Figure 13). Its installed energy capacity is mainly renewable with hydro accounting for over half of the available resources and fossil fuels fuel making up over a quarter of supplies. But the installed electrical generation capacity is insufficient to meet the demand for electricity, which leads to Namibia importing large amounts of electricity from South Africa. Namibia's installed electricity generation capacity is 498 MW. Namibia is considering exploration of geothermal resources for development of power generation plants to add to its renewable energy installed capacity.

FIGURE 13: Geographic map of Namibia

2.4.1 Geological setting

Namibia's varied geology encompasses rocks of Archaean to Phanerozoic age, thus covering more than 2,600 million years of Earth history. About half of the country's surface area is bedrock exposure, while the remainder is covered by Cenozoic deposits of the Kalahari and Namib Deserts (Figure 14). Highly deformed gneisses, amphibolites, diverse metasediments and associated intrusive rocks are exposed within several metamorphic inliers in the Central and Northern parts of the country and represent the oldest rocks of Archaean to Palaeoproterozoic age (ca. 2,600 to 1,600 Ma) in Namibia.

2.4.2 Geothermal occurrences in Namibia

There are over 24 reported geothermal springs in Namibia, with the majority concentrated in the Damara Orogenic belt formed by collision between Congo and Kalahari Cratons – where the Kalahari Craton subducted, creating significant deformation, metamorphism, and intrusions (Figure 15). The Damara orogenic belt defines the SW branch of the East African Rift System, which extends into the Okavango rift in Botswana, Kariba and Luangwa rifts in Zambia, which then merges into the Western branch of the EARS. The most significant hot springs are mainly located within the Damara shear zone (Figure 14). Rehoboth hot spring is located at the Southern border of the Damara shear zone. The extensive fracturing/faulting associated with the Karoo Magmatism in the area could have generated permeability and heat to drive a geothermal system. The Ganigobes and Ai Ais hot springs are the only significant hot springs in Namibia that are outside of the Damara belt. The Ganigobes is associated with a Late Karoo Dolerite intrusion to the South of the country inland. The hot springs are controlled by fractures. The Ai Ais hot springs occur within a faulted Neo Proterozoic formation of the Gariep Complex.

2.4.3 Uses of geothermal resources in Namibia

Hot springs in Namibia are extensively used for hot baths and spas for tourism. The most popular spas include Gross Barmen, Ai Ais (Figure 16), Ganigobes and Rehoboth hot springs. The Government of Namibia is looking into detailed investigation of the resources for power generation and is keen to license private developers to undertake exploration in some of the sites like Rehoboth and Ganigobes where estimated hydrothermal reservoir temperatures vary from 60°C to 126°C at less than 2 km depths.

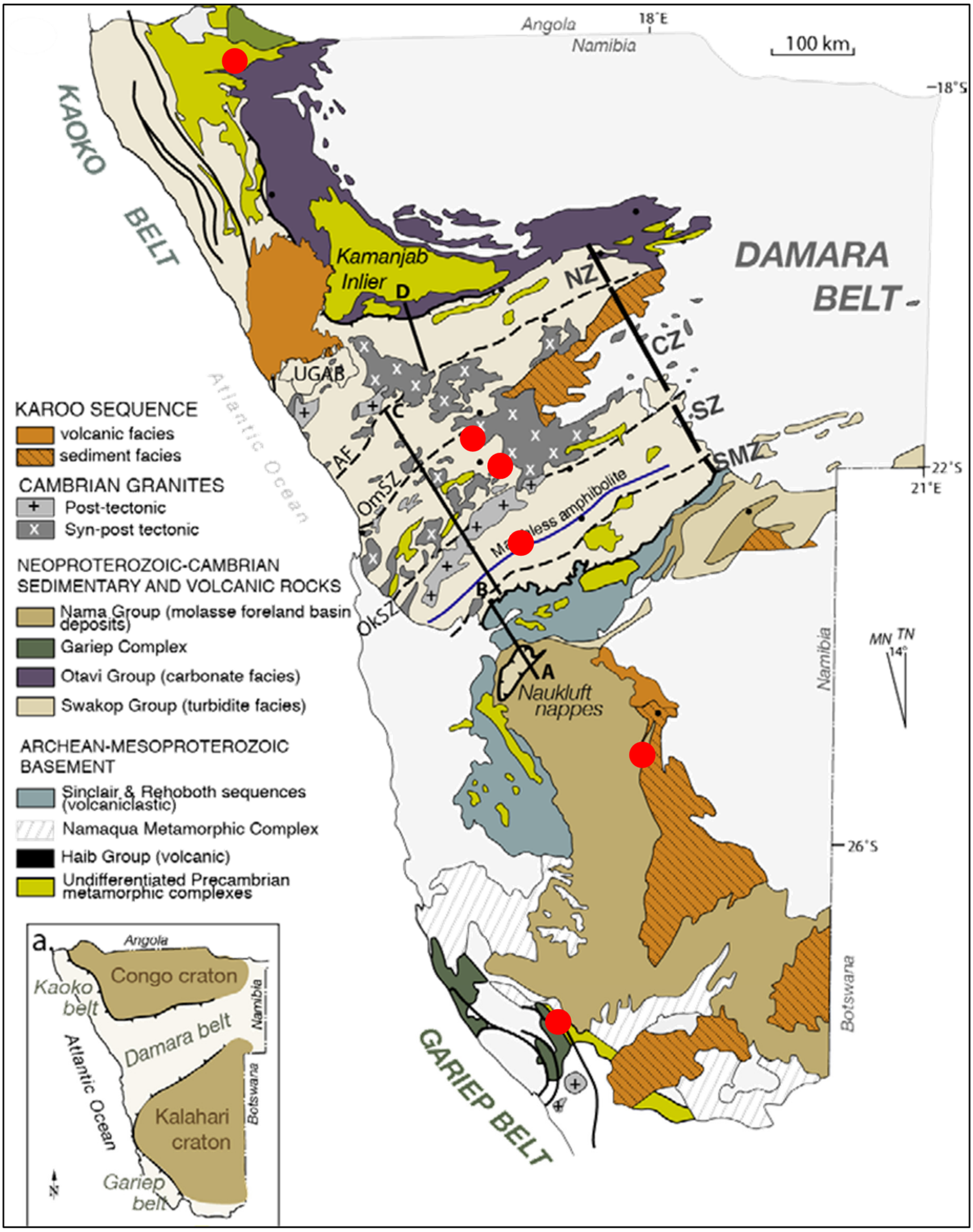

FIGURE 14: Geological map of Namibia showing the Damara Orogenic belt and hot springs locations

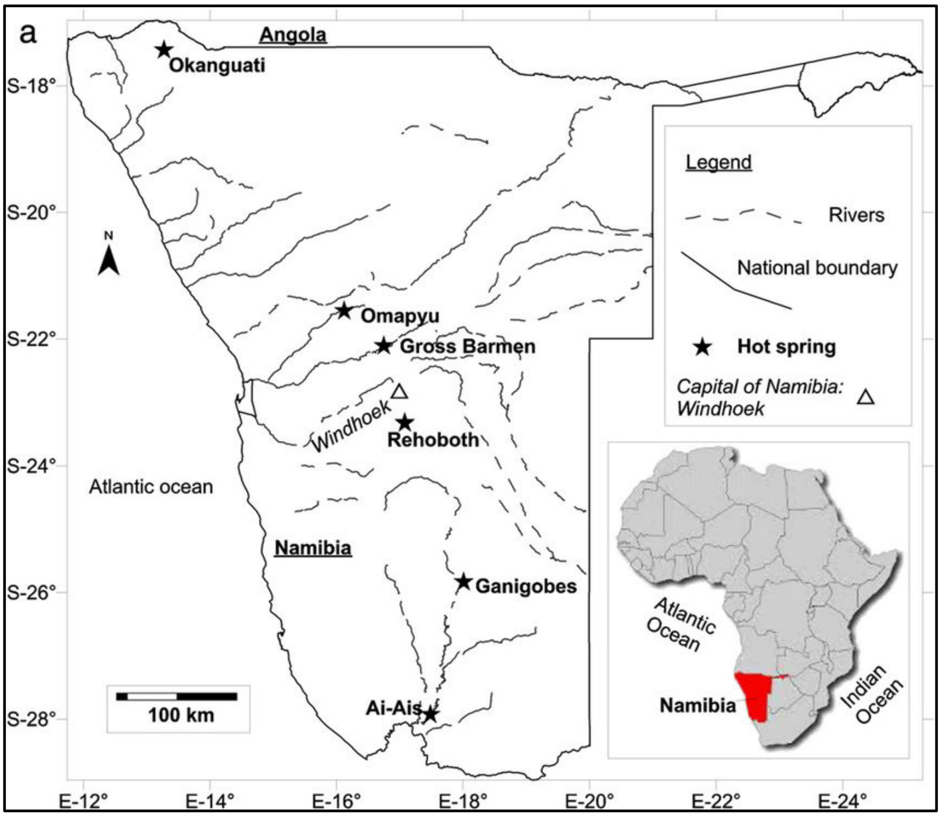

FIGURE 15: Map of Namibia showing the location of hot springs (Sracek et al., 2015)

FIGURE 16: Ai Ais hot spring, Namibia

2.5 Nigeria

The country's topography ranges from lowlands along the coast and in the lower Niger Valley to high plateaus in the North and mountains along the Eastern border (Figure 17). Much of the country is laced with large river systems. The Benue Trough and the Niger Basin dissect the Southern part of the country and Jos Plateau is a major physiographic feature in the Central part of the country.

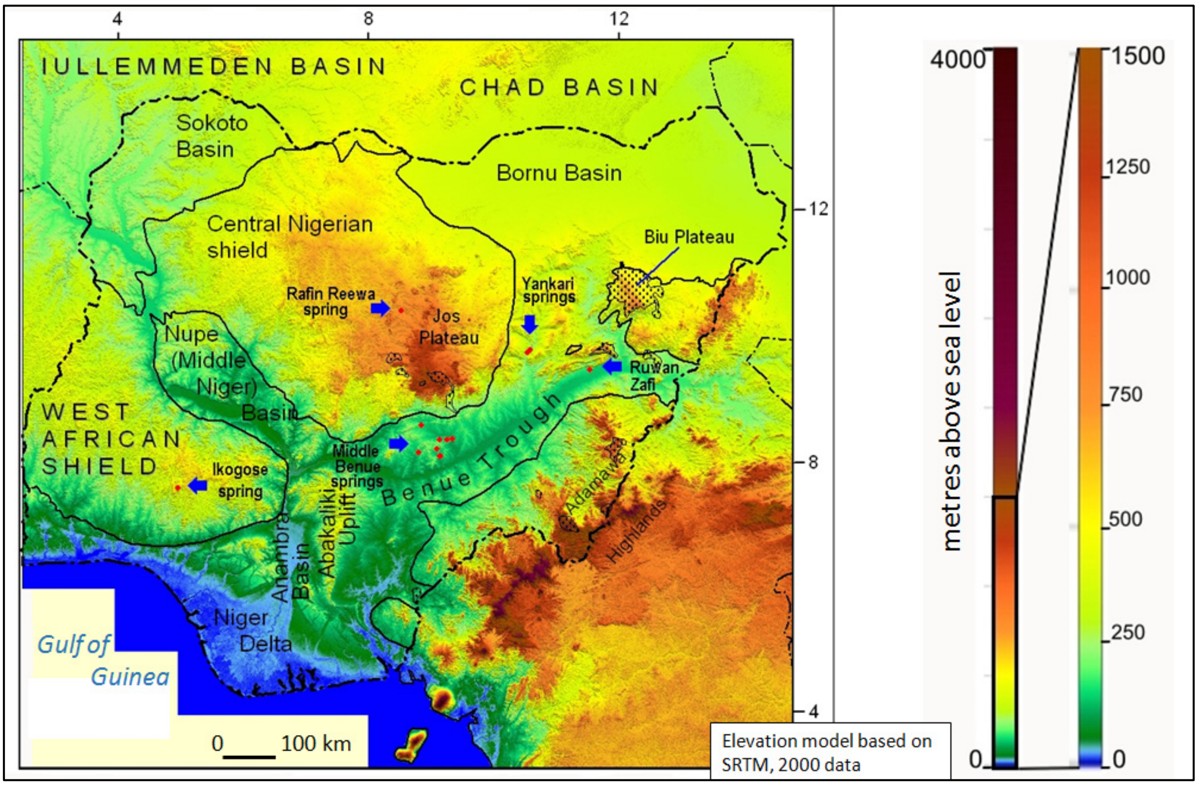

FIGURE 17: Map of Nigeria showing the major physiographic features (Kwaya and Kurowska, 2018)

2.5.1 Geological setting

Nigeria lies within the Pan African mobile belt in between the West African and Congo cratons. Therefore, Nigeria is geologically dominated and made up of two main rock types: Precambrian and Mesozoic to Tertiary Basement complex, volcanic rocks and the Mesozoic to Tertiary sedimentary basins, which are equally dispersed (Figure 18). Other minor formations are younger granites which comprise several Jurassic magmatic ring complexes centred within and on Jos Plateau and other parts of North-Central Nigeria (Kwaya and Kurowska, 2018).

2.5.2 Geothermal potential of Nigeria

Nigeria, with a total area coverage of 923,768 km^2, is the most populous country in Africa with more than 170 million people. With this large population in a wide geographical and regional distribution, the energy demand is increasing and the energy available is grossly inadequate. Geothermal energy, which is a renewable source that may contribute to the country's energy mix, has not been developed so far. Reconnaissance studies reveal possibility for the occurrence of low to medium temperature geothermal resources that can be developed for electricity production and direct use applications. The high potential areas are dominantly within the rift basins.

The sedimentary basins with significant geothermal occurrence include the Chad Basin, the Sokoto Basin, the Niger Delta Basin, the Anambra Basin, and Middle Benue Trough (Figure 19). The Chad Basin is a large structured depression which spans five countries: Cameroon, Central African Republic, Niger, Nigeria and Chad. The Chad Basin belongs to a series of Cretaceous and later rift basins in Central and West Africa. The Bornu Basin (Nigerian sector of the Chad Basin) makes up approximately 10 percent of the basin in North-Eastern Nigeria. Thickness of the sediments in the Chad Basin in Nigeria, reaches up to 10 km. High geothermal gradients have been recorded in oil wells drilled in the basins.

FIGURE 18: Tectonic map of Nigeria (Kurowska and Schoeneich, 2010)

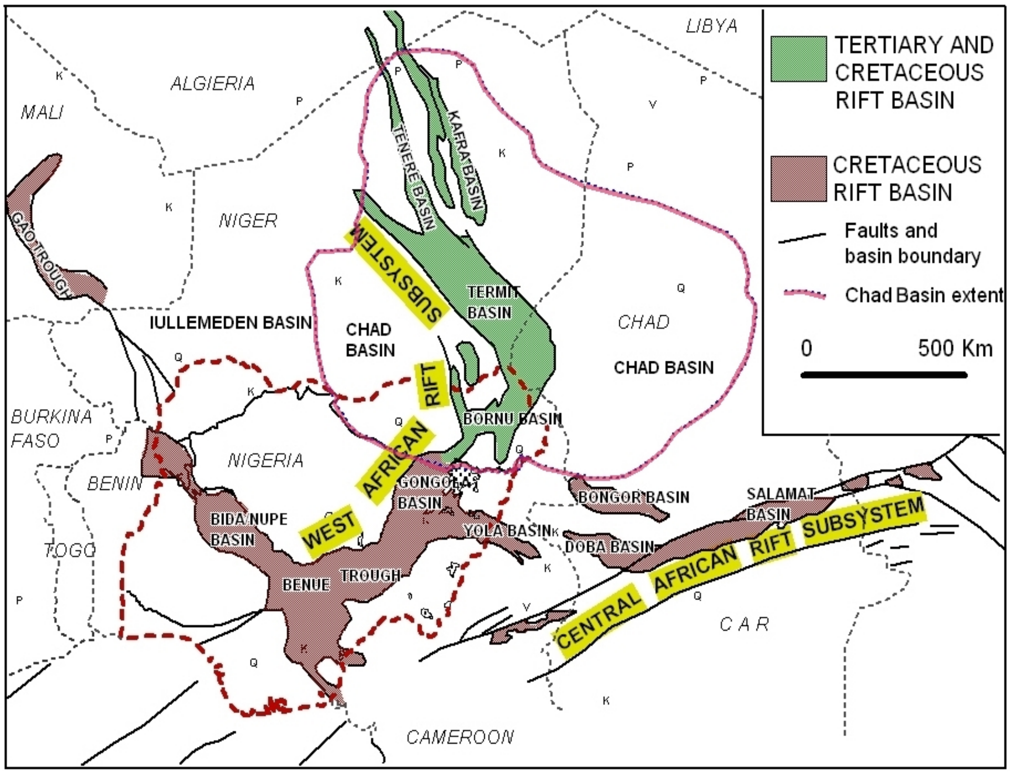

FIGURE 19: Location of Nigeria and Chad/Bornu Basin within regional geological map with rifts of West and Central African Rift System (Kwaya and Kurowska, 2018)

2.5.3 Geothermal utilization in Nigeria

There are more than 13 hot springs in Nigeria with temperatures between 32°C and 54°C. Several of the springs occur within the crystalline province and some within the Benue Trough. The best known hot springs are the Ikogosi warm spring located in Ondo State and the Wikki warm spring located in Bauchi State. The Ikogosi spring (54°C) emanates from Precambrian basement and schist belt and a recreation resort has been developed. Other hot springs include the Rafin Rewa warm spring with a discharge temperature of about 42°C, and Akiri and Ruwan Zafi thermal springs are also at temperatures of about 54°C. Most of the hot springs have been developed as recreational resorts for hot baths and spas. The Nigerian Government and the Nigerian National Petroleum Corporation plans to evaluate the areas of high heat flow within the basins for possible development of geothermal projects for power generation. These basins also have large number of abandoned oil wells with high temperatures, for which the company is investigating the possibility of repurposing for geothermal use (Kwaya and Kurowska, 2018).

2.6 Somalia

Located in Eastern Africa, Somalia characterizes the "horn of Africa" which is not considered strictly belonging to the East African Rift System (EARS) where geothermal resources are known to occur (Figure 20). It was therefore not considered previously as a target for geothermal development. This results from the fact that Somalia is considered by the geological community as a continental plate, sub-plate of the African continent that is essentially a stable platform lacking geothermal manifestations. There are a few sites in Puntland where warm springs have been identified and the most important ones being Biyo Kulule (BK) and Qow hot springs in Puntland (Omenda et al., 2022). No site had ever been considered for its geothermal potential until now in Somalia; the nearest known geothermal site is Asal, in Djibouti Republic, more than 500 km away to the West.

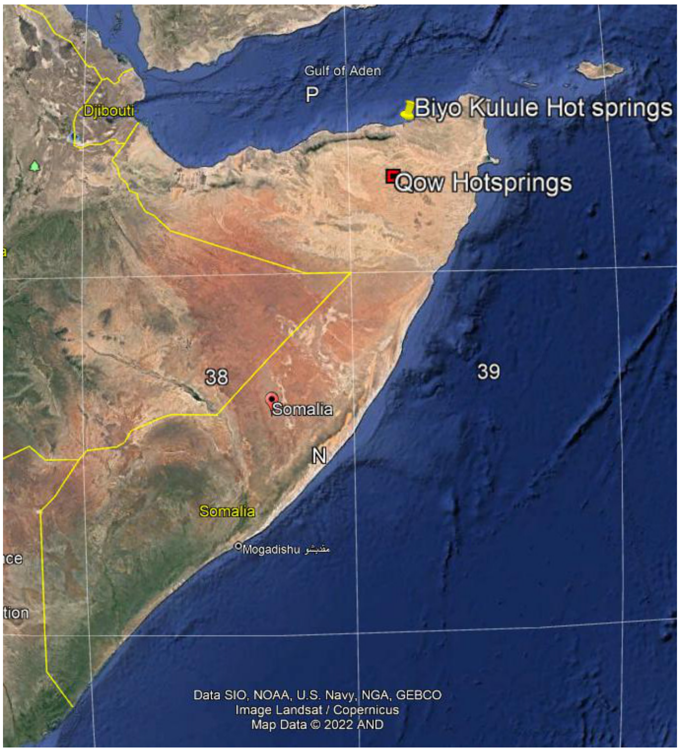

FIGURE 20: Geographic map of Northern Somalia showing the location of the BK geothermal site, which lies 10 km East from Bosasso, the capital of Puntland

2.6.1 Geological setting

Puntland is the North-Eastern most extremity of the African continent, and is the coast of the Indian Ocean extending South of the horn (with Socotra Island as the Easternmost extension of the Somalian plate); it is a rather stable continental shelf, whereas the Northern coastline sits along the Southern border of the Gulf of Aden, which is an active rift. Along the Aden Ridge, the spreading rate is over 2 cm a year; that is 10 times faster than the Kenya rift valley, with a huge amount of heat released along its axis. The geodynamics of the Gulf of Aden is characterized by numerous short WNW-ESE spreading segments, connected Transform Faults (TF) trending NE-SW, controlled by Fracture Zones (FZ) of the same direction (Abbate et al., 1986, 1993; Barberi, et al., 1974; Bosworth et al., 2005) (Figure 21). The fracture zones affecting this ocean floor – made of mid-oceanic ridge basalts (MORB) – extend into the continent, where normal faults parallel to the spreading axis are also observed. In Figure 21, spreading segments are divided by TF and FZ (red lines). The Biyo Kulule (BK) geothermal site is figured with a red filled circle while Qow hot springs site is marked by yellow filled circle. Both sit along the Southern extension of a major FZ (Omenda et al., 2022).

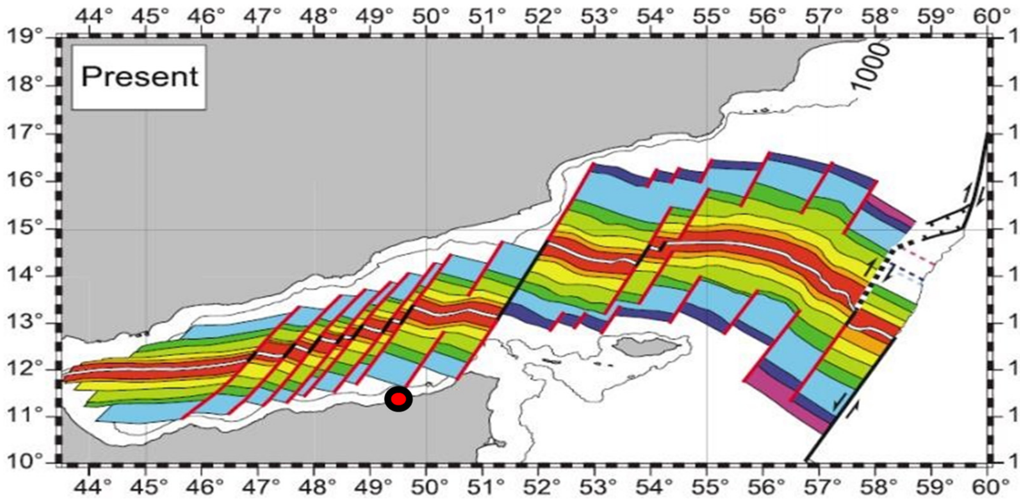

FIGURE 21: Geodynamic structure of the Gulf of Aden, an active mid-oceanic rift. Socotra Island is the Easternmost extension of the Somalian plate. Colours are ranging from blue to red showing the age of the sea floor from the oldest (18 My) to the youngest (from Fournier et al., 2010).

The geology of the area is dominated by the general context described above, which characterizes the continental margins of the Gulf of Aden. The sedimentary sequence, from early Jurassic to late Cretaceous, covering the Pre-Mesozoic basement of the Afro-Arabian shield (late Pan African Orogeny, with greenschist metamorphic facies and associated plutonic intrusion; Varet, 2018), was faulted in a NW-SE to WNW-ESE direction due to an early extension event predating the opening of the Gulf of Aden. In addition, NE-SW trending major discontinuities (fracture zones), also marking the shore-lines on both sides of the Gulf, characterize this early structural pattern which also marks the major spreading discontinuities (Pons et al., 1992). And as a consequence, similar units and structural patterns are observed on both sides of the Gulf, along the Southern Arabian plate margin (in Yemen) and Northern Somalian plate margin.

2.6.2 The geological system of the geothermal sites

The BK system does not belong to the classical high temperature model, with a cap-rock produced by self-sealing (clay cap and impermeable hydrothermal deposits). We rely here upon a fault controlled system affecting sedimentary units, building a thick sequence of permeable (karstic limestones, eventually sands and gravels) and impermeable (clay, shales and marls) lithologic units, as seen on the geological map of Figure 22. The Jurassic karstic limestones are believed to act as excellent geothermal reservoirs, even if the geothermal fluid up-flow is most probably issued from the deeper fractured basement, as shown from water geochemistry.

2.6.3 Surface geothermal manifestations

The important geothermal hot springs in Somalia are at Biyo Kulule and Qow. The hot springs are characterized by emergences of hot-springs, emitted from the faulted sedimentary sequence. The hot-springs area (in the blue oval) merge from a low-land area (70-120 m asl) surrounded North and South by cliffs of up to 500 m high. Two major sets of faults dominate the area, trending WNW-ESE and NW-SE, which characterize the Gulf of Aden geodynamic system. Geothermometry suggests equilibrium reservoir temperature of 140°C to 210°C (Omenda et al., 2022).

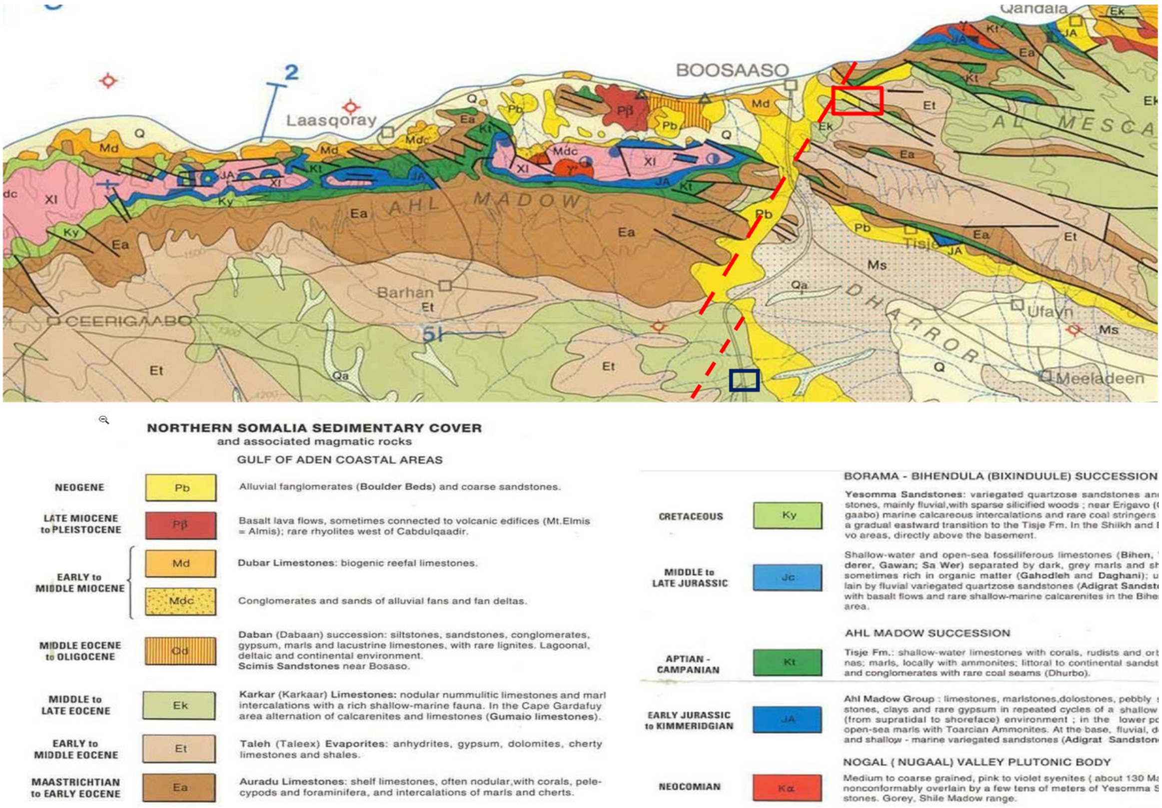

FIGURE 22: Geological map of the BK geothermal site (red quadrangle) and Qow (blue rectangle), located in the vicinity of Bosasso, township and port along the Aden coast line (Abbate et al., 1994)

2.6.4 Geothermal utilization in Somalia

Biyo Kulule is the largest hot spring in Somalia and is mainly used for recreational purposes. The hot springs are supplemented by shallow wells drilled in the area to increase the volume of water for the pool (Figure 23). Somalia Government is keen to explore possible utilization of geothermal resources for power generation given that the country is underserved and with a very high tariff. UNESCO (1982) gave a potential of at least 50 MWe from geothermal resources for Somalia but more studies are required.

FIGURE 23: Biyo Kulule hot springs, Somalia

2.7 South Africa

South Africa consists of a high plateau rimmed to West, South and Southeast by the escarpment and the rugged mountains of the Cape Fold Belt and the narrow coastal plain. The geology of South Africa is highly varied including cratons, greenstone belts, large impact craters, as well as orogenic belts. The basement of much of the North-Eastern part of South Africa is made up by the Kaapvaal Craton. To the South and East, the craton is bordered by the Namaqua-Natal belt (Figure 24). There is no evidence of young volcanism in the region

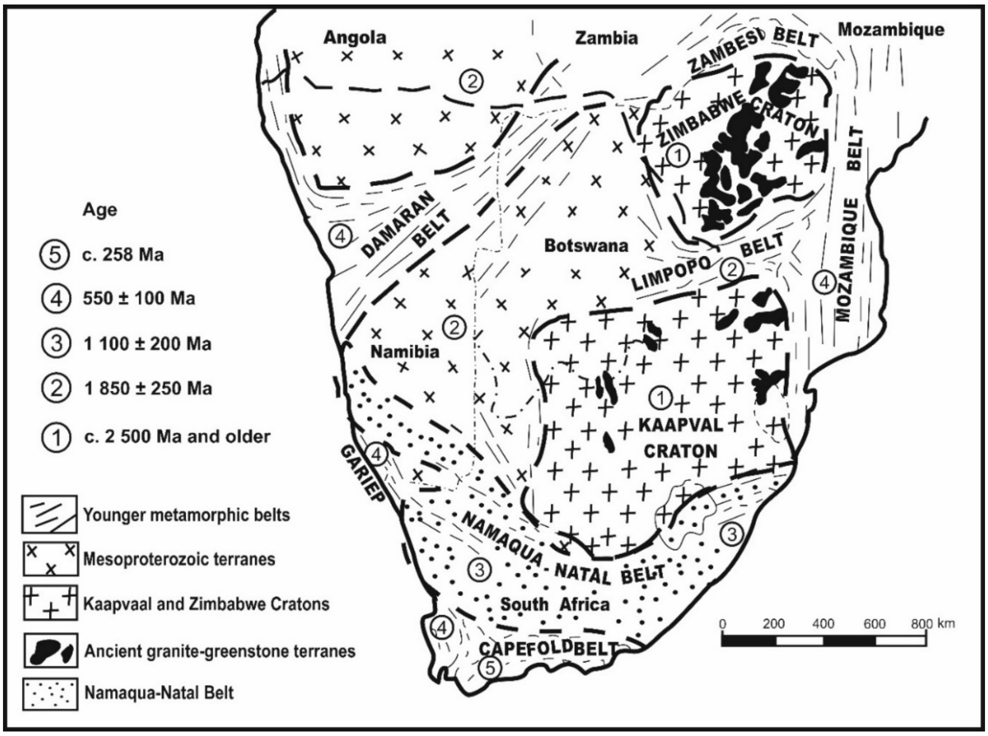

FIGURE 24: The tectonic setting of Southern Africa (Yibas, 2022)

2.7.1 Geothermal manifestations in South Africa

Geothermal resources in South Africa occur both in fractured terranes and within granitic terranes. The migration and localization of the South African geothermal springs is dominantly controlled by the deep geological structures, such as folds, fractures, faults, and dykes. These structures provide the necessary channels of recharge and discharge maintaining the local and regional ground water systems, as well as heat exchange system between the rocks and the circulating subsurface water, before rapidly returning to the surface. Most of the thermal springs came along to the surface or shallow part of the subsurface along fault zones or fissures and along dykes (Yibas, 2022; Tshibalo et al., 2015).

South Africa has more than 81 thermal springs distributed across varied terranes in the regions from the Central Plateau, Southern fold belts and the Northern mobile belts (Figure 25). For example, the Siloam hot spring in the Soutpansberg Basin is associated with narrow dykes while all the Limpopo hot springs in the North are associated with faults and impenetrable dykes or sills. Shallow to medium depth aquifers are very common in South Africa. Exploration drilling and hydrogeological studies in the Karoo have shown several fractured shallow aquifers of temperatures of about 26°C and 30°C. Hot springs associated with high-heat producing granite buried underneath a thick pile of sedimentary rock occur in several places in the Northern Cape, especially at the contact between granitic basement and the Karoo sediments. These include granites South of Upington and the Namaqualand region and Northern part of Kwazulu-Natal. Temperatures of 100°C to 150°C at depths of 3000 to 5000 m have been recorded. Deep fractured aquifers are also identified in the Limpopo belt and Cape folded belt were temperatures of 60°C to 80°C at depths of 1,000 to 2,000 m could be measured.

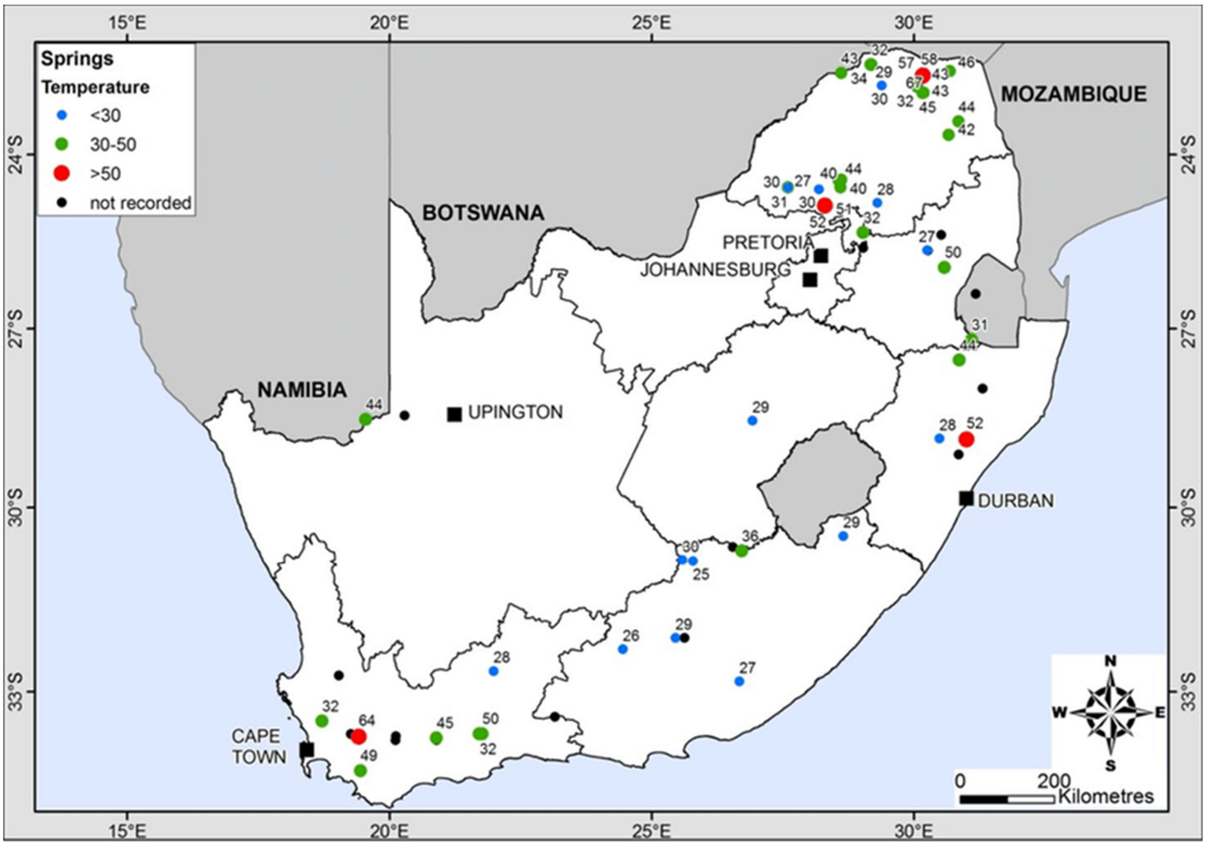

FIGURE 25: Hot springs of South Africa. Very hot springs (above 50°C) are found in the Limpopo Province in the North of the country and in the Western Cape Province in the South-West (Tshibalo et al., 2015)

2.7.2 Geothermal utilization in South Africa

The most popular current use of South African thermal springs is as resorts for leisure and tourism. More than 30 hot springs have been developed for spas and hot baths. At some, water is bottled and sold for therapeutic purposes and in other instances the thermal spring is the sole source of water for the entire resort. Unacceptably high values of trace elements such as antimony, mercury, selenium and arsenic were found at some springs and so not all hot spring waters are potable. There are experiments ongoing to test potential for hot dry rock technology to utilize some resources for electricity generation.

2.8 Sudan

Sudan is largely underlain by Precambrian rocks, particularly in the Southwest, centre and Northeast, which were almost exclusively reactivated during the Neoproterozoic Pan-African tectono-thermal event (Figure 26). Large parts in the North of the country are covered by continental clastic sequences of the predominantly Mesozoic Nubian cycle (previously Nubian Sandstone), and in the South by Tertiary to Quaternary unconsolidated superficial sediments. Some Tertiary and younger basalts occur in the border zone with Ethiopia.

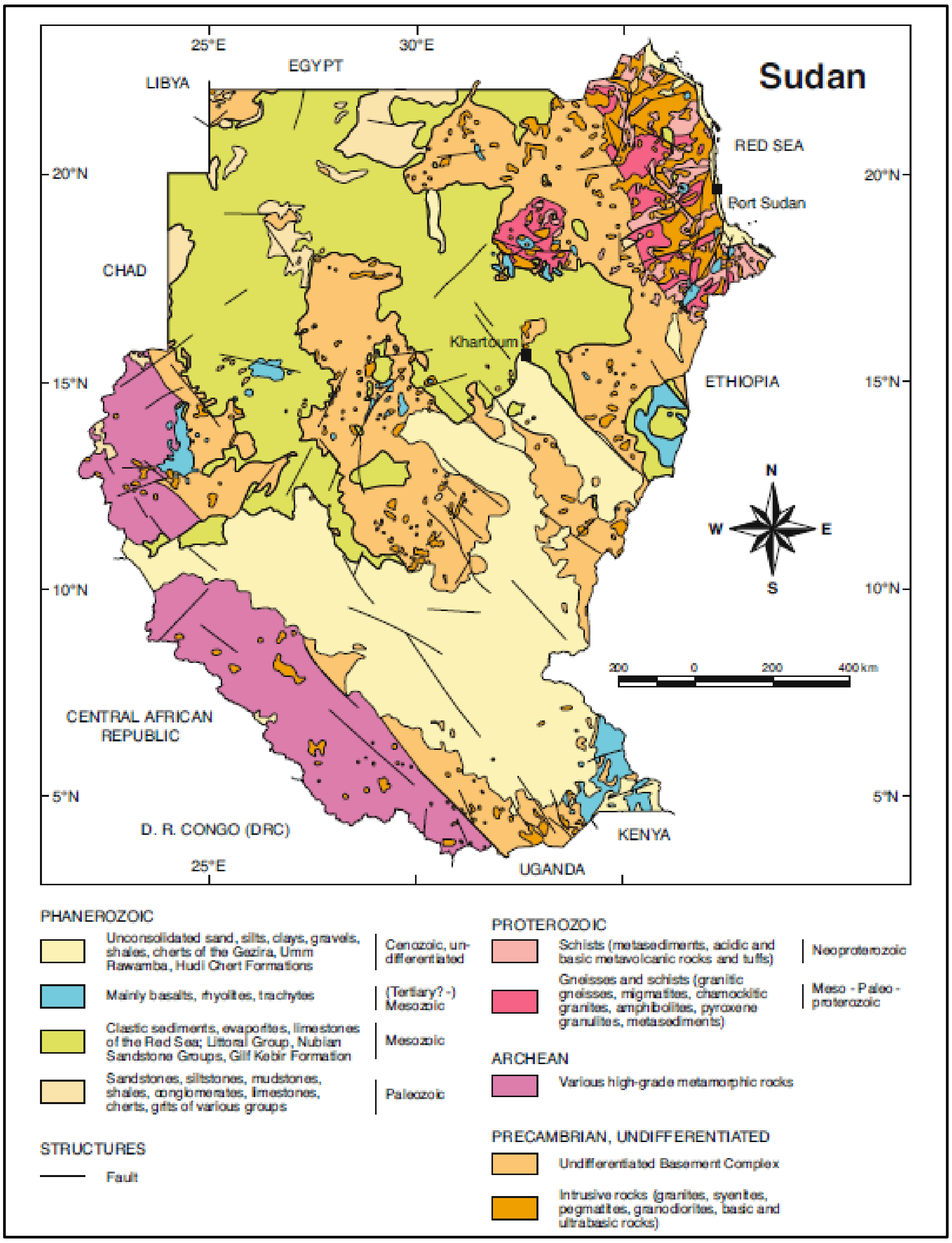

FIGURE 26: Combined geological and structural map of Sudan and South Sudan (Ministry of Energy and Mines, Geological and Mineral Resources Department, Khartoum)

2.8.1 Geothermal resource areas in Sudan

According to Renewable Energy and Energy Efficiency Partnership (REEEP), there is about 400 MW of potential geothermal energy in Sudan. Geothermal potential is located in different regions around the country, for instance, in the Darfur region, the Jabel Marra volcano, and the Tagbo and Beidob hills have registered high temperatures; while further North towards the Red Sea there are areas of geothermal activity (Figure 27; Blinker and Grassi, 2001). The Central African Rift System (CARS) is a rift system of Cretaceous age and spun across the African continent from Cameroon in the West to Sudan in the East and geothermal resources are thought to occur along it. The shear zone dates to at least 640 Ma (million years ago). Motion occurred along the zone during the break-up of Gondwanaland in the Jurassic and Cretaceous periods. Other rifts in Sudan are Cretaceous to Paleozoic.

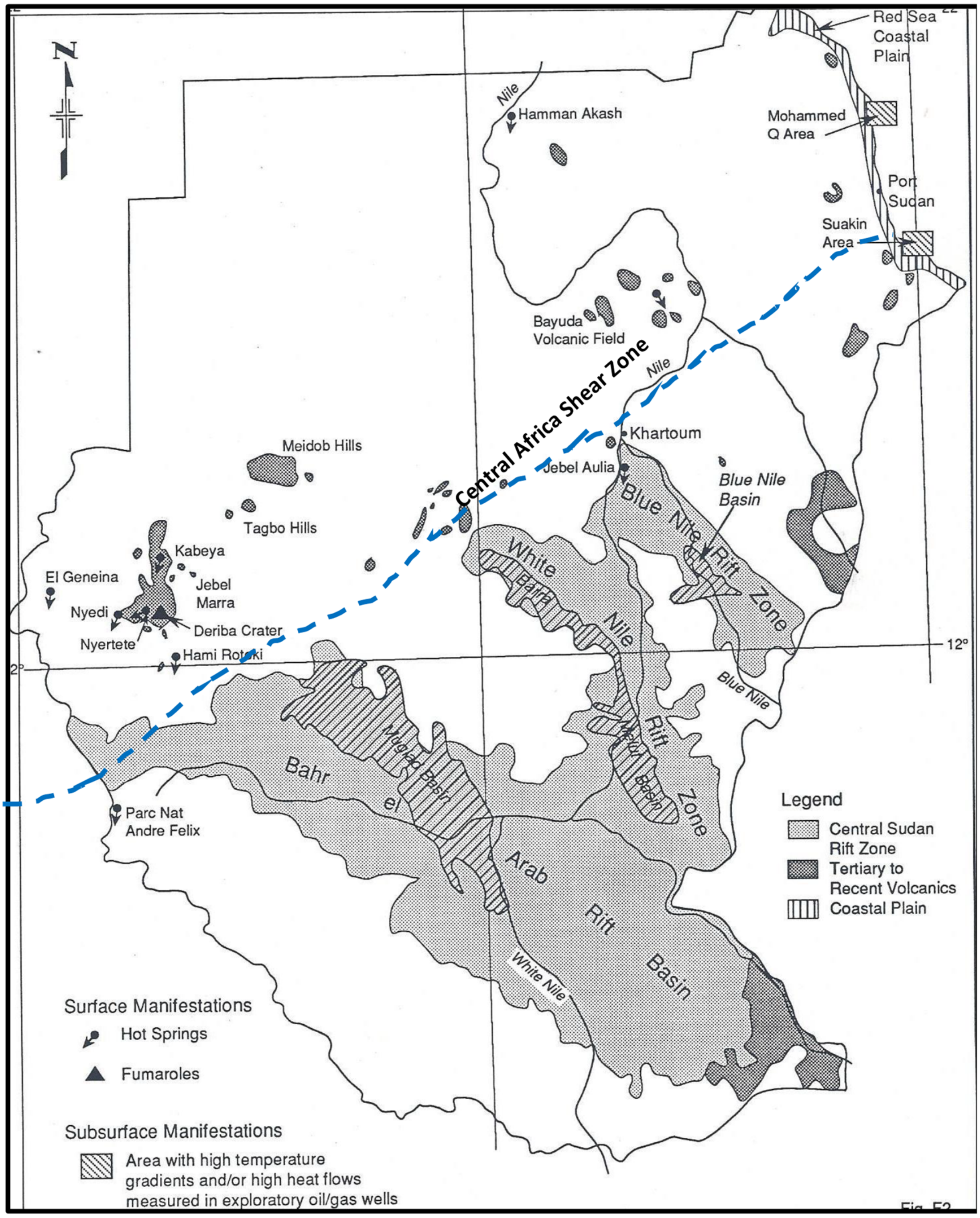

FIGURE 27: Areas with potential geothermal resources in Sudan

The geothermal resources at the Red Sea Coast are a geopressurized with geothermal gradients of 51°C/km to 180°C/km and bottom-hole temperatures of more than 196°C at 2,400 m. At Tagbo and Meidob hills to the NE of Jebel Marra within an area of volcanic activity, a few hot springs possibly exist at low temperatures and indications are largely interpreted from the presence of young volcanism (Figure 28). The same interpretation is made for the Bayuda volcanic field where no surface manifestations has been recorded. Here, the volcanism is of Pleistocene to Recent.

The Jebel Marra intra-plate alkalic volcanic complex, which elongates N-S with a maximum elevation of 3,042 m and covers an area of about 8,000 km^2 is the most important geothermal site in Sudan (Davidson and Wilson, 1989; BRGM, 1994). It is considered to be situated at a possible triple junction in the African lithosphere between the CARS and the Abu Gabra Rift, which is the Northern extension of the Bhar el Arab graben. It is part of the domally uplifted and volcanically active Darfur swell (Bermingham et al., 1983). The origin of the uplift, the associated thinning of the lithosphere and the volcanism has been attributed to upwelling of hot asthenosphere. Deriba is a Pleistocene or Holocene caldera in Darfur, Sudan further attesting to the presence of magma chambers in the area. Hot springs and fumaroles occur in this area. KenGen did a reconnaissance survey in this area that included geology, geochemistry and resistivity surveys but the results have not been made public.

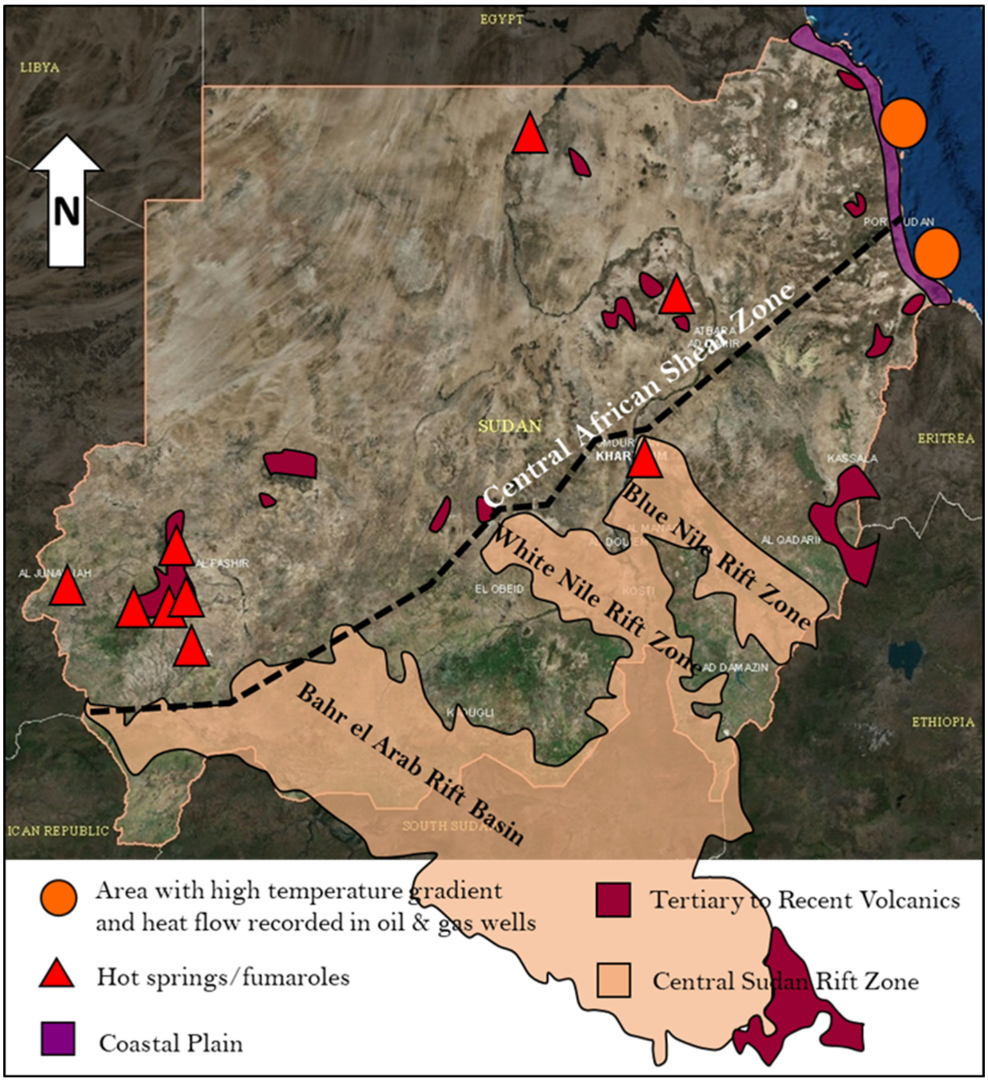

FIGURE 28: Map of Sudan and South Sudan showing the location of hot springs

2.9 South Sudan

South Sudan is located in Central Africa and bordered by Ethiopia, Sudan, Central African Republic, Democratic Republic of the Congo, Uganda and Kenya (Figure 29). South Sudan's geology ranges from Precambrian crystalline basement rocks to Quaternary unconsolidated alluvial deposits and Quaternary volcanics in the South-East (Figure 26). Significant periods of erosion during the Paleozoic and Mesozoic removed the majority of sedimentary cover deposited on the crystalline basement during these times. Much of Northern South Sudan is underlain by deep, oil-bearing rift basins, with sedimentary rocks up to 14 km thick. Lacustrine shales, claystones, sandstones and conglomerates formed in the Jurassic and Cretaceous.

FIGURE 29: Map of South Sudan

2.9.1 Geothermal sites in South Sudan

The rift basins in South Sudan include the Cretaceous to Tertiary Jonglei Basin, Muglad Rift Basin (Bar el Arab rift part in South Sudan) and the Melut Basin (also known as White Nile basin), a passive rift basin with numerous oil-rich rift sub-basins having inversion structures with uplifts and faulted blocks. The other areas of geothermal surface manifestations include areas of Tertiary to Recent volcanism in the Southeast of the country; marsh at the Kanataruk hot springs at the South Sudan border with Uganda. Other hot springs include Liyu hot spring located in Central equatorial state; Latuke, Kajo Keji and Lobonok.

3. CONCLUSIONS

Geothermal resources occur in almost all countries in Africa but with varying resource enthalpy from low to high. The geothermal systems span the range from volcanogenic, geopressured, fracture controlled and hot dry rock. The heat sources are therefore either from magma, deep circulation, sedimentary basins or heat generating granites. The resources have potential to be used for some power generation and direct applications that include greenhouses, fish farming, and industrial heating applications. Detailed exploration studies involving structural mapping and geophysical surveys could delineate larger resources that can be used in a cascaded system from ORC power generation to various direct use applications.

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