A summary of the East Africa Rift Temperature and Heat flow Model (EARTH)

Overseas Development Assistance Programme

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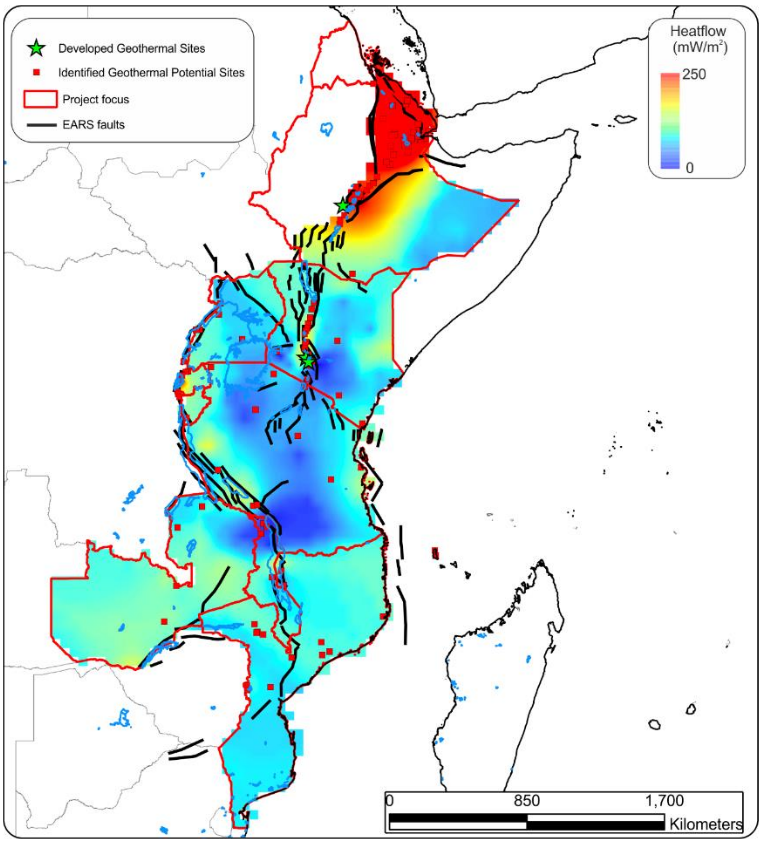

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OVERSEAS DEVELOPMENT ASSISTANCE PROGRAMME

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A summary of the East Africa Rift Temperature and Heat flow Model (EARTH)

D. J. R. Jones

Contributor/editor

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British Geological Survey offices

Environmental Science Centre, Keyworth, Nottingham NG12 5GG

Tel 0115 936 3100

BGS Central Enquiries Desk

Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales

Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP

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Tel 020 7589 4090
Tel 020 7942 5344/45 email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place, Cardiff CF10 3AT

Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford, Wallingford OX10 8BB

Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw, Belfast, BT4 3SB

Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU

Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House, Swindon SN2 1FL

Tel 01793 444000
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1 Introduction

Geothermal energy is potentially an abundant source of energy across the East African Rift System (EARS) covering Burundi, Djibouti, Eritrea, Kenya, Mozambique, Rwanda, Tanzania, Uganda and Zambia. According to the International Geothermal Association (IGA) East Africa is estimated to have geothermal resource potential of 20,000 Megawatt electrical (MWe). The demand for energy in East Africa remains significant. Although the share of population in East Africa without access to electricity has fallen from 90% in 2000 to 61% 2016 (IEA, 2017), the absolute number of people has increased by 8 million as electrification efforts have been outpaced by rapid population growth (Hafner et al., 2019). A BGS study by Jones (2018) highlighted the need for East African countries to diversify their energy portfolios and identified geothermal as a potential source of energy that could help these countries support their growing populations and economies.

East Africa currently has an installed electricity capacity of 8000 MW, with geothermal power having the potential to increase this capacity by 250%. Currently only Kenya and Ethiopia have a few operational geothermal sites with a combined installed geothermal energy capacity of 137 MWe. Since the 1980s the largest geothermal field in Kenya is Olkaria which now generates 130 MWe (Kombe and Muguthu, 2018). The rest of the regions potential remains poorly defined. To understand the regional potential for geothermal resources across the EARS, a summary of available data and knowledge is required in a way that permits estimation of the resource to help direct future research and exploration in the area.

2 Aims

The study conducted has two main aims;

(1) Compile all existing BGS and open source geothermal data into a GIS product called the EARTH model to highlight areas of specific geothermal energy potential for poverty-stricken regions in East Africa. This complements the UN Sustainability Development Goal 7, Affordable and Clean Energy.

(2) Using heat flow and geothermal gradient data from well boreholes and lake-bottom probe measurements, generate a 2D regional heat flow map across onshore East Africa to identify regions of geothermal interest.

3 The East African Rift System (EARS) and geothermal systems

The East African Rift System (EARS) is a Tertiary continental rift system which forms a narrow 50-150 km wide, generally N-S elongate system of faults and rift depocentres that extends 3500 km from the Red Sea at Eritrea and Djibouti to the Indian Ocean in Mozambique (de Wit, 2002). The EARS is formed of two sections: the Eastern and Western Branches (Figure 1), which has been refined further into a series of rifts (Chorowicz, 2005). The Eastern Branch is a volcanic rich system, which started forming in the Paleogene consisting of the Afar, Main Ethiopian, Omo-Turkana, Kenyan, Gregory and North Tanzania Divergence Rifts (Figure 1).

The Western Branch is younger, developing from the late Miocene (Ebinger, 1989) and is characterised by a series of narrow deep rift lakes such as Lake Tanganyika and Lake Malawi/Nyasa, while containing fewer volcanic centres compared to the Eastern Branch. This branch consists of the Albertine, Edward-Kivu, Tanganyika, Rukwa and Nyasa Rifts (Figure 1). These rift basins can reach maximum sediment thicknesses of 6-7 km (Morley, 1989).

Favourable conditions to generate geothermal energy generally require temperatures to exceed 100°C in the subsurface and be in close proximity to an active source of water or steam produced to run turbines in order to generate electricity. Along the East African Rift System, it is generally assumed these conditions are related to areas of young volcanic activity and/or high heat flow associated with current activity and active tectonism. Geothermal sites currently identified in East Africa are found in high temperature (>100°C) hydrothermal systems associated with rift-related volcanic/magmatic activity. Figure 2 shows the surface geology across East Africa, identifying the Tertiary and Quaternary volcanic centres along the Eastern Branch of the EARS. A mixture of Tertiary and Quaternary volcaniclastic sediments are shown at surface within the rift margin and shoulders in northern Tanzania/southern Kenya, which is replaced by predominantly Tertiary volcanics in southern and central Ethiopia and then replaced by Quaternary volcanics in northern Ethiopia, Djibouti and Eritrea towards the Red Sea. There is a lack of recent volcanism along the Western Branch of the EARS with just some localised volcanic centres around Lake Kivu. Further south there is some Quaternary volcanism between Lake Rukwa and Lake Malawi/Nyasa. In general, most of the identified geothermal prospects are located within or adjacent to Cenozoic volcanic centres. Some exceptions are found in Tanzania, Zambia, Uganda and Mozambique. As shown in Figure 2 most of the identified and developed geothermal sites are associated with these volcanics. These volcanics act as a cap rock preventing the ascent of thermal waters and act as an insulator preventing heat escaping to the surface (Chandrasekharam et al., 2018).

In total there are three active developed geothermal sites in East Africa. Olkaria and Eburru in Kenya and Alutu Langano in Ethiopia. Figure 3 shows the location of these sites and spatial distribution of identified potential geothermal sites across East Africa overlying a digital elevation model (DEM) map of East Africa. It highlights that the EARS is characterised by two main topographic highs with average elevations of 1,500 m above sea level; (1) Afar Dome located below the Afar/Ethiopian Rift and (2) East African Dome (below the Gregory Rift). These domes are approximately 1000 km is diameter and associated with upwelling zones from the Africa Superplume; an area of upwelling mantle (Ebinger and Sleep, 1998; Nyblade and Robinson, 1994). Recent geothermal studies using geochemical (Kieffer et al., 2004; Furman et al., 2006) and seismic velocity data (Emry et al., 2019; Fishwick and Bastow, 2011; George et al., 1998) suggest this may consist of several plumes rather than just one. In the Western Branch there are more localised areas of high topography along the Albertine/Kivu-Edward Rifts, as well as the southern part of the Tanganyika and northern Nyasa Rifts (Figure 3). These high topographic features located on the rift shoulders of EARS correlate to areas of geothermal activity. Hochstein (1999) identified up to 54 major geothermal systems along the Eastern Branch of the EARS. Figure 4 illustrates the type and spatial distribution of hot springs identified across the EARS. It shows that the Eastern Branch is dominated by volcanic hydrothermal systems, whilst in the Western Branch it is hot / thermal springs.

4 Previous work

4.1 GEOTHERMAL RESOURCE STUDIES

Initial geothermal exploration in the EARS began as early as the 1950s with two geothermal wells drilled at the Olkaria site in Kenya supported by the United Nations Development Programme. Drilling continued at experimental sites in Ethiopia (Gizaw, 1993) and Djibouti (Khaireh, 1989).

Furthermore a British-Kenya geothermal exploration project was undertaken between 1985-87, as part of a regional resource assessment, as described by Allen et al. (1989).

Phase I of the British-Kenya geothermal exploration project focused on southern part of the Kenya, in the Gregory Rift between Lake Magadi and Lake Bogoria (Allen et al., 1989). This study consisted of fieldwork and collecting hydrogeological data with aim to provide a greater understanding of the thermal waters in the rift. Key findings were that the permeability of the surface volcanic rocks underlying the rift valley are generally poor, with good permeability found in the reworked or fractured volcanics. This study concluded the geothermal areas at Eburru, Olkaria-Domes, Longonot, Suswa and Magadi are individual geothermal fields with local high temperature heat sources (100-130°C) providing geothermal fluids which originate from groundwaters and lakewater. The regional model suggests groundwater flow from the rift escarpments onto the rift floor and axial flow.

Allen and Darling (1992) conducted phase II looking at understanding the location, nature and movement of thermal waters in the Kenyan Rift, specifically the hydrogeology, particularly in the region between Lake Baringo and Lake Turkana. This involved mapping the geology and understanding the hydrogeological systems and geothermal properties of four volcanic centres: Korosi, Paka, Silali and Emuruangogolak.

Phase III by Darling (1991) focused on southern part of Omo-Turkana Rift, conducting a geochemical sampling campaign on young volcanic centres on shores and islands on Lake Turkana. The lack of surface thermal water meant most of the samples were taken from fumarolic gas rather than water geochemistry. The results from gas geothermometry to define reservoir temperatures were inconsistent and found to be inconclusive.

Dunkley et al. (1993) provided a regional geothermal resource assessment along length of the Kenyan rift, particularly focusing on six volcanic centres between Lake Baringo and Lake Turkana. They identified six main geothermal prospects in the region with Silali, Emuruangogolak and Paka having the highest temperature geothermal systems. Further recommendations were to look at geophysical data to look for volcanic centres, identifying intrusive bodies which could provide heat for geothermal systems. Resistivity data could be useful to identify prospects where young lava fields cover the area.

No further work was conducted on geothermal in Kenya until 2018, when a BGS workshop took place in Kenya, funded as part of a Global Challenges Research Fund (GCRF), to get leading African and UK scientists together with an interest in sustainable development of volcanic and geothermal resources. Rochelle (2018) summarised the workshop, and identified various key areas where BGS could be involved, in particular understanding processes of the EARS through using of remote sensing, seismic, gas and water monitoring, as well as more focused site-specific surveys.

4.2 HEAT FLOW IN EAST AFRICA

Many studies into heat flow have been made across East Africa (Branchu et al., 2005; Von Herzen and Vacquier, 1967; Ebinger et al., 1987; Golubev and Klerkx, 1991) with the continent having an average value of 49 mW/m^2 (Sclater, 1980). Evans (1976) was first to study the use of bottom hole temperature data from deep oil and gas wells to help calculate an average heat flow of Eastern Africa of 64 mW/m^2. Fadaie and Ranalli (1990) were able to distinguish average heat flow measurements taken mainly from lake-bottom sediments of 106±51 mW/m^2 for the Eastern Branch and 68±47 mW/m^2 for the Western Branch. Macgregor (2019) stated East Africa has a limited amount of heat flow data with around two thirds coming from North Africa. Heat flow data in East Africa itself is generally poor with little amounts of published data available.

Currently the best heat flow model for East Africa is of relatively poor resolution and was produced by Davies (2013) as part of a global heat flow data map from regional compilation of data from shallow cores and boreholes. Most of the potential in East Africa have been identified using surface temperature, surface geology and water geochemistry. No attempt has yet been made to produce a regional heat flow map for East Africa using the available data from subsurface well information to assist with identification of geothermal areas of interest. This project aims to put in place the first attempt to produce a robust regional model for heat flow and geothermal gradient.

5 The EARTH model

5.1 INTRODUCTION TO MODEL

A Geographic Information System (GIS) model was created by collating publicly available data on geothermal site and hot spring locations, digital elevation, dynamic topography, surface temperature, bottom hole temperatures, thermal conductivities and geothermal gradients from borehole and lake-bottom sediment data, heat flow, surface and structural geology, rivers and aquifers and electrification grid systems across the EARS. This product has been named the East African Rift Temperature and Heat flow (EARTH) model. This data is now openly available hosted on the BGS National Geoscience Data Centre (https://www.bgs.ac.uk/services/ngdc/accessions/index.html#item132705) projected in Geographic Projection System World Geodetic System (WGS) 1984. The sections below illustrate the different types of data available in the model and where explain the data has been sourced.

5.2 CULTURE DATA

Data was collected on geographic information in the form of shape files that included: African coastlines, country polygons, capital cities and lake outlines. The location of power plants and planned/existing electricity grid lines from East Africa were taken from a GIS database World Bank project archive.

In addition the location of operational power plants and the planned/existing electricity grid lines for East Africa were taken from a World Bank study (Arderne, 2017). A raster containing population density of East Africa, taken from (Nelson, 2004), is presented with a spatial gridding resolution of 2.5km.

Access was also made to a global digital elevation model (DEM), the USGS Global 30 Arc-Second Elevation GTOPO30 (USGS, 1997). Here this DEM provides terrain elevation data across East Africa with a horizontal grid spacing of 30 arc seconds (~1km).

5.3 GEOTHERMAL SITES

Geothermal sites contains data on developed and identified geothermal sites across the region are taken from (AGID, 2017). Hot spring information has been gathered from published literature (Branchu et al., 2005; Ebinger et al., 1987; Hochstein et al., 2000; Hochstein, 1999).

5.4 GEOLOGICAL DATA

The geological data contains a shapefile of the main bounding faults of the EARS, digitised from Chorowicz (2005), and the surface geology of East Africa which was provided from a clipped version of the surficial geology of Africa (geo7_ag) taken from Persits (2002). The Archean basement cratons is also available and digitised from Van Hinsbergen et al. (2011).

5.5 HEAT/TEMPERATURE DATA

Average surface temperature data was taken from the National Oceanic and Atmospheric Administration (NOAA) found at (ftp://ftp.ncdc.noaa.gov/pub/data/noaaglobaltemp). The data used is clipped to the countries of interest from the NOAA merged land-ocean surface temperature analysis (formerly known as MLOST). It is spatially gridded using least-squares trend in 5° x 5° boxes, with an average global surface temperature data from 1880 to present.

The global heat flow database was sourced from the International Heat Flow Commission (https://engineering.und.edu/research/global-heat-flow-database/) which is managed by The University of North Dakota, USA. The global dataset consists of 35,523 terrestrial and 23,013 marine data points. For the purpose of this study 182 data terrestrial points were used to develop a heat flow model for East Africa. As heat flow measurements can be obtained in a variety of methods, the purpose of this dataset has been for users to have all open data in a standard format for ease of use. All the heat flow and temperature data used has come from shallow well (<500 m depth), deep well (>500 m) or from lake bottom probes (0-5 m). These measurements were taken from a variety of publications (Chapman, 1977; Evans, 1976; Hochstein et al., 2017; Morgan, 1973; Morley, 1989; Nyblade, 1997; Nyblade et al., 1990; Sebagenzi et al., 1993; Wheildon et al., 1994; Williamson, 1976). The shapefile contains information on site name, latitude, longitude, min and maximum depths, geothermal gradient, thermal conductivity, heat flow, data source and data type.

5.6 BGS PREVIOUS WORK

BGS previous work contains polygons of the geographic areas completed as part of previous BGS geothermal studies.

6 Discussion

Figure 5 shows a map displaying the total distribution of geothermal gradients from the data collected across East Africa. It demonstrates a wide range of geothermal gradient values across East Africa from <20 °C/km to >200 °C/km. The hottest values range from 103 to 298 °C/km correspond to young Quaternary volcanics of the Main Ethiopian and Kenyan rift and Quaternary Lake sediments of the Western Branch (Edward-Kivu, Tanganyika and Nyasa rifts) related to the latest stage of active rifting. Whilst the coldest values of <20 °C/km and are often associated with the cool, thick lithosphere associated with the Precambrian Bangweulu, Kibalian and Tanzania Cratons, as well as Neoproterozoic Zambezi orogenic belt (Figure 5 and Figure 6). These high and low geothermal gradients generally correspond with high and low heat flow values (**Error! Reference source not found.** In general both geothermal and heat flow values decrease the further away from the EARS. There is also much more variability in geothermal gradient and heat flow values in the Western Branch compared to the Eastern Branch based on the data presented.

The data source type for these heat and temperature measurements varies across East Africa and with this brings some uncertainties. Deep well data provides the most accurate data source for geothermal gradient and heat flow, followed by shallow well data. Whilst lake-bottom probe measurements often are inconclusive as they penetrate very shallow depths. The data types are split into three distinct areas: (1) the Eastern Branch of the EARS taken from shallow and deep well data (2) In the Western Branch of the EARS data is mainly from lake-bottom probes measurements with a few points from shallow or deep wells (3) Deep well data associated with Permo-Triassic and older sediments in Zambia, coastal Kenya, Tanzania and Ogaden region of Ethiopia. The fact that the highest variation of both geothermal gradient and heat flow values are from lake-bottom probe measurements indicates a level of uncertainty with these readings. Issues with the heat flow map could also be the prediction is biased by a lack of deep measurements and possibly issues related to lateral heat transfer caused by thermal conductivity lithology contrasts. Furthermore the distribution of this data is very much focused on the southern part of the Eastern Branch and central and southern parts of the Western Branch. Little information is available in the Afar and Main Ethiopian rift and so a lot of assumptions are made on one or two data points. There are no data points covering the Albertine or northern part of Edward-Kivu Rift. So again another limitation of this dataset is the sparsity of measurements across East Africa. Some consideration needs to be made of the very low geothermal gradient values plotted which may be representative of data quality issues within the dataset.

An attempt was made to interpolate the heat flow data further across East Africa. This surface was interpolated using the inverse weighted distance (IDW) gridding algorithm using the spatial analyst tool in ArcGIS. This algorithm was best suited to the data and assumes data points closer together are more representative of the data than those further apart. A 100 km grid spacing was chosen and the result was a heat flow map as shown in Figure 7. Changes for heat flow across East Africa could be related not only to surface geology and lithospheric thickness but also mantle heat flow variation utilising gravity modelling i.e. East African superplume, thinning of radioactive layer in subsurface and lateral heat production contrast i.e. along a fault, lateral thermal conductivity contrasts. Interpolation of the heat flow data have identified 7 potential areas of interest with high heat flows to focus on further geothermal exploration in the Afar/Ethiopian, Kenyan, Edward-Kivu, Tanganyika, Rukwa and Nyasa Rifts (Figure 7).

The installed capacity network of electrification across East Africa is shown in Figure 8. It displays that out of the 7 areas of geothermal interest identified in this study only 3 are located with current installed capacity. Furthermore analysis of the population density per km^2 in East Africa based on data from the year 2000 (Nelson, 2004) is shown in Figure 9. Using a combination of the population density as a proxy for energy demand needs and areas of installed electrification has allowed us to high grade areas for further geothermal research. These have been labelled in order from highest priority to lowest: (1) south of Addis Ababa, Ethiopia; (2) NW of Nairobi, Kenya; (3) Lake Kivu, Rwanda; (4) Lake Nyasa, Malawi; (5) Lake Tanganyika, Tanzania (6); Lake Rukwa, Tanzania; (7) Afar region, Ethiopia/Djibouti. Most of these areas of high heat flow and geothermal gradient correspond to the known geothermal sites identified, except the areas identified on Lake Tanganyika, Lake Rukwa and Lake Nyasa,

7 Conclusions

A compilation of data from various open source publications has delivered a regional heat flow model across East Africa, improving on the resolution of the existing global model delivered by Davies (2013). High heat flow and geothermal gradients are observed along both Eastern and Western Branch of the EARS which correspond to known geothermal areas of interest except for Lake Tanganyika, Lake Rukwa and Lake Nyasa. Based on this data seven geothermal areas of interest have been identified for potential future research. Further analysis of these areas using maps of existing electrification infrastructure and population density has high graded the top three areas of interest for further geothermal research. These are (1) south-west of Addis Ababa in Ethiopia, (2) north-west of Nairobi in Kenya and (3) Lake Kivu, Rwanda.

Data points are limited around the rift and come from various measurements sources but provide us with the best model available. Additional regional work may include performing an estimate of Curie point depth based on magnetic anomaly data which is an indirect temperature indicator and may give additional evidence to help back up this heat flow.

Access is required to existing oil and gas well data, particularly to the drill stem tests (DST) which give accurate measurements of down-hole formation temperature at times shortly after drilling. Bottom hole temperatures (BHT) from oil and gas wells can also analysed on Horner Plots to give us corrected temperature values and therefore give a better understanding on geothermal sites on a country-level scale.

In order to get a robust temperature map across East Africa full modelling is required of heat transfer through detailed understanding of the thermal conductivities rather than linear extrapolations from borehole information. Seismic data will aid with this allowing us to account for the geometry of sedimentary layers and any physical properties resulting from changing of lithology or temperature. In addition, crustal modelling will also help to develop a more reliable regional model. Alternatively, a more focused study on a country-level could be done integrating all available heat flow and geothermal data into a 3D model.

East Africa could be a world leader in geothermal energy, providing a clean low-carbon energy resource to combat the energy crisis and population growth in the region. However there are still some associated risks with the development of geothermal energy. The main risks are the high upfront capital costs, resource exploration risk, inadequate grant support for drilling and lack of technical expertise in country. The slow pace of geothermal development is due to the initial cost of ~$5-10 million per test well. There are also institutional and policy barriers with most East African governments having no clear policy on renewable energy and/or low budget allocations, with high investment attracted in "low hanging fruit" such as the extraction of hydrocarbons in Kenya, Uganda, Tanzania and Mozambique.

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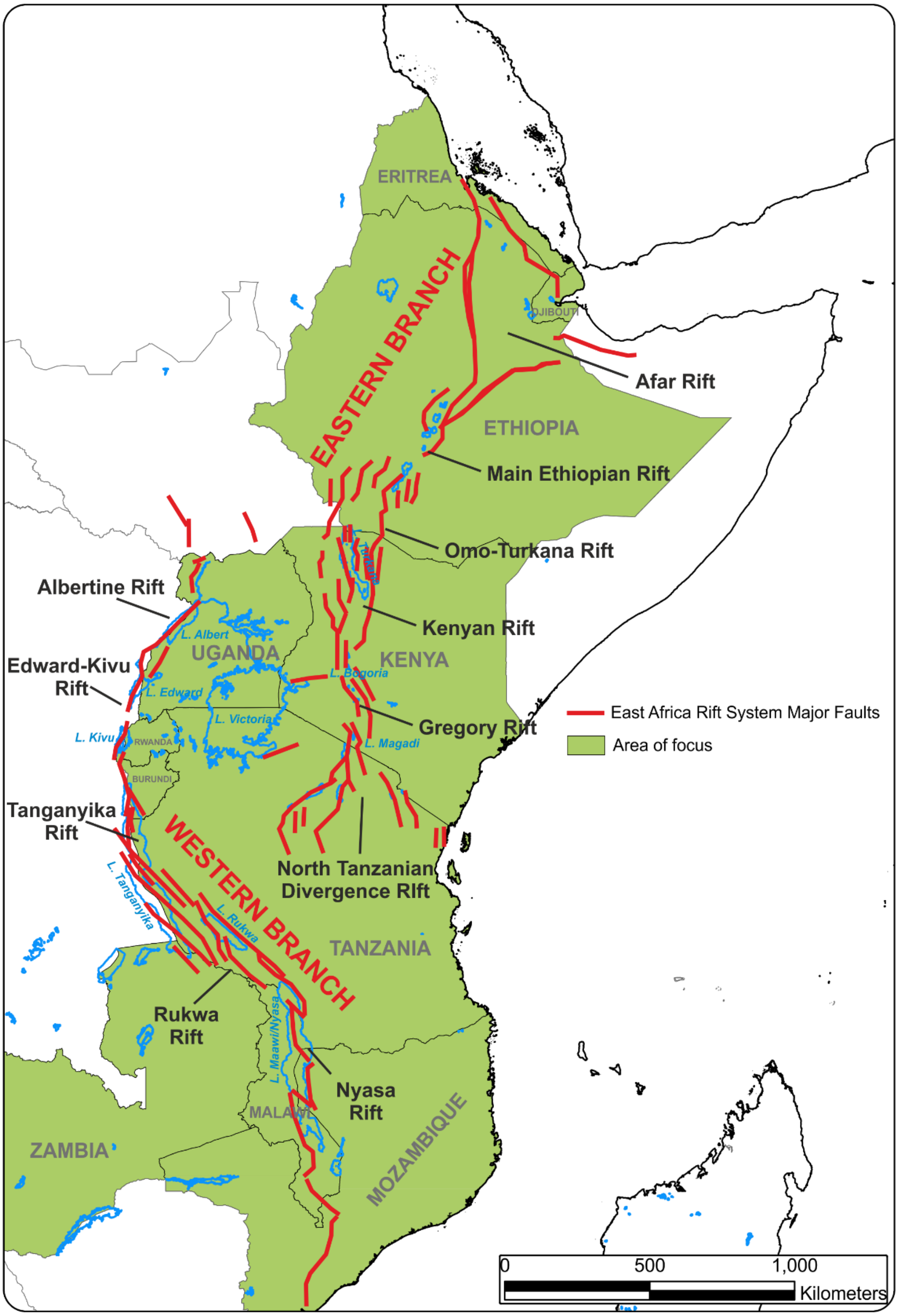

Figure 1. A map illustrating the East African Rift System (EARS) with the red lines indicating the main bounding faults. The fault interpretation has been adapted from Chorowicz (2005).

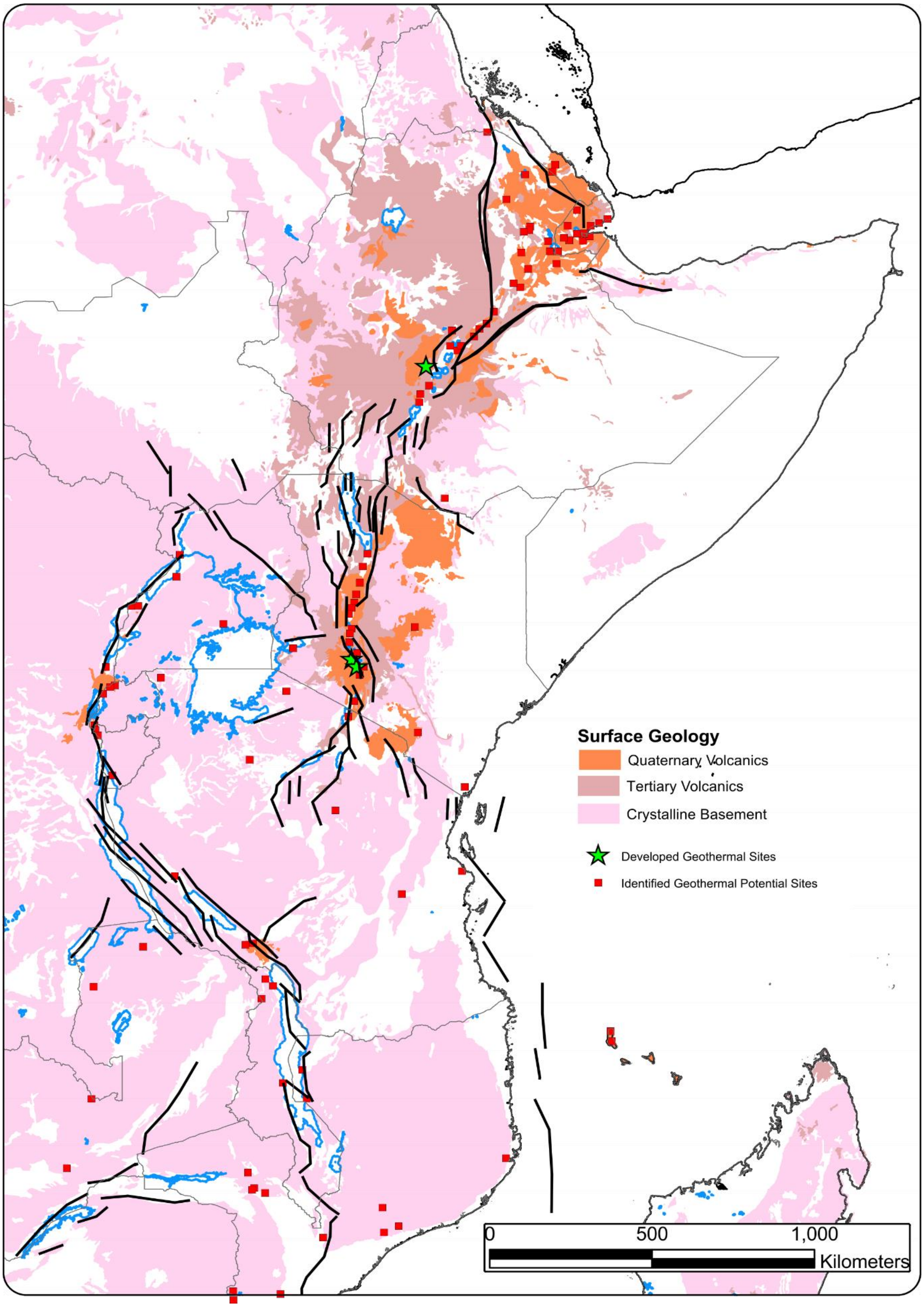

Figure 2. Map showing the spatial location of developed and identified potential geothermal sites across East Africa. The surface geology of East Africa is shown, highlighting where crystalline basement, volcanics and Palaeozoic to Cenozoic cover is present. Note surface geology is taken from Persits et al (2002). Locations of the geothermal potential sites have been taken from AGID (2017). Image created using ArcGIS. Copyright © Esri. All rights reserved.

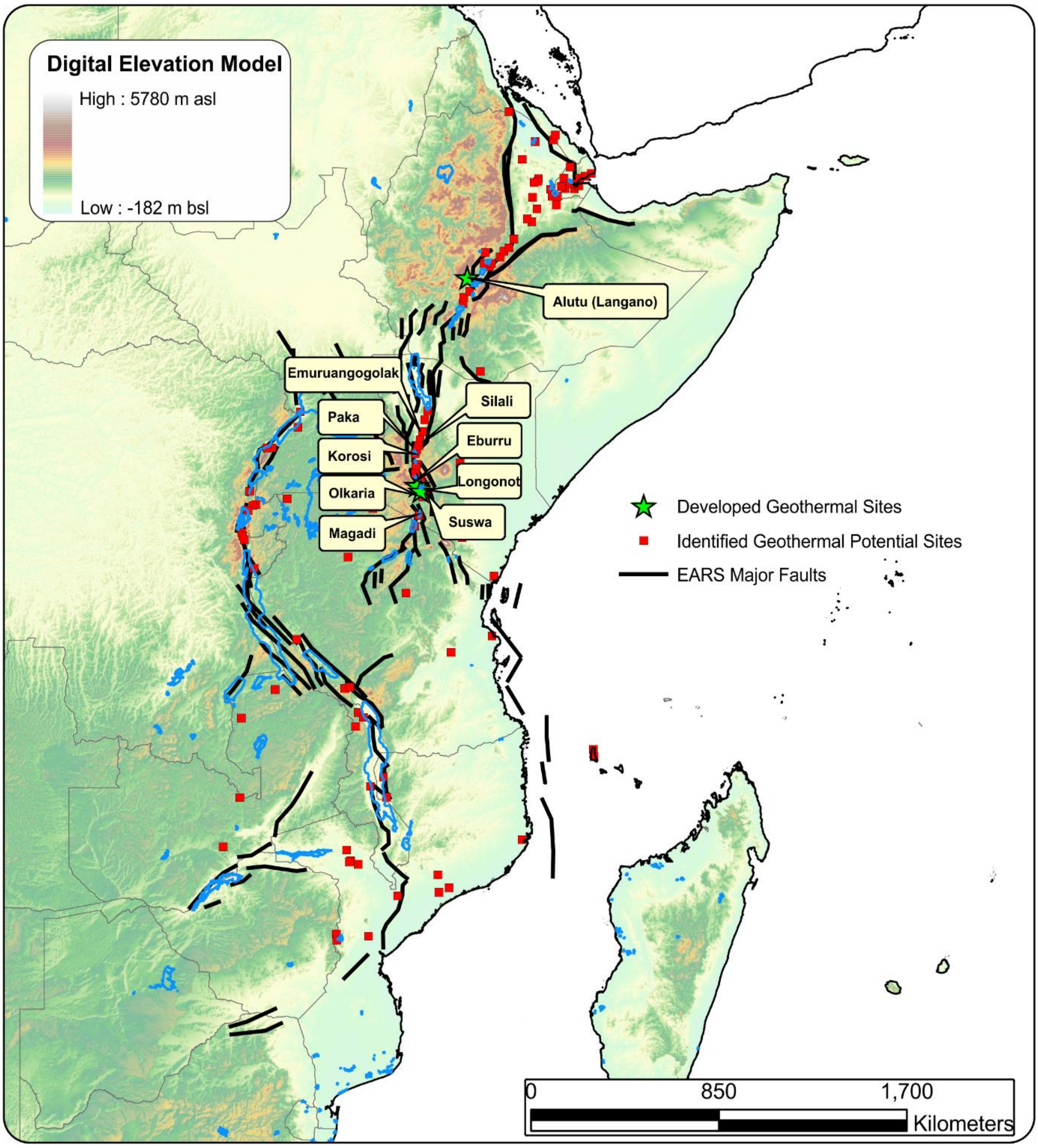

Figure 3. A digital elevation model (DEM) of East Africa showing the location of development and identified potential geothermal sites. The DEM shown here is taken from USGS (1997). Image created using ArcGIS. Copyright © Esri. All rights reserved.

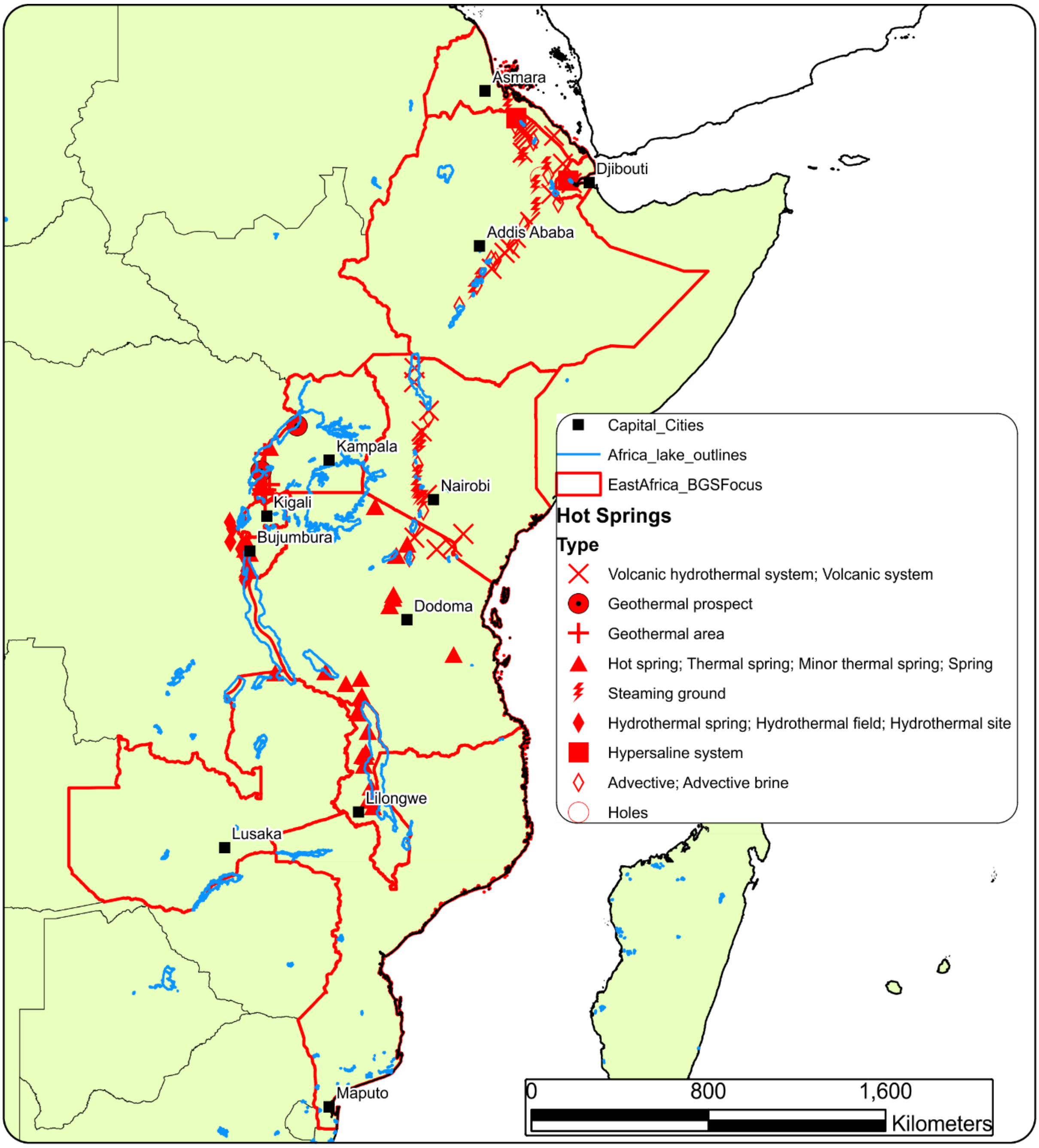

Figure 4. Map showing the location of various hot springs across East Africa. Image created using ArcGIS. Copyright © Esri. All rights reserved.

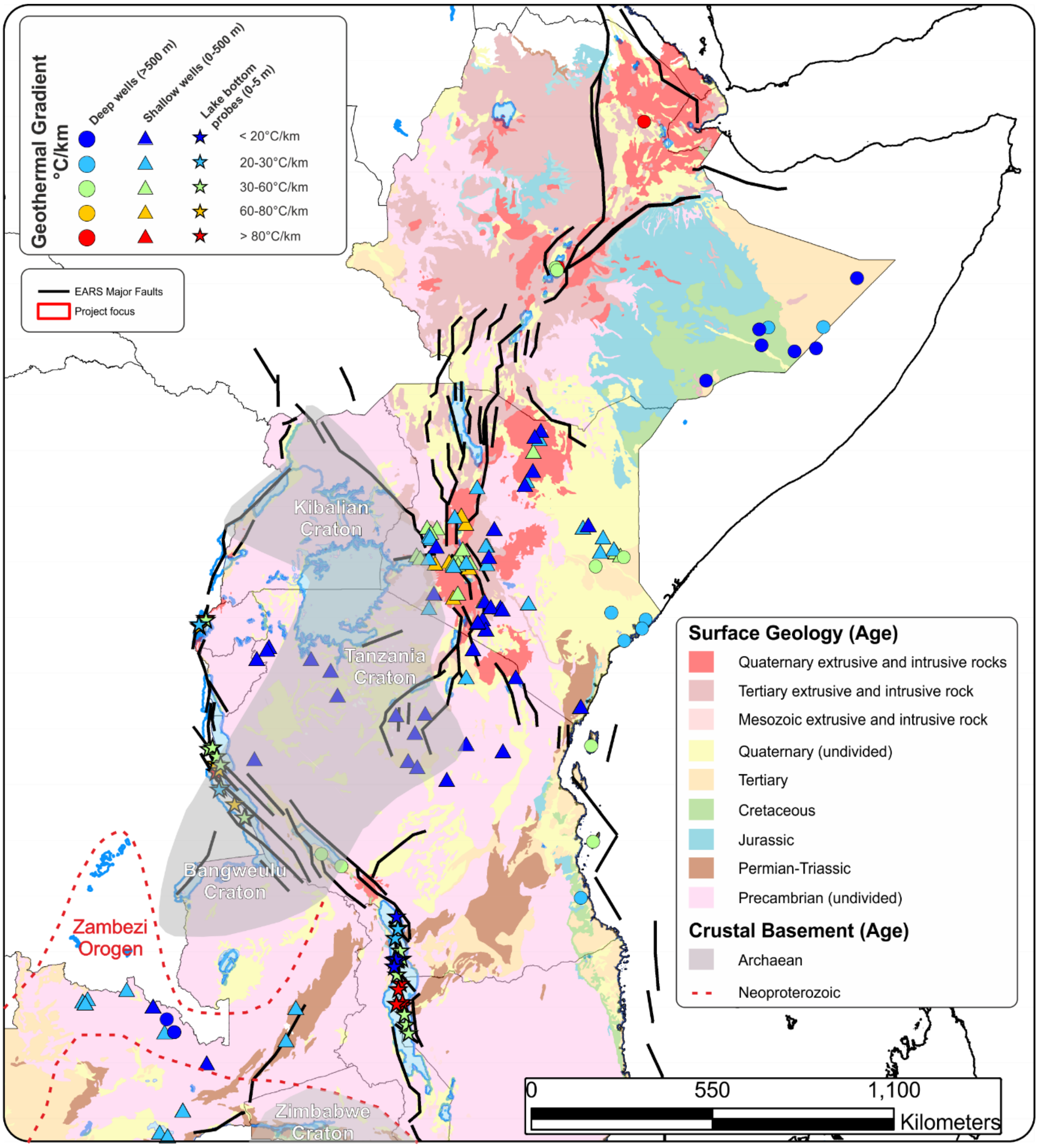

Figure 5. A map showing the distribution of geothermal gradient measurements across East Africa. Note all geothermal gradient measurements were taken from the global heat flow database of the International Heat Flow Commission, managed by the College of Engineering and Mines at the University of North Dakota, USA. Underlying these data points is a full surface geology map taken from Persits et al. (2002) and selected Neoproterozoic and Archaean crustal basement from Van Hinsbergen et al. (2011). Image created using ArcGIS. Copyright © Esri. All rights reserved.

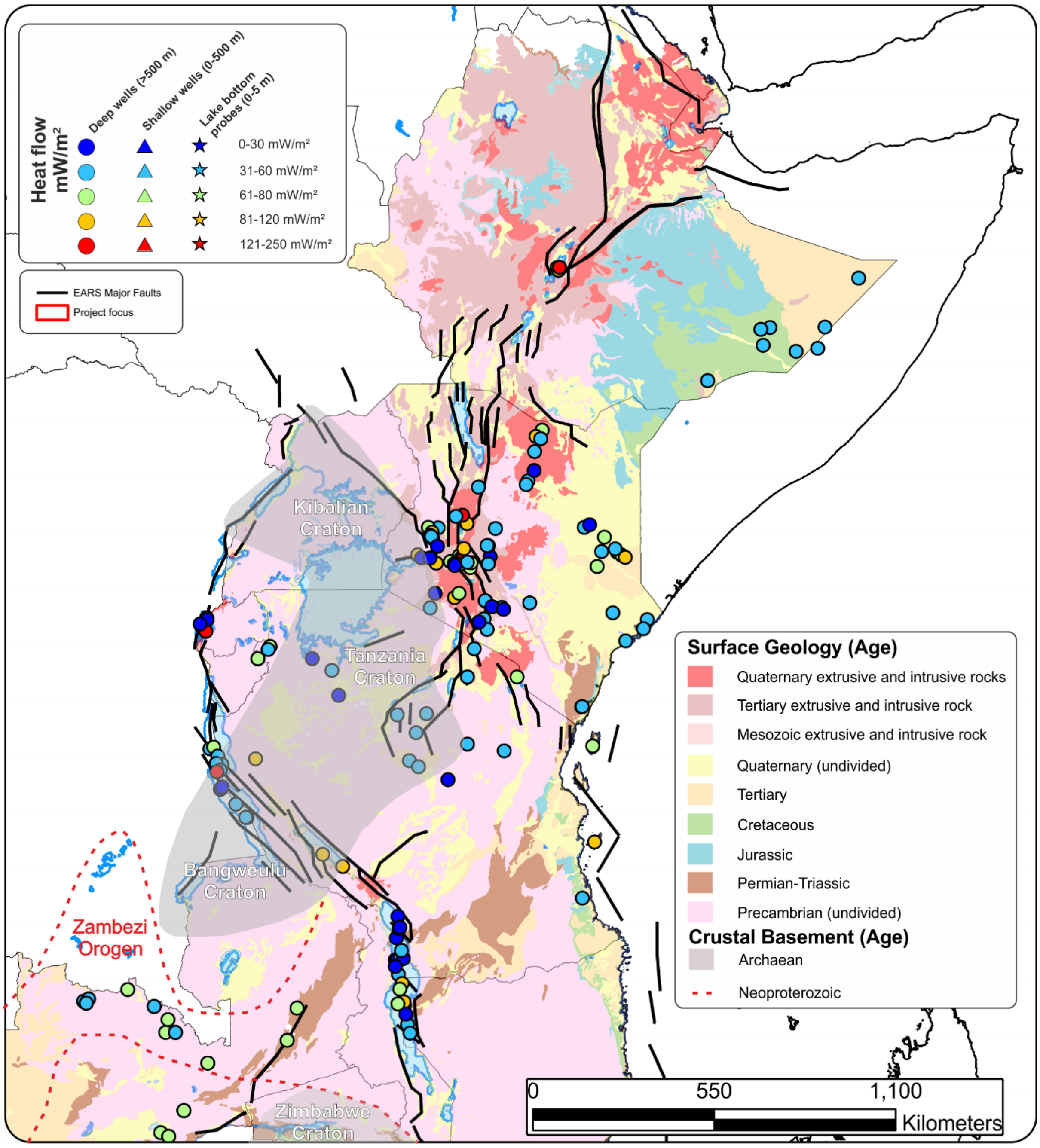

Figure 6. A map showing the distribution of heat flow measurements across East Africa. Note all geothermal gradient measurements were taken from the global heat flow database of the International Heat Flow Commission, managed by the College of Engineering and Mines at the University of North Dakota, USA. Underlying these data points is a full surface geology map taken from Persits et al. (2002) and selected Neoproterozoic and Archaean crustal basement from Van Hinsbergen et al. (2011). Image created using ArcGIS. Copyright © Esri. All rights reserved.

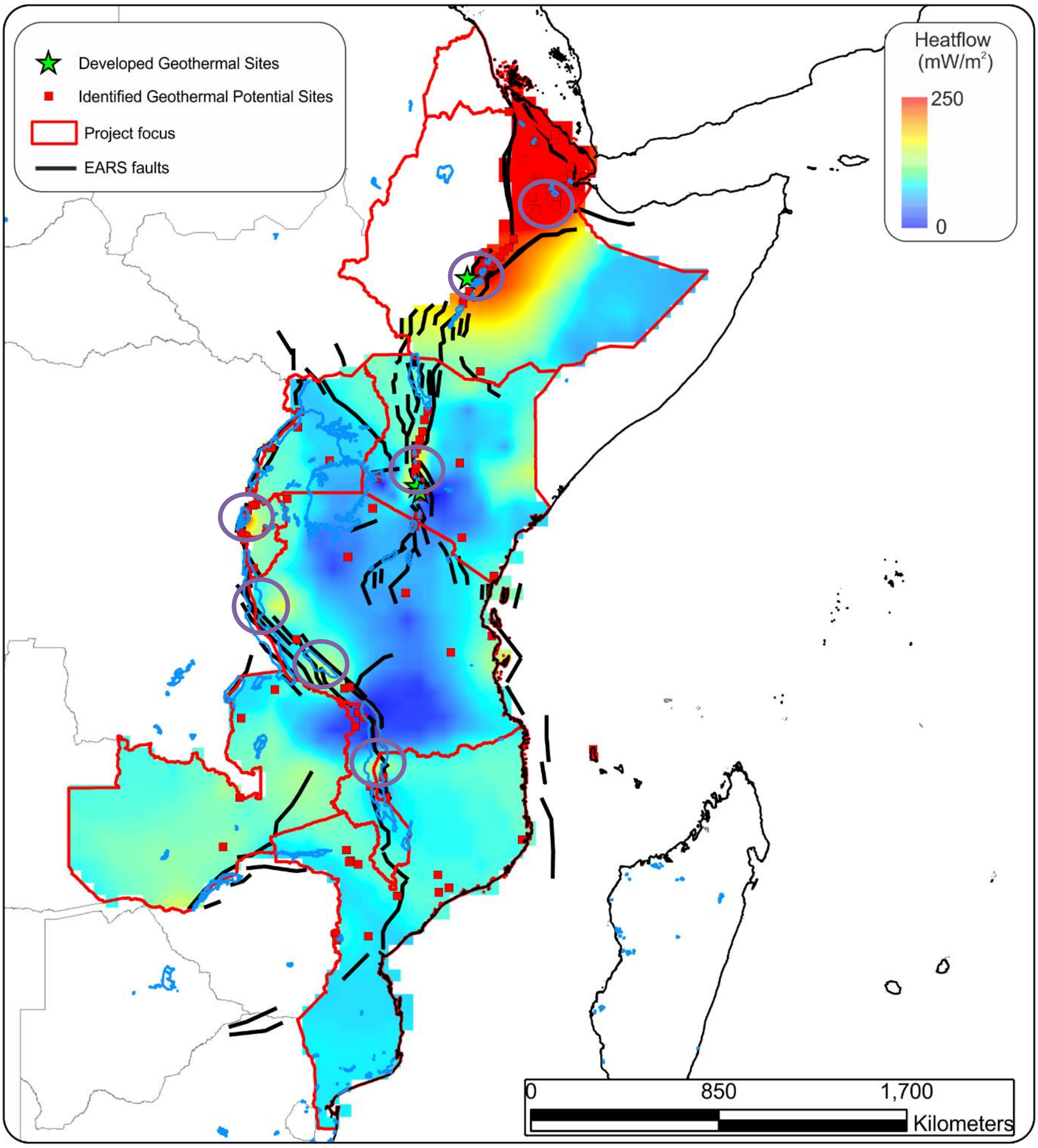

Figure 7. A gridded heat flow map showing the distribution across East Africa taken from the heat flow points. Purple circles highlight areas associated with anomalous high heat flow across the EARS during this study. The location of developed and identified potential geothermal sites are shown, along with the main structural framework of the EARS shown by black lines. Image created using ArcGIS. Copyright © Esri. All rights reserved.

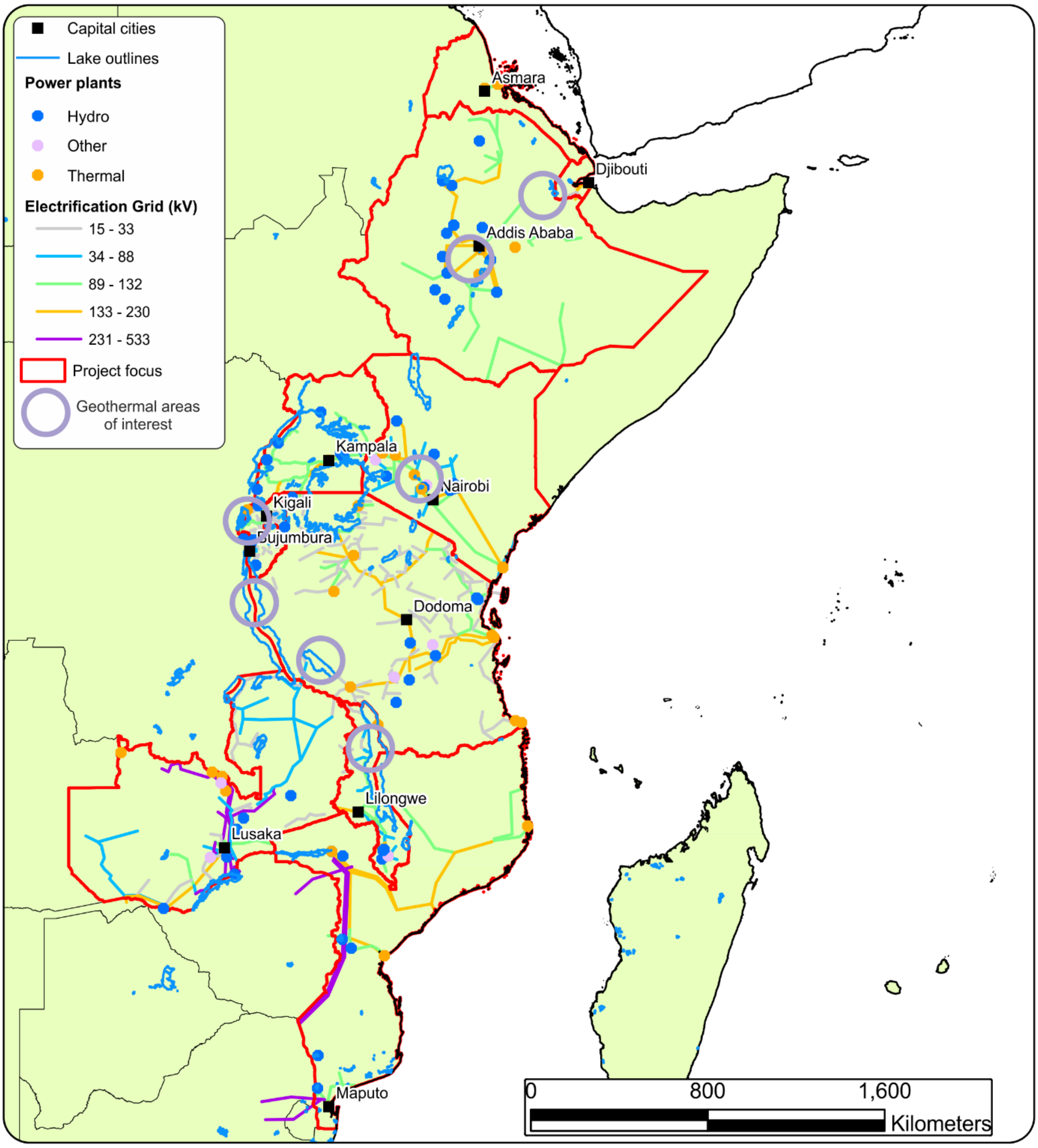

Figure 8. Map showing the installed capacity of electrification grid network and operational power plants across East Africa. Purple circles are locations identified in this study which highlight areas of high heat flow and where future geothermal research should focus on. Image created using ArcGIS. Copyright © Esri. All rights reserved.

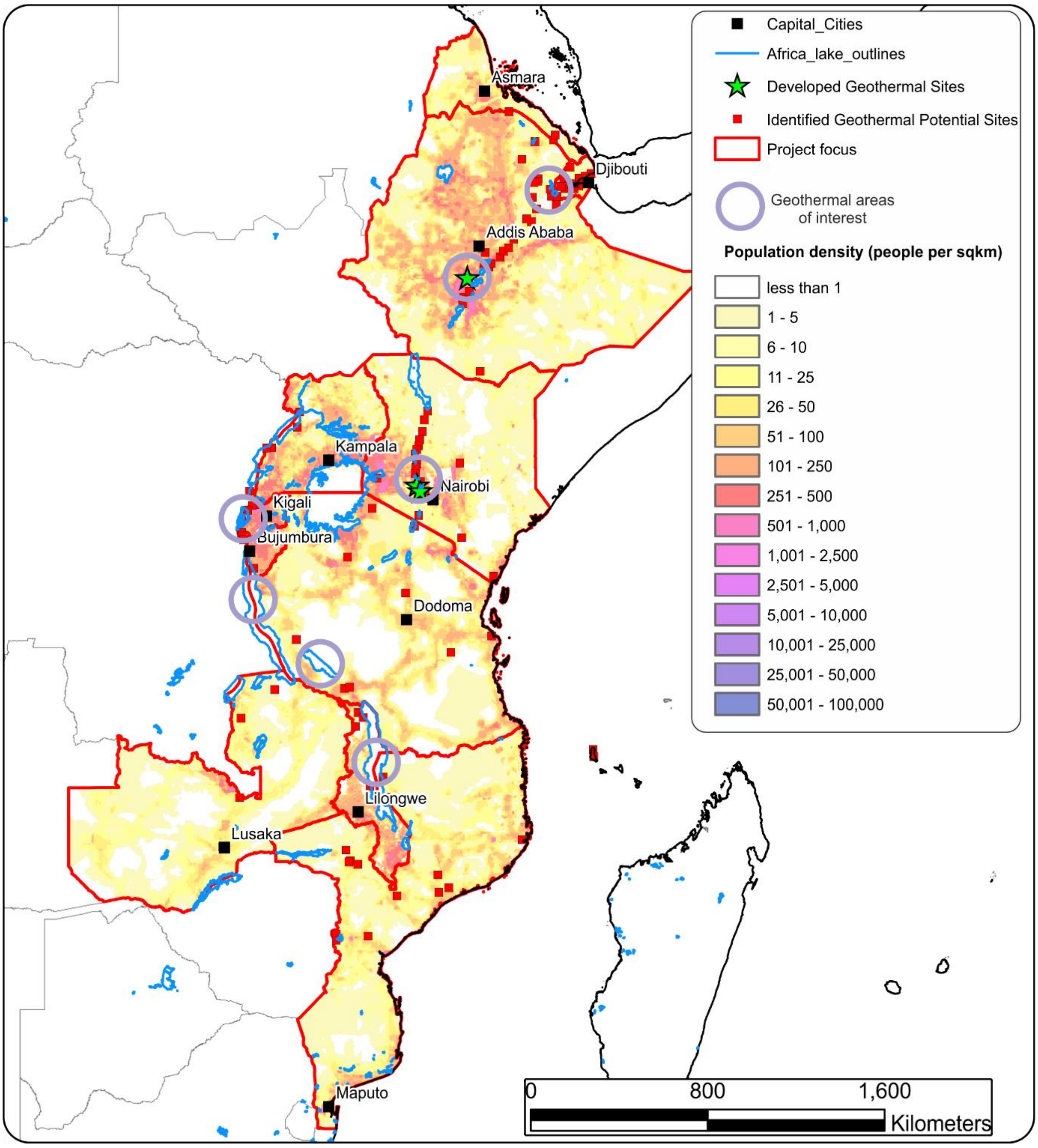

Figure 9. Map showing the population density across East Africa. The location of development and identified potential geothermal sites has been overlain. Purple circles are locations identified in this study which highlight areas of high heat flow and where future geothermal research should focus on. Image created using ArcGIS. Copyright © Esri. All rights reserved.