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A Review on the Geomaterial Aspects of Geothermal Reservoirs and Its Exploration

Worku Janka Negawo
Vrije Universiteit Brussel, Faculty of Engineering
*Email: worku.janka.negawo@vub.ac.be workujanka@yahoo.com

Abstract

In this work a review on the geomaterial aspects of geothermal energy will be presented based on scholarly articles and published materials. As introduction an overview of basic geothermal resource concepts such as the occurrence of geothermal energy, mechanisms of heat flow in the ground and its reservoir types will be explained. Following this, properties of geothermal reservoir formations like permeability and thermal properties of rocks will be presented in detail. Geothermal resource and reservoir characteristics exploration methods including geophysical, geochemical and thermal gradient wells are also broadly discussed in this review. Moreover, a brief presentation on the geothermal resource and related research activities in Ethiopia will be addressed. The objective of this review is to discuss the role of geomaterials on the utilization of geothermal energy.

1. Geothermal Energy

Geothermal energy is the energy contained in the earth's interior. The source of heat to the planet earth is from both external and internal sources of energy. The major sources of external energy are from solar irradiation and gravitational force. The solar energy source is being the largest by providing about 1.5 x 10^{22} J of energy to the earth's surface every day. On the other hand, the interior part of the earth receives energy from four major sources. These include the radiogenic heat, the original heat, potential and frictional energy. The radiogenic energy is the heat released from the decay of radioactive isotope elements that form the earth itself whereas the original heat is the heat content of the infant earth immediately after its formation. Potential energy is the energy released in the form of heat during the formation of new crust and finally the frictional heat is the heat that generates from the elastic energy released during the event of earthquakes. The largest internal energy source of the earth is from the decay of radioactive isotopes in the earth's interior and this is amounted to about 8.6 x 10^{20} J of heat energy every year or it is about 62% of all the internal heat sources (Clauser, 2006).

2. Variation of Temperature in the Earth's Crust

The temperature of earth's crust varies laterally as well as vertically depending on a number of factors. This irregular distribution of heat is due to factors such as the content of radioactive isotopes in the rock and the tectonic and hydrological nature of an area. The average values of temperature variability ranges from 10 Kelvin km^{-1} to 60 K km^{-1} in continental crust that has a thickness of 25 to 45 km. In oceanic crust of 5 to 8 km thickness the variation may be elevated much more than this due to the elevated hydrothermal activity in this environment (Clauser, 2006).

3. Types of Geothermal Reservoirs

Various types of geothermal reservoirs exist in the earth's crust and underneath. These reservoirs can be classified by the level of its temperature and amount of fluid it contains. Geothermal energy of magmatic origin has the highest temperature and is relatively poor in water content. The range of temperature in magmatic environment varies from 650 to 1,300^{o}C depending on the chemical composition of magma (Sass and Duffield, 2003).

Commonly geothermal reservoirs are categorized into four major types based on the content and phase of the fluid they contain. These are vapour-dominated, liquid-dominated, geo-pressured and hot dry rock reservoirs (Sass and Duffield, 2003; Somerton, 1992).

Vapour-dominated reservoirs: as its name indicates this form of reservoir contains higher amount of vapour than liquid fluids. Vapour dominated reservoirs occur relatively in few numbers as compared to other types of reservoir. Sustainable production of energy from this reservoir needs re-injection of fluid as the enhanced outflow of vapour from the reservoir can surpass the natural recharge rate of the reservoir.

Liquid-dominated reservoir: liquid phase is the dominant pressure determining phase in this reservoir. The water in this reservoir is a chemical solution containing numerous soluble compounds. The heat recovery from this reservoir is higher as compared to that of vapour dominated reservoir.

Geo-pressured reservoirs: this type of reservoir contains fluids with higher pressure than hydrostatic and commonly occurs in areas that are covered by an impermeable rock layers. The temperature of this system is high due to the low heat conductivity and high specific heat capacity of this type of reservoirs.

Hot dry rock reservoir: in this system fluid does not involve in heat transfer. The exploitation of this reservoir is only achieved by circulating water between wells through artificially fractured rock.

4. Mechanisms of Heat Flow in the Ground

There are three major mechanisms by which heat from the interior of the earth travels to the surface. These are advection, radiation and conduction. In the earth's lithosphere the dominant transport mechanism is conduction. However, depending on circumstances advection and radiation also play a significant role in the heat transport from deep ground to the surface. Advection has an important place in areas where the permeability of reservoir formation is optimal and ample amount of fluid recharge is available. On the other hand, the role of radiation in heat transport becomes important only when the ambient temperature gets about 600^oC or more in polycrystalline geomaterials. These heat transport mechanisms are dependent on factors intrinsic to the rocks such as thermal property of the rocks and also to factors that determine the permeability of the rocks such as porosity, discontinuities and fractures. In addition to the geological properties of the geothermal reservoir and related parameters, the efficiency of heat transport systems from a given reservoir is considerably dependent on the depth of the geothermal resource (Clauser, 2011; Sass and Duffield, 2003; Somerton, 1992). The following section of this work will discuss the role of those factors on the flow of geothermal heat from deep ground to surface.

5. Property of Geomaterials and Heat Flow

A wide variety of rock types may be found in geothermal reservoirs. These may include poorly consolidated to well consolidated rocks. Poorly consolidated rocks may contain fractures, secondary deposition of dissolved minerals and cemented materials that influence the permeability and porosity of the reservoirs. The dominant types of rock in hot and dry reservoirs are usually of igneous or metamorphic origin. These rocks are characterized by having little storage and limited fluid flow capacity if extensive natural fractures do not exist. For this type of reservoir should be intended to use for geothermal power generation, artificial methods need to be employed to create extended fractures. The thermal property of reservoir formation and the depth of the reservoir itself are also other important factors that regulate the flow and storage of heat in geothermal reservoirs. These properties of geomaterials that substantially influence the flow of geothermal heat from deep ground to the surface are discussed in detail as follows.

5.1 Permeability of geothermal reservoir formation

All geothermal systems require some level of reservoir permeability to allow the flow of heat from the reservoir to surface where it is converted to electricity. Permeability of geothermal reservoirs largely depends on the porosity, networks of fractures, fault structures and lithologic contacts (Dipippo, 2008). These features need to be traversed by wellbores to effectively transport heat bearing fluids to the surface. The permeability of the reservoir is not only required for steam extraction but it also plays a similar role while re-injecting the fluid to replace the extracted fluid to permit continuous heat supply. Therefore, it is critical to determine permeable parts of the geothermal reservoir to install wells so as to obtain reliable energy source. Although the use of naturally created permeable zones of the rock has a number of advantages for geothermal resource exploitation, there are also methods that help in enhancing the permeability of rocks in areas where rock permeability is a constraint.

These methods are called permeability stimulation methods and it involves acid fracturing, hydraulic fracturing and thermal fracturing (Abass, et. al, 2006). These methods provide a means to improve the connection of the drill hole with the natural fractures of the reservoir resulting in enhanced fluid flow rate. These technologies employ different principles in creating and maintaining fractures. Acid fracturing involve the injection of acid into subsurface to etch and open channels in the rock. Whereas, hydraulic fracturing involves exerting extremely high hydraulic pressure on the formation of the reservoir to create fractures. On the other hand, thermal fracturing hinges on the thermal contraction imposed by creating significant temperature difference between the cold fracturing fluid and the hot rock formation to form new cracks (Abass, et. al, 2006, Aqui and Zarrouk, 2011). The permeability and fracture of rocks is usually measured using a standard 61 mm diameter triaxial pressure cell by loading cored rock samples under confining and axial pressures (Aqui and Zarrouk, 2011)

5.2 Thermal properties of Rocks

The thermal property of material contains two specific dimensions. The thermal conductivity and heat capacity of materials as presented below.

5.2.1 Thermal Conductivity of Rocks

Thermal conductivity is the capacity of material to transmit heat. It is the coefficient (λ) in Fourier's Law of heat conduction: $q_i = -\lambda_{ij} dT/dx_j$ (1)

where q_i=heat flux, in w/m^2, λ_{ij}= thermal conductivity (w/(m.K)), dT/dx_j= temperature gradient.

The measurements of temperature in boreholes are usually performed along vertical profiles, providing the vertical component of the temperature gradient. As a result, knowledge on the isotropy of thermal conductivity of different rock is essential (Somerton, 1992). Thermal conductivity of volcanic and plutonic rocks is isotropic in general. As a result, in this formations heat predominantly flows vertically upward. So, it is sufficient to consider the vertical component of equation (1).

On the contrary, the thermal conductivity of sedimentary and metamorphic rocks is highly anisotropic which can result in significant horizontal heat flow. To take this into account, information on the horizontal heat gradient of the formation can be obtained from laboratory measurement of cored rock samples in different direction (Clauser and Huenges, 2013).

The stress to which a reservoir formation is subjected has an effect on the thermal conductivity of the formation. This effect is more pronounced for poorly consolidated materials, an increase of stress may have substantial increase in the thermal conductivity of rocks as this process reduce the fluid content of the reservoir. On the other hand, the thermal conductivity of consolidated rocks is only slightly affected due an increase of stresses (Clauser, 2011; Somerton, 1992).

5.2.2 Heat capacity of rocks

Heat/thermal capacity of a material is the amount of heat energy required to change the temperature of an object by a given amount. Or in other word, it is the capacity of material to store heat. A related term to the heat capacity of material is specific heat capacity. The specific heat capacity of rock is derived from the amount of heat required to raise the temperature of a unit mass of rock by one degree under standard condition. Large variability exists in the specific heat capacity of rocks. However, studies show that there is a general trend of specific heat flow depending on the age of rocks (Clauser, 2006). The specific heat flow in younger and tectonically active rocks is higher than that of older and tectonically stable rocks (Figure 1).When compared to water the specific heat of rock is about one quarter of that of water.

Since heat capacity is measured based on mass, a change of stress in the reservoir doesn't cause much effect on this property of the formation. However, in cases where specific heat is calculated based on the volume of the material a change of stress does have an effect on the specific heat capacity of the reservoir formation. Heat capacities of selected sedimentary rocks are shown in Table 1.

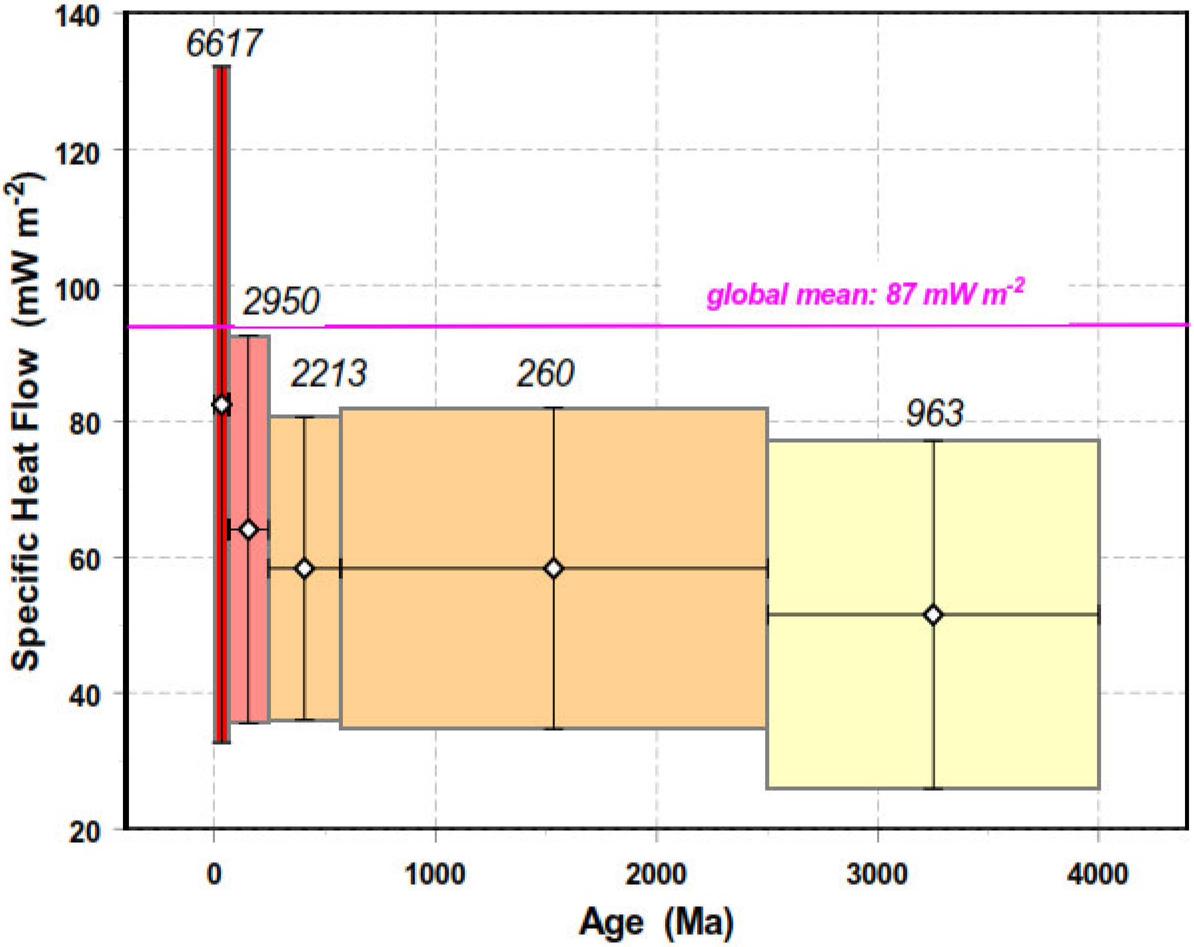


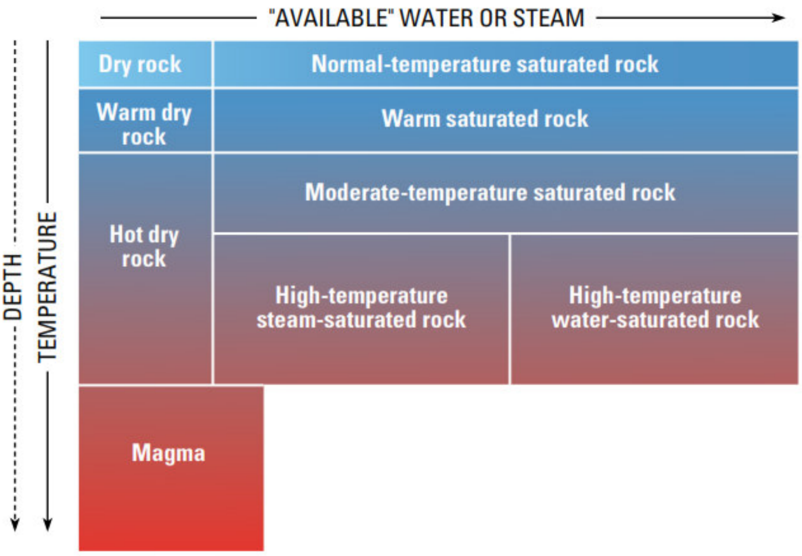
Figure 1.Variation of specific heat flow with age based on 13003 observations in the continental crust. Diamonds show mean values for specific heat flow. The number of observations in each geologic era is shown above the corresponding box. Width and height of each box represents the duration of the different eras (from left to right: Cenozoic, Mesozoic, Paleozoic, Proterozoic, Archean) and one standard deviation above and below the mean specific heat flow, respectively (Source: Clauser, 2006)

Table 1. Experimental heat capacity of some sedimentary rocks at a temperature of 227°C (Source: Somerton, 1992).

Rock type	Heat capacity (cal/g.K)
Sandstone	0.241
Silty sandstone	0.254
Siltstone	0.249
Shale	0.244
Limestone	0.247

5.3 Depth of the heat source

Observations from drill holes, mines and other excavations demonstrate an increase of temperature as depth increases into the earth's interior (Figure 2).The depth to which one requires to drill boreholes for the extraction of heat affects the feasibility of power generation from geothermal energy resources. Large quantities of geothermal heat are mostly concentrated deep in the earth's interior and so exploitation of this resource with current technology appears to be not feasible. However, a number of situations exist where geothermal energy sources occur close to the surface of the earth. These areas are commonly located close to plates which form the earth's lithosphere that contains the earth's crust and the solid part of the under laying layer called mantle. High heat source is also associated with thermal plumes or hot spots whose origin is related to narrowly focused upward movement of hot mantle material from very deep strata within the earth. Hot spots can also occur at plate boundaries. Regions of stretched and fault-broken rocks (rift valleys) within plates, such as those in East Africa are also favourable areas for high concentrations of the Earth's heat at relatively shallow depths. Due to this, plate-boundary zones and hot spot regions are prime target areas for the exploitation of commercially feasible geothermal energy. With the current existing technologies boreholes up to 4,000 m can be drilled and economically extracted for electric power generation (Sass and Duffield, 2003).



Different types of geothermal environments in the Earth's upper crust. Generally, temperature increases with depth, but the depth line is dashed to indicate that the rate of temperature increase varies within the crust. "Available" refers to water and steam in rocks that can be tapped by a well and produced at the Earth's surface. High- and moderate-temperature rocks with considerable available water and (or) steam are the only geothermal environments that can currently be developed to generate electricity.

Figure 2. Different types of geothermal environments in the earth's upper crust (Source: Sass and Duffield, 2003).

6. Exploration of Geothermal Energy

Under this section, exploration technologies that are most employed for the localization of geothermal reservoirs and characterization of reservoir formation will be discussed in detail.

Some easily visible features of geothermal energy are volcanoes, hot springs, geysers, and fumaroles. However, it is not always possible to observe most geothermal energy reservoirs from surface observation. Usually geothermal energy is found deep underground and a number of geological mapping, geophysical studies and geochemical exploration methods need to be employed for reliable information on the potential of the resource and for an efficient exploitation of the resource. Various methods exist to perform these tasks and major methods that have been extensively applied for geothermal exploration and reservoir characterisation will be discussed in detail as follows.

6.1 Satellite imagery and aerial photography

The locations of potential geothermal sites are often manifested by the presence of features such as geysers, hot springs and fumaroles. Moreover, surface features like evaporites, altered rocks, opal and travertine are unique geomaterials in geothermally active zones. From satellite and aerial photographs such features are commonly detectable for a wide range of area and can be used as a preliminary means of identifying potential areas for further studies.This method takes less time and effort as this information can be easily accessed from already collected data in other studies nationally or regionally (Jennejohn, 2009).

The other advantage of remote sensing is that combination of thermal infrared technology and hyper spectral survey is possible to image surface heat flow. LiDAR (Light Detection and Ranging) technology is also a new development in remote sensing technology that enables to detect recent changes in the topography of an area due to processes such as faulting which are often related to geothermal resources.

6.2 Volcanological observation

Surface manifestation of recent volcanic activities in an area provides important preliminary information for the occurrence of geothermal resources. Evaluation of volcanic activities can be undertaken in a number of ways. These include analysis of topographic and geologic maps, regional geological syntheses such as stratigraphy, structural geology and history of volcanism. Particularly information on the presence and characteristics of hot springs, fumaroles and hydrothermal alterations provide satisfactory evidences on the volcanic activities of a region.

The extent of potential geothermal resource of a region can also be estimated from the study of past and current volcanic activities. This may be achieved through identification and mapping of recent faults, investigation of lithic clasts in pyroclastic deposits and determination of the degree of hydrovolcanic activities responsible for pyroclastic deposit (Wohletz and Heiken, 1992). In the north part of Ethiopia, for example, the Afar rift is the most active segment of the entire East African Great Rift system with Erta Ale volcano being presently active (Figure 3 & Figure 5). In this area the rift floor is mainly covered with rhyolitic and basaltic volcanoes. Furthermore, studies show the occurrence of huge geothermal energy resources in the rest of Great Rift Valley of East Africa where volcanoes are largely built from intermediate lavas and the associated pyroclastics (Omenda, 2010).

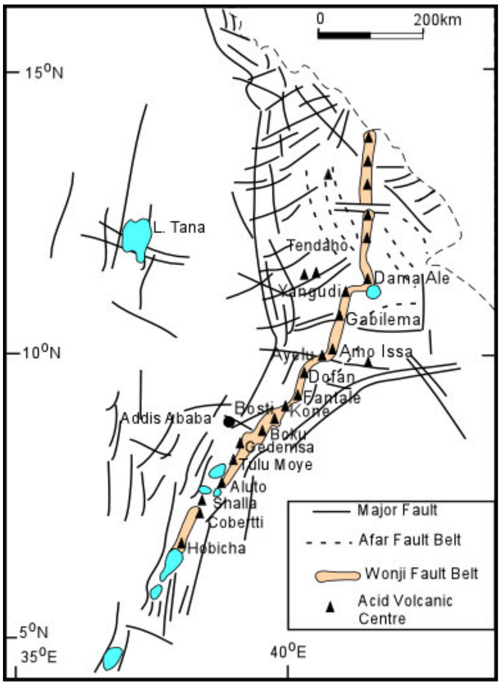


Figure 3: Structural map of the Ethiopian Rift showing locations of Quaternary volcanoes (Source: Abebe, 2000)

6.3 Geochemical survey

Geochemical survey is an important tool in the estimation of the temperature of a given geothermal reservoir prior to drilling. Studies have shown that chemical tests of minerals and spring fluids on the surface considerably help in determining the temperature regime of geothermal resources deep in the earth (Jennejohn, 2009). From the analysis of the type of minerals found on the surface of the earth near the geothermal pool, it can be possible to know the temperature at which these minerals form and therefore the temperature of the geothermal reservoir. Other type of improved geochemical survey method is soil and gas geochemistry. This method employs gas detectors at the surface to detect the flow of gases such as mercury and carbon dioxide which are related to geothermal reservoir.

6.4 Geophysical survey

Several types of geophysical methods exist for the exploration of geothermal resources. Among these seismic survey, gravity survey, electrical and electromagnetic survey methods are widely employed in the assessment of geothermal resource.

6.4.1 Seismic survey

In seismic survey, controlled seismic waves are generated at ground surfaces and the refraction of these waves at geologic boundaries is recorded by seismic sensors (geophones) assembled on the ground surface for this purpose. From this record the travel times and the velocity of the waves in each geological boundary are determined to get a clue about the type of geomaterials in the region as the speed of sound is influenced by the material's properties such as density and fractures. Furthermore, the thickness of a particular geologic layer can also be estimated from this measurement. From seismic survey the distribution of the subsurface geological interfaces such as faults can be mapped. Identification of such geological structures is crucial as it helps in analyzing the flow pattern of fluids in the reservoir which is important in determining appropriate place to install extraction and re-injection wells in the field (Mariita, 2010).

6.4.2 Gravity survey

In this method the variation of gravitational fields of the subsurface geology is investigated to gain information on the density of the surrounding rocks. The lateral variation of gravitational field is related to anomalous density distribution within the subsurface formations. With regard to geothermal exploration, the general trend is that areas that experiences recent volcanism, faulting or geothermal activities which have direct implication for the occurrence of geothermal resources show gravity highs. This method has been widely used in the exploration and monitoring of geothermal energy in the Great Rift Valley of East Africa (Mariita, 2010).

6.4.3 Electrical and electromagnetic surveying

In these methods either naturally occurring earth's magnetic field or artificially introduced electrical fields in to the ground are used to investigate subsurface anomalous. The resulting potential differences from these fields are measured at the surface and interpreted to deduce subsurface inhomogeneity. The deviation of potential differences from what would normally be expected from homogeneous ground gives a clue on the information about the form and electrical characteristics of underground inhomogeneity such as vertical and horizontal discontinuities. From the information gained by these methods the depth and thickness of hydrogeological and thermal structures associated with geothermal reservoirs can be delineated.

6.5 Thermal gradient hole

Thermal gradient holes are commonly drilled after sufficient information has been gained from methods shown above due to the difficulty in its implementation and high costs. As its name indicates, thermal gradient hole helps to accurately delineate the temperature gradient of the geothermal reservoir deep in the ground. Higher thermal gradient is associated with greater temperature anomaly. For example, in the explored parts of Ethiopian Great Rift Valley the thermal gradient often reaches up to 250^{o}C which is capable to generate electricity. Moreover, thermal gradient hole drilling method is also employed to measure the thermal property and permeability of geomaterials from core drilling to estimate the rate of heat flow in the ground (Jennejohn, 2009).

In summary, in the exploration of geothermal reservoir and characterisation of reservoir formation properties, the customary practice is usually to employ those different methods in combinations as appropriate rather than using one method alone.

7. The Geothermal Resources of Ethiopia

In the final part of this review, a brief overview of geothermal resources of East Africa particularly that of Ethiopia and its current development status will be presented.

The volcanic and tectonic activities of the East African Great Rift Valley started about 30 million years ago as a result of faulting and eruption of large volumes of mafic and silicic lavas and pyroclastic (Omenda, 2010). The areal extent of the Great Rift Valley ranges from North Syria in the Middle East to Mozambique in South East Africa extending over 6,000km.

The Great Rift Valley encompasses large reservoir of geothermal energy. Countries such as Ethiopia, Kenya, Tanzania and Uganda have the greatest share from this resource. According to studies geothermal energy in the region is estimated to exceed 15,000MWe. From this, Ethiopia alone possesses more than one third of the total potential energy (Mwangi, 2010; Omenda, 2010). In Ethiopia, the Great Rift Valley covers an area of more than 150,000km^2 extending over a distance of 1000km from northeast to south Ethiopia.

Geothermal activities in the Great Rift Valley of Ethiopia is manifested by the occurrences of quaternary volcanoes, fumaroles, hot and steaming grounds, hot springs, geysers and sulphur deposits (Omenda, 2010).

The manifestations are more observable and vigorous within the axis of the rifts than on the flanks because of the favourable hydrology and relatively shallow heat sources. The heat sources of the geothermal systems in the Ethiopian Great Rift Valley are related to: shallow magma chambers associated with the young rhyolite volcanoes (this are common in the southern Afar and Main Ethiopian Rifts) upper mantle intrusion/upwelling associated with the thin crust in the area that averages between 5 and 20 km

In Ethiopia, the exploration of geothermal resource was started in 1969 (Teklemariam, et al, 2000). Since then various exploration projects have been implemented and proved the existence of huge potential in this resource. During this time about eighteen areas were identified as potential geothermal resource sites and areas which have been under extensive study include Aluto-Langano, Tendaho, Corbetti, Abaya, Gedemsa and Tulu Moye sites (Figure 4 below). The studies were based on a number of exploration methods including geological, geochemical and geophysical investigation including thermal gradient well drilling. In the Aluto-Langano geothermal field, for example, eight deep exploratory wells were drilled to a maximum depth of 2,500m and among these wells five of which were found to be potentially productive and has a potential of 30MWe (Teklemariam, et al, 2000; Mamo, 2002). Similarly, in the Tendaho geothermal fields, three deep and three shallow exploratory wells were drilled to a depth of 2,100m and found temperature gradients up to 260°C. The study results show that four out of the six wells could supply enough steam to operate a pilot power plant of 5MWe capacity. The total geothermal potential of this study area is estimated to about 20MWe.

According to Abebe (2000) the primary permeability of volcanic rocks in the Ethiopian Rift Valley is generally low except for some coarse grained and unconsolidated pyroclastic rocks. On the other hand, secondary permeability in hard lava flows is generally good although the Rift fracturing is usually in block forms which may restrict fluid flow locally. Hence, enhancement of the permeability of rocks by using artificial methods could help in improving the permeability of the geothermal reservoir in this area.

Concerning the recharge of groundwater in potential geothermal regions, there is a concern especially in the Afar rifts as the precipitation is scarce in this area. Whereas in the central part of the country also known as the 'Lakes District' the source of water for recharge wouldn't be a potential constrain (Figure 5).

Recent geothermal exploration results of the Ethiopian rift valley could not be included in this study as most of the results have not been published yet. This is because most of the works are being undertaken by the government projects where the major focus is gaining information in the form of internal report. However, currently there is news which states the establishment of agreement between the Ethiopian government and Reykjavik Geothermal, an Icelandic-American energy company, to develop geothermal electric power generation at Corbetti site (in the Lakes District) of Ethiopia. The project implementation will cost about 4 billion USD and upon completion this project will produce 1,000 MWe and it is highly anticipated to improve the power supply of the country. If this project is implemented successfully, it will be a great forward leap by the country in utilizing its geothermal resource.

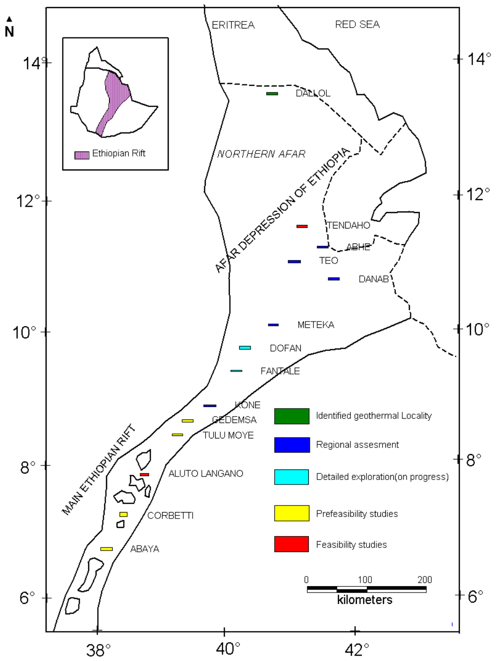


Figure 4: Location Map of the Ethiopian Rift and Geothermal Prospect Areas (Source: Teklemariam and Kebede, 2010).

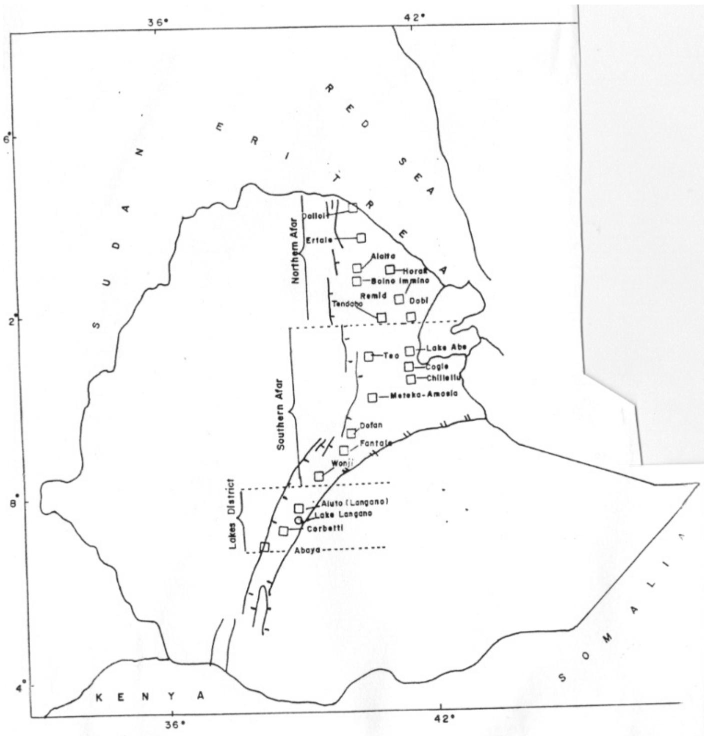


Figure 5. Location of geothermal prospecting areas in the Ethiopian Rift Valley and Afar depression (Source: Teklemariam, et al, 2000).

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References

Abass, H.H., Al-Mulhem, A.A., Alqam, M.S., and Mirajuddin, K.R. 2006. Acid Fracturing or Proppant Fracturing in Carbonate Formation? A Rock Mechanics View. SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers.

Abebe, T. 2000. Geological limitations of a geothermal system in a continental rift zone: Example of the Ethiopian Rift Valley. Proceedings of World Geothermal Congress, 2025-2030.

Aqui, A. R. and Zarrouk, S. 2011. Permeability Enhancement of Conventional Geothermal Wells. New Zealand Geothermal Workshop. Auckland, New Zealand.

Clauser, C. 2011. Thermal Storage and Transport Properties of Rocks, II: Thermal Conductivity and Diffusivity. In: Gupta, H. (Ed.), Encyclopedia of Solid Earth Geophysics, 2nd ed., Springer, Dordrecht, preprint.

Clauser, C. 2006. Geothermal Energy, In: Heinloth, K. (ed), Landolt-Börnstein-Numerical Data and Functional Relationships, New Series, Vol. VIII: Energy Technologies, Sub-volume 3: Renewable Energies, Springer Verlag, Heidelberg-Berlin.

Clauser, C. and Huenges, A. 2013. Thermal Conductivity of Rocks and Minerals. In: Ahrens, T. J. (ed), Rock Physics & Phase Relations: A Handbook of Physical Constants. American Geophysical Union.

Dipippo, R. 2008. Goelogy of Geothermal Regions. Geothermal Power Plants (2nded.). Oxford, Butterworth-Heinemann: 3-18.

Jennejohn, D. 2009. Research and Development in Geothermal Exploration and Drilling. Geothermal Energy Association, Washington, D.C.

Mamo, T. 2002. Geothermal Exploration in Ethiopia, Country Report. Ninth Volcanic Geothermal Research Report. 11: 12-15.

Mariita, N. O. 2010. Application of Geophysical Methods to Geothermal Energy Exploration in Kenya. Kenya Electricity Generating Company Ltd-Kengen. Available at: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-11-24a.pdf. Accessed on Dec. 2013.

Mwangi, M. N. 2010. The African Rift Geothermal Facility (ARGEO) Status. A paper presented at Short Course V on Exploration for Geothermal Resources, Kenya. Available at: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-11-48.pdf. Accessed on Nov. 2013.

Omenda, P. A. 2010. The Geology and Geothermal Activity of the East African Rift. A paper presented at Short Course V on Exploration for Geothermal Resources, Kenya. Available at: http://www.os.is/gogn/unu-gtp-sc/UNU-GTP-SC-05-34b.pdf. Accessed: Nov. 2013.

Sass, J. H and Duffield, W. A. 2003. Geothermal Energy_Clean Power From the Earth's Heat. U.S. Geological Survey, Reston, Virginia.

Somerton, W. H. 1992. Thermal Properties and Temperature-Related Behavior of Rock/Fluid Systems. Elsevier Science Publishers, The Netherlands.

Teklemariam, M and Kebede, S. 2010. Strategy for Geothermal Resource Exploration and Development in Ethiopia. Proceedings World Geothermal Congress.

Teklemariam, M., Beyene, K., AmdeBerhan, Y. and Gebregziabher, Z. 2000. Geothermal Development in Ethiopia. Proceedings of World Geothermal Congress. Kyushu - Tohoku, Japan.

Wohletz, K. and Heiken, G. 1992. Volcanology and Geothermal Energy. University of California Press.