Université de Neuchâtel
Centre d'hydrogéologie et géothermie

Continuing education at the University of Neuchâtel, Faculty of Science

Certificate of Advanced Studies

Exploration & Development of Deep Geothermal Systems (DEEGEOSYS)

6th Edition 2022-2023

Technical Report

Geology and hydrogeology of the central part of the Main Ethiopian Rift: review and conceptual model, incidence on geothermal resources

Timothée DUPAIGNE

Supervisors: Sverrir Thorhallsson, Reza Sohrabi

Partners:

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Bundesamt für Energie BFE
Office fédéral de l'énergie OFEN
Ufficio federale dell'energia UFE

suisseénergie

groupe e

Date : 31st of May 2023

1. Introduction

The East African Rift System (EARS) drains growing interest from policy makers and investors due to its tremendous potential in terms of geothermal resources.

Still, projects are rare if we consider the geographical extent of the EARS. Consequently, data are scarce and it is therefore difficult to have a synthetic understanding of phenomena at a greater scale than concession extent. Though geological, hydrogeological and thermodynamic processes do take place at regional scale rather than local, geothermal field scale. A broader view on underground phenomena could also help in derisking geothermal projects.

The technical work proposed here aims to bring a multidisciplinary reflexion on underground processes leading to the development of geothermal resources, at a regional scale: approximately 100 Km x 100 Km. The selected area of work is the central part of the Main Ethiopian Rift System (C-MER). The work will be addressed based on available data.

2. Methodology

The work to be realized is listed as follows.

a) Definition of the study area

The area of study will be selected according to the amount of data available and to its properties in terms of geothermal resources.

b) Volcano structural analysis

The volcano-structural analysis will consist in reviewing most relevant bibliography to analyze the particular context of the Main Ethiopian Rift, being an intracontinental rift with recent magmatism. Foreign bibliography, if relevant for comparison, will also be reviewed.

c) Considering water circulation

The water circulates underground due to the properties of the rocks themselves, but also in relation with the fracturation and the presence of heat sources.

This chapter will focus on the hydraulic properties of volcanic rocks, the recharge processes and different flowpaths, and the hydrothermal processes. This analyze will be accomplished based on Ethiopian bibliography, but possible gaps will be fulfilled with foreign bibliography.

d) Thermodynamic considerations

Underground water interacts with heat sources according to their temperature, creating complex system and convection cells, with two-phases (vapor and liquid). The knowledge of these systems is fundamental for the understanding of the geothermal resources. Existing documents on Ethiopian sites will be reviewed, and eventually completed with international sites.

e) Synthesis: conceptual model

The synthesis will consist in a commented conceptual model for the system, with associated map. The objective of this conceptual model will be to compile all the results reviewed in the bibliography, in a global view including deep processes.

f) Critical analysis / discussion

The critical analysis will aim to identify possible gaps in the study, and will suggest tracks for further analysis.
Furthermore, the conceptual model will be analyzed in terms of geothermal resources and possible exploitation.

3. Review of processes generating the geothermal resources in the Central part of the Main Ethiopian Rift (Results)

3.1. Definition of the study area

The East African Rift System (EARS) spreads from the Afar triangle, at the Red Sea-Gulf of Aden junction, southwards through to Mozambique. It is therefore a 3500 Km extensive feature, divided into two branches: west and east, and it forms a series of segmented tectonic basins that extend.

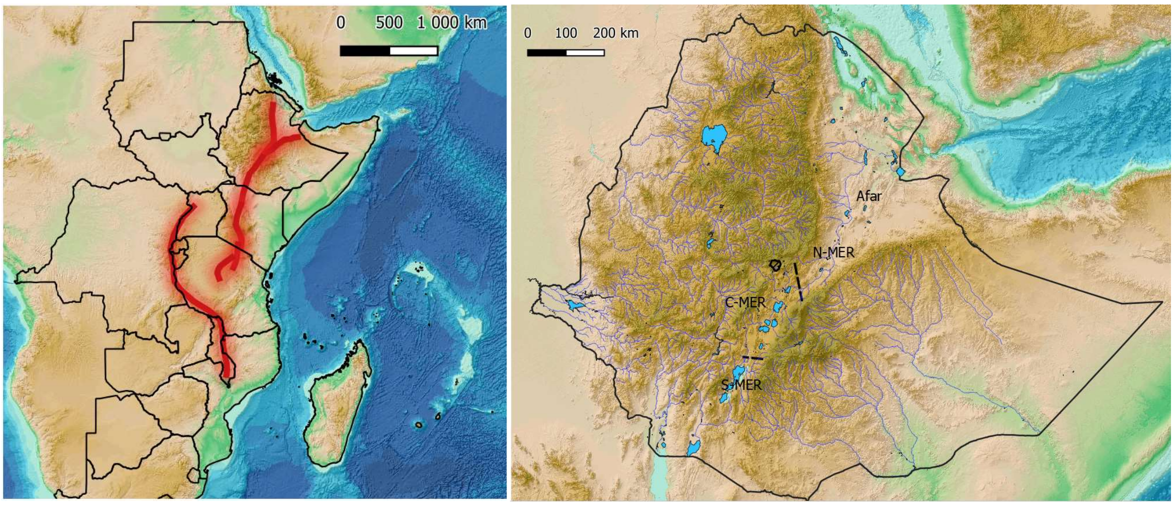

Figure 1 : The East African Rift System (EARS) *and the Main Ethiopian Rift* (MER)

Left – East Africa and main faults of the EARS
Source : UN Environment Africa Geothermal Inventory Database
Right – Ethiopia and the MER divided in Afar and the 3 sections North, Central and South
(after Corti, 2009)

The Main Ethiopian Rift (MER) constitutes the North end of the EARS and is traditionally separated into three main segments (Northern, Central and Southern). It is commonly considered that the MER is more mature in Afar (North) and evolves toward a less mature rift in the South.

The MER is the place for important geothermal resources, due to the vicinity of magma linked to the undergoing rift.

Only one plant is being operated, with unconstant production due to technical problems: Aluto-Langano.

This combined cycle flash steam and binary plant (7.2 MW) was commissioned in 1998 and faced many problems related to production wells and the power plant and is now out of service.

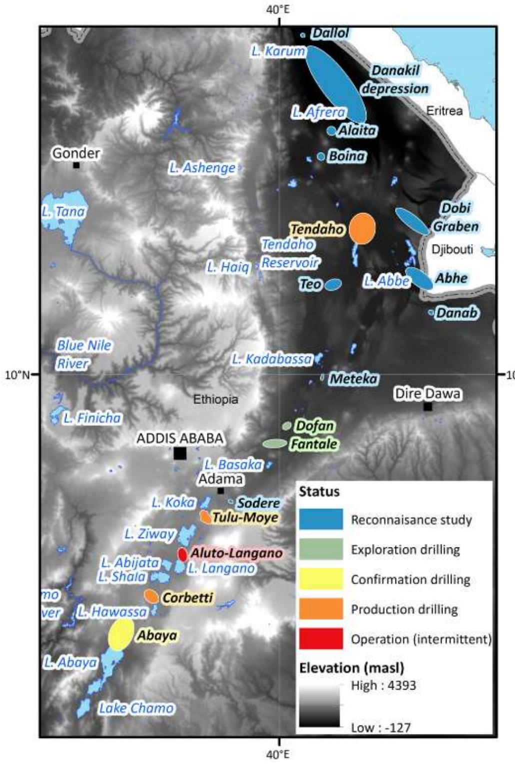

Figure 2 : Status of main geothermal prospects in Ethiopia (as of 2019) – from Burnside et al. (2021)

However, many other sites are prospected, with different stages of investigation: Abaya, Corbetti, new investigations on Aluto-Langano, Tulu-Moye, Fantale, Dofan, Tendaho, and others being not yet public.

As several sites are under prospection in the Central MER, more data is available, and recent data. It is therefore proposed here to focus in an area that would go North and South of lake Ziway, allowing to benefit from available data from Tulu-Moye and Aluto-Langano sites.

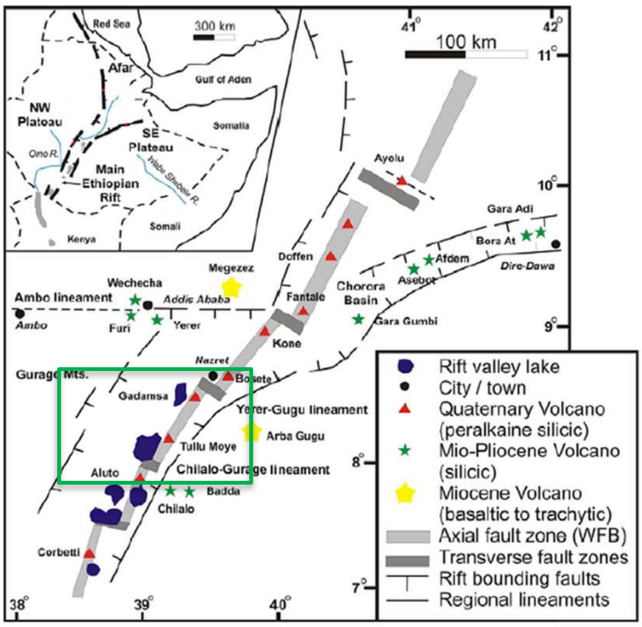

Figure 3 : Location of the study area (green frame) on the map from Sisay (2016)

3.2. Volcano structural analysis

3.2.1. Volcano-structural context

The illustrations presented here-after are summarizing the main events in terms of volcano-structural evolution of the MER. This synthesis was elaborated based on the following main articles: Agostini et al. (2011); Corti et al. (2022); Corti et al. (2013) ; Corti (2009) ; Bonini et al. (2005) ; Rooney (2011).

The area of interest is located in the middle of the central part of the MER, and is therefore concerned by the shift between the early orthogonal rift and the oblique rift around 3,2 My.

This event has several consequences for the analysis:

- The area is concerned by boundary faults located at the shoulders of the rift and associated with a certain type of volcanism, which stopped.
- The fact that the rift became oblique in a later stage resulted in the apparition of the Wonji Fault Belt (WFB), with high rate of fracturation and volcanism orthogonal (aligned with) the fracturation, in the axis of the rift. Volcanism is very recent in the WFB.

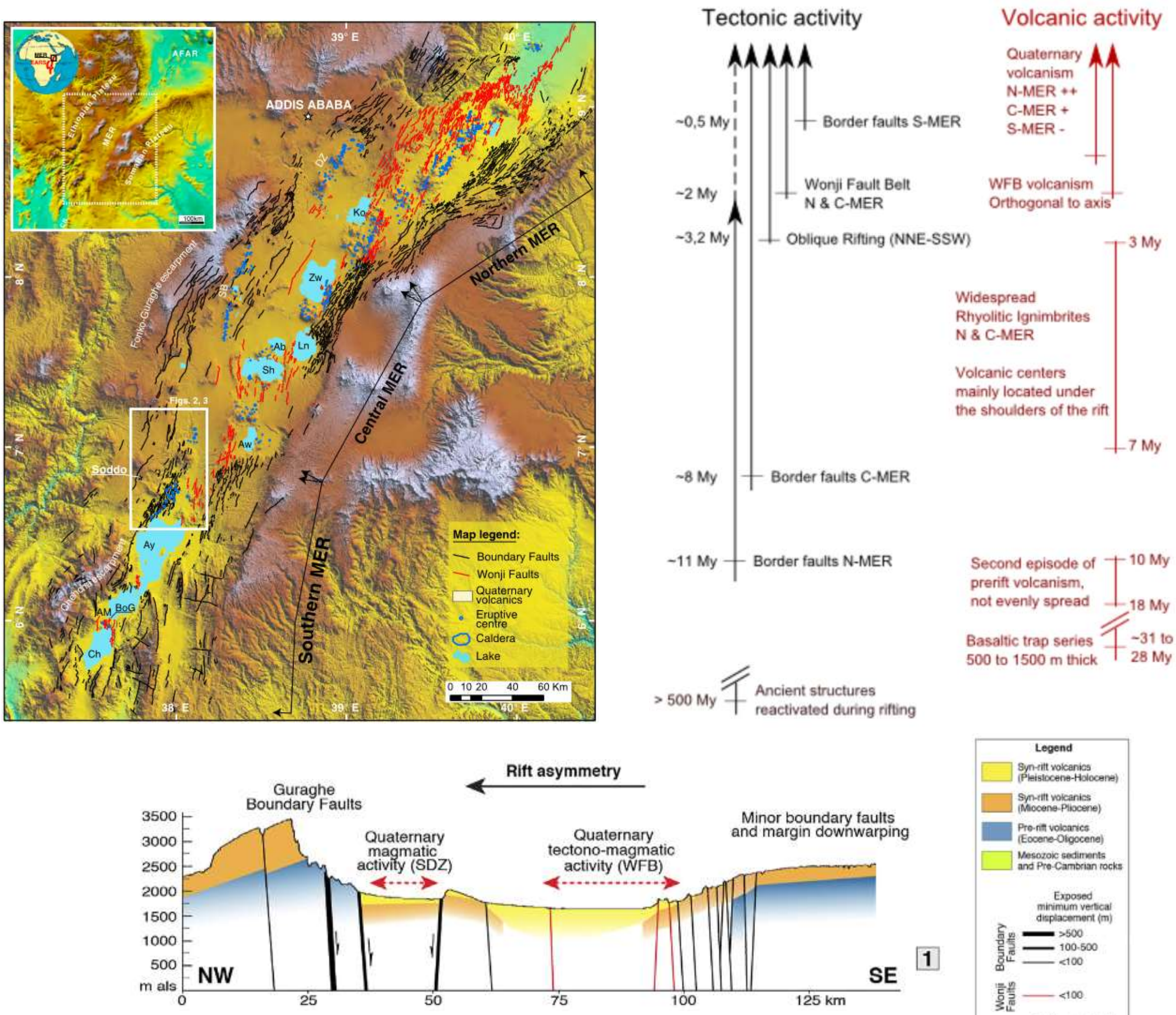

Figure 4 : Volcano-structural context of the MER
*Map : from Corti et al. (2013) - Red lines : **Wonji Fault Belt, Black lines : Boundary faults;***
Cross-section : from Corti et al. (2022)
Chronological chart based on Agostini et al. (2011); Corti et al. (2022); Corti et al. (2013); Corti (2009); Bonini et al. (2005) ; Rooney (2011)

Several recent articles emphasize the fact that ancient structures, inherited from geological events preceding the rift apparition, have major influence on (1) the rift propagation, (2) volcano-tectonic activity and (3) recent fracturation at large, medium and local scale. Two major alignments have been identified: Yerer-Tullu-Wellel (YTVL) and Goba-Bonga (GBL) volcano-tectonic lineament (Figure 4). They are deeply rooted into the lithosphere, and influence processes at every scale.

3.2.2. Associated volcanism and fluids circulation

According to the works of Hutchison, 2015 for Aluto (and Corbetti) and Tadesse et al, 2023 for Tulu Moye, the main volcanic events for those sites can be summarized as follows:

- ➔ > 2Ma: Ignimbrites (welded / unwelded pyroclastics)
- ➔ 2 to 0,5 Ma: development of Wonji Faulting and regional basaltic fissure eruptions
- ➔ 500 to 310 ka: Trachytic edifice construction
- ➔ 310 to 200 ka: major ignimbrite eruptions and caldera formation (Gedemsa / Tulu Moye, Corbetti, Aluto, Shala volcanoes)
- ➔ After 200 ka: post caldera magmatism – explosive and effusive activity with pyroclastic deposits, scoria, aphyric basalts with fissures, and obsidian domes and coulees.

The work of Hutchison et al. (2015), shows that for the site of Aluto there are evidence that fluid circulation is driven by faults: boundary faults, Wonji Fault Belt, as well as Caldera Rim Faults at volcano scale. In particular, it has been shown that CO_2 is circulating through these faults. Boundary faults occurred before WFB and Calderas, therefore they had a role in the ascent of the magma and in the apparition of vents and dykes. However, they might have a secondary role in fluid circulation once WFB appeared, and/or that big silicic volcanoes with calderas happened.

Geothermal prospects (Burnside et al., 2021) such as: Aluto, Corbetti, Tulu Moye, Langano, Abaya, etc., are located nearby major, most recent, volcanic systems. Geophysical investigations intend to locate the magma underneath the volcano, and therefore to produce a conceptual model of the system. As for example, Samrock et al. (2021), clearly show the magma accumulation and ascent channel through fault for Tulu Moye and Aluto.

3.3. Considering water circulation

This chapter combine different sources of information on the hydrogeology in volcanic context, and when available in Ethiopia, being given than in hydrothermal complexes the main source of fluid is rain water.

3.3.1. Hydraulic properties of volcanic rocks

Hydrogeology of volcanic units is complex:

- It is primarily controlled by the type of volcanic products (lava, pyroclastic deposits, tuffs, etc.) and depositional environment;
- These primary properties are then influenced by compaction phenomenon, hydrothermal alteration, chemical precipitation of secondary minerals, and fracturing (tectonic, phreato-magmatic and thermal).

The resulting hydraulic characteristics are highly scale dependent: it presents highly variable at low scale and tend to homogenize at bigger scale. This is also true for thermic properties.

Jasim et al. (2018), propose a synthetical view on hydrothermal complexes in volcanic context, including a table gathering permeabilities for volcanic products, with very wide range of values.
As described by Mueller et al. (2011), a link exists between pyroclasts porosity and the volcan explosivity of the event that initiated them. As a consequence, one can assume that the major ignimbritic eruptions that occurred ca 310-200 ka in Ethiopia produced quite porous environment, while effusive basaltic floodings are poorly porous.

In geological contexts where rocks have poor primary and matrix hydraulic characteristics, fracturation is of highest importance for water circulation.

Bertrand et al. (2018), analyzed the Rhenan rift in France, and classified faults into three orders: first order accommodates the crustal deformation, second order forms the horst and graben system, third order are formed inside the second order blocks and are well detected in topography. As an analogy, Yerer-Tullu and Goba-Bonga lineaments would be of first order, boundary and Wonji faults would be secondary order, and third order would be the smaller lineaments detected in DEM analysis.

Khodayar et al. (2021) show that, in Iceland context which has some similarities with MER, oblique-slip faults have a major role on water circulation. As a comparison, this might suggest that Wonji Faults are more susceptible to water drainage than boundary faults.

Cant et al. (2018) accomplished a detailed work on matrix permeability of reservoir rocks in Ngatamariki geothermal field in New Zealand, at sample scale (in opposition to In-Situ testing of fracture permeability, which give information for macro-scale), and concluded on several facts:

- Geological sequence encountered is made of volcanic deposits (Ignimbrites, volcaniclastics, tuffs) and intrusion of age 1,22 Ma or younger (which is comparable to Ethiopian context)
- The volcaniclastic units show a large variation in connected porosity, dry bulk density, sonic velocity, permeability, and microstructure, attributed to the compositional range of pumice and lithic components and depositional processes resulting in vastly different primary textures
- In general, microfracture-dominated samples have lower permeability than pore-dominated samples
- Pressure affects more permeability for microfractured than pore-dominated samples
- Lithology, burial diagenesis, and hydrothermal alteration and dissolution all play a role in controlling the physical and mechanical properties of the reservoir rocks

This study allows us to understand that in volcanic context, at microstructure scale, micro fractures will have less influence than pores on a well-developed reservoir. It also means that, in general, at greater depth porosity and permeability will decrease (Cant et al., 2018). Hydrothermal alteration and mineralization also play an important role at greater depth by decreasing porosity.

3.3.2. Recharge and flow paths

Kebede et al, 2007 and Ayenew et al. (2008) demonstrate that the pathways for groundwater from the highlands where most of the precipitations occur, to the rift, are multiple and depend on the tectonic configuration. They show that transverse structure such as YTVL (roughly E-W structures, see 3.2.1.) act as a major drainage system conveying water from highlands to lowlands. In the absence of such transverse structures, faulting associated with marginal grabens act as hydraulic barriers and infiltration zones at the same time. Thermal waters are demonstrated to have infiltrated in highlands and slowly reach the deep aquifers in the rift and are therefore older than other groundwaters.

Azagegn et al. (2015), show the role of sedimentary rocks underlying basaltic deposits for groundwater circulation in the upper Awash basin (around and North to Addis Abeba). This study also shows the major role played by YTVL fault system on groundwaters. It is important to note here that Addis Abeba was settled by emperor Menelik II along the YTVL axis in the 19th century due to the presence of hot springs (Filwuha). One can assume that the drainage resulting from YTVL is also observed for GBL (see 3.2.1) further to the South.

Ghiglieri et al. (2020), focused on Fluoride enrichment in shallow groundwaters. They emphasize the role played by marginal graben and altered fracture zones on the infiltration toward deeper aquifers.

Most other hydrogeological studies consulted (e.g. Haji et al. (2018); Engida (2001); Furi (2010), Demlie et al. (2005)) are focused on shallow aquifers, usually because of being a potential resource for water supply and agriculture, and identify thermal springs as the outflow from deep systems. Deep hydrothermal systems are often reduced to being the origin for Fluoride enrichment and temperature increasement, and for their geochemical particularities. Investigations on Ethiopian aquifers consulted in the frame of the present work don't address the whole cycle of deep thermal waters.

3.3.3. Interaction with heat sources, hydrothermal processes

In magmatic hydrothermal systems, the fluid contained in the host rock is set in motion by a heat source. In Ethiopia, the precipitations occur mostly in mountainous areas which provides potential energy to the groundwaters, therefore flowing toward the lowlands of the rift. These two sources of energy (heat and topography) interfere to create complex circulation systems. McLellan et al. (2010) also emphasize the importance of pore pressure variations due to the extensional context in continental rift systems (such as New Zealand and Ethiopia), which adds to thermal and topographical effects.

McLellan et al. (2010) further analyze the different parameters that influence the evolution of convection cells, namely: heat source, existence of several layers of different permeabilities, faults with different characteristics, existence of heat losses at the surface (due to drainage toward surface waters), tectonics, fluids released by magma. Rowland et al. (2004) show that in segmented rifts (e.g. New Zealand), accommodation zones concentrate hydrothermal flows, when tectonically maintained (i.e. tectonically active).

Meyer et al. (2022), propose a focus on the permeability of basalts through the brittle-ductile transition, which is of primary importance for Superhot Rock Geothermal projects, but which has been identified as a preponderant parameter for high enthalpy projects in general – permeability decreasing quickly in ductile regime of rocks. Keranen et al. (2004) localize this brittle to ductile transition at around 7 Km depth in MER.

3.4. Thermodynamic considerations

3.4.1. Generalities

Geothermal resources can be categorized into: Low Enthalpy (Single phase flow), Medium Enthalpy and High Enthalpy (Multi-phase flow). Those three types are expected in Ethiopia, but the most energetic systems are of course the two-phase ones (liquid + vapor. The existence of the two phases, the liquid saturation and the depth at which boiling occurs are mainly the result of: the geological context, the depth and the temperature of the heat source (magma in Ethiopia), the hydraulic properties of the rocks (porosity and permability) and the thermic properties of the rocks.

McLellan et al. (2010) report as follows: *“In trying to deal with the heat budget of the Taupo Volcanic Zone (New Zealand), several considerations must be addressed (Bibby et al. (1995); Simmons and Brown (2007)): (1) heat is transferred into the mid-crust by advection within magma pooled near the brittle–ductile transition, and this heat flux may be an addition to the background geothermal gradient provided by deep underplating or asthenospheric upwelling (e.g. Price et al., 2005); (2) heat advection via fluids accounts for N70% of the heat transfer through the upper crust (Hochstein, 1995); and (3) heat is lost from the system at the surface to geysers, runoff or lakes.”*

3.4.1. Main findings from Ethiopian prospects

Main heat sources in Ethiopia are expected nearby recent volcanic centers, i.e., quarternary volcanoes. Most current prospects (if not all) are associated with steam at the surface which proves two-phase systems.

Figure 5 displays two examples of temperature profiles for Tendaho and Corbetti. Other documents show similar schemes for other site: Aluto-Langano (e.g. Hutchinson, 2015), Abaya (Gudbrandson et al., 2019) and Tulu Moye (Gudbrandson et al., 2020) for instance.

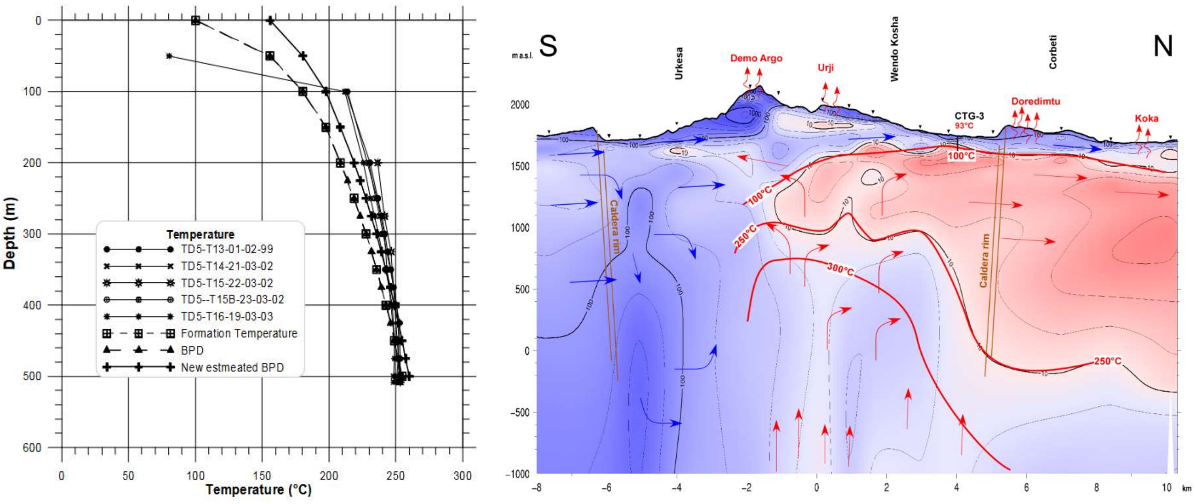

Figure 5 : Examples of temperature profiles of two sites in Ethiopian Rift
Left : Temperature curve vs depth at Tendaho site from Seifu (2004)
Right : Conceptual model of the geothermal system for Corbetti, from Gislason et al. (2015)

In these conceptual models, the two phases (vapor and liquid) circulate with counter flow: liquid water goes down while vapor goes up, which is classical when boiling occurs.

All available documents for Aluto Langano, Tendaho, Corbetti, Abaya and Tulu Moye show temperature greater than 200°C in the geothermal reservoir.

Conceptual models and temperature profiles available for these sites show no heat accumulation under the clay cap, with temperature inversion as observed in comparable geothermal sites worldwide. The only exception is Dubti geothermal field in Tendaho (Battistelli et al., 2001) where hot water accumulates in the sediments near the surface. Though, temperature profiles are only available for Tendaho on the consulted bibliography, and therefore this observation doesn't lead to any particular conclusion.

According to Benti et al., 2023, 14 deep geothermal wells were drilled in Ethiopia in two sites: Tendaho and Aluto Langano . However this doesn't include Tulu Moye and recent wells from Aluto Langano, which would bring it to around 18 boreholes. This low number of wells explains the lack of data and the difficulties to interpretate the observations.

3.5. Synthesis: conceptual model for hydrothermal processes

Based on paragraphs 3.1 to 3.4, a conceptual model has been realized to better illustrate the findings of the present technical report and to compute all information, with dimensions 130 Km x 65 Km x 10 Km (depth).

This conceptual model illustrates the different findings on a geoscientific point of view and emphasizes on the fact that water is a main vehicle for heat transport and therefore drainage zones are of primary importance: ancient structures such as YTVL, boundary faults, brittle-ductile transition at depth, Wonji Fault Belt (and caldera rims) in the rift axis.

The geothermal gradient is expected to be rather high in Ethiopia, though no data were found for the Ethiopian plateaus.

Main sources of heat are however recent (quaternary) magma accumulations beneath WFB and off-axis volcanic centers (such as Debre Zeit volcanic centre which is seen on the conceptual model on the left part).

Water circulation is driven by hydraulic properties of faulted, volcanic rocks, topography, heat which acts on densities and viscosity, and changes in porosity due to the extensional context (see 3.3). The brittle to ductile transition zone is identified as an important place for fluid circulation.

Recharge mostly occurs on the plateau but marginal grabens can also contribute.

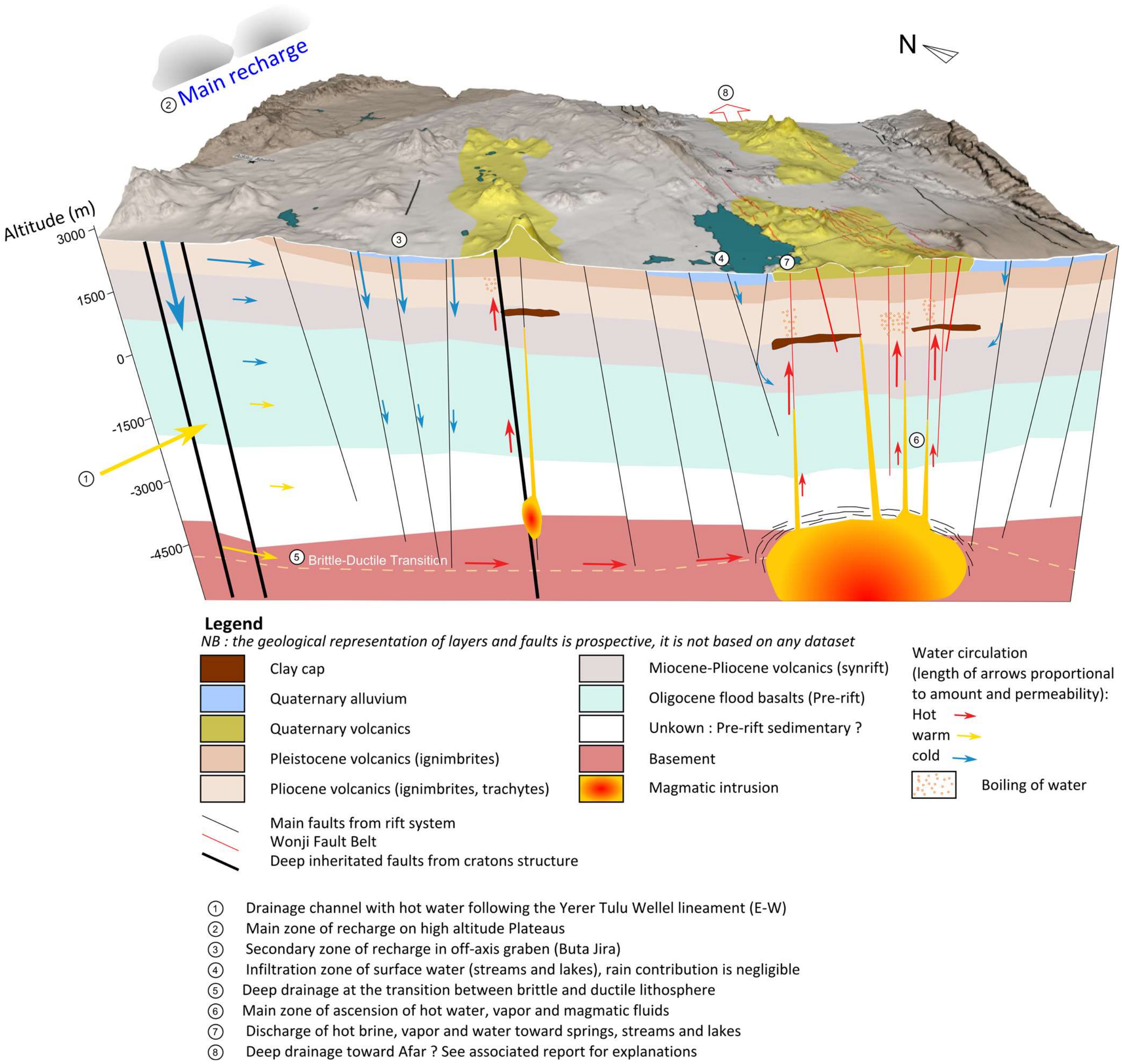

Figure 6 : Conceptual model showing the full cycle of the hydrothermal system from recharge in highlands to outflow zones in the main Ethiopian rift

The following synthetic map, realized in the frame of the technical report, aims to represent the information in a plan view and is complementary to the conceptual model. Note the location of existing geothermal prospects.

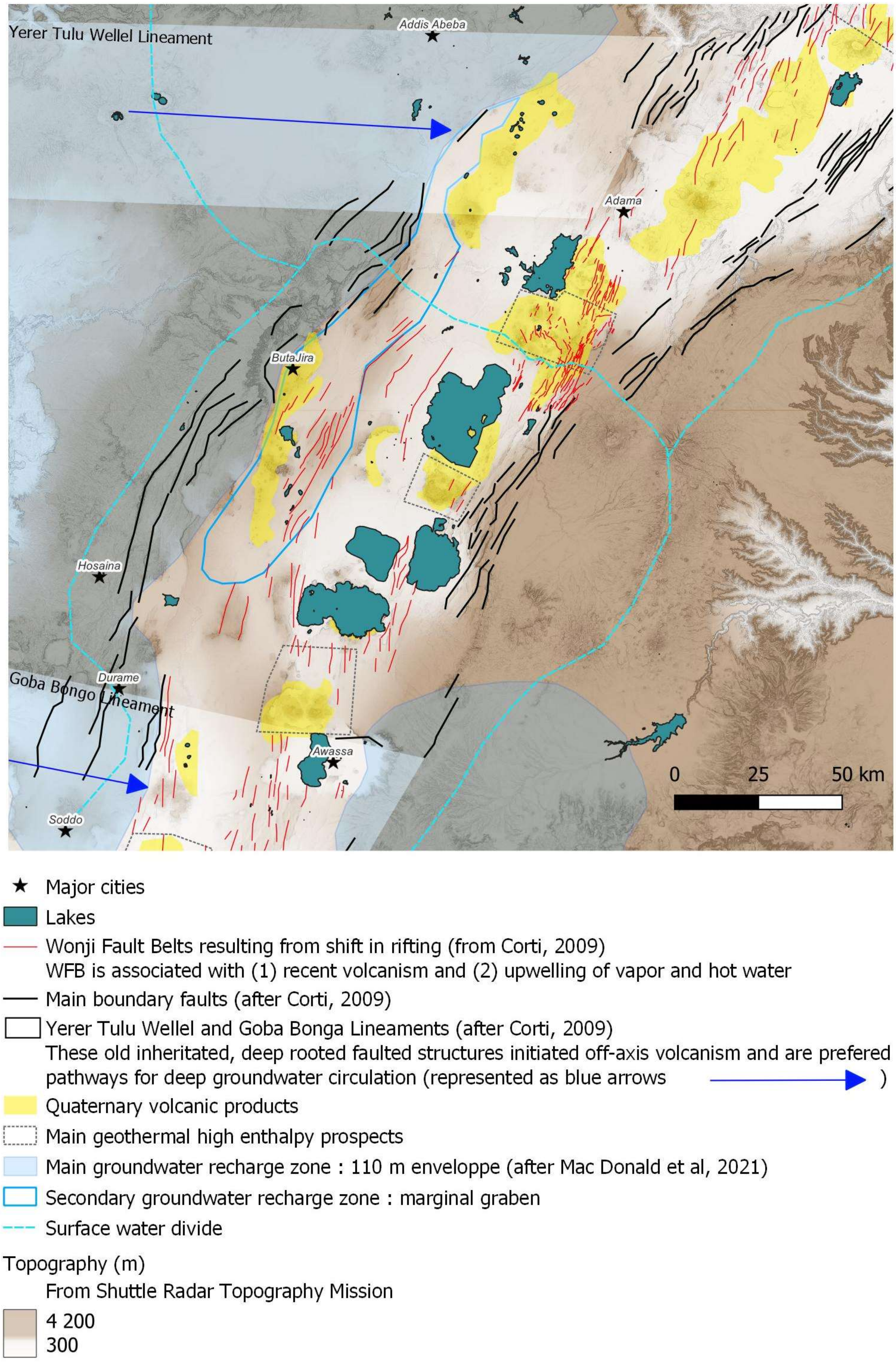

Figure 7 : Map of the main features controlling the hydrothermal system in the central Main Ethiopian Rift

Building the model, a reflexion was made to understand the general directions of the hydrothermal flow. In the Central-MER, the area used for the conceptual model represents a water divide: north to this zone water is drained by Awash river toward Afar, and south to it goes to the endoreic basins hosting lakes of big capacity. Several reflexions are proposed in paragraph 4.

4. Critical analysis / discussion

4.1. Further investigations on hydrothermal flow

Because of the different parameters driving hydrothermal flow, the hypothesis is made that an important part of the flow goes to Afar. This can be deducted from the following facts:

- Faster opening of the rift in Afar, resulting in enhanced porosity,
- Nearer magma and therefore more heat resulting in more energetical heat pump,
- Bigger topographical gradient with higher potential in drainage toward streams and rivers.

This hypothesis could benefit from deeper investigations.

In addition, one can notice that most high-capacity lakes are lying on the rifts floor south to the water divide, and few lakes of reduced capacities are present to the north. This brings the fundamental question: where does the excess of water comes from? The answer would be given by a general water balance taking into account: rainfall (probably higher in the south), evapo-transpiration (probably higher in the north), run-off (probably equivalent), groundwater storage (probably equivalent), and thermal upwelling (probably higher in the north). Evapo-transpiration might be of critical importance for this process.

Fluoride is identified in many articles focusing on water resources (because of exceeding the international health thresholds - WHO guideline value for fluoride in drinking-water is 1.5 mg/L), as being of hydrothermal origin, mostly present in the rift (i.e. not on the plateaus) and getting concentrated because of evaporation in surface waters. Fluorides could therefore be utilized as a tracer for the evaluation of the volumes expelled by hot springs. Such information would be of critical importance to realize a full water balance including hydrothermal flows.

4.2. Significance of the study for geothermal exploitation

The realization of the synthetic conceptual model has several meanings from the scope of geothermal exploration and exploitation.

4.2.1. High enthalpy resources

It appears that most (if not all) prospects are focused on recent volcanic centres (quaternary) along the Wonji Faul Belt. These prospects are seeking high enthalpy geothermal reservoirs, which is consistent with geoscientific findings.

However, one can see that no prospect is inventoried around Adama and in direction of Afar while there might be potential resources (quaternary volcanic centres and WFB). As exploration in Ethiopia is recently the object of a renewed interest, several ongoing prospects might not yet appear on the internet, which could explain the absence of information on these sites.

In addition, due to the relatively small amount of geothermal prospects, there are still some uncertainties due to lack of data and / or misinterpretations of observations, which results in a greater risk.

4.2.2. Low to Medium enthalpy resources

There are considerable low to medium enthalpy resources which have not yet been investigated or utilized. If we consider resources in a range of 100 to 200°C at less than 2000 m this could concern the whole rift valley and the two lineaments of YTVL and GBL.

These warm to hot water resources, in order to generate interest, would need basic exploration such as heat fluxes measurements at surface, inventory of fumaroles and hot springs, resource mapping, etc. These low-cost actions are a prerequisite to any exploitation, and have been partly realized over time. They would greatly benefit from recent technologies (such as DEM, Lidar, drone surveys, GIS mapping, etc.).

To enhance the development of utilization of low to medium enthalpy resources in Eastern Africa (and not only Ethiopia), pilot projects should also be realized, as most of the existing examples for direct use come from northern country with colder climates, and very different priorities.

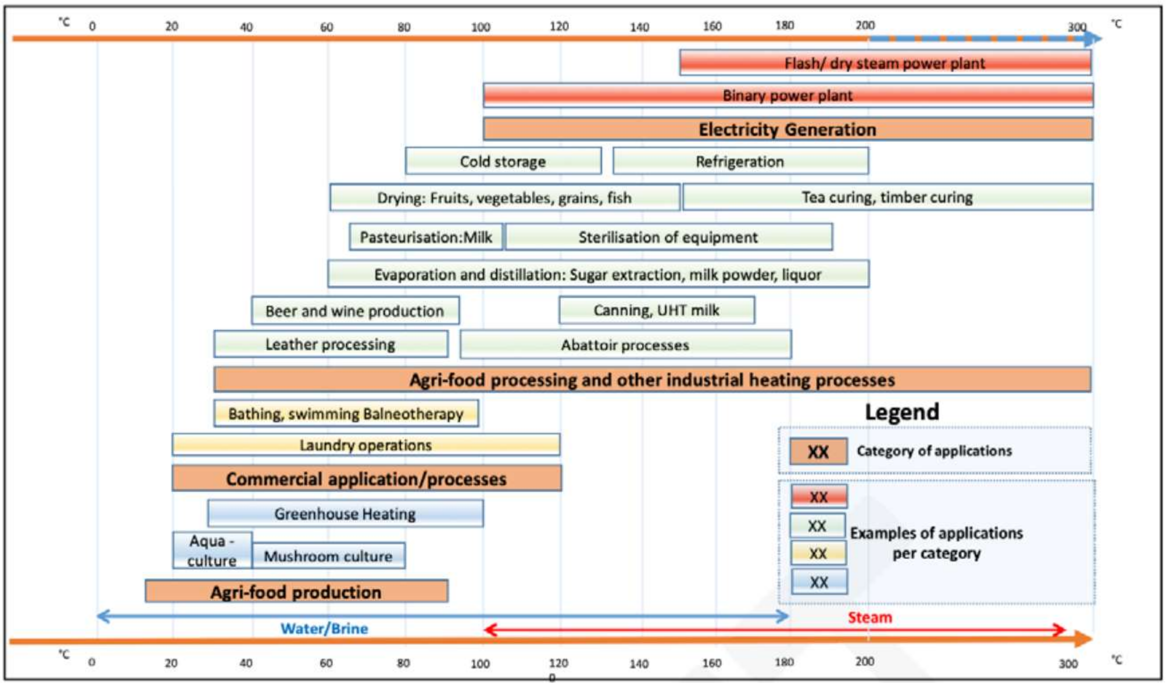

Figure 8 : Lindal Diagram – source: *Geothermal development in Eastern Africa, IRENA, 2023*

Industries in Ethiopia would also benefit from this carbon-free energy. As anywhere else worldwide, there is a need of communication from geothermal experts toward captains of industry to update them about geothermal potential, potential uses and most recent technologies. In Europe this link is assured by government - related agencies.

4.2.3. Critical analysis on direct use of geothermal resources in Ethiopia

Each direct use application has its specificities and requirements. A table summarizing what has been seen as favorable or less favorable, in Ethiopia, for different types of those applications is proposed here after. This table can be used as a reference for further discussion.

Type of use	Temperature required (°C)	Other requirements	+	-
Cold storage	80-130	Near production centers or consumption basin	Many possible and releavant applications (e.g. food conservation)	This T°C range requires investigations and is not necessarily available everywhere
Drying : fruits and vegetables, meat and fish, other cultural foods	60-150	Near production centers	Many possible applications for national (including traditional items like dirkosh or quanta) and international market Would help to improve food security	This range of T°C requires investigations
Coffee baking	100-150	Near production centers Coffee preparation requires several steps before baking	Ethiopia is a major producer of coffee	This range of T°C requires investigations Baking with geothermal might not be optimal for flavour - see Costa Rica for further investigations
Pasteurisation of milk	65-110	Near production centers	Big potential market Would help to improve food security	This range of T°C requires investigations
Sterilization of equipment	110-190	Near big cities and industrial centers	Many potential applications	This range of T°C is not yet proven near big cities, it would probably require the installation of heat pumps
Distillation	60-200	A wide range of T°C for a wide range of applications	Liquor industries already exist in Ethiopia	According to the product, high temperatures might be required and need investigations
Sugar extraction	152	Near production centers	Ethiopia produces 400kt of sugar, some of them in favorable geothermal environment	This range of T°C requires investigations
Milk powder	70-200	Different procedures	Important needs in milk powder for food security	High temperature requirements which need investigation
Beer and wine production	40-90	Hygiene requirements	Beer industry already exists in Ethiopia, the T°c range is easily found nearby production centers	
Leather processing	30-90	To investigate	Ethiopia has a growing leather industry T°C range is easily accessible nearby production centers	
Abattoir process	90-180	Hygiene requirements	Ethiopia has one of the biggest cheptel in Africa	This range of T°C is not yet proven near big cities
Balneotherapy	30-100	Hygiene requirements	Ethiopia has several existing thermal centers across the country	The geopolitical context is not favorable for these activities
Laundry operations	20-120	Hygiene requirements	Big potential around major cities, T°C range accessible	What is the state of laundry industry in Ethiopia?
Greenhouse heating	30-100	Water for irrigation	Big potential in highlands	Local temperatures don't justify supplementary heating except in highlands
Aquaculture (fisheries)	20-40	Pure water	Big potential national market, low temperatures required	Requires a lot of pure water that might not be easily available
Pre-heating of cement	As hot as possible		Cement industry already exists in Ethiopia	High temperatures requires, to be proven with investigations

Figure 9 : Direct use applications in Ethiopia – pros and cons

This quick analysis, realized in the frame of the present study based on Lindal diagram and available information on internet, allows to identify some of the applications that could get better chances to be successfully implemented.

The ones that require low temperature could easily be developed, for instance: leather processing, beer and wine production, aquaculture (if water available which is not the case everywhere). Drying, pasteurization and laundry would also find a market, being given that the resource is sufficient in heat and yield. Coffee baking would finally be a very relevant application, but it shouldn't affect the flavor and quality of the final product.

5. Conclusions and recommendations

The present work, accomplished in the frame of the technical report for CAS Deegeosys edition 2022-23, is a preview for many possible detailed studies or research topics related to geothermal resources in the Main Ethiopian Rift.

As often in geothermal resources assessment, hydrogeology is not sufficiently considered. There would be interesting perspectives of development by reconnecting water considerations to geothermal considerations. This would also allow to treat two problems at once in countries, such as Ethiopia, which need it. More specifically, in Ethiopia the Fluoride concentrations in groundwaters would be a very relevant topic linking water to energy.

Ethiopia, as many other countries in Eastern Africa, would greatly benefit from pragmatic studies, such as geothermal resources mapping and assessment, rather than very fundamental scientific studies (even though they are of primary importance as well). However, those types of studies can not always be supported by local governments and are not usually funded by any grants.

On a scientific point of view, estimating the water balance from recharge to outflow zones would probably help to point out the mechanisms undergoing, and the repartition of hydrothermal waters. This would be of great help to select promising geothermal prospects.

On an exploitation point of view, there is a lack of drillings to confirm sites. Vertical slimholes or core drillings, would be of great help to acquire data and derisk exploration in Ethiopia.

6. Bibliography

Agostini A., Bonini M., Corti G., Sani F., Mazzarini F., 2011, *Fault architecture in the Main Ethiopian Rift and comparison with experimental models: Implications for rift evolution and Nubia–Somalia kinematics*

Ayenew T., Demlie M., Wohnlich S., 2008, *Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers*

Azagegn T., Asrat A., Ayenew T., Kebede S., 2015, *Litho-structural control on interbasin groundwater transfer in central Ethiopia*

Benti N.E., Woldegiyorgis T.A., Geffe C.A., Gurmesa G.S., Chaka M.D., Mekonnen Y.S., 2023, *Overview of geothermal resources utilization in Ethiopia: Potentials, opportunities, and challenges*

Battistelli A., Yiheyis A., Calore C., Ferragina C., Abtaneh W., 2001, *Reservoir engineering assessment of Dubti geothermal field, Northern Tendaho Rift, Ethiopia*

Bertrand L., Jusseaume J., Géraud Y., Diraison M., Damy C., Navelot V., Haffen S., 2018, *Structural heritage, reactivation and distribution of fault and fracture network in a rifting context: Case study of the western shoulder of the Upper Rhine Graben*

Bonini M., Corti G.,Innocenti F.,Manetti P.,Mazzarini F., Abebe T.,Pecskay Z., 2005, *Evolution of the Main Ethiopian Rift in the frame of Afar and Kenya rifts propagation*

Burnside N., Montcoudiol N., Becker K., Lewi E., 2021, *Geothermal energy resources in Ethiopia: Status review and insights from hydrochemistry of surface and groundwaters*

Cant J. L., Siratovich P. A., Cole J. W., Villeneuve M. C., Kennedy B. M., 2018, *Matrix permeability of reservoir rocks, Ngatamariki geothermal field, Taupo Volcanic Zone, New Zealand*

Corti G., 2009, *Continental rift evolution: From rift initiation to incipient break-up in the Main Ethiopian Rift, East Africa*

Corti G., Sani F., Philippon M., Sokoutis D., Willingshofer E., Molin P., 2013, *Quaternary volcano-tectonic activity in the Soddo region, western margin of the Southern Main Ethiopian Rift*

Corti G., Maestrelli D., Sani F., 2022, *Large-to Local-Scale Control of Pre-Existing Structures on Continental Rifting: Examples From the Main Ethiopian Rift, East Africa*

Demlie M., Wohnlich S., Gizaw B., Stichler W., 2005, *Groundwater recharge in the Akaki catchment, central Ethiopia: evidence from environmental isotopes (d18O, d2H and 3H) and chloride mass balance*

Engida Z.A., 2001, *Groundwater study of Addis Ababa Area*

Furi, 2010, *Hydrogeology of complex volcanic systems in continental rifted zone. integrated geochemical, geophysical and hydrodynamic approach. Middle Awash basin, Main Ethiopian Rift, Ethiopia*

Ghiglieri G., Pistis M., Abebe B., Azagegn T., Engidasew T. A. , Pittalis D., Soler A., Barbieri M., Navarro-Ciurana D., Carrey R., Puig R., Carletti A., Balia R., Haile T., 2020, *Three-dimensional* *hydrostratigraphical modelling supporting the evaluation of fluoride enrichment in groundwater: Lakes basin (Central Ethiopia)*

Gislason G., Eysteinsson H., Björnsson G., Hardardottir V., 2015, *Results of Surface Exploration in the Corbetti Geothermal Area, Ethiopia*

Gudbrandsson S., Eysteinsson H., Mamo T., Cervantes C., Gislason G., 2020, *Geology and Conceptual Model of the Tulu Moye Geothermal Project, Oromia, Ethiopia*

Haji M., Wang D., Li L., Qin D., Gui Y., 2018, *Geochemical Evolution of Fluoride and Implication for F- Enrichment in Groundwater: Example from the Bilate River Basin of Southern Main Ethiopian Rift*

Hutchison W., Mather T., Pyle D., Biggs J., Yirgu G., 2015, *Structural controls on fluid pathways in an active rift system: A case study of the Aluto volcanic complex*

Hutchison W., 2015, *Past, present and future volcanic activity at restless calderas in the Main Ethiopian Rift*

Jasim A., Hemmings B., Mayer K., Scheu B., 2018, *Groundwater flow and volcanic unrest*

Keranen K., Klemperer S.L., Gloaguen R., 2004, *Three-dimensional seismic imaging of a protoridge axis in the Main Ethiopian rift*

Khodayar M., Björnsson S., 2021, *Fracture Permeability: Outcrop Analogues from Active Plate Boundaries and Intraplate Contexts of Iceland*

MacDonald A.M., Lark R.M., Taylor R.G., Abiye T., Fallas H.C., Favreau G., Goni I.B., Kebede S., Scanlon B., Sorensen J.P.R., Tijani M., Upton K.A., West C., 2021, *Mapping groundwater recharge in Africa from ground observations and implications for water security*

McLellan J., Oliver N., Hobbs B.,Rowland J., 2010, *Modelling fluid convection stability in continental faulted rifts with applications to the Taupo Volcanic Zone, New Zealand*

Meyer G.G., Garrison G., Violay M., 2022, *Permeability of Basalt Through the Brittle-Ductile Transition, Implications for Superhot Rock Geothermal*

Mueller S., Scheu B., Kueppers U., Spieler O., Richard D., Dingwell D.B., 2011, *The porosity of pyroclasts as an indicator of volcanic explosivity*

Samrock F., Grayver A., Bachmann O., Karakas Ö., Saar M., 2021, *Integrated magnetotelluric and petrological analysis of felsic magma reservoirs: Insights from Ethiopian rift volcanoes*

Seifu A., 2004, *Evaluation of recent temperature and pressure data from wells in Tendaho geothermal field, Ethiopia and from well HG-1 at Hagongur, Iceland*

Sisay S.W., 2016, Subsurface geology, hydrothermal alteration and 3D modelling of wells LA-9D and LA-10D in the Aluto-Langano geothermal field, Ethiopia

Tadesse A.Z., Fontijn K., Caricchi L., Bégué F., Gudbrandsson S., Smith V.C. , Gopon P., Debaille V., Laha P., Terryn H., Yirgu G., Ayalew D., 2023, *Pre-eruptive storage conditions and magmatic evolution of the Bora-Baricha-Tullu Moye volcanic system, Main Ethiopian Rift*