

**OVERVIEW**

# Geothermal energy resources in Ethiopia: Status review and insights from hydrochemistry of surface and groundwaters

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**Abstract**

Ethiopia has an estimated >10,000 MW of geothermal energy potential, more than double its current power generating capacity (4,400 MW). Electricity access stands at 44% of the total population, with 31% in rural areas, so effective development of this low-carbon resource could make a significant impact to equitable delivery of electricity. However, geothermal energy exploitation must be done responsibly to protect valuable water resources under stress from climate-change driven drought conditions and competing uses across agricultural, domestic, and industrial sectors. Our review provides progress updates on geothermal developments—which soon aim to deliver more than 1,000 MW of electricity—and performs a high-level assessment of hydrochemical data for ground and surface waters across Ethiopia. A water quality database was built using publicly available information and three quality control criteria: well-defined sample location, cation-anion balance (CAB) of  $\pm 10\%$ , and clear fluid type definition. Ethiopia hosts two major geothermal water types, sodium-alkalinity dominated in the Main Ethiopian Rift and sodium-chloride dominated in the Afar Depression, separated by sodium-mixed waters between Dofan-Fantale and Meteka. H and O stable isotopes suggest a largely meteoric source for geothermal waters, with  $\delta^{18}\text{O}$  enrichment adding to evidence of a high enthalpy resource at Tendaho. Hydrochemical investigations provide critical information for successful delivery of sustainable geothermal energy developments. However, the current lack of data available for Ethiopia poses a significant challenge for completion of predevelopment baselines and ongoing environmental impact assessment. We encourage the release of unpublished findings from private companies and government agencies to build upon our database and demonstrate social and environmental responsibility in the development of Ethiopian geothermal resources.

This article is categorized under:

Engineering Water > Methods

**KEYWORDS**

Ethiopia, geothermal, groundwater, hydrochemistry, low-carbon energy, sustainable resource development

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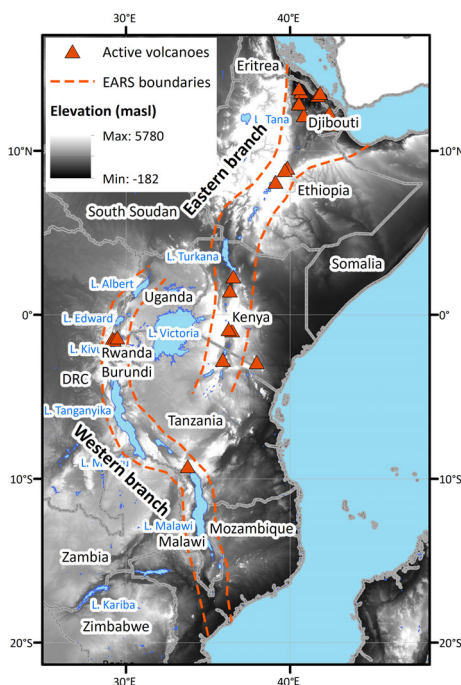
## 1 | INTRODUCTION

### 1.1 | East African Rift setting

The East African Rift System (EARS) is an active intracontinental ridge system, which extends from the Afar Triple Junction in the north to the Mozambique Channel in the south (Chorowicz, 2005). It is divided into two main lines, which skirt around Lake Victoria (Figure 1). The eastern branch runs c. 3,000 km from the Afar Triple Junction and terminates with the submarine Davie Ridge (Mougenot et al., 1986). The western branch diverges from Lake Albert, Uganda, and runs c. 2,100 km to the southern end of the EARS. The eastern branch has far more tectonic and volcanic activity, resulting in an abundance of high enthalpy groundwater resources and a greater geothermal potential in associated nations, such as Ethiopia (Darling, 1998; Omenda, 2009; Teklemariam, 2008; Box 1).

### 1.2 | Power generation and access in East Africa

Most EARS countries are highly dependent on hydropower for electricity production, with the exception of Eritrea (>99% oil) (IEA, 2020). For the six nations where International Energy Agency audited data is available, hydropower provides >80% of electricity for Ethiopia, the Democratic Republic of Congo (DRC), Mozambique, and Zambia, and about one third for Tanzania and Kenya. The importance of hydropower for Mozambique, Zambia, and the DRC is not unexpected considering their important freshwater resources (World Bank, 2018). However, Ethiopia has comparatively limited water resources and there is strong competition for access between agricultural, domestic, and industrial sectors (Jansen et al., 2007; Parker et al., 2016; World Bank, 2006). Due to global climate change and pressure from population growth, EARS nations have experienced severe and persistent droughts since the 1960's (Gebremeskel Haile et al., 2019). In addition, these countries face a growing demand for electricity due to increasing populations and ambitions to deliver more equitable energy access for all (Kammen et al., 2015). With the exceptions of Kenya (64%) and Djibouti (60%), less than 50% of the populations within EARS countries have access to electricity. For Ethiopia, this number stands at 44% and includes a large contrast between urban (97%) and rural (31%) population accessibility



**FIGURE 1** The eastern and western branches of the East African Rift System. Digital Elevation Model (DEM) published in 1996 by the U.S. Geological Survey's Centre for Earth Resources Observation and Science (EROS) and available at <https://databasin.org>; water bodies published in 2015 by the Regional Centre for Mapping of Resources for Development (RCMRD) and available at <https://energydata.info/>; and active volcanoes as identified by Wadge et al. (2016)

### BOX 1 Development of high-enthalpy geothermal resources

Geothermal reservoir potential has been debated in the literature, but can generally be divided into three categories based on temperature: high enthalpy  $>180^{\circ}\text{C}$ , medium enthalpy  $100\text{--}180^{\circ}\text{C}$ , and low enthalpy  $<100^{\circ}\text{C}$ . The end use of a geothermal resource depends on reservoir temperature and available technology. The high-enthalpy geothermal resources in the EARS can be used to generate electricity, with “spent” geothermal waters maintaining high enough temperatures for heating and direct use applications, such as greenhouses, aquaculture, and recreational spas. The energy potential of a geothermal field is typically expressed in megawatts (MW) and the electricity that can be generated from this resource by a power plant is expressed as megawatts electric (MWe). Another measure of electricity is MW hours (MWh)—a unit equivalent to 1 million watts of electrical power being used over 1 h. Gigawatt (GW) units can be used for dealing with larger quantities of power, with 1000 MW equaling 1 GW.

High-enthalpy geothermal development consists of several stages (Gehring & Loksha, 2012):

*Preliminary survey:* Reconnaissance study, often at nationwide or regional scale, based on existing data, which allows initial screening of promising areas.

*Exploration:* Focused investigation of promising location to produce a prefeasibility study. Includes geochemical and geophysical studies and drilling of shallow temperature gradient boreholes.

*Test drilling:* Completion of three to five deep geothermal wells (or slim boreholes) for more detailed reservoir interrogation.

*Project review and planning:* Review of all pre-existing and new data to complete a feasibility study.

*Field development:* Diligent site selection and drilling and testing of production and reinjection wells.

*Construction:* Installation of all geothermal power plant components and connections to energy distribution network.

*Start-up and commissioning:* Fine-tuning of plant efficiency before commencing operation.

*Operation and maintenance:* Management of system throughout operational life span to ensure consistent production of desired energy output.

(World Bank, 2018). These factors provide significant motivations for advancing development of indigenous geothermal resources.

## 1.3 | Potential of geothermal energy in Ethiopia

Ethiopia and Kenya could both potentially contain geothermal reserves in excess of 10,000 MW (JICA, 2015; Kahlen et al., 2019; Solomon Kebede et al., 2020). To put this into some perspective, it is more than double that of Ethiopia's current total power capacity of 4,400 MW and nearly five times Kenya's current total power capacity of 2,200 MW (IRENA, 2020). Kenya leads the way with geothermal development in the region— it is the main source of electricity in the country, providing 38% of total generated power in 2019 (IRENA, 2020). Ethiopia has a single installed power plant at Aluto-Langano, which has intermittently produced less than 1 MW per year since 2013, solely to meet the demands of plant operation (IRENA, 2019; Tadesse, 2018). However, with ongoing expansion of the Aluto-Langano plant to 75 MW and advancing plans for two further 500 MW projects in Corbetti and Tulu Moye (Tadesse, 2018), Ethiopia appears to be en route to becoming a significant producer of geothermal energy.

## 1.4 | Scope of this review

To meet the equitable energy demands of a growing population, Ethiopia is looking to accelerate geothermal development. We start with an overview of the status of geothermal prospects across the country. This narrative literature review details the stage of development, exploration history, and fluid chemistries of the four most important geothermal prospects identified thus far and provides short summaries of available information for further sites of interest. In each case, it is critical that diligent evidence-based appraisal of the resource is carried out to ensure effective and responsible utilization. This should include

assessment of all potential economic, environmental, and social impacts associated with geothermal energy development (Axelsson et al., 2005; Shortall et al., 2015). We then collate publicly available ground and surface water hydrochemistry data and perform a synthetic review to provide a high-level assessment of geothermal resource development within the wider context of water use. It is hoped that this review and the hydrochemical database that accompanies it will be expanded upon by ongoing and future investigations and provide a catalyst for release of nonpublicly available data to allow for more robust baselines to be performed at prospective geothermal developments.

## 2 | STATUS OF GEOTHERMAL ENERGY IN ETHIOPIA

### 2.1 | History of geothermal development

Exploration for geothermal energy in Ethiopia started in 1969 with initial surface geology, geochemistry, air photo interpretations, and infra-red airborne survey investigations (UNDP, 1973). These were later complimented by focused hydrochemical and isotopic studies (Scripps Institute of Oceanography, 1977). Twenty-five prospects have thus far been deemed to be suitable for electricity generation (Kebede et al., 2020), many of which are associated with Quaternary volcanism (Chandrasekharam et al., 2015; Omenda, 2009). Among these areas, Aluto-Langano is the only prospect to have ever produced geothermal energy. Near-future installation of pilot power plants are anticipated in Tendaho, Corbetti, Tulu Moye, and Abaya geothermal fields (Figure 2). A more detailed summary of each of these geothermal fields, and locations under further investigation is provided below.

### 2.2 | Aluto-Langano

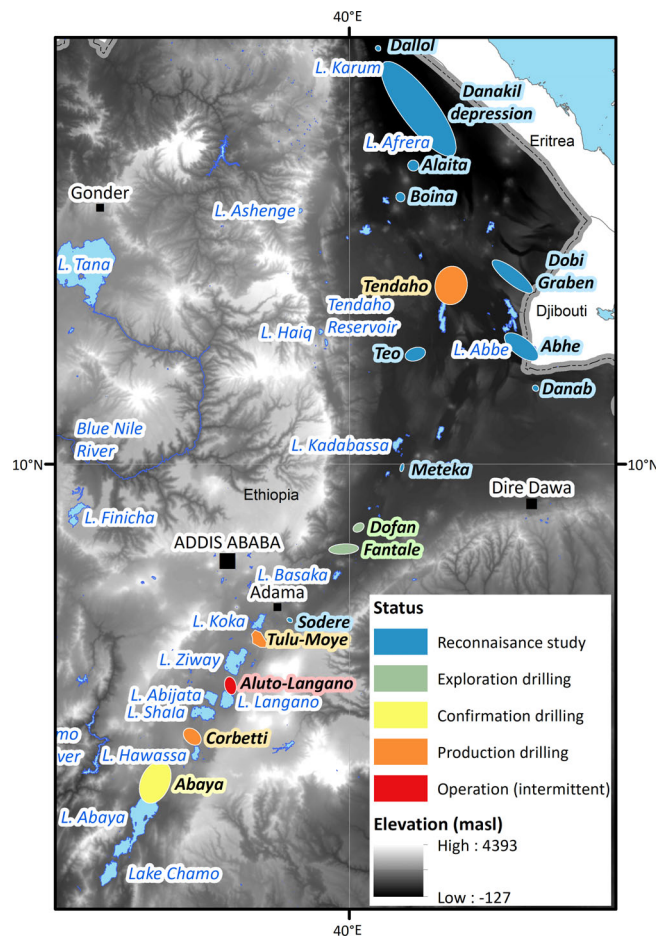
Exploration at Aluto-Langano started in the 1980s (1981–1986) with the drilling of eight deep exploratory wells, of which four were productive. The geothermal resource is a water-dominated sodium-mixed (bicarbonate-chloride) type fluid (Gianelli & Teklemariam, 1993), with 6.3% by weight (wt%) CO<sub>2</sub>-rich noncondensable gas (NCG) in the steam fraction of the fluid (Geremew, 2012).

The reservoir is located 2,000 m below ground level (mbgl) and its temperature varies from 230 to 360°C (Biru, 2016; Gizaw, 1993). Initial resource development took place in the 1990s and culminated in the construction of Ethiopia's first pilot power plant in 1998, with exploitation based on extraction from four production wells and a single reinjection well (Teklemariam & Beyene, 2001). The plant had a total electrical generation output of 52 GWh from 1998 to 2001 and 64 GWh from 2008 to 2011 (IEA, 2020). The intervening hiatus from 2002 to 2007 was the result of operational issues including declined well pressures, scaling, corrosion, and leakage problems (Biru, 2016; Tassew, 2010, 2015). Because of intermittent operations, the plant has been producing under 1 MWe per year since 2013, just enough for self-sufficiency (IRENA, 2019; Tadesse, 2018).

Two new exploration wells were drilled between 2013 and 2015 to assess expansion of site generation capacity to 70 MWe (Cherkose & Mizunaga, 2018; Gebru, 2017). Measured bottom-hole temperatures were over 300°C and production testing suggests that these two wells could generate 2.7–3.8 MWe each (Biru, 2016). Conceptual modeling of a magmatic up-flow center to the east of existing wells in Bobesa has suggested a further 35 MWe of potential in the area (Kebede et al., 2020). While efforts aimed at drilling further production wells are ongoing (drilling reported to start in April 2021- EEP, 2021a), early generation of power from initial wells by installation of a geothermal wellhead power system (a portable modular small-scale power plant) is under consideration (JICA & WJEC, 2017; Kebede, 2016). This is a similar technique that has been successfully deployed in Kenya at the Olkaria (Chege et al., 2017) and Eburru (Mendive & Green, 2012) geothermal fields.

### 2.3 | Tendaho

This prospect consists of three targeted areas: Dubti, Ayrobera, and Allalobeda. Geothermal exploration started in 1979–1980 via eight shallow temperature gradient wells (TGW; Amdeberhan, 2005). Following a techno-economic study of the Dubti area in the early 1980s, three deep exploration wells and a shallow well were drilled from 1993 to 1995 near a cotton plantation, followed by two additional shallow wells during 1997–1998 (Ali, 2005). Kebede



**FIGURE 2** Status of main geothermal prospects in Ethiopia (as of 2019). Base DEM sourced from the Consultative Group for International Agricultural Research-Consortium for Spatial Analysis (CGIAR-CSI) website (<http://srtm.csi.cgiar.org>). All other background map elements from OpenStreetMap (<http://download.geofabrik.de>)

et al. (2020) reports that: (i) the three shallow wells are 500 m deep and produce fluid at  $>250^{\circ}\text{C}$ ; and (ii) the three deep wells are completed into low-permeability strata at an average of 2,000 mbgl and encountered temperatures of up to  $270^{\circ}\text{C}$ . This site is in an active tectonic setting, at the central part of the Tendaho graben, where a transition from continental rifting to oceanic crust formation occurs (Bridges et al., 2012; Lewi et al., 2015; Temtime et al., 2018). A partial melt at a depth of about 10 km has been mapped underneath this resource with a very dense and newly formed crustal lithologic unit at the central part of the rift axis (Johnson et al., 2015; Lewi et al., 2015). In line with the information detailed by Kebede et al. (2020), two distinct sodium-chloride (Na-Cl) type fluid composition reservoirs have been suggested: (i) a shallow 250–550 mbgl liquid-dominated reservoir of up to  $255^{\circ}\text{C}$  and NCG steam concentration of 0.1 wt%; and (ii) a deep 2,000–3,000 mbgl liquid-dominated reservoir with estimated temperature comparable to (i) and a NCG content of 1 wt% (Ali, 2005; Pasqua et al., 2014). Additional surface exploration took place in the late 1990s (Lemma et al., 2010), followed by an environmental impact assessment (EIA) for the area (Kebede, 2005), further surface exploration studies in 2007, 2011–2012 and 2012–2013 (Kebede, 2015; Workalemahu, 2015) and a feasibility study for exploitation of the shallow reservoir in 2013–2014 (Pasqua et al., 2014). The Ethiopian Government subsequently received funds from the French Development Agency (Agence Française de Développement—AFD) and the European Union Infrastructure Trust-Fund (EU-ITF) to drill a further six shallow and two deep geothermal wells (AFD, 2018; Government of Ethiopia & AFD, 2015).

The other two targeted areas have undergone detailed surface-based surveys (Solomon Kebede, 2015; Workalemahu, 2015) but are in a nascent stage of development. An initial conceptual model exists for the Ayrobera area, but further investigation is required (Stimac et al., 2014). Priority areas for test drilling have been identified and planning is underway to drill two to three exploration wells (Kebede, 2016). A conceptual model is also available for



the Allalobeda area which suggests a reservoir between 1,000 and 1,200 mbgl and an estimated resource temperature of 200–220°C (Kebede, 2016; Pasqua et al., 2016).

## 2.4 | Corbetti

Surface exploration in Corbetti started in the 1980s and was followed by exploration drilling in 1986–1987 (Endeshaw, 1988). Eight shallow wells were installed ranging from 93 to 184 mbgl. The deepest well recorded a bottom hole temperature of 95°C. Geothermal fluid chemistry is of sodium-bicarbonate (Na-HCO<sub>3</sub>) type. Results of this exploration phase are found in Solomon Kebede and Abdulkadir (1987), who concluded on the probable presence of a deep reservoir with temperature in excess of 250°C. A mafic magma intrusion, into partially melted compressible and inelastic crust, has been mapped at about 7 km depth (Gottsmann et al., 2020). Efforts quiesced until Reykjavik Geothermal (RG) was awarded a concession in 2011. This enabled detailed surface exploration, synthesis of a conceptual model and proposal of two sites for installation of deep exploration wells to c. 2,500 mbgl (Gislason et al., 2015).

The Corbetti Geothermal Public Limited Company (Plc.) was set up in 2014 to deliver geothermal energy from the site. The initial phase of development aims to demonstrate the viability of the geothermal resource by drilling up to six exploratory wells, followed by a further four to seven wells and the construction of a fully operational 50 MWe power plant by 2023. A second phase would aim to add a 100 MWe power plant (InfraCo Africa, 2020). If successful, subsequent phases could see Corbetti progressively increasing its installed capacity to 520 MWe (Cervantes et al., 2020).

## 2.5 | Tulu Moye

Detailed surface exploration was carried out between 1985 and 1987 (Mamo, 2001). Further investigations between 1998 and 2001 included five shallow TGWs (Mamo, 2001; Teklemariam, 2006) ranging in depth from 150 to 185 mbgl (Teclu & Gizaw, 2001; Teklemariam, 2006). The chemical composition of the geothermal fluids was of Na-HCO<sub>3</sub> type (Teclu & Gizaw, 2001). When combined with geological and geophysical efforts, these studies suggest the presence of a shallow c. 200°C high-enthalpy reservoir and highlight sites to target for deep exploration drilling (Teklemariam, 2006).

RG has had a geothermal exploration license for the Tulu Moye concession since 2011. A summary of recent investigations at this prospect can be found in Varet and Birba (2018). The Tulu Moye Geothermal Plc. was formed in 2017 to take charge of geothermal development through implementation of two main phases. During Phase 1, 12 wells are to be drilled to 2,500 mbgl in order to supply a 50 MWe pilot power plant by 2023 (Bekele, 2019; Getachew, 2020). Phase 2 will enable extension of capacity to 150 MWe with the completion of a second 100 MWe power station by 2025 (Getachew, 2020). If successful, subsequent phases could see Tulu Moye progressively increasing its installed capacity to 520 MWe (Cervantes et al., 2020). An Environmental and Social Impact Assessment (ESIA) for the first phase was completed in 2016 (VSO Consulting, 2016). Drilling started in March 2020, as reported by Getachew (2020), and two wells have now been drilled (EEP, 2021b).

## 2.6 | Other potential prospects

The remaining geothermal prospects demonstrate different degrees of exploration (Figure 2).

### 2.6.1 | Abaya

A review of resource exploration at this prospect is available in Chernet (2011). Ayele et al. (2002) identified a potential reservoir at >260°C and a Na-HCO<sub>3</sub> fluid composition. The Abaya geothermal concession was awarded to RG and their surface exploration between 2018 and 2019 confirmed the presence of a geothermal reservoir located from a few hundred meters to 2,000 mbgl, with temperatures in excess of 230°C. Geothermal development will take place in two phases: the first phase aims to build a 50 MWe power station, the second will seek to extend the power capacity to 300 MWe (VSO Consulting, 2019). No dates have been put forward regarding the execution of the phases. The ESIA for the first phase is underway (VSO Consulting, 2019).

## 2.6.2 | Dofan-Fantale

Detailed surface exploration in the Dofan-Fantale area started in 1993. Estimates of the reservoir temperatures are variable, with the most recent suggesting 163–195°C (Pürschel et al., 2013), significantly lower than the previously described prospects. The geothermal fluids are of Na-HCO<sub>3</sub> composition (Teclu, 2006).

The Fantale geothermal license was awarded to Hotspur Geothermal in 2015. They completed a resource assessment in 2017 which concluded a geothermal energy potential in excess of 100 MWe (Hotspur Geothermal, 2017). OrPower 12 Inc. is planning a drilling programme in the Dofan prospect after receiving funding from GRMF (2018).

## 2.6.3 | Remaining prospects

Other geothermal prospects, including Kone, Meteka, Danab, Teo, Lake Abhe, and Dallol (Figure 2), were investigated during reconnaissance studies in the 1980s. They all require further assessment. The Dallol hydrothermal field, home to spectacular geothermal surface manifestations (Box 2), has been the focus of a few recent scientific studies (Darrah et al., 2013; Franzson et al., 2015). The Meteka and Teo prospects are believed to hold the highest potential for economically exploitable high temperature geothermal resources. However, these areas are currently considered to be low priority for development due to their large distances from existing national grid infrastructure (Kebede, 2009).

# 3 | METHODS: CONSTRUCTION OF HYDROCHEMICAL DATABASE

## 3.1 | Database structure

A detailed literature review was used to construct a database of water resource quality in relation to geothermal energy development in Ethiopia. The compilation draws on information published in open-access scientific journals and reports. Additional data exists but is largely inaccessible due to its sensitive (e.g., recent work by private companies) or

### BOX 2 Geothermal Landscapes

Many of the Earth's observable geological processes are caused by convection of heat within the mantle, including the constant movement of tectonic plates. At divergent boundaries, the upwelling of buoyant mantle forces the Earth's crust to be pushed apart and break, extruding molten rock then solidifies, leading to the formation of new crust at spreading ridges. Where plate edges collide, subduction consumes denser crust, and elevates buoyant crust to create mountain ranges. The forces involved are monumental: for example, Mid-Atlantic Ridge crust production pushes Africa and Europe away from the Americas at a similar speed to human fingernail growth. Heat generated at spreading and subduction zones results in volcanic activity and creation of geothermal landscapes, where surface manifestations may evidence the presence of subsurface geothermal reservoirs. These features can take various forms, such as:

*Hot springs:* Heated high-solute concentrated groundwaters from a deep reservoir. Can mix with shallow, fresher groundwaters during migration to the surface. Often accompanied by precipitation of siliceous or carbonate mineral formations as fluid equilibrates with surface conditions.

*Geysers:* Periodically erupting hot springs. Result from rapid volumetric expansion of superheated groundwater flashing to steam during ascent into near-surface low-pressure environments.

*Fumaroles:* Surface vents that emit steams and gases such as carbon dioxide (CO<sub>2</sub>) and hydrogen sulfide (H<sub>2</sub>S) from magma or groundwater flashing.

*Bubbling mud pools:* Viscous water-limited slurries that typically form in rich volcanic soils or clay dissolved from surrounding rocks.

*Steaming grounds:* Percolating water rapidly boiled to steam by geothermally heated ground.

*Odor:* Due to prevalence of hydrogen sulfide (H<sub>2</sub>S) in volcanic gases, most geothermal manifestations are accompanied by the smell of rotten eggs.

proprietary (e.g., contracted work by international geological surveys) nature. However, data sourced from unpublished primary works cited in publicly available studies were included in the database if quality control criteria were satisfied. Database access details can be found in our Data Availability Statement at the end of this article.

Each record represents a unique water sample for which at least one parameter was measured at a specific location and at a specific point in time. Information gathered for each record is summarized in Table 1. We attributed a unique project ID to each record, with all other information sourced from the literature. Data sources are listed in order of: (i) the reference of the original research; (ii) all subsequent references citing the original source from oldest to most recent; and (iii) unpublished original information sources cited in publicly available papers and reports.

In the source literatures, coordinates were expressed using different systems (Clark 1880 and WGS84), projections (Universal Transverse Mercator—UTM vs. geographic coordinates) and formatting (Degree Minute Second—DMS vs. decimal notation). To facilitate the analysis, all the coordinates were converted to the same system and formatting (Latitude/Longitude in decimal notation) using ArcGIS® (Esri, version 10.1). The coordinate values were divided into four categories depending on their method of recording: field measured GPS coordinates, coordinates read from a large-scale map (e.g., detailed map), coordinates read from a small-scale map (e.g., regional scale), and coordinates from site identification in Google Maps. A relative precision is also provided ranging from very low (radius >5,000 m) to very high (radius <100 m).

A distinction was made between productive wells, nonproductive wells, injection wells, and unknown (i.e., no information on type of well available), though it must be noted that the designation of each unique well may change over time. Groundwater source was differentiated between drilled boreholes and excavated wells. Where unspecified, groundwater was assumed to come from a drilled borehole. Surface water was divided between lakes/reservoirs and rivers.

### 3.2 | Database validation

The presence of each measurement and/or sample within the database was checked before creating a new record. However, duplicate entries could not be completely avoided due to improper citation of the original source work or divergent sample reporting for identical locations across different published studies. All duplicate entries were removed or

**TABLE 1** Information gathered in the database

Type of information	Detailed information
Identification information	Project ID (unique, attributed by the present authors) Sample name Well ID Sampling date Literature reference
Spatial information	Locality Geothermal field Sample coordinates Source of coordinates Relative precision of coordinates Elevation
Type of sampled fluid	Classified by origin (geothermal well, temperature gradient well, springs, fumaroles, groundwater, surface water, rainwater, and unknown)
Geothermal well characteristics	Well depth (applies also for groundwater wells) Downhole temperature Wellhead pressure Sampling pressure Enthalpy
Physico-chemical parameters	Field parameters (e.g., temperature, pH, and conductivity) Lab analyses (e.g., major and minor ions, trace elements, isotopes, and gases)
Calculated temperatures	Using a range of published geothermometers



merged before attributing a unique project ID. The database was also corrected for spurious values inconsistent with the locality or resource type, which we assume to be the result of human data recording error. Coordinates were homogenized for samples taken at the same location over the years by different authors, with the choice of site coordinates based on the relative precision of measurement and Google Maps where appropriate (for locations identifiable on satellite images such as geothermal well pads).

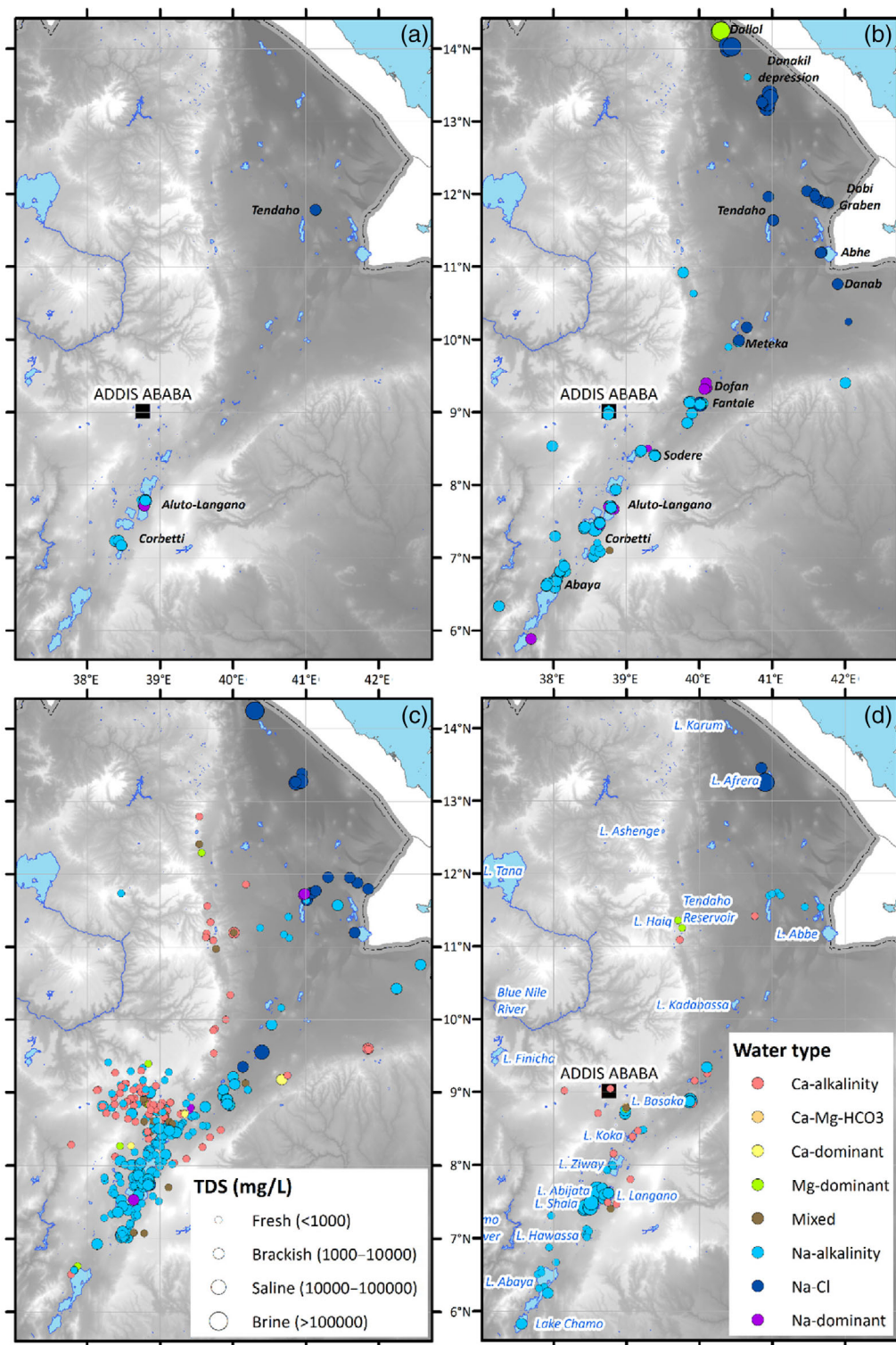
### 3.3 | Criteria for data selection

The quality of the chemical analyses was assessed by calculating the CAB (Appelo & Postma, 2005) taking into account the main cations (calcium, magnesium, sodium, and potassium) and the main anions (bicarbonate/carbonate, sulfate, chloride, and fluoride and nitrate where available). A range of  $\pm 10\%$  was considered to account for the improvement of analytical and sampling techniques with time (the oldest samples are from the 1920s) as well as for the expression of alkalinity (acid neutralizing capacity, mainly from bicarbonates  $\text{HCO}_3^-$  and carbonates  $\text{CO}_3^{2-}$ ). Reported alkalinity values did not always provide measurement units or clarity on type of alkalinity. The following quality control boundaries were applied to utilized database samples: CAB of  $\pm 10\%$ ; have

**TABLE 2** Type of analysis available in the database (numbers refer to samples with location estimated within a 1 km radius of true location)

Type of analysis	Quantity
<i>Major ions (CAB <math>\pm 10\%</math>)</i>	966
<i>Minor elements</i>	
• Si or $\text{SiO}_2$	735
• N species	163 ( $\text{NH}_4^+$ ), 673 ( $\text{NO}_3^-$ ), 31 ( $\text{NO}_2^-$ )
• P species	2 ( $\text{HPO}_4$ ), 25 (P), 59 ( $\text{PO}_4^{3-}$ )
• B species	219 (B), 4 ( $\text{B}_2\text{O}_3$ ), 290 ( $\text{HBO}_2$ ), 5 ( $\text{HBO}_3$ )
• $\text{F}^-$	1,149 (including 865 with CAB $\pm 10\%$ )
• Li	322
• $\text{H}_2\text{S}$ (dissolved)	137
<i>Trace elements (<math>n &gt; 100</math>)</i>	287 (Br), 130 (Fe), 214 (I), 151 (Mn), 112 (Sr)
<i>Isotopes</i>	
• $\delta^2\text{H}$ and $\delta^{18}\text{O}$ ( $\text{H}_2\text{O}$ )	523
• Tritium ( $^3\text{H}$ )	192
• $\delta^{13}\text{C}$ -DIC	111
• $^{14}\text{C}$	31
• $\delta^{13}\text{C}$ - $\text{CO}_2$	30
• $\delta^{18}\text{O}$ - $\text{CO}_2$	4
• $\delta^{13}\text{C}$ -CO	7
• $\delta^{18}\text{O}$ - $\text{SO}_4$	9
• $\delta^{13}\text{C}$ - $\text{CH}_4$	10
• $\delta^{15}\text{N}$ - $\text{N}_2$	7
• $\delta^{87}\text{Sr}/^{86}\text{Sr}$	50
<i>Gas (total concentrations)</i>	69 (He); 57 ( $\text{CO}_2$ ); 47 ( $\text{CH}_4$ , $\text{H}_2\text{S}$ ); 46 ( $\text{H}_2$ , $\text{N}_2$ ); 27 ( $\text{C}_2\text{H}_6$ , $\text{C}_3\text{H}_8$ ); 25 (Ar); 18 (CO); 17 ( $\text{O}_2$ ); 14 ( $\text{C}_6\text{H}_{10}$ ); 12 ( $\text{C}_4\text{H}_{10}$ ); 9 (NCG); 7 (gas fraction, $\text{C}_3\text{H}_6$ , i- $\text{C}_4\text{H}_8$ , i- $\text{C}_4\text{H}_{10}$ , n- $\text{C}_4\text{H}_{10}$ , $\text{C}_7\text{H}_8$ )
<i>Rare gases</i>	8 ( $^{36}\text{Ar}$ , $^{84}\text{Kr}$ , $^{20}\text{Ne}$ , $\text{N}_2$ excess)
<i>Gas isotopic ratios</i>	44 ( $\text{R}/\text{R}_a$ ); 30 (He/Ne air); 8 ( $^4\text{He}/^{20}\text{Ne}$ , $\text{CH}_4/^3\text{He}$ , $\text{CO}_2/^3\text{He}$ ); 5 ( $^4\text{He}/^{22}\text{Ne}$ ); 2 ( $^{40}\text{Ar}/^{36}\text{Ar}$ )

well-known locations (within an estimated radius of 1 km from the true sampling location); and the type of the fluid (Table 1) clearly identified. In total, the database contains 966 unique hydrochemical records for Ethiopia (Table 2).

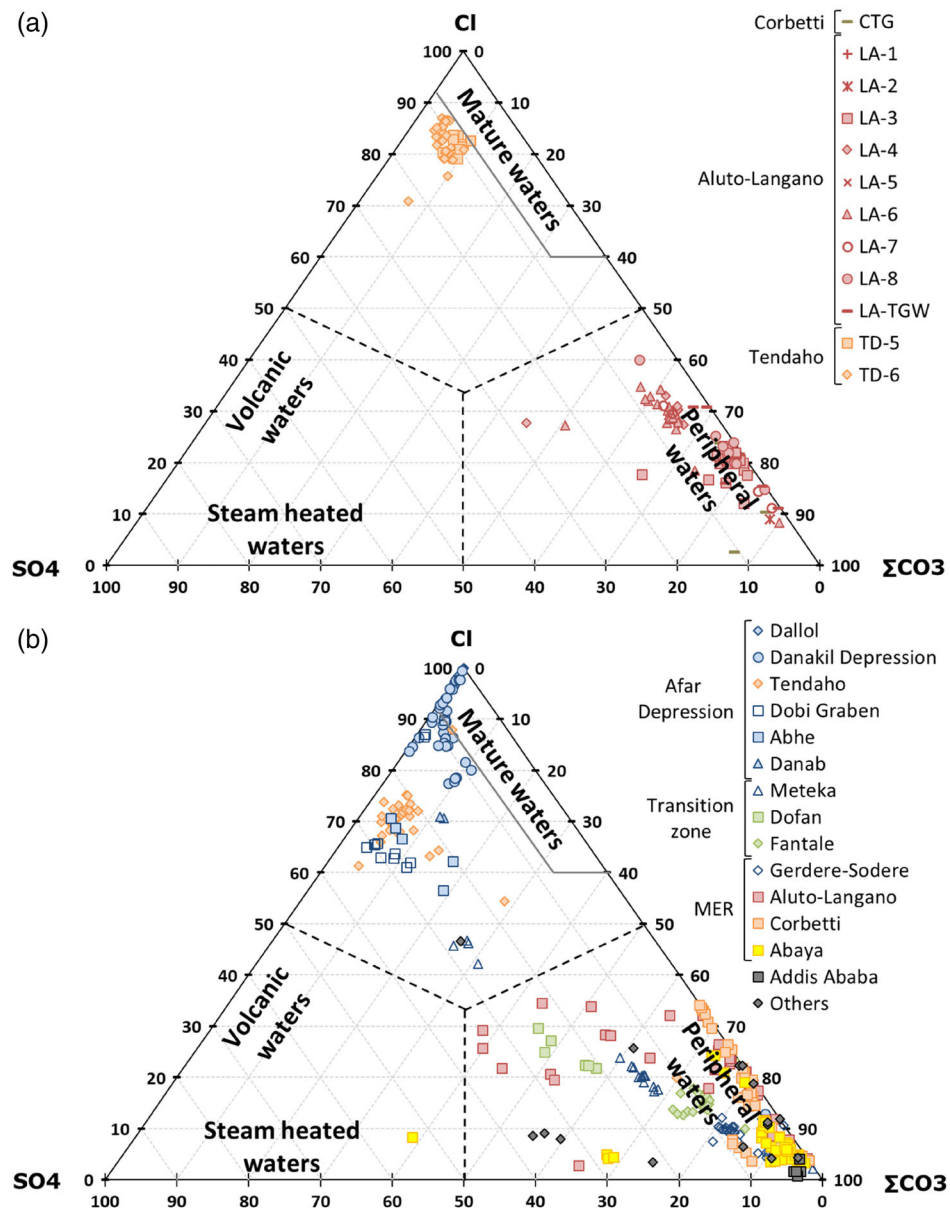


**FIGURE 3** Distribution of water type and calculated Total Dissolved Solids (TDS) in Ethiopia: (a) Geothermal fluids from geothermal wells and temperature gradient wells; (b) Geothermal fluids from hot springs and fumarole condensates; (c) Groundwater from boreholes, cold springs, and dug wells; and (d) Surface water from lakes and rivers

For isotopic and gas analyses, only the criteria related to the sampling location and the origin of the fluid were applied. A total of 523 analyses are available for  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  stable isotopes (by far the widest available type of isotopic analyses, Table 2).

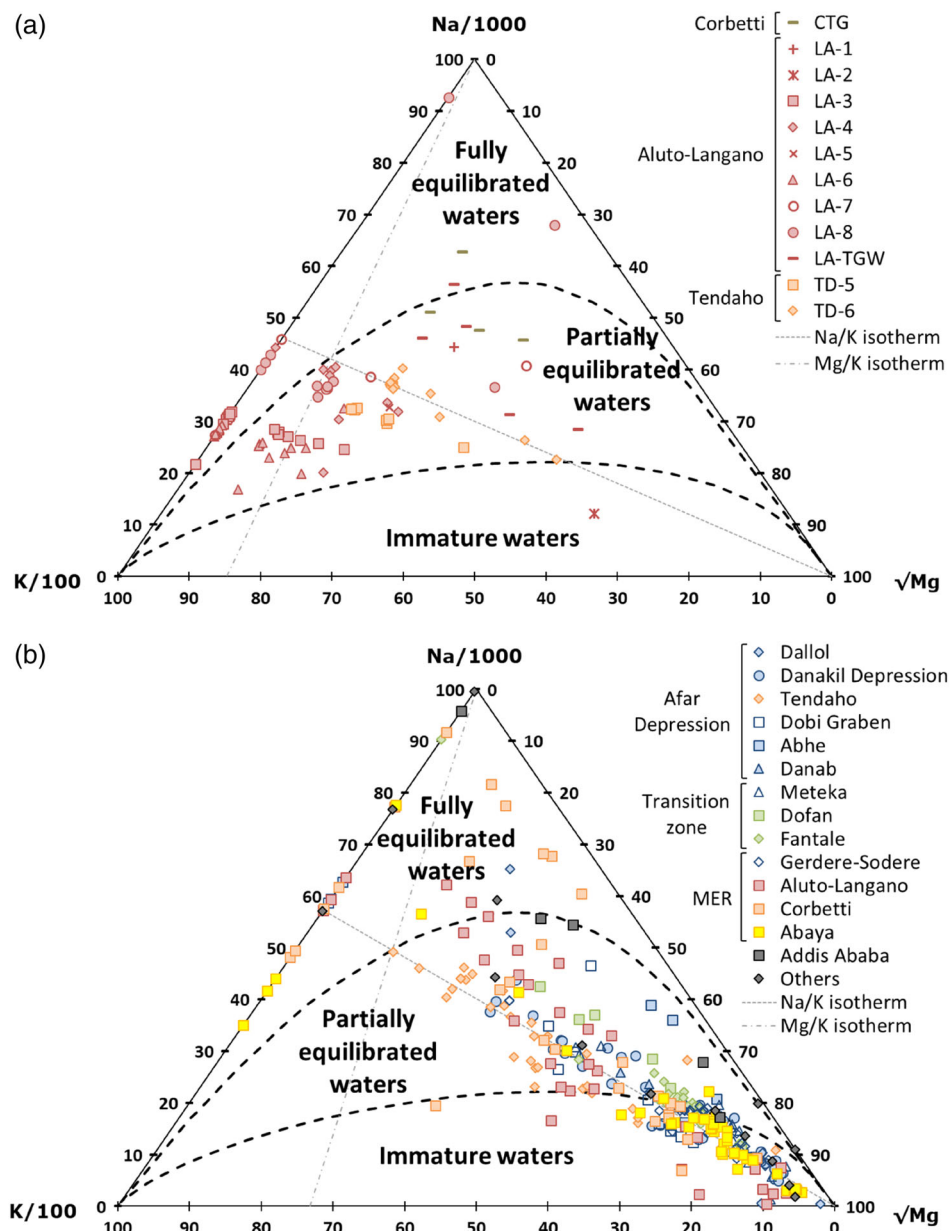
### 3.4 | Classification into water type

To allow assessment of the chemical quality of Ethiopian waters, the selected samples were classified into water types following the method outlined by Cloutier (2004), with each concentration of major ion expressed as a percentage of



**FIGURE 4** Trilinear diagram  $\text{Cl}-\text{SO}_4-\Sigma\text{CO}_3$  for the classification of geothermal waters according to Giggenbach (1988) with geothermal fluids from (a) geothermal wells and (b) hot springs. CTG and LA-TGW represent temperature gradient wells. Plot axes represent the relative concentrations (in mg/L) of major anions (chloride:  $\text{Cl}^-$ , sulfate:  $\text{SO}_4^{2-}$ , and carbonates species:  $\text{HCO}_3^-$ ,  $\text{CO}_3^{2-}$ , or  $\text{CO}_3$ ). MER samples plot as “peripheral waters,” typically indicative of  $\text{CO}_2$ -rich soda springs or local heating of groundwater by steam and other volcanic gases. Afar Depression samples plot closely to “mature waters,” corresponding to highly concentrated chloride brines representative of thoroughly-equilibrated fluids from major up-flow zones. The chemistry of steam-heated and volcanic waters are typically related to gas absorption and oxidation processes (Giggenbach, 1988; Haizlip, 2016; Younger, 2014)

the sum of concentrations (in meq/L). The water-type is defined by the dominant cation and anion concentrations in excess of 20% of total fluid composition (usually one of each). In other cases (none above 20% or two concentrations above), the water type is considered mixed (either for cation or anion, rarely for both). In many studies, bicarbonate ( $\text{HCO}_3^-$ ) and carbonate ( $\text{CO}_3^{2-}$ ) are undifferentiated and not accompanied by pH measurement. In such cases, we use the term “alkalinity” to describe the sum of these two anions. Results from this approach are similar to those from Piper or Stiff plots (Appelo & Postma, 2005). However, our approach presents several advantages: it is more systematic, it can be easily implemented in the database (especially considering the number of analyses), and it allows for direct mapping of the spatial distribution.



**FIGURE 5** Trilinear diagram of water-rock chemical equilibration conditions for Na–K–Mg with geothermal fluids from (a) geothermal wells and (b) hot springs. The axes show relative concentrations (similar to the anion trilinear plot). For clarity, only the 245 and 210°C isotherms are shown respectively in (a) and (b) as examples. Isotherms are calculated from the equations of equilibrium water–mineral interactions for  $\text{K}^+$  and  $\text{Na}^+$  (Na/K isotherm) and for  $\text{K}^+$  and  $\text{Mg}^{2+}$  (Mg/K isotherm), according to Giggenbach (1988). The intersection of the two isotherms represents equilibrium conditions at this temperature. Samples plotting on the “K/100” axis have magnesium concentrations below detection limit (which vary from <0.1 to <1 mg/kg where reported). For other abbreviations, see Figure 4



## 4 | SYNTHETIC REVIEW OF GROUND AND SURFACE WATER HYDROCHEMICAL DATA

### 4.1 | Chemical composition of geothermal fluids

#### 4.1.1 | Major ions

Geothermal fluids from exploration wells (Figure 3a) or hot springs (Figure 3b) can be classified into two broad groups according to their chemistry. In the Main Ethiopian Rift (MER), geothermal waters are mostly of sodium-alkalinity type (i.e., typically >30% Na and >20% alkalinity) with moderate total dissolved solids (TDS <10,000 mg/L). In the Afar Depression the dominant water type is sodium-chloride (typically 30–45% Na and 35–50% Cl) and the fluids have higher TDS values, especially in the Danakil Depression (2,000–53,000 mg/L) and Dallol (12,000–430,000 mg/L). The transition zone between these two broad fluid types in the area between Dofan-Fantale and Meteka (Figure 3b) is dominated by Na-mixed waters (typically 40–50% Na). This spatial distribution was first documented through hot springs (UNDP, 1973) and later confirmed with geothermal exploration wells, where the following water types are identified: Na-HCO<sub>3</sub> for Corbetti, Na-Cl for Tendaho, and Na-dominant for Aluto-Langano (Figure 3a). At Aluto-Langano, about 87% of the samples are Na-alkalinity, with the remainder of Na-Cl or Na-mixed type. Na-mixed waters have high concentrations of both alkalinity and chloride (Cl<sup>-</sup>) and low concentrations of sulfate (SO<sub>4</sub><sup>2-</sup>). Compared to hot springs in the region, the presence of high chloride concentrations in geothermal well samples suggests minimal mixing with shallow groundwater (Pürschel et al., 2013).

The distinct compositional difference between MER and Afar Depression waters is further demonstrated by an anion trilinear plot (Giggenbach, 1988). In Figure 4a, geothermal well fluids from Tendaho cluster near the “mature waters” zone (Cl apex), whereas well fluids from Aluto-Langano and Corbetti are “peripheral waters” ( $\sum\text{CO}_3$  apex). In Figure 4b, hot springs from the Afar Depression occur in the Cl-dominated upper segment of the diagram, with waters from Dallol and the Danakil Depression plotting within the “mature waters” zone. Meteka hot springs form two clusters (Gizaw, 1996) between the Cl and  $\sum\text{CO}_3$  dominated water extremes, with the latter group indicating “peripheral waters.” Dofan hot springs plot between these two clusters (Beyene, 2000), whereas Fantale hot springs plot in the “peripheral waters” zone.

Giggenbach (1988) also produced a cation trilinear plot to evaluate water–rock equilibration conditions for the Na–K–Mg system (Figure 5). This plot indicates the degree of chemical equilibrium between reservoir fluids and the host reservoir lithology, with immature waters indicating comparatively little water–rock interaction, and can be used to project reservoir temperatures by calculating and plotting lines of equal temperature known as isotherms.

Geothermal fluids in Tendaho have not yet reached full equilibrium with their host rocks, whereas Aluto-Langano waters are close to equilibrium (especially LA-4 and LA-8; Figure 5a). Although the composition of geothermal fluids in Tendaho shows some variability, all the points cluster along the Na/K isotherm of 270°C for TD-5 and close to 245°C for TD-6 (Figure 5a), suggesting that the geothermal reservoir has reached equilibrium with respect to the Na/K isotherm. Samples from Aluto-Langano with magnesium concentrations above detection limit also cluster along specific Na/K isotherms (LA-3—310°C, LA-4—255°C, LA-6—325°C, and LA-8—265°C). These temperatures are similar to reported downhole temperatures (Endeshaw, 1988; Gizaw, 1993, 1996, 2008; Pürschel et al., 2013; Teklemariam & Beyene, 2001, 2002). Aluto-Langano TGW samples produce isotherms of 175–225°C and Corbetti TGWs indicate a temperature of 200°C or less. Some outliers plot above the equilibrium line due to abnormally low potassium concentrations compared to the other samples (LA-8) and are therefore within the domain of fully equilibrated waters.

Most hot springs plot within the immature section of the Na–K–Mg trilinear plot, suggesting either lower reservoir temperatures or mixing with shallow groundwaters (Figure 5b). A few springs near Corbetti, Aluto-Langano, Abaya, and Tendaho geothermal fields are close to the equilibrium line or within the domain of fully equilibrated waters. Some hot springs are partially equilibrated (e.g., Dofan) contradicting observations made by Beyene (2000), which were based on an erroneous Na–K–Mg diagram. Similar to fluids from geothermal wells, partially and fully equilibrated hot spring waters cluster along specific Na/K isotherms, for example, 200°C for Tendaho and 180°C for Dofan-Fantale (Pürschel et al., 2013). Results also suggest that some hot springs in the Corbetti geothermal field correlate with equilibration at a lower temperature (90°C). The remainder are immature waters.



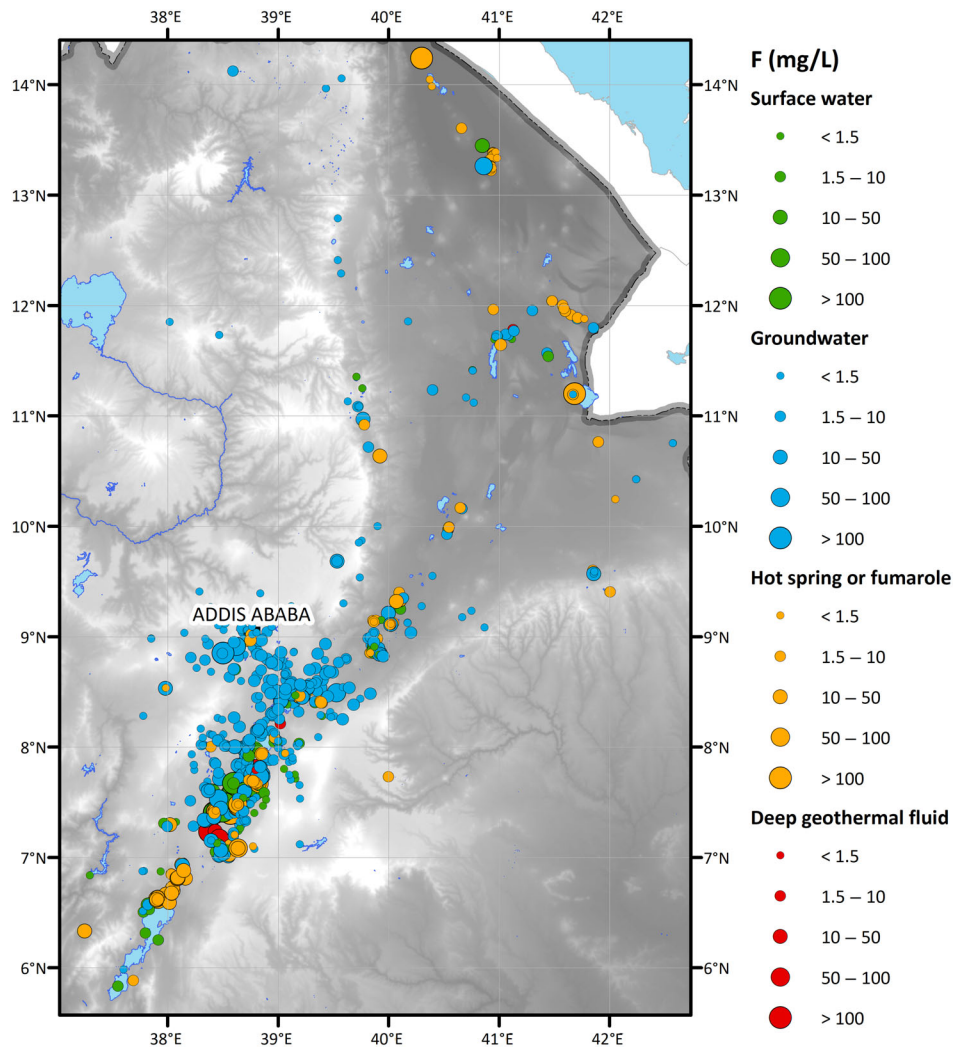
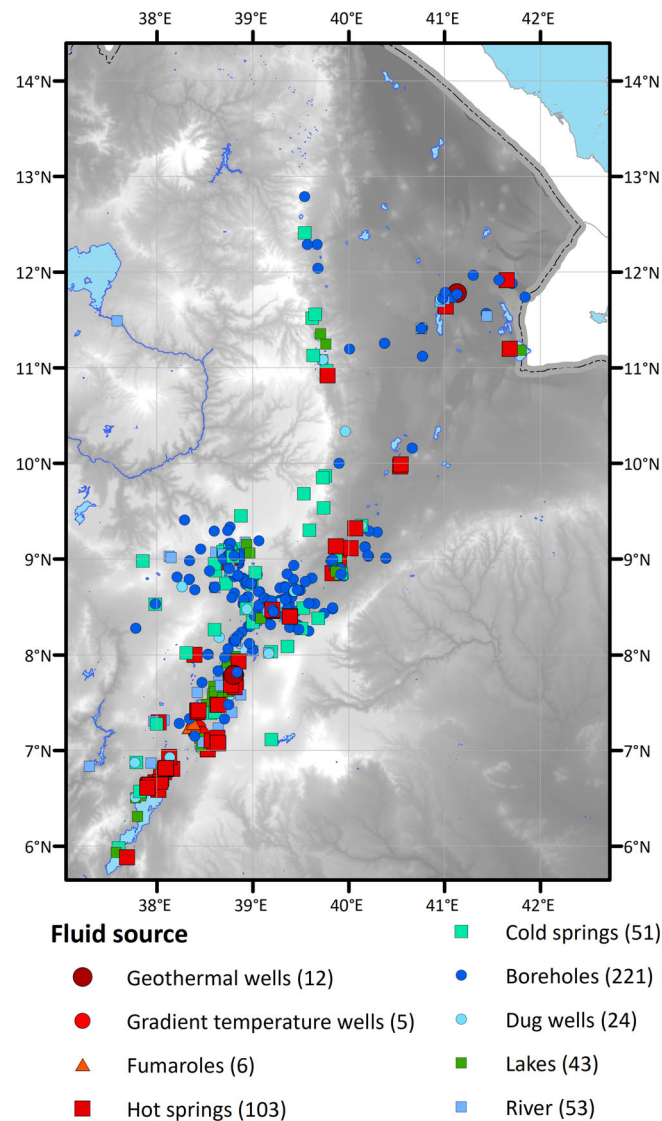


FIGURE 6 Distribution and concentration of fluoride for each water type. Background elements as per Figure 2

Hot springs from Dallol and the Danakil Depression appear to be mature in the anion trilinear plot (Figure 4b) but only partly equilibrated in the cation plot (Figure 5b). This apparent contradiction is related to the atypical geochemistry of the fluids (especially at Dallol) due to the dissolution of evaporites which alters their chemical composition (UNDP, 1973). Initially, Na-HCO<sub>3</sub> type geothermal fluids from the MER were believed to result from mixing between fluids of deep origin and shallower bicarbonate waters (UNDP, 1973). Gizaw (1996) noted the wide divergence in the igneous country rock between these regions (felsic in the MER and mafic in the Afar Depression) and concluded that the different chemical signatures result from water-rock interactions with different lithologies. The presence of bicarbonate in MER fluids is attributed to silicate dissolution by CO<sub>2</sub>.

#### 4.1.2 | Minor and trace elements

Other minor or trace elements of significance to geothermal fluids are silica and fluoride. Both have concentrations which are generally higher in deep geothermal waters (i.e., from wells) than from hot springs. Silica can be sensitive to sampling and storage conditions as shown by Teklemariam and Beyene (2002), who report different values from field and lab analyses. Fluoride concentrations also vary significantly in their spatial distribution (Figure 6) with higher concentrations in the MER (up to 180 mg/L in one of Corbetti TGWs) than in the Afar Depression (<10 mg/L except in Dallol). Fluoride in the geothermal fluids comes from magmatic contribution at depth coupled with chemical

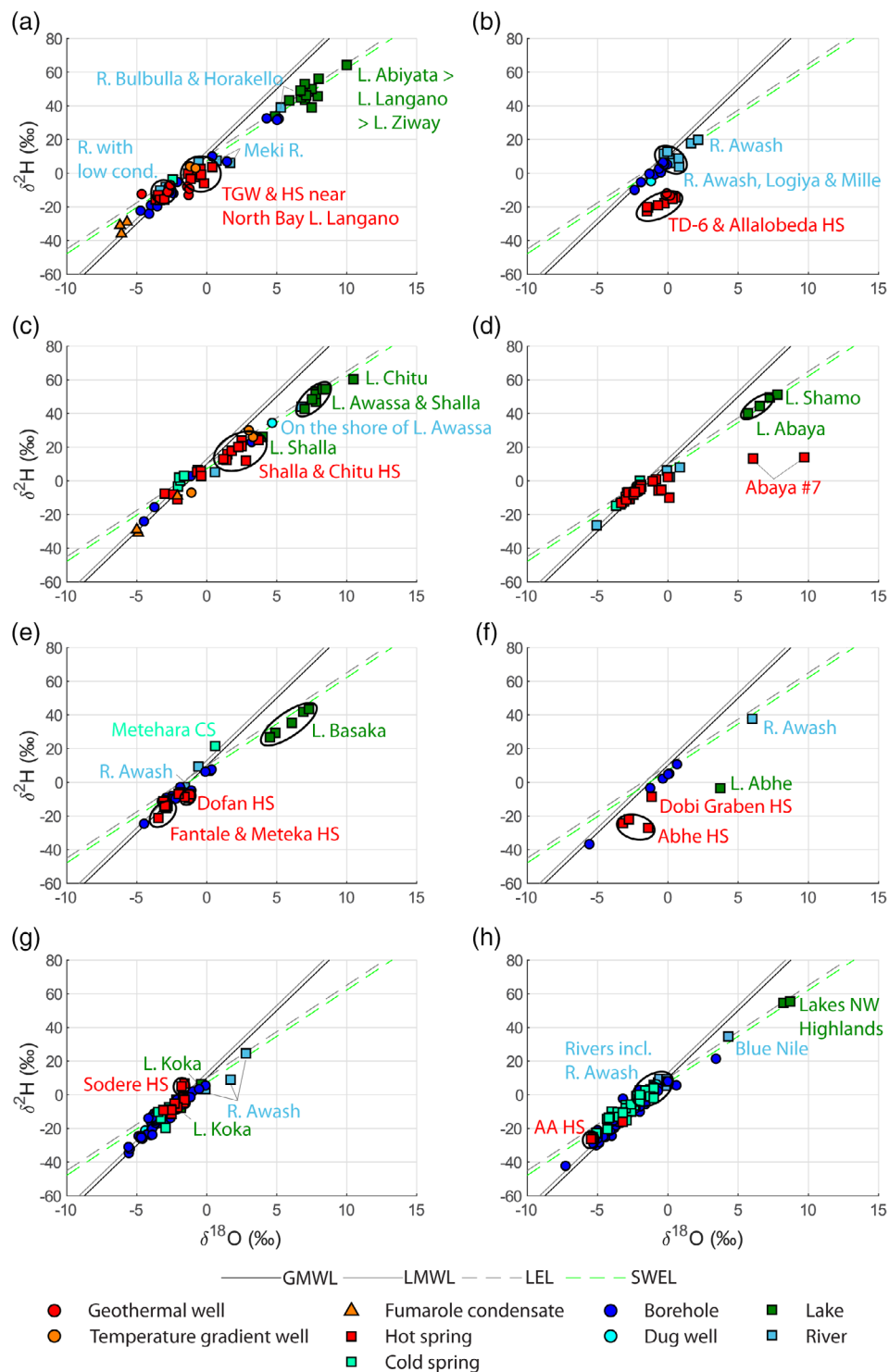


**FIGURE 7** Distribution of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope data as a function of fluid source. The bracketed values indicate the total number of measurements for each source. These totals include both single locality measurements and features that were sampled multiple times

weathering and dissolution (Gizaw, 1996). Similar to bicarbonates, fluoride concentrations are controlled by the composition of the host lithology, with felsic rocks generating higher fluoride contents (Alemayehu, 2000).

## 4.2 | Chemical composition of ground and surface waters

The spatial distribution of water types in groundwater from boreholes, cold springs, and dug wells reflect that of the geothermal fluids (Figure 3c). Na-Cl type and high TDS values are found in the Afar Depression and Na-alkalinity type are mainly located in the MER. Waters from the MER have varying TDS contents, reflecting different residence times (Alemayehu, 2000). In the Highlands (lighter shade of gray), Ca-alkalinity water type is dominant and TDS values are typically <1000 mg/L (Figure 3c). The distribution of the different water types between boreholes and dug well samples is similar although the classification between these two groups is uncertain. The proportion of Na-Cl water type is significantly higher for cold spring samples and may indicate mixing with deeper groundwater or geothermal fluids (Alemayehu, 2000; Gizaw, 1996). Fluoride concentrations in groundwater (Figure 6) are often higher than WHO's recommended of 1.5 mg/L limit (WHO, 2017).



**FIGURE 8**  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope data as a function of fluid source for the following geothermal areas: (a) Aluto-Langano; (b) Tendaho; (c) Corbetti; (d) Abaya; (e) Dofan, Fantale and Meteka; (f) Abhe and Dobi Graben; (g) Remaining Rift Valley; (h) Outside Rift Valley (Highlands). GMWL: Global Meteoric Water Line as defined by Craig (1961); LMWL: Local Meteoric Water Line; LEL: Local Evaporation Line; and SWEL: Surface Water Evaporation Line (based on compiled data). The LMWL and LEL for Ethiopia were calculated using available data in the Global Network of Isotopes in Precipitation (GNIP) database (IAEA/WMO, 2019)

Surface water samples are mostly Ca- or Na-alkalinity type and largely reflect the signature of groundwaters. Lakes are mostly Na-alkalinity water type whereas river samples are a mixture of both types (Figure 3d). The predominance of sodium in surface and groundwater originates from the weathering of felsic rocks (Abiye, 2008).

Among the lakes, notable exceptions are freshwater bodies located in the Highlands, such as Lake Tana ( $\text{Ca-HCO}_3$ ), Lakes Haiq, and Arbido ( $\text{Mg-HCO}_3$ ), and the Bishoftu lakes just southeast of Addis Ababa (mixed water types with TDS values ranging from 300 to 5600 mg/L). Lake Afrera to the north of the Afar Depression is of regionally typical Na-Cl type but with a supersaline TDS of 143,000 mg/L. A lakelet 15 km to the NNW is of the same water type but a much lower TDS of 1600 mg/L. Lakes of Na-alkalinity water type have variable TDS values ranging from freshwater (e.g., Abaya, Awassa, Chamo, Gamari, Koka, and Ziway) to brackish (e.g., Beseka, Debhile, and Langano) and saline (e.g., Abijata, Chitu, and Shalla). Lake salinity concentrations are reliant on the balance between inflow and outflow conditions (Gizaw, 1996). For example, Lake Awassa is a freshwater lake within a limited drainage, or endorheic, basin. Its freshness is guaranteed by some subterranean outflow (Abiye, 2008; Darling et al., 1996), which ensures constant movement and replenishment of lake water and mitigates the effects of evaporation.

Rivers generally have TDS values lower than 500 mg/L. The Horakello River flowing from Lake Langano to Lake Abijata has a similar chemistry to Lake Langano with TDS values above 1000 mg/L and elevated fluoride concentrations ( $>15$  mg/L) compared to other rivers which generally have concentrations  $<3$  mg/L. Lake fluoride concentrations increase with salinity ( $>100$  mg/L in Abijata, Chitu, and Shalla) due to a combination of low calcium concentrations ( $<5$  mg/L), preventing the precipitation of calcium fluoride ( $\text{CaF}_2$ ), and evaporation (Gizaw, 1996).

### 4.3 | Isotopic composition of Ethiopian waters

The spatial distribution of the sampling points for  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  isotope data is shown in Figure 7. Under two-phase conditions, the heavier stable isotopes ( $^{18}\text{O}$  and  $^2\text{H}$ ) preferentially partition into the liquid phase and lighter stable isotopes ( $^{16}\text{O}$  and  $^1\text{H}$ ) partition into the vapor phase (Haizlip, 2016). Natural variation of isotopic signatures can be used to determine water source and subsequent alteration processes. The origin of Ethiopian geothermal waters is predominantly from local meteoric water (Beyene, 2000; Haile & Abiye, 2012; Teclu, 2003, 2006). A generally linear relationship exists between  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  called the global meteoric water line (GMWL; Craig, 1961). Deviations in the stable isotope composition from this line may indicate processes such as: (1) increasing  $\delta^{18}\text{O}$  (enrichment) but little change in  $\delta^2\text{H}$  compared to meteoric waters, evidencing water-rock interactions in excess of  $150^\circ\text{C}$  (Craig, 1963; Kato, 2000); (2) mixing with other water and fluids resulting in shifts for both  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$ ; or (3) evaporation or boiling and precipitation or condensation producing isotopically depleted steam and enriched residual water (Haizlip, 2016). Isotopic investigations have demonstrated the presence of  $\delta^{18}\text{O}$  enrichment in waters believed to be from a vapor-dominated section of a geothermal reservoir (Montcoudiol et al., 2019), suggesting that such deviations can be used to help identify high enthalpy zones within geothermal prospects.

Figure 8 plots isotopic data with respect to meteoric and evaporation lines. Most of the samples lie close to the Local Meteoric Water Line (LMWL) which is defined using data from the Global Network of Isotopes in Precipitation (GNIP) database (IAEA/WMO, 2019). This is the case for all samples from cold springs, most samples from boreholes and dug wells, and some river samples. These samples are unaffected by evaporation processes and reflect the dominance of meteoric recharge (Ayenew et al., 2008; Scripps Institute of Oceanography, 1977). Their isotope signature is depleted in comparison to the rain weighted mean ( $\delta^{18}\text{O}$ :  $-1.3\text{‰}$ ;  $\delta^2\text{H}$ :  $+3\text{‰}$ ), potentially indicating recharge during cooler periods. Many hot springs also plot along the LMWL, indicating rapid circulation of moderately heated meteoric water (Scripps Institute of Oceanography, 1977).

All lake and deviating river and borehole samples are closely correlated with the Local Evaporation Line (LEL) or the Surface Water Evaporation Line (SWEL), defined using the compiled data within this review. The observed enrichment of these samples is attributed to comparatively large evaporative losses in relation to precipitation and lake inflow (Scripps Institute of Oceanography, 1977). The influence of seasonal rainfall and evaporation on isotope values is amply discussed by Scripps Institute of Oceanography (1977) and Seifu Kebede and Travi (2012).

Publicly available isotope data from subsurface geothermal exploration activities are limited. These comprise of 12 samples from deep geothermal wells (6 samples from 4 different wells in Aluto-Langano and 6 samples from one well in Tendaho) and 5 samples from TGWs (a single sample from 3 Corbetti wells and 2 Aluto-Langano wells). Meaningful interpretation of isotopic behavior in each of these geothermal systems is difficult due to the lack of spatial and temporal reservoir data. However, when coupled with rain and surface and ground water data (including hot and cooler springs), they can provide some initial insights into the potential hydrogeological behavior of these prospects.

In Aluto-Langano (Figure 8a), isotopic signatures from geothermal wells have  $\delta^2\text{H}$  values of  $-13$  to  $-7\text{‰}$  and  $\delta^{18}\text{O}$  values of  $-4.7$  to  $-1.2\text{‰}$ , which may reflect variability of reservoir conditions or some degree of water-rock interaction.

They are depleted in deuterium compared to the rain-weighted mean, suggesting boiling and/or reservoir recharge during comparatively cool seasonal periods (Truesdell et al., 1977). Local hot springs form two distinct groups,  $\delta^2\text{H}$  values of the first match the geothermal wells, further supporting recharge during cooler periods. The second group is all from near North Bay, Lake Langano, and cluster close to the rain-weighted mean with local TGWs, indicating a recent meteoric origin and perhaps that TGWs encounter the same geothermal groundwaters that supply these springs.

The isotopic signature of Tendaho geothermal well TD-6 (Figure 8b) was consistent over a 6-week sampling period (Ali, 2005). Samples from the Allalobeda hot springs, located 20 km southwest of well TD-6, produced similar results (Figure 8b). All these points cluster together away from the LMWL, toward positive values of oxygen-18 (+3‰ from LMWL), suggesting high-temperature water–rock interactions. Tracing back toward the GMWL/LMWL, candidate parent fluid isotope values are lighter than the rain weighted mean, evidencing an isotopically depleted palaeowater (Scripps Institute of Oceanography, 1977).

In the Corbetti geothermal field, hot springs form three clusters (Figure 8c). Two of these, from Wondo Genet and Kenteri springs to the east of Lake Awassa, have  $\delta^{18}\text{O}$  and  $\delta^2\text{H}$  values like those observed in Aluto-Langano. Springs with positive values plot along the LEL together with two TGW samples. This cluster consists of hot springs located on the shores of lakes Shalla and Chitu, and are believed to be a mixture of ground and lake water (Scripps Institute of Oceanography, 1977).

Most hot springs near Lake Abaya lie on the LMWL (Figure 8d). Some show evidence of oxygen isotopic shift of up to c. +2‰ and may therefore indicate source temperatures in excess of 150°C. Abaya #7 is a perched acid spring (i.e., not connected to a deeper geothermal reservoir) demonstrating a significant shift (+5 to 9‰) toward higher oxygen-18 values, attributed to decreased atmospheric water vapor interaction during high-temperature kinetic evaporation in the near-subsurface environment (Scripps Institute of Oceanography, 1977).

Abhe hot springs (Figure 8f) show a slight shift toward higher oxygen-18 values (by +1.5 to 4‰), so may hint at water-rock interaction of a strongly isotopically depleted parent palaeowater. Lake Abhe, which straddles the Ethiopia-Djibouti border (Figure 3), has an unusual isotope value in comparison to other lakes (Figure 8f), but this is likely due to an error in the data source publication (Ayenew et al., 2008). It differs greatly from values reported in the literature by Houssein et al. (2014) for Djibouti samples, cited by both Chandrasekharam et al. (2018) and Awaleh et al. (2015). Values reported by these authors plot near the evaporation line, in the vicinity of the Awash River (Figure 8f).

The hot spring sample from the Dobi Graben (Figure 8f) shows little evidence of  $\delta^{18}\text{O}$  enrichment and has a higher  $\delta^2\text{H}$  value (−8.5‰) in comparison to results from other geothermal fluids at Tendaho (average −16‰) and Abhe (average −24.5‰), indicating a different water source, more contemporaneous with modern precipitation, in this part of the Afar Depression.

## 5 | DISCUSSION AND OUTCOMES

### 5.1 | Geothermal prospects in Ethiopia

With an estimated total national resource >10 GW (Kebede et al., 2020), Ethiopia has enormous potential for generation of low-carbon electricity from geothermal energy. Twenty-five geothermal prospects suitable for power generation have so far been identified, though most are at a nascent stage of development. Delivery efforts are currently focused on the Aluto-Langano (the first and only site that was inaugurated in 1998 and intermittently producing power since 2002), Tendaho, Corbetti, Tulu Moye, and Abaya prospects. If all goes according to reported plans, these sites will ultimately provide >1 GW of electricity generation capacity, which given latest total power capacity (4.4 GW) and population electricity access (44%) figures, may provide power to a further 10% of the population (equivalent to c. 11 million people). If successfully delivered, this would represent a significant disruption of an Ethiopian power mix which overwhelmingly depends on hydropower (World Bank, 2018) and has to deal with the dual challenge of rapid population growth and persistent drought conditions driven by global climate change. By relieving the burden on hydropower, geothermal exploitation could provide extra energy system resilience and may allow for better energy access for rural populations in the vicinity of geothermal prospects. Ethiopia also has highly competitive multi-sector demand for its limited water resources. To ensure responsible development, geothermal exploitation should be mindful of pre-existing stresses on surface and ground water resources and do its utmost to understand geothermal reservoir fluid origins and how prospect reservoirs are connected to wider



critical-waterbody-hosting hydrogeological systems. Such issues can be assessed using hydrochemical investigations of geothermal, ground, and surface waters.

## 5.2 | Development of hydrochemical database

We conducted a review of journal papers and reports accessible in the public domain to establish the level of hydrochemical information freely available for water resources in Ethiopia. As a result, information from 98 separate studies was synthesized to create a database of Ethiopian water resource quality. In total, our database contains 966 hydrochemical, 523 isotopic, and 445 gas records from geothermal fluids (including geothermal wells, TGWs, hot springs, and fumarole condensates), nongeothermal groundwaters (including shallow boreholes, cold springs, and dug wells), and surface waters (including lakes and rivers). Each record is unique, either in spatial location (i.e., different sites) or temporal resolution (i.e., different samples from the same site taken at different time periods). Hydrochemical data had to pass quality control criteria to be included within our review, including a well-defined spatial location, a cation-anion balance of  $\pm 10\%$ , and a clear sample fluid source. Isotopic and gas data had to have location and fluid origin to be included. The database was used to assess patterns in fluid chemistry- despite the presence of information gaps it was possible to draw out some broad interpretations with respect to geothermal resources.

## 5.3 | General overview of pooled database information

### 5.3.1 | Regional trends in water type

Ethiopia is dominated by two major geothermal water types. In the Main Ethiopian Rift, waters are sodium-alkalinity dominated due to mixing with shallower, fresher groundwater, or interaction with  $\text{CO}_2$ -rich volcanic gases within felsic host lithologies. Following the rift to the NE and into the Afar Depression, geothermal waters are sodium-chloride-rich brines that have seen little to no mixing with fresher waters during their ascent through mafic host lithologies. In the transition zone between these two regions, waters are sodium-mixed and partially equilibrated with host rock geochemistry.

### 5.3.2 | Resource temperatures

Plotting data onto anion and cation trilinear plots (Giggenbach, 1988) allows for further insights into the maturity of waters, degree of water-rock interaction with host lithology and likely reservoir temperatures.

Afar Depression Tendaho samples from two separate wells indicate mature, highly-concentrated Cl-brines that are partially chemically equilibrated with surrounding rock. Sodium-potassium (Na/K) isotherms for these waters suggest reservoir temperatures in the region of 245–270°C, in close agreement with measured bottom hole temperatures (Kebede et al., 2020). Hot springs in the area cluster along the 200°C isotherm, suggesting mixing of vertically migrating thermal waters with cooler near or at-surface waters.

MER Aluto-Langano and Corbetti samples are carbonate-dominated peripheral waters, with some samples (LA-4 and LA-8) close to full chemical equilibrium with the reservoir mineral matrix, suggesting a longer residence time than Tendaho waters. Na/K isotherms for Aluto-Langano geothermal wells imply a reservoir temperature from 255 to 325°C, similar to reported downhole temperatures (Endeshaw, 1988; Gizaw, 1993, 1996, 2008; Pürschel et al., 2013; Teklemariam & Beyene, 2001, 2002). Aluto-Langano TGWs produce significantly lower Na/K isotherms of 175–225°C, likely due to resident groundwater mixing with cooler, more recent meteoric percolation.

The only data available to produce isotherms for Corbetti comes from TGWs (200°C or less) and hot springs (90–200°C). The temperature disparity between well types in Aluto-Langano and sample types in Tendaho serves as a note of caution for extrapolating deeper reservoir temperatures from TGW or hot spring data at Corbetti or any other geothermal prospect under investigation.

### 5.3.3 | Further insights from isotopic data

Stable isotopes of O and H are useful tools for determining the origins of geothermal waters and their connection to the wider hydrosphere. Unfortunately, they have so far been sparingly used in the assessment of Ethiopian geothermal reservoirs but combining geothermal well with additional surface and groundwater data allows for further insight into water sources and interactions. Geothermal waters across Ethiopia evidence a range of recharge ages. Deep geothermal wells are isotopically depleted in comparison to the rain weighted mean, suggesting an ancient palaeowater source for mature brines (Tendaho) or recharge during recent cool seasonal periods for more peripheral waters (Aluto-Langano). Hot springs show a wider range of values, including more modern meteoric values and values synonymous with ingress and mixing of local isotopically enriched lake waters. Evidence of oxygen-18 isotopic enrichment occurs at several geothermal sites, with the most consistent and convincing indications of high temperature water-rock isotopic exchange in Tendaho wells and hot springs, providing added confidence of a high enthalpy geothermal resource at this prospect.

### 5.3.4 | Potential environmental impacts

The most studied element by far is fluoride (Table 2) due to its direct and obvious impact on human health. Our database demonstrates comparatively elevated fluoride concentrations in MER waters (Figure 6). A more extensive review of fluoride in Ethiopian ground and surface waters can be found in Reimann et al. (2003) and Tekle-Haimanot et al. (2006). These studies accessed a nonpublicly available database of 1,438 well and spring tests collated by regional divisions of the Ethiopian Ministry of Water Resource. Their findings showed that Rift Valley waters had a far greater proportion (41.2%) than non-Rift Valley waters (3.5%) of F concentrations in excess of the World Health Organization (WHO) recommended drinking water limit of 1.5 mg/L (WHO, 2017). Concerningly, 25.3% of Rift Valley waters were either within the concentration zone considered to result in skeletal (3–6 mg/L) or crippling (>10 mg/L) fluorosis with prolonged water consumption. The correspondence of high fluoride concentrations with geothermal fluids means that operational exploitation must take care to avoid contamination of potable water resources.

## 5.4 | Implications for management of geothermal fluids

Geothermal waters can contain challenging chemistries for effective utilization in power generation. Temperature, pressure, and chemical property alterations occur when fluids are extracted from subsurface reservoirs and brought to the surface. Depending on composition, solute concentration, and gas content, geothermal fluids can clog or corrode engineering infrastructure (Allahviridizadeh, 2020; Andritsos et al., 2010; Frick et al., 2011; Vallejo Vitaller et al., 2020).

When geothermal fluid migrates to the surface it experiences rapid temperature and pressure decrease, resulting in degassing (including rising pH where CO<sub>2</sub> is released) and oversaturation of potential scaling compounds. Precipitation kinetics for most scaling species is typically slow, but the presence of solid surfaces and microorganisms can encourage rapid fouling (Frick et al., 2011). The most common types of scaling compounds for geothermal systems include calcium carbonate (predominantly as calcite, the least soluble polymorph) and silica. Despite low calcium concentrations (typically <1 mg/L), significant calcite scaling has been found in Aluto-Langano production well LA-4 as a result of liquid flashing in the wellbore (Melaku & Thomasson, 2010). Injection of phosphorous-containing compounds (such as phosphonate) upstream of the flash-point could provide an effective method of calcite scale dispersion and growth inhibition (Andritsos et al., 2010). All four of the current production wells at this prospect are oversaturated with respect to quartz (Teklemariam & Beyene, 2001). Silica deposition tends to pose a greater challenge in managing high temperature geothermal fluids due to potential nucleation throughout geothermal installations and blockage of reinjection formation pore space by silica colloids (Andritsos et al., 2010). Silica scaling has typically been addressed using progressive fluid acidification, though promising efforts have been made to develop alternative organic inhibition strategies (Gallup & Barcelon, 2005; Ikeda & Ueda, 2017).

Corrosion is driven by electrochemical or chemical reactions with certain concentrated species in geothermal fluids and can lead to the spontaneous degradation of construction materials (Vallejo Vitaller et al., 2020). High concentrations of chloride can be problematic for ferrous-based metals, such as stainless and carbon steel, but the greatest risk of corrosion comes from dissolved acidic gasses (Allahviridizadeh, 2020). Two of the most commonly encountered are CO<sub>2</sub> and H<sub>2</sub>S (the source of the rotten egg odor synonymous with many geothermal manifestations), which when dissolved

lower the pH (i.e., increase concentration of aggressive  $H^+$  ions) of water to form highly corrosive compounds such as carbonic ( $H_2CO_3$ ) and sulfuric ( $H_2SO_4$ ) acid. Fluid gas concentrations reported for Tendaho are a maximum of 1 wt% (Ali, 2005; Pasqua et al., 2014), indicating little risk of acid gas material degradation. Corrosion has been highlighted as an operational issue at Aluto-Langano (Alemayehu & Bogale, 2018; Gebregiorgis, 2007; Tassew, 2010), particularly with respect to wellhead valve stems and steam turbine blades (Melaku & Thomasson, 2010). Little information regarding culprit chemical compounds is available, but indications of corrosive steam (Gebregiorgis, 2007; Tassew, 2015) coupled to noted presence of both  $CO_2$  (6.3 wt%) and  $H_2S$  (0.05 to 1.5 wt%) (Geremew, 2012) suggests that more resistant nickel or titanium-based alloys (Allahvirdizadeh, 2020) should be incorporated into future engineering works. Geothermal fluids rarely contain dissolved oxygen- this gas acts as an oxidizing agent and corrosion accelerator (Vallejo Vitaller et al., 2020), so any enforced maintenance related downtime of operations should be kept as short as possible to minimize the risk of oxygen ingress into power generation and fluid reinjection infrastructure.

## 5.5 | Data limitations and need for detailed baseline surveys

Learnings from our water quality database are discussed above, but perhaps the main finding from this review is that there is a real paucity of publicly available baseline studies for the areas surrounding geothermal prospects in Ethiopia. The available information does not match up with the progress being made to develop various geothermal prospects across the country- so there is likely to be a significant volume of hydrochemical data that has not been placed in the public domain. Though much of this may be considered as proprietary information, we believe there is much to be gained for understanding of geothermal system behavior and the social and environmental responsibility of geothermal development should thus far unpublished data be released to complement our database.

Most published investigations take the spatial component (sampling in different places) into account but rarely apply anything like the same rigor with respect to capturing time-series information (e.g., to help measure any seasonal variation). Though it must be recognized that each study was likely bound by project specific limitations (such as budget and time), there is also an issue with a lack of systematic sampling of essential (alkalinity) and highly desirable (trace elements and isotopes) parameters. Alkalinity measurement is required for cation-anion balance calculation, a key check on the quality control of sampling, preservation, and hydrochemical analysis of water; however, many reported alkalinity values did not confirm chemical species or measurement units. There have been a lack of investigations into potentially toxic trace elements, such as lead, which has been observed at elevated levels in thermal springs in the MER but has an ambiguous, possibly anthropogenic source (Alemayehu, 2000). Better understanding of trace elements is needed for further insight into geothermal reservoir processes and for identification of candidate species not commonly present in surface or near-surface waters to track any geothermal related contamination of these environments.

Without a proper baseline, it is a challenge to assess the sustainability and environmental impact of geothermal exploitation. To achieve a robust baseline survey, studies should look to collect at least 12 consecutive monthly samples from each point of interest for physicochemical, ionic concentration and, where possible, water isotopes and trace elements. This serves two main purposes: (1) ensure capture of underlying natural or anthropogenically influenced variations in parameters; (2) enable confident comparison with future sampling campaigns during construction and active operation of geothermal power plants. By coupling baseline and ongoing data collection, it is easier to determine important factors such as mixing between geothermal reservoir fluids and cooler waters, evolution of water-rock interactions, and possible release of toxic elements into potable water resources (Heasler et al., 2009).

## 6 | CONCLUSIONS AND RECOMMENDATIONS

Our high-level assessment of hydrochemical and isotopic data from scientific journals and publicly available reports emphasizes their usefulness for the characterization of geothermal resources in Ethiopia. Considering the comparatively low cost of hydrochemical investigations, within the context of geothermal powerplant delivery, and the important information these can deliver with respect to subsurface conditions and infrastructure considerations, prospective operators should invest in this area to ensure effective and sustainable energy production. Care should also be taken to recognize geothermal fluid communication with wider hydrological systems in order to avoid contamination of important already-stressed water resources with potentially toxic concentrations of fluoride or dissolved trace elements.

There is a lack of publicly available baseline hydrochemical data for Ethiopia. Further information exists in private and proprietary reports, but the volume and thoroughness of these additional efforts is uncertain as it is currently unavailable for assessment by the scientific community. With the limited information currently available, it is difficult to perform adequate baselines for investigations into geothermal resource behavior and any potential environmental impacts resulting from their exploitation. Our review highlights the importance of the following topics for focused research efforts:

- Determination of natural (seasonal and climate change related) and anthropogenic (industrial and agricultural processes) hydrochemical variability to enable effective monitoring of geothermal energy development and production
- Elucidation of the interactions between thermal waters and cooler groundwaters to clarify the sources, movement and mixing behaviors of geothermal reservoirs
- Screening of geothermal fluid trace elements for assessment of scaling risks, possible economic mineral extraction, and potential use as tracers of environmental contamination
- Assessment of possible future impacts arising from geothermal energy exploitation on the water quality of adjacent surface and groundwater bodies

It is hoped that this review and accompanying database will act as a starting point to build a comprehensive geothermal resource baseline for Ethiopia to be further enriched by ongoing and future research efforts and already collected, but unpublished data. With geothermal development rapidly gathering pace to meet an ever growing national energy demand, we emphasize the need for comprehensive monitoring of geothermal prospects in Ethiopia prior to any attempt at power generation in order to guard against difficult operational conditions (such as those as found at Aluto-Langano) and unintended environmental impacts. We therefore encourage the release of findings from private companies and government agencies to benefit the scientific community, show greater transparency, and demonstrate clear social and environmental responsibility with respect to the development of geothermal resources in Ethiopia.

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## CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

## AUTHOR CONTRIBUTIONS

**Neil Burnside:** Conceptualization (lead); formal analysis (supporting); funding acquisition (lead); investigation (equal); methodology (equal); project administration (lead); resources (lead); supervision (equal); writing—original draft (equal); writing—review and editing (lead). **Nelly Montcoudiol:** Conceptualization (supporting); data curation (lead); formal analysis (lead); investigation (equal); methodology (equal); supervision (equal); visualization (lead); writing—original draft (equal); writing—review and editing (supporting). **Kerry Becker:** Data curation (supporting); formal analysis (supporting); investigation (supporting); writing—review and editing (supporting). **Elias Lewi:** Conceptualization (supporting); funding acquisition (supporting); investigation (equal); methodology (supporting); project administration (supporting); writing—original draft (supporting); writing—review and editing (supporting).

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the University of Strathclyde KnowledgeBase Research Information Portal at <https://doi.org/10.15129/68b5e36e-fc2f-47b8-b0a0-88ab6f9f0a21>.

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