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Groundwater in Ethiopia

Features, Numbers and Opportunities

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Chapter 2
Groundwater Occurrence in Regions and Basins

2.1 The Broad (Oligo-Miocene) Volcanic Plateau and Associated Shields

Geology and Stratigraphy

The broad volcanic plateau (Fig. 1.2) accounts for about 25 % of Ethiopian landmass. The Ethiopian volcanic plateau is a thick monotonous, rapidly erupted pile of locally deformed, flat lying basalts consisting of a number of volcanic centers with different magmatic character and with a large range of ages. The trap volcanics including the associated shield volcanoes cover an area at least 6×10^5 km^2 (around two-third surface of the country), and a total volume estimated to be at least 3.5×10^5 km^3 (Mohr 1983) and probably higher than 1.2×10^6 km^3 according to Rochette et al. (1998). Flat-topped hills and nearly horizontal lava flows is a common scene in the broad volcanic plateau. Topographic features of the basaltic plateau are vertical cliffs, waterfalls, V-shaped valleys, vertical and mushroom-like outcrops of columnar basalts, and step-like hill terraces. Interlayered with the flood basalts, particularly at upper stratigraphic levels, are felsic lavas and pyroclastic rocks of rhyolitic, or less commonly, trachytic compositions (Ayalew et al. 1999).

The traps are traversed by dykes. The width of dykes ranges from a few centimeters to about 6 m. The dykes act either as barriers or as conduits for flow of groundwater depending upon their nature as resistant to weathering or highly weathered and fractured. The densest network of dykes is noted in the Lake Tana Basin and the upper Tekeze watershed. The basal formation of the trap basalts is the most frequently cut by dykes.

According to the traditional classification of the Ethiopian flood basalts there are four different stratigraphic units all diachronous: from bottom to top, Ashangie (Eocene), Aiba (32-25), Alaji (32-15 Ma) and Termaber (30-13) (Mohr 1983; Mohr and Zanettin 1988). A more recent classification of the stratigraphy of the broad volcanic plateau put forwards four stratigraphic units (Fig. 2.1). These are (a) the basal basalt sequence forming gentle and rugged terrain corresponding to

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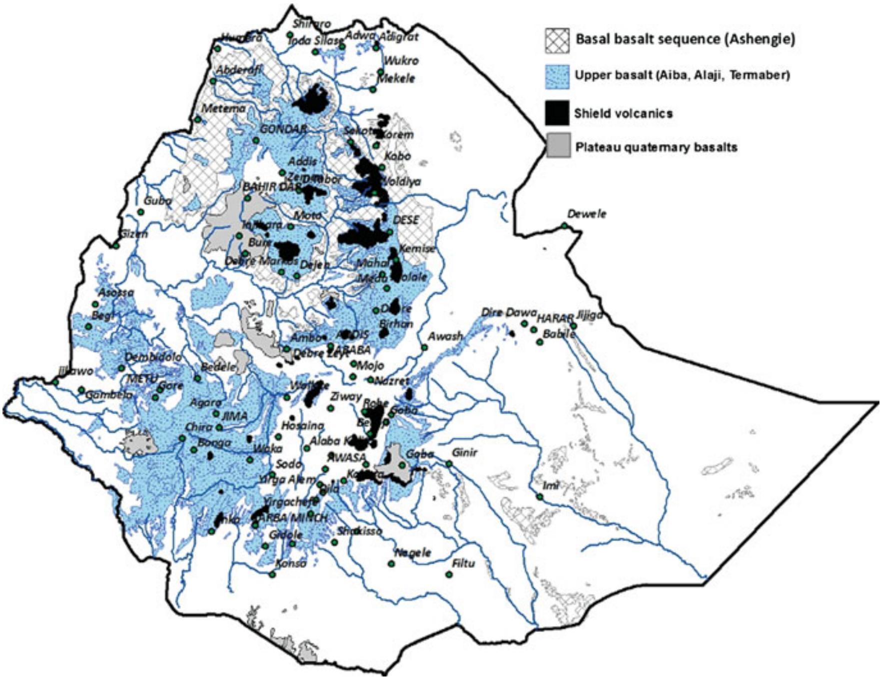


Fig. 2.1 Map showing the distribution of plateau flood basalts, prominent shield volcanics and associated central volcano related quaternary basalts

the Ashengie, (b) the upper basalt sequence forming the plateau proper corresponding to the Aiba-Alaji-Termaber sequences, (c) broad based shield volcanics caping the plateau and d) quaternary scorea basalts associated with the shields (Kieffer et al. 2004). Unlike the former classification which put the plateau basalt into four groups the new classification put the plateau basalt only into two categories. The whole volcanic sequence has been emplaced with no apparent development of paleosol and erosional surfaces (Rochette et al. 1998).[1]

The *Ashangie* is basaltic formation marked by its deep weathering, thin layering (<10 m), smooth topography and cross cutting sets of dykes. There are minor acid products (such as volcanic ash, rhyolites, and ignimbrites) in the Ashangie formation. Individual flows are discontinuous laterally and have irregular thicknesses. Intrusions of diabse and dykes are common in the Ashangie formation. In the north central sector extensive quartz and opal mineralization owing to paleothermal groundwater circulation has been noted. In most parts brecciated materials has been noted. The most extensive breccia has been observed in the Weleh valley south of Sekota (*see* Fig. 2.1 *for location*) area at the foot hill of the Amdework ridge. Acidic rocks are minor in the Ashangie formation (Fig. 2.2).

[1] For the upper part of the flood basalt volcanism a number of other names have been given in the literature including: Jima volcanics, Mekonnen basalts, Wolega basalts etc.

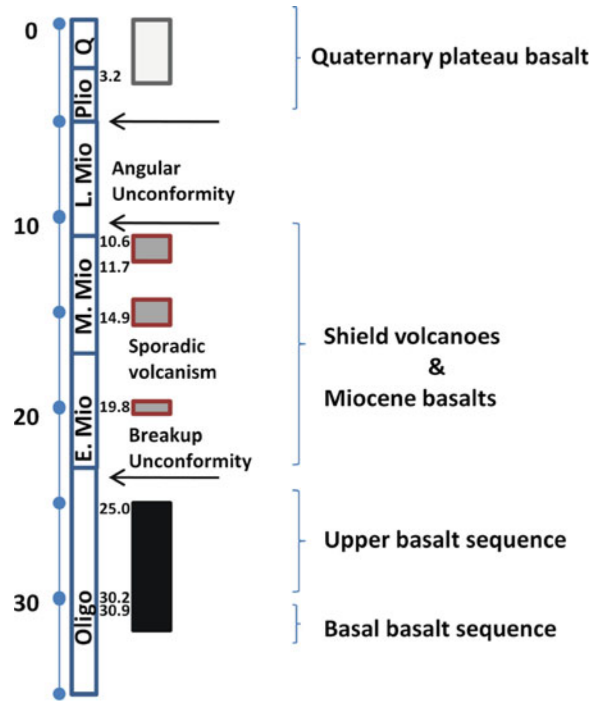


Fig. 2.2 Stratigraphy of the Trap basalts numbers are age in Ma

By contrast, the Aiba formation is a succession of massive cliffs corresponding to thick (10–50 m) basaltic flows (Rochette et al. 1998). The Aiba and Alaji formations are marked by their low degree of weathering, thick layering, and cliff forming topography.

Frequent lacustrine deposits have been marked in the Aiba formation as evidenced by lenses of diatomites and porcelain lithologies particularly surrounding the Sekota area. The Termaber formation is marked by its jointing, thick layering, cliff forming topography with flat tops.

Geomorphology

The volcanic terrain of Ethiopia comes in variety of landforms that is of significant importance to groundwater occurrence and movement. Table 2.1 shows list of landform features that can be observed in the volcanic provinces. The distinct landforms particularly the composite stratigraphy manifested by the flood basalt pile provides a rapid field based evidence to distinguish different stratigraphic/hydrostratigraphic units.

Table 2.1 Landform features associated with the broad Cenozoic basalts

Name	Volcanic landform
Monogenic landforms and fields	Continental flood basalts, Cinder or scoria cones, tuff cones and tuff rings Maars and diatremes, domes, lava flows and fields, ash flows and ignimbrite sheets, plains and plateaus
Polygenic volcanoes and calderas	Stratovolcanoes. Intermediate silicic multivent centers, calderas, volcano tectonic depression
Erosional landforms	Composite stratigraphy, flat topped plateau, volcanic plugs etc
Other landforms	Dykes, plugs, dolerite intrusions, faults, shield

Dykes are prominent landform features that play a role in concentrating groundwater flow and storing groundwaters. A detailed account of the role of Dykes in groundwater dynamics can be found from (Mege and Rango 2010).

Hydrogeology and Groundwater Occurrence

Four broad hydrogeologic units can be recognized for the entire volcanic province of the of Ethiopian Plateau. The recognition of the four hydrostratigraphic units is based on geomorphic manifestations (which in turn are the result of permeability of the lithologies and resistance to weathering), aquifer properties and mode of groundwater occurrence, groundwater flow and discharge. The contrast in geomorphic appearance of the various stratigraphic sequences of the plateau flood basalt is the manifestation of differences in erosion resistance which in turn is partly related to permeability structure of the formations (Fig. 2.1, Table 2.2). The four hydrostratigraphic units are:

1. **Basal sequence**: The gently undulating, rugged thinly bedded, brecciated, deeply weathered and low permeability[2] base of the flood basalts (traditionally called Ashangie basalts)
2. **Upper sequence**: The flat topped, cliff forming, thickly bedded scoriacious, slightly weathered, permeable and relatively higher productivity aquifers with some intercalations of acid rocks, capping the entire Ethiopian volcanic plateau. Traditionally this hydrostratigraphic unit is made of the Aiba, Termaber and Alaji formations. Other names have also been previously used including Jima volcanics, Wellega basalts, Mekonnnen basalts etc.
3. **Shields**: The morphologically prominent, shield volcanics made up of composite stratigraphy of volcanic materials (ashes, rhyolites, trachytes, basalts) occupying broad area. Typical hydrogeologic features are emergence of springs (some prolific) at various locations of shield volcanoes.

[2] In previous hydrogeological classification of Ethiopia (Chernet 1993) the Ashengie formation is considered as high productivity aquifers although evidence now show that the Ashengie basalts are the least productive aquifers compared to younger flood basalts and rift volcanics.

Table 2.2 Summary of geological and hydrogeologic framework of the volcanic aquifers associated with the board plateau of North western and eastern Ethiopia

Hydrostratigraphic unit	Geologic frameworks	Hydrogeologic framework
Basal Basalt sequence (Ashangie basalts)	Rugged topography, thinly bedded, with cross cutting dykes, deeply weathered, low permeability, dissected and irregular morphology, brecciated, reddish when deeply weathered, closer look at Ashangie formation may reveal presence of three zones-the lower gentle slope forming part, the middle more resistance layer and the upper gentle slope forming unit. The middle part when exposed by erosion may form locally extensive plateau which is normally rare in Ashangie formation (e.g. around Upper Tekeze plains around Lalibela and Belesa plain). More resistant layers are thin, the less resistance layers are mostly scoracious, several thin beds of clay soils are common in the Ashangie basalts, deformed and dipping in northern section up to 40°	Recharge takes place vertically from the overlying upper basalt, springs are rare, discharge takes as diffuse discharge to slopes and leading mostly to land sliding, cliff forming sub layers are more productive, contact between Lower basalt and upper basalt is characterized by discharge of springs, primary porosity and secondary porosity are highly sealed by secondary mineralization (calcite, zeolite, silica). Dykes crosscutting through the lower basalt are sites of groundwater convergence and discharge, Rugged topography does not allow extensive lateral size of the lower basalt, depressions within the rugged terrain are site of scree slope and groundwater discharge. At its base it is affected by mineralization filling the fractures, dykes and gabro-diabase intrusion. In several sectors the Ashangie basalts are brecciated. Field evidence show that the brecciate parts are characterized by lower permeability
Upper basalt sequence (Aiba, Alaji, Termaber)	Dual porosity, permeable, plateau and cliff forming, artesian, confined, Aiba formation contains intercalations of rhyolitic formations, Termaber forms or are associated with shield volcanics, uniform topography and flat topped, shows columnar jointing, mostly massif basalt but columnar jointed layers are common, Laterally the most extensive, layers of acidic rocks rhyolites and tuffs are common, paleosol layers may be visible between the contact of Ashangie and Aiba, flat laying	Recharge vertically through soil zone and fractures, discharge to wetlands, and spring at the margin of cliffs, water table varies between 0 and 250 m, yield generally up to 20 l/s, transmissivity in the order of, groundwater occurs in joints, fractures and scoracious layers, Pumping test analysis and well logs of Termaber formation show that, the aquifer system can be categorized as fractured aquifer where the dominant aquifer types are, confined-double porosity and single plane vertical aquifer. The double porosity aquifers are related to deeply drilled wells reflecting presence of large and narrow fracture systems with high permeability but lower storage capacity. Transmissivity varies between 0.5 and 1,400 m^2/day. The Ashangie formation has transmissivity ranging between 0.5 and 85 m^2/day

(continued)

Table 2.2 (continued)

Hydrostratigraphic unit	Geologic frameworks	Hydrogeologic framework
Shield volcanics	The basal diameters of the shields range from 50 to 100 km, radiate from peak and dip at an angle of 5°, compared to the flood basalts rhyolites and trachytes are more common	Recharge through fractures at highlands, discharge in form of springs. Prolific springs are common at the foot of the shields. The intercalation of volcanic ash along with basaltic flows allow a dual groundwater system whereby the ash act as storage medium and the fractured part act as flow conduits. Shields dominated by acid volcanic rocks show lower groundwater potential (e.g. in the Bale Massif)
Quaternary basalts	Related to volcanic centers, are mostly vesicular and scoracious, limited lateral extent, associated with shield volcanoes, The most extensive is found in the Lake Tana Basin	Highly productive, yield of wells reach 20 l/s, discharge takes place to rivers and fracture springs, Elsewhere in Ethiopia the quaternary volcanics are highly productive with dual porosity nature

4. **Quaternary basalt sequence**: Scoraceous basalt thinly bedded, central volcano related, highly productive quaternary basalt (occurring in head waters of Ghibe, Tepi, Lake Tana, Borena, Bale massif etc).

Vast area of the broad volcanic plateau is mainly covered by the *upper sequence*. It forms gently undulating plain that receives adequate rainfall and has moderate run-off resulting in good direct rainfall infiltration and formation of extensive and moderately productive or locally developed and highly productive *fissured* aquifers.

According to earliest investigation by USBR (1964) the *upper sequence* is fairly tight basaltic cap covered with slowly permeable clays, and scarcity of groundwater outcrop in the deep eroded canyons don not suggest the presence of large quantities of groundwater. The streams reflect only a very slow yield from groundwater, since their flow is almost entirely depleted soon after rains cease. However, the wells that have been dug and other observations indicate that generally an adequate water supply for groundwater sources for domestic use could be obtained in most locations within the basin.

Some of the older, more massive lavas, *the lower sequence*, can be practically impermeable (such as the Ashangie basalts in the Upper Tekeze Valley) as are the dykes, sills and plugs which intrude them, and the thick beds of younger air-fall ashes that may also be extensive in some volcanic areas. However, younger lavas (the Quaternary basalts and the Shield volcanoes) provide some of the most prolific springs (see Table 2.3).

Groundwater occurrence in the broad Ethiopian volcanic plateau is in phreatic condition in the weathered zone above the hard rock and in semi-confined to confided condition in the fissures, fractures, joints, cooling cracks, lava flow junctions and in the inter-trappean beds between successive lava flows, within the hard rock.

Table 2.3 Location and discharge of major springs associated with shied volcanoes

Springs associated with shields	Discharge (l/s)	Volcanic shield	E	N
Lomi Springs	120	Choke		
Jiga	400	Choke	372269	1040679
Sanka	70	Abune Yoseph	546289	1320128
Bure Baguna	30	Choke	288084	1184475
Bahir Timket	1,045	Debretabor	354299	1304392
Tankua Gebriel	28	Debretabor	355074	1309388
Debark	20	Simen	379314	1459196

A feature of volcanic areas is the prevalence of springs which develop at the basal contact of the *shield sequence* and the *upper basalt* cap. Volcanic spring discharge rates are generally <0.1 l/s but may be adequate for a village water supply. Exceptionally high spring discharge from volcanic highlands exceeds 100 l/s. These happens when discharge is taking place from lava tubes or when regional groundwater flow emerge to the surface along the foot hill of vast volcanic shields (Table 2.3). The *quaternary basalt sequence* provides some of the highest yielding shallow aquifers in Lake Tana basin (Fig. 2.1). Springs flowing from volcanic rocks (e.g. Lomi Wuha spring Fig. 2.4) are the source of water supply in Bahrdar-Capital of Amhara regional state (Fig. 2.1 for location of Bahrdar). Most of the springs emerging from tertiary volcanic rocks are topographically controlled and others emerge along structures indicating that the groundwater flow is controlled by both factors.

Infiltration is particularly good in areas where the plateau is covered by thick elluvial sediments. Aquifers outcropping in the plateau area also feed deeper fissured aquifers developed in underlying volcanic and sedimentary rocks.

The groundwater flow direction in the whole basin coincides with the topography following the surface water flow direction. The flow is partly controlled by the structure and partly by the geomorphology of the area. Local groundwater flow directions vary from place to place according to the local topography.

The altitudinal zonality in groundwater discharge distribution is observed in volcanic rock areas. Generally the basal (Ashangie) unit (lower basalt) shows the least groundwater potential owing to closure of the porosities by deep weathering and isolation of the unit from recharge by overlying cap. The upper sequence of the basalt which forms the 'plateau proper' has highest groundwater storage and recharge owing to well developed fractures and connection to modern day recharge. The broad shield overlying the plateau is highly rugged hindering any meaningful accumulation of groundwaters, nevertheless ash beds intercalated within the shield volcanics act as storage medium while the fractured rocks as a permeable medium through with groundwater move. These properties when combined locally results in emergence of sustained and high discharge springs (Table 2.3 and Fig. 2.4).

Rainfall is also highest in the areas covered by upper sequence of the basalt (top units of flood basalts) and increases towards top of shield volcanoes. The *basal unit* (Ashangie) is mostly found in the rain shadowed northern Ethiopia (e.g. The

Tekeze valley) leading to lower recharge rates. Thus, the altitudinal climatic zonality determines the potential possibility of replenishment of groundwater resources. The upper basalt units exposed in the south western Ethiopia (Fig. 2.1) are also located under highest rainfall condition leading to well developed regoliths which allow shallow groundwater circulation and storage and enhanced recharge. This general picture of the zonal distribution of groundwater potential in the volcanic plateau may be disrupted in some areas by the azonal manifestation of individual factors of conditions such as alluvial deposits, regional structural disturbances (e.g. In the YTVL, Lake Tana basin, Belesa plain, Lalibela plain, Sekota plains groundwater potential is much higher than the surrounding owing to tectonic structures and presence of alluvial materials).

Analysis of extensive pumping test data shows that the top part of the *upper basalt sequence* (traditionally called the Termaber formation) has been categorized as consolidated fractured aquifer system where the dominant aquifer types are 'confined double porosity' and 'confined single plane vertical fractured' aquifers. The observed double porosity aquifers are mainly related presence of two fracture systems; the first are large and wide fractures of high permeability and low storage capacity and the second is; the matrix blocks of low permeability and high storage capacity. Depth wise and age wise transmissivity variation analysis shows that the younger trap basalts have higher aquifer productivity than the older and both the older and younger volcanic products shows decreasing aquifer productivity trend with increased well depth (Gebresilassie 2010). A closer look at the structure of upper basalt sequence reveals the presence of heterogeneity. The more massive flows are generally impermeable, although the junctions of many flows can be highly productive, as they may contain shrinkage cracks and rubbly zones caused by the covering over of the rough surfaces of the lava by the chilled bottoms of the next flows.

Little work exists on the hydrogeology of the broad volcanic plateau of the South Eastern Ethiopia. However it is observed that the behavior of the aquifers in that sector is similar to those in the North Western Plateau. The Shield volcanics of Bale Massif manifests emergence of several high discharge springs. The Quaternary basalts occupying the vast plain around Robe, Goba and Goro are highly fractured and productive. The acid volcanic products forming the shield are however of low productivity aquifers.

2.2 The Shield Volcanics (Choke, Guguftu, Simen, Guna and Batu etc.)

Geology

The Ethiopian Plateau is made up of several distinct centers of different ages (Figs. 2.3 and 2.4). The Choke Mountain is one such shield. A number of large shield volcanoes developed on the surface of the volcanic plateau cap the flood

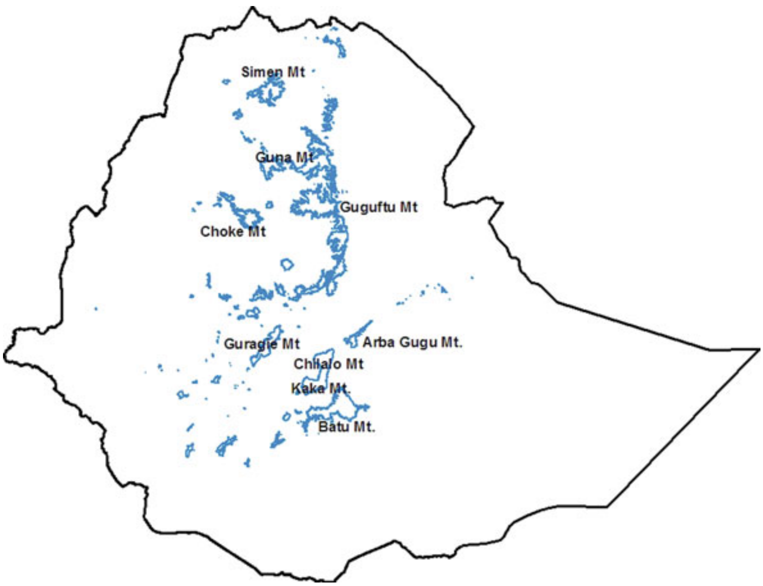


Fig. 2.3 Distribution of shield volcanoes

basalt province of northern Ethiopia. These volcanic shields are a conspicuous feature of the Ethiopian Plateau and distinguish it from other well known, but less preserved, flood basalt provinces such as the Deccan and Karoo (Kieffer et al. 2004). The basal diameters of the shields range from 50 to 100 km and the highest point in Ethiopia, the 4,533 m high peak of Ras Dashen (Simen Shield, Fig. 2.4), is the present summit of the eroded Simen Shield. Although smaller in diameter, the summits of many of the other shield volcanoes also exceed 4,000 m. Mt Choke has a basalt diameter of over 100 km and rises to 4,052 m, some 1,200 m above the surrounding flood volcanics. Guguftu is more highly eroded and its original form is difficult to discern (Kieffer et al. 2004).

Type examples of continental flood basalts, such as those of the Deccan and Karoo provinces, are described as thick, monotonous sequences of thick, continuous, near horizontal flows of tholeiitic basalt. In contrast, the Ethiopian province reveals a series of flood basalts overlain by large and conspicuous shield volcanoes. Owing to the young age of the flood basalt volcanism of the Ethiopian plateau, the upper most section of the flood basalts including the shields are well preserved while in other flood basalt provinces (e.g. Deccan trap), are higly eroded and lateralized.

The Choke shield is one of the three major shield volcanoes enclosed within a large meander of the Blue Nile. It is a broad flat symmetrical shield made up dominantly of lava flows and extends radially out from the central conduit with dips less than 5°. The contacts between different lava flow units leads to enhancing permeability and storage properties of the shields.

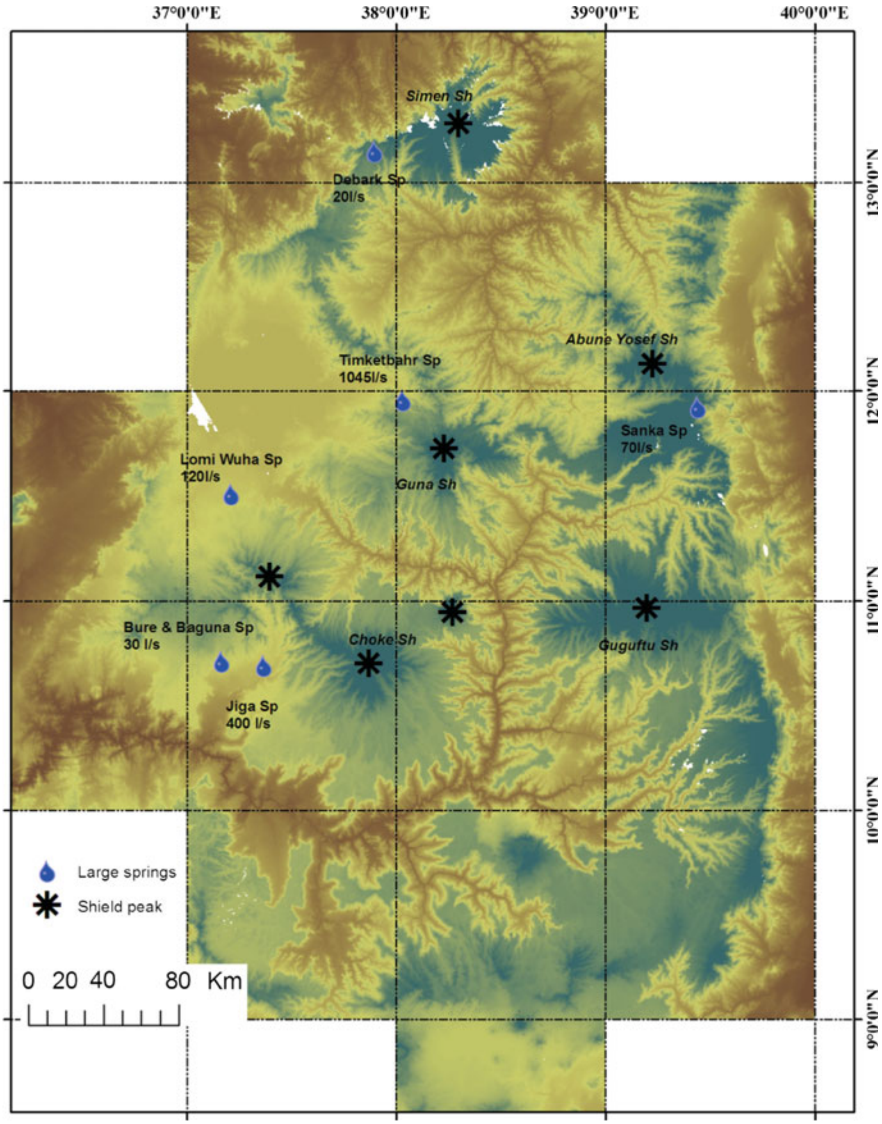


Fig. 2.4 Location of some prolific springs associated with the shield volcanoes

Hydrogeology and Groundwater Occurrence

In the shield volcanoes, the interlayer of acidic lava and ash components with fractured basaltic layers create a unique feature for groundwater storage in movement. In the shields where lavas alternate with air-fall ash, productive two-part aquifer systems has been encountered as revealed by discharge of high yield springs

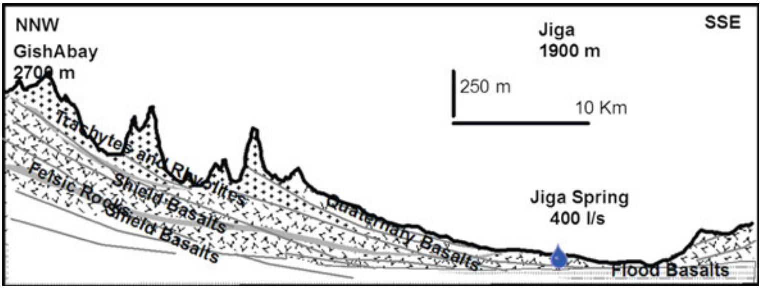


Fig. 2.5 Hydrogeolgic section showing the origin of the Jiga spring (cross section after Kieffer et al. 2004)

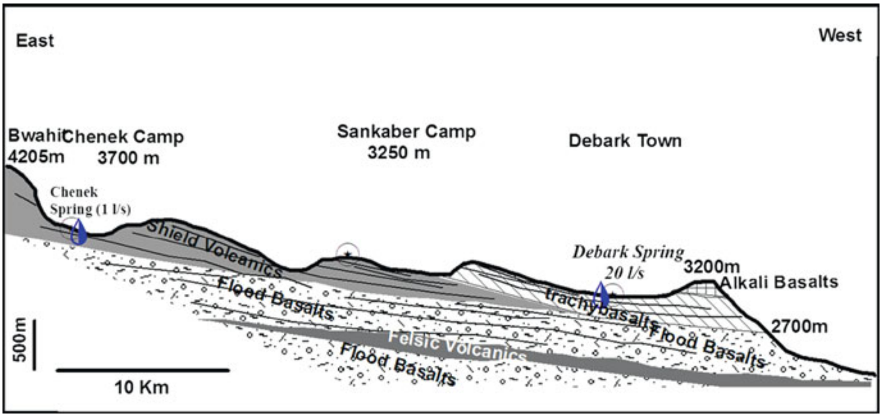


Fig. 2.6 Hydrogeologic cross section showing the origin of the Debark springs (cross section modified from Kieffer et al. 2004)

(Table 2.3). Highly permeable but rubbly or fractured lavas act as excellent conduits but have themselves only limited storage. Leakage from overlying, porous but poorly permeable, volcanic ash compensates for this by acting as aquitards, and is the storage medium for the system. Figures 2.5 and 2.6 show schematic model of emergence of prolific springs associated with shield volcanoes.

Apart from the significance of these prominent geomorphic characteristics of the shield volcanoes in the groundwater recharge and circulation, the structure of the lava flow units make the shield volcanoes a distinct hydrogeologic units as compared to the underlying horizontally lain flood basalt plateau. The lava flows the shield volcanoes are thinner and less continuous than the underlying flood basalts. This leads to the close association of spring emergence at frequencies with the shield volcanoes. One of the largest discharge spring recorded in Ethiopia (Jiga Springs) emerges at the foot hill of the Choke shield volcano (Figs. 2.4 and 2.5). Assasa spring at discharge of 500 l/s emerges at the foot hill of Arsi-Bale mountains (east of Mt Kaka, Fig. 2.4) in South Eastern Ethiopia.

The Jiga spring is located within the area occupied by geographically young lava flows, originating from recent volcanic craters higher on the mountain slope north of the spring eye (Fig. 2.5). This late phase of volcanism spread a veneer of basaltic lava along the previously eroded slopes and valleys forming wide or broad, gently sloping land area. The Jiga springs are believed to emerge to the surface being forced by subsurface water flowing over impervious bedrock (upper basalt sequence) materials. The same emergence model has been proposed for other springs associated with the shield volcanoes (e.g. The Bure Baguna springs emerge to the surface being forced by permeability difference between the upper basalt aquifer and underlying Mesozoic sandstones). A number of other springs are noted along the foothill of such volcanoes. These include the Sanka spring in the foothill of Abune Yoseph shield, the Debark Springs at the foothill of the Simen (Fig. 2.6), the Wanzaye and Gurambaye springs at the foothill of the Guna shield in the Lake Tana basin.

Particular limitation of groundwater use associated with high rising shield volcanoes is that frost and rime are frequent during the dry season excluding the plantation of most tropical crops.

2.3 The Lake Tana Basin

Geology

Unlike most part of the head water system of the Blue Nile basin (dominantly covered by upper basalt sequence) the Lake Tana basin is characterized by complex lithologic and tectonic features. The main geologic features of the basin are subsidence and block fault formation, accumulation of Miocene organic rich sedimentary rocks, Plio Pleistocene basin volcanism and late quaternary volcanic activity and recent lacustrine and alluvial deposition along the margin of the lake. Geothermal system also exists in an otherwise tectonically stable part of Ethiopia.

According to Chorowicz et al. 1998, Lake Tana basin is situated at the junction of three grabens (Fig. 2.7): the Dengel Ber (buried), Gondar (exposed by erosion) and Debre Tabor (reactivated). This structural complex was notably active during the build-up of the mid-Tertiary flood basalt pile, into which the Tana basin is impressed. Fault reactivation occurred in the Late Miocene–Quaternary, accompanied locally by predominantly basaltic volcanism. Fault-slip indicators are consistent with crustal subsidence centered on the present morphologic basin. Concentric and radial dike patterns common features in the Tana region.

The northwestern Plateau of Ethiopia is almost entirely covered with extensive Tertiary continental flood basalts that mask the underlying formations. Mesozoic and Tertiary sediments are exposed in a few locations surrounding the Lake Tana area suggesting that the Tana depression is an extensional basin buried by the 1–2 km thick basalt sequences. However a most recent study by Hautot et al. 2006

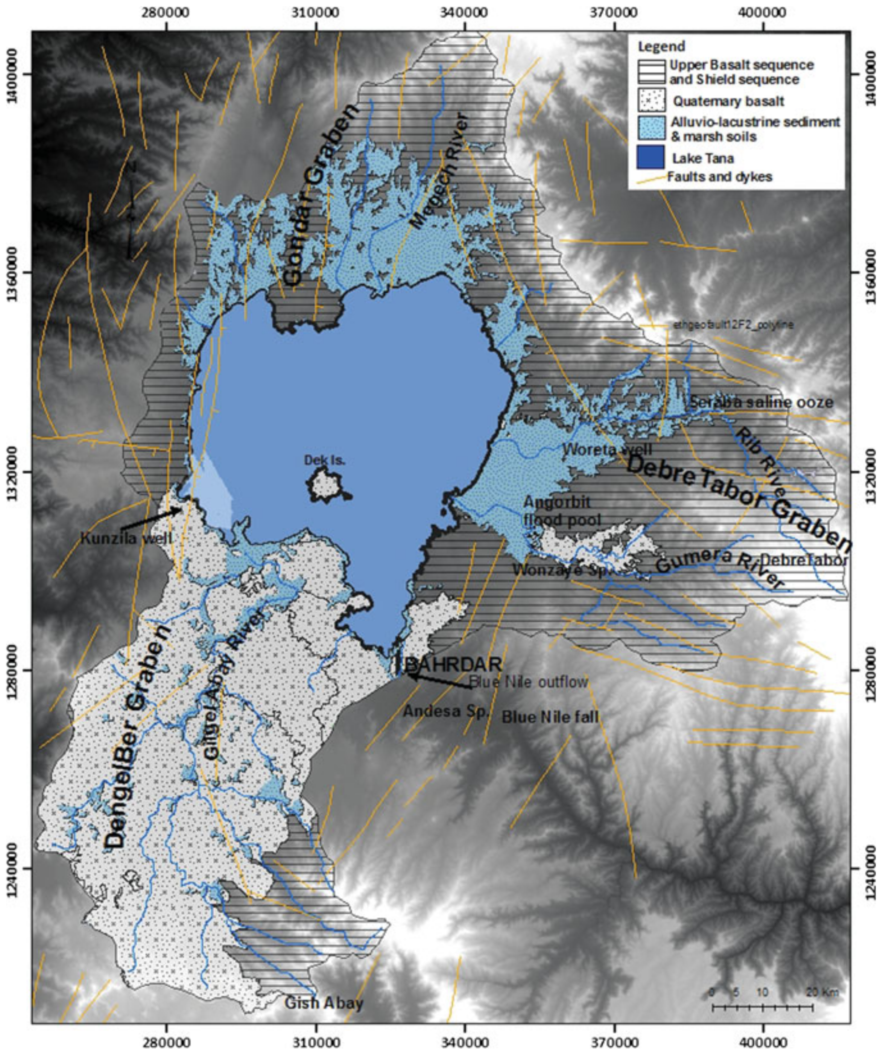


Fig. 2.7 **a** Simplified geologic map of the Lake Tana Basin

using magneto telluric imaging that carried out south and east of Lake Tana revealed that there is a consistent NW–SE trending sedimentary basin beneath the lava flow (Hautot et al. 2006). And the lave flow in the Tana plains is merely 250 m think (Fig. 2.8). The thickness of the sediments has been estimated at 1.5–2 km, which is comparable to the Blue Nile stratigraphic section, south of the area. The thickness of sediments overlying the Precambrian basement and underlain 0–250 m thick continental flood basalts averages 1.5–2 km, which is comparable to the Blue Nile stratigraphic section, south of the area. A km thickening of sediments (middle of Fig. 2.8) over 30–40 km wide section suggests

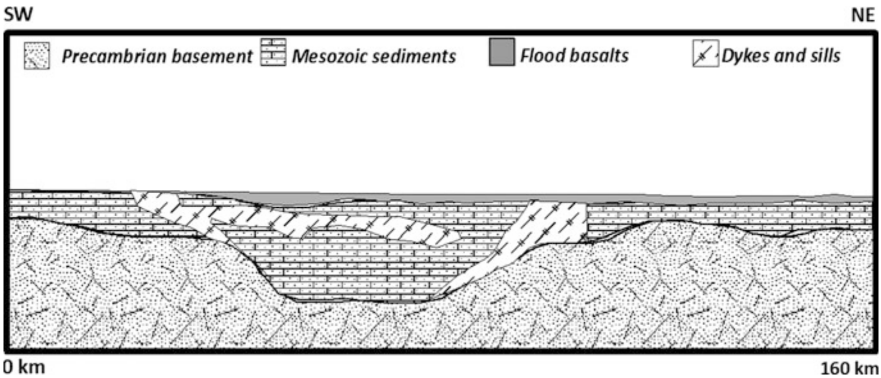


Fig. 2.8 Schematic geological cross-section interpreted from the resistivity model (adopted from Houtot et al. 2006)

that the form of the basin is a half graben (Hautot et al. 2006). The presence of Mesozoic sediments beneath the volcanic cover has been previously postulated from groundwater geochemistry and isotopic investigation in the Lake Tana basin (Kebede et al. 2005). Particularly the carbon isotope data of a spring (Andesa near Tis Abay fall) reveal signature of marine carbonate testifying the presence of these sediments underneath the volcanic cover.

Hydrogeology and Groundwater Occurrence

There are at least four major categories of aquifers in the Lake Tana basin these are the Tertiary volcanics (upper basalt sequence and shield volcanics), Quaternary volcanics, Miocene sediments, and the alluvio lacustrine sediments. Groundwater flow is mainly controlled by regional tectonics associated with the formation of the Lake Tana graben itself.

- The alluvial aquifer is recharged from lateral groundwater inflows from the volcanic aquifers from the upper catchments. The aquifer is discharges to Lake Tana during low Lake level and to evapotranspiration from the wetlands.
- The volcanic aquifer of quaternary vesicular basalt is recharged from rainfall and most of its recharge water later discharges to springs, wetlands, streams and directly to the southern sector of Lake Tana.
- The Tertiary scoraceous basalt is recharged from rainfall within the Lake sub-basin principally discharges to springs and streams.

Groundwater occurrence and yield: According to the Hydrogeological study of Abay River Basin Integrated Development Master Plan Project (BCEOM 1999), the Tertiary basalts and recent lava flows which are widely distributed in the Tana sub basin are grouped as extensive aquifer with fracture permeability.

The maximum average depth drilled in this formation is about 120 m. The water point inventory data (BCEOM 1999) shows that the average depth of boreholes drilled in this rock unit is in the order of 70–80 m. Yield from the Tertiary basalts is estimated at 13 l/s.

The Miocene Lacustrine deposit extensively lies in the northern part of Lake Tana and occupies the localities known as Chilga-Gondar graben. These sediments are composed of clay, silty claystone, silty sandstones volcanic ashes, and lignite beds. Bore hole drilling result shows that the thickness of Lacustrine deposit reaches 90 m and it is underlain by volcanic rocks. Wells drilled in these sediments turns out to be dry.

The dominantly scoraceous and fractured quaternary basalts underlying most part of the Gilgel Abay sub catchment (Fig. 2.7) show the highest groundwater potential as measured by its high infiltration capacity (20 %) and hydraulic properties. Many high discharging springs emerged from this rock unit act as base flow for Gilgel Abay River, which drains to Lake Tana. Areke and Lomi Wuha springs are high yielding springs, which currently serve as water supply for Bahrdar town, have a discharge rate of 120 and 50 l/s respectively.

Alluvial sediments are commonly distributed along the mouth of the Megech, Rib and Gilgel Abay Rivers. Alluvial sediments have limited distribution within Lake Tana sub-basin dominantly at the eastern and northern side of the Lake. The thickness reaches more than 50 m. There is a progressive fining of the sediments as one go from the foot of the mountains towards the lake shore. Bore hole drilled (depth 53 m) for Woreta town (Fig. 2.7) showed significant discharge with relatively low drawdown ($Q = 7$ l/s, drawdown $= 4$ m).

According to SMEC (2007), the aquifer transmissivity and yields of the sediments are relatively low and the aquifer properties are highly variable laterally. It is considered that even with a combination of wells, the yields required to meet the demands of a large scale irrigation development are unlikely to be achieved from the aquifers in most areas. The general conclusion is that there would be inadequate resources available for large scale, sustainable groundwater based irrigation development. However there shallow groundwater can be economically extracted and used for household and small scale commercial farming activities.

Geothermal waters are also noted in the Lake Tana graben. The most prominent ones are the Wanzaye thermal waters and the Andesa springs on the Bahrdar to Tis Isat Fall. The thermal waters are associated with heating related dykes penetrating through the basin aquifers (see Figs. 2.7 and 2.8).

Aquifer property: The upper basalt sequence and the shield volcanic aquifer system is scoraceous in nature in most parts. Transmissivity values from pumping test results are with the interval of 6–40 m^2/day. SMEC (2007) report shows transmissivity of the Tertiary basalts varies from 0.1 to 32 m^2/day. The productivity of this aquifer is highly controlled with intensity of the fracture and the presence of the major structure affecting the area. It is aquifer with a relatively moderate productivity. The Yields of Tertiary volcanic aquifers are in the order of 0.7–17 l/sec. Specific capacity ranges are generally low, with average values of 0.25 and 0.27 l/sec/m (SMEC 2007).

Quaternary basalts are the most productive aquifers system which is characterized with plenty of vesicles and highly weathering. The relative occurrence of high discharge springs and wells implies its potential for bearing of high ground water. The major springs of Areke and Lomi emerge from this aquifer unit with 140 and 50 l/s respectively.

The productivity of alluvial aquifer is associated with the pores of unconsolidated gravels and sand. The available data on this aquifer indicate high productivity with boreholes yielding more than 6 l/s with from shallow depth.

Groundwater flow: Groundwater level data (SMEC 2007) show convergence of groundwater into the lake from all directions. Groundwater surface elevation contour shows that groundwater elevation generally follows the ground surface contours with the groundwater flow directions largely consistent with the surface water catchment boundaries (Fig. 2.9). High groundwater heads occur in the south and east around the two shield volcanoes of Mt Choke and Mt Guna with the hydraulic gradient radiating from these points. Elsewhere around the eastern and western basin margins, there is a steep hydraulic gradient towards Lake Tana flattening on the plains adjacent to the lake. The hydraulic gradient in the Ribb and Gumera catchements is relatively steep at around 0.02 although it appears to be a relatively even grade in the direction of the Lake. In low lying areas, particularly the plain east of Lake Tana there is a sharp reduction in head and lower hydraulic gradient (approximately 0.01) beneath the plain. A similar situation occurs in the Megech valley where the hydraulic gradient flattens out in the low laying areas from 0.02 around Gondar to 0.006 beneath the plains. In the Gilgel Abbay, the groundwater gradient reduces from around 0.02 in the south to around 0.005 in lower laying areas approaching Lake Tana. East of the Gilgel Abay, as the topography drops sharply into the Abay River, the hydraulic gradient steepens. As noted previously, it is expected that groundwater is close to the ground surface in the downstream parts of Gilgel Abbay, with discharges to high volume springs and also to low lying swampy areas. The groundwater elevation flattens in the lowland areas around the Lake and it is considered that groundwater level in these areas is likely to be controlled by the discharge to streams. There is a potential for water logging in low lying areas away from the drainage lines as the piezometric level approaches the ground surface. It is expected that this level will be controlled by evapo-transpiration. Areas prone to flooding largely coincide with areas in which the groundwater gradient decreases.

Groundwater lake water interaction shows that groundwater contributes less than 7 percent of lake water budget (Kebede et al. 2006). The low contribution of groundwater to the lake may be due to the thick exceeding 80 m stiff clay underlying the Lake Tana bed. Isotopic evidence (Kebede et al. 2006; 2011) precludes the presence of appreciable amount of groundwater leakage from the Lake to adjacent aquifers.

Base flow as index of recharge: Stream hydrograph analysis results in the upper Blue Nile basin shows that about 15 % of annual flow is derived from shallow groundwater. However, for some catchment it reaches 44 %. Kebede et al. (2011) and references therein) indicated that about 45 % of the total surface water inflow

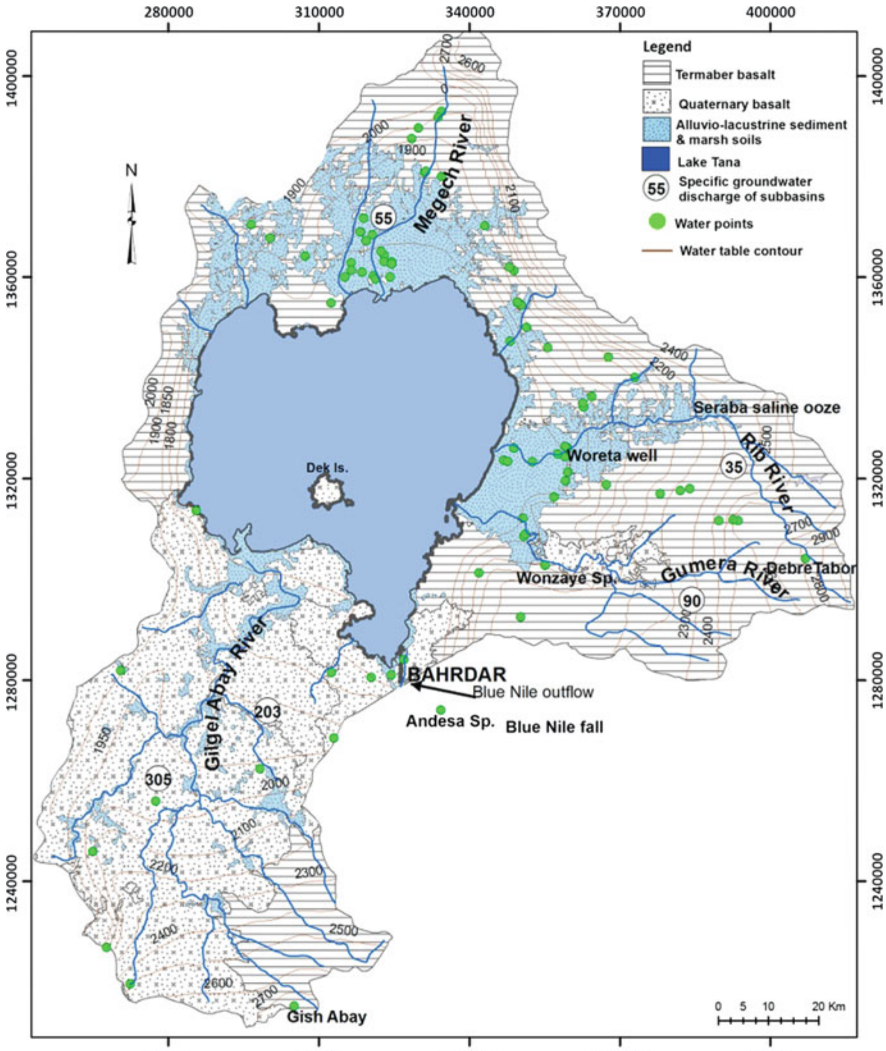


Fig. 2.9 Some hydrogeological features of the Lake Tana basin (water table map in meters above sea level) numbers inside circles are specific discharge of the sub basins

to Lake Tana (about 500 mm/year) is derived from ungauged basins. The annual recharge into the basin, which is obtained from integrated methods (chloride mass balance, base model, base flow separation, etc.) varies between 70 and 120 mm/year. Hence, the annually renewable groundwater recharge is estimated to vary between 1.2 and 2 billion m^3. Table 2.4 and Fig. 2.9 shows the highest groundwater contribution to surface waters (or indirectly high recharge) takes place in the Gilgel Abay sub catchment while the lowest is in Rib. The Gilgel Abay drains the high rainfall highlands in the south and is underlain by porous quaternary basalts—

Table 2.4 Summary of base flow index for the sub catchments of the Lake Tana basin (BCEOM 1999)

Sub basin	Station	Latitude		Longitude		Catchment Area (Km^2)	Groundwater specific discharge (mm/year)
Gilgel Abay	Bahir Dar	11	22	37	02	1,664	305
Koga	Merawi	11	22	37	03	244	203
Rib	Addis Zemen	12	00	37	43	1,592	35
Gumara	Bahir Dar	11	50	37	38	1,394	90
Megech	Azezo	12	29	37	27	462	55

reasons for high groundwater contribution to surface waters while the Eastern sub catchment, Rib drains the Debretabor shield which has lower hydraulic conductivity.

Groundwater Surface Water Interaction and Wetlands

There are a number of wetlands and groundwater dependent ecosystem in the Lake Tana catchment. Most of these wetlands remain green even in the dry seasons. The wetlands are depressions formed by volcanic topography or by tectonic depressions. The plains surrounding the lake (Fig. 2.9) form extensive wetlands during the rainy season. As a result of the high heterogeneity in habitats, the lake and surrounding riparian areas support high biodiversity and are listed in the top 250 lake regions of global importance for biodiversity (SMEC 2007). In some places, close to the lake shore there is extensive growth of papyrus (*Cyprus papyrus*). The littoral zone (depth 0–4 m) of the lake, which comprises water logged swamps, the shallow lake margins and the mouths of rivers feeding the lake, is relatively small, covering about 10 % of the total surface area.

Lake Groundwater Interaction

An earlier investigation of Lake and ground water interaction is predicted by isotope geochemical studies of groundwater in the vicinity of the Lake which show little evidence of mixing lake water with the adjacent aquifers (Kebede et al. 2005 and Kebede et al. 2011). The same study predicted less than 7 % Lake Inflow is from ground water. The study also shows possible but unverified inflow of groundwater inflow to the Lake in the southern part from the quaternary sediments into the rocky lake bottom around the town of Bahrdar. The linkage of groundwater outflow or inflow from the Lake is probably limited by the thick and stiff clay sediments occupying the Lake bed. Drilling the middle of the Lake shows that the thickness of sediments in the Lake Tana floor exceeds 80 m and is composed of stiff clay and silt.

The analysis of the SMEC (2007) with assumption of an average lake level of 1,785 m and even with an underlying head of say 1,800 m, the vertical leakage through the 80 m thick clay, with a vertical hydraulic conductivity of 0.0001 m/day would suggest a leakage rate of 7 mm/year (58,397 m^3/day).The assumption take a head in the aquifer beneath the lake with a relative high magnitude, but vertical leakage to and from the lake into the underlying aquifer is considered negligible. The prevailing low hydraulic gradient in areas surrounding the Lake does not likely lead to significant lateral leakage into or out of the lake. Applying the regional gradients from the groundwater elevation contour ranging from 0.02 to 0.005 towards the lake, assuming discharge into the lake from a 50 m thick aquifer with hydraulic conductivity of 1 m/day, the discharge into the lake will be less than 1 mm/year (8,342 m^3/day) SMEC (2007). In summary the inflow to the lake from vertical leakage through the clay materials and lateral inflow from the aquifers is estimated at 66,739 m^3/day, which is inconsiderable compared with direct rainfall on the Lake and surface water flow to the Lake.

2.4 The Upper Tekeze River Basin and Associated Massifs

Geology

The Upper Tekeze area is marked by prominent uplifting, massif volcanoes, deep dissection and erosional fragmentation. The basin has undergone several changes in base level of erosion and stream geometry. The boundaries of the basin are defined by prominent regional structures (the rift margin from east, the Lake Tana graben from south and west, and the basement foliation from north) and prominent shield volcanoes (e.g. Simen, Guna, Debre Trbor, Abune Yosef etc.).

The basin is underlain be the basement complex at the base (composed of low grade meta-sediments and metavolcanics), the Mesozoic sediments mainly composed of sand stones and marine sequences, and extensive think Cenozoic volcanic cover (Fig. 2.10). Quaternary Climate change has also left its imprints as lacustrine sediments and glacial moraines. The marine sequences are localized to the north eastern sector of the upper Tekeze basin. The extension under the volcanic cover of the Mesozoic sediments, in the south though indirectly indicated, is yet to be proved-thought the regional E-W geologic cross section by USBR (1964) shows the presence of the Mesozoic sedimentary rocks under the volcanic cover (Fig. 1.3). However a deep well drilled recently to a depth of 500 m around Guhala town (Fig. 2.10) does not encounter the Mesozoic sediments.

Most of the outcrop in the Upper Tekeze basin is underlain by volcanic pile accounting for 80 % of the landscape. The volcanic eruptions come in four major formations, all diachronous: from bottom to top, Ashangie (Eocene), Aiba

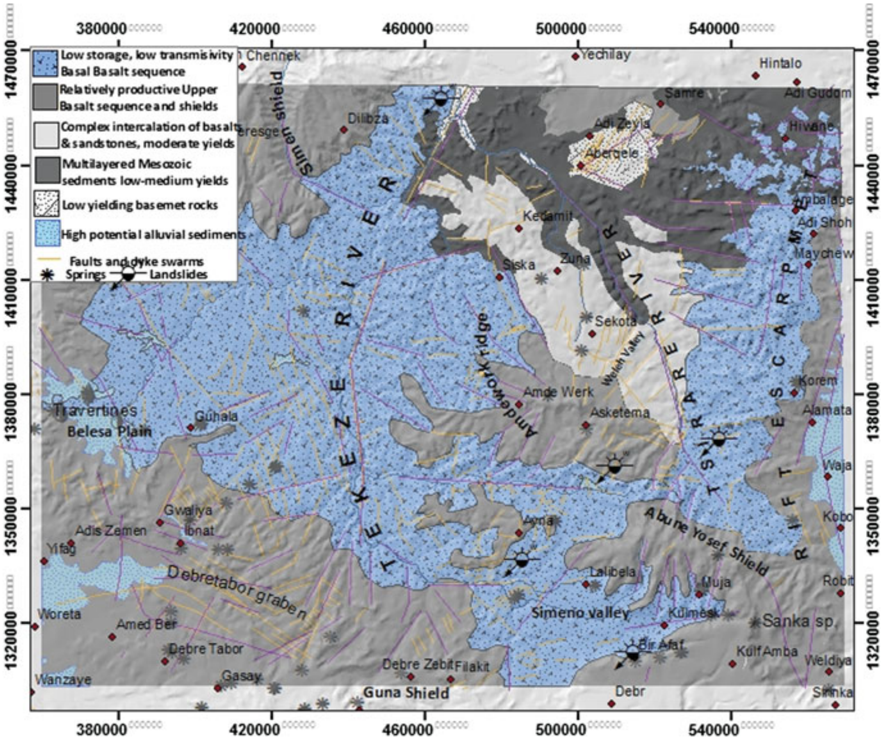


Fig. 2.10 Geologic map and some water resources feature of the of the upper Tekeze upper river basin

(32-25 Ma), Alaji (32-15 Ma) and Termaber (30-13 Ma) (Mohr 1983; Mohr and Zanettin 1988). According to the new stratigraphic classification the four units are classified in two folds as the basal unit (Ashangie) and upper unit (containing the remaining three formations). The whole volcanic sequence has been emplaced with no apparent development of paleosol and erosional surfaces (Rochette et al. 1998).[3]

The basal sequence (*Ashangie*) is basaltic formation marked by its deep weathering, thin layering (<10 m), rugged and gentler topography and cross cutting sets of dykes. There are minor acid products (such as volcanic ash, rhyolites, and ignimbrites) in the Ashangie formation. Individual flows are discontinuous laterally and have irregular thicknesses. Intrusions of diabase and dykes are common in the Ashangie formation. In the north central sector extensive quartz and opal mineralization owing to paleo thermal groundwater circulation has been noted. In most parts brecciated materials has been noted in the Ashangie

[3] It should be noted that in the new classification and modified hydrogeological map of Ethiopia the trap basalts are classified as Lower basalt (traditionally called Ashengie) and the Upper basalt (Aiba, Alaji, Termaber).

formation. The most extensive breccia has been observed in the Weleh valley south of Sekota town at the foot hill of the Amdework ridge. Evolved acidic product is minor in the Ashangie formation.

By contrast, the Aiba formation is a succession of massive cliffs corresponding to thick (10–50 m) basaltic flows (Rochette et al. 1998). The *Aiba and Alaji* formations are marked by their relative freshness, thick layering, and cliff forming topography. Frequent lacustrine deposits have been marked in the Aiba formation as evidenced by lenses of diatomites and porcelain lithologies particularly surrounding the Sekota complex. The *Termaber* formation is marked by its jointing, thick layering, cliff forming topography with flat tops.

Among the Mesozoic sediments the Adigrat Sandstones are the most predominant formations in the Upper Tekeze. Exposure of the Marine Antalo sequence is limited to the North Eastern part. In a few pocket areas in the Weleh Valley metamorphosed limestone of a few meters thick has also been noted. The contact between the Adigrat sandstone and the underlying basement is characterised by white reddish coarse breccia with abundant clastic materials coming from the weathering of the schistose basement and characterized by a dimension of tens of centimetres. In places between the Adigrat sandstone and the basement the Palaeozoic sandstones (Enticho sandstones) have also been observed. When cut by rivers the Adigrat sandstone form vertical cliffs often of several hundred meters thick.

The Adigrat Sandstones represent the basal horizon of the Mesozoic sedimentary sequence of the Central and Northern Ethiopian Plateau. The Adigrat sandstones are generally reddish in colour and very compact near its top part. Generally the sandstone is characterized by a prevailing quartz component, often also silicate with abundant feldspars content, but not as much clay. In some localities highly weathered phyroclastic layers constituted by white grey ash fall tuffs, settled within an environment characterized by the occurrence of a free water surface have been noted.

The Adigrat Sandstones are mainly constituted by clasts of quartz, feldspars, micas, tourmaline, etc., typical components of the granite and diorite rocks and crystalline schists, but also by fragments of the same rocks. The most abundant mineral occurring in these rocks is undoubtedly the quartz, with associated micas and heavy minerals, while the feldspars are quite subordinated. The quartz grains are mainly sharp cornered, but rarely are they also round shaped.

The *Undifferentiated volcanic and associated dolerites*. These are formations occupy the areas between Sekota and Tsirare River on the road between Sekota and Samre. The dolerites often come as intrusions and in places they form isolated circular domes and cones. The Dolerite volcanics are highly jointed and the columnar joints are narrowly spaced. This makes them highly fragmented-fragments of fresh and hard dolerites. In this formation there are several lacustrine diatomites and porcelinaites of different sizes.

Tectonic Structures

Regardless of its location in the center of the Ethiopian plateau, which is otherwise known as tectonically stable, the upper Tekeze is cut by prominent regional faults. For example the NW–SE running Tsirare River follow a regional fault that cut the Abune Yoseph Mountain and intersect with the Afar rift margin around Woldia area. Dyking and dyke swarms are also common features. Complex tectonic and stratigraphic features are also noted in the north central part of the area surrounding the Sekota district. The complexity in stratigraphy is the direct impression of the tectonics processes.

The boundaries of the Upper Tekeze drainage basin are formed by prominent regional tectonic. From the East Tekeze drainage is bounded by rift margin faults; to the west by the Chilga-Gondar sub rift of the Lake Tana structure; to the south by the Debretabor sub-graben of the Lake Tana rift. In its central part it is cut by a prominent NNW-SSE running Tsirare fault system. Within its bounds the Upper Tekeze is characterized by presence several dyke swarms, fractures, faults and regional slumps which are the manifestations of the basin boundary tectonics. The Tekeze River also runs N–S following a regional tectonic feature originating as far north from the Mekelle Outlier. The major curved shape valley dissecting the Simen massif also taught to be the result of regional slump.

Several prominent faults belonging to the Lake Tana graben (the northern extension of the Chilga-Gondar sub rift), the rift domain and the E–W structures dissect area. The intensive erosion however has masked most of this geologic structure therefore evidence for faulting mostly comes from interruption in lateral discontinuity of lithologies. The NNW–SSE running major tectonic feature (Tsirare fault) dissect the upper Tekeze into two and pass just east of the Abune Yoseph massive pile. The spring with the highest discharge (Sanka spring—see Fig. 2.4) recorded in the area emerge on the southern extension of the Tsirare fault. In the Eastern part of the Upper Tekeze river, the drainage which should have been oriented E-W because of the flexuring of the rift margin is now draining NW owing to the Tsirare fault system. Dolerites cones and domes also crop out at the NW end of the Tsirare fault. A number of NW–SE running faults are also observed in the Sekota area. The faults are responsible for block rotation, lateral disruption of lithologies, and emergence of springs in the area. The tectonic features are described as follows:

The North Lake Tana graben bounding from west: North South running fault system which makes part of the Lake Tana basin, responsible for the conveyance of groundwater from the RasDashen massive towards the Debark Debat plain. These are the north ward extension of the Chilga and north Tana sub-grabens. Faults belonging to this regional tectonics mark the western boundary of the Tekeze drainage.

The Debre Tabor graben bounding from south west: East–west running parallel faults affecting the drainage divides between the Lake Tana and the upper Tekeze. The DebreTabor sub graben runs E–W for nearly a 100 km. Several faults belonging to this regional tectonics are noted in the south western part of the Tekeze. The prominent fault bounding the Debretabor graben from north is also responsible for the formation of the half graben around Ibnat town. The Ibnat half graben is locally filled by 5–10 m thick alluvial sediments. The mountains bounding the Belesa plain from south form the northern margin of DebreTabor Subgraben.

The Tsirare fault dissecting the North Eastern part: Deep regional fault running NNW-SSE and responsible for the emergence of the Sanka springs (50–60 l/s) near Woldia.

The Sekota complex structures: These are *m*ainly NNW-SSE running fault systems pre-dating Cenozoic volcanic activity or contemporaneous with them. Responsible of permeability contrast between lithologies, juxtaposition of rocks of contrasting ages, rotated fault blocks. The Sekota complex is probably an old failed rift of 'basin and range' characteristics the original topography of which is masked by young volcanics and recent tectonism. The prominent fault among the Sekota complex structures is the regional fault that run SSE ward from around Sekota and run towards Hamusit town. IN this region complex stratigraphy including juxtaposition of metamorphosed limestones and sandstones with the Cenozoic volcanics is probably related to these structures. The orientation of the May Lomi River north of Sekota also follows this regional structure. This *sub*-region is characterized by complex stratigraphy variously tilted sedimentary formations overlying and underlying igneous rock units. Horizontal stratigraphic lithologic interfaces, tilted beds and tectonic contacts which are also affected by faulting and dyking, doleritic intrusions, engulfing and pushing up older sequences are very distinctive.

Dyke Swarms and other lineaments: Commonly observed in southern part of the upper Tekeze area particularly in the Simeno valley near Lalibela and in the foot hill of the DebreTabor and Guna shields. The dyke swarms are the manifestations of the boundary faults and are related to tectonic events.

The Basement structures: These are mainly a N–S running regional faults and associated E–W striations developed on the Basement outcrops in the northern sector of the region. Folds, foliations, faulting have been noted in the basement complex; all associated with continental scale deformation.

In most part of the Upper Tekeze area where the Adigrat sandstone is exposed, it is overlain by the Cenozoic volcanics or by upper sandstone (sometimes also called Tekeze sandstones). The absence of the Antalo sequence is not surely due to full erosion of the calcareous and clayey layers, but more properly to their lack of deposition by means of the notable palaeogeographic and environmental continuity which has characterized the whole area not allowing any other sedimentation if not that of the sandy materials.

Drainage and Hydrography

The upper Tekeze basin is generally water stressed dissected highland. The present day water stress in the Tekeze basin is the outcome of general drying and erosion fragmentation of the plateau and lack of suitable drainage and geomorphologic

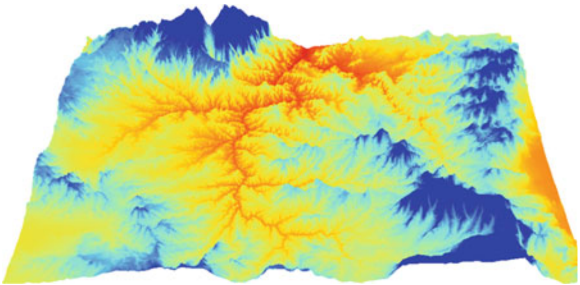


Fig. 2.11 Geomorphic features of the Upper Tekeze river basin. Note that the highland in the Southeastern part of the area is the most water stressed owing to its geomorphology and rain shadow effects. The twin summits in the north western sector is the Simen (Ras Dashen) massif

features for storage of surface and groundwaters (Fig. 2.11). Regardless of this generally a number of potential areas exist to store and transmit groundwaters particularly at deeper levels. The basin is occupied by several denuded shield volcanoes (Rasdashen, Abune Yoseph, Guna, and DebreTabor). These volcanoes play prominent role in controlling the drainage pattern. The Simen, DebreTabor and Guna diverts the surface water to converge in the Main Tekeze river which runs S to N. Separate from this is the Tsirare water shed which runs NW starting from the Abune Yoseph mountain. The pattern of the Tsirare River itself is controlled by a NW–SE running regional fault. The southern western margin of the Upper Tekeze is bounded by the Northern boundary of the DebreTabor Graben which runs towards Lake Tana. North of DebreTabor for instance E–W striking faults with a morphologic expression indicating southerly down throw can be traced further east, where they turn to ESE–WNW before termination against the Guna Shield volcano. The faulting then reappears on the southeastern flanks of the shield.

Mean long term denudation rate for the Tekeze basin since the emplacement of the volcanics and onset of erosion is estimated at 0.03 mm/year (Pik et al. 2003). More than 85 % of the project area has slope greater than 60° indicating the major part of the area is dissected, cliffs with minor small often less than 1 ha inter-mountain valleys available for agriculture. Out of the less than 15 % area with slope less than 60; the Belesa plain (Fig. 2.10) and plains in the Lalibela (e.g. Simeno valley) area account for the major part. The rest are small patches of land such as landslide or talus slopes, riverine terraces, and tops of dissected plateaus, tectonic depressions or intermountain valleys.

Tectonic features also affect the drainage pattern in the region. The prominent example is the trend in Tsirare River which follows NNW–SSE structure, probably reactivated Mesozoic rift. Likewise, uplifting owing to fault plane movement affecting river channel depth observed on the Siska drainage system whereby deep erosional river morphology is observed upstream of a fault scarp while the downthrown part shows slightly dissected river channel.

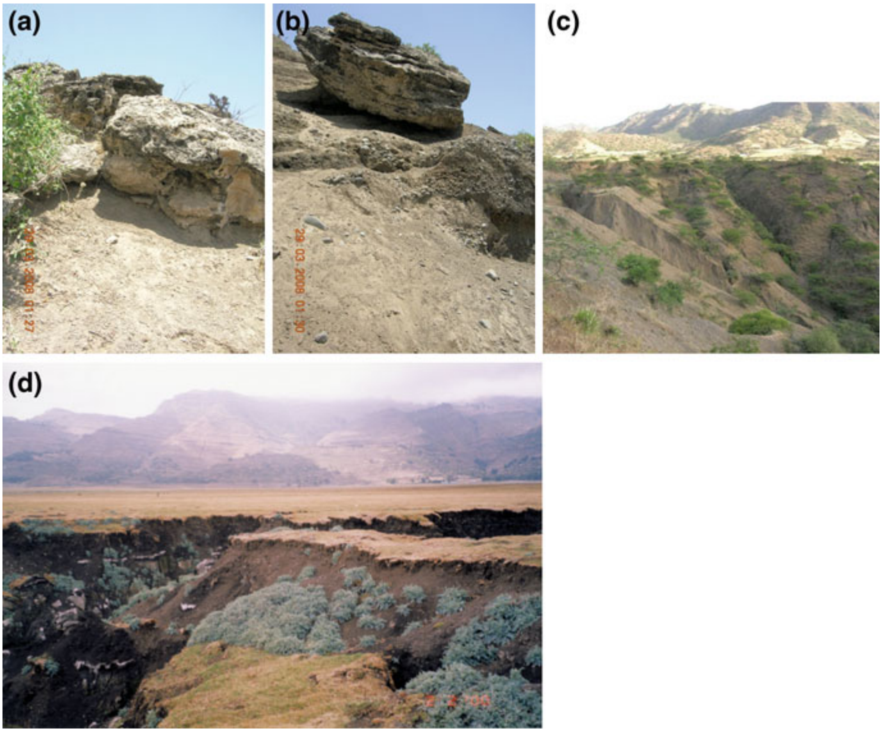


Fig. 2.12 Plate showing alluvio-lacustrine sediment and associated spring travertines in the Belesa Plain (**a** and **b**) and thick alluvio lacustrine sediments in the Taba village East Central Tekeze (**c**) and gully erosion in the Ashangie plain probably indicating lowering of water table probably staring 17th century owing to the lake Holocene drying

Geomorphology and Environmental Change

The regional geomorphology is dominated by the massif volcanoes which are also responsible for the drainage patterns (Fig. 2.11). The Simen Massif, the Abune Yosef Massif and the Guna Shield are prominent Volcanoes. In addition to their role as major controls on drainage control the volcanoes also are responsible for rainfall redistribution in the Upper Tekeze area.

Regions adjacent to the Upper Tekeze undergo remarkable Holocene climate changes as documented in valley fill sediments in the Tigray region (Nayssen et al. 2003; Mechado et al. 1998) lake level data in from sediment proxies in the rift (Gasse 1977) and in sediment beneath the lake Tana sediments (Lamb et al. 2007) Although evidence lack from dated sedimentary records in the Tekeze there are a number of imprints and indicators of climate and base level changes in the Upper Tekeze (Fig. 2.12). Notable among these are the 30 m thick alluvial-lacustrine sequence in the South Western corner of the Tekeze basin (namely the Belesa plain); the pockets of spring travertine deposits dotting the region; and the alluvial sediments in several sectors (e.g. around Taba village in the central highland). That most of these paleosediments lack major incisions could be indicative of their formation in the recent epoch probably belonging to the climate changes in the Holocene. Dates on the travertine occurrences in the Upper Tekeze basin is lacking but their geomorphic characteristics and stratigarphic position suggest similar genesis as that of other travertine sequences elsewhere in northern Ethiopia. For the past 1,000 year, and in particular since the early 17th century, stratigraphic records together with historic chronicles suggest increasing aridity. Pediments dissected by gullies common in many areas in upper Tekeze (Fig. 2.12d) are indicative of these general drying.

Hydrogeology and Groundwater Occurrence

The major reason for lower groundwater storage in the Upper Tekeze is the erosional fragmentation of the plateau and fragmentation of the aquifers into small sizes with no meaningful storage volume. Suitable locations where extensive aquifers could exist include the Lalibela area, the Belesa and Sekota areas (Fig. 2.12).

The volcanic rocks particularly the Upper basalt sequence are important aquifers in the Upper Tekeze area. These rocks, which, form the western and eastern highlands, bear considerable amount of secondary porosities resulting from the effects of extensive weathering, jointing, faulting and fracturing. Emergence of springs of significant discharge from these basalt sequences suggests the productivity of the Aquifer systems.

Field evidences on recharge and discharge zonation, description of topographic and geological and structural features, conventional evidences such as springs, tree lines, wet grounds etc. allow the identification of the groundwater occurrence zones in the Upper Tekeze catchment as depicted in Table 2.5 and hydrogeologic description of stratigraphic units in the basin is given in Table 2.6.

Groundwater Recharge and Discharge

Springs and streams are the major discharge path ways. In limited localities discharge to talus slope and diffuse discharge on slopes have been noted. Spring discharge data shows that most of the springs from the volcanic highlands range in their discharge between 0 and 0.5 l/s. The prominent springs with large discharge are associated with major volcanic massifs or with regional tectonic features. The spring with largest discharge (Sanka discharge (>70 l/s) on the way from Woldia to Lalibela, emerging at the escarpment of the Wolo highland) for examples emerge as the result of the intersection between the Tsirare regional fault cutting the study area and the N–S oriented rift margin faults (Figs. 2.12 and 2.4). Most of

Table 2.5 Groundwater occurence in the Upper Tekeze basin

Groundwater occurrences	Characteristics of the occurrence
Mesozoic sediments underneath the volcanic pile when exhumed by erosion or when the volcanics are thinned	May form regional aquifers of several thousand kilometer square, mostly regional flows of good water quality, groundwater occur mainly in fractures as primary porosity is low
Mountain bounded alluvial valleys	Shallow or deep groundwaters in extensive alluvial plains such as Belesa, Lalibela etc. Groundwater mainly occur in alluvial sediments and volcanic piles underneath the alluvium
Tectonically formed depression	Several such depression of a few tens of km 2 are observed around the villages of Weleh, Taymen and Ibnat; because of the depressions formed by faulting and graben structures groundwater converges to these low points and may result in shallow groundwater occurrence
Pockets of alluvial valleys	Several such valley but of a few hundred meters sq in extent occur in depressions formed by erosion of the volcanic pile, this may form local shallow groundwaters
Extensive fractured basalts particularly the Ashangie formation	The flood basalt which cover nearly 80 % of the project site form in some localities extensive aquifers over several thousands of sq km. Groundwater mainly occurs in contact zones, along dyke swarms and in weathered volcanic materials
Talus slope and paleo or modern landslide bodies	In several localities (e.g. Just on the road from Gashena to Lalibela on the slope of the escarpment several landslide bodies exist). The lose bodies of landslide allow groundwater inflow from the mountain body and springs emerge in most of these landslides. Locally the landslide body and associated loose fragment of soil allow development of groundwater for household irrigation

major discharge springs emerge at the contact between the Ashangie sequences and the underlying Adigrat sandstone (e.g. a spring near Siska village on Sekota Siska road). The Adigrat sandstone is in places highly indurated and thermally compacted in its top part.

The most water stressed area is the N–S running ridge resting in the middle of the Tekeze river basin bounded from the east by the Tsirare River and the west by the main Tekeze River (Fig. 2.11). Both surface water and groundwater flows away from this ridge and very limited suitable condition for storage of groundwater exist in this sector of Tekeze. Mostly perched groundwaters can be exploited from the region.

Table 2.6 Hydrogeogic characterization of aquifers in the Upper Tekeze area

Aquifer type	Transmissivity m^2/day	Yield (l/s)	Characteristics
Basement		<0.1 l/s	These are low grade metamorphic rocks mostly metasediments (phylites), groundwaters mostly occurs in shallow part. In places N S running basement faults and foliations coupled with EW shears enhance permeability of the rocks
Dolerite sills and intrusions		<2	These are highly fragmented and jointed, the joints are narrowly spaced, and the dolerites form intrusions and remain within the Adigrat sandstones, in many places particularly associated with the Tsirare fault system they make it to the surface forming isolated hills and domes. Because of their limited lateral extent
Adigrat sandstone		<2	Highly indurated, massive, and cemented sandstone with low primary porosity, the top part of which is encrusted by heating from Cenozoic volcanism, groundwater springs emerging at the contact of the Adigrat sandstone and the volcanic formation indicate low permeability of the sandstone, Fracture sets are common on the sandstone
Basal Basalt sequence	0.5–80	0.7–5.6	Deeply weathered, flows are laterally discontinuous; several springs emerge at the contact between this lithology and the underlying Adigrat sandstone, at its base it is affected by mineralization filling the fractures, dykes and gabro-diabase intrusion. In several sectors the Ashangie basalts are brecciated. Field evidence show that the brecciate parts are characterized by lower permeability
Upper Basalt sequence	1–100	1–20	Thickly bedded, columnar jointed product covering extensive area. The columnar joints are very closer to each other, Several lacusterine sediments sandwiched between the sequence can be noted. Individual flows are laterally extensive. In some places vesicular texture is common. Intercalation of rhyolites and ignmbrites capping the Cenozoic volcanic products are noted in highlands bounding the Tekezer river from West. Yield of wells can be very low in case of sites on shields. Dry wells are common example around the Guna Shield volcano. The rhyolitc and ignimbritic components are poor aquifers. Owing to their topographic location the shield volcanoes do not allow storage of apreiacble amount of groundwater although in some case prolific springs are associated with them

(continued)

Table 2.6 (continued)

Aquifer type	Transmissivity m^2/day	Yield (l/s)	Characteristics
Alluvial sediments	1–500	20	These are alluvial materials probably developed during accompanying the Holocene climate fluctuations, the alluvial materials are composed of diatomites, red beds, fluvial materials and paleosols. The most extensive deposit occurs mantling the Belesa plain while several such pockets are also common in the Lalibela area, in the Taba village, and filling paleo channels in sekota area
Talus slope, landslide bodies, alluvial terraces		1–2	These are small pockets of 0.5–2 km^2 slope material. The loose texture of the material enhance permeability in some places and groundwater from the mountain body often diffuse towards the talus slope and landslide bodies, cold springs are common in this materials. The slope material also supports several villages in the basin because of their gentler slope, soil development and groundwater discharge foci

The groundwaters of upper Tekeze are characters by low total dissolved solids and mostly satisfy the drinking and irrigation water quality standards. Incipient pollution of the groundwaters around the well heads has been noted. Groundwaters mainly occur in the volcanic cover. Tectonic depressions also play a major role in localizing groundwaters.

Recharge to the aquifers mainly occurs from rainfall and losing streams. Total annual recharge rate within the Tekeze basin is estimated at 50–100 mm/year from global estimates. WAPCOS (1990) estimated recharge in the basin at 100 mm/year. WATBAL estimate using the soil water balance book keeping method yields a deep recharge of 19 mm/year the majority of this recharge takes place in August and September (WWDSE 2009). According to previous isotope hydrological study (Kebede et al. 2005) groundwater recharge to aquifer in the regions surrounding the Tekeze basin basically takes from summer rainfall.

WATBAL soil water balance method The WATBAL (an Integrated Water Balance Model) model is used to estimate recharge over upper Tekeze valley from which rainfall and runoff data are available. A total of 178 million m^3 recharge for shallow aquifers which ultimately become base flow above the gauging station and a total of 565 million m^3 of deep aquifer recharge which leave the basin elsewhere has been estimated. Therefore the total groundwater recharge is estimated at 743 million m^3 of recharge goes to shallow and deep groundwaters.

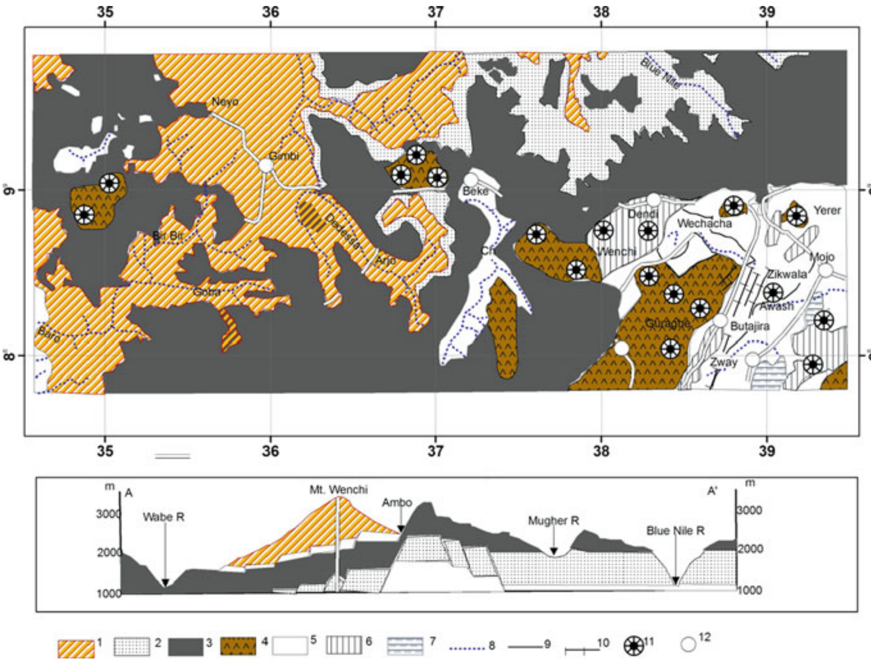


Fig. 2.13 Geology of the Yerer Tullu Wellel Volcanic Lineament zone where coordinates in the map is given in degrees. *1* Precambrian basement, *2* Mesozoic cover, *3* Oligocene volcanics (Ethiopian plateau volcanics), *4* Late Miocene volcanics, *5* Quaternary volcanics, *6* Alluvial cover, *7* Lakes, *8* Rivers, *9* Main escarpment, *10* Faults, *11* Central volcanoes, *12* Hot springs (modified from Abebe et al. 1998)

2.5 The Yerer Tulu Welel Volcanic Lineament Zone and the Wonchi Volcano

Geology

The YTVL is an east–west trending regional structure that partly crosses the Blue Nile basin (Fig. 2.13). It has a length of 800 km and a diameter of 80 km. The YTVL is a kind of half graben bounded by the Ambo fault from the north (Abebe et al. 1998). The Ambo fault has a throw of about 500 m. The major lineaments in the YTVL zone are the Dedessa Lineament (DL) and the Ambo-Butajira Lineament (ABL). These lineaments are deep faults and lineaments that cut across the YTVL. The lineaments are fed by dykes and aligned volcanic plugs.

Along the YTVL, three main rock successions crop out: the Precambrian basement, the Mesozoic sedimentary rocks, and the Cenozoic volcanics. The volcanics are predominant whereas the basement and the sedimentary rocks are locally exposed. The sedimentary rocks (sandstones and limestones) thin out towards the southern part of YTVL. The Quaternary volcanics which cover the YTVL are mainly rhyolites and trachytes with abundant alkali-feldspars, alkali-amphiboles and quartz. Faulting in the YTVL (the Ambo fault and associated lineaments) for instance juxtaposes the Mesozoic sediments and the volcanic cover favoring the formation of high discharge, hypothermal springs in the region. These hypothermal springs have unique geochemistry. They are low pH, high $p\mathrm{CO_2}$, *and* Na–Ca-Mg–HCO_3 springs containing naturally sparkling gas. They are oligo-mineral waters rich both desirable and undesirable trace elements.

Geochemistry and Origin of Naturally Sparkling (High pCO_2) Groundwaters

The majority of the low temperature thermal groundwater springs from the YTVL have high TDS (generally greater than 1,000 mg/L). Sodium (Na) and potassium (K) dominate their cation species and bicarbonate (HCO_3^-) is the dominant anion. These groundwaters fall in the Na–Ca–HCO_3 type groundwaters in the Piper plot. This is because with further hydrolysis of silicate minerals by the Ca–Mg–HCO_3 type waters, the concentration of sodium, potassium, magnesium and bicarbonate increase but Ca and Mg enrichment is limited by an earlier saturation and precipitation of carbonates. The high TDS and the enrichment of sodium therefore testify that the thermal and the high TDS groundwaters have undergone a relatively pronounced degree of groundwater chemical evolution. High fluoride (F) is observed in few water points issuing from acid volcanic rocks of the Quaternary acid volcanics in YTVL and in the groundwaters associated with thermal systems. The high fluoride in the groundwaters associated with acid volcanism has its source from leaching of fluoride bearing accessory minerals. Some rock forming minerals of acid volcanic rocks such as alkali amphiboles, alkali mica or accessory minerals such as apatite often contain F^- associated with OH^- groups of the minerals releasing F^- up on rock water interaction.

Naturally sparkling springs associated with the Wonchi volcano: Figure 2.14 depicts a schematic model characterizing the origin of the low pH high CO_2 springs associated with YTVL. Major hydrologic processes responsible for the origin of the thermal springs are (a) Recharge at high altitude by Ca–HCO_3 type waters, (b) major residence in acid volcanic rocks, open system hydrolysis of silicate minerals, lowering of pH by addition of CO_2 from metamorphic de-carbonation of the underlying Mesozoic sediments or from direct CO_2 input from deeper sources along the fault zone, (c) release of CO_2 on emergence or before emergence and deposition of travertine and silica sinter leading to waters with Na–HCO_3 characteristics as final composition.

Naturally sparkling water in Didessa valley: Here naturally sparkling thermal springs occur in association with dykes. The most notable are those in Wama river valley NE of the confluence with Didessa River, many hot springs are observed emerging along NE–SW trending alkaline basaltic dykes in the flat lowlands of

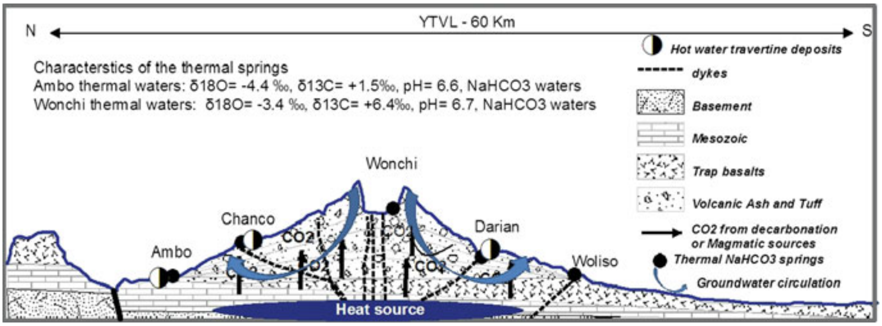


Fig. 2.14 Schematic model showing the mechanism of origin of the naturally sparkling groundwaters around Wonchi Volcano

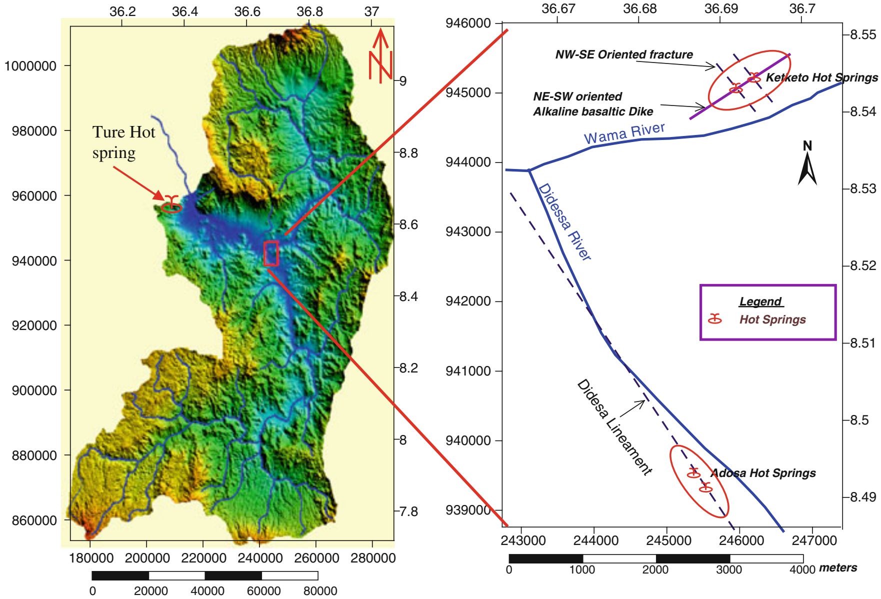


Fig. 2.15 Relation between thermal springs and lineament features in the Didessa valley

Didessa and Wama river valleys. The dykes are 4–5 m wide, composed mainly of K-feldspars, and are vertical, and fractured in the NW–SE direction which is in the major Didessa Lineament direction (Fig. 2.15). In Adosa area, in Didessa river valley, SE of the confluence of Didessa with Wama river, the springs emerge along the main Didessa Lineament. All the springs are related to regional tectonic structure and are aligned along the faulting direction of the area. Deep rooted NE-SW oriented dike, probably to the depth of heat convicting layer cut by younger NW–SE oriented vertical fractures may be responsible for the emergence of the hot springs from regional groundwater flow system. The hot springs may also be indicative of the presence of magmatic anomaly in the area. There are many hot springs at distance of 5–250 m along Ketketo hot springs, and these springs have similar pH, Temperature and EC values and are categorized together under Ketketo springs.

The springs in Didessa valley have relatively higher temperature than those reported in YTVL. The maximum temperature recorded is at Katkato hot spring (maximum 48 °C) as compared with the temperature reported in YTVL hot springs, 25–40 °C (Kebede et al. 2005). The springs are characterized by high Na^+, lower Ca^{2+} and Mg^{2+}, high HCO_3^-, SO_4^{2-} (115–140 mg/l), F^-(5.6–9.6 mg/l) and Cl^- (32–58 mg/l) than ordinary groundwaters in the region. This shows intense rock water interaction that produces the geochemistry of thermal springs because of heating and mantle CO_2. The lateral extension of this sandstone under the volcanic succession and its relation with the hot spring of the study area is not well mapped but like in the Wonchi volcano plays an important role in releasing CO_2 for rock water interaction. This is evidenced by low pH and high HCO_3 type water.

2.6 The Volcanic Aquifers Bounding Addis Ababa

Geology

The Addis Ababa area is located at the junction of the Ethiopian plateau and the Northern section of the Main Ethiopian Rift. As the result the geology is marked by the presence of both the Plateau volcanic cover and the rift related volcanic sequences. The area is covered by the Oliogo-Miocene plateau unit, Miocene rift shoulder basalts, ignimbrites, rhyolites and quaternary basalts and alluvio-lacustrine sediments. The region is also dotted by several central volcanoes such as Furi, Yerer, Wachacha, Menagesha, Bedegababe, etc. (Fig. 2.16).

Oligo-Miocene Plateau Unit (*Termaber and Alaji units-basalts*, *rhyolites and trachytes*): At the base of the rift margin volcanic rocks, the trap basalt (22.8 Ma) of the Plateau unit is in fault contact with the overlying Entoto unit (22.2-22.0 Ma) (Morton et al. 1979; Chernet et al. 1998). The Entoto unit consists of trachyte-rhyolite flows and associated ignimbrites at its base (22.2 Ma) and plagioclase phyric basalt (22.0 Ma) in its upper part. Because of their close relationship, the Plateau and Entoto units are here collectively referred to as the plateau unit (specifically the Upper basalt sequence of the Plateau volcanic). In traditional stratigraphic nomenclature the top part of plateau basalt sequence is composed of the Termaber Basalt and the Alaji Rhyolites. The Alaji Rhyolites unit is exposed in the northern central part of the study area. It is consisting of rhyolites, ignimbrites and subordinate trachytes. Obsidian bearing rhyolites are common. The Termaber Basalt is the dominant unit exposed in the western and northern plateau parts and watershed divide of the Awash and Abay river basins. In the rift valley part of the

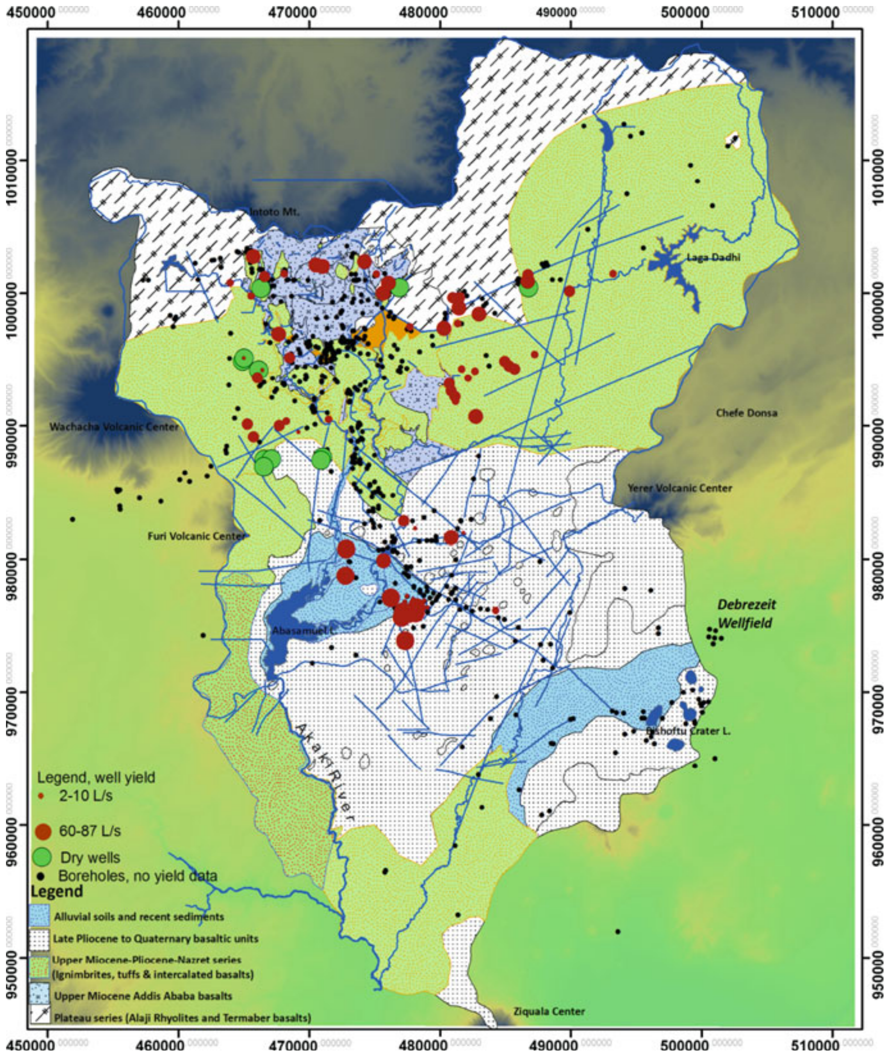


Fig. 2.16 Geological Map of the Addis Ababa area (Akaki river catchment). *Green circles* show sites of dry wells (modifed from AAWSA 2002)

study area this unit is downthrown by the regional east west running Ambo fault (which marks the northern boundary of the YTVL-see Sect. 2.5) and is covered by thick (300 m) younger ignimbrite (Lega Dadi and Melka Kunture area mapping boreholes data) or Middle to Upper Miocene Addis Ababa Basalts. It is consisting of mainly scoraceous lava flows and at places it is columnar olivine bearing basalt as pockets within the scoraceous components. It is highly weathered and fractured.

Upper Miocene Addis Ababa basalts: This unit is composed of principally of coarse grained olivine-plagioclase phyric basalts. The vertical extent of these basalts in less than 130 m and overlies the ignimbrites associated with the earlier trap basalts. The eruption of the Addis Ababa basalts took place at 7–9 Ma after considerable hiatus between 22 and 10 Ma.

Upper Miocene-Pliocene rift series (*Nathret group*) *volcanic*: This unit comes in complex pattern and is composed of unwelded tuff, welded tuffs, ignimbrites, rhyolites and trachytes. They are associated with or derived from prominent trachytic volcanic centres such as Ziquala, Furi, Yerer, Wachacha, Menagesha etc. The thickness of the units may rich 300 m or more. The unit comes in complex inter-fingering of volcanic products coming from different volcanic centres. The base of the Nazret group unit is made up of the Upper Miocene Addis Ababa basalts. The Nazret group rocks crop out in most part of Eastern part of Addis Ababa. Here is composed of welded tuff (ignimbrite) and non welded pyroclastics fall (ash and tuff). It is greyish to white colour and when welded it exhibits fiamme textures, elongated rock fragments of various colour. Around the Lega Dadi plain and Melka Kunture (northwest of Ziqala) area the thickness of this unit reaches up to 200 m. In the Becho plain area (west of Furi volcano in Fig. 2.16) it is covered by thin 5–7 m thick residual soil developed from the same rock. In the Southern part of the Akaki catchment (Fig. 2.16), this unit is represented by sequence of welded per alkaline rhyolitic ignimbrite. The unit comprises numerous rhyolitic and trachytic domes. Rock fragments and crystals, generally broken, are abundant; alkali feldspars, quartz, aegirine and amphiboles are the most common crystals. In Chefe Donsa are the unit consist of fall deposits (ash, tuff and pumice) and poorly welded ignimbrites of rhyolitic composition. Central volcanic units of tracytic composition in this unit include the Wachacha, Furi and Yerer Trachytes. These are mainly trachytic lavas exposed at Wechecha, Furi, Yerer, Western and South western ridges forming an elevated ridges or mountain picks. The Yerer trachyte is elevated about 1,000 m from the surrounding plain. Basalt formation is also associated with this unit though it has been argued that these basalts within the Nazareth series are equivalent to the Upper Miocene Addis Ababa basalt.

Late Pliocene to Quaternary basaltic units: This unit represents basalt flows associated with numerous scoria cones found on the subdued escarpments of southern part of Addis Ababa and around Debrezeyit. These basalts typically range in age between 2.8 and 2 Ma and are often referred to as the Bishoftu Basalt. Bishoftu basalts are characteristically alkaline. Volcanism of quaternary in this unit is represented by various spatter cones and maar lakes and fissural basalts around Debrezeyit. In Akaki area the basalt units are highly vesicular basalt and in places the vesicles are filled by secondary minerals. It is dotted by scoria and spatter cones. Thickness of the entire units exceeds 200 m.

Tectonics

The geology of **Addis Ababa** is the result of the intersection of two major tectonic features and Cenozoic to quaternary volcanism. The two tectonic features are the

Yerer Tullu Welele Volcanic Lineament (YTVL) and the western margin of the Main Ethiopian Rift (MER). The YTVL is an East–West running fault and volcanic zone (Sect. 2.5). Abebe et al. (1998) elaborately described the origin of the structures in YTVL, their evolution and their importance in controlling the origin of quaternary volcanics in the region. The intersection between YTVL and MER created the Addis Ababa embayment, where the rift become wider and the step faults defining the rift are subdued. Kebede et al. (2005) described this zone as ‘the YTVL hydrogeologic switch’ whereby the groundwaters are drained from central part of the Plateau and flows down the rift following regional topography. The E–W faults act as a barrier to the N–S groundwater flow around Addis Ababa resulting in the emergence of productive thermal springs in the central Addis Ababa.

Groundwater Occurrence and Flow

The hydrogeology of this region is of critical importance because the Addis Ababa City (population >3,000,000) gets 40 % of its water supply from groundwater (Akaki well field in southern suburb of Addis Ababa) which is part of the intersection zone. Recharge rate estimation in the region have been the subject of many previous studies (Gizaw 2002 and references therein). Many previous studies assume groundwater flow path follow the topography (AAWSA 2002) and it is generally from north to south.

Mirroring the four geologic units four hydrostratigraphic units can be recognised in Addis Ababa area (Fig. 2.16, Table 2.7). The *Plateau series* composed of Alaji rhyolites and the Termaber formation are exposed mainly in the higher grounds in a high rainfall area in the north. When exposed these units are characterised by the presence of shallow circulating groundwaters and discharges to low discharge springs as evidenced by numerous springs emerging in the Entoto ridge and regions in the north. Groundwater occurs in scoraceous layers and in flow contact zones. The southward extension of the plateau series is intercepted by the prominent E-W running Ambo fault of the YTVL (the fault defines the contact between the plateau series and the rift series rocks-Fig. 2.16). The throw of this fault is around 500 m (see elevation contrast between the highland and the lowland from the background coloured topo-map in Fig. 2.16). MWR (2007) reports that, the Termaber basalts extend underneath the Rift series and the Quaternary volcanic of the region forming important regional aquifers. This aquifer is characterised by artesian and confined condition. The confinement is locally assisted by the presence of low permeability ignimbrites and tuffs belonging to the Nazareth series volcanic.

The upper *Pliocene-quaternary basalts* form an important shallow to deep aquifers and is currently the most widely exploited for water supply in Addis Ababa region. Because of its scoraceous structure this unit holds important volume of groundwater. Prominent well fields such as the Akaki and the Debrezeyit well fields tap this aquifer. The aquifer is mostly unconfined while locally the intercalated ash units and paleosols favour semi confined or confined conditions.

Table 2.7 Hydrogeologic properties of major aquifers around Addis Ababa

Aquifer unit		Average yield of water well (l/s)	Transmissivity (m^2/day)	Storativity	Remark
Late Pliocene to Quaternary basaltic units (Scoria, scoraceous basalts, vesicular and fractured basalts including the Akaki and Debrezeyit well fields		3–87	1,833–100,000	0.0065–0.016	Highly productive
Upper Miocene Addis Ababa basalts-fractured and weathered basalt aquifer with inter volcanic coarse sediment		0.5–20	2–6,000		Moderately productive
Upper Miocene to Pliocene-ignimbrites, welded tuffs, ashes and unweldded tuff and associated basalt intercalations		0.4–15	15–110	0.0001–0.003	Least productive
Oligo-Miocene plateau unit (Upper Basalt Sequence)	Termaber basalts	5–200 l/s	??	??	Semi confined to artesian condition
	Alaji rhyolites	Very low	Non aquifer, fractured and weathered zones in this region are important recharge zones and shallow circulating groundwater could be tapped through hand-dug wells and from springs		

The thickness of the unit reaches more than 300 m in places. The lateral continuity of this unit is often interrupted by the Nazareth series units and volcanic centres. The transmissivity of this aquifer is highly variable as a function of faulting and fracturing and the type of basalts. It varies from 50 to 27,000 m^2/day. The yield of boreholes varies accordingly. Geochemically the groundwaters are characterized by fresh groundwater with electrical conductivity value less than 700 μS/cm and TDS less than 400 mg/l. Most of the groundwater of this aquifer forms the baseflow of the streams in upper Awash and part of it is discharged into Debrezeyit lakes, where most of the outflow from these lakes is through evaporation and also recharges the lower basaltic aquifers.

The *Nazareth series* volcanics because of their low permeability and storage properties act as local aquifers of low yields or act as regional confining layer for the Plateau series units. The phyroclasitc units and welded ignimbrites act as low productivity aquifer along the weathered and fractured zones. In central, eastern and south western corner of Akaki River catchment (Fig. 2.16) the unit act as a confining layer for underlying plateau basalts and leads to a number of artesian wells (e.g. Well at Melka Kunture, CMC, and Legadadi etc.). Most of wells which turn dry on drilling are mostly located on this unit (Fig. 2.16). The Upper Miocene Addis Ababa basalts also form locally important aquifer.

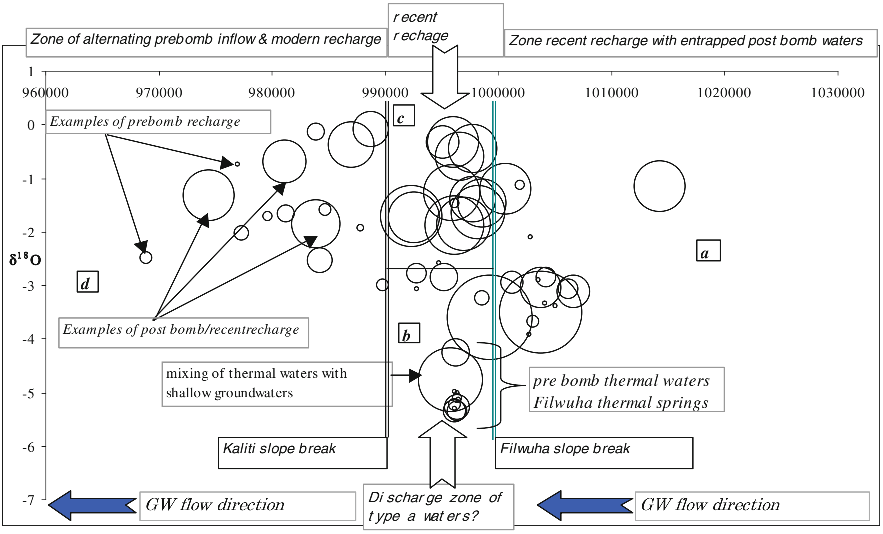


Fig. 2.17 Spatial tritium and oxygen 18 variation in groundwaters of Addis Ababa. The figure show latitudinal variation (along a transect taken parallel to longitude 470500 UTM coordinate) in δ^{18}O and tritium content of groundwaters around Addis Ababa along Entoto-Akaki transect. Tritium concentration varies between 0.1TU (the *smallest circle*) and 20TU (the *largest circle*)

Groundwater flow is generally from north to south following the topography. Direct recharge from rainfall through soils is the principal source of groundwater recharge. Discharge takes place to springs and streams and in central part of Addis Ababa discharge also takes place to thermal springs.

Isotopic and Geochemical Evidence of Groundwater Occurrence and Flow

Geochemical and isotopic evidence show there are at least four recognizable groundwater compartments between Entoto and Akaki. The four compartments of groundwaters are identified based on tritium (^{3}H) content, δ^{18}O and the geographic distribution of the samples as shown in Fig. 2.17. The following major observations can listed from the examination of the figure.

1. Around the Entoto ridge (type *a*) both very high tritium and very low tritium (pre-bomb[4]) waters are observed (North of 10,000,000 UTM north)

[4] Exclusively pre bomb recharge refers tritium content less than 0.6 TU if measured in 2003 in Addis Ababa.

2. In the central transect (between 9,850,000 and 10,000,000 UTM north) of the town two types of groundwater exist. These are (1) the ^{18}O enriched but tritium rich waters (type c) and (2) the ^{18}O depleted but low tritium waters (type b). The Filwuha thermal springs the most depleted of the ^{18}O depleted low tritium waters of type b.
3. The Filwuha thermal springs (type b) are depleted in $\delta^{18}O$ than the modern day or the pre-bomb waters of Entoto
4. Some of the Filwuha springs although they are the most depleted they contains some tritium (~3TU)
5. Excluding the Filwuha thermal springs which are the most depleted, the low tritium containing waters in central transect (type b) of the town have similar $\delta^{18}O$ composition to the Entoto groundwaters
6. The low tritium and ^{18}O depleted waters of the central transect of the region (type b) are rarely observed in the low lying plain (south of 9,800,000 UTM north) beyond Kaliti (type d). Likewise the ^{18}O depleted water of Entoto type is rarely observed in the southern sector of Addis Ababa. Generally water around the Akaki well field (type d) has similar $\delta^{18}O$ composition to that of c type waters. But the low tritium waters of type d are more similar in $\delta^{18}O$ to the zone c waters. Most high tritium containing waters of zone d waters generally contain also enriched $\delta^{18}O$

Origin of Groundwaters Around Addis Ababa

1. Groundwaters of the region occur in compartments. At least four compartments vertical/horizontal can be identified from isotopic evidence
2. The presence of pre-bomb type groundwaters in Entoto indicates entrapment or slow flow of groundwaters in rhyolitic Entoto ridge. This shows the low transmissivity of the ridge. This is consistent with the aquifer transmissivity distribution of Addis Ababa (AAWSA 2002) determined from physical approaches
3. Entoto type meteoric waters (low $\delta^{18}O$) are not observed in groundwater wells or springs beyond the Kaliti slope break, therefore the Entoto ridge is not the major recharge source to shallow groundwater wells beyond Kaliti including the Akaki well field. The flow of Entoto type water underneath the well field at greater depth (exceeding 250 m) cannot be ruled. However, low tritium waters in the central sector (type b) which have similar $\delta^{18}O$ as that of the Entoto waters are most likely recharged by infiltration at Entoto.
4. The similarity in their ^{18}O content shows that the groundwaters of type b in central sector of Addis Ababa seems to be the main recharge water/zone for the low tritium groundwaters south of 980,000 UTM north. The difference in tritium is related to radioactive decay (ageing of the water) as it moves from the central sector of the transect to the lowland.
5. The high tritium and ^{18}O enriched groundwaters beyond south of 980,000 UTM north are most likely recharged locally by vertical infiltration. The enrichment in ^{18}O and the high tritium indicate local vertical recharge.

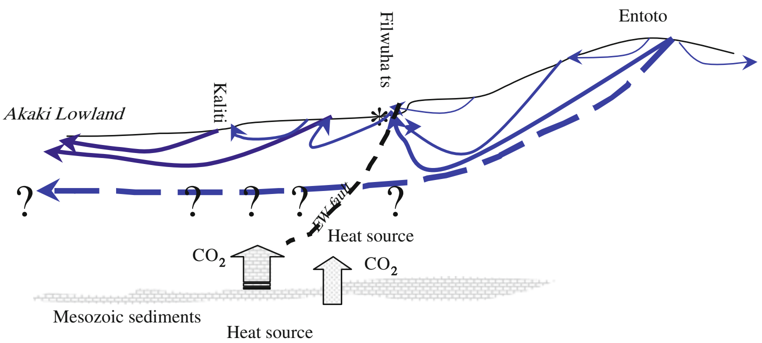


Fig. 2.18 Schematic diagram of groundwater flow patterns along N–S transect. The E–W fault in the central sector of the region acts as a major barrier to the N–S flowing groundwaters. Carbon dioxide from de-carbonation of the Mesozoic sediments is the principal catalyst for the hydrolysis reaction that produced the Filwuha high TDS high HCO_3 waters. Along the east west Filwuha fault barrier the groundwater inflow from west parallel to the fault can not be ruled out

6. The source of tritium in tritium containing thermal waters of Addis Ababa is local mixing with shallow tritium containing waters of the sector (c) upon ascent.

The Recharge Role of Entoto Ridge

The role of mountains in recharging adjacent groundwater bodies (alluvial fills or mountain front aquifers) is not as simple as one can imagine as '*mountains are recharge sources and valleys or adjacent low lands are discharge areas*'. The role of mountains in recharging adjacent aquifers depends on the permeability of the mountain block, the rainfall condition on the mountains, the presence of favourable geologic structures, and the proximity of the mountains to the aquifers. Figure 2.18 shows schematic groundwater flow pattern across the Entoto (North) Akaki (South) transect.

Figure 2.17 shows that the majority of groundwater wells and springs at the foot of the Entoto Mountain have higher tritium content than the majority of springs emerging within the mountain. This testifies that the Entoto Mountain is not feeding these wells and springs at its foot. One would imagine that the infiltration at Entoto follows deeper flow paths and is not detectable in shallower aquifers at the foot of the mountain. However, deeper aquifers further south of the Entoto ridge contains ^{18}O enriched waters than the Entoto ridge springs or wells. The groundwaters in the southern sector of Addis Ababa have similar ^{18}O content to aquifers in the central part of the transect. Thus main recharge source for the aquifers at furthest distance (Akaki) from Entoto seems the central sector of the slope (foot of Entoto Mountain) or local vertical recharge for those ^{18}O enriched (shallow) aquifers.

Origin of the Filwuha Thermal Springs

Figure 2.18 shows schematically the origin of the Filwuha thermal springs. Chemically and isotopically ($\delta^{18}O$, $\delta^{2}H$ and $\delta^{13}C$) the Filwuha thermal springs (type b in Fig. 2.17) are distinct from adjacent cold temperature groundwaters. As already noted by Gizaw (2002) the springs are characterised by high TDS, high Na and bicarbonate. Furthermore the springs are enriched in carbon-13. They are the most depleted in oxygen 18 and deuterium. All these observations indicate that the waters are characterised by intensive degree of rock water interaction relative to the cold groundwaters. Moreover, on Entoto plateau the present day $\delta^{18}O$ content of groundwaters is 2 ‰ more enriched than the Filwuha springs. These suggest:

1. The present day recharge on Entoto ridge is not the major source of recharge for the Filwuha springs
2. The Filwuha springs follow deeper circulation path and were recharged under a relatively colder climate than today but they were recharged at Entoto or elsewhere
3. The enrichment in carbon-13 is caused by CO_2 coming from mantle or from the metamorphic de-carbonation of the Mesozoic sediment buried at deeper levels.

Aquifer Vulnerability Map Versus Tritium Distribution

Tritium composition of groundwaters can indirectly tell the vulnerability of aquifers to pollution. The assumption is that tritium containing groundwaters are recently recharged and have a direct connection to the surface. Low tritium waters represent those flow lines which follow deeper circulation pathways or those with longer subsurface residence time. There is a likely hood of high vulnerability near recharge zones. The tritium distribution shows groundwater aquifers type b, which contains the highest tritium, is located in the central sector of Addis Ababa. These aquifers are the most vulnerable. The deeper aquifers of the Akaki plain and some region of the Entoto ridge are the least vulnerable. Although some slight differences are observed around the Entoto ridge, evidence from tritium is consistence with the GIS based aquifer vulnerability map (Alemayehu et al. 2005) of Addis Ababa.

2.7 Scoria Cones, Maars and Associated Groundwater Resources

Geology

A maar is a low relief volcanic crater that is created by an explosion caused by lava or magma coming into contact with groundwater. Typical feature of a maar is low relief of the surrounding terrain and maar are found below the general low relief surface. Maars are shallow, flat bottomed depression having formed as a result of violent expansion of magmatic gas or steam. Most maars have low rims composed of a mixture of loose fragments of volcanic rocks and rock torn from the walls of the diatreme. Maar depressions when filled with water form maar lakes.

Several maar lakes are found in Ethiopia many of which occur as clusters of maar lakes or dry depressions. Notable cluster of maar lakes are found in the following locations:

1. Central Ethiopia in western shoulder of Main Ethiopian rift. These are the five Bishoftu Crater Lakes (Hora, Babogaya, Bishoftu, Arenguade and Kilole and more than 4 other empty maars) (see Fig. 2.16 for location of Bishoftu Crater Lakes).
2. Southern Ethiopian lowland bordering Kenya. These vast volcanic plain of the western Borena (Fig. 1.2) lowland is dotted by numerous maar lakes often filled with salt deposits or brines (e.g. Mega Crater, Goray etc.).
3. The maar lakes occur in the central Ethiopian rift near the head waters of Bilate River. This cluster is located on the southern portion of the so called Siltie Debrezeyit ridge (a fault zone that runs parallel to the rift and defining the western margin of the central Ethiopian rift). This cluster includes the Budameda, and Ashenta maar lakes at the foot hill of Butajiara mountains.
4. The fourth cluster occurs in the central Gojam plateau on the flanks of the Choke mountain shield. These include the Zengena and Tirba maar lakes.

All these maars have several things in common. For example all are associated with quaternary basalt volcanics. They are fed by groundwater as dominant form of water inflows.

Groundwater Hydrology

Typical linkage of maar lakes with groundwater lies in the fact that the very genesis of maar is related to subterranean explosion of a land surface because of interaction between an intruding magma (dyke or sill) and shallow groundwaters. Secondly because of their isolation from surface water drainage owing to the low relief and narrow maar walls the major water and solute flux to maar lakes come from groundwaters.

Clustered maar lakes are therefore indicators of presence of shallow groundwater aquifer (at least at the time of their explosion). Maar lakes are also important reservoirs that maintain recharge to downstream groundwaters. For example water wells in Debrezeyit town obtain up to 50 % of their recharge from Bishoftu Crater Lakes (Kebede et al. 2002). Wetlands south of Lake Zengena are fed by groundwater outflow from the lake.

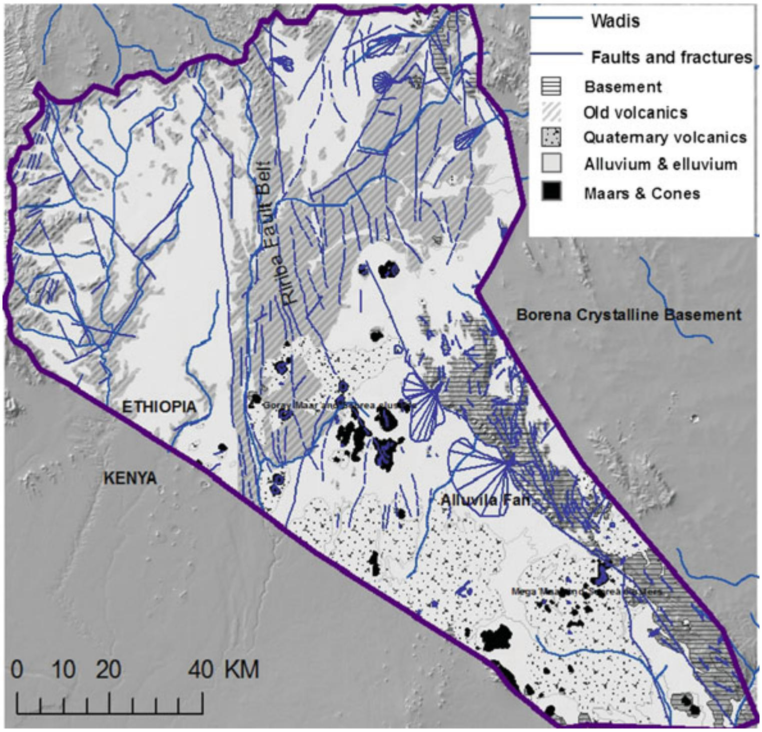


Fig. 2.19 Distribution of maar lakes and quaternary basalts in the western lowlands of Borena

Maar Lakes and Depression in Western Borena Lowlands

The scoria cones, maars and flows in the southern Ethiopia bordering Kenya are associated with volcanism related to current development of a new rift refered to as Ririba fault belt. The lithologies associated with these features are mostly vesicular basalts and scoraceous ejecta. The formation of maar signal explosive activity when magma interacts with groundwater. The scoria cones and maars are confined to the central and south eastern part of the Ririba basin. The cones and maars are often up to 2 km in diameter and protrude up to 200–400 m above the surrounding plain. The cones are well preserved except in places where they have been breached by subsequent eruption centers. The maar lakes contain extremely salty waters and in places salt deposits (e.g. Goray and Mega craters).

Hydrology of these maar lakes is poorly known. Nevertheless the maars in the south eastern tip of Fig. 2.19 are associated with productive and high potential aquifers. Groundwaters associated with the basaltic aquifers are characterized by relatively low EC and high HCO_3. The waters have low pH (high pCO_2) indicative of volcanic gas input from deeper sources. Ca, Mg and Na dominate the cations. The accumulation of salt in the crater lakes (Magado Crater and Goray) is indicative of groundwater inflow to the lakes but limited or no groundwater outflow, a situation that leads to accumulation of salt over time.

The Bishoftu Crater Lake in Central Ethiopia

The Bishoftu Crater Lakes are located on the western escarpment of the Main Ethiopian Rift, 45 km southeast of Addis Ababa, at 1800 to 2000 elevation (Fig. 2.20). The five permanent lakes are Hora (also known as Beite Mengist), Babogaya (Pawlo, Bishoftu Guda), Bishoftu, Kilol (Kilotes), and Arenguade. Artificial lakes and ponds in the area include Lake Kuriftu, a reservoir that fills an originally dry crater depression following the diversion of a tributary of the nearby Mojo River. Lake Cheleleka is a large, shallow swamp that has been present since the early 1970s. They are roughly circular in shape, with areas between 0.6 and 1 km^2. The lakes range in depth from 6.4 m (Lake Kilole) to 87 m (Lake Bishoftu). The lakes have no perennial surface inlets or outlets, and are fed by direct precipitation, surface runoff from the crater walls, and by groundwater.

The bedrock of the area is composed of 9 Ma old basalts and 1–4 Ma old acid volcanics (Gasparon et al. 1993). The maars, cinder cones, and lava flows represent more recent (10 Ka) volcanic activity.

The transmissivity of the older basaltic aquifers range from 400 to 21,600 m^2/day. The younger basic pyroclastic rocks interbedded with minor acidic products make up the largest part of the Ada'a plain and have transmissivities ranging from 1,100 to 18,000 m^2/day. The scoria cones and the acid volcanic domes are believed to be the major zones of groundwater recharge. Isotope hydrological and chloride mass balance studies have shown the water budget of the Lakes as indicated in Table 2.8 (Kebede et al. 2002). The lakes major water inflows are groundwaters. The low salinity of the Lakes is indicative of loss of significant portion of their water to groundwaters, though evaporation account for more than 75 % of water loss in all cases. Table 2.8 shows the water balance of the Bishoftu Crater Lakes and contribution of groundwater to the lakes.

Isotope evidence (Fig. 2.20) shows groundwater in the south western sector is more enriched than groundwaters in northern, western and north eastern sector the region. This implies that groundwater from all the region converges to the crater lakes and leaves the lakes towards the southwestern sector.

The Maar Lakes at the Foot Hill of the Butajira Mountain

Here there are cluster of three maar lakes filled by shallow saline waters. Of the three lakes better hydrogeologic data exists for Lake Tilo. Lake Tilo lies within a maar formed by explosive release of volcanically heated water below the Rift floor. It is one of three adjacent craters lying at an elevation of 1,545 m near the

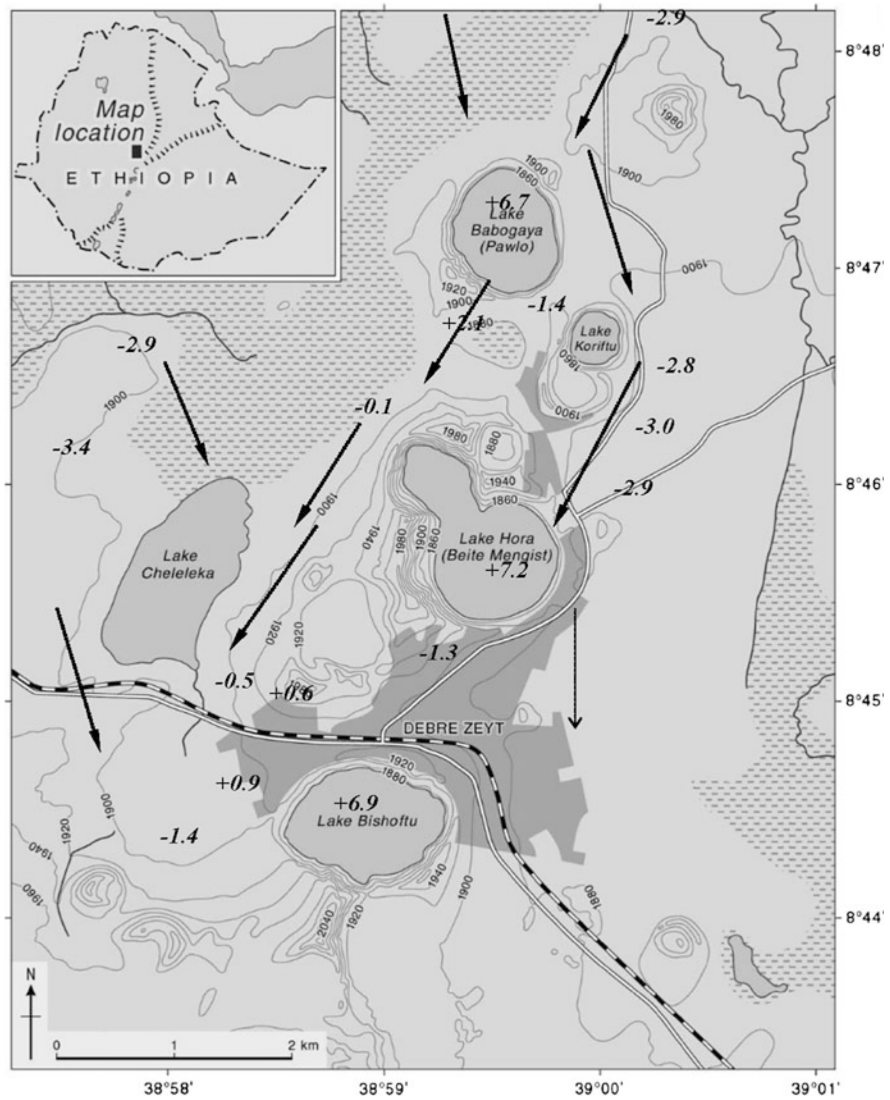


Fig. 2.20 Geomorphic features of the Bishoftu Crater Lakes, arrows indicated inferred groundwater flow direction around the Bishoftu Crater Lakes. Inset numbers are indicative of δ^{18}O content of groundwaters and Lakes

western edge of the Rift in south central Ethiopia (Fig. 2.21). Lacustrine marls with abundant freshwater mollusks and ostracods are evident on the crater walls, 40–60 m above the present lake surface indicating shallow groundwater discharge to this site in the past. The lake has a maximum depth of 10 m and is saline and dark brown in color; the hot springs are relatively dilute. Estimates of the

Table 2.8 Water balance of Bishoftu Crater Lakes and the role of groundwater in their hydrology

	Unit	P	Gi	R	E	Go
Hora	m^3/year	854070	552355	353165	1759590	~0
	%	49	31	20	~100	~0
Babogaya	m^3/year	4805570	587514	121595	990090	199590
	%	40	50	10	83	17
Bishoftu	m^3/year	771070	804586	160190	1588590	147256
	%	44	46	9	92	8

P Precipitation on Lake, *Gi* Groundwater inflow, *R* Runoff to the lake from crater wall, *E* Open water evaporation, and *Go* Groundwater outflow to adjacent aquifers

hydrological and salinity budgets for the lake (Telford and Lamb 1999) suggest that the springs account for only twelve per cent of water inflows to the lake (Fig. 2.21), but sixty-seven per cent of the solute inflows, the remaining thirty-three percent of the solute inflows being derived from the surface catchment via overland flow (Telford 1998).

The Maar Lakes of the Central Gojam Plateau

Here two prominent maar lakes are encountered namely Lake Zengena and Lake Tirba (in association with the quaternary basalts exposed around Injibara town). Both lakes have depth exceeding 150 m. They are flat bottomed. The principal source of water input is groundwater while evaporation accounts for 50 % of water loss and the rest is accounted by groundwater outflow. The lakes occupy high elevation plateau in the northwestern slope of the Choke mountain chain. They are surrounded by high aquifer productivity quaternary basalts. Salinity of both lakes is very low and is in the order of 100–200 mg/l.

2.8 The Alluvial Grabens Bordering the Rift

Geology

The junction between the highlands and the rift valley come in several types of architecture. A detailed account of the geometry of the plateau—rift interface can be referred from Bosellini (1989) and the hydrogeological significance from Kebede et al. (2007). Marginal grabens are one of such characteristics of the geometry of the plateau rift interface. Marginal grabens are smaller rifts bounding the principal rift. The can also be called 'rift within rift' structures. When these marginal grabens are filled by alluvio lacustrine sediments they offer sites of

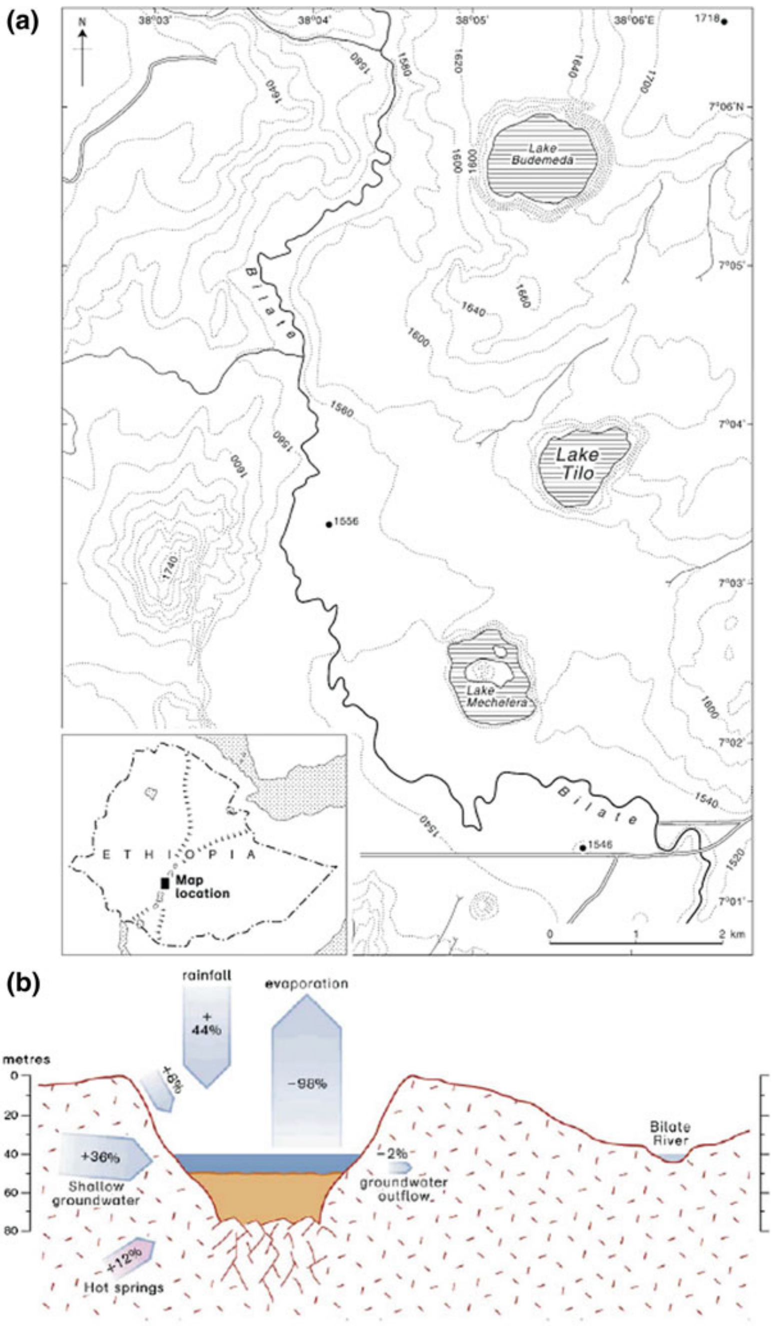


Fig. 2.21 Simplified hydrological characteristics of the Tilo maar lake (from Telford 1998)

highest potential of groundwater storage and availability. Several prominent alluvial sediment filled marginal grabens bound the Ethiopian Rift (e.g. Raya graben—Fig. 2.24; Boyo graben—Fig. 3.11; Shinile graben—Figs. 3.2 and 3.3; see also Sect. 3.13). The thickness of sediments and the sedimentary facies vary from one graben to another. The graben with the thickest and extensive sediment fill is the Shinile graben followed by the Raya graben.

Box 1: Communal features of alluvio-lacustrine sediments in the tectonic valleys

- Generally coarse grained near the escarpment front where they occur and fine grained away from the escarpment, property of aquifers mirror this changes in grain size and sorting. Higher transmissivity are usually noted near the foot slope and decreases away from the foot hill
- The geochemistry of groundwaters also mirrors changes in the grain size and groundwater flow direction. Generally at the foothills waters are of Ca–HCO_3 type with minor Cl and SO_4. Away from the foot hills TDS, Na, Cl and SO_4 increase and waters become mostly Na-HCO_3–SO_4–Cl type

The Borkena Kobo and Raya grabens share similarities in their geology and structure. Despite the significant distance in the N–S direction of this transect, the E–W progression in geology, tectonics and aquifer composition are similar. The plateau and the escarpments are covered by trap series volcanics, and the marginal grabens are filled by alluvial materials and thin lenses of lacustrine sediments. The transitional slope between the rift floor and the grabens is covered by basalts belonging to the Afar Stratoid, and the rift floor is covered by Quaternary basalts at depth and marine, lacustrine and alluvial sediments near the surface. The marine and lacustrine sediments contain thin lenses of evaporites (Battistelli et al. 2002). Detailed account of hydrogeology of each of the grabens is given in different sections in this book but Box 1 gives a common hydrogeologic features of the alluvial grabens.

2.9 The Bulal Basalt Aquifer and Associated Aquifers

Geology

The Bulal basalts underlay a half bowl shaped low laying areas between the Tertiary volcanic highlands from west and the Borena Precambrian basement rocks from east (Fig. 2.22). The volcanic highland in the west separates the Bulal Basalts from the Chew Bahr Rift. Separating the Bulal basalts and the Precambrian

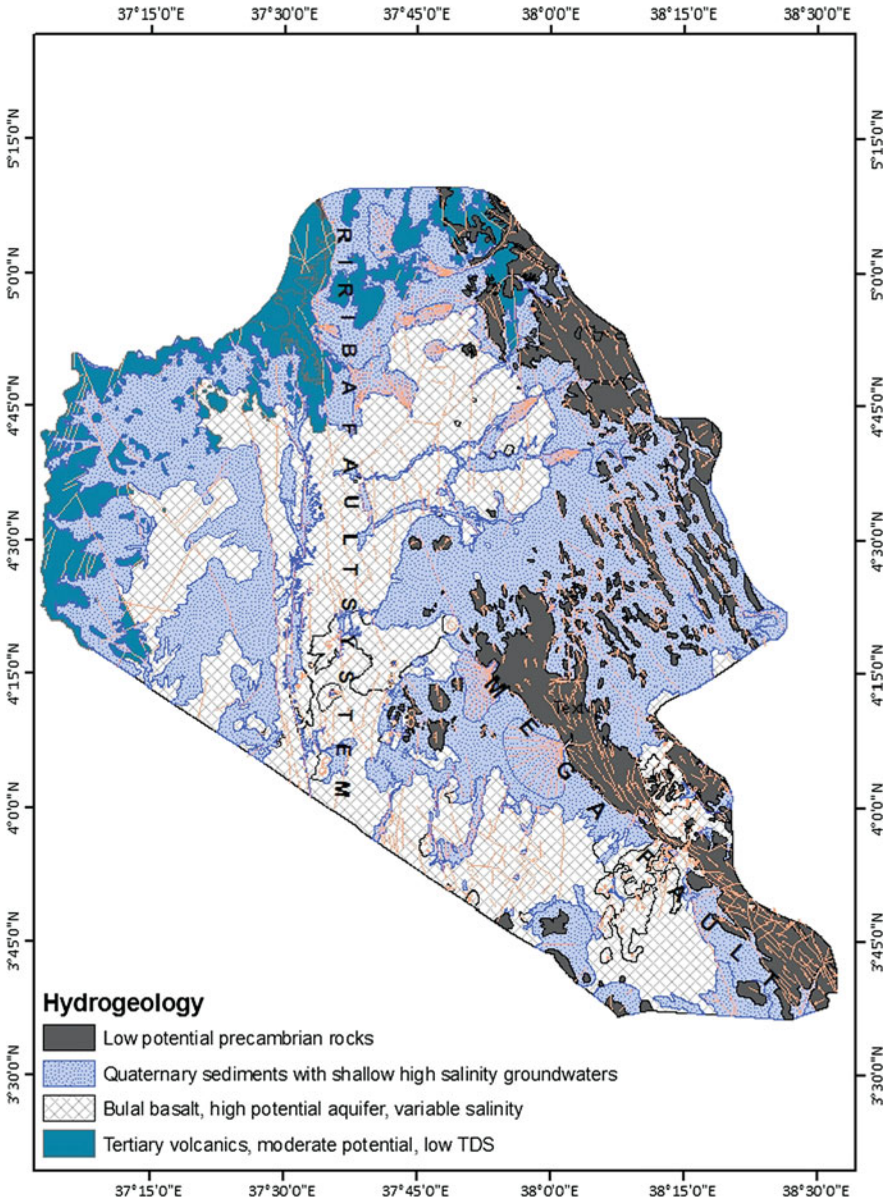


Fig. 2.22 Geologic map and cross section of the Bulal basalt aquifers and associated lithologies (from OWWDSE 2009)

basement in the east is the regional Mega fault belt running NW–SE. The basalts are made up of horizontally layered sheets of extensive flood basalt of late Tertiary age. The major fault/fracture systems in the area (Ririba fault system) run NS trend extends south into Kenya. Quaternary basalts also occur dotting the region as scoria cones, maar and craters. The major part of the volcanic formation is mantled by up to tens of meters thick alluvio-lacustrine sediments.

Hydrogeology and Groundwater Occurrence

Recharge to the Bulal aquifer mainly takes place at basin boundaries along the Mega fault belt and from floods confined to the Ririba fault system. Annual recharge rate is estimated to vary between 40 and 60 mm/year. Drainage is entirely intermittent. Flood water converges in the valley bottom and flow towards Kenya during flood periods. The mean annual aerial rainfall of the area is estimated to be about 593 mm and occurs between September and November and March and June. Mean annual potential evapo-transpiration reaches 1,700 mm/year. Maar lakes dotting the plain are indicative of groundwater circulating at deeper levels during the explosion of the Maar Lakes. The N–S oriented fault zones act as underground water conduits connecting recharge areas located in Ethiopia with discharge areas in Kenya.

The highest recharge takes place in the Ririba fault zone and it covers about 44 % of the area. The overall weighted average recharge estimated for the area is about 54 mm per year. Taking into consideration the low Cl groundwaters (0–50 mg/L) and the mean Cl content or rainwater from March–April rain at 2–3 mg/L (Kebede 2004) and mean annual rain in the highland regions at 700 mm, recharge has been estimated to vary between 30 and 45 mm/year.

Water table map in the Bulal basalts and adjoining highlands (Fig. 2.23) show that mostly groundwater converges towards the Ririba fault zone from the adjoining highlands and leave the volcanic plain of Borena to flow towards Kenya in the south.

Geophysical investigation (Vertical Electrical Sounding-VES) surveys indicate that the area is underlain by four main resistivity layers. These layers correspond, from bottom to top, the Precambrian basement rocks, highly weathered and/or fractured basalts, slightly fractured to massive basalt and the surficial loose and unconsolidated material. Geoelectric sections indicate that thick (50–90 m) deposits of unconsolidated materials (clay, silt, sand, gravel) cover the Ririba and Bulal River flood plains. Direct evidence from lithologic logs indicate the Bulal basalt is characterized by alternating layers of fractured basalt and scoraceous basalt with top part covered by silty clay soil of 2–6 m thickness.

Main groundwater strikes range from about 75–157 m below the ground. The water table is under confined and semi–confined condition with recorded pressure heads ranging from about 11–61 m above the water strike. The yield of the wells was found to be highly variable. The test wells located within the main Ririba rift area locality relatively higher yields.

The drilling result shows the main aquifer in the volcanics is situated between about 100 and 250 m depth. Below this depth lies the basement rock that acts as regional impermeable layer.

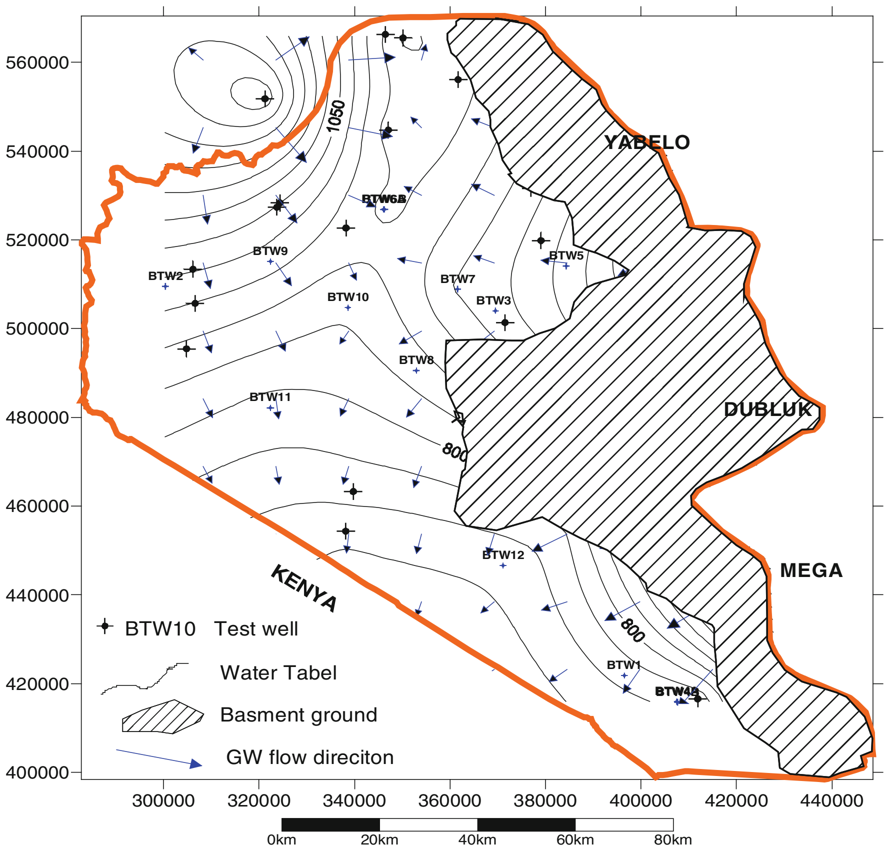


Fig. 2.23 Water table map of the Bulal basalt aquifer (from OWWDSE 2009)

From the drilling and testing results as well as related field hydrogeological evidences two other laterally less extensive aquifers of local importance has been recognized. These are (a) the alluvial deposits mantling the Bulal basalt and (b) the quaternary scoria and basaltic tuffs in the south eastern sector of the area bordering Kenya. Pumping test results indicate the transmissivity of the Bulal basalt aquifers is in the range of 10 m^2/day 100 m^2/day.

2.10 Groundwaters in the Main Ethiopian Rift and Flow Along Plateau-Rift Transects

The volcanic aquifers of Eastern Africa are placed as the least understood hydrogeologic system (UNESCO 2006). Compared to other aquifers in Africa, the volcanic aquifers of Eastern Africa are known for their lateral discontinuity, low storage capacity, and shallow groundwaters circulation following shallow flow paths.

The suitability of groundwater for water resource use in the rift is hampered by water quality limitations. In the center of East African rift, higher levels of salinity (Reimann et al. 2003) and fluoride (Kilham and Hecky 1973; Yirgu et al. 1999; Ayenew 2008) and elevated concentrations of trace elements such as uranium and arsenic (Reimann et al. 2003) are the most widely documented groundwater water quality degraders. In a recent survey in the Central Ethiopian Rift, Kassa (2007) documented that 80 % of groundwater well failures and abandonment after construction is related to discharge of poor quality (high salinity and high fluoride) waters.

In mountain bounded aquifers such as the Ethiopian rift aquifers because of the complexity of the stratigraphy and hydrography understanding the hydrogeology of the rift floor necessitates an understanding of the mechanism of groundwater flow and origin along the mountain—valley transect. Through this transect analysis important hydrogeological questions are sought to be addressed including (a) at what rate—fast, slow—groundwater recharged at high plateau reaches the valley aquifers, (b) what is the mechanism of the flow-diffuse, focused, (c) what is the contribution of each component of recharge—mountain block recharge, mountain front recharge (e.g. valley precipitation, flood water, lateral inflow from mountain etc.), (d) at what depth-shallow or deep—the groundwater from the highlands reach the valley bottom. Addressing this necessitates a closer look at the hydrogeology of mountain valley transects as given below.

The Western Afar Transect

The western side of the Afar depression is straddled by the Ethiopian plateau with elevation ranging between 3,600 and 4,000 masl. There is a sharp scarp transition zone over a distance of 70 km from 3,700 m at the edge of the plateau, to 500 m in the depression, which comprises an almost continuous Plio-quaternary rift following the 600 km stretch of the Afar western margin, only 10–15 km wide. This graben system is separated from the Afar low plains by an elongate continuous tilted block (600 km long, 30–60 km wide, 1,000–2,000 masl in elevation), dipping gently eastward towards Afar depression (Zanettin and Justin-Visentin 1974) (Fig. 2.24, also marked as 8 in Fig. 3.1).

This transect is characterized by the presence of marginal grabens bounding the principal rift floor. Three prominent marginal grabens (Kombolcha, Kobo and Raya) run N–S parallel to the principal rift axis. Despite the significant distance in the N–S direction of this transect, the E–W progression in geology, tectonics and aquifer composition are similar. The plateau and the escarpments are covered by trap series volcanics, and the marginal grabens are filled by alluvial materials and thin lenses of lacustrine sediments. The transitional slope between the rift floor and the grabens is covered by basalts belonging to the Afar Stratoid, and the rift floor is

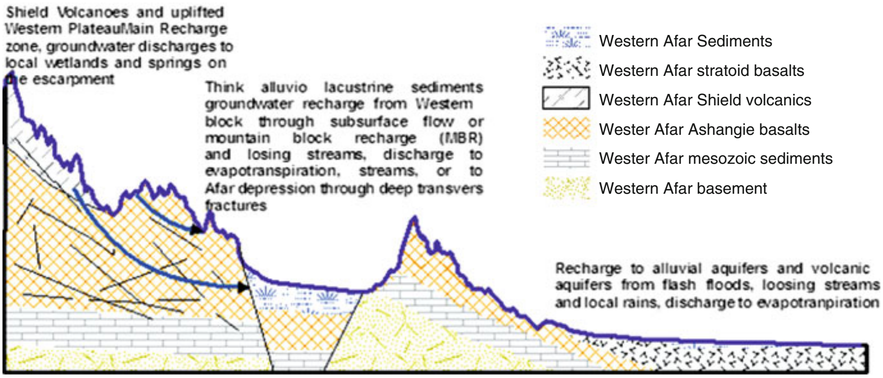


Fig. 2.24 Typical conceptual groundwater flow and recharge model along the Western Afar Transect, Modified after Kebede et al. 2007

covered by Quaternary basalts at depth and lacustrine and alluvial sediments near the surface. Thermal manifestations are localized in the axial part of the rift and around central volcanoes. These include the Tendaho and Allalobad springs located in the axial part of the rift and the Dobi springs near the Ethio-Djibouti border. The transmissivity of the alluvial aquifers in the marginal grabens vary from 0.5 to more than 500 m^2/day. The volcanic rocks making up the mountains are characterized by transmissivity ranging from 1 to 100 m^2/day. Rainfall decreases from 800 mm/year near the mountains to less than 200 mm/year in the rift floor.

The major 'sinks' for groundwaters coming from the mountains as mountain block recharge and runoff are the grabens. There is clear isotope hydrological evidence (Kebede et al. 2007) that the groundwaters from the mountains bounding the marginal grabens emerge first in the alluvial sediments as groundwater inflow. These groundwaters later join the streams and undergo evaporation. The evaporated waters later infiltrate through channel loss to recharge the groundwaters in the transitional slope and in the Afar rift floor.

In northern part of this transect, the region is drained mostly by intermittent streams which emerge from the highlands and disappear in the valley bottom to the alluvium or lacustrine sediments. The central part of Danakil depression is a flat salt encrusted plain, from which rises Dallol 'Dome', a notable topographic feature, composed of salt. The Teru depression (Sect. 3.13) is part of this transect and forms one of the regions receiving significant flows of rivers emerging from the highlands. Close to intermittent streams groundwater can be found at depth ranging from 80–120 m. In majority of the area alluvial sediments are the main source of groundwater for water supply uses. Fresh groundwater bodies can be found in association with alluvial materials and basalts and where evaporite sediments are minimum. Generally groundwaters are dominated by Na and Ca and Cl and SO_4 implying involvement of evaporation and salt dissolution in imparting salinity. The alluvial aquifers are found occupying grabens formed by tectonic activities.

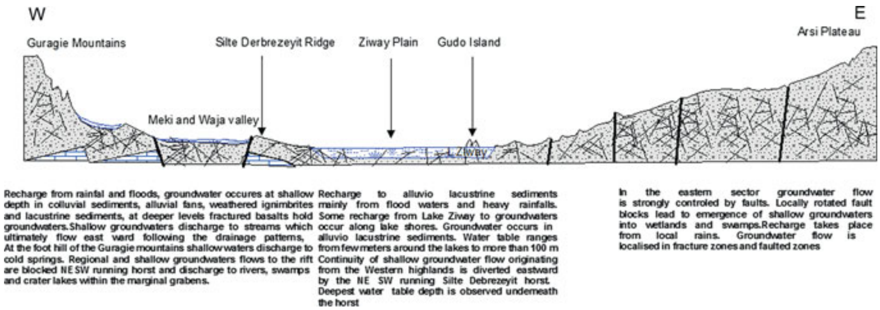


Fig. 2.25 Figure schematically showing features of groundwater recharge, flow and geochemistry along the two shields located in Guragie mountain—Arsi plateau transect (approximately between Welkite and Robe towns in Fig. 2.1)

The Butajira-Asela Transect

This transect extends from the Guragie mountains in the west to the Chilalo and Arsi massif in the East (Fig. 2.25). Typical feature of this transect is the abundance of acid volcanic rocks such as tuffs, ignimbrites and ash fall collectively known as the Dino formation. This formation is characterized by low aquifer productivity and yield. While the western margin is defined by a single prominent fault and minor marginal graben filled with sediments (e.g. Meki and Waja valley), the eastern margin is characterised by a series of step faults running parallel to the rift.

At the shoulder of the western escarpment, the geology is characterized by coarse grained (alluvial) deposits at the base of the scarp (pediment plain), and features shallow groundwater and springs. Well depths are in the order of approximately 90 m deep which penetrate mixed grain sized sediments, overlying ignimbrite formation. These aquifers have a yield of up to about 7 l/s. The transmissivity of the aquifer is indicated to be in the range of 16–137 m^2/day, values of 95–137 m^2/day are considered typical (Halcrow 2008). In the active western marginal graben also called Silti—Debrezeit fault zone contains lacustrine sediments and welded tuff on which are several interspersed coalescing nested scoria cones aligned parallel to the Guragie escarpment.

The groundwater around Siltie Debrezeyit ridge is deep within the fractured ignimbrite, groundwater being primarily found in large open joints. In a borehole drilled to a depth of 244 m at the Center of the Ridge (Koshe town), the main water strike was recorded between 234–244 m depth within the lithified pumaceous tuff (ignimbrite?) aquifer. Similarly, another well drilled in the area, to a depth of 229 m, has a recorded static water level of 174 m and yield of 5 l/s against draw down of 18 m from aquifers within water lain pyroclastics and rhyolite. Within the Woja River valley, groundwater occurs at relatively shallow depth in alluvial material (overlying ignimbrites) and offers some potential. One borehole in this area, 64 m deep, yielded 8.5 l/sec, with a static water level of 9.6 m, and a transmissivity of 232 m^2/day.

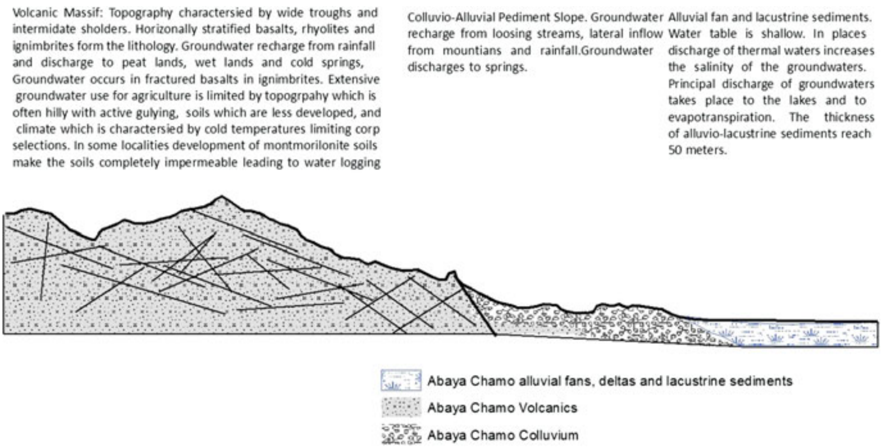


Fig. 2.26 Schematic hydrogeologic section of the Western Abaya Chamo Transect (transect running East wards from the town of Waka—see Fig. 2.1 for location of Waka)

At the valley floor (Ziway Plain), the depth to groundwater is shallow within the lacustrine deposits, particularly close to the lake, but declines (within the lacustrine deposits) away from the lake shore. The mixed sediments (sand, gravel, silt, clays, tuff, and diatomaceous materials) are in general anticipated to posses low to moderate permeability and but could provide moderate yields where coarser horizons are intercepted.

The eastern margin of the Ziway Shalla lake basin is marked by the dense Wonji fault belt which is dotted by several volcanoes. Faulting and fissural basalt flows are along the eastern margin are more intense than along the Siltii-Debrezeyit fault zone.

The Western Abaya Chamo: Lake Abya Chamo Transect

This transect is characterized by Tertiary volcanic cover making up the highlands in the west and alluvio-lacustrine sediments mantling the lowlands surrounding the Abaya-Chamo Lakes (Fig. 2.26). The center of the rift is only 30 km from mountain peak in the west (the transect in Fig. 2.26 runs between the town of Waka in Fig. 2.1 and the center of the rift in 20 km east of the mountain). The drainage basins are compact. This has led to the development of extensive colluviums deposits and associated alluvial fans extending down to the rift center and starting from the highlands. Unlike other Plateau-Rift transects in the whole Ethiopian Rift System, think alluvial-fan, colluviums deposits and lacustrine sediments directly extend to the center of the rift immediately mantling the plateau lithology. The western highlands stratoid basalts belonging to the Trap series form the dissected plateau on the top. Covering the trap series are Pliocene and early

Pleistocene ignimbrite sheets. Other prominent features are trachy-rhyolitic complex of Mount Damota (Located at Sodo in Fig. 2.1), a highly degraded shield-volcano. Fissurral basalt and associated scoria cones which date from Pleistocene cover a vast area to the north of Lake Abaya. Stratified lacustrine deposits of predominantly silty and clay texture cover the region west of Abaya. The alluvial cones lie on the piedoment slopes of the mountain ranges and stretch right down to the shores of Lake Abaya and Chamo. These sediments are chiefly alluvial and colluvial deposits which consists basaltic materials. Corse components pebbles mix with sand and silt. A recent strip of alluvial deposits is also found along the Bilate River and it opens into a wide delta in the Lake Abaya. Alluvial fans cover an area of 50,000 ha while the colluvio alluvial materials pediment surface covers an area of 41,000 ha. While the mountain bounding the rift from the West is characterized by low permeability rhyolites trachytes, the rift floor is mantled by alluvio-colluvial materials of hydrogeological importance. The hydrogeological features of this transect is shown in Fig. 2.26.

The Upper Awash: Middle Awash Transect

Geology and tectonics: This transect runs between the town of Addis Ababa in the West and and the Awash in the East (Fig. 2.1). The western margin of the northern MER[5] is displaced westward relative to Afar, forming what is commonly known as the Addis Ababa rift embayment (see unshaded area in Fig. 2.1 South of Addis Ababa stretching East–West). As a consequence, the rift is relatively broad here compared with other sectors of the Main Ethiopian Rift. The plateau–rift transition is gradual, because normal faults with displacements of up to tens of meters are generally confined to the region east of Debrezeyit (Damte et al. 1992; Mohr 1973). Within the rift valley are a series of asymmetric sedimentary basins, for example the Adama basin, bounded on one side by steep border faults (Ebinger and Casey 2001) and containing Pleistocene volcanic, volcaniclastic and lacustrine strata which overlie the Miocene—Pliocene felsic and mafic sequences of the Kesem and Balchi formations (Wolfenden et al. 2004).

Four principal geologic units (similar to the stratigraphy of Addis Ababa area-see Sect. 2.6, Fig. 2.27) crop out in this region. These are (a) the 30 Ma old flood basalts at the base of all the volcanic formation and resting unconformably on Mesozoic sediments; (b) a 10–11 Ma old second basalt sequence also called Addis Ababa basalt; (c) a 3.5 to 2.5 Ma old felsic volcanics containing ignimbrites, tuffs and rhyolites and (d) a 1.8 Ma old or younger intercalation of basalts and ashes. As a whole the basalts may constitute up to 60 % of the total volume at least in the northern MER (Wolfenden et al. 2004). Basalts are usually associated with monogenetic vents

[5] MER—Main Ethiopian rift is a depression running from the Gidole area in the south west to the Awash town in the north East, see Fig. 2.1. Its width is around 80 km.

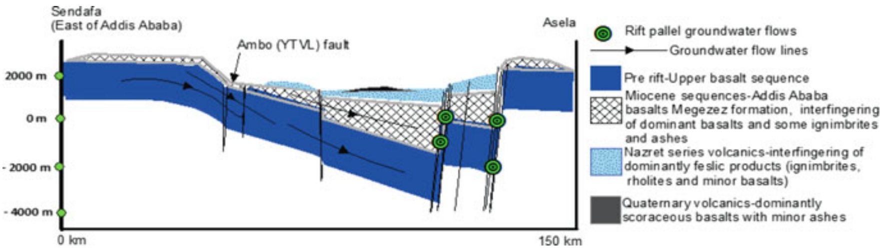


Fig. 2.27 Shematic figure showing major geologic features and hydrostratigraphic units central Ethiopian rift across the W–E transect from Northern plateau (east of Addis Ababa to East of Asela

and/or fissure eruptions, at the side of the main central volcano (Ebinger and Casey 2001). The MER is, therefore, mostly floored by several basaltic fields, silicic domes and calderas. These are interlayered and covered with Plio-Quaternary fluviolacustrine sediments (Le Turdu et al. 1999; Woldegabriel et al. 1992).

Hydrogeology and groundwater occurrence: In the Addis Ababa area, the intersection of Rift faults with an older, E–W trending structure (the Yerer-Tulu-Wellel Volcanic Lineament, YTVL, see Sect. 2.5) has formed transverse faults orthogonal to other rift faults, creating a "hydrogeological window" that enables groundwater flow from the escarpment to the Rift in this area (Kebede et al. 2007). This zone of transverse faults also enables the Awash River to drain the western escarpment, flowing into the Rift and continuing its course on the Rift floor, the only major river to do so (river running E-W south of Addis Ababa in Fig. 2.1).

The role of the Oligocene volcanics in holding and transmitting water in the central part of the rift is unknown however these lithologies are believed to be principal deeper aquifers around Addis Ababa (MWR 2007). At higher elevations on the Rift escarpments (1,900–2,400 masl), fractured basalts when covered by ignimbrites and volcanic ash, form confined to and semi-confined conditions in some places, with depth to water table given as ranging from 0 to 120 m (Kebede et al. 2007). Recent investigation (MWR 2007) reveals that this sequence yield up to 200 l/s and the aquifer is under confined or semi confined condition. The younger quaternary scoraceous basalts and associated ahses form highly productive aquifers in the Akaki and Debrezeyit areas (1,800–1,900 masl), at times with a thick cover of alluvial material (Kebede et al. 2007; Demlie et al. 2007). Borehole depth in the Rift often exceeds 200 m. Rift aquifers around Nazareth (Fig. 2.1 for location) and further east towards Welencheti (in a typical Adama graben, 10 km north east of Nazreth) are characterized by complex interlayering of alluvial/lacustrine sediments, pumice, fractured basalts and ignimbrites in a highly faulted terrain (Kebede et al. 2007). Water-bearing formations in the Lake Beseka area (100 km north of Nazreth) are mainly composed of very young fractured basalts and scoraceous basalts, as well as pyroclastic deposits such as pumice, tuff and volcanic breccias (Ayalew 2008). Alluvial and lacustrine cover is also predominant in this region.

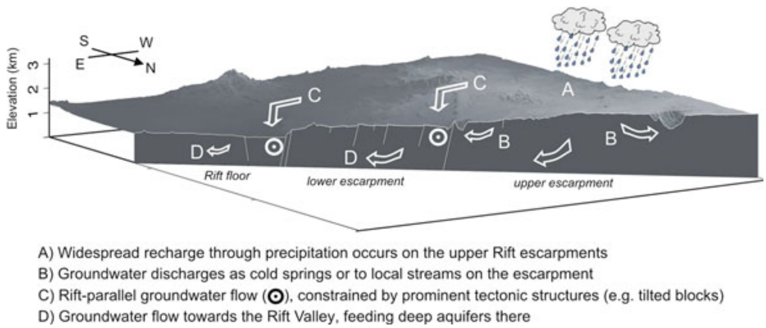


Fig. 2.28 Schematic groundwater flow and dynamics developed from multiple evidence including isotopes, geochemistry and tectonics (from Bretzler et al. 2011)

Vertical structuring of the aquifers apparently occurs, as is observed in the existence of a shallow and a deep groundwater system in the investigation area. Shallow groundwater frequently discharges as cold springs on the upper Rift escarpments, though boreholes also tap deeper sources in this area. Shallow hand-dug wells (depth <20 m) only occur locally and infrequently in the Rift Valley. Associated with active fault zones, numerous thermal springs occur in this transect, especially in the tectonically active Fantale/Lake Beseka area on the Rift floor and around the Bosetti volcano. Figure 2.28 shows groundwater flow and origin schematically stretching from the higher escarpment around Addis Ababa to valley floor around Nazret.

Groundwater geochemistry: Groundwater from the upper and middle Awash basin shows a clear spatial hydrochemical distribution. Water discharging from cold springs at high altitudes (>1,900 masl) on both the eastern and western escarpment is distinguished by low electrical conductivities (median ~300 μS/cm) and a predominating Ca-(Mg)-(Na)-HCO_3 water type. Boreholes on the lower escarpment (1,600–1,900 masl) also show this water type, but an increase in electrical conductivity (median ~600 μS/cm), pointing to longer residence times and increased water–rock interaction. There is a distinct shift from Ca–HCO_3 to Na–HCO_3 dominated waters when moving from the escarpment to the Rift floor. The increasing concentrations of Na+ correlate with a corresponding increase in HCO_3^- ($r^2 = 0.88$) and subsequent decrease in Ca^{2+}. Electrical conductivities in Rift Valley groundwater are the highest in the whole study area (median ~1,100 μS/cm) (Bretzler et al. 2011).

The main chemical process determining the hydrochemistry of Rift floor groundwater is the weathering and hydrolysis of silicate minerals such as feldspars, as has also been confirmed by previous studies (Darling et al. 1996; Gizaw 1996; Rango et al. 2009). This results in an increase in HCO_3^-, Na^+ and K^+ concentrations in the water with increasing residence time and water–rock interaction (Herczeg and Edmunds 2000). Silicate hydrolysis is aided by the high CO_2 partial pressure observed in the Main Ethiopian Rift (Darling et al. 1996; Gizaw 1996), explaining the very high HCO_3^- and Na^+ concentrations especially observed in thermal waters circulating in active fault zones where geogenic CO_2 rises up from mantle sources. As Rift floor groundwater becomes oversaturated with respect to calcite and dolomite, seen in saturation indices >0, these mineral phases precipitate. Cation exchange of Ca^{2+} for Na^{+} on clay minerals is most probably another process, which together with precipitation, is responsible for the near complete removal of Ca^{2+} and Mg^{2+} from solution (Rango et al. 2009).

Tectonics and groundwater flow: At regional scale the flow of groundwater from the highlands in west to the rift center is facilitated by the 'suitable geohydrologic condition of the YTVL hydrogeologic window'. The intersection of the YTVL with the MER created a situation where by groundwater movement from the escarpments to the Rift floor therefore seems to occur orthogonally to the main SW–NE fault direction. When viewed on a smaller scale, groundwater flow paths are affected by local structural setting. One area where the connection of groundwater flow to tectonic structures can be observed are the tilted block structures on the first escarpment step near the towns of Bolo Gyorgis and Arerti (Fig. 2.29). Normal faulting during rifting has resulted in a series of large, tilted blocks dipping towards the Rift border. This dipping block of rocks channel groundwater flow parallel to the dip direction and discharges where the dipping blocks come in contact with the fault scarps. This typical case of the Bolo Gyorgis-Arerti block has resulted in emergence of springs at the Kesme dam axis during recent excavation.[6]

2.11 The Mesozoic Sedimentary Aquifers of Ethiopia

Geology

Mesozoic sediments occur in three regions of Ethiopia. The sediments are exposed in South Eastern Ethiopia (with three sub region including Wabishebele, Genale-Dawa and Ogaden), the Mekelle-Metema and Blue Nile basins (Fig. 1.2 for location). The stratigraphy of the succession is given in Fig. 2.30. In the Blue Nile plateau the wedge of sedimentary rocks, although over 2,000 m in thickness where it is exposed in the steep canyon walls, actually covers but a relatively small surface area of the Blue Nile River Basin in comparison with the area covered by volcanics and basement Precambrian rocks. Mekelle sedimentary basin (in the North) occupy 12, 000 km^2. Abay basin sedimentary basin covers 55,000 km^2.

In Ethiopian hydrogeological reports it is common to find estimation of hydrogeological features (such as permeability, storage properties and aquifer potential) of the Mesozoic sediments adapted from other sedimentary basins based

[6] The Kesme dam is a dam to be built on the Kesem river for irrigation purpose. While excavation has been taking place to anchor the core to key trench several artisan springs emerged on the dam axis hindering construction activities.

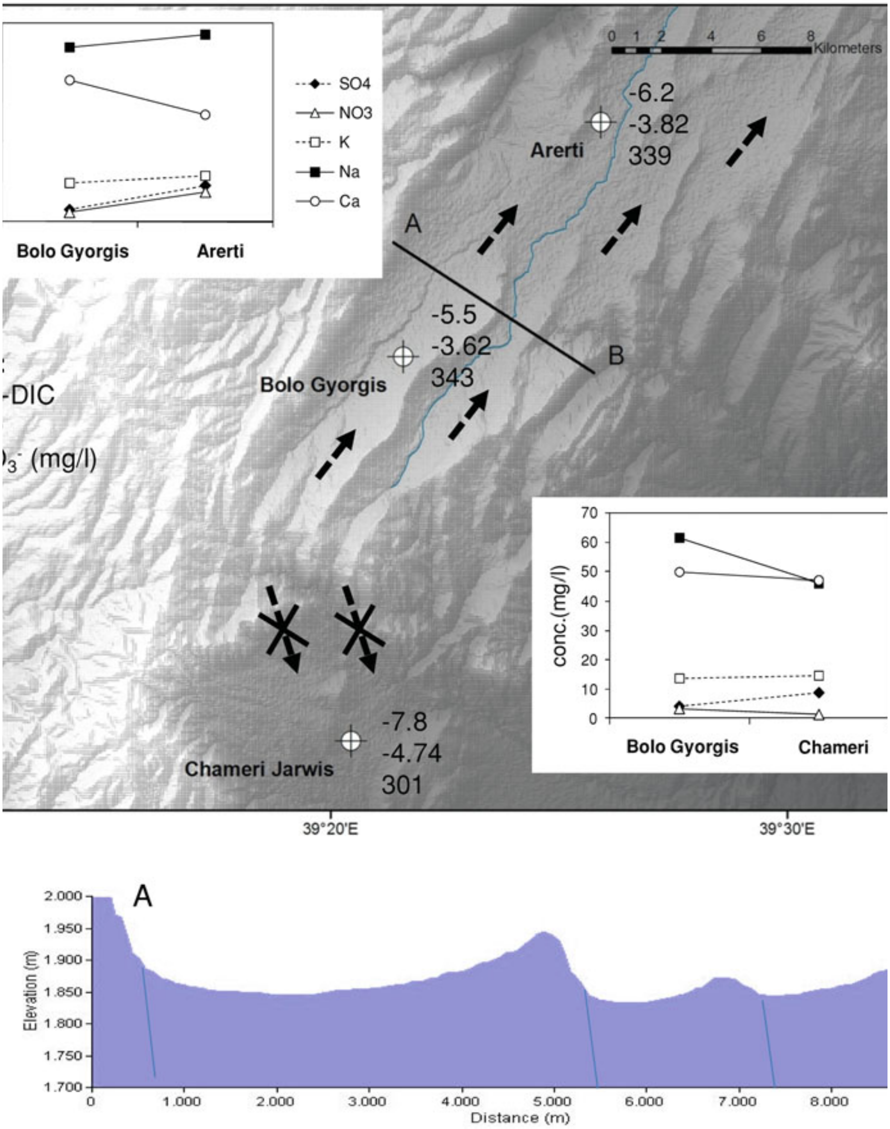


Fig. 2.29 Close-up of the Arerti/Bolo Gyorgis area, including a cross-section showing the morphology of tilted block structures of this region. Changes in hydrochemistry between the boreholes Bolo Gyorgis, Arerti and Chameri Jawis are shown on the plots. Presumed groundwater flow directions, supported by hydrochemical data, are indicated by the *arrows* (Bretzler et al. 2011)

on lithologic similarity. For example the Mesozoic Adigrat sandstone aquifers were anticipated to have similar hydrogeologic properties as that of the Nubian sandstone underlying the vast region of north east Africa (Chernet 1993). However

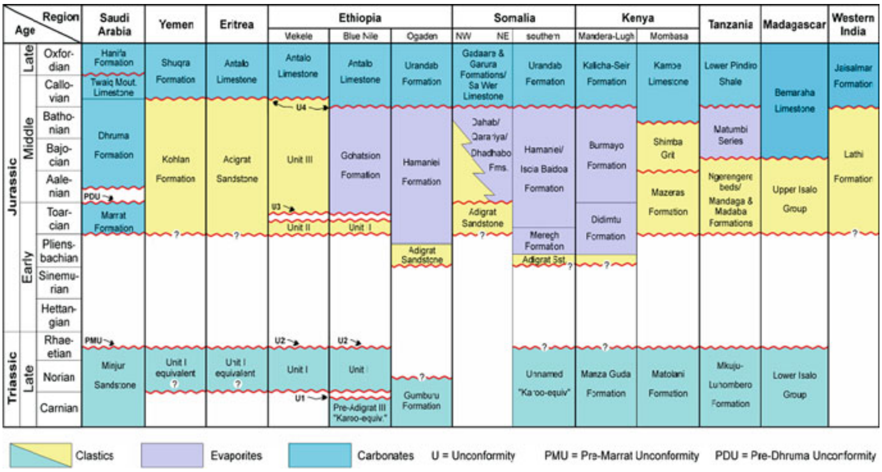


Fig. 2.30 Correlation chart of the Mesozoic successions of the Horn of Africa and Arabia (Enkurie 2010)

there is a major distinction between the geologic history of the Continental-Marine sediments of the Paleozoic–Mesozoic era of Ethiopia and the rest part of Africa and Arabia (Enkurie 2010). In both the East African and North East African sedimentary basins, the sedimentation occurred thanks to the intraplate extensional deformation. But this extensional deformation ceased in southeastern Gondwana (including Ethiopia and Horn of Africa) and was replaced by a major crustal uplift and accompanied intraplate magmatic activity. In contrast, the northeastern part of East Africa and Arabia formed part of stable and slowly subsiding Neotethyan passive margin. These regional scale tectonic cycles have resulted in differences in hydrogeologic properties and groundwater resources potential.

Stratigraphy of the Sedimentary Sequences

A detailed account of the stratigraphy, lithofacies, and correlation of the three sedimentary basins of Ethiopia is given in (Enkurie 2010). The following descriptions are mainly excerpt from this work.

Northern Ethiopia: The Paleozoic and Mesozoic sediments of North Ethiopia can be divided into six stratigraphic units namely Enticho sandstones, Edagaarbi glacial, Adigrat sandstone, Antalo Limestone, Agula shale and Upper Sandstone (Amba Aradom formation).

Central Ethiopia: In Central Ethiopia Paleozoic and Mesozoic succession come in five stratigaphic units namely, the Pre-Adigrat formation, the Adigrat formation, Gohatsion formation, Antalo Limestone, Muger Mudstone and DebreLibanos sandstone.

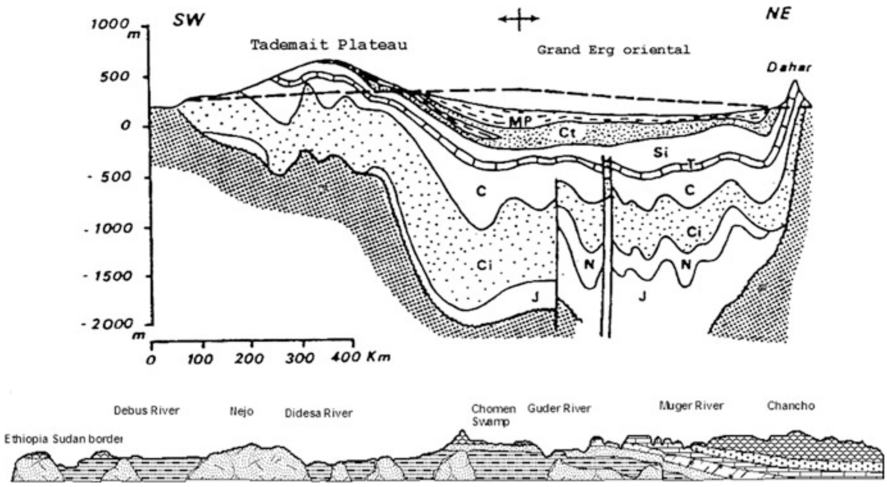


Fig. 2.31 Comparison of cross-sections of geologic structures of sedimentary basins of Ethiopia with that of the Northern Africa. Upper figure shows structural and stratigraphic setup of the Sedimentary basins of North Africa (Algeria-Tunisa) and the lower figure shows the same in sedimentary basins of Blue Nile Plateau. *Upper* figure from Castany (1982) and *lower* figure from USBR (1964)

Southeastern Ethiopia: Grossly the Mesozoic sediments of Eastern Ethiopia is subdivided into three broad stratigraphic units namely the Adigrat sandstone, the Antalo super sequence and the Upper sandstone unit.

In northern Ethiopia the Enticho sandstone has a thickness of 200 m and it overlies Neoproterozoic basement rocks (Fig. 2.34). It is composed of sandstones and channels fill conglomerates. The Edagaarbi glacial consist predominantly of grey, black or purple clay and siltstones that often contain dispersed pebbles or boulders up to 6 m in diameter. The thickness of the succession is highly variable but attains a maximum thickness of 150 m near its type section. The thickness of Adigrat sandstone reaches 670 m. It is composed of well sorted fine to medium grained sandstone at the base and muddy sandstone at the top. The thickness of Antalo limestone varies from 300 to 800 m. The unit is composed of pure limestone cliffs and marl interbeddings. The Agula Shale with a thickness of up to 300 m is composed of fine sandstones, laminated black shales, mudstones, dolomites and gypsum beds. The Ambaradom formation unconfromarbly rest on the Agula shale and consist of white or red sandstones with interbeded silt and mudstones, lateritic paleosols and lenses of conglomerates. The Amba Aradom sandstone correlates with the Debrelibanos sansstone of the Blue Nile basin.

In central Ethiopia the pre-Adigrat sandstones form extensive unit underlying the Adigrat sandstone. They are composed of principally well sorted sandstone. With a thickness reaching 300 m, the Adigrat sandstone here is composed of fine grained sandstone at base, coarse grained sandstone at the base and silty to muddy sandstone at the top. The Gohatsion formation at 450 m thickness consists of dolostones, marlstones, and shales, bioturbed mudstones with thin siltstone intercalations, fine grained sandstones and thick gypsum beds. The Antalo Limestone has a thickness of 420 m and consist of mudstones, marl and limestone intercalations at base followed by interbedding of marly limestone and marls at the middle part and up to 50 m thick limestone cliffs at top. The Muger mudstone ranges in thickness from 15–320 m. It consists of alternating beds of gypsum, dolomite, shale, sand, silt and mudstones. This unit is equivalent to the Agula shale in northern Ethiopia. The Debrelibanos sandstones cap the entire formation. The thickness of the Debrelibanos formation varies between few meters and 172 m. It is composed of alternating beds of mudstone, fine grained sandstones, and massive cliff forming sandstone.

In the sedimentary basin of south eastern Ethiopia the pre-Adigrat formation of the Blue Nile basin and Mekelle Outlier is represented by Karoo sedimentary sequence which is only encountered in drilled petroleum wells. The Karoo sediments are composed of Calub Sandstone, Bokh Shale and the Gumburo sandstone. Unlike the two other sedimentary basins, where sedimentation ended in upper cretaceous, in the South Eastern Ethiopia sedimentation continued until Eocene and thus the entire package of sedimentary rocks is much thicker and lithologically variable. The Mesozoic sequence is composed from base to top the Adigrat Sandstone, the Hamainile-Urandab-Gabredarre Limestone formation, the Korahe formation the Multahil gypsum formation, The Ambaradom sandstone, Ferefer, Belete Uen, Jesoma sandstone, Auradu limestone and Taleh (anhydrite, gypsum, shale and dolostone) formations.

The Hamainile formation is carbonate-clastic-evaporite unit. Urandab formation is dark grey black organogenic shales and subordinate limestone layers. The Gabredarre formation is a thinly bedded alternating oolitic and marly limestone, interbedded in the upper section with gypsum and shale. The Korahe formation is composed of sequence of gypsum, anhydrities, iron carbonates, sandstones, shales, marl and dolomitized limestones. The Mustahil formation is composed of yellowish, fine grained, highly fossiliferous limestone.

Structural Setup of the Mesozoic Sediments and Groundwater Potential

As shown in Fig. 1.3, by volume, the Mesozoic sediments are the most extensive lithologies in Ethiopia. However, the Mesozoic and Tertiary sediments cover less than a quarter of Ethiopia. Outside the zones where these sediments are exposed, the surface structure is little known because of the plateau is covered by a large volume and thick (often exceeding 1 km) volcanic materials which erupted between 40 and 22 Ma.

Notable hydrogeologic and geologic feature of the Mesozoic sediments of Ethiopia are (a) Uplifting and formation of tabular plateaus (b) deep incision by

Table 2.9 Relation of tectonics, climate and hydrogeologic properties of sedimentary aquifers

Subsiding	Paleogroundwaters	Karstic aquifers
	Paleokarsts	Artesian basins
	(*North Africa*, *Middle east*)	Paleogroundwaters (*Europe*, *China*)
Uplifting	Fractured aquifers	Karst aquifers
	Little karstification	Low storage in the basin
	(*East Africa*)	(*Europe*, *China*, *Asia*)
	Low rainfall	High rainfall

river gorges, (c) absence or limited karstification intensity in karistifiable rocks (d) absence of regional folding and flexures at their margins, (e) extensive cover by the volcanics. These contrast with the typical sedimentary basins elsewhere in Northern and Eastern Africa. In contrast to the Sedimentary basin aquifers of northern and Sahel Africa, in the Ethiopian Mesozoic sediments, structural traps such as syncline formed from compressional deformation are uncommon leaving little room for large volume groundwater storage. Figure 2.31 and Table 2.9 compare the tectonic structure of a North African sedimentary basin and that of the Abay basin.

Regardless of their isolation by the thick volcanic cover in some places buried Mesozoic sediments play an indirect role in affecting the shallow groundwater regime in the overlying volcanics (Kebede et al. 2006, see also Sect. 2.5 and Fig. 2.13). In Lake Tana basin and the Yerer Tulu Welel Volcanic Lineament zone the presence of volcanic activity and low enthalpy geothermal systems lead to the heating of the underlying Mesozoic sediments which then liberate a considerable among of carbon dioxide gas and other gases (nitrogen, sulphur and argon). The CO_2 gas emanating from the Mesozoic sediment de-carbonation has led to the formation of numerous naturally sparkling springs, notably around Ambo, Woliso, Diddessa Valley, South of Lake Tana, and Filwuha thermal springs around Addis Ababa.

Groundwaters in the Ogaden Multilayered Sedimentary Aquifers

The sedimentary basins of Southeastern Ethiopia occur in three geologic zones namely the Ogaden, the Wabishebele and the Genale Dawa basins. The western boundary of the Ogaden (Fig. 3.32) is separated from the Wabisheble basin (west of the Ogaden sedimentary basin) by a prominent NNW-SSE running regional fault called the Marda fault.

Groundwater occurrence: In the Ogaden sedimentary basin six aquifer types occur (Fig. 2.32). Detailed account of the groundwater occurrence in the Ogaden sedimentary basin is given in Hadwen et al. (1973) most of the knowledge to date about the hydrogeology of this region is derivative of this study.

In the lowlands of the Ogaden the main near surface aquifers are the superficial deposits confined in the major valleys. Minor aquifers are found in the Mustahil,

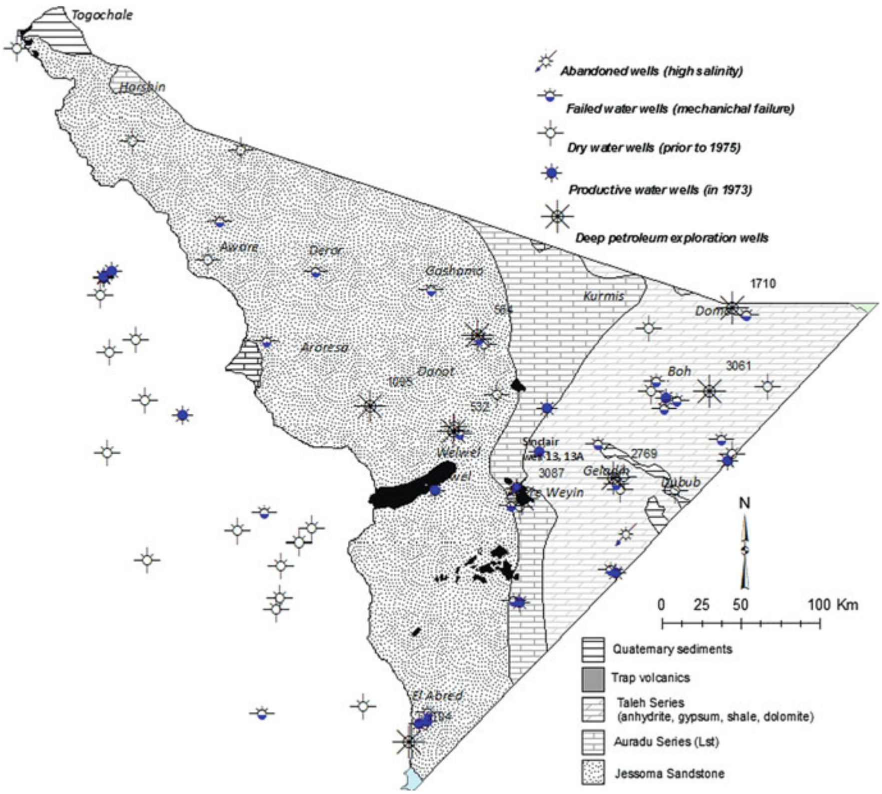


Fig. 2.32 Simplified geologic map and distribution of successful and failed water wells in the Ogaden sedimentary basin. Deep petroleum wells and their depth are also indicated

Belet Uen and Auradu Series, in trap series basalts and in localized superficial deposits. In Jijiga area (Northern most tip of Fig. 2.32) the lower sandstone and Antalo limestone form a single continuous aquifer and are exposed west of the map (not indicated in the map because of scale).

Few kilometers south of Jijiga boreholes drilled for the town water supply, reached the total depth of 70 m after having encountered between 20 and 50 m of water saturated Urandab Limestone and Adigrat sandstone. They have shown a discharge from 7.6 to 16.8 l/s with as specific capacity from 0.6 to 2.6 l/s meter drawdown (Hadwen et al. 1973). However boreholes with much lower discharge have been drilled north of Jijiga which showed an average discharge of less than 1 l/s with a specific capacity of about 0.3 l/s per meter drawdown, having encountered a thickness of only 10 to 20 m of saturated Urandab limestone and Adigrat sandstone. In Jijiga area the quality of groundwater contained in the limestone and sandstone is quite variable, showing TDS content from 1,500 to 2,000 ppm in boreholes located in Jijiga plain. Generally evaporites layers within the Limestone Group, causes splitting, stagnation and salinization of the underground water elsewhere in the Sedimentary basin aquifers in SE Ethiopia.

The Jessoma sandstone covers the most extensive area in the Ogaden. It underlies most of the Ogaden. It is poorly recharged it does not have a regional water table and even perched water lies deeper than 300 m, and moreover because of its friable and uncemented nature the formation gives great difficulties in drilling. Several wells drilled (e.g. at Derar, Gashamo, Aroresa) in early 1970s turns out to be dry or abandoned due to mechanical failure (Fig. 2.32). In Jesoma sandstone drilling data shows water table is deeper than 250 m. However when water is encountered at shallow depth the water quality is potable.

Deeper drilling for petroleum holes reveal salt waters (up to 20 g/l) below depth of 1,560 m and fresh water zones above depth of 1,560 m (less than 10 g/l) in the 3,061 m deep Boh well. Severe circulation loss has been encountered in variety of locations in the Jessoma sandstone.

The Auradu Seiries (Late Paleocene early Eocene limestone) formation is massive limestone and yields some fairly fresh water. There are successful boreholes, notably at Burdar, Agarewein and Ado (Sinclair wells 13 and 13 A). The formation thins westwards, in Somalia it is as much as 450 m thick, but in Ethiopia it seldom exceeds 200 m, though petroleum well at Boh (Fig. 2.32) shows above 430 m thick Auradu series rocks under the Taleh formation. A number of boreholes were not completed due to problems of lost circulation. Most of the water production holes drilled by oil companies were originally capped as there was then no population in areas.

Taleh series is of alternating anhydrite, gypsum and shale with some thin interbeds of dolomite. The unit is of Middle to Early Eocene age. Gypsum does not occur everywhere in the sequence and several boreholes yield potable waters. At Geladi, drilled wells struck mineralized water and sometimes with high ammonia content. At BH-18 water is purgative but used. At Boh several holes were drilled through the Taleh Series into the underlaying formation yielding up to 2 l/s with no evidence of declining yields and in places the wells return potable water.

As concluded earlier by Hadwen et al. (1973) water supply in Ogaden cannot depend on drilling boreholes into the three principal lithologies (Jesoma, Auradu or Taleh formations), except perhaps in areas of Jurassic limestones around Jijiga or in Mustahil formation west of the Marda fault, and even in those areas pockets of tracts of salty water are common.

Alluvial deposits are the most reliable aquifers, and especially in the northern sector of the alluvial valleys considerable storage of good quality water can be safely exploited to a much higher degree (see Sect. 3.16 for details). South of Kebre Dehar (Fig. 3.19) alluvial waters become more and more saline. Alluvial deposits also play great role even in higher grounds of the Wabisheble basin (Fig. 3.16). In Fik shallow wells with hand pumps on Fik stream and water holes on the wadi are the main source of water for the town of Fik. Hamero town's water supply source is a shallow well with hand pump on the bank of Hamero stream. The Fik wadi beds are covered by lose sediments, composed of boulders, gravel and sand.

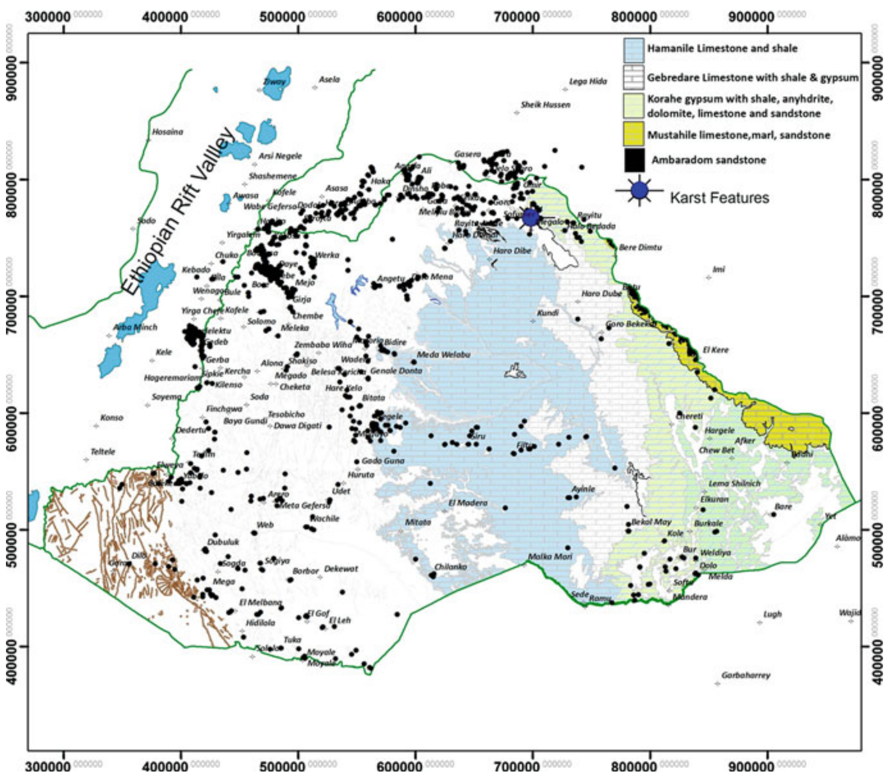


Fig. 2.33 Geological and hydrogeologic features of the Genale Dawa basin

Recharge and geomorphology: The extensive flat surface east of the Marda fault is covered by sandy soils coated with reddish soil or calcareous duricrust (caliche). This limits recharge rate going down to the aquifers. Recharge is considerably low, rainfall is less than 200 mm per year in Eastern most zone and increases only to 500 mm/year in the northern sector of the Ogaden. Vertical recharge that occurs is concentrated along major valleys, especially in their superficial deposits and in fault gouges in valleys that are structurally controlled. In the mountains and foothills erosion is so deep that recharge water soon finds its way towards valley axis, to become streams or subsurface wadi gravel flow.

Groundwater Occurrence in the Multi-Layered Sedimentary Basin of the Genale Dawa Area River Basin

Physiographically the Genale Dawa basin is characterized by low relief tabular plateau made of Mesozoic sediments separated by deep river incisions. The elevation ranges from around 200 m to over 4,300 m in the North.

In the Ganale Dawa basin (Fig. 2.33) the Amba Aradom sandstones are variegated qurtzose sandstones of fluvial and/or littoral origin. In the south and north east, the Amba Aradom is an aquifer of relatively high productivity. Its high permeability and productivity is a result of the moderate to coarse grain size, loose cementation and limited shale intercalation. The Amba Aradom sandstone is exposed in the eastern strip of the Genaledawa basin.

The Gabredarre include oolitic limestones, marls and some gypsum. This formation is horizontally bedded and is characterized by solitary caves and karst features. In this region the limestones exhibits the highest degree of karstification when compared to low degree of overall karstification in karitifiable rocks of the country. The Garbredarre formation has limestone cliffs that are moderately jointed and having intercalations of sand, marl and gypsum beds. It has moderate permeability and productivity and saline groundwater is encountered in wells. The famous Sofomar caves are located in the Garredarre formation (Fig. 3.33 marked as karst). The Gabredarre formation grades down to the underlying Urandab formation that is equivalent of the Antalo limestone.

The Haminile formation has organogenic and oolitic limestones with shale and sandstone. These limestones are well jointed and they have moderate to high permeability. According to the boreholes between Filtu (center of Fig. 2.33) and Negele (west in Fig. 2.33), the groundwater level is very deep (deeper than 200 m). When water table is shallow the Hamanile series limestone has a relatively higher productivity but the depth to water table generally exceeds 200 m in the highlands and midlands where it is exposed. On the Dolo to Negle Borena road around Bidre, the Haminile limestone plateau is observed. This limestone is marly limestone, fractured with thin beds of about 1 m. The Haminile Limestone here has a number of boreholes in a line running in an east west direction. Towards the contact with the Basement to the north, some boreholes did not stick groundwater at depth greater than 200 m.

Around Negele Borena the Hamanile limestone formation come in at least five sub-units characterized by variable lithologies and intercalations. Nearby Negele town the lowest thickness of the succession is recorded. The maximum thickness of this succession is considered to reach about 700 m in the surrounding of Filtu. It is a carbonate sequence constituted by mudstone to grainstone interlayered/interbedded with shale, marl, etc.

The Korahe formation is known as aquifer of low productivity. It is dominated intercalation of sandstone, gypsum, shale, anhydrite beds. Groundwater in this formation is saline and has poor quality.

Groundwater Occurrence in the Mekelle Outlier

The Mekelle Outlier, in northern Ethiopia, is made up of a variety of clastic (Enticho and Adigrat formation) and calcareous sedimentary rocks (Antalo formation) capped by thin layers of clastic sedimentary rocks (Ambaradom formation).

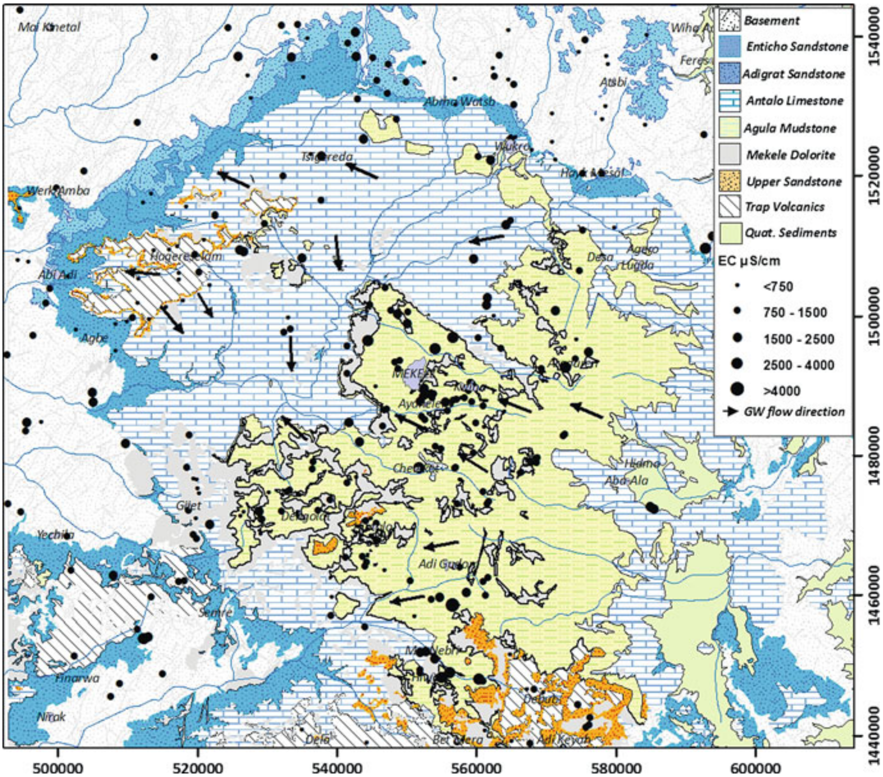


Fig. 2.34 Geological map of the Mekelle Outlier, the map also shows water points and associated groundwater electrical conductivity. The *arrows* indicate direction of groundwater flow

The upper members of Antalo formation are intruded locally by dolerites. The sedimentary outlier is in turn covered by extensive basalt flows (Trap series) in the south and south west. The Paleozoic–Mesozoic sedimentary sequence is bounded in the north, west and east by Precambrian metamorphic rocks (Fig. 2.34). Main structural features noted in the sedimentary rocks include bedding with variable thickness, high degree of fracturing and tilting of the sedimentary bedding in different directions: south, north, west and east.

All the lithologies are known to hold and transmit water at variable rates. The major challenge to groundwater storage is the dissection of the plateau by river incision and regional faults leaving isolated tabular plateau of small lateral extent. The low annual recharge and its concentration to 2 months of the year (July and August) limit the overall recharge rate. When suitable structures exist, high yielding aquifers can be found.

The major regional structural element related to tectonics in the area is normal faults with varying trends, lineaments and fractures. Two systems of faulting are noted in many places. The earliest faulting generally trends WNW–ESE and is the oldest. This system is affected by relatively small N–S faulting dipping to the east or west at higher angles.

2.12 The Karst Aquifers of Ethiopia

Karst

Karst is a geomorphic name of landscape shaped by the dissolution of a layer or layers of soluble bedrocks usually carbonates, limestones or dolomites. Karst can also develop in marbles, sandstones, evaporates and volcanic rocks. Many karst regions display distinctive surface features, with sinkholes, dolines being the most common. However, distinctive karst surface features may be completely absent where the soluble rock is mantled, such as by glacial debris, or confined by superimposed non-soluble rock strata. As it appears the term karst has its origin from Indio-European word Karra meaning stone. Notably several terms of similar Cushitic and Semetic philological linkage and similar connotation are used to describe rocks or geomorphic features. For example Kerasa means rock or dry stream valley in Oromo Language, Kars means open earth, gara means knoll or mountain. Such philological similarities signify how much karst related landforms (particularly caves) must have strong link human with the environment. One of the karstified regions in Ethiopia is Kersa in Eastern highlands.

Worldwide Karst aquifers contribute more than 25 percent of drinking water supply. Most of these prominent karstic aquifers underlie significant portion of countries in the high latitudes (Europe, China, and North America).

Distribution of Karstifiable Rocks in Ethiopia

In Ethiopia more than 20 % of the land is underlain by karstifiable lithologies (limestone, dolomite, marble and sandstone) of which less than one percent is karstified (Fig. 2.35). Of these only few karst landforms and karst aquifers are documented to exist in Ethiopia. For example hydrogeological investigation in the Eastern section of Abay Valley (central region in Fig. 2.35) reveal that structures like stylolites, karsts, and chert nodules, indicative of limestone dissolution, are only observed in very few exposures and mostly towards the bottom of the limestone. The report on the Jema valley (Sima 2009) also shows the degree of karstification as only embryonic. Rather groundwater occurrence in the limestone terrain of Ethiopia is dominated by fissured porosities or dual porosity (fracture and matrix porosity) medium.

Karstifiable rocks occur in three regions of Ethiopia including the Mekele region, the north eastern plateau -Ogaden, the Blue Nile gorge and the Afar

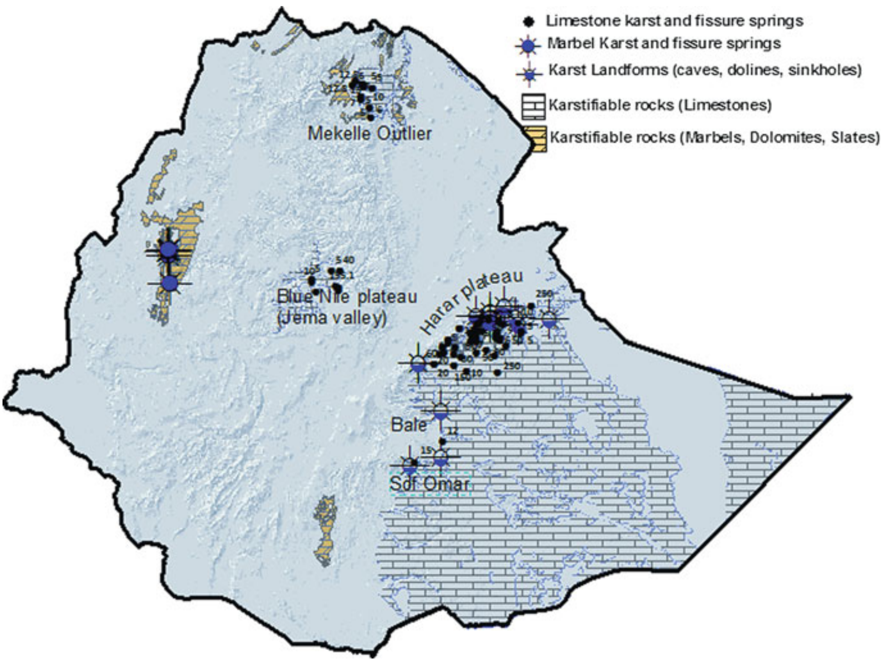


Fig. 2.35 Distribution of major karst features of Ethiopia and extent of karstifiable rocks (mainly Mesozoic sediments: sandstones, limestones, gypsum, shale etc.) and prominent karst features and karst springs (numbers near symbols indicate discharge rate of springs)

depression. Karstified regions in basement aquifers of western Ethiopia is of minor importance because of its aerial extent. In the Blue Nile gorge limestone members of the Antalo formation include a high proportion of marl and clay layers, pure limestones not exceeding 50 m. In the Mekele region, the Antalo limestones outcrop over a large area and attain a thickness of about 800 m, the thickest well exposed succession in Ethiopia. Much of it is marly limestone, however, with many clay and shle layers.

The rarity of well developed karst land from in the Mekelle outlier and the Abay valley is attributed to the small thickness of pure limestone beds as compared to the intercalated marl and shale layers. In Harar plateau and Bale area however the thickness of the pure limestone layers reaches several hundred meters thick allowing development of karst landforms and larger interconnected caves.

By far the most important cave bearing formation in Ethiopia is the Antalo Limestone. As normally defined this formation includes associated shales, siltstones and gypsum, whose thickness may be greater than limestones themselves.

Notable ones include the SofOmar Cave and karst systems, and karst systems of upper Wabishebele basin in Harar plateau (Mechera, Kersa, etc.). A few caves are also noted in the Mekelle Sedimentary outlier with limited or patchy development of cavernous landforms. Some village water supply in the Harar plateau depends partly on karst aquifer resources (example: Kersa, Bedesa, Mechera).

In a number of places high discharge karst springs are reported in marble aquifers of western Ethiopia. A typical example is the Dalati springs in Asosa area. The discharge of this spring is documented to range from 15 to 20 l/s in dry seasons.

In Tigray region of Ethiopia (north Ethiopia) particularly north of Wukro several shallow caves (less than 10 m long) occur in a dark grey Precambrian limestone which has well developed clints and grikes on the hilltops. Similar karstic features are developed elsewhere in northern Ethiopia on limestones and marbles, but no caves or potholes of any bigger size nor large dolines or sinkholes have been reported.

Basement Marble Aquifers of Ethiopia

In northwestern Ethiopia bordering Sudan in number of places marbles corresponding to the basement lithologies show some karstification leading to groundwater storage and flow (Fig. 2.35). The marbles come with spatially recognizable trends of productivity. The marble aquifers in western Ethiopia are the most productive compared to similar rocks in north Ethiopia, principally owing to differences in degree of karstification. High rainfall in western Ethiopia allows karstification of the marble aquifers. Several karst springs from fractures of marbles have been documented to emerge from the marble karsts in western Ethiopia (Fig. 2.35). In general, the highest groundwater accumulation within the marble seems to be near anticlinally (synclinally) folded parts of the marble in which more penetrative vertical joints are developed; or along faults and major joints. The vertical joints easily recharge the karstic aquifers with fresh rainwater, and partly allow the water to flow along other joints that are connected with these sets of vertical joints and the foliation. The faults seem also to cause high brecciating and thereby free groundwater accumulation and flow within the marble outcrop. In Eritrea for instance in zones where there are intense ductile strain or late brittle faulting, the marble layers develop secondary permeability. They are targets of small scale supplies of potable water (Drury et al. 2001).

Karst Hydrogeology

As direct hydrogeological evidence such as pumping test or other methods such as tracer tests are practically nonexistent discharge of springs and their variability from the various carbonate aquifers have been used to derive hydrogeological prosperities (storage, flow properties) of these aquifers (Fig. 2.36) and compare groundwater flow and storage properties in various carbonate aquifers in Ethiopia.

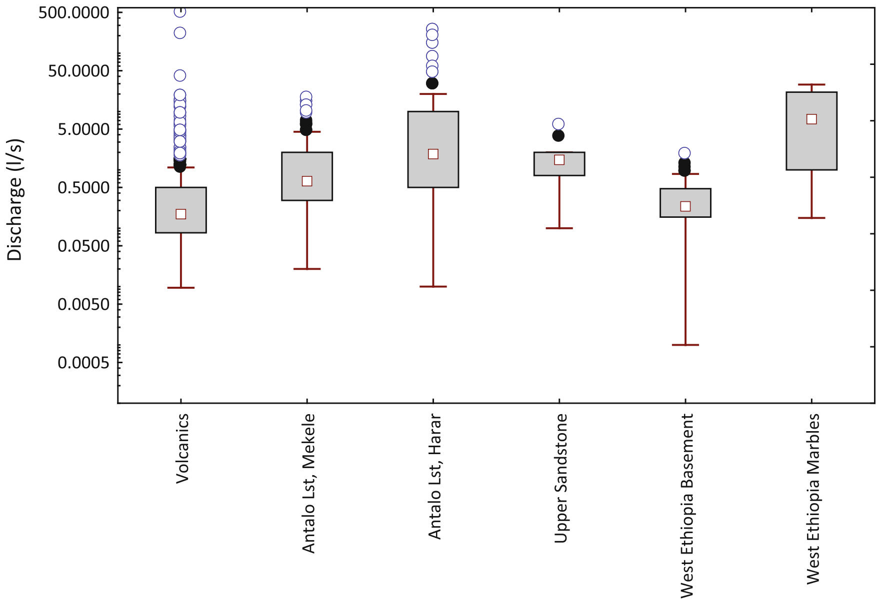


Fig. 2.36 Box and whisker plot showing spring discharge variations in various lithologies including the limestone aquifers of south eastern plateau around Harar and limestone aquifers of the Mekelle outlier. A total of 2504 spring discharge data has been used in the drawing of the box and whisker plots (2044 from volcanics, 250 from basement, 120 from Mekele Outier, 7 from marbles and 40 from *upper* sandsotone and 70 from Antalo limestone of Harar)

Comparison of spring discharge data (Fig. 2.36) shows the Limestone aquifers of the SE plateau including Harar area is characterized by high discharge variability, highest recorded discharges and higher mean discharge of springs as compared to the limestone aquifers of northern, western and central Ethiopia. This discharge variability corresponds to the degree of karst development and recharge rates. It clearly indicate that the Limestones of the higher elevation areas of the SE plateau is more karstified while the limestone of the Mekele outlier and Blue Nile basin can be categorized as fractured limestones.

In the Bale region of the SE plateau, most of the caves are located above the current regional water level in the unsaturated zone, though originally formed under phreatic conditions (ex. Nur Mohammed cave, Sof Omar cave etc.). The present day hydrology of Sof Omar cave varies considerably between the dry and wet seasons, the former lasting from November to March. The wet season has two maximum, the first in April and the second in September. In the dry season the river passage exhibits extensive cobble banks and all the fords are less than 1 m deep. In the wet season the river rises 7 m. There are also sections of the cave that holds ephemeral lakes of various sizes.

In the Upper Wabi Shebele Basin, the highlands bounding the multi layered sedimentary sequences from north and the rift valley from south a number of karsitifed features have been documented. Among these karst geomorphic

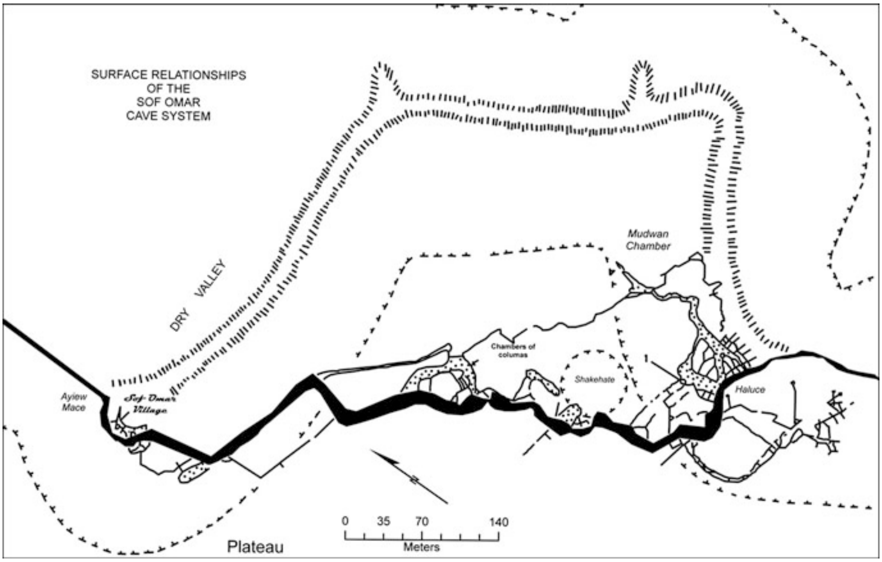


Fig. 2.37 The SofOmar karst features. The cave forms when the meandering Weyib River breaches the limestone plateau until it re-connects with the main channel 1 km downstream

features, sinkholes, dolines, solution cavities and large springs and boreholes yielding large of up to 250 and 15 l/s respectively were obtained from this aquifer. As it appears from the orientation of the Karst features and elongation directions initiation of karstification and its breakthrough appears to be controlled by rift related faults.

Investigation by BSEE (1973) of karst features of Ethiopia reveals that in Northern Ethiopia little evidence exists for the karstification of marbles and dolomites of the Precambrian basement.

Gypsum karst has been previously recorded in the Ferfer formation in the Ogaden (Hadwen et al. 1973). Karstic features are seen in several places, notably in Fafen depression south of Shilabo. There groundwater potential is limited by the high salinity associated imparted to groundwaters by dissolution of evaporate components. The role of the karst in groundwater circulation is largely unknown.

Principal Karst Features of Ethiopia

Caves in Ethiopia have widely been explored and their features documented by the British expedition in early 1970s. The geometric characteristics, origin, structure, hydrology and biological aspect of these caves have been documented in detail in BSEE (1973). The descriptions of these principal caves given below are excerpted from this literature.

SofOmar: The Sof Omar Cave system is one of the most prominent karst feature in Ethiopia (Fig. 2.37). The SofOmar cave is a spectacular example of a flood-water maze developed at three successive levels in horizontally bedded limestones beneath a basalt cap-rock. It is a meander cut-off system that floods frequently during the rainy season. The flood water caves develop in low gradient vados caves where fissure frequency is high. Because of its unique genesis related to combination of scouring and dissolution the SofOmar cave have been widely mentioned in scientific literature on origin of cave (Ford and Williams 2007).

The SofOmor cave forms because of allogenic flash flooding invading a limestone plateau. Floodwater maze development is most significant where caves drain large and rugged allogenic catchments (i.e. where large floods are applied rapidly to one point in the karst) and is most prominent at the upstream end of systems. The flow of the Weyib river itself is controlled by a prominent regional fault that cuts across the sedimentary formation in NW–SE direction.

Melka Mena: At a total length of 294 m Melak Mena (located in Bale) is one of the prominent karst features in South Eastern Ethiopia (Fig. 2.41). The entrances of Melka Mana is drystone formations, which can be seen by daylight. After 75 m, the main passage takes a sharp swing to the south, but a 1 m high passage continues straight forward. This leads to a 4 m climb down into a low chamber with three ways on-all close down rapidly. From the bend the main passage follows the same southerly bearing for 110 m averaging 10 m wide and 4 m high, making an easy walk. Just beyond the bend are several large stalagmite bosses on broken slabs of rock. While there is much evidence of roof collapse the cave shows its phreatic origin in many sections where the roof is arched and obviously following joints. The cave ends as a wide, low bedding less than 0.3 m high (Fig. 2.38).

Nur Mohammed: At 2.5 km Nur Mohammed cave is the second longest cave in Ethiopia. Nur Mohammed is a complex network of passages with four entrances from a cliff. The cave is characterized by solutionally enlarged cavities, dusty rock strewn floor, mud floored tubes, chambers, shallow water pools. Notable small streams emerging and dying within the caves and drip waters are common features. The cave system is located above the current regional water table and river water levels. The entrance in the cliff front is more than 100 m away from a river which is flowing at a lower level than the base of the karstified limestone. The basic alignment of the cave is west east, while the north to south passages and solution features all point to a phreatic origin. Many of the passages take form of rift/joint, though there are sections which show the classic tube shape. Some basalt boulders are noted inside the cave. This combined with large passages in some sites indicate that the cave must have hosted through flow of water in early stages of development. There is little vertical development of the cave except few avens through which water drips down and deposit calcite in forms of tall pillars. But owing to lack of extensive dripping water formation of pillars are rare.

Gara Hakim: Immediately south of Harar lies a hill of impure limestones and marls and several karst features (Fig. 2.39). Topping this is a level plateau of more massive limestone which exhibits karst features. The northern half of the plateau is known as Gara Hakim while the southern part is Gara Barcalle. Three kilometers

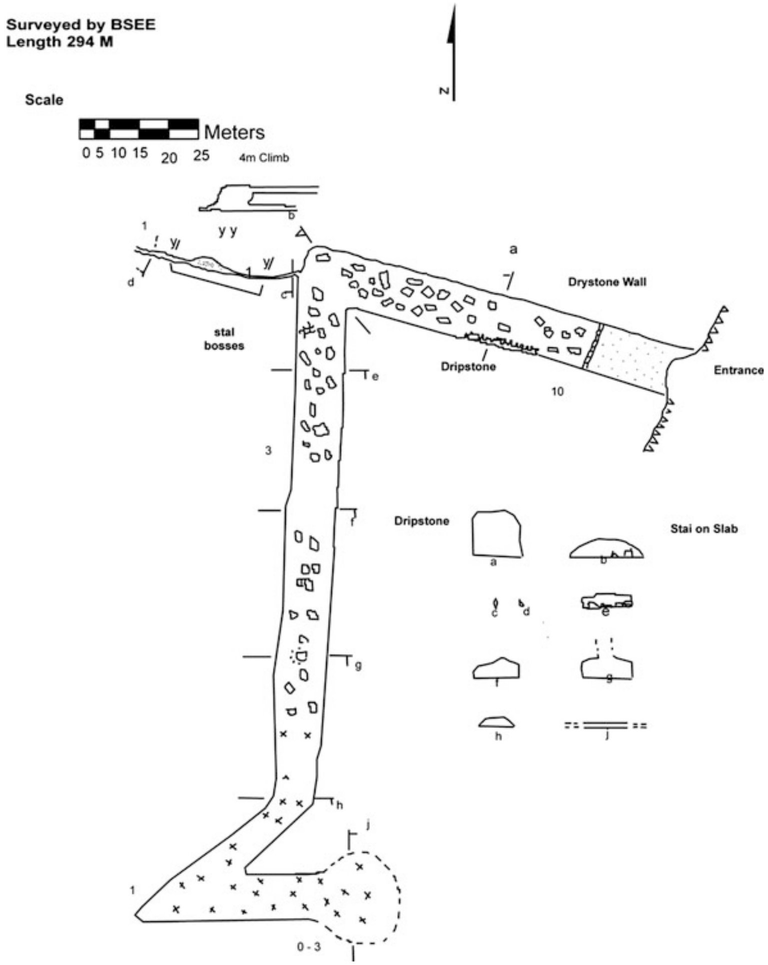


Fig. 2.38 Features of the Melka Mena cave in SE Ethiopia

of the south lay the smaller plateau of Gara Bilalu. This plateau shows a doline karst which was not seen elsewhere in Ethiopia. Most of the potholes where found amongst the areas of limestone pavement which tended to outcrop round the perimeter of the dolines, some of the clints protruding up to 5 m. In general the dolines are shallow, gently sloping, and closed depressions up to 200 m diameter. Parts of the plateau are cultivated, including some of the dolines. Where the limestone outcrops it tends to be well jointed showing much faulting and small scale solution depressions. In some impure lower successions on the eastern side of Gara Hakim several small rock shelters were found developed along bedding planes. Features of these were heavy incrustation of tufa, dense and prickly

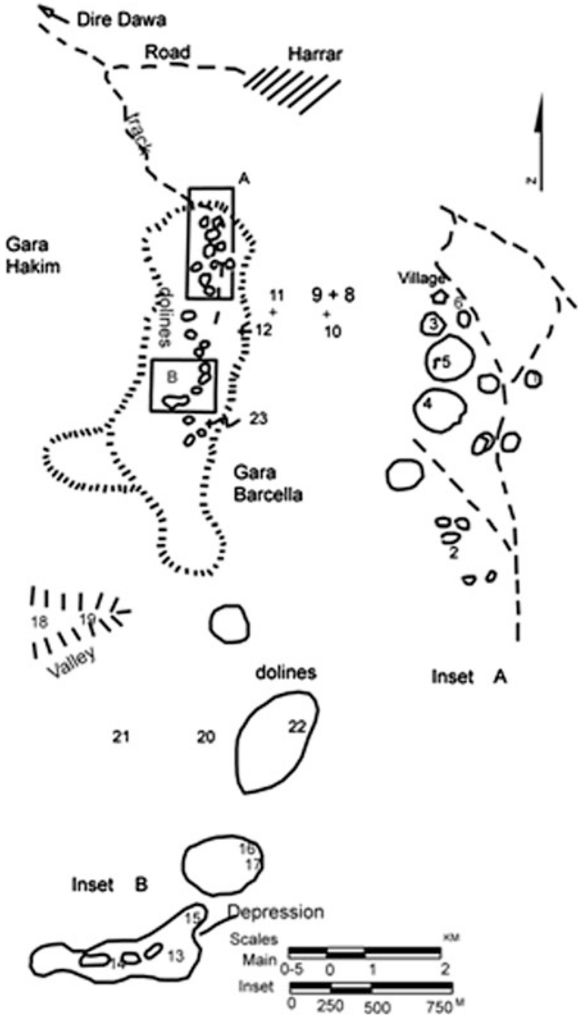


Fig. 2.39 Distribution of caves, potholes, dolines in the Harar Gara Hakim plateau

surrounding undergrowth and their inhabitants. Around 23 caves and potholes have been discovered by the British exploration team (Table 2.10).

Table 2.10 Table describing the karst features of the Gara Hakim in Harar highlands

Name	Description of Karst features at Gara Hakim plateau
GH 1	30 m deep pothole ending in a choke, entrance in a rift between clints
GH 2	Entrance in clints, Two neighboring potholes, 10 and 12 m in depth
GH3	A 20 m deep pothole
GH 4	Three entrances among clints unite in a chamber developed in a 1 m thick shale band part way down the 17 m first pitch. 7 m pitch follows, then climb down to chamber with stalactites with passage spiraling down to sump (figure)
GH 5	Several small pots amongst the clints on both sides f this large doline
GH 6	Five entrances in clints lead to two chambers with flowstone on walls (fig)
GH 7	Entrance in clints. Winding cave passable about 40 m long
GH 8	Shallow bedding cave in face of cliff, 5 m long
GH 9	Rock shelter 3 m long
GH 10	Four bedding caves up to 10 m long at various heights in cliff
GH 11	Bedding cave 6 m long
GH 12	16 m deep pothole amongst clints. Two constricted pitches of 7 and 9 m with a squeeze in between
GH 13	Entrance in shakehole to 19 m pitch to steep slope ending in blockage at 21 m
GH 14	From shakehole bottom, 5 m pith leads to a chamber, with unentrable pitch of 20–24 m following
GH 15	Entrance in shakeholes to 27 m deep pothole. Short tight winding passable descents steeply then four short pitches
GH 16	Amongst Clints near edge of doline 7 m deep open pot connected to a 10 m deep pothole
GH 17	Amongst clints, 13 m deep pothole next to 12 m deep open pot
GH 18	7 m deep pothole with small chamber in lower of two shakeholes in small valley
GH 19	13 m deep pothole in clints in upper of two shakeholes in small valley
GH 20	Entrance in extensive limestone pavement. First pitch 33 m in 1 m by 4 m shaft ending in a boulder floored chamber. Squeeze in rift at south end of chamber leads to 4 m climb down to a 12 cm wide rift leading to an pitch of 20–25 m
GH 21	8 m deep open pot in pavement
GH 22	Entrance amongst undergrowth near edge of doline. Open pothole 23 m deep to boulder floor
GH 23	8 m deep pothole

2.13 The Precambrian Basement Aquifers of Ethiopia

Geology

The Precambrian lithology of Ethiopia consists mainly of metamorphic rocks. The rocks are exposed in five regions (Fig. 2.40). In the northern Ethiopia they comprise low grade metavolcanics, greywackes and slates with minor marbles, while in western and southern Ethiopia higher grade schists and gneisses are characteristics. Granitic intrusions locally cut the metamorphic rocks and ultrabasic masses occur in the western part of the country. As will be seen later in this section, the clear difference in the basement rock lithology lead to differences in groundwater and hydrogeologic properties of the basement rocks in Ethiopia.

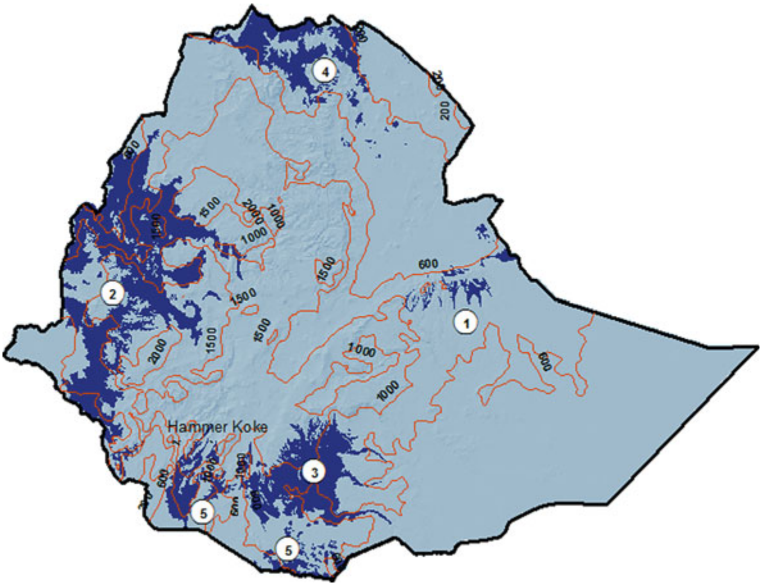


Fig. 2.40 Distribution of the Precambrian basement rocks

Hydrogeology, Groundwater Occurrence, Structures and Regoliths

The productivity of basement aquifers in Ethiopia largely depends of the presence of regolith, fractures, type of metamorphic rocks or grades and sustainability of recharge and topography. Two of the principal control of groundwater occurrence in basement rocks are the density of fractures and the presence of regoliths mantling the basement rocks. Previous groundwater maps of Ethiopia (EGS 1996) and hydrogeological reports (Chernet 1993) put the entire metamorphic rocks of the country as low yielding regional acquicludes. It is widely stated that groundwater occurrence in basement rocks of Ethiopia is mainly confined to fracture zone and to regoliths when such profiles are developed. Nevertheless little previous attempt has been made in order to understand the genesis of regoliths on the basement rocks of Ethiopia.

Topography that favors convergent hydrographic networks is more suitable for groundwater occurrences. In valley bottoms or secluded valleys between adjacent highlands groundwaters convergence to valley bottom enhance groundwater accumulation. The regolith thickness also enhances accumulation of groundwaters. In steeper slopes (hilicrest) regolith thickness is usually small that in gentler and flat topographies (pediments). At the core of the process responsible for regolith development is the cycles of striping and deep weathering which is strongly tied to tectonic cycles of uplifting and tectonic quiescence. Generally porosity in the regolith is orders of magnitude higher than in the fractured bedrock. As a result, the relative amount of extractable water is much higher in the regolith than in the unweathered bedrock.

Depending on the depth of weathering, influence of structures and presence of lower permeability pedocretes, infiltration can be lowered leading to less recharge and more surface runoff. This is typical hydrologic feature in arid areas of Borena (marked 3 in Fig. 2.40) and Northern highlands (marked 4 in Fig. 2.40).

Development of deep weathering profile requires long periods of time under stable tectonic conditions (although still the present day hydrologic processes are also linked to nature of weathering profiles), a few millions to a few tens of millions years. Thus, relatively flat topographic areas are required to avoid the erosion of weathering products (saprolite), but also to favor water infiltration. Thus, such profiles cannot develop in regions of sharp topography where the erosion rate is higher than the one of weathering.

Critical research in geomorphologic history of the Ethiopian basement rocks is scarce. Deeply weathered landscapes occur throughout equatorial regions and are transformed by cycles of deep weathering and stripping. These processes are driven by rainfall that infiltrates the subsurface as groundwater recharge or runs across the landsurface (Taylor and Howard 2000). Deeply weathered landscapes, unaffected by Pleistocene glaciation and aeolian erosion, are common to low-latitude regions of Africa, Asia, South America and Australia. These terrains reflect a prolonged geomorphic history, which is characterized by alternating cycles of primarily mechanical or chemical denudation (Fairbridge and Finkl 1980; Thomas 1989; Taylor and Howard 1998). Mechanical denudation is effected by the action of water running across the land surface and involves the physical removal (i.e. 'stripping') of unconsolidated material from the surface by colluvial and fluvial erosion. Chemical denudation is achieved by the movement of percolating rainfall (i.e. direct groundwater recharge) which removes chemically mobile species from the land surface in solution through 'deep weathering'.

One of the very few work on the geomorphic history of the basement rocks of Northern Ethiopia shows, despite its location in low latitude setting, evidence for presence of deep weathering products in northern Ethiopia is lacking (Coltorti et al. 2007). These indicate that Northern Ethiopia in particular and eastern Africa in general underwent long episodes of tectonic quiescence in Paleozoic during which erosion processes were able to planate the surface at altitudes not too far from sea level (Coltorti et al. 2007).

In Western Ethiopia three phases of saprolite and laterite formation has been recognized (Belete et al. 2004) based on model of Thiry et al. (1999) which characterizes the origin of basement surfaces in Africa. The oldest palaeosurface with weathering mantle covers the crystalline basement. It was formed in hiatus before Mesozoic transgression. The second palaeosurface is over the Mesozoic sediment, which was formed in hiatus before outpour of the tertiary flood basalt. The third weathering mantle on the present surface was formed from tertiary to recent time. There the laterites formed due to climatic conditions, which favor greater mobility of alkalies, alkali earth and Si than Fe and Al as the product of rigorous chemical selection. The laterites were subjected to ferricrete formation, equivalent to climatic conditions with expressed dry season.

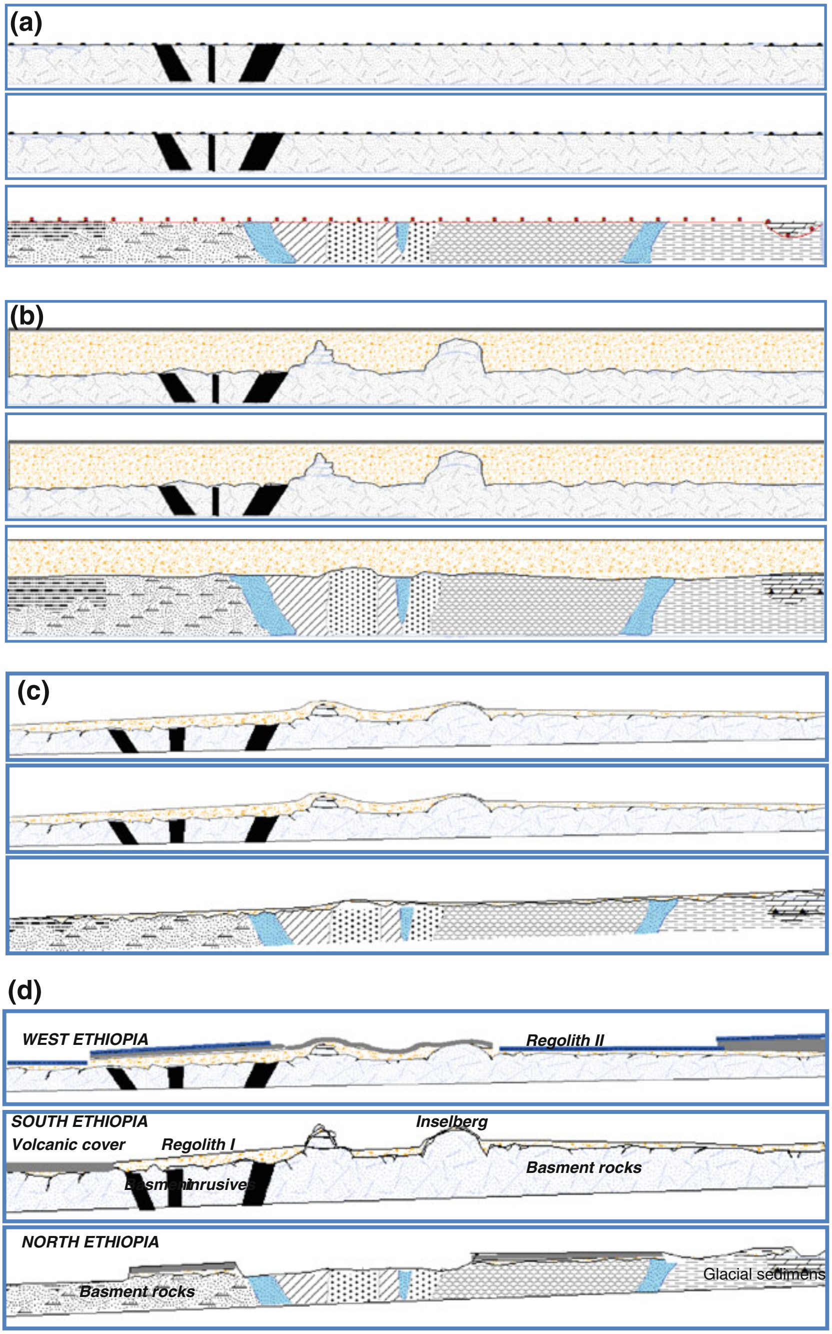
The lithology, texture, and structure of the parent rock govern the characteristics of the saprolite, as many features of the parent rock are preserved in the saprolite (see box ii for details). There is a general tendency for the gneiss and quartzose schist to weather to a sandy, fairly permeable saprolite, whereas the gabbro, metabasalt, and ultramafic rocks weather to saprolite with a higher clay content and lower permeability (Nutter and Otton 1969).

Generally basement aquifers with lowest productivity are located in the northern Ethiopia and the Borena lowlands. Basement rocks in western and south-central part of Ethiopia are generally productive. Yield of springs in basement outcrops bounding the Tekeze River valley in northern Ethiopia rarely exceed 0.1 l/s.

Polycyclic Deep Weathering and Stripping History: Implication for Basement Aquifer Potential

Evidence in many countries and several works in Africa (Tylor and Howard 1998; Tylor and Howard 2000; Foster 1984; Acworth 1987) suggest that tracing the geomorphic evolution of weathered land surfaces and identifying the dominant geomorphic process operating on those land surfaces (i.e. deep weathering or stripping) provide an understanding of the hydrogeological and hydrological characteristics of basement aquifer areas. This is a holistic approach that can provide greater insight. Furthermore, it is of practical importance to planners, because it enables definition of suitable areas for the development of the weathered mantle aquifer and intensive groundwater abstraction from the weathered mantle and fractured bedrock (Taylor and Howard 1998). Such holistic approach in understanding the hydrogeologic potential of basement aquifer of Ethiopia is lacking. Most previous studies suggest in very generic term that groundwaters in basement aquifers occur in fractured and weathered layers without giving any clue on the spatial pattern of such geomorphic processes. For example in the hydrogeological map of Ethiopia, the basement aquifers all over the country are classified as local, less extensive aquifer with fracture porosity. Evidences and model given below (Fig. 2.41a–d) try to develop a comprehensive model of weathering and stripping cycles in Ethiopia since the Phanerozoic taking three regions (North, West and South Ethiopia). This model is aimed at improving the previous models which are regional in nature to the scale of Africa (e.g. Thiry et al. 1999) or localized to explain wreathing and striping history of local significance (e.g. Coltorti e al. 2007). All in all five prominent stripping-deep weathering stages with significant implication to the present day groundwater occurrence and flow, can be recognized for Ethiopia. The evidence for the model largely comes from literature across Africa, consideration of mega geologic events (Table 1.4) in Ethiopia and corroboration of these using field evidences.

Stage I. Erosion of early and middle Paleozoic landscape by Carboniferous glaciation: During this stage Northern Ethiopia in particular and eastern Africa in


(a)
(b)
(c)
(d)
WEST ETHIOPIA
Regolith II
SOUTH ETHIOPIA
Volcanic cover
Regolith I
Inselberg
Basment rocks
NORTH ETHIOPIA
Basment rocks
Glacial sedimens

◀ **Fig. 2.41** Proposed schematic model showing the evolution and development of weathering surfaces and their stripping (see Fig. 2.41d for legend). **a** Stage i. Complete stripping of the Paleozoic and Precambrian basement surface by Late Carboniferous/Permian glaciations. Paleozoic rhythmic striping surfaces in at least two stages, all the area is brought to sea level by the glacial erosion and scouring, formation of two cycles of glacial sediments in north Ethiopia—onene during pre Ordovician the second in late Triassic (see also Fig. 1.3) (*top*: South Ethiopia, *middle*: West Ethiopia and *bottom*: Tigray) (see Fig. 2.41d for legend). **b** Stage ii. Cretaceous deep weathering (150 m thick laterite under Oligocene volcanic in Eritrea, laterite soils on *top* of Ambaradom, remnants of the Cretaceous deep weathering profile is still seen in Borena, Western Ethiopia, and elsewhere in the country where it escapes later denudation (see Fig. 2.45d for legend). **c** Stage iii. Cretaceous to *mid* Miocene uplifting, stripping and volcanism (e.g. Isolated mesas and buttes with laterites on *top*). The more pronounced uplifting from sea level to about 3,000 masl reduced the regolith to near abscent to patchs here and there particulary from the areas where it was initially not well developed because of subsidence below sea level. (see Fig. 2.45d for legend). **d** Stage iv. *Mid* Miocene to recent rhythmical and differentiated stripping and deep weathering new regolith on basalts visible in western Ethiopia, following local topography further uplifting and intensification of stripping, unloading of the Oligocene flood basalts and further intensification of stripping aridification recharge decreasing The second lateriazation event is very well preserved in flat depression example in the Dabus plateau etc

general underwent stripping by advancing carboniferous glacier during which glacial scouring left a very flat surface dotted by glacial moraines. The erosion processes was able to planate the surface at altitudes not too far from sea level (Coltorti et al. 2007). As seen in Fig. 2.41a, the relief was similar in the entire region of Ethiopia. The same surface is common elsewhere in central Africa (e.g. Uganda) (Tylor and Howard 1998).

Stage II: *Cretaceous deep weathering* (*Africa surface*): During this stage tectonic quiescence and optimum climate lead to the development of thick regolith in all region of Ethiopia (BSEE 1973). There are evidences for the fact that the early Cenozoic was a low laying terrain (Sengor 2001; Merla and Minucci 1938) that was product of erosion and deep weathering and according to Burke and Gunnel (2008) this surface represent the African surface which is known elsewhere in Africa. This surface is widespread in Africa and is known as Africa surface. The deep weathering is favored by more humid climate which accompanies the new tectonic position of the region north of the equator in subtropical setting (thus high temperature and humidity). The thickness of the regolith varies from region to region depending on the mineralogy and metaphoric grade of underlying basement rocks. Generally higher grade rocks shows higher development of regolith and low grade rocks show low development. In Eritrea for instance up to 150 m thick sediments have developed on the high grade Barka domain rocks. This thick weathering profile is common elsewhere in Ethiopia. According to Drury et al. (1994) humid conditions in the southern part of the Arabian Nubian shield led to the development of Fe-rich lateritic soils during the early Tertiary times. These paleosols are overlain by tertiary flood basalts in part of Eritrea, Ethiopia, Saudi Arabia and Yemen and have been exhumed where the basalts are removed by erosion. In Eritrea, laterites that underlie the 30 Ma basalt represent a widespread and lengthy period of humid conditions in the early

Cenozoic. The laterites cap basement rocks as well as the Jurassic Adigrat sandstones. Lateritazed part of upper sandstone is also visible at Amba Aradom in Tigray (Moeyersons et al. 2008).

Stage III: Cenozoic uplifting and striping: During this time the whole of Ethiopia and East Africa (Kenya for example) underwent uplifting preceding the volcanic activity. Burke (1996) attached particular significance to the absence of a laterite covered African Surface from a roughly circular area ~ 100 km in diameter center on the Afar Dome. He suggested the erosion as the dome started to rise and before the eruption of the Ethiopian traps began could account for the absence of laterite from the roughly circular region. According to Burke and Gunnel (2008) the absence of laterite in a wider regions is due to a kilometer scale topographic swell that took place 32–30 Ma leading to stripping of the African surface, causing laterite stripping on an upward African surface as well as canyon cutting through the erupted flood basalts and underlying basement. In many areas the laterite cover has been completely removed. The elevation of the Afar plume, the associated eruption of the Ethiopian traps, the establishment of the Ethiopian rift, and the development of red sea and the Gulf of Aden, have led to complex and episodic topographic deformation of the African Surface. In many areas, the lateritic cover has been completely removed by erosion. In southern Ethiopia calcrete, fericrite and silicrite occupying most of the ridges in Borena are indication of stripping of the surface of the rocks. Other indicators of stripping are inselbergs dotting the wider Borena plain in Basement region of southern Ethiopia. However in several locations including the Northern Ethiopia, the flood basalt eruption that follows the uplifting protected further erosion of the Africa surface. In several localities now laterites mark the contact between the basement and the flood basalts sequences (e.g. in northern Ethiopia). In Borena stripping has progressed only moderately leaving extensive tabular residuals (inselbergs) capped by laterite (or silcrete and calcrete) duricrusts which protect the soft underlying zones of the weathered layer on hard rock terrains. Along preexisting fault zones quaternary wadi beds cut across the weathered layers. In the Hammer Koke block (western area basement rocks marked 5 in Fig. 2.40) including the Konso area the rejuvenated and uplifted peneplains under active erosion has the earlier developed weathered layers partly or completely stripped away leaving only spectacular badlands (Fig. 2.42). Figure 2.42c show for instance a 4 Ma old basalt resting directly on the basement rocks with no presence of regolith in between suggesting complete stripping either in early Cenozoic uplifting or since Miocene. In Northern Ethiopia because the low grade metamorphic rocks did not allow widespread regolitization, the accompanying striping event even reduced the regolith much further and only isolated regoliths are noted or the thickness is very small.

Stage IV: Miocene to recent cycles of deep weathering and striping: This stage is a much complex phase with weathering and formation regolith taking place and accompanied by striping and erosion. These complex processes follow regionalization of processes following development of different climate and landscape across Eastern Africa following the Cenozoic uplifting and volcanism. Undoubtedly, the tectonic uplift following the preceding the volcanic eruption resulted in

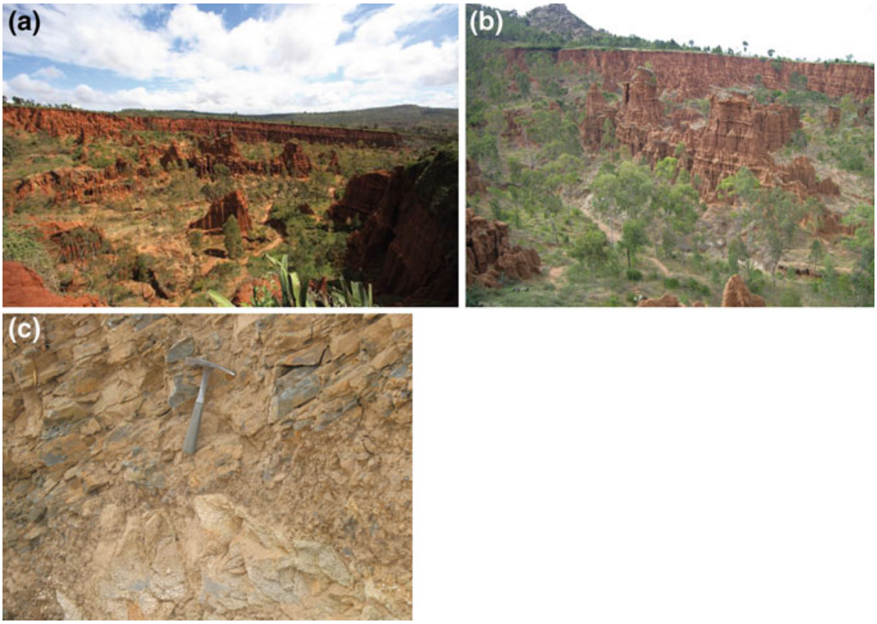


Fig. 2.42 Surfaces typical to the basement surfaces of southern Ethiopia, the badlands are result of stripping of Africa surface since Cenozoicr, **a** and **b** taken from a locality called Konso and **c** is taken from southern end of the south Ethiopian basement

regionalization of climate, rainfall and temperature leading to variability in regolith production rate in different sectors of Ethiopia. The more humid western Ethiopia has been undergoing intensive denudation and regolithizations while the in northern Ethiopia chemical denudation since Miocene lead to less regolith development. Prominent shields (Fig. 2.3) which act as moisture shadows have also been formed during the late Cenozoic (e.g. the Choke shield, the Simen Shield, the Guna, Guguftu) isolating the northern Ethiopian highlands from heavy and prolonged rains which could have resulted in widespread regolitization. Climatic conditions favorable for deep weathering, particularly precipitation exceeds evapotranspiration to produce rainfall fed groundwater recharge occur since Miocene in Western Ethiopia to sustain deep weathering that continued in West but not in east and north. Little evidence in Ethiopia exists to substantiate this however works in Uganda show the presence of such conditions since Miocene (Taylor and Howard 1998).

The regionalization of striping-weathering processes has lead to three distinct present day landscape of the basement regions of southern, northern and western Ethiopia. In Northern Ethiopia, the landscape is a nearly completely stripped basement with only patches of regoliths (Fig. 2.43a–c). When isolated by the volcanic cover, thickness of regoliths may reach 20–30 m (e.g. around Shire Indasilassie). The eruption of the flood basalts leads to protection of the remaining laterite materials in several places. For instance in Shire Indasilassie deep groundwater wells normally penetrate the laterite sandwiched between the basement and the overlying volcanic cover. Continued stripping in northern Ethiopia is affected by a low ratio of annual recharge to runoff. The significantly reduced recharge flux, relative to that the surface of deep weathering, is transmitted to well incised drainage channels by the fractured bedrock and, in places by localized aquifers in the weathered mantle. Discharge is in terms of highly variable stream flow (wadi bed discharge etc.). The extensive wadi beds in the lowlands of Borena and Hammer Koke blocks are typical examples of active ongoing stripping since at least the Miocene time.

In Eritrea, and thus by extension in Northern Ethiopia, the erosional sequence from rising massifs was first the stripping of up to 600 m of Mid Oligocene flood basalts and then the deeply weathered regolith (locally in excess of 150 m, depending on basement lithologies) beneath an Early Tertiary lateritic paleosol. Both source materials weather to clay rich debris (montmorillonite illite from basalts, kaolinite-illite from paleogene laterite and regolith). The bulk of lowland terraces comprise clay rich loams beneath lag gravels shed by basement progressively exposed to erosion by uplift (Durry et al. 2001). Sections through some of these terraces show a sequence from lower dark illitic soils, covered by red kaolinitic soils, originating from later erosion of deeply weathered basement, an inversion of the stratigraphic sequence that remains in higher elevation. Because the terraces have undergone uplift and incision at some stage in this evolution, perhaps as a consequence of erosional unloading, most debris released from unroofed basement that is not affected by Paleogene deep weathering moves not only in the active channels. Much of it passes through lowland areas to be deposited in the lower areas to be deposited in the lower reaches of the main rivers to form gravels, sands and silts that have low fertility. These Recent channel deposits constitute the main soils currently under crops. Because of this uplift, the loams in uplifted terraces have only a thin cover of sand and gravel (Drury et al. 2001).

In Western Ethiopia, Miocene two contemporary deep weathering results from a large ratio of annual recharge to runoff (25–40:1) with recharge events during the major long rainy monsoon seasons. In Western Ethiopia therefore one can see two prominent regolith and deep weathering events. One related to Africa surface and the other developing since Miocene to present. The later regolitization is taking place on basalt outcrop while the former developed on the basement lithologies.

In southern Ethiopia much of the present day surface is characterized by indurated caliche surface, deeply cut regolith badlands, and isolated granite inselberges caped by frecrite and calcrite all indicating active stripping since Miocene or earlier (see Fig. 2.42).

Box 2: Lithologic control on weathering profile development

UNESCO (1984)

The mineralogic composition and lithologic texture of the host rock also play important roles in the development of the weathered layer. These are commonly thickest and contain the most permeable (c) zones on coarse-grained salic rocks such as granites; granodiorites, and orthogneisses. Among all the various categories of hard rock terrains the granite, granodiorites and orthogneisses generally seem to have the greatest susceptibility to deep weathering (as much as 100 m deep in places). Also in these quartz-rich rocks zone (c) layers are commonly thicker and more permeable than in mafic rock terrains. In large and extensive granite batholiths which have been subject to prolonged weathering, zone (c) may range from 10 to 30 m in thickness

All other factors being equal the finer-grained rocks are less susceptible to weathering than the coarse-grained ones. In the inselberg-and-plains terrains of northwest India, for example, fine-grained granites commonly form inselbergs or erosional residuals of unweathered rock and subjacent coarse-grained granites beneath lowland plains are weathered to depths of 30 m or more

On some metamorphic rocks of unstable mineral composition such as slates, phyllites and argillaceous schists, weathered layers may be thin or absent, even when these rocks underlie extensive peneplains in climates otherwise favorable for deep weathering. When developed on mafic rocks such as diorites, gabbros, diabases and dolerites, the weathered layer may be thick but the (c) zones tend to be clayey and poorly permeable. Among the metamorphic rocks in hard rock terrains, quartz mica schists and thin-bedded quartzites may develop fairly permeable (c) zones in the weathered layer. These zones are seldom more than 5–10 m thick in contrast with those in the granites. Massive quartzites, however, commonly resist weathering and form linear inselberg ridges rising above lowlands of other weathered rocks

Examples from Ethiopia

Observation in northern Ethiopia shows; in clastic meta sediments of Shiraro block contain weathering material of reddish laterites. In places the regoliths are completely absent in other places the remnants of yellowish brown badlands are visible on the Eritrean side. The Chila domain metasediments with relatively abundant vegetation and water storage owing to abundance of graphite and soil development. Adwa domain dominantly metavolcanics show less developed or no evident weathered beds. Weathered surfaces are more common on metasediments of Shiraro block and Chila domain than in the metavolcanics

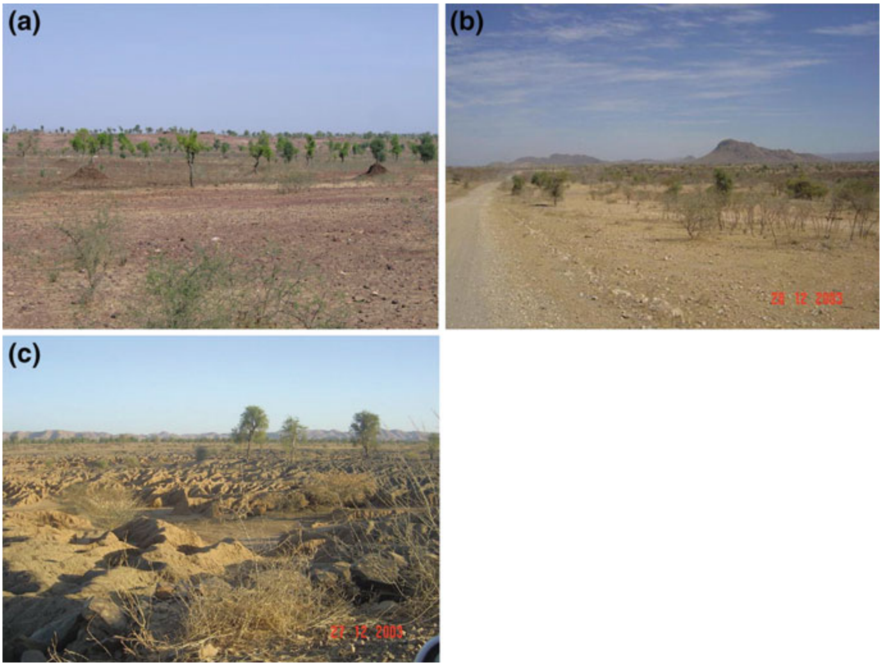


Fig. 2.43 Photo showing the surfaces of present day exposure of the North Ethiopian basement

Implication of Geomorphic History to Groundwater Occurrence

Based on development of regolith, degree of fracturing, water holding capacity and degree of fracturing the five zones of basement aquifer has been discussed separately. A typical basement aquifer with well developed regolith has the form as shown in Fig. 2.44. Nevertheless the complex stripping and deep weathering history of Ethiopia as discussed above led to most of this sub layers not present in Ethiopian case. In the north Ethiopia for instance the whole regolith surface is stripped completely or exists only in patchs (Fig. 2.43), in southern Ethiopia around Borena the regolith thickness tough laterally extensive is reduced vertically. In the western Ethiopia a well developed regolith has similar appearance as the one indicated in the schematic model (Fig. 2.44).

To be significant aquifers with exploitable groundwater, the weathered layer must attain a minimal areal extent and thickness and have sufficient porosity and permeability to store water and to yield it to wells from season to season and from year to year. Extensive and thick weathered layers are likely to contain the most viable and productive aquifers. Thin weathered layers may contain no significant aquifers or, at best, intermittent ground-water bodies which do not persist through long dry periods. Locally, however, even relatively thin weathered layers may sustain perennial aquifers, provided there is prevailing high recharge, either natural

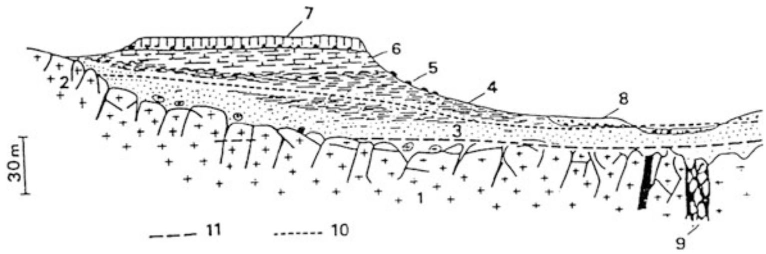


Fig. 2.44 Schematic section of aquifers within the granitic regions. (From Guiraud 1997). *1* Fresh basement, *2* Fissured zone, *3* Granitic sands, *4* Clay sands, *5* Plastic clays, *6* lateritic clays, *7* Lateritic duricrust, *8* Recent alluvial deposits, *9* Crushed zone, *10* Water level during wet season, *11* Water level during dry season (from Guiraud 1997)

or artificial. In some irrigated areas of India, for example, return seepage from irrigation plus natural recharge sustain wells in weathered layers only 5–7 m thick. In most places, however, weathered layers less than 10 m thick do not generally contain exploitable aquifers. Even where the weathered layer is of maximal thickness (as much as 50 to 70 m or even more in some places in the humid tropics) only 10–15 % of the total thickness may contain materials sufficiently permeable to yield water to wells. The thickness of the weathered layer and the presence of permeable zones in it depend on the interplay of a number of factors, among which are climate, topographic position, mineralogic composition and lithologic texture, and the distribution and spacing of the fracture system in the host rock.

The Basement Aquifers of Southern Ethiopia and Borena

Geology: The Precambrian basement of southern Ethiopia (marked 3 and 5 in Fig. 2.40) consists mainly of high grade and low grade metamorphic rocks and granite intrusives (Fig. 2.45). The low grade metamorphic rocks are composed of metasediments and metavolcanics consisting of slates, phyllites, schists and greystones. The high grade metamorphic rocks include gneisses, schists, granites and marbles. Several types of granitic intrusives are present including metagranites (high grade gneisses and granulites, metamorphosed granites), syntectonic granites with abundant pegmatites, and late-post tectonic granites.

Thin but extensive regolith (elluvium) developed over bedrock units ubiquitously occur throughout the Borena high grade metamorphic rocks, covering slopes, foothills, and flat-lying topography. The elluvium developed over basement grounds mainly consist of red to reddish brown sandy soil, with minor silt and clay. It has resulted from weathering of the basement rocks and is less than 10 m thick (Gerra and Abreham 1999). Nodules of limonite, boulders, cobbles and pebbles of various rocks of the underlying basement, and vein fragments litter the soil. The soil thus covers a mantle of weathering of the underlying basement units.

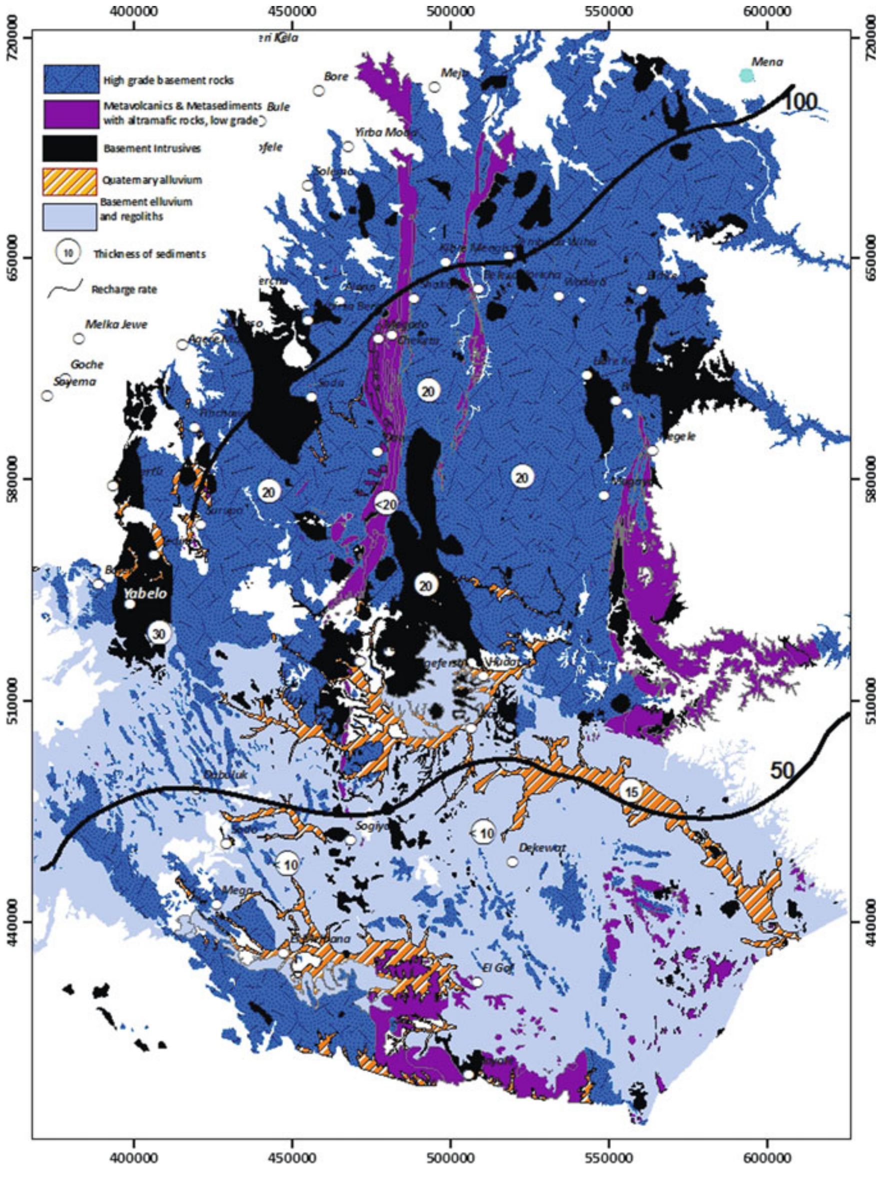


Fig. 2.45 Geologic map of the Borena basement rocks, associated regoliths and some hydrogeologic features

Climate: The area is dominated by a semi-arid climate. Annuals mean temperature varies from 19 to 35 °C with little seasonal variation and these decreases 1 °C with each 200 m increase in elevation. Average annual rainfall varies from 300 to 800 mm distributed within two-rain seasons. Rainfall delivery is bimodal: 59 % of annual precipitation occurs from March to May and 27 % from September to November. A dry year is defined as one in which annual rainfall is less than 75 % of average and this may occur one year in five. The probability that two consecutive years will have average or above average rainfall, one dry year, or two dry years is thus 0.64, 0.32 and 0.04, respectively. At least two consecutive dry years constitute a drought.

Groundwater occurrence: Regoliths and fractures are the main groundwater holding and transmitting media in a metamorphic terrain. The basement rocks of Southern Ethiopia show variable degree of fracturing and regolith development. Groundwater investigation for and production wells drilled in the Yabelo plain between 1972 and 1974 by the ministry of Agriculture show the crystalline hard rocks provide a yield ranging between 0.13 and 0.33 l/s.

The nature of regoliths also varies from parent rock to parent rocks. The northern sector of the region (Fig. 2.45) develops shows typical regolith layers as shown in Fig. 2.44. The southern sector on the other hand is characterized by complex setting of layers made up of in situ regoliths (elluvium) and transported sheet of alluvial material (alluvial sediments). The alluvial sediments are thicker in valleys and low laying areas. The alluvial sediments are also found in broad river valleys in the northern sector of the region.

For example around Kibremengist, alluvium deposits are noted to cover most of the valleys. Here bedrock is encountered at depths of less than 30 m in most places. Most of the groundwater comes from an aquifer in the alluvium, which is both porous and permeable. The underlying low and high grade rocks act generally as an aquiclude. The aquifer is recharged by the high rainfall in the region. Water table in the alluvium and marshy area is in the order of 7–10 m below the ground. The marshes are the result of groundwater discharge to the low laying areas and accumulation over low permeability bed rock.

Granites and gneisses usually weather into sand sized regolith materials. In Yabelo area for example the granitic intrusives are highly weathered into fine sand covered by thick red soils. Weathering products of metagranites in southern Ethiopia give rise of sandy regoliths. Late to post tectonic granites give rise to sandy regoliths and coarse grained materials. The post tectonic granites show exfoliated layers larger than 4 m. At depths greater than 5 m all the granites become massive with wider spacing of joints (5–10 m joint spacing). Some seepages and low discharge springs emerge from the granites fractures when such granites form a domal morphology.

The high grade metamorphic rocks of southern sector of Fig. 2.45, the weathering products are mostly fine grained clay, silt and sand. The thickness of the regolith is usually small and groundwater occurs whenever hydrologic process allows the weathering products to accumulate in nearby areas adjoining river valleys and streams.

In the low grade metamorphic rocks the topography is characterized by broad valleys. This morphology allows accumulation of alluvial sediments and preservation of regolith. There could be fine sand aquifers in the weathered zone and alluvials. Thick (20 m) decomposed fine grained regoliths makes up the weathered parts below the top red soils.

A clear geographic groundwater potential zonation of the basement rocks exists in southern Ethiopia. In basement rocks in the highlands straddling the rift from north, regolith thickness is higher (may reach 30 m in valleys) and recharge rate is higher owing to higher rainfall. Shallow groundwaters occur in the regoliths and alluvial materials in the low laying areas, recharge is relatively higher (around 50 mm/year). At 500–1,500 mg/L, total salt content of the groundwaters are also suitable for domestic water supply. Fractures in granitic intrusive also provide low discharge springs during wet seasons. The schematic model in Fig. 2.44 can very well represent the conceptual groundwater model in the basement aquifers of southern Ethiopia.

In the midlands between the lowlands of Borena and the highlands in the north show thin layers of weathering products, groundwater occurrence is limited to low laying areas in alluvial sediments, total dissolved solids is higher and may exceed 1,500 mg/L.

In southern part of the basement areas quaternary alluvials and eluvials resting on the basement rocks provide shallow groundwater in valleys where recharge is relatively high, they have moderate salinities (1,500–3,000 mg/L). The eluvial lateritic crust in the southern sector of the area consists of clay, silt and fine sand but it has dominantly silt and fine sand, with well developed layers similar to the model given in Fig. 2.44. The materials are promising hydrogeologic features from the point of view of construction of artificial water retention structures such as subsurface dams for water collection and storage. The duricrust capping the eluvium materials have low permeability and small thickness of less than 15 m. The significant reduction in thickness of the regolith is owing to stripping taking place since Miocene under arid condition. The aridity is the process that lead to formation of the extensive duricrust. This duricrust can also be noted capping inselberges dotting the southern sector of Fig. 2.45. Exceptionally thicker weathering products are recorded in the plains of Yabelo reaching 35 m (Alamneh 1989). It could contain shallow groundwaters in low laying areas where they are overlain by some alluvial materials. Traditionally groundwaters from the shallow eluvial and alluvial materials in the lowlands of southern Ethiopia are exploited through large diameter wells called ‘Elas’. To fetch water from elas a number of persons line up and stand on the steps and they convey the water up to the ground surface by giving it to one another in a pot.

In southern part of the area also there are extensive deposits of flat laying alluvial deposits. These deposits generally constitute good aquifers being composed by gravel and sand, like in Udat. Poor water quality owing to high TDS (>1,500 mg/L) is the main challenge for groundwater development in the alluvial materials (especially south of Negele around Bulbul, Boba, Udet, etc.). In these areas, it is usual to find underground whitish salts deposits mainly constituted by sulphates, which are very soluble in presence of water. Again, in Udat area, the water quality worsens with the depth in relation with the presence of salts deposits that increase with the depth. Due to fluctuation of the aquifers levels in these semi-arid areas, availability of groundwater in dry season is limited to areas with thick alluvium. In case of prolonged droughts the static water level can drastically decrease (up to 2–3 m) leaving the hand dug wells dry. On the other hand, deeper water exploitation gives water of worse quality. Due to the distances between the recharging area and the Wachile-Udet plains, there is an out-of-phase recharging cycle, which makes the lowest static water level correspondent with the rain seasons, and the highest static water level with the dry seasons.

The quaternary alluvium (Fig. 2.45) represents deposits of detritus material which is transported by rivers and streams. Valley floors stream courses in the Borena plain are the main areas of occurrences of the alluvial deposit. The alluvial deposit over basement grounds consist of light brown to grayish colored sand and gravel, with minor silt and clay, filling river channels and stream courses of flat areas. Thickness of the unit is generally estimated to be tens of meters; yet, over 50 m thickness may occur when topography allows.

The Crystalline Basement Aquifers of Northern Ethiopia

Geology: Typical characteristics of the North Ethiopian basement rocks is the dominance of low grade metamorphic rocks (meta volcanics and meta sediments) such as phyllites, slates, schists, marble, mainly chlorite-sericite schists, greywackes, ultramafic rocks (gabro, talk chlorite schists) etc. The low grade metavolcanic rocks come in belts running parallel to each other striking north south. The number of such belts with distinct geochronology, metamorphic grade, tectonics and lithology is unclear. Earlier geological mapping (Beyth 1972) identified three belts while (Tadesse et al. 1999) identified seven belts.

Groundwater occurrence: Unlike the basement rocks of western Ethiopia in northern Ethiopia there is a clear rarity of thick regolith materials. Furthermore field observation shows that the low grade metamorphic rocks decompose into fine grained weathering products which often with time fill the basement fractures and reducing the storage properties of the rocks. Generally the basement rocks have low groundwater potential. Groundwaters occur generally in fractures which penetrate the upper few meters of the rocks, in patches of alluvial sediments straddling river valleys and in very thin regolith materials.

In many localities alluvial sediments occur draping the basement lithologies. The alluvial sediments under favorable condition stores appreciable amount of water & are characterized by high water infiltration capacity. Thus being shallow with limited aerial extent the alluvial sediments in the area can considered as perched aquifer with high permeability. Springs and hand-dug wells with yield ranging between 0.05 and 0.17 l/s are inventoried in the alluvial sediments associated with the basement rocks in the region.

The north ward extension of the basement rocks in Northern Ethiopia occurs in Eritrea. Here dilatational structures which post date the basement hold considerable potential owing to their orientation which links high rainfall highlands to the low rainfall midland depressions (Drury et al. 2001). Steeply dipping and highly fractured marbles are known to yield good volume of potable groundwater in

Eretria, alluvium and regoliths on top of granite inselbergs also hold some groundwater. Report shows that over most of Eritrea the earliest Phanerozoic cover is a thin lateritic paleosol that rests on deeply weathered basement and predates the overlying Mid Oligocene flood basalts. Intensive erosion has progressively stripped the Early Tertiary cover, leaving only a few isolated outliers of volcanic plateau (e.g. around Adwa, Axum and around Asmara in Eritrea).

The Crystalline Basement Aquifers of Western Ethiopia

Geology: *The* Western Ethiopian basement rocks are the most extensive Precambrian rocks extending North South from Akobo to the Western Low lands of the Beles basin (Fig. 2.46). The basement covers areas such as Gore-Gambela, Asosa, Gimbi, and Beles lowlands. The Precambrian rocks of Western Ethiopia have been classified into three N–S running zones: the western high grade gneisses, the central low-grade volcano-sedimentary belt with associated ultamafic rocks and the eastern high-grade belt (Abreham 1989). The three belts are intruded by basement felsic and mafic intrusive. Like the Basement aquifers of Southern Ethiopia and unlike the basement rocks of northern Ethiopia, high grade basement rocks are dominant.

From a hydrogeological point of view the most important phenomenon is the deep weathering mantle of saprolite and laterite. There are two principal weathering palaeosurfaces in the western Ethiopia (Fig. 2.43) basement coinciding with the erosion phase of geological development. The oldest palaeosurface with weathering mantle covers the crystalline basement. It was formed in upper cretaceous just prior to the outpouring of the flood basalts. The second weathering mantle on the present surface was formed from tertiary to recent time.

Groundwater occurrence: Unlike the basement rocks of the rest part of Ethiopia, the basement rocks in Western Ethiopia have better groundwater storage. The higher groundwater potential is related to high rainfall which favors continuous recharge, relatively thick regolith which favors groundwater storage, and rugged undulating topography which favor accumulation of weathering products in depression and flat plains allowing groundwater storage and circulation. A number of springs which are not noted elsewhere in other Ethiopian terrain are observed in Western Ethiopian basement owing to high rainfall and well developed regolith zones. The regolith thickness in western Ethiopian basement region reaches 60 m exceeding greatly those in Southern (20 m) and northern Ethiopia. There is also a general variation in thickness of the regolith when the three belts of the basement rocks in the western Ethiopia are compared. Thicker regoliths are observed on high grade belts in the East and west. The middle domain which is characterized by low-grade meatavolcanics and metasediments are characterized by variable thicknesses of regolith. The thickness is higher on granitic instructions and negligible on dioritic and basic intrusive.

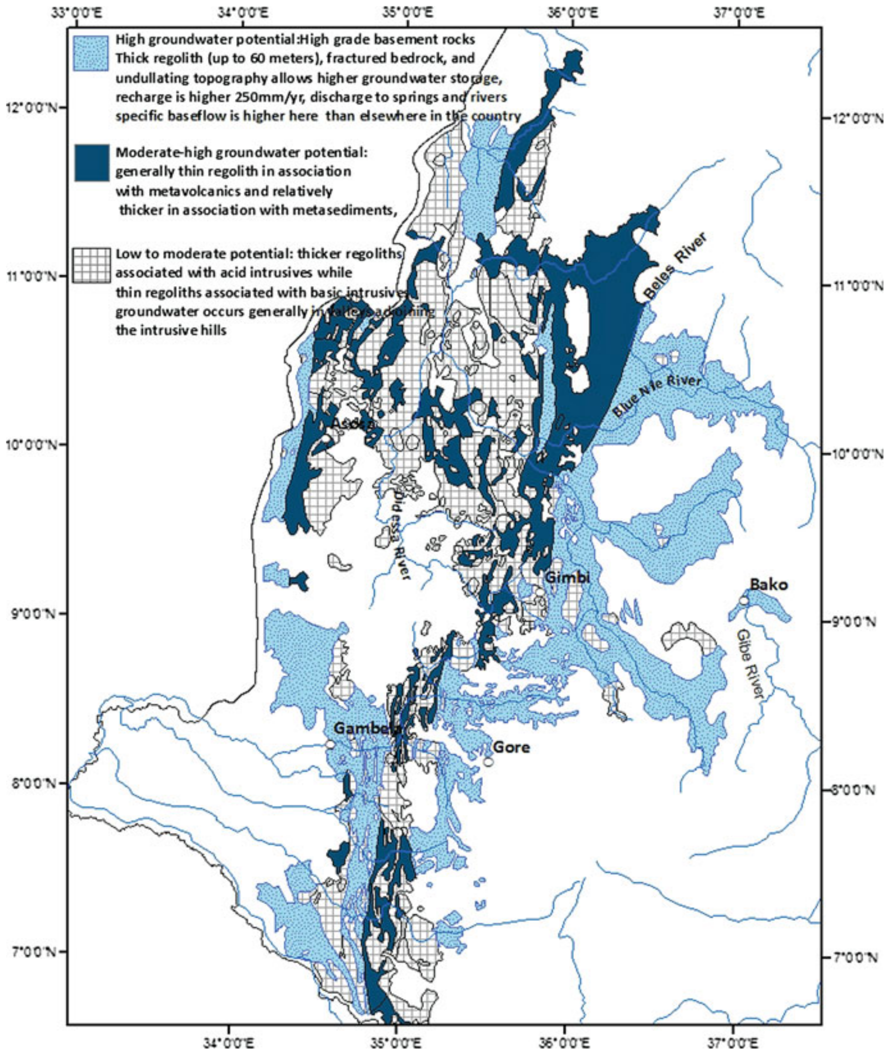


Fig. 2.46 Geologic and some hydrogeologic features of the West Ethiopian basement

Specific baseflow discharge data[7] from river discharge in the Western Ethiopian basement area shows relatively higher values compared to rivers draining the volcanic highlands and the whole Blue Nile River Valley (Belete et al. 2004). This could be indicative of higher groundwater storage potential given recharge is

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[7] Specific baseflow discharge of the whole Abay Basin at Ethiopia Sudan border is estimated at 0.45 l/s/km^2. Specific baseflow discharges for the Hoha, Sirkole, Beles and Gilgel Beles Rivers which drains the basement rocks of Western Ethiopia are estimated at 0.8, 2.42, 0.51, 0.68 l/s/km^2 respectively.

sustainable in the vast basement rocks regardless of the low transmissivity of the basement rocks. This put the basement aquifers of western Ethiopia as non negligible aquifers. Basin discharge is buffered by the high storage capacity of the thick weathered mantle in western Ethiopia.

In upper Gibe basin for example basement aquifers composed of gneiss form an important water sources for urban and rural water supply. The high grade granitic aquifer here represents discontinuous fissures in which flow is mainly in fissures and weathered mantle of crystalline rock (gneiss). It is exposed around Bako town. From lithologic logs of these wells it can be seen that, two major secondary processes enhance the permeability of this unit to be classified as aquifer. Weathering affects the most upper part of the aquifer. The weathered column of this aquifer ranges from 50 m around Bako town. The weathering column is thicker in lower altitude areas which preserves the weathered mantle. The weathering product has significant porosities and specific yield, it therefore, acts as a reservoir, storing infiltrated water and releasing it to the well which has intercepted fractures. The lithologic logs of these wells, confirm this fact, which are samples of highly fractured gneiss was obtained below the weathered column of this aquifer.

Accordingly, from pumping test result of wells drilled in Eastern sector of the area the average yield of wells tapping this aquifer is 5 l/sec (Bako & Abakoran). The hydraulic conductivity of this aquifer varies from 0.12 to 2.3 m/day. Water table fluctuation in the regoliths of western Ethiopia varies by as much as 10 m mirroring seasonal changes in rainfall. Normally during wet seasons water level is as shallow as 1–2 m and during peak dry season it goes down below 10 m below ground surface.

The Basement Aquifers of the Hammer Koke Block

Geology: In the Hammer Koke domain (Figs. 2.40 and 2.47) the metamorphic basement rocks are highly deformed and metamorphosed and reach granulites facies (Davidson 1983) implying they belong to the high grade belt. This belt is chiefly composed of various coarse grained and foliated rocks.

The rocks of this complex are metamorphosed to the highest degree ranging from amphibolites to granulites facieses. Structurally broad and gently dipping synforms and antiforms are characteristic styles. Outcrops of this complex are localized along the South, Southeast, and western parts of Ethiopia and are rare in the northern Ethiopia (Kazmin et al. 1978). In the crystalline basement rocks the variations in structural styles, metamorphic grades and rock assemblages has led to their subdivisions into three domains. The Hamar domain gneisses generally dipping toward the east—northeast, but show some variations from place to place. West of the Chew Bahir rift system (Hamar range), overturned and recumbent isoclinal folds have themselves been folded into open antiforms and synforms that trend and plunge northward. Foliation is generally sub-parallel to the layering sometimes making slight angles to it.

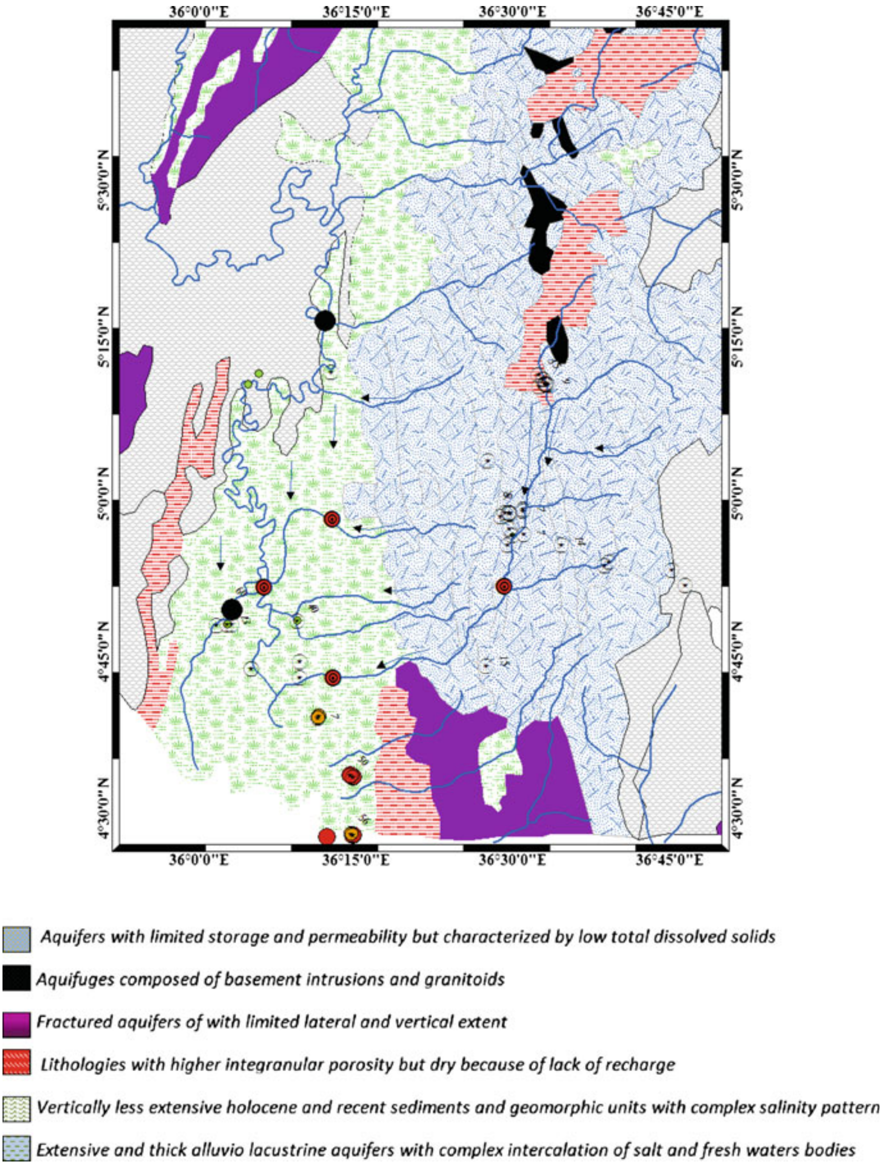

Fig. 2.47 Simplified Hydro-geological Map of the Hamer Koke block and surrounding Omo delta regions. The colored filled circles are EC indicators (small size correspond low TDS) and the open *circles* with star inside stands for water points

Red beds exposed in the northern part of the Hamar Koke block reaching a depth of 10 m and composed of fine sand and silt represent remnant of older laterite deposits formed on the Precambrian basement and later striped by Cenozoic or recent striping processes (Fig. 2.47). Because of their topographic position

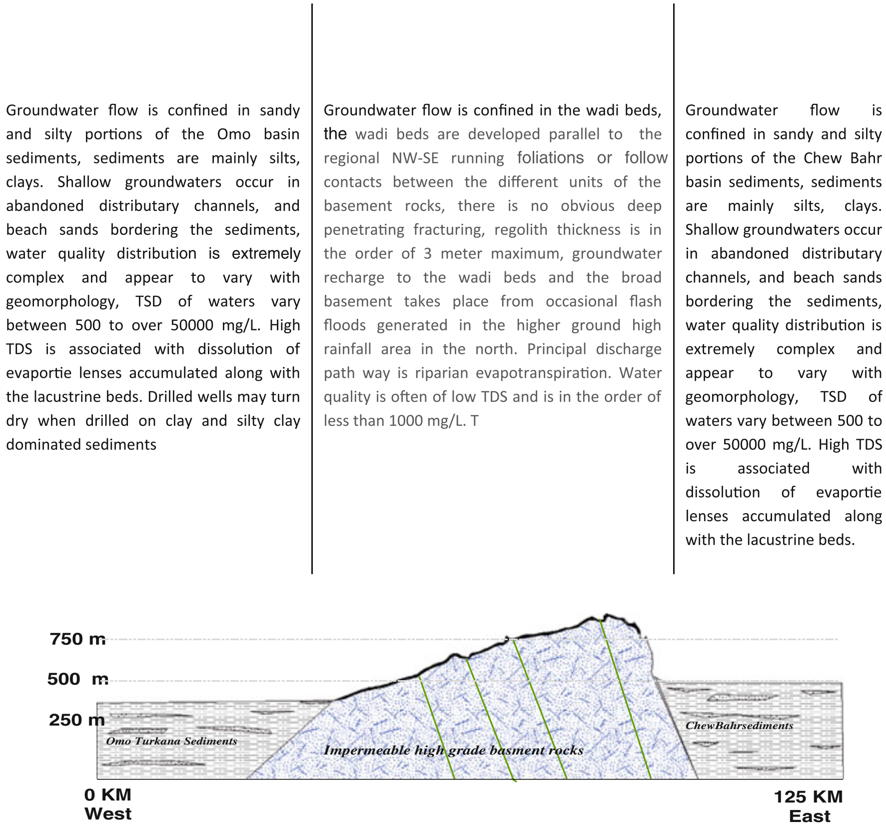

Fig. 2.48 Conceptual groundwater flow and recharge model of Hammer Koke area and surrounding Omo and ChewBahr rifts

and low prevailing recharge in the areas, the regoliths have very little potential as source of groundwater in the region.

For most part of the basement of the Hammer Koke block and the Teltele highlands the yield of wells is less than 1 l/s and mostly less than 0.1 l/s (Sima 1987). Groundwater recharge, flow, discharge conditions of the Hammer Koke block is depicted in Fig. 2.48.

The Basement Aquifers of Ethiopia as Compared to the Basement Aquifers of Africa

Groundwaters in basement aquifers of Ethiopia are mostly associated with low grade mobile belts of the Arabian Nubian shield there generally low grade nature of Ethiopian basement particularly those in the north leads to least developed regolith unlike a well developed regolith on high grade Craton materials of central and equatorial Africa. The complex but persistent uplifting since Cenozoic has also resulted in stripping of the African deep weathering surface (surface that has been formed during stage ii of landscape evolution, see Fig. 2.43). Current rainfall is also lower than the Central Africa leading to runoff exceeding recharge and thus limiting further active regolitization (except in western Ethiopia).

2.14 The Omo Delta and Chew Bahr Rift

The Omo delta is located in southern Ethiopia near the junction of the Omo River with Lake Turkana (marked 13 in Fig. 3.1). Currently the principal source of water supply for livestock and human consumption in the lower Omo and adjoining regions are river bed excavations and hand dug wells drilled into the river beds, and the Omo River. Roof water collection is also becoming an important source of water harvesting technology in the lowlands which do not have access to the above mentioned facilities. For drinking purposes as there is very scarce modern water purification technology, the local people inhabiting the Omo river use root of a plant locally called Gluf (*Maerua Subcordata*) and known to be rich in polysaccharides (*good as coagulating agent*) to physically purify the otherwise turbid Omo river. Of drilled wells in the Omo delta more than 50 % are abandoned due to unsuitable salt content often for both cattle and human consumption.

The Omo depression (Turkana rift) is underlain by Crystalline gneisses and amphibolites with intrusions of granite and pegmatite from the east, volcanic highlands from the north, up to 3 km thick Pliocene to mid Holocene deltaic and littoral beds bounding the lakes and recent deltas, mudflats and beaches straddling the lake Turkana from north (Fig. 2.47). The Omo delta is situated in a complex tectonic depression. Directly overlying the Precambrian Basement Complex are the Tertiary volcanic products. These consist of thick succession of flood basalt and overlying undifferentiated volcanic rocks of horizontally inter bedded flood basalts, trachytes, trachy-basalt and rhyolite, intercalated with tuff and volcanic ash. The tertiary volcanics cover the upstream part of the Omo Turkana basin.

At least seven prominent geomorphic units (Fig. 2.49) can be recognized in the Omo delta. The first six of these units were identified by Butzer (1971). These geomorphic units are presented as follows. The meander belt (1) is characterized by meandering channels with natural levees, cut off meanders, oxbow lakes, clay plugs and restricted flood basins.

The eastern flood plain (2) forms dispersal and gathering streams and non outlet depressions that serve as back swamp.

The delta flat (3) is a broad flat surface that acts as flood basin. It consists of non-functional inter distributary basins, lagoon mud flats and networks of distributary channels. Gathering streams are associated with seepage from meander belts.

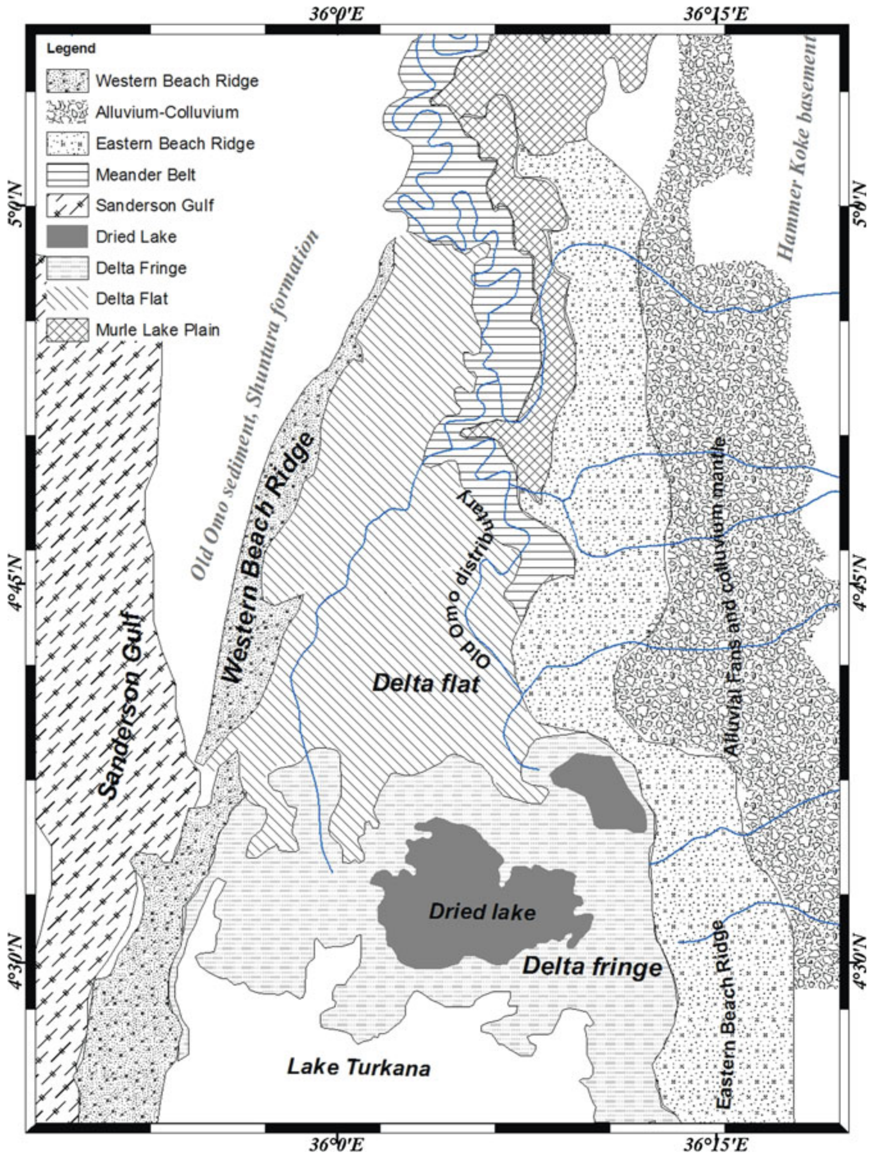

Fig. 2.49 The geomorphology of the Omo delta and Turkana sediments. Modified from Butzer 1981

The delta fringe (4) is a flat surface with bird foot shape and it consists of two active sub deltas (Erdet and Dielrhiele), one extinct sub-delta (Murdizi) and extinct lakes. The Murdizi subdelta is formed at the confluence between an old extinct Omo meander with Lake Turkana. Geomorphic units such as flood plains, inter-

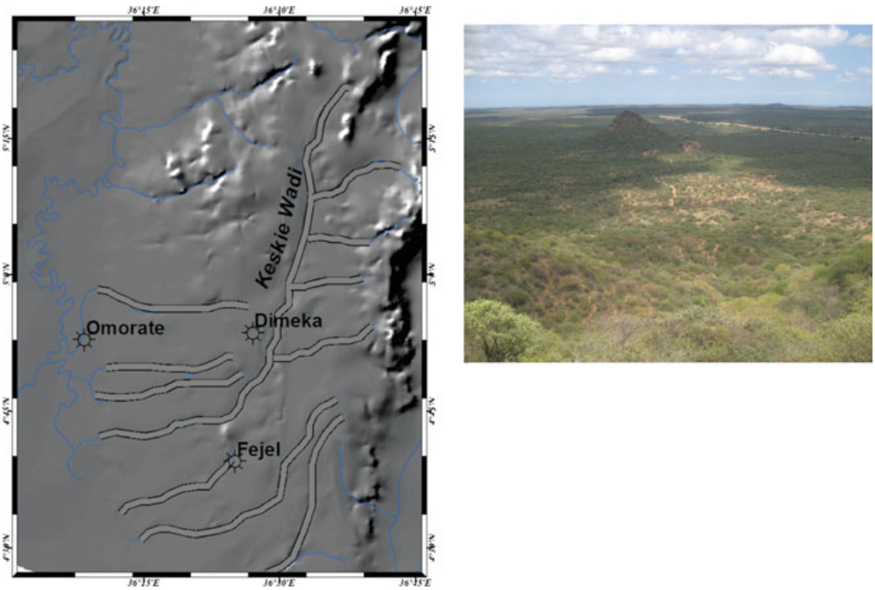

Fig. 2.50 Prominent Wadi beds in the Hammer Koke block. The most prominent of all Wadis is the Keskie which runs North south following the regional trend of the metamorphic basement and the contact between meta sediments in the west and meta volcanic in the east

distributary bays, distributary mouth bars are common. The beach ridge plains (5) are discontinuous belts of sub-parallel, non functional beaches. Most of the beach ridges are narrow (1 km) and topographically prominent. The beach ridges separate the crystalline highlands bounding the Omo valley and the Omo delta sediments.

The murle lake plain (6) is an extensive plain of an old lake floor, fringed by beach ridges. An active Lake Dipa is located within the Murle Lake plain and is connected to the active flows of Omo River.

Recent alluvial fans and wadis (7) form localized or about 2 km^2 alluvial fans composed of sands, gravels and pebbles. The alluvial materials are found at the confluence of the wadi beds draining the Hammer Koke highlands in the east and the Omo valley. The alluvial fans contain distributary channels and sand bars.

The Hamer-Koke block is underlain by extensive North–South trending high grade metamorphic rocks. This highland is bounded from the East and west by the Omo and the Chew Bahr tectonic depressions filled by alluvio-lacustrine sediments. In the Omo Turkana basin, the sediment thickness is estimated to reach 3–4 km accumulates since 4 million years (McDougall et al. 2008). Volcanic rocks of tertiary age are limited to the northern boundary of the area (Fig. 2.47). Some patch outcrops of volcanic materials were also recognized in the center of the Hammer Koke highland and the lowlands bordering Kenya. The volcanic rocks bordering the Ethio-Kenya border are named as Gombe basalts. This lithology is believed to underlie the Omo Turkana sediments.

Wadi bed sediments mainly composed of sands and gravels, and *alluvial fans* composed of gravels, sands and silts at the outlet of the wadis from the highlands and before joining the Omo delta are features with small lateral extent (see Fig. 2.50) for the distribution of the wadi bed sediments). Regardless of their small aerial extents the wadi bed sediments are the principal source of groundwater in the Hammer Koke block.

Elsewhere in the world crystalline basement rocks are known for their low permeability and storage potential. In crystalline aquifers of Central and tropical Africa, the basement rocks are significantly weathered and the thickness of the regolith may reach 90 m. This regolith zone enhances permeability and storage properties of basement aquifer and ultimately provides storage for shallow groundwaters in several regions of tropical Africa (e.g. Uganda, Congo). As described in Sect. 2.13 the basement aquifers of Ethiopia because of the uplifting since Cenozoic and low grade nature of the basement the thickness of regolith is not as pronounce as those seen in central Africa. In the Crystalline block of Hammer Koke, probably owing the low rainfall (<400 mm/year), dry conditions, and prolonged stripping since the Cenozoic, regolith is very thin (in the order of 2 to 3 m). In some localities foliations associated with basement rocks act as storage and transmission medium. In the Hammer Koke block however the basement rocks are high grade (granite to granulite facies). Such rocks lose their foliation related permeability. Therefore the basement rocks of the Hammer Koke block can be considered as the least productive aquifers in the region.

Primary porosity is the principal storage and transmission medium in the wadi beds, alluvial fans and in the Omo delta sediments.

Total groundwater storage in wadi bed sediments has been estimated by assuming a porosity of 0.2, total wadi length of 300 km and thickness of sediment at 3 m and the average width of 10 m. This approximation is the minimum storage as this estimate takes into consideration only prominent wadis. The minimum groundwater storage that can be guaranteed in the wadi bed is estimated at 2–4 million meter cube. The actual storage of the groundwaters in the Wadis varies from place to place. Since the head water of the Keskie Wadi (Fig. 2.47) rests in the northern part of the area where the annual rainfall is in excess of 500 mm/year the wadi sediments have sustainable recharge from the north. Frequent flooding around Trumi (10 km south of Dimeka) of by Keskie wadi associated with high rainfall in the higher grounds in the north is a common hydrologic event.

Groundwater flow and discharge pathways in the Omo sediments are complex. Since the permeability of the sediments unless locally inter fingered by sediments such as sands, and silts is low, discharge of groundwaters to the Lake Turkana should be small. Previous isotope hydrological investigation on Lake Turkana also reveals the fact that groundwater contribution to the lake is insignificant (Kebede et al. 2009). In the **Omo** sediments the principal groundwater discharge path way should therefore be riparian vapor-transpiration.

Groundwater geochemistry here has been used as a tracer of recharge and groundwater flow and also to determine water quality for different water uses. Generally groundwaters in the crystalline highlands have lower total dissolved solids (<1,000 mg/L). The volcanic highlands are also characterized by comparable total dissolved solids. The Omo delta and sediments are characterized by very complex groundwater geochemistry (Fig. 2.47). Here fresh low TDS groundwater zones intervening with saline or brackish groundwaters are common observations. The fresh groundwater lenses is often associated with distributary channels connected to Omo, or with beach ridges bounding the Omo delta from East and West, or with the alluvial fans intruding into the Omo sediments at the emergence zone of the wadi beds from the Hammer Koke block.

TDS, NO_3, F are principal water quality constraints in the region. The high NO_3 are often associated with hand dug wells. In the Omo sediments high F is associated with evaporative enrichment and leaching of F from the sediments while in the crystalline highlands F can have its source from weathering of rock forming minerals associated with the basement lithologies. The fact that high NO_3 occurrence in association with hand dug wells could be suggestive of pollution the waters from lack of hygiene around the water points. One clear example is note in a hand dug well equipped with hand pump in the Dimeka town. The well is located underneath the shade of an acacia tree with no obvious anthropogenic impact on water quality but the well returns water with foul odder.

A well drilled 18 km north east of Omorate in the alluvial fan deposits draping on the basement rocks shows a transmissivity value of 57 m^2/day and yielding 3.9 l/s at a drawdown of about 8.5 m. The alluvial fan material (Fig. 2.49) is composed of silt, sand pebbles and gravels and contains good quality water for domestic water use.

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