CONTENTS

1. SUMMARY

Hawasa town was built on Early Pleistocene Hawasa Caldera and in the shade of two silicic volcanoes emerging from the floor of Middle Pleistocene Corbetti Caldera. This geological setting should be respected during future land use and construction plans. Early Pleistocene Hawasa ignimbrites are the oldest rocks cropping out in the area of the Hawasa subsheet. These are overlain by Middle Pleistocene Corbetti ignimbrites and post-caldera volcanic rocks and non-volcanic sediments (mostly represented by re-sedimented pyroclastics). The Hawasa Caldera is transacted by a belt of basaltic rocks composed of scoria- and tuff-cones and basaltic lavas emitted from the cones.

The geological situation significantly influences the water resources. More welded ignimbrites represent fissured aquifers whereas younger ignimbrites with non-welded facies and pumice fall intercalations represent combined aquifers. Unconsolidated pumiceous deposits and sediments are porous aquifers whereas obsidian lavas are weakly productive fissured aquifers and aquicludes. General northward (from Lake Hawasa towards Lake Shalla) flow of groundwater is supposed. Surprisingly, no hot springs are associated with the active Corbetti Volcano on the shores of Lake Hawasa.

Despite the fact that the Chabi Volcano is predominantly dormant, it has experienced several explosive events, but the deposits of these explosive events are not very widespread. Obsidian lavas with high viscosity flow relatively slowly and allow the evacuation of the scarcely populated zone bordering the Chabi Volcano. Fortunately, there is no permanent habitation on the Chabi Volcano. Wendo Koshe seems to be a highly explosive volcano with violent Plinian eruptions. A thick accumulation of pumice fall may cover the town of Hawasa but most likely the areas around the town of Shashemene and between Shashemene, Hawasa and Wendo Koshe. In addition, these Plinian eruptions are associated with pyroclastic flows. These endanger the area within Corbetti Caldera to the north of Wendo Koshe (Korbeti village and its surroundings). Systematic monitoring of the Wendo Koshe Volcano is highly recommended.

The Hawasa Cladera is filled by thick accumulations of unconsolidated sediments and resedimented pyroclastics. Such a setting has the potential to also amplify seismic effects during earthquakes in the wider surroundings. For this reason, higher buildings should preferably be constructed in the eastern part of Hawasa town on the basaltic ridge. The western part of the Hawasa Caldera (west of Lake Hawasa) is strongly affected by spreading of the rift floor and formation of ground cracks (fissures). Unexpected opening of these cracks causes loss of property and occasionally also loss of life.

Young silicic pyroclastic rocks (pumice) contain high amounts of leachable fluorine. Groundwater contaminated with fluorine used as drinking water causes fluorosis of teeth and bones. Technology for removing fluorine from the water sources should be applied to protect public health.

2. INTRODUCTION

The set of earth-science maps of the Hawasa subsheet 0738-C4 has been compiled through the cooperation of the Czech Geological Survey (CGS), Geological Survey of Ethiopia (GSE) and AQUATEST a.s. within the framework of the Czech-Ethiopian Development Cooperation project “Capacity building in environmental geology - Mapping of geo-risks including hydrogeological conditions in Dila and Hosaina areas, Ethiopia” financially supported by the Czech Ministry of Foreign Affairs through the Czech Development Agency and by the Ethiopian Ministry of Finances and Economic Development.

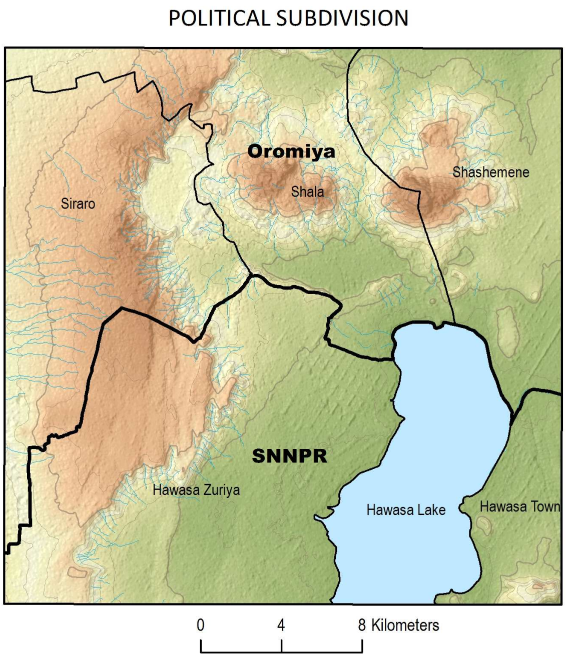

Figure 2-1. *Political subdivision of the area covered by the subsheet 0738-C4 Hawasa. Names of regions in bold, names of weredas (counties) in plain text.*

The Hawasa subsheet spreads over 763 km^2. It is located in the central part of the Main Ethiopian Rift in Southern Ethiopia, some 165 km south of the capital Addis Ababa. The map subsheet is limited by the latitude 7°N on south and 7.25°N on north and by longitudes 38.25°E on west and 38.5°E on east. The boundary between the SNNPR and Oromiya Regions crosses the area of the Hawasa subsheet (figure 2-1). The Hawasa subsheet is named after the Town of Hawasa, which is the capital and administration centre of the Southern Nations, Nationalities and Peoples Region (SNNPR) and has more than 150,000 inhabitants. Growth of Hawasa town and its increasing importance as well as increasing number of inhabitants requires better knowledge on the geological setting of this area giving the limits to construction work and growth of the town. The area of Hawasa subsheet is divided among five weredas. Siraro, Shala and Shashemene belong to Oromiya region and Hawasa Town with Hawasa Zuriya to the SNNPR region.

Hawasa Town is connected by an asphalt road with Shashemene and further on with Addis Ababa to the north and to the south to Dilla and continuing to Moyale with a border check-point to Kenya. Just north of the subsheet the east-west asphalt road transecting the rift valley connects the town of Shashemene with Alaba-Kulito. Hawasa airport is currently not in use and an appropriate location for the construction of a new airport is being sought.

The north-western part of the map, including Wendo Koshe and Chabi Volcanoes, belongs to the Sinkile-Siraro hartebeest sanctuary. Amora Gedele Park is located on the peninsula on the south-western edge of the town, which consists of a tuff-cone.

The highest point of the map is the Chabi (syn. Chebi) peak, 2,314 m a.s.l., the top of the Chabi silicic shield volcano. The lowest point is Lake Hawasa fluctuating around 1,685 m a.s.l. Lake Hawasa occupies nearly 11 % (82 km^2) of the subsheet area. The only river of the subsheet area, Tikur Woha, connects Chaleleka Lake (east of the Hawasa subsheet, on Shashemene subsheet) with Lake Hawasa. Recently, the channel of the river has filled up with sediment. Most of the streams flow to Lake Hawasa, except those to the west of the edges of the Hawasa and Corbetti Calderas, which flow towards the Bilate River.

Table 1. *Used abbreviations.*

CGS	Czech Geological Survey
GSE	Geological Survey of Ethiopia
ICP-MS	Mass spectrometer with inductively coupled plasma
mg#	$= 100 \times MgO/(MgO + FeO_{tot})$ in molar values
RP	reference point
SNNPR	Southern Nations, Nationalities and Peoples Region
vol. %	volume percentages
wt. %	weight percentages
XRF	X-ray fluorescence

3. METHODS

The map of morphological forms and features displays the spatial distribution of the principal geomorphological landforms and their relations. The map was constructed based on visual interpretation of stereoscopic aerial photos approximately at scale 1 : 60 000 and satellite images. With an aim to detect the basic geological setting of the area of interest, several distinct types of data were applied. Satellite multispectral image data Landsat TM/ETM+ and ASTER were used. As the Landsat TM/ETM+ data were obtained in several time horizons (31.1. and 9.2. 1987, 21.1. and 30.1. 1995, 5.2. and 12.2. 2000 and 16.12. 2010 and 10.1. 2011), the detection of surface changes was also available. The ASTER data were acquired on 27.1. 2006 (day-time data) and 22.11. 2006 (night-time data). The thermal bands of ASTER data were used for surface temperature estimation applied primarily on water bodies. Detection of terrain linear structures related to brittle tectonics and terrain morphology were interpreted using ALOS/PALSAR satellite radar data. Terrain morphology was studied mostly on the basis of a slope dependent morphometric map as well as aspect, slope and multidirectional-weighted shaded relief raster layers derived from the SRTM digital elevation model. Such an approach facilitates rapid evaluation of geomorphological forms and units and their spatial delineation. Different morpho-structures have to be distinguished and their geomorphological position determined. The character of the defined geomorphological units has been verified during subsequent field campaigns.

Due to the inaccessibility of large parts of the area and the limited time, the spatial distribution and limits of the lithological units are based on geomorphological studies including interpretation of aerial photographs, satellite images and digital elevation models. The lithologies were described in the field, where, if possible, geomorphology-based boundaries were verified and corrected. Approximately 55 reference points were documented during the field campaign (figure 3-1). Relative ages of obsidian lavas were estimated based on light-reflection variability determined from satellite images, but finally the superposition and intersection relationships of the lithological units were confirmed by field observations. In the area of Hawasa, several boreholes had lithological descriptions, which were used for the construction of the map. The field structural analysis was undertaken in order to study the distribution, orientation and degree of development of primary structures in volcanic sequences and non-volcanic deposits, lithological contacts, geological boundaries and superimposed brittle structures. Field structural data were evaluated in the programs SPHERISTAT and STEREONET using the equal projection to the lower hemisphere. The Hawasa ignimbrites related to the Hawasa Caldera and Corbetti ignimbrites (Corbetti Caldera) are distinguished mainly based on K-Ar geochronological data (JICA 2012).

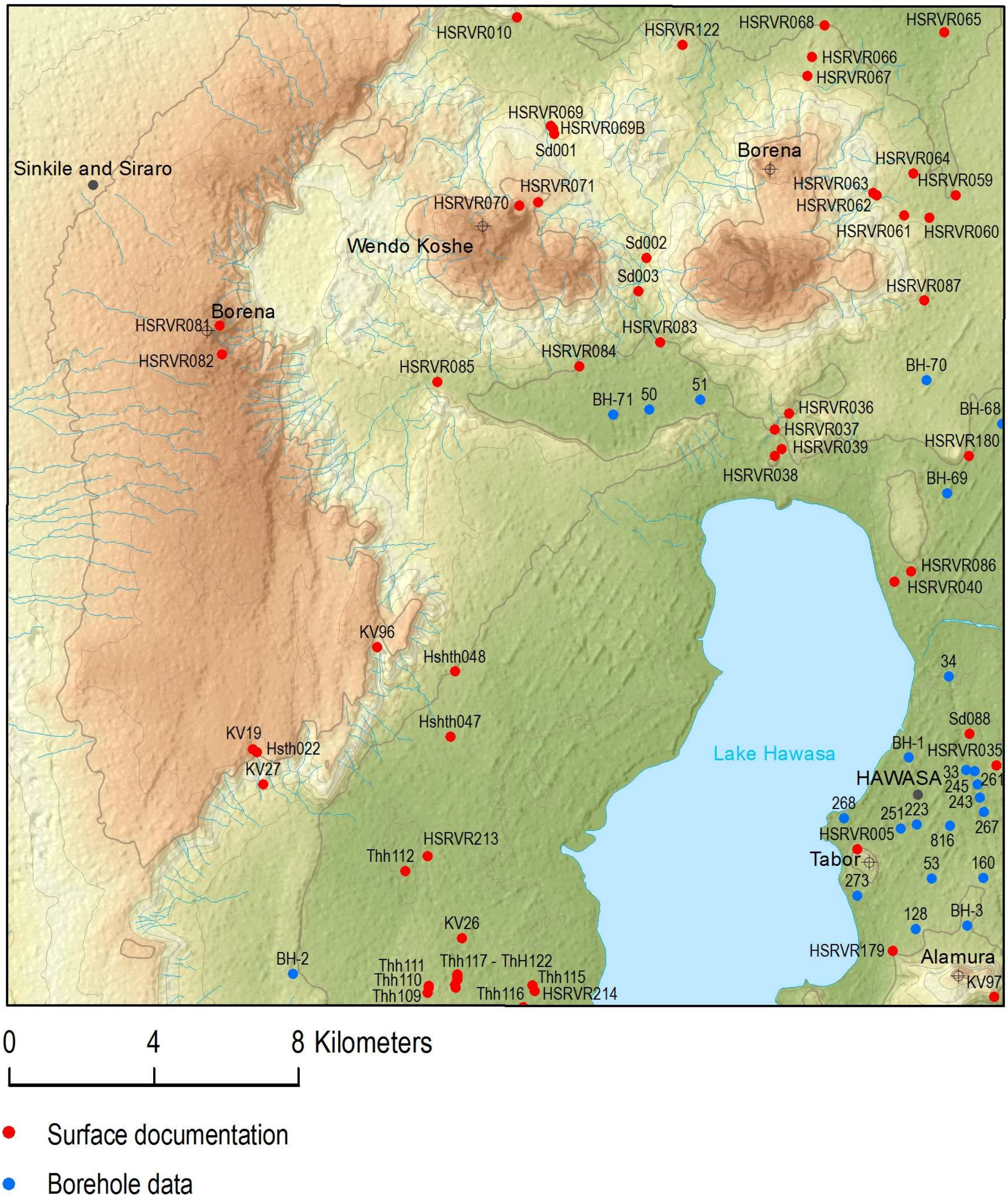

Figure 3-1. *Sketch map of reference points and location of borehole data used for construction of the maps.*

Twelve rock samples were taken in the area of Hawasa subsheet and an additional 2 samples in the nearby surroundings for geochemical analyses. All samples were crushed and pulverized in the GSE laboratory in Addis Ababa. Samples of silicic rocks were analysed by the wet method for major oxides and by XRF and ICP-MS for trace elements in the CGS laboratories in Prague. Samples of basaltic rocks were analysed by the wet method for major oxides and by XRF for selected trace elements (Co, Cu, Ni, Pb, Zn) in the GSE laboratory in Addis Ababa. Analytical data were processed and visualized using GCDkit Software (Janoušek et al. 2006). For the analytical results see Appendix 1.

Hydrogeology of the Hawasa subsheet is based on the assessment of data collected from existing reports and maps and during field work. The field water point inventory was based on a desk study, during which the relevant materials like geological and drilling reports and maps and aerial photographs were collected from the regional geology department of GSE. Important climatic and gauging station data and topographic maps were obtained from various offices. The desk study also included preliminary data interpretation and preparation of field maps using satellite images, aerial photographs and a digital elevation model (DEM) of the terrain with the geology as a background. Data assessment was mainly dedicated to data organization, processing, and interpretation in the form of maps and the text of the presented explanatory booklet. The geographic information system (GIS) ArcGis was used for compilation of the maps.

The hydrogeological map is compiled based on the methodology and standardized legend for hydrogeological maps published by the International Hydrogeological Association. The methodology classifies various lithological units based on their permeability (porous, fissured, mixed, non permeable) into aquifer/aquiclude/aquitard system.

Classification of natural water was used to express the groundwater chemistry on the hydrochemical map. Hydrochemical types are classified based on the Meq% representation of the main cations and anions. The results of the hydrochemical study were integrated into a hydrogeological conceptual model with the aim of helping to understand the groundwater circulation within the aquifers in addition to comparing the water quality with various standards.

Hazardous phenomena were adopted from the geological and geomorphological maps to compile the map of geological hazards. Similarly, the geological map served as a basis for the construction of the hydrogeological map, and displaying the permeability properties of the lithological sequences.

4. PREVIOUS STUDIES

4.1. Geology

The Main Ethiopian Rift cannot be compared with the Afar region in terms of intensity of geological research. The area of interest has been covered by several overview geological maps of large scales. The early two-million scale map (Kazmin 1972) has been actualized by Mengesha et al. (1996). The area of the Hawasa subsheet is also covered by the half-million geological maps by Di Paola (1972a), Kazmin et al. (1981) and JICA (2012). We have to express strong criticism of the last map, as it does not respect either geological observations or morphology. A gelogical map of the 1 : 250,000 scale comprising the area of Hawasa subsheet was compiled by Basalfew (2012). More detailed geological information can be found in 1 : 75,000 Engineering geology map (Tadesse and Zenaw 2003). A geological sketch of the Corbetti caldera is also presented in the Report of UNDP (1971).

The early description of the Corbetti caldera, which is the most prominent geological structure of the area, was published by Di Paola (1972b). A set of geochemical and geochronological data on silicic rocks from the central part of the Main Ethiopian Rift was presented by WoldeGabriel et al. (1999). This publication deals with geochronological data published previously by WoldeGabriel et al. (1992). This work unfortunately lacks precise location of samples. Two K-Ar geochronological data from the area surrounding the Hawasa subsheet are presented in the Report of JICA (2012).

4.2. Hydrogeology

Compilation of the water resources of the Hawasa map sheet is based on the assessment of data collected from existing reports and maps and during field work.

Previous hydrogeological work at a scale of 1 : 250,000 includes the Hosaina sheet (Kefale Tilahun and Šíma 2013). The area is covered by the hydrogeological map of Ethiopia at a scale of 1 : 2.000,000 published by Tesfaye (1993), and by several regional hydrogeological studies.

The first regional hydrogeological study of the Rift Valley itself was done by Tesfay in 1982 (Hydrogeology of the Lakes Region, Ethiopia). He stated that most of the rift area is covered by volcanic rocks like basalt, ignimbrite, trachyte, rhyolite and pumiceous pyroclastic with accompanied lacustrine sediments. The extensive occurrence of the lacustrine sediments covers the rift floor. Most of these rocks have overlapping values of permeability. High fluoride concentrations in surface as well as groundwater are common.

The project entitled "Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project, June 2008, Halcrow Group Limited and Generation Integrated Rural Development Consultants, Ministry of Water Resources, The Federal Democratic Republic of Ethiopia" compiled studies of both the geology and the hydrogeological conditions of the Rift Valley Lakes basin. Representative aquifer characteristics were assessed from the point of view of water point yield and the yield for ignimbrite is 0.1 to 8.0 l/s, for basalt 2.7 to 3.0 l/s, for lacustrine sediment 1.0 to 6.6 l/s and for alluvium 1.0 to 6.0 l/s. Springs with records of both yield and temperature were also evaluated. The evaluation shows that most of the springs with high yields are from thermal spring sources. It can also be noted that thermal spring yields are highly variable (from 1.5 l/s up to 75 l/s).

An assessment of the potential of various aquifers based on the discharge of wells and springs and the major lithology by JICA (2012) showed variability of the average yield of water points from 2.8 l/s (alluvium) to 6.3 l/s (basaltic tuff). In general, highly productive water sources can be found at the foot of the escarpment based on the conclusions of the JICA (2012) study.

A detailed hydrogeological and engineering geology study of the Hawasa catchment was done by Zenaw (Tadesse and Zenaw 2003), including a point inventory and calculation of the water balance of the catchment finalized in the compilation of detailed hydrogeological and engineering geology maps.

Geothermal studies consisting of geological, geochemical and geophysical investigations were carried out in the Rift Valley to determine the potential and to define feasible sites for geothermal power development (UNDP 1971).

4.3. Geological hazards

Deformation due to magmatic activity within the Corbetti volcanic complex has been interpreted from satellite interferograms by Biggs et al. (2011) suggesting magmatic activity underneath the Corbetti Caldera. Prominent geological hazards in the Hawasa area are surface erosion, ground fissures and hazards related to fluctuations in lake water levels. The rate of gully development in the Hawasa area was studied by Moges and Holden (2008). Controlling factors of gully development related to surface erosion were investigated by Carnicelli et al. (2009). Ayalew et al (2004) report causations and processes related to the formation of ground cracks. Tadesse and Zenaw (2003) and Ayenew (2009) note the causes of fluctuations of water levels in Lake Hawasa and losses caused by the rise of levels affecting Hawasa town.

5. GEOMORPHOLOGY

The dynamic geomorphologic map is focused on an explanation of the genesis of each landscape form and the study of geological and climatological predisposition and the resulting geomorphological position. The geomorphological forms and units are subdivided into two groups: endogenic and exogenous (denudation and accumulation) according to their origin.

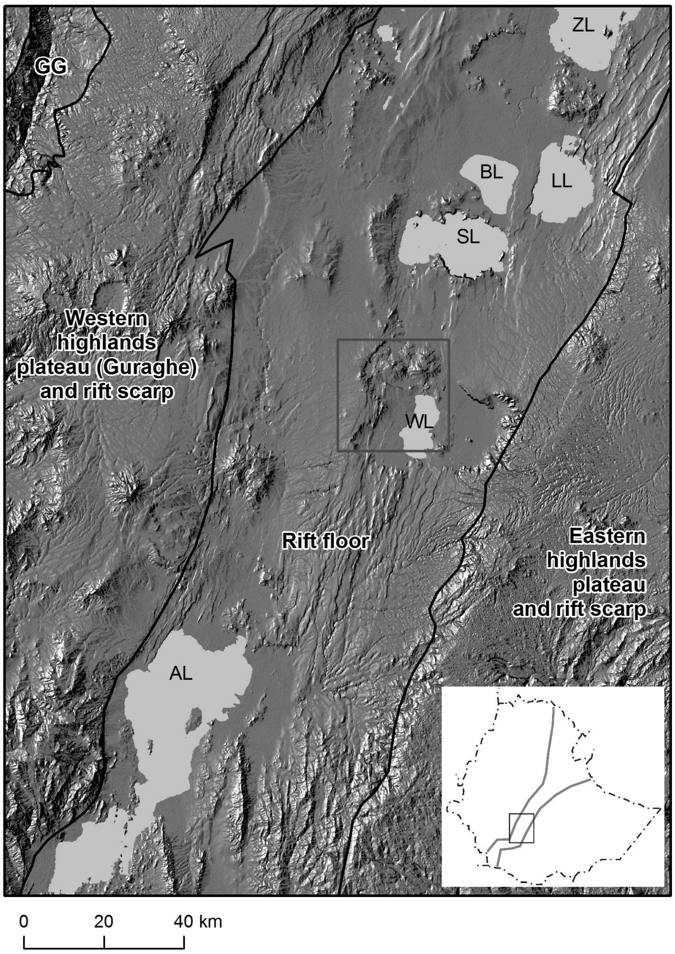

Figure 5-1. *Position of the Hawasa subsheet 0738-C4 within the central part of the Main Ethiopian Rift. GG – Gibe Gorge; AL – Abaya Lake; BL – Abijata Lake; LL – Langano Lake; SL – Shala Lake; WL – Lake Hawasa; ZL – Ziway Lake. Limits of the Hawasa subsheet indicated.*

5.1. Geomorphological position

The studied area is located within the central segment of the Main Ethiopian Rift and morphologically belongs to the rift floor zone near the eastern rift escarpment (figure 5-1). A dominant part of the map sheet is represented by Lower Pleistocene Hawasa Caldera, namely its floor. In the northern part, Hawasa Caldera is overprinted by Middle Pleistocene Corbetti Caldera, within which two principal volcanic cones emerge: Wendo Koshe and Chabi (figure 5-2).

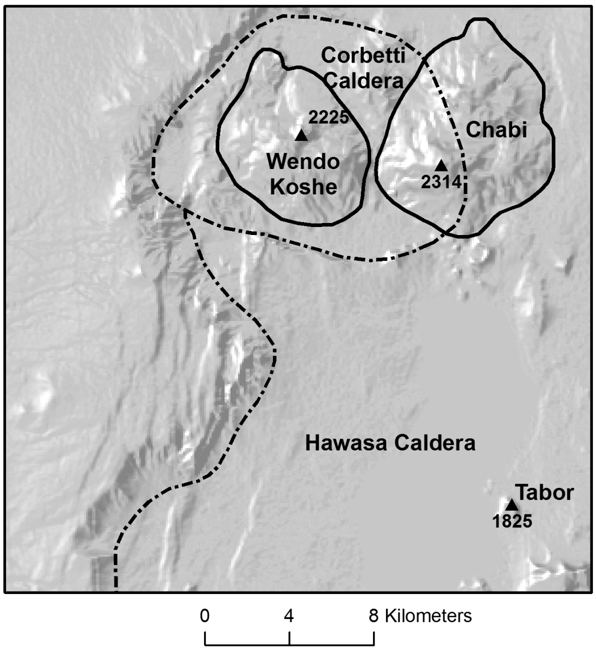

Figure 5-2. *Main volcanoes and calderas of the Hawasa subsheet area.*

5.2. Geomorphological forms and features

ENDODYNAMIC FORMS AND FEATURES

TECTONIC FORMS AND FEATURES

1 Tectonic elevation (horst) is an elongated elevation separated from the surrounding landscape by fault scarps. Expressive horst can be found in the western part of the Hawasa Caldera separating Chenchenema graben from the rest of the caldera floor.

2 Tectonic collaps depression (graben) forms by tectonic subsidence of lithological block along normal faults. Such grabens are frequent on the Rift floor. Larger graben can be found in the SW part of the subsheet between Chenchenema and Abaye. Occasionally, a small lake may form on the bottom of the graben resulting in **21 Temporary flooded depression**. These can be found near Koremo and Muleti. The lakes are strongly dependent on tectonic activity and opening of cracks along faults may drain the lakes. This happened in the 1980s when a lake near Muleti disappeared (Ayenew 2009).

3 Tectonic and diastrophic block. The system of tectonic diastrophic blocks is developed on the western fault-affected caldera scarp between Shamen Hurufa and Lalima. The geometry and orientation of these blocks correspond to a tectonic horst and graben system. These tectonic processes postdate the Hawasa Caldera.

4 Fault or forced fold slope or exhumed fault or forced fold plane. Such slopes follow the tectonic system in the western part of the Hawasa caldera and are associated with the origins of horsts, grabens and tectonic diastrophic blocks. **22 Morphologically evident fault** corresponds with edges of the horst, graben or tectonic diastrophic blocks, respectively.

VOLCANIC FORMS AND FEATURES

5 Volcanically derived expressive scarp represents the inner scarp of a volcanic crater or caldera. In the mapped area this is represented by the Hawasa and Corbetti calderas and numerous smaller craters. **23 Caldera fault** is displayed along the bottom edge of the caldera scarp.

6 Structural slope of monogenetic volcanic cone (tuff cone, maar, scoria cone, lava cone etc.) forms the outer slopes of smaller volcanic cones near Hawasa town or cones in the Corbetti Caldera.

7 Eroded structural slope of paleovolcano occurs as the widespread gently dipping slopes of the Hawasa Caldera in the western part of the subsheet or southern slopes of the Corbetti Caldera. Relics of early post-caldera volcanoes can be found within the Corbetti Caldera.

8 Tectonic and erosional remnants of paleovolcano (tectonic desintegration, erosional relief, denudated) are preserved as small remnants near Tikur Woha or larger volcanic bodies near Wendo Dika or near Guge. Some occurrences of this unit remain near Tulu, Birbo and Gemeto Gale in the SE part of the subsheet.

9 Volcanic plateau (polycyclic lava and ignimbrite plateau) forms a large and widespread area between Tikur Woha in the south and Tatisa and Kombolcha in the north. The volcanic plateau partly covers the floor of the Hawasa caldera.

Five different stages of lava flow within the Corbetti caldera forming post-caldera volcanoes can be subdivided based on geomorphologic investigations. These are: **10 Youngest stage of lava flow, 11 Youngest stage of lava flow (middle), 12 Youngest stage of lava flow (older), 13 Subrecent lava flow, 14 Older lava flow**. **26 Direction of lava flow** is also indicated on the map.

15 Pumice flow forms a fan-like relief on the northern flank of the Wendo Koshe Volcano.

EXODYNAMIC FORMS AND FEATURES

EROSIONAL FORMS AND FEATURES

16 Erosional slopes occur scarcely due to the young age of the Hawasa Caldera and also all the younger volcanic units. Most of the erosional slopes correspond to the partly eroded caldera scarps. The erosion of the caldera scarps is documented by linear erosional V-shape valleys. **24 Erosional valley of V shape** is a typical form on the caldera slopes. They are short and not very deep.

17 Lake shore is the zone of the fluctuational level of the lake due to seasonal rains and floods.

25 Small stream valley is a shallow valley, which originates on young volcanic structural slopes or on the polygenetic infill of caldera floors.

ACCUMULATION FORMS AND FEATURES

18 Polygenetic infill of broad valley is mapped only near Tikur Woha on the northern edge of Hawasa town. The broad valley connects Chaleleka Lake (Shashemene subsheet) with Lake Hawasa. This drainage becomes filled with sediment as does the entire Chaleleka Lake. In recent times, water is seen in both Chaleleka Lake and the channel only during the rainy season. During the rest of the year, water enters the mouth of the channel from Lake Hawasa. The infill of the Hawasa Caldera also comprises basaltic lavas forming the Hawasa basaltic belt.

19 Alluvial cone is not a frequent landform in the area. There are a few near Dore, Birbo and Abaye. The alluvial cones are not well developed as the relief is very young.

20 Polygenetic infill of crater or caldera is really widespread unit in the area of Hawasa subsheet. The bottoms of the calderas and encircled craters are local erosional bases usually lacking superficial drainage. Loose pyroclastic accumulations and products of weathering are usually eroded by sheet run-off and deposited in the caldera basins. Such infill is characterized by flat morphology.

6. GEOLOGY

The area of Hawasa subsheet is located within the central part of the Main Ethiopian Rift. Upper Miocene to Pliocene volcanic rocks of the Nazret Group dominated by rhyolitic ignimbrites form the basement of the Main Ethiopian Rift. The Nazret group rocks do not crop out in the mapped area and are covered by younger volcanic sequences. The Hawasa subsheet covers the north-western segment of the Lower Pleistocene Hawasa Caldera. Significantly smaller Middle Pleistocene Corbetti Caldera overprints the north-western margin of the Hawasa Caldera. Basaltic lavas and pyroclastics were erupted in the Hawasa basaltic belt in south-eastern part of the subsheet most likely also during the Middle Pleistocene. The rhyolitic volcanic activity continued in the area of Corbetti Caldera also after Middle Pleistocene. The early predominantly explosive Artu Volcano was later buried by the newly emerging Wendo Koshe Volcano to the west and Chabi Volcano to the east.

6.1. Lithology

The lithological units described in following text are arranged generally in stratigraphic order from the oldest to youngest ones with descending numbering.

UPPER MIOCENE – PLIOCENE

28 Nazret Group ignimbrites (only in the geological cross-section) do not crop out in the area of the Hawasa subsheet but cover large areas in the surrounding region namely in the rift scarps and on the rift shoulders. Welded and non-welded ignimbrites dominate in this unit, with intercalations of co-ignimbrite fall deposits and minor lavas. The chemical composition of the rocks representing this group corresponds to alkaline rhyolites and trachytes. The age of the Nazret group has been determined as between 9.5 and 3 Ma (Kazmin and Seife 1978). The thickness of the Nazret Group reaches several hundred meters (400 m around Aluto Volcano: Abebe 1984; EIGS-ELC 1985; 600 m on the eastern margin of the rift WoldeGabriel et al. 1990; 500 m in the rift escarpments Basalfew 2012).

LOWER PLEISTOCENE

DINO FORMATION-HAWASA CALDERA

27 Hawasa rhyolitic ignimbrites were produced by voluminous eruptions of a rhyolitic magma from the Hawasa Caldera. These ignimbrites are the oldest rocks exposed in the area of the Hawasa subsheet. The thickness of this unit remains unclear due to the lack of borehole data and difficult distinction of the overlying Corbetti ignimbrites. This unit comprises various alternating facies (welded, non-welded) of rhyolitic ignimbrites and associated fall deposits. Crystaloclasts of quartz and feldspars can be identified enclosed in a groundmass of deformed glass shards and frequent fiamme. On the contrary to the Nazreth Group, ignimbrites of the Dino Formation can be linked to individual source vents. Apart of the Hawasa Caldera, Ziway Caldera and most likely also Shalla belong to the Dino Formation. The ignimbrite of the Hawasa Caldera has been dated using the K-Ar method (JICA 2012) to 1.28 Ma on the sample taken 3 km south of the mapped area. This age corresponds well to the ignimbrites surrounding Lake Shalla (1.35 Ma, K-Ar: JICA 2012). Ages 1.1–1.85 Ma (K-Ar) are also given by WoldeGabriel et al. (1999). Compared to younger volcanic units, Hawasa ignimbrites are intensively jointed and faulted, also in areas where younger volcanic rocks remain un-fractured.

MIDDLE PLEISTOCENE

CORBETTI CALDERA

26 Corbetti rhyolitic ignimbrites represent the last stage of caldera-forming eruptions in the studied area. The Corbetti Caldera is situated in the north-western part of the ancestor Hawasa Caldera. As the petrography and composition of Middle Pleistocene Corbetti ignimbrites resemble characteristics of

Lower Pleistocene Hawasa ignimbrites, the boundary between these two remains unclear in most parts of the map. The thickness of the Corbetti pyroclastic deposits likely reaches 200 m on the outskirts of the caldera, whereas within the caldera, this thickness will probably be significantly higher. The ignimbrites consist of welded (figure 6-1) as well as non-welded facies. The proportion of non-welded facies most likely increases with distance from the caldera. The ignimbrite units at the caldera rim are represented by lag-fall breccias dominated by large (up to couple of meters) blocks of pumice. The individual flow units are separated by pumice fall deposits of variable thicknesses. At the caldera scarp, layers of pumiceous lahars were also observed, documenting that Corbetti was formed a strato-cone prior to the climactic caldera forming eruption (RP HSRVR010). The ignimbrite sampled at the point HSRVR010 has a composition of peralkaline rhyolite to trachyte. The rock consists of slightly resorbed crystaloclasts of K-feldspar, oval, strongly resorbed crystals of quartz and small amphibole crystals enclosed in a matrix of welded glass-shards (figure 6-2). Resorbed crystals suggest a magma mingling process precedent to the ignimbrite eruption. The ignimbrite from Corbetti Caldera sampled at Alaba-Kulito (approx. 20 km west of the Hawasa subsheet) was dated using the K-Ar method (JICA 2012) to 0.19 Ma. According to geomorphology (see geomorphology map), lava domes have possibly erupted on the western and north-western edges of the caldera. The presence of these structures could not be approved in the field. If present, these lava domes are covered by thick accumulation of pumice fall from the Wendo Koshe Volcano.

Figure 6-1. *Welded facies of trachytic to rhyolitic ignimbrites exposed in the Corbetti Caldera scarp (RP HSRVR010). Photo V. Rapprich.*

Figure 6-2. *Crystaloclasts of alkali feldspar enclosing amphibole within the groundmass of deformed and re-crystallized glass-shards (RP HSRVR010). Plane-polarized light, photo V. Rapprich.*

MIDDLE PLEISTOCENE – HOLOCENE

ARTU VOLCANO

25 Artu pumice cone. Artu Volcano represents the first stage of post-caldera volcanic activity within the Corbetti Caldera. Artu Volcano is represented by erosional remnants in between the younger volcanoes Chabi and Wendo Koshe which overlay marginal parts of this ancient volcano. This volcanic edifice has been built up by thick accumulations of unconsolidated rhyolitic pumice. Grain size of pumice deposits varies among individual layers, but coarse-grained units prevail. Observed layers have both a clast and matrix-supported texture, suggesting near-vent pyroclastic fall and pyroclastic flow deposition took place during construction of the cone. Loose pumice deposits are affected by erosion resulting in numerous deep erosional gorges. In the walls of these gorges, a thick accumulation of pumice can be observed (point HSRVR083). Neither obsidian lavas hardening the edifice nor welded ignimbrites were observed within the sequences forming the Artu Volcano. Artu was created by numerous Plinian eruptions emitting large amounts of pumice.

POST-CALDERA MAFIC VOLCANISM

24 Hawasa basalt form a ridge transecting the Hawasa Caldera in a NNE-SSW direction. The ridge subdivides the caldera into the western part (with Lake Hawasa) and the eastern part (with Chaleleka Lake –Shashemene subsheet). Lavas of the Hawasa basaltic ridge were emitted from several scoria- and tuff-cones arranged along the ridge. The basaltic lavas and coherent feeders of pyroclastic cones consists of relatively larger phenocrysts of olivine (up to 1 mm, mostly discomposed) and plagioclase (up to 2 mm) and frequent smaller phenocrysts of clinopyroxene (not exceeding 0.3 mm) enclosed in a matrix of plagioclase, clinopyroxene, olivine and magnetite. We suppose a thickness of basaltic lavas of several tens of meters probably overlying the earliest layers of resedimented pumice filling the Hawasa Caldera. The later resedimented pumice deposits overlay marginal parts of the basaltic ridge. The basalts are slightly alkaline and are plotted in the TAS diagram (sub-chapter Geochemistry, figure 6-11) at the boundary with basanite.

23 Basaltic lapilli-stone (tuff-cone) form the Tabor volcanic cone within the town of Hawasa (RP HSRVR005), unnamed volcanic crater (RP HSRVR179) on the southern skirt of Hawasa town and an unnamed hill representing an erosional remnant of a tuff cone (RP HSRVR180) to the west of the road from Hawasa to Shashemene. The extent of the lapilli-stones is limited to the size of tuff cones and their thickness to the height of these cones. The lapilli-stones are poorly-sorted clast supported and dominated by massive non-vesicular basaltic clasts with a prevailing grain-size of 1 cm, but larger clasts (up to 20 cm), often with xenolith in the core, may occur as well. These pyroclastic deposits were produced by phreatomagmatic (Surtseyan) eruptions in marshy or shallow-lake environments. Therefore these deposits are located on margins of the basaltic ridge and not on its top, where scoria cones occur. The tuff cone on the Hawasa-Shashemene road (RP HSRVR179) penetrates and overlays old obsidian from Chabi Volcano, suggesting the mafic volcanism of the Hawasa basaltic ridge might be of Middle Pleistocene age. A younger age of this sequence is not likely as the volcaniclastic deposits are significantly altered and affected by erosion.

22 Basaltic scoria (scoria cones) can be found forming two small cones along the Hawasa bypass (HSRVR035, figure 6-3). The scoria is poorly sorted and clast supported, dominated by fragments of scoria predominantly 5–10 cm in diameter, frequently with large bombs. The bombs are flattened in the crater facies, whereas in the wall facies spindle shaped bombs can be found. The scoria cones are associated with basaltic lavas and were produced by Strombolian style eruptions. Similarly to the lapilli-stones, the extent of the scoria deposits does not exceed the size of the scoria cones and their thickness is equivalent to the height of the cones. The age is estimated as being Middle Pleistocene. No current fumarolic activity has been documented associated with the scoria cones.

WENDO KOSHE VOLCANO

21 Wendo Koshe obsidian IV. In the accessible eastern part of the Wendo Koshe Volcano, obsidian lava flows were documented beneath the younger obsidian and pumiceous accumulations of the older Wendo Koshe Volcano. Similarly to other Quaternary obsidian lavas in this area, this obsidian is dark green to black in colour and very poor or even lacking any phenocrysts. Similar obsidian lavas could occur within the pyroclastic sequences of the Wendo Koshe pumice cone, but significant parts of this volcano are difficult to access or are even inaccessible.

20 Wendo Koshe pumice cone III occupies the central and western part of the Corbetti Caldera, rising some 200 m above the caldera floor. The area of the Wendo Koshe pumice cone is difficult to access as loose pumice is strongly affected by erosion and its surface is scarred by many erosional gorges. The few exposures which are accessible display thick accumulations of pumiceous deposits with minor intercalations of obsidian lavas. In the northern and eastern parts, the Wendo Koshe pumice cone is buried by younger obsidian lava and pyroclastic deposits of the latest Wendo Koshe eruption.

19 Wendo Koshe obsidian II is large obsidian lava overlying the eastern part of the Wendo Koshe cone. Only the south-eastern margins of this obsidian lava at the foothill of the volcano can be reached and the rest has been mapped using satellite and aerial images. The surface of this lava differs significantly from the surface of the remaining Wendo Koshe Volcano, as deep erosional gorges are not evolved in obsidians. The lava is covered by a thin pumice fall deposit from Wendo Koshe I. The obsidian lacks macroscopically visible crystals and resembles other obsidian lavas erupted mostly from Chabi Volcano.

18 Wendo Koshe pumice fall and minor flow deposits cover large areas in the north-eastern sector of the map. The deposits are mostly well sorted and clast-supported suggesting fall deposition. Locally matrix-supported layers with reverse grading interpreted as pyroclastic flow deposits can be observed (figure 6-4). These were produced during the last big explosive event of the Wendo Koshe Volcano. The pyroclastic (mostly fall) deposits cover a large area of the northern part of Hawasa subsheet and extend as far as Bura and Shashemene. The loose pyroclastic material was mostly blown away, for this reason these pyroclastic deposits are not displayed on the geological map covering the older obsidian lavas of the Chabi Volcano, despite remnants of these deposits being found on them. Near the volcano, up to 6 m of the youngest pumice overlay a 2 m thick deposit of pumice fall from a previous explosive eruption that seems to be of smaller magnitude (RP HSRVR069). These two layers are separated by a thin paleosoil horizon. Along the Shashemene – Alaba-Kulito road (just north of the subsheet), 0.5 m of young Wendo Koshe pumice overlays a 6 m thick accumulation of ochre fine ash with abundant accretionary lapilli of an unclear source. Even along the Hawasa-Shashemene road, the thickness of the young Wendo Koshe pumice reaches 2 m. The exact age of this violent eruption has not been determined, as no charcoal was found at the base or within this deposit.

Figure 6-3. *Scoria deposits exposed in temporary quarry on the margin of the Hawasa Town (RP HSRVR035). Photo V. Rapprich.*

Figure 6-4. *Last explosive eruption of Wendo Koshe Volcano deposits. Non-welded pyroclastic flow deposits overlain by pumice fall. (RP HSRVR041). Photo V. Rapprich.*

17 Wendo Koshe pumice flow deposits with intercalations of obsidian lava form a fan spreading from the horse-shoe shaped crater of Wendo Koshe. These deposits originated from the same eruption as the pumice fall (item 19), but very proximal facies are dominated by pyroclastic flow deposits and small obsidian lavas. The pyroclastic flow deposits are matrix-supported, reverse-graded and non-welded dominated by pumice fragments, with occasional obsidian clasts.

16 Wendo Koshe cone dominated by pumice has been constructed by repeated Plinian eruptions of rhyolitic magma. It consists of coarse-grained deposits (lag-fall breccias, crater facies fall deposits, etc.) significantly altered due to ongoing fumarolic activity. Active fumarole was observed in 2012 on the western margin of the crater.

Chabi Volcano

15 Chabi obsidian old is a unit comprising all of the ancient obsidian lavas with unclear relations. These obsidians outcrop along the margins of the Chabi Volcano. Even in these parts, obsidians are overlain by thin layers of later pumiceous fall deposits. In inner parts of the volcano, these ancient lavas are buried by thick accumulations of younger volcanic products. Structural surfaces on these lavas occasionally dip towards the volcano, which can be explained in terms of the deformation of the volcano's substrata and near surroundings due to a thick accumulation of massive obsidian lavas. These obsidians are moderate to rich in crystals enclosed in dark-grey partly hydrated or re-crystallized rhyolitic glass and differ from younger obsidian lavas mostly lacking any macroscopically visible crystals. Quartz and alkali feldspar phenocrysts predominate in these ancient obsidians (e.g., HSRVR010 in figure 6-5). The obsidians are flow banded, when individual bands differ in amount of microcrysts. The tiny needles are too small to be identified optically. Occasionally, perlite-cracks can be documented in the glass (figure 6-5: around the quartz).

14 Chopa pumice cone is a remnant of an explosive phase of the dominantly effusive Chabi Volcano. The pyroclastic sequences of the Chopa pumice cone are mostly buried by younger lavas. In stream gorges at the foothill of the volcano (RPs HSRVR062 and HSRVR063) fall deposited pumice alternates with flow deposits and surge deposits with associated phreatomagmatic fall (including large erratic blocks with bomb-sag structures) as well as with mass-flow deposits (lahars). These sequences demonstrate that in the Chabi Volcano some phases can be violently explosive with Plinian and phreatomagmatic eruptions.

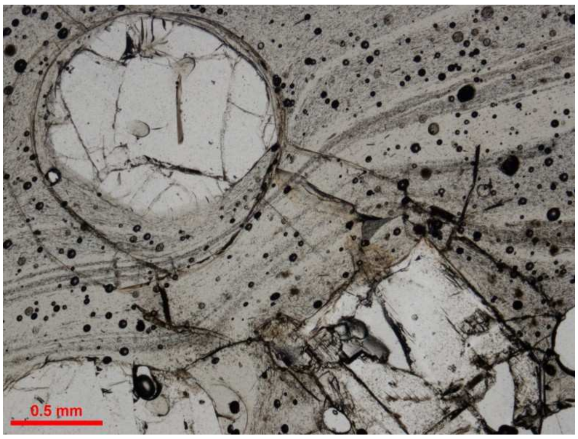

Figure 6-5. *Partly resorbed quartz (upper left) and crystal of K-feldspar (bottom right) in flow-banded obsidian lava of Chabi obsidian old (RP HSRVR068). Plane-polarized light, photo V. Rapprich.*

Figure 6-6. *Older obsidian lava (Chabi obsidian VI) partly covered by Wendo Koshe young pumice fall (in front) and overlain by Chabi obsidian III lava. Photo V. Rapprich.*

13 Chabi obsidian VI is older obsidian lava exposed on the eastern side of the volcano. Chabi obsidian VI is overlain by a thin deposit of young pumice from the Wendo Koshe Volcano and by Chabi obsidian III lava (figure 6-6). Chabi obsidian VI has only a very thin cover of pumice deposit, very likely represented solely by the youngest Wendo Koshe pumice, whereas the older Chabi obsidians are covered by thicker pumice deposits probably produced by several previous eruptions. Except for the old Chabi obsidian, all the younger units resemble each other, being poor in crystals.

12 Chabi pumice cone V cropping out in the central part of the Chabi Volcano could not be reached by the terrain survey and was detected based on satellite images. It was identified from the surrounding obsidian lavas by its significantly different surface. Loose pumice leads to the formation of a dense network of erosional furrows. Its stratigraphic position is deduced from its morphology compared to the surrounding units of similar lithology.

11 Chabi obsidian V is the youngest obsidian lava covered by the young Wendo Koshe pumice fall. It is exposed in the north-western part of the Chabi Volcano, and it is overlain by Chabi obsidian IV which is already free of any pumice cover. According to the similarities in morphology and light-reflectance in satellite images (which seems to depend on the stage of glass hydration), it is likely that Chabi obsidian V is of similar age to Wendo Koshe obsidian II. This lava unit also makes up the volcanic pile of Borena.

10 Chabi obsidian IV, **9 Chabi obsidian III**, **8 Chabi obsidian II** and **7 Chabi obsidian I** are four obsidian lava flows post-dating the large explosive eruption of the Wendo Koshe Volcano. These lavas create the current shape of the Chabi silicic shield volcano. All of the lavas have identical petrography, dominated by pure rhyolitic glass with a lack of crystals. Their mapping was based on interpretation of satellite images and verification of superposition and lava front positions in the field. No petrographic tool could be used to distinguish between the lava units. Their compositional similarity is shown also by their uniform chemical composition. Chabi obsidian IV forms the northern slopes (an area called Borena) of the Chabi Volcano. Chabi obsidian III flows to the east, where it overlays the Chabi obsidian VI. Chabi obsidian II forms the central part of the volcano and its western slope. The last lava flow erupted from the Chabi Volcano is represented by Chabi obsidian I (figure 6-7).

Figure 6-7. *Front of the youngest obsidian lava (Chabi obsidian I) from the Chabi Volcano (in rear). Photo V. Rapprich.*

Figure 6-8. *Monogenetic pumice cone within the Corbetti Caldera. Photo V. Rapprich.*

SILICIC MONOGENETIC VOLCANOES WITHIN THE CORBETTI CALDERA

Apart from the large volcanoes emerging within the Corbetti Caldera, several small silicic edifices can also be found.

6 Monogenetic obsidian lava in Corbetti Caldera forms a small and short lava flow emitted from a monogenetic pumice cone. The monogenetic obsidian lava overlays resedimented pumice and is covered by the Wendo Koshe young pumice fall deposit. Neither petrography nor chemical composition differ from obsidians erupted from the Chabi Volcano.

5 Monogenetic pumice cones in Corbetti Caldera were formed by small-scale monogenetic explosive eruptions of small portions of gas-saturated rhyolitic magma. These occur mainly on the margins of the Corbetti Caldera. Three small cones and two pumice rings can be found on the southern edge of the Chabi obsidians; two other small pumice craters are located to the north of the Wendo Koshe Volcano and one bigger cone on the northern edge of the Corbetti Caldera. Even though the volcanic landforms (figure 6-8) resemble scoria cones and other forms of monogenetic basaltic volcanism, these small volcanic edifices consist of rhyolitic pumice. The composition of the pumice does not differ from obsidians of the Chabi Volcano.

NON-VOLCANIC DEPOSITS

4 Polygenetic sediments (resedimented pyroclastics, alluvial sediments, lacustrine sediments) fill the bottoms of Hawasa and Corbetti Calderas. They are characterized by alterations of beds and successions with various origins and lithology. The character of the infill is a result of tectonic, volcanic and exogenous processes and fluctuations of lake water levels. Resedimented pyroclastics are mainly formed by angular clasts of pumice or mixtures with a low portion of silt, sand or soil. Locally clasts of weathered ignimbrites, and tuffs occur. Rarely, obsidian clasts are also present. Alluvial deposits are represented by resedimented soil sands and silt with various portions of weathered volcanic rocks. Lenticular beds of gravels were observed inside the walls of a fissure in the Jara Dado area. Lacustrine deposits consist of a heterogeneous sequence of silts with a thin intercalation of sands and resedimented pumice. Locally, gastropod shells occur within the silt beds. There is no exact information about the thickness of the infill, however based on drill data from Muleti Village it can be greater than 30 meters (Ayalew et al. 2004); an average thickness of 40–50 m is reported by Chernet (1982) from elsewhere in the rift.

HOLOCENE

NON-VOLCANIC DEPOSITS

3 Colluvial sediments do not form voluminous deposits in the area of Hawasa subsheet even though, steep slopes are frequent on caldera scarps. Predominant sandy material and gully erosion on the scarp do not create favourable conditions for colluvial sediments. The sediments are related to the rare occurrences of accumulation parts of landslides. The deposits are formed by blocks of weathered ignimbrites and pyroclastics.

2 Alluvial sediments are bounded with recent alluvial fans. The creation of an alluvial fan is related to erosion of material in the slope during rainfalls, transported by sheet-flows or density currents. Alluvial fans are generally formed in the areas with abrupt decrease of gradient. The sediments accumulate due to a deceleration of flow at lower gradients. The alluvial fans are located in the mouths of stream-flow valleys or erosional valleys and gullies. In the Hawasa subsheet area they are located on the foothill of the western escarpment (north of Muleti, west of Lake Hawasa). Alluvial sediments are formed by re-sedimented soil and fine to medium grained sands with a high portion of weathered volcanic and volcaniclastics. The angular clasts of pumice are common within the sandy sediments.

1 Fluvial sediments are very rare on the Hawasa subsheet because of a lack of fluvial systems in the area. Limited occurrence of fluvial sediments is related to a drain channel (Tikur Woha) connecting Lake Hawasa with Cheleleka Lake (east of the subsheet). Sediments are formed by silty and muddy unconsolidated deposits.

6.2. Tectonic setting

The geological map 1:50,000 Hawasa sheet is located in the eastern half of the NNE-SSW to NE-SW trending Main Ethiopian Rift which is part of the regional East African Rift System (e.g., Bonini et al. 2005). Both of these rift structures have accommodated the active extension between the Nubia and Somalia Plates since the Late Miocene (e.g., Ebinger 2005). The Main Ethiopian Rift recorded the typical evolution of continental rifting, from fault-dominated rift morphology in the early stages of the continental extension to magma-dominated extension during break-up (e.g., Agostini et al. 2011).

PRIMARY STRUCTURES IN VOLCANIC SEQUENCES AND NON-VOLCANIC DEPOSITS

Planes of sedimentary bedding mainly with a subhorizontal orientation were identified in the alluvial sediments and resedimented pumice, located in the southern part of the map sheet (figure 6-10a). Primary magmatic layering (banding) dips predominantly at the low angles to the WNW to NW in the

Middle Pleistocene Corbetti ignimbrites and Lower Pleistocene Hawasa ignimbrite (central and western part of the map sheet: figures 6-9a; 6-10b).

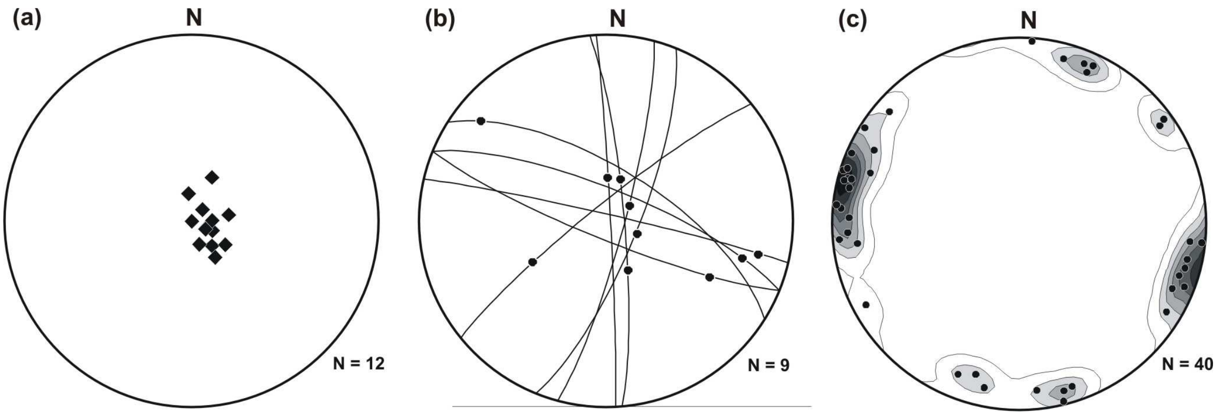

__Figure 6-9.__ Orientation diagrams of structures (geological map 1:50000, sheet Hawasa). (a) Magmatic layering in rhyolites of the Corbetti Caldera and Dino Formation; (b) Regional fault structures and associated lineation (slickensides); (c) Extensional joints. Projection to lower hemisphere.

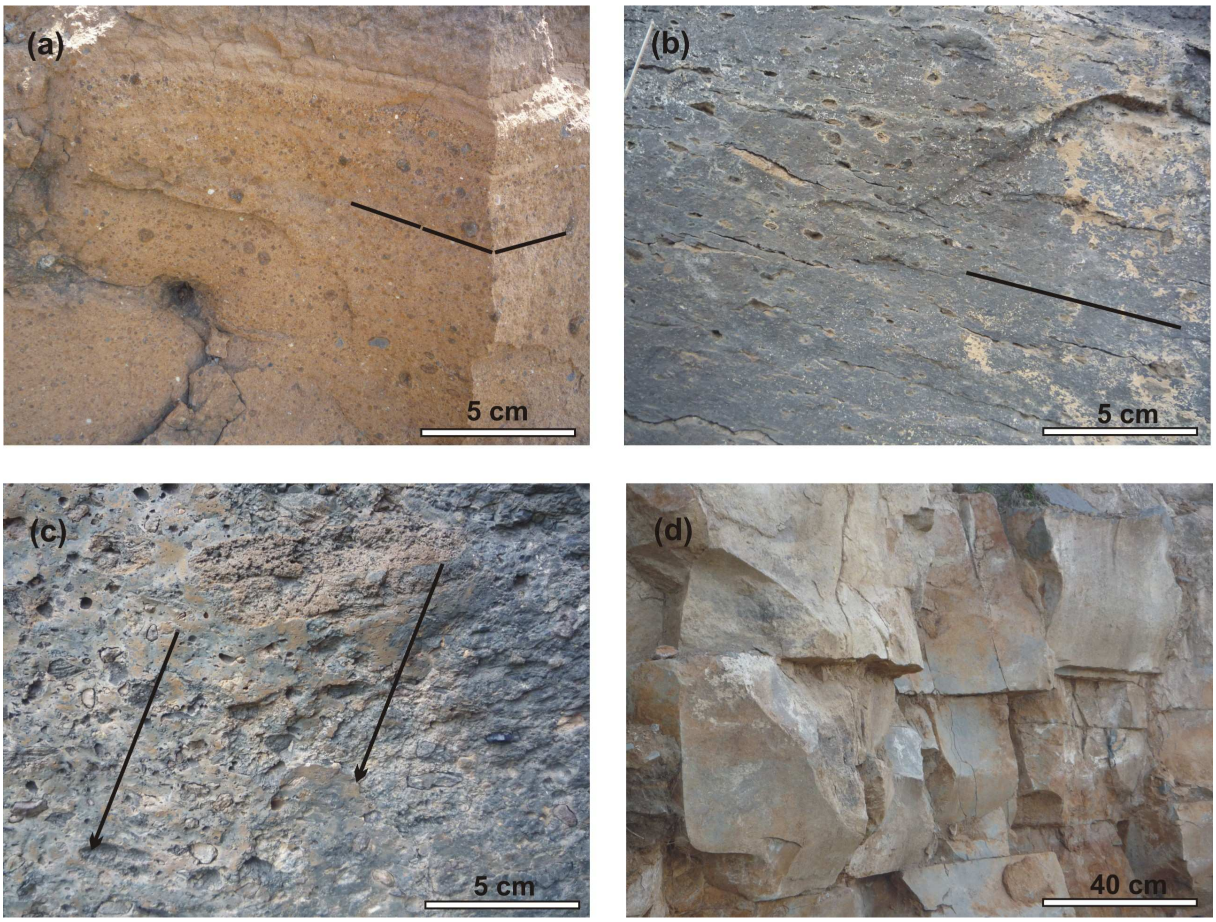

__Figure 6-10.__ Field photographs of identified structures: (a) sedimentary bedding in Pleistocene to Holocene alluvial sediments; (b) magmatic layering in rhyolitic ignimbrites defined by planar preferred orientation of gas bubbles, fiamme, lithics and minerals; (c) regional fault plane with well-developed lineations (slickensides) and indicators of normal kinematics; (d) extensional joints.

Only in the proximity of the marginal fault of the caldera system the orientation of the magmatic layering is more variable. The bands of approximately centimetre scale often contain slightly elongated gas bubbles and have a slightly different size of grains and fragments. Linear preferred orientation of minerals or gas bubbles was not observed. The origin of these structures was probably related to the streaking out of glassy or devitrified layers of the rhyolite magma during lava flow.

BRITTLE STRUCTURES

Across the mapped area the superposition of different brittle structures is observed (e.g., caldera-related faults, regional normal faults and strike-slip faults, shear joints, extensional joints). Caldera-related faults (caldera marginal fault) have an irregular shape on the surface cross-section, which is mostly parallel to the caldera rim. These faults dip steeply to moderately towards the central part of the caldera and have normal kinematics. Regional faults related to the Main Ethiopian Rift System exhibit a predominantly N-S to NNE-SSW trend, dipping steeply to the E or ESE (figures 6-9b, 6-10c). Here, well-developed lineations (slickensides) systematically plunge under steep angles to the ENE to ESE. Identified kinematic indicators (e.g., slickenside asymmetry and relationships to older structures) reveal a normal movement in the direction of the lineation. The subordinate faults are dipping steeply to the NNE or SSW bearing gently plunging lineation (figure 6-9b) with no clear kinematic evidence. At several localities across the mapped area these strike-slip faults appear to be relatively younger than regional normal faults. Well-developed extensional joints occur in two distinct sets (figure 6-9c). The more frequent is the set of ENE or WSW steeply dipping joints, which are mostly parallel to the orientation of regional normal faults. Extensional joints belonging to the second set have a subvertical orientation and are mostly perpendicular to the previous ones.

6.3. Geochemistry

Twelve samples representing the most important lithological types from the Hawasa subsheet were complemented with two samples of the rocks exposed in the subsheet but taken from near surroundings of the subsheet area. One sample (HSRVR010) represents Middle Pleistocene Corbetti ignimbrite, two samples (HSRVR035 and HSRVR177) Middle Pleistocene Hawasa basalts, five samples (HSRVR037, HSRVR039, HSRVR041, HSRVR069C and HSRVR069D) represent pumice deposits of post-caldera silicic volcanism and remaining six samples (HSRVR036, HSRVR038, HSRVR067, HSRVR068, HSRVR071 and HSRVR087) represent post-caldera obsidian lavas.

The analysed basaltic rocks plot in the TAS diagram (figure 6-11a) to the field of basalt, close to the basanite boundary. Despite low silica content, low mg# values (40–43), low MgO content (6–6.3 wt. %) as well as low content of compatible trace elements (Ni = 22–29 ppm) suggest these basalts do not represent primitive melts. These are the only basic rocks present on the Hawasa subsheet and are described for the first time in this Report.

The sample of Corbetti ignimbrite falls within the cluster of data of Pleistocene to Holocene obsidians and pumice from Wendo Koshe, Chabi and silicic monogenetic volcanoes in the TAS diagram (figure 6–11a). On the other hand, in the Nb/Y vs. Zr/Ti classification diagram (Pearce 1996, figure 6-11b) the Corbetti ignimbrite sample display higher Nb/Y ratio suggesting more alkaline tendency. Whereas the post-caldera silicic rocks display nearly uniform content of Zr (about 1500 ppm except of the oldest Chabi obsidian – sample HSRVR068 with 813 ppm of Zr), the Corbetti ignimbrite is much poorer in Zr (629 ppm).

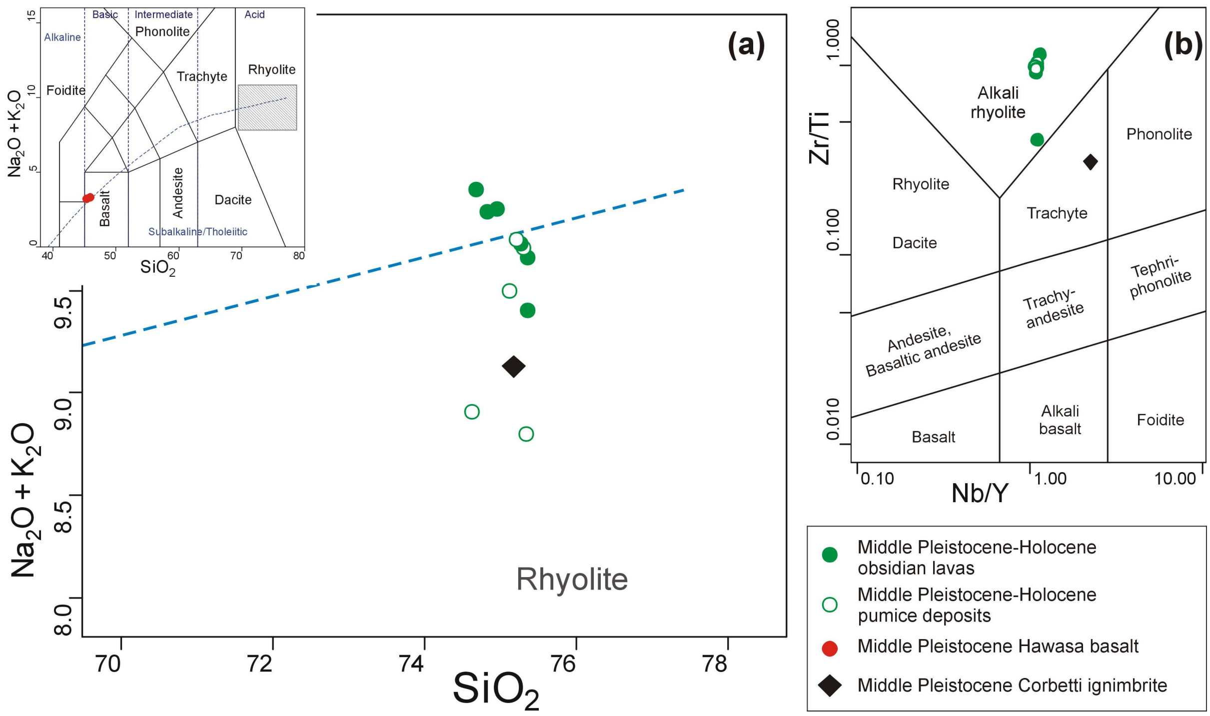

Figure 6-11. *Classification diagrams of analysed rocks: a) TAS diagram (Le Bas et al. 1986); b) Nb/Y vs. Zr/Ti diagram (Pearce 1996).*

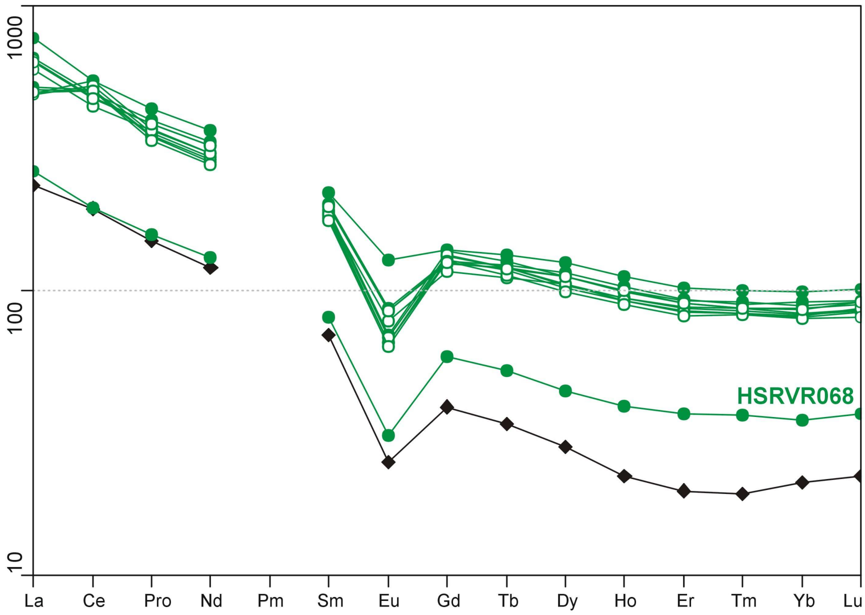

Figure 6-12. *Spider-plot of analyzed samples normalized to chondrite composition (Boynton 1984). Symbols correspond to figure 6-11.*

The Corbetti ignimbrite differs from younger rhyolitic rocks also in the significantly lower content of rare earth elements (ΣREE = 367 ppm compared to 930–1150 ppm in post-caldera rhyolites, except the oldest one with 408 ppm). The Corbetti ignimbrite is characterized by higher LREE/HREE enrichment (La_N/Yb_N = 11.15) compared to younger rhyolitic rocks (La_N/Yb_N = 5.9–7.9). A negative Eu anomaly for Corbetti ignimbrite (Eu/Eu* = 0.48) can be compared with values for the younger rhyolitic rocks (Eu/Eu* = 0.42–0.54 except for one rock giving a value of 0.73). In the REE chondrite-normalized pattern of the Corbetti ignimbrite, the U-shaped trend for HREE can be seen (figure 6-12), that is typical for strongly differentiated alkaline rocks.

We may conclude that trachytic to rhyolitic ignimbrite (sample HSRVR010) represents the final stage of differentiation of the silicic alkaline melt. The post-caldera rhyolites must be derived from other source than the Corbetti ignimbrite as they have higher ΣREE with less prominent LREE to HREE enrichment compared to younger rhyolitic rocks. The only exception is the oldest sampled obsidian (HSRVR068) showing composition in between the Corbetti ignimbrite and younger volcanic products (figures 6-11 and 6-12). Uniform chemical composition of all later eruptives of the Corbetti volcanic system suggests the presence of a single common magma chamber to which both principal volcanoes (Wendo Koshe and Chabi) as well as all monogenetic cones are most likely attached.

6.4. Geological evolution

After depositing Nazret ignimbrites during Late Miocene and Pliocene, the area around the current Hawasa experienced a climactic eruption leading to the formation of Hawasa Caldera during the Lower Pleistocene. After the formation of Hawasa Caldera, the new Corbetti Volcano started to emerge in its north-western sector culminating in another climactic (but smaller scale compared to the Hawasa Caldera forming eruption) eruption forming Corbetti Caldera in the Middle Pleistocene. Shortly after the caldera-forming eruption, new volcanoes started to emerge in the area of Corbetti Caldera. The first one – Artu Volcano is being buried by products of the predominantly explosive Wendo Koshe, and mainly effusive Chabi Volcanoes. We do not know the timing of the last big explosive event of the Wendo Koshe Volcano, which spread around a large amount of pumice covering the area north of Hawasa town and around Shashemene town with a pumice layer up to a few metres thick. Four large obsidian lava flows from Chabi Volcano postdate this last big explosive event. The formation of post-caldera rhyolitic volcanoes was for a short period accompanied by basaltic volcanism in the area of Hawasa town. Since the formation of Calderas, these large sedimentary basins are filled predominantly with resedimented pyroclastics washed off the caldera scarps and newly emerging volcanoes. This process continues to-date as does the spreading of the rift floor resulting in the opening of dangerous ground cracks. Fumarolic activity is also documented in the area of Corbetti Caldera.

6.5. Geological localities

1. Corbetti caldera scarp exposes a sequence of volcanic rocks documenting the complex evolution of the Corbetti Volcano prior to the climactic caldera forming eruption. Pumiceous lag-fall breccias, welded and non-welded ignimbrites and pumice fall deposits alternate with the lahar deposits.

2. Wendo Koshe crater is very difficult to access (figure 6-13). The horse-shoe shaped crater is the place of the last big explosive eruption in the area of Corbetti Caldera. The crater is surrounded by areas with several metres thick deposits of this eruption. Short obsidian lava can be seen in the bottom of the crater. Fumarole on the western edge of the crater is still active and causes alteration of the surrounding volcanic rocks.

3. Front of the youngest obsidian lava is accessible on the southern foothill of the Chabi Volcano. The lava stopped when it reached one of the monogenetic pumice cones and older small obsidian lava emitted from another monogenetic pumice crater. The front of the obsidian lava is about 10–12 m high and consists of large blocks of dark greenish grey to black rhyolitic glass. The obsidian is not covered with soil and it is only poorly vegetated. This place hosts a colony of rock hyraxes.

Figure 6-13. *Wendo Koshe Volcano with horse-shoe shaped crater open towards northwest. Photo V. Rapprich.*

Figure 6-14. *Rock tower of scoria remaining after scoria exploitation in Hawasa. Photo V. Rapprich.*

4. Hawasa Caldera scarp exposes fabrics in rhyolitic ignimbrite and regional faults related to the Main Ethiopian Rift System. Primary bedding in rhyolitic ignimbrite is defined by lattice preferred orientation of elongated gas bubbles, fiamme and lithics dipping homogeneously under low angles to the WNW. A set of superimposed subvertical N-S trending normal faults with well developed steeply plunging slickenslides is mostly parallel to the main escarpment structure.

5. Scoria cone in Hawasa Town was exploited and exposed by a temporary quarry. Exploitation was focused on non-welded non-consolidated scoria layers whereas lava facies and welded or consolidated (cemented) scoria layers were left behind. The quarrying of only selected parts of the scoria cone resulted in a picturesque labyrinth of blocks of scoria deposits (figure 6-14).

6. Tabor Hill rising above Hawasa Town offers fantastic views of Hawasa town, Lake Hawasa and also Chabi Volcano behind Lake Hawasa. Tabor Hill is a remnant of a tuff cone produced by a shallow-water Surtseyan style eruption of a small portion of the basaltic melt. Numerous outcrops on the slopes of the hill expose layered tuffs of the phreatomagmatic (Surtseyan) eruption with angular non-vesicular basalt fragments of various sizes. The hill can be easily reached from the town and it is a popular touristic attraction, but there have been recent reports of robberies.

7. HYDROGEOLOGY

The Hawasa area is located on the rift floor and it has a subtropical (Weina Dega) climate. Sedimentary formations form a flat plain and are eroded only along river/wadi banks and dominant volcanic structures are located throughout the whole rift floor. The rain gauge at Hawasa is situated at an elevation of 1,765 m a.s.l. and its annual rainfall average is 969 mm. The Hawasa area is part of the Rift Valley Lakes closed basin and its sub-basins of Hawasa and Shalla lakes. The Tikur Woha River drains water from the eastern escarpment and a swampy area of the former Lake Shallo feeds Lake Hawasa (figure 7-1).

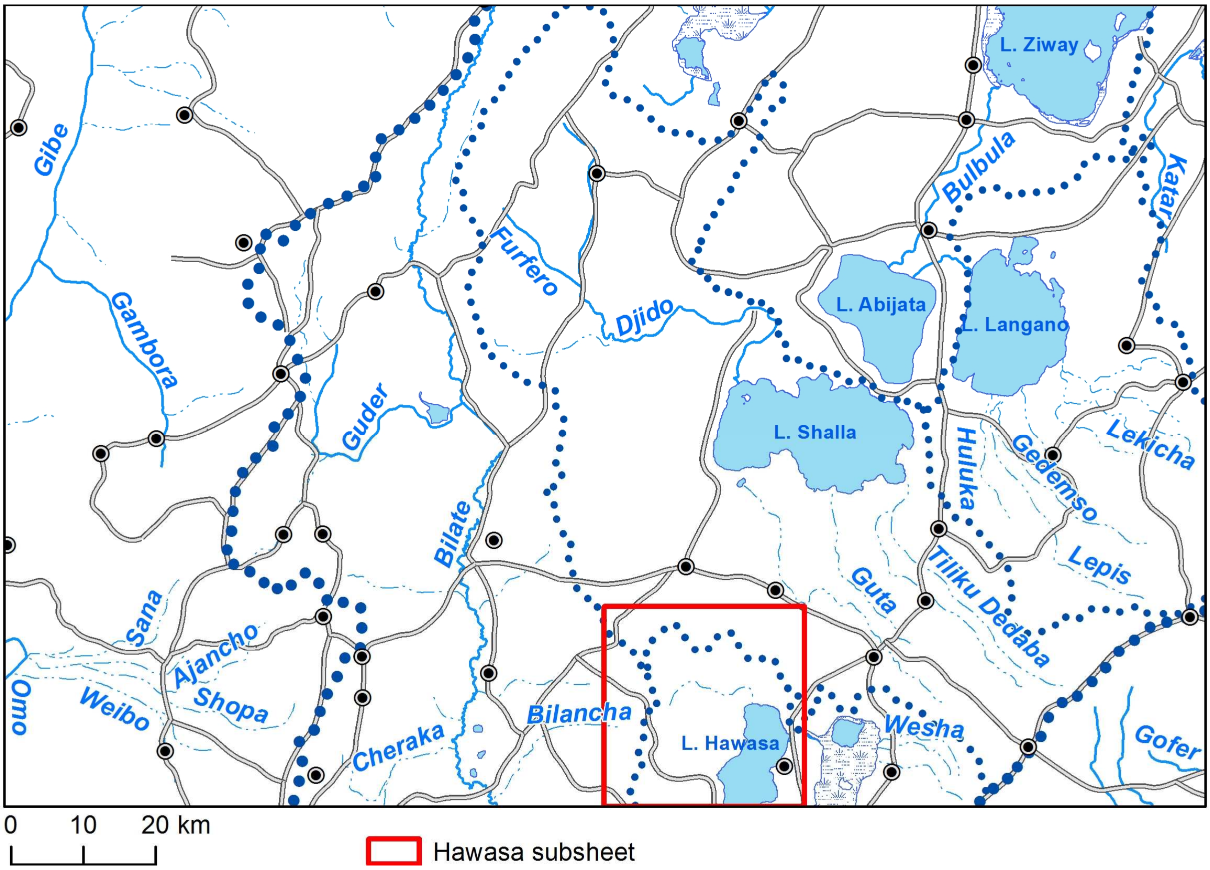

Figure 7-1. *The river scheme of the Hoseina 1:250 000 sheet (location of the Hawasa subsheet in red, surface water divides in dotted blue lines).*

Table 7-1. *Main river characteristics*

River	Station	Mean flow [m^3/s]	Annual flow [mm]	Area [km^2]	Specific runoff [l/s.km^2]	Specific baseflow [l/s.km^2]*
Tikur Woha	Hawasa	6.6	?	?	?	?
Tikur Woha	Dato village	3.62	199	625	4.25	1.54
Bilate	Near Alaba	11.06	174	2,009	5.5	1.1–3.4
Butara /Werka	Near Wondo Genet	0.26	200	41	6.3	?
Wesha	Wondo Genet	0.63	197	40	15.8	13.3–15.3
Debaba	Kuyera	1.04	201	163	6.4	0.9-4.9
Guta	Melka Oda	0.32	135	75	4.3	?

**Specific baseflow was assessed by Kille and hydrograph separation methods.*

The main characteristics of the Tikur Woha River and rivers surrounding the Hawasa sheet area are shown in table 7-1. There is an idea that water from the Lake Hawasa is drained to the north supplying Lake Shalla in the form of groundwater inflow in lower topographic positions.

The lakes represent the drainage basin of the area. They represent flooded calderas distinctly separated from the surrounding highlands and even the rift floor by steep mountain slopes. The maximum depth of Lake Hawasa is 20 m. The fluctuation in levels of Lake Hawasa has been measured since October

1969. The specific runoff of 5 l/s/km^2 and baseflow of 1.0 l/s.km^2 was adopted for the floor of the Rift Valley Lakes basin.

7.1. Elements of the Hydrogeological System of the Area

The qualitative division of lithological units is based on the hydrogeological characteristics of various rock types using water point inventory data from the Hawasa map sheet and from the surrounding area. The lithological units were divided into groups with dominant porous and fissured permeability and mixed permeability. This division served for a definition of the aquifer/aquiclude system of the Hawasa map sheet. Since quantitative data such as permeability, aquifer thickness and yield are not adequate or evenly distributed enough to make a detailed quantitative potential classification; analogy was used for characterization of rocks without the adequate number of water points. The hydrogeological map shows aquifers and aquicludes defined based on the character of the groundwater flow (pores, fissures), the yield of springs and the hydraulic characteristics of boreholes. The following aquifers/aquicludes were defined:

1. Extensive and moderately productive or locally developed and highly productive porous aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5 l/s). The aquifers consist of Quaternary lacustrine and fluvial sediments. The aquifers are shown in light blue.
2. Extensive and moderately productive fissured aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with Q = 0.51–5 l/s). The aquifers consist of ignimbrite – Hawasa rhyolite ignimbrite and Hawasa basalt, tuff and scoria cones. The aquifers are shown in light green.
3. Extensive and moderately or locally developed and highly productive mixed porous and fissured aquifers (T = 1.1–10 m^2/d, q = 0.011–0.1 l/s.m, with spring and well yield Q = 0.51–5 l/s). The aquifers consist of sequences of sedimentary, coherent volcanic rocks, pyroclastic rocks of the post-caldera Central volcanic complexes, and pumiceous pyroclastics related to the Corbetti ignimbrites. The aquifers are shown in light green and light blue horizontal hatching.
4. Formation consisting of a minor fissured aquifer with local and limited groundwater resources – Aquiclude. The formation consists of the obsidian and pith stone. The rocks are shown on the hydrogeological map in light brown.

7.1.1. EXTENSIVE AND MODERATELY PRODUCTIVE POROUS AQUIFERS

Porous aquifers, where groundwater is accumulated in and flows through pores of an unconsolidated or semi-consolidated material. Porous materials of Quaternary age are represented mainly by lacustrine sediments of Lake Hawasa with subordinate fluvial, colluvial and eluvial sediments developed in depressions of Lake Shallo (Chaleleka) and/or along valleys of former and existing rivers or by pumiceous pyroclystic and unwelded tuff materials erupted from quaternary volcanic centers. The porous aquifers are widely developed over the study area. The rocks with porous permeability forming aquifers are expressed on the hydrogeological map in blue.

A porous aquifer on the shore of Lake Hawasa is large and thick and its groundwater is developed by a large number of drilled wells in Hawasa town and drilled and dug wells on the western shore of the lake. The porous aquifer is a very good source of groundwater depending on the thickness, sorting and recharge conditions. Lacustrine sediments are mainly recharged by direct infiltration by percolating rain water, but can be also recharged by bank infiltration during floods with high levels of water in river channels as well as high levels of water in lakes. Deep regional groundwater flow can also recharge lacustrine sediments of Lake Hawasa by lateral flows from the western and possibly eastern escarpments.

Volcano-sedimentary rocks are developed in shallow depressions of the Corbetti volcanic complex and are generally represented by volcanoclastic strata associated with volcanic eruptions, which have the characteristics of sedimentary materials. These are dominated by clastic sediments of a volcanic origin intermixed with lacustrine and fluvial units and tuff materials. Moderate yields may be found locally where the aquifer provides important local supplies.

The yield of boreholes drilled to the aquifer varies from 1 to 5 l/s. The average thickness of the aquifer is about 50 m but we can say that the thickness varies from 40 m to more than 200 m. Basic statistics of yield of water points from lacustrine sediments of the Hawasa subsheet and its surroundings are given in table 7-2.

Table 7-2. *Basic statistics of yield of water points from porous aquifers in l/s*

Number of data	Max	Min	Median	Average
90	75	0.029	2.5	4.61

Drilled wells in this aquifer around Lake Hawasa were observed to strike groundwater at a depth of 10–80 m with discharge of 1.5 to 22 l/s for the wells. There are also many shallow wells and dug wells taping the shallow groundwater, particularly on the western shore of the lake, despite the fact that most of the shallow wells have a high content of fluoride and relatively high value of TDS.

7.1.2. EXTENSIVE AND MODERATELY PRODUCTIVE FISSURED AQUIFERS

Fissured aquifers are aquifers where groundwater accumulates in and flows through the weathered and fractured parts of volcanic rocks. The porosity of lava flows may be high but the permeability is largely a function of a combination of the primary (pores) and secondary structures (joints and fissures) within the rock. In addition, the permeability of lava flows tends to decrease with geological time. The pyroclastic rocks between lava flows are generally porous but usually less permeable due to poor sorting. They can be represented by impermeable unwelded tuff in some parts of the volcanic sequence. Hence, extensive volcanic ash beds may form semi-horizontal barriers to water movement (infiltration) resulting in lower productivity of basaltic units located at greater depth. Layers of paleosoil of various thicknesses in between lava flows are also less permeable and usually consist of clay material on the one hand, whereas layers of fluvial and lake sediments and pumiceous pyroclastic materials between various lava flows can enhance well yield on the other hand.

Quaternary volcanic rocks are represented by Hawasa ignimbrites of the Dino Formation and Pleistocene Hawasa basalts which are intensively jointed and faulted form aquifers with good fissured porosity. The units with fissured permeability forming moderately productive aquifers are expressed on the hydrogeological map in light green.

Ignimbrites are usually interbedded with tuff, pumice and lacustrine or alluvial deposits. Groundwater flows through joints, fractures and pores of non-welded layers and interbedded sediments, however fissure flow is adominant hydrogeological characteristic of these rocks. Open faults and fault systems may also provide significant groundwater flow paths, which may allow regional transfer of groundwater where they are extensive.

Outcrops of ignimbrite are mostly well jointed providing a good possibility for direct infiltration as well as indirectly by overlaying mixed aquifers within the Corbetti complex. The continuity of fractures in both horizontal and vertical planes provides the aquifers their hydraulic continuity with adjacent units and aquifers. Yields from both boreholes and springs may vary widely. The basic statistics of yield of water points of the Hawasa sheet and its surroundings area are shown in table 7-3.

Table 7-3. Basic statistics of yield of water points from fissured aquifers in l/s

Number of data	Max	Min	Median	Average
190	70	0.035	3	4.67

Wells developing groundwater from fissured aquifers located on the map have a yield of about 5 l/s documenting the moderate productivity of the aquifer. The groundwater level is about 20 to 60 m below the surface in the eastern part of the sheet. The level of groundwater is between 150 and 300 m below the surface in the elevated western part of the sheet, but can vary significantly based on the topographical position of the drilled wells. The yield of wells in the western part is about 3 l/s.

7.1.3. EXTENSIVE AND MODERATELY PRODUCTIVE MIXED POROUS AND FISSURED AQUIFERS

Volcanic rocks are often mixed with sediments accumulated in between lava flows and or volcanic episodes in rivers and lakes. The rocks are also intercalated with relatively thick layers of unwelded tuffs, ash-flows and pumiceous pyroclastic material. These intercalated porous materials do not act as independent aquifers but they form a mixed fissured and porous multilayered aquifer together with the volcanic rocks. Porous materials can significantly contribute to the safe yield of wells when they are developed together with volcanic rocks. The permeable porous sediments in between lava flows form a body that can accumulate large volumes of groundwater by draining the surrounding fissured aquifers and contribute to the yields of wells developing groundwater from this mixed aquifer, which is more productive than fresh basalt, ignimbrite, trachyte and rhyolite that are normally considered as rocks with moderate and/or low permeability.

Quaternary volcanic rock is represented by ignimbrite, coherent peralkaline silicic volcanic rocks (trachyte, rhyolite), resedimented pyroclastics, lacustrine beds, unwelded tuff, and ash-flow deposits form aquifers with well-mixed porous and fissured porosity. The units with mixed permeability forming moderately productive aquifers are expressed on the hydrogeological map in light green and light blue horizontal hatching.

The mixed aquifers are exposed in the northern part of map sheet where they form eastern to north-eastern gently sloping plains of the rift floor and the highest mountains in the large Corbetti complex.

The aquifers are recharged directly by percolating rain water as well as indirectly by overlaying porous aquifers within the Corbetti complex. The presence of tuff and sediment at the top of the ignimbrite means that recharge into this group of rocks is also limited. The aquifers show both watertable and confined aquifer systems. The basic statistics of yield of water points of the Hawasa subsheet and its surroundings area are shown in table 7-4.

Table 7-4. Basic statistics of yield of water points from mixed aquifers in l/s

Number of data	Max	Min	Median	Average
132	78	0.01	2	4.84

Wells developing groundwater from mixed aquifers located on the map have a yield of between 2.2 to 5.5 l/s documenting moderate productivity of the aquifer. The groundwater level is about 20 to 50 m below the surface in the eastern part of the sheet. The level of groundwater is between 150 and 300 m below the surface in the elevated western part of the sheet, but can vary significantly based on the topographical position of the drilled well.

7.1.4. FORMATION CONSISTING OF A MINOR FISSURED AQUIFER - AQUICLUDE

Volcanic rocks with local and limited groundwater resources – Aquicludes are units where groundwater is neither stored nor transmitted through the rock. Groundwater development for limited individual water supply is very difficult and even impossible in places. These are groundwater resources with poor or no exploitation potential and are represented by obsidian and pitch stone of the Corbetti complex. The units with limited groundwater resources are expressed on the hydrogeological map in light brown.

7.2. Hydrogeological Conceptual Model

The general concept of infiltration and groundwater circulation on the Hawasa map sheet on the rift floor should also consider the relevant parts of the highlands and escarpment areas.

The eastern plateau area is covered with various volcanic rocks forming a gently undulating plain that receives adequate rainfall and has moderate runoff resulting in good infiltration and the formation of extensive and moderately productive or locally developed and highly productive fissured and mixed aquifers. Infiltration is particularly good in areas where the plateau (out of the subsheet) is covered by thick elluvial cover. Aquifers outcropping in the plateau area also feed deeper fissured aquifers developed in underlying volcanic and sedimentary rocks. The escarpment area is relatively steep for infiltration; however, some of its parts provide a good opportunity for water to percolate underground and feed the aquifers. The groundwater flow system and direction in the escarpment area are mainly controlled by its faults. There are also some faults which seem to act as barriers to flow.

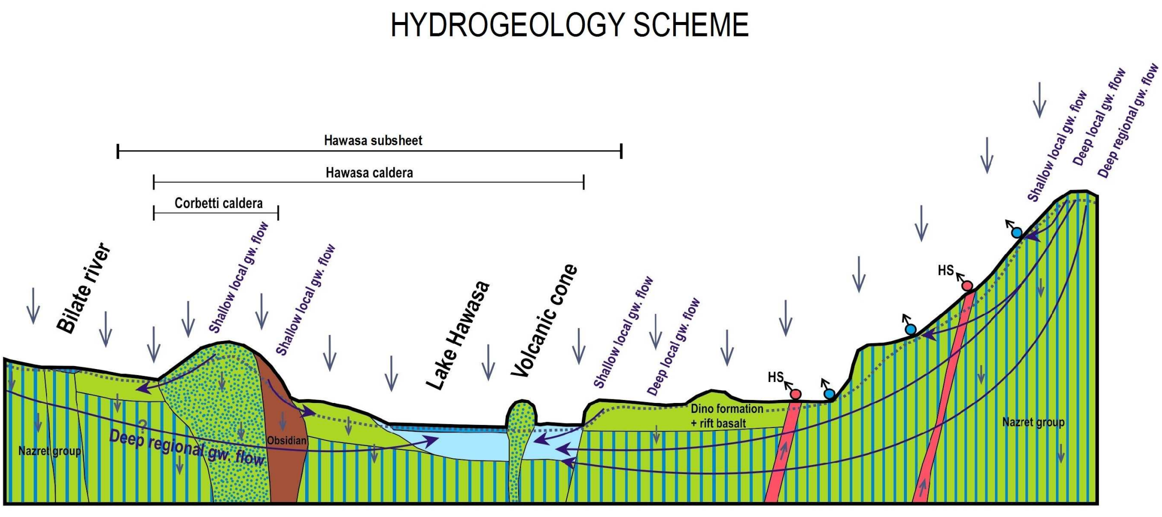

Figure 7-2. *Conceptual hydrogeological model of the Hawasa area.*

Springs at the foothills of the escarpment are large (there are even hot springs at Wondo Genet on the Shashemen sheet) representing deep local groundwater flow; however, they can also be fed by part of the deep regional groundwater flow. Hot springs in Ziway, Langano, Shalla and Hawasa areas represent deep regional groundwater flow. Groundwater flowing from the eastern and possibly also western escarpments feeds the volcanic and sedimentary rocks of the rift bottom (shown by long arrows on the hydrogeological map). Local ridges on the rift floor generate shallow local groundwater flow and form local groundwater divides which conform to the surface water divides (shown by short arrows on the hydrogeological map). This shallow local as well as deep groundwater flow recharges the lacustrine sediments of lakes which form the regional drainage on the map sheet and the Rift Valley Lakes basin. It is also possible that the lacustrine sediments are recharged from rivers and lakes when the water level in the rivers and lakes is higher than the surrounding groundwater level in the aquifers. A conceptual hydrogeological model is shown in figure 7-2.

The principles of the general conceptual model of the Hawasa sheet are based on the main mechanisms of recharge as well as discharge as follows:

- direct recharge to outcropping aquifers
- vertical recharge from overlying aquifers into underlying aquifers
- horizontal recharge from neighbouring aquifers, rivers and lakes
- direct discharge by springs from outcropping aquifers (cold and hot springs at the foot of the escarpment and the rift floor)
- direct discharge to rivers and lakes
- indirect discharge from one aquifer to another (vertical as well as horizontal)

Groundwater is under watertable conditions; however, artesian conditions are also known from the mixed volcano sedimentary aquifers of the plateau, escarpment and rift floor.

Groundwater flow is in general parallel with the surface water flow system and is from the highlands through the escarpment to the rift floor. On the rift floor itself, the groundwater flow direction is governed by the relative elevations between the individual sub-basins.

Groundwater (drilled and dug wells) remains the main source of water supply for towns and villages within the Hawasa sheet. Halcrow (2008) estimates groundwater makes up 92 % of the water supply.

7.2.1. ANNUAL RECHARGE IN THE AREA

There is a large volume of data from different reports about the assessment of recharge; however, these data vary significantly. The regional mechanism of recharge of aquifers in the area has been described above. As is the case in other areas, the groundwater is recharged from precipitation depending on its intensity and annual distribution, topographical gradient of the area, as well as the lithological composition (particularly in the vertical profile) of outcropping rocks and their tectonic disturbance. A substantial part of the groundwater is recharged from direct precipitation. There is also a seasonal but less significant amount of recharge to localized aquifers from the permanent as well as intermittent streams and lakes after rains when the level of water in rivers and lakes is above the groundwater level in the surrounding aquifers.

Tesfaye (1993) characterized recharge to be less than 150 mm in the highlands and between 70 to 100 mm in the rift basin based on baseflow data of Katar and Meki rivers. Recharge based on rainfall infiltration according to the rainfall infiltration factor (RIF) was defined by WWDST (2003) to be about 6 % for alluvium and basaltic rocks if the slope of the terrain is less than 20 %.

Tadesse and Zenaw (2003) assessed recharge for the Hawasa basin to be about 5 % of the rainfall (67 Mm^3/year). WABCO (1990) in Water Resources Development Master Plan for Ethiopia refers to 5 % recharge to the aquifers in RVLB representing about 57 mm of annual recharge.

Taking into consideration the adopted average baseflow values for the rivers in the highlands and the rift floor, the recharge is about 200 mm and 50 mm. Compared to the adopted average depth of precipitation of 1,100 mm the calculated infiltration (recharge) can be assessed as being 18 or 5 % of the precipitation depth.

7.2.2. HYDROCHEMISTRY

A study of the groundwater quality was carried out on the different aquifers (geological formations) of the area. The results of the hydrochemical study can help to understand the groundwater circulation within the aquifers in addition to comparing the water quality with various standards. A total of 35 water samples from boreholes and dug wells were analyzed for chemical composition. One sample was taken from Lake Hawasa. The analytical results were presented graphically on a hydrochemical diagram (inset map) to facilitate visualization of the water chemistry, TDS and fluoride content. Suitability of groundwater for drinking, industrial and agricultural purposes is assessed based on the pertinent quality standards.

CLASSIFICATION OF NATURAL WATERS

Hydrochemical types are classified based on the Meq% representation of the main cations and anions. Basic hydrochemical type is the only type in the area and its content of the main cation and anion is higher than 50 Meq%. This chemical type is expressed on the hydrochemical diagram by a solid colour.

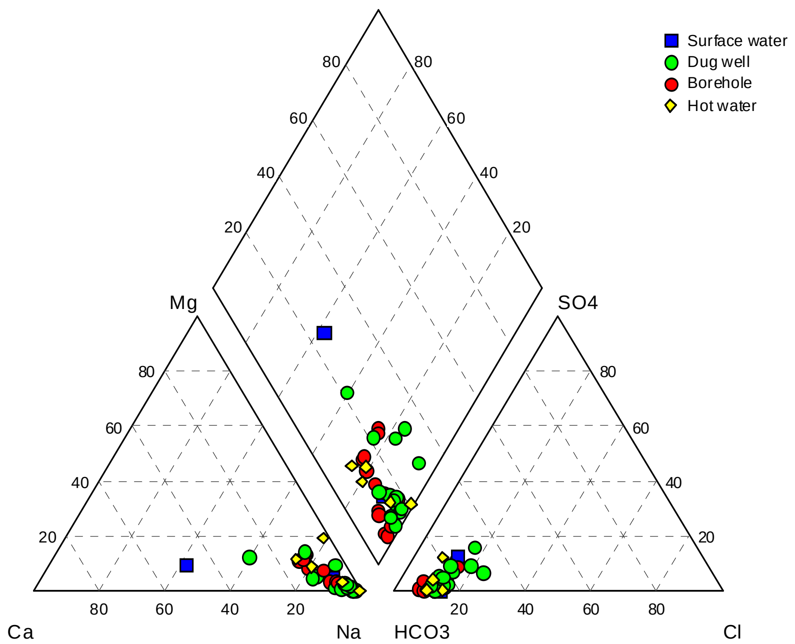

Figure 7-3. *Piper diagram for classification of natural waters.*

The only hydrochemical type of groundwater in the study area is sodium-bicarbonate. The type of groundwater within the Rift Valley Lake basin depends on the morphological position of the aquifer if it is located on the plateau (Ca-HCO_3 basic and transient), escarpment (Na-HCO_3 transient and basic) and/or rift floor (Na-HCO_3 basic). Groundwater residence time along flow paths, length of water-rock interaction, lithology, ionic exchange, and evaporation may play a significant role in the increment of groundwater composition. The contact of water and hot rocks, including groundwater enrichment by carbon dioxide is believed to form the sodium bicarbonate groundwater chemistry of the majority of the groundwater on the rift valley bottom. An important interaction is the leaching of fluoride from acid volcanic rocks, mainly from obsidian and rhyolitic pumice. The chemistry of groundwater in the Hawasa area reflects it position on the rift floor.

Medium groundwater TDS (between 800 and 1,000 mg/l) in the plain areas of the rift floor outside of the Lake Hawasa basin indicate the slow hydrogeological regime of the area receiving a relatively high volume of precipitation where groundwater flows in young fractured volcanic rocks. High TDS (between 1,000 and 1,700 mg/l) as well as high content of fluoride (between 3.4 and 16.7 mg/l) inside the Lake Hawasa basin also indicate a slow hydrogeological regime in the drainage area where the groundwater flows mainly in porous aquifers hosted by lacustrine sediments.

The water of Lake Hawasa is also Na-HCO3 type but has lower TDS (651 mg/l) than groundwater in the lacustrine sediments.

To facilitate the visualization of the classification of water types, the percentage of the major cations and anions of the analyzed samples is plotted on the Piper diagram shown in figure 7-3.

WATER QUALITY

Water quality of the mapped area was assessed from the point of view of drinking, agriculture and industrial use.

To assess the suitability of water for drinking purposes, the results of the chemical analyses were compared with the Ethiopian standards for drinking water published in the Negarit Gazeta No. 12/1990 and the Guidelines of Ministry of Water Resources (MoWR, 2002).

Results of chemical analyses show that groundwater of the Hawasa area is not convenient for drinking because of high TDS and fluoride content, which can exceed the maximum permissible level (1.5 mg/l) in porous aquifers hosted by lacustrine sediments pertinent to the Lake Hawasa basin. Groundwater is of good quality in the rest of the area in aquifers hosted by volcanic rocks. The content of nitrates above 20 mg/l in two samples shows that shallow groundwater can be polluted by human activities.

Water of Lake Hawasa can be used for drinking and cattle watering, agriculture and industry after appropriate treatment because its content of fluoride is high (6 mg/l).

Agricultural standards for the quality of groundwater used for irrigation purposes are determined based on the Sodium Adsorption Ratio (SAR), total dissolved solids and United States Salinity Criteria (USSC). The Sodium Adsorption Ratio (SAR) is good to fair for irrigation with moderate salinity. There is no limit to the use of groundwater for livestock watering.

Groundwater is not suitable for direct use in most industries without the appropriate treatment.

7.3. Thermal Water

Thermal water is very common in the rift valley. Hot springs are known in the east of the Hawasa subsheet in the Wondo Genet area and Shallo (Cheleleka) area as well as in the north of the Hawasa subsheet on the shores of Lake Shalla. Hot water in drilled wells is known on the western shore of Lake Hawasa along the main road to Shashemene and near the Corbetti volcanic complex as well as from Alaba-Kulito to the west of Corbetti.

The temperature of water in Lake Hawasa (figure 7-4) shows a difference between the southern and northern part. The water is warmer on the southern shore of the lake than in the north despite the fact that the northern shore is located near the Corbetti volcanic centre with high geothermal potential. This fact supports other hydrogeological indications that the lake recharges aquifers through its northern shore. Recharged groundwater flows through aquifers in a northerly direction through the Corbetti geothermal field and is discharged in the form of hot springs on the shores of lakes Shalla and Chitu. The warmer water in the southern part of the lake originates from hot springs in the Qraha Quhe area and other hidden inlets of hot water through aquifers developed in lacustrine sediments on the southern shore of the lake.

There are no hot springs and only fumarole activity is associated with the Corbetti volcanic centre. UNDP (1971) inventoried features consisting of fumaroles and hot ground on west side between Chabi and Urgi massifs, just north of Urgi, south of Adicho Amelo village, and Demo Argo cone at Chabi.

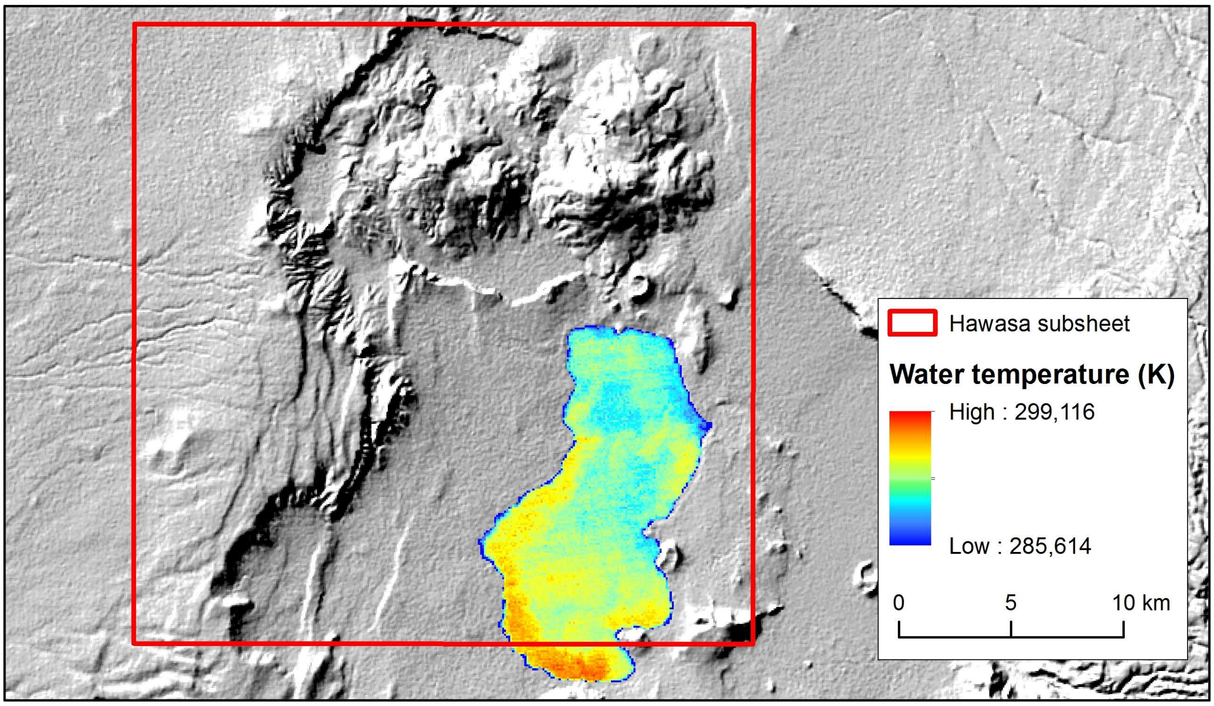

Figure 7-4. *Satellite (ASTER) data on lake surface temperature at night. Hawasa subsheet limits in red.*

7.4. Water Resources

Water resources of the area depend mainly on rainfall and other climatic characteristics, as well as the hydrological, geological and topographical settings of the study area. As part of an integrated water resource and development program the use of surface and groundwater must be dealt with keen interest in addressing the acute problems of adequate and safe water supply schemes in the study area.

The long-term mean annual rainfall of the area has been assessed to be about 1,000 mm/year. For further calculations, the area of subsheet is 720 km^2 and the value of specific surface runoff is 5 l/s.km^2 and specific baseflow is 1.0 l/s.km^2 for the aquifers of the Hawasa sheet. The assessed water resources of the Hawasa area are shown in table 7-4. There are good water resources to be used for irrigation, as well as for drinking water supply of people living within the area.

The total water resources of the area have been assessed to be 114 Mm^3/year. The surface water of Tikur Woha and Lake Hawasa should be primarily used for irrigation; construction of irrigation dams in intermittent rivers of the western part of the sheet can support agricultural production. The irrigation plans, including assessment of irrigation potential and environmental impacts are discussed in detail by Halcrow (2008) for the Rift Valley Lakes basin.

Table 7-4. *Assessment of water resources of the Hawasa area.*

	Input	Area [km^2]	Resources total	Remark
Precipitation	1,000 mm	720	720 Mm^3/year	
Total water resources – map	5 l/s.km^2	720	114 Mm^3/year	16 % rainfall
Renewable groundwater resources aquifers	1.0 l/s.km^2	720	22 Mm^3/year	3 % rainfall

The river gauge measurements show that nearly 16 % of precipitation is drained as total runoff from the area and about 3 % of precipitation infiltrates and appears as baseflow. There are good groundwater resources to be used for the supply of drinking water to people living within the area; however treatment of water (de-fluorization) is necessary because of high fluoride content in groundwater. There is also the potential to use groundwater of the area to support irrigation. The total volume of renewable groundwater resources of active aquifers in the area has been assessed to be 22 Mm^3/year.

Most of the people within the area live in Hawasa town and in small towns and villages in the western part of the sheet, which are supplied from drilled and dug wells. Additional to further development of dug wells the water supply based on drilled wells represents the most sanitary secure water and should be applied for Hawasa and small towns as well as for rural inhabitants.

To select appropriate areas, data from regional as well as detailed surveys have been evaluated, and a strategy was chosen which consists in siting the hydrogeological wells for supplying the population on the following basis:

1. Groundwater accumulated in the volcaniclastic and volcano-sedimentary deposits contains increased concentrations of TDS as well as fluoride, which highly exceed standards for potable water.
2. Volcanic rocks like basalts and ignimbrites contain groundwater, the quality of which mostly corresponds with the standards for potable water.
3. The yields of the wells, which penetrate volcanic rocks (fissured and mixture aquifers), fluctuate between 2 and 10 l/s, and they are sufficient for the supply of as many as 8,000 to 40,000 inhabitants, the consumption of per person being 20 l/day.

The strategy for the layout of the wells, resulting from the above mentioned presumptions, is as follows:

1. To prefer the location of the boreholes on the outcrops of dark rocks (basalt, trachyte, rhyolite and ignimbrite).
2. If there are only light-colour volcanic-sedimentary rocks, to perform a geophysical survey to determinate the boundary line between these rocks and the underlying volcanic rocks.
3. To locate the open section of the well in the fissured part of the volcanic rocks.
4. To obdurate the overlying volcanic-sedimentary rocks in the boreholes by a cement seal to avoid fast penetration of the water from these rocks along the stem of the well.

Table 7-5. *Proposed sites for drilling of water supply wells.*

Site No.	Site	Grid or map reference (UTM)			Site tested by geophysical investigation	Aquifer / lithology
		East (X)	North (Y)	Elevation m a.s.l.		
1	Abaye (farm)	428475	781532	1,740	VES	Porous / polygenetic sediments
2	Shamena Germana	420980	779656	2,040	VES	Fissured / Hawasa ignimbrite
3	Ilu	419153	789059	2,000	VES	Mixed / Corbetti ignimbrite
4	Sinkele and Siraro	419474	796610	1,980	VES	Mixed / Corbetti ignimbrite
5	Korbeti	433806	800394	1,740	VES	Mixed / polygenetic sediments, Corbetti ignimbrite

Remark: VES–Vertical Electrical Sounding

The chosen strategy should be applied in the sedimentary rocks on the eastern as well as western shore of Lake Hawasa, where ignimbrite and basalt ridges can be found within lacustrine sediments. It is assumed that the borehole, drilled in accordance with the above proposal, will have sufficient yield and that the water will not contain an excessive concentration of fluoride. Other areas for drilling of water wells are in fissured and mixed aquifers of the Hawasa sheet. Table 7-5 documents the location of the sites proposed for drilling of wells. These sites are shown on the hydrogeological map but the exact well setting should be checked by individual geophysical investigations prior to drilling. These drilled wells are proposed in the western part of the area to support drinking water supply for people working in dynamically developing state farms.

The proposed depth of boreholes should be designed based on the optimum cost and yield of individual wells. During the final siting of each well it is necessary to consider that the final depth of the proposed wells is governed by the level of groundwater which is given by the drainage level (surface water level in river or lake) and the surface level of the site selected for well drilling. The drainage level (groundwater level) for each specific site should be derived from the nearby surface water level in the river and should be confronted with the site specific surface level of the drilling site and wells drilled before in the vicinity of the proposed well. Other technical, quantitative and qualitative data for the proposed drilled wells are shown in table 7-6.

Table 7-6. *Technical, quantitative and qualitative data for the proposed drilled wells.*

Site No.	Depth (m)	Drill diam. (mm)	Drill method	SWL (m)	Yield (l/s)	TDS (mg/l)	Temp. (C^o)
1. Abaye (farm)	100	432 / 356	DTH / Rotary	50	2.5	1000	25
2. Shamena Germana	400	432 / 311 / 254	DTH	350	3	500	35
3. Ilu	350	432 / 311 / 254	DTH	300	3	500	35
4. Sinkele and Siraro	330	432 / 311 / 254	DTH	280	4	500	35
5. Korbeti	100	432 / 356	DTH	50	2.5	900	50?

The most difficult question will be supply to rural areas with a widely spread population. This should be done from local centres where water wells will be drilled and connected to places of water use with relatively long distribution pipes. Effectiveness and cost of water supply systems for the rural population should be studied as a site specific problem in the future.

The potential of groundwater resources is not enough for current needs of people living in these areas. There is a chance to use the groundwater of the eastern highlands and escarpment for water supplies of the central part of the rift valley, particularly where there is a problem with water quantity and quality (high TDS and fluoride content).

Deeper wells currently represent a safe type of water supply; however, they have to be protected against pollution from local sources like human and animal waste (sources of pathogens and nitrates) as well as from potential industry (tanneries, textile industry, flower plantations, etc.). The minimum required distance of water supply wells and potential pollution sources should be maintained during water resource development in towns and villages. The same level of interest should also be applied to the development and protection of groundwater resources for rural communities. It should be necessary to start with relatively concentrated communities where the feasibility and impact of developed schemes will be most significant.

In addition to priority in development of groundwater for safe drinking water supply it should be possible to select the most fertile soil nearby human settlements and adequate water resources to be developed for irrigation based on groundwater to increase the stability of food supply in prolonged periods of drought. Development and protection of the water resources of the area and the environment as a whole have a principal importance for the development of the infrastructure with subsequent impacts upon the eradication of poverty (development of irrigated agriculture, maintaining livestock during drought).

8. GEOLOGICAL HAZARDS

8.1. Endogenous hazards

8.1.1. SEISMIC AND TECTONIC HAZARDS

SEISMICITY OF SOUTHERN ETHIOPIA

Southern Ethiopia reveals seismic activity, which combines several types of earthquakes. Shallow seismic swarms are connected with the movement of magma and magma-derived fluids (vapour, CO_2, etc.). The swarms consist of many thousands of weak to moderate earthquakes with magnitudes of less than 5. Another type of earthquake accompanies direct volcanic eruptions as observed several times in history (Gouin, 1979). Strong tectonic earthquakes are believed to be connected with normal movements on faults parallel to the rift valley. However, alternative models are possible as well. Young tectonic movements of various orientations, even non-parallel to the rift, have been observed on the surface. Historical earthquakes are poorly located and cannot be assigned to known faults. The focal mechanisms of historical earthquakes are completely unknown and their hypocentral depths are undetermined too. The seismic exploration of this area is inadequate to define the source zones for seismic hazard assessment. This means that a strong earthquake should be considered possible anywhere in Southern Ethiopia. For this reason, the scope of the sub-chapter was extended from the sub-sheet area to the entire Southern Ethiopia.

There are three reported earthquakes with epicentres fitting to the area of the Hawasa subsheet. The earthquake from September 6th 1944 is likely to have taken place in the south-eastern corner of the subsheet, but the location and even the occurrence of this event is very uncertain. There was, however, a strong earthquake (magnitude 6.3) on July 14th 1960 most likely in the area of the south-western slopes of the Chabi Volcano (Gouin 1979). The USGS earthquake catalogue has been available since 1973, this catalogue contains another earthquake from January 20th 1995 which most likely occurred within the edifice of the Chabi Volcano. Due to the poor coverage of seismic stations in the area, not even the latest event is localized with a precision exceeding ± 50 km. The older earthquakes are localized with a precision of ± 200 km. For this reason, we have not plotted the epicentres of these earthquakes on the map at the scale of 1 : 50,000.

SEISMIC HAZARD ASSESSMENT

Seismic hazard assessment has usually been based on a probabilistic approach in recent studies. Only a few results have been yielded by regional studies for Southern Ethiopia (Kebede and Eck 1997). The most important input data for seismic hazard assessment are: catalogue of historical earthquakes, seismograms of recent earthquakes recorded by seismic stations, paleoseismological observations, seismotectonic data, an attenuation model of seismic wave propagation and a local model of seismic velocities. The probabilistic method consists of three basic steps:

1) Definition of source zones and their parameters. This step has not been performed yet because of the lack of data due to the short history of the records. The most important parameter is maximum magnitude assigned to a given source zone. It is clear that at least in some source zones the maximum magnitude can exceed a value of 7. More accurate estimates are required.

2) Construction of attenuation curves. Southern Ethiopia represents a special geological structure (Rift Valley), which significantly influences attenuation curves. Therefore, standard attenuation curves are of limited use. A large set of recorded seismograms is necessary for construction of regional attenuation curves.

3) Computation of probabilistic seismic hazard curves. The result of the computation is an estimation of the probability of exceeding defined values of seismic acceleration or other characteristics of seismic motion. The resulting probability has to include local conditions. The effect of local conditions is very strong in Southern Ethiopia due to layers of thick sediments in the Rift Valley.

LOCAL AMPLIFICATION OF SEISMIC WAVES

Generally speaking, localities with thick sedimentary layers (characterized by low S-wave velocities) reveal the strongest amplification of seismic motion. These areas are shown on the map. However, many other factors are also important, namely the topography of the surface and of the bottom of the sedimentary layers, types of propagating seismic waves, their azimuth and angle of incidence, frequencies close to eigen-frequencies of the structure model, depths of earthquake hypocenters, propagation effects along the wave path between the source and the site, etc. For this reason, the areas shown on the map should be considered only as the first approximation of the most hazardous areas.

FISSURES

Ground cracks have been documented in various localities of the Ethiopian Rift Valley (Asfaw 1998). Their origin is related to the tectonic opening of cracks within solid rocks in the basement of the rift floor and subsequent subsurface erosion of loose material overlying the bedrock. The potential risk of fissures is associated with the flat surface of the rift floor, where the volcanic bedrock is covered by unconsolidated or poorly consolidated sedimentary successions. On the Hawasa subsheet, fissures are documented in an area west of Lake Hawasa (Jara Dado and Shamena, Muleti village; figures 8-1, 8-2). The fissures generally create ground crack systems parallel to faults related to the Main Ethiopian Rift System, exhibiting a predominantly N-S to NNE-SSW direction. In Shamena, the fissures are bound to a WNW-ESE fault system. The mechanism of formation of the ground cracks is uncertain and the occurrence of fissures is random and unexpected. The conformity of the youngest fault system and fissures indicates a tectonic origin of this phenomenon. The association of ground cracks and vertical displacement along normal faults is known elsewhere in the world (e.g., Holzer 1984, Bell et al. 1992, Carpenter 1993).

Figure 8-1. *N-S oriented fissure system in the Jara Dado area. Photo J. Malík.*

Figure 8-2. *Subsurface erosion pipe associated with ground fissures in the western part of Hawasa Caldera. Photo J. Malík.*

Another hypothesis is aquifer-system compaction and horizontal seepage stresses, which are connected to a decline in the groundwater table (Ayalew et al. 2004). The fissure origin could be also caused by irregular topography (bedrock highs, scarps or buried pediment) at depth such as when compressible deposits overlie bedrocks (Schummann and Poland 1970, Carpenter 1993). The fissure development is accompanied by surface and shallow subsurface processes such as piping (Figure 7-2.), hydrocompaction and changes in the volume of material. This process causes rapid and unexpected subsidence of surface and collapses of fissures side-walls. The occurrence of fissures can be very discreet and in some cases hollows several decimetres deep can develop on the surface. Ground cracks-lines with a width of up to 3 meters are common. Sometimes gravitational collapse of sidewalls and subsidence of blocks is present and the fissure system extends in a range of tens of meters. The visible depth is up to approximately 10 meters. The development of fissures and accompanying processes represents a very dangerous geological hazard resulting in the loss of buildings, infrastructure and agricultural land. These processes can have an impact on areas with high population density and human activity. The destruction of houses and infrastructure as well as loss of human lives and animals are documented in connection of ground fissures development. For this reason the area affected by fissure systems is not suitable for human activities.

8.1.2. VOLCANIC HAZARDS

The Hawasa subsheet area is dominated by two quaternary volcanoes resting within the Corbetti Caldera: Chabi and Wendo Koshe. The magmatic activity beneath the Corbetti Caldera is active as revealed by deformations documented by Biggs et al. (2011). A significant period of deflation was documented during 1997–2000, whereas inflation took place in 2010. These processes might represent emplacement of new magma batches.

Reactivation of basaltic monogenetic volcanism in the Hawasa area is unlikely as the scoria and tuff cones are significantly affected by erosion and weathering and no fumarolic activity is described associated with these cones.

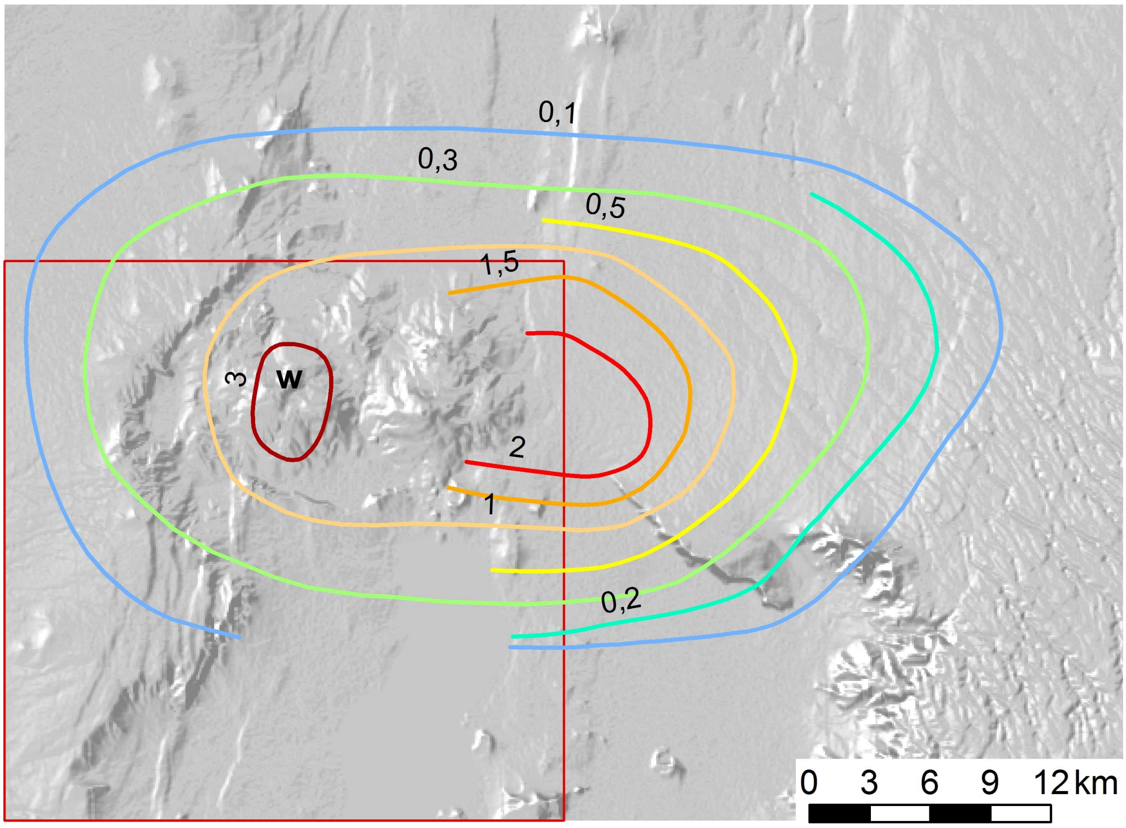

Figure 8-3. *Isopach scheme of the young Wendo Koshe pumice fall deposit (Hawasa subsheet in red; Wendo Koshe crater indicated by “w”).*

EXPLOSIVE ERUPTIONS

According to the geological record, explosive eruptions in the area of the Corbetti Caldera do not happen as frequently as effusive eruptions during the Holocene. The main polygenetic explosive vent remains Wendo Koshe in the central part of the Corbetti Caldera. The time since the last explosive eruption and the frequency of explosive eruptions are not known. Should a new Plinian style eruption take place on the Wendo Koshe Volcano, villages within the Corbetti Caldera north of Wendo Koshe would be destroyed by pyroclastic flows immediately with no time for evacuation. The eruption would also emit a large amount of ash and pumice which would settle in thick accumulations to the north of Hawasa and around Shashemene. The thickness of fall deposits from the last explosive eruption exceeds one meter along the Shashemene-Hawasa road. Systematic monitoring of this volcano is highly recommended to estimate the potential for early warning prior to a major eruption.

An isopach map of the thickness of pumice fall from the last explosive eruption of the Wendo Koshe Volcano is shown in figure 8-3.

EFFUSIVE ERUPTIONS

Compared to explosive eruptions, effusive eruptions were much more frequent during the Holocene. The Chabi Volcano has emitted four large obsidian lava flows since the last big explosive eruption of Wendo Koshe. The area of the Chabi Volcano is not inhabited as the blocky and sharp surface of the obsidian lava cannot be used for agriculture. Obsidian lavas may reach the weakly inhabited zone around Chabi Volcano and destroy grass-houses. Due to high viscosity, obsidian lavas flow relatively slowly and give enough time for evacuation. No casualties are expected from effusive eruptions.

8.2. Exogenous hazards

The area of the Hawasa subsheet is characterized by expressive escarpments in the western part and a flat area representing the main rift floor. Rapid expansion of settlements and the associated needs for agriculture and other human activities have changed the land use abruptly over the last tens of years. By consequence, exogenous geological hazards are becoming an ever more serious problem to the people living in the area. The area is strongly affected by various types of erosion related to loss of land and creation of fissures on the surface of the rift floor.

8.2.1. EROSION-RELATED HAZARDS

SOIL EROSION

Soil erosion is a major cause of land devastation in the Hawasa area. Water is the most important agent of erosion, however wind erosion is sometimes observed. Erosion features are a common feature of the landscape in Southern Ethiopia (e.g. Billi and Dramis 2003). As a natural exogenous process of the landscape it is frequently accelerated by agricultural and related human activities and deforestation and the escarpments to the west of Lake Hawasa are strongly affected by this geological hazard. Weakly compacted alluvial and lacustrine deposits, resedimented volcaniclastics, and other pyroclastic materials, which are easily workable, cover the Hawasa area, the soils can be detached easily by agricultural and livestock activities.

GULLY AND RILL EROSION

Gully and rill erosion is a prominent type of geological hazard in the Hawasa subsheet area. Rapid surface flow and channelling of runoff water is the most common mechanism of the creation of rills and gullies. However, piping as a result of subsurface erosion can be a result of gully growth (e.g., Morgan 1996, Bryan and Jones 1997). Poor vegetated erosional slopes and fault scarps formed by unconsolidated weathered ignimbrites, volcaniclastics or alluvial and lacustrine deposits are vulnerable to rill and gully erosion (figure 8-4) and during heavy precipitation new individual rills and gullies can also form on still unaffected areas. The creation of erosional structures is accompanied by subsequent processes as well as mass flow movement and rapid accumulation of material at the foot of slopes.

Rills are characterized by V-shaped erosional structures in the upper parts of the slope; at the foot of the slope box-shaped structures with vertical side walls are predominant. Locally, the landscape of scarps is characterized by badland morphology (un-vegetated surface dissected by a high density of rills and gullies).

A well-developed gully system is located in the structure (caldera) scarp to the west of the Muleti sub-basin. The depth of gullies ranges up to 20 meters and the documented width is up to 25 meters; however 33 meter wide gullies are reported by Moges and Holden (2008). The length of the gullies ranges from tens of meters to several kilometres. Gully development accompanied by the gravitational collapse of side-walls is also documented. Pipes are also reported by Moges and Holden (2008) in the lowermost parts of the scarp close to the area of Muleti. Locally, badland morphology (high density of rills and gullies in un-vegetated landscape) is developed in the western caldera scarp (e.g., the area around Muleti and Shemena).

Several gullies are also developed in the structure slope with a low gradient in the western part of the sheet. Gullies tens of metres wide and up to 10 meters deep form a drainage system of poorly vegetated landscape towards Bilate river basin. The gully development could also be accompanied by mass-flows and rapid accumulation of material in the foothills.

The erosion and gully development represent a serious problem, they cause degradation and loss of soil and strongly affect the livelihoods of farmers, and the loss human lives and serious injuries are also known. Erosional processes strongly affect the infrastructure; the gullies can cut across roads and reduce accessibility to the area.

SHEET EROSION

Sheet erosion strongly affects the area along the Bilate River. Nevertheless, the area of the Hawasa subsheet remains unaffected by voluminous sheet erosion. Despite the fact that the area is not so affected these days, we must not exclude the possibility of expansion of the sheet erosion from the Bilate river basin to the western part of the subsheet, where ignimbrites producing light sandy soils prone to erosion, occur.

8.2.2. ACCUMULATION-RELATED HAZARDS

HIGH RATES OF SEDIMENTATION

The greatest risk of high rates of sedimentation is in areas with an abrupt decrease in slope gradient, where the water current velocity and competency decrease. This could result in rapid sedimentation of material eroded and transported from upper parts of the scarps during heavy rains. The highest rate of sedimentation corresponds to active alluvial fans, situated in the mouth of gullies, as well as erosional and streams valleys. Sedimentation of material causes problems in agriculture, but Moges and Holden (2008) also describe raised health problems without being specific.

SLOPE DEFORMATION

Slope deformations are not a prominent risk on the Hawasa sheet. Several landslides occur on the main (Hawasa Caldera) scarp. The largest landslide is located near the road from Hawasa to Shamena. The length of the landslide is about 800 meters, and width is 650 meters. This complex polygenetic (block-slide and landslide, Figure 8-6) slope deformation is probably a result of tectonic processes and gravitational collapse. The slope deformation area is located on the observed normal fault. The slope deformation is temporally inactive. The surface has a character of badlands with a high density of erosional rills and gullies. The other slope deformations have a character of shallow seated landslides or areal shaped landslides. These landslides are formed in Lower Pleistocene Hawasa ignimbrites. Younger volcanic deposits seem to be less prone to slope deformations.

Figure 8-4. *Gully erosion in weathered ignimbrites cutting the Hawasa Caldera scarp. Photo J. Malík.*

Figure 8-5. *Gravitational collapse of the valley side-wall. West of Muleti village. Photo J. Malík.*

Figure 8-6. *Polygenetic slope deformation on the caldera scarp strongly affected by tectonics. Photo J. Malík.*

8.3. Hydrological and hydrogeological hazards

Hazards related to water are mainly concentrated to the following episodes: Heavy rainfall causing erosion and floods, increasing depth of rainfall over several consecutive years accompanied by a rise in Lake Hawasa water levels with flooding of the town and use of groundwater and surface water rich in fluoride for drinking purposes.

8.3.1. INUNDATION

Inundation does not represent a serious problem in the area of the Hawasa subsheet as the fluvial system is not very dense and drains small catchments. However, heavy rainfall might cause flash floods in many ephemeral rivers systems and erosional valleys. The endorheic (drainless) depressions related to tectonic subsidence in the SW part of the subsheet can be temporally inundated during heavy rainfall periods.

Water level fluctuation of the Lake Hawasa represents a serious natural hazard for the town of Hawasa. The level of Lake Hawasa has risen since 1970. The cause is not clearly established and whether it is related to tectonic processes, climatic factors or anthropogenic factors.

Ayenew (2009) adds the role of tectonic processes to the lake level rise, which is demonstrated by the disappearance of Lake Debra in the Muleti sub-basin, after the formation of fissures generated by an earthquake in the late 1980s. Draining of the water of Lake Derba to Lake Hawasa could be a possible cause (Gebreegziabher 2004). The role of tectonic processes would be demonstrated by change of lake morphology, unequal changes of coast line (landward progradation of the coast, as well retreat on the opposite side of the lake). However, only minor changes in the shape of the lake have been observed during the last 26 years (figure 8-7). Propagation of minor alluvial fans and deltas on the western bank of the lake could not explain the rise of the water level in the lake. We also do not see a systematic eastward shift of the lake, that would be expected either for the siltation or for the tectonic model.

Zenaw (2003) states that the lake level rise is a result of siltation of Lake Cheleleka (east of the subsheet), which is connected with Lake Hawasa. The surface area of Lake Cheleleka was about 12 km^2 in 1972, but currently it is completely filled by sediments transported from the eastern highlands due to deforestation of this area. Recently sediment load flows directly to Lake Hawasa (Gebreegziabher 2004). The change of the lake level could also be caused by climatic factors. The rise was caused by high rainfall intensity during years 1996, 1997 and 1998, which is 16%, 7% and 12% above average values (Gebreegziabher 2004 – figures 8-8 and 8-9). The total damage caused by the expansion of Lake Hawasa was estimated by Zenaw (2003) to be Birr 43,490,524.

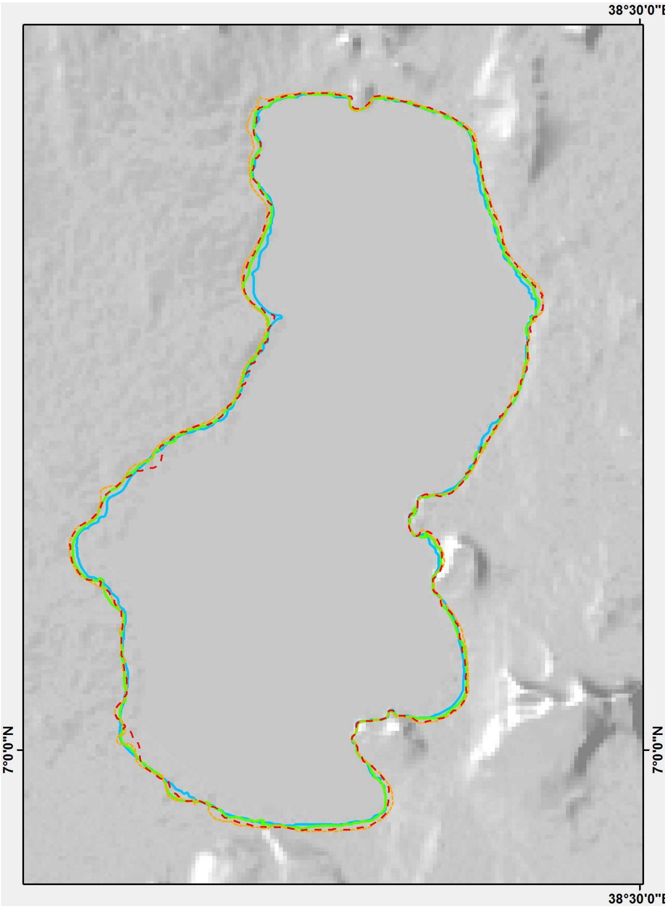

Figure 8-7*. Changes in the outline of Lake Hawasa determined from Landsat images: blue – 1987, green - 1995, yellow – 2000, red – 2011.*

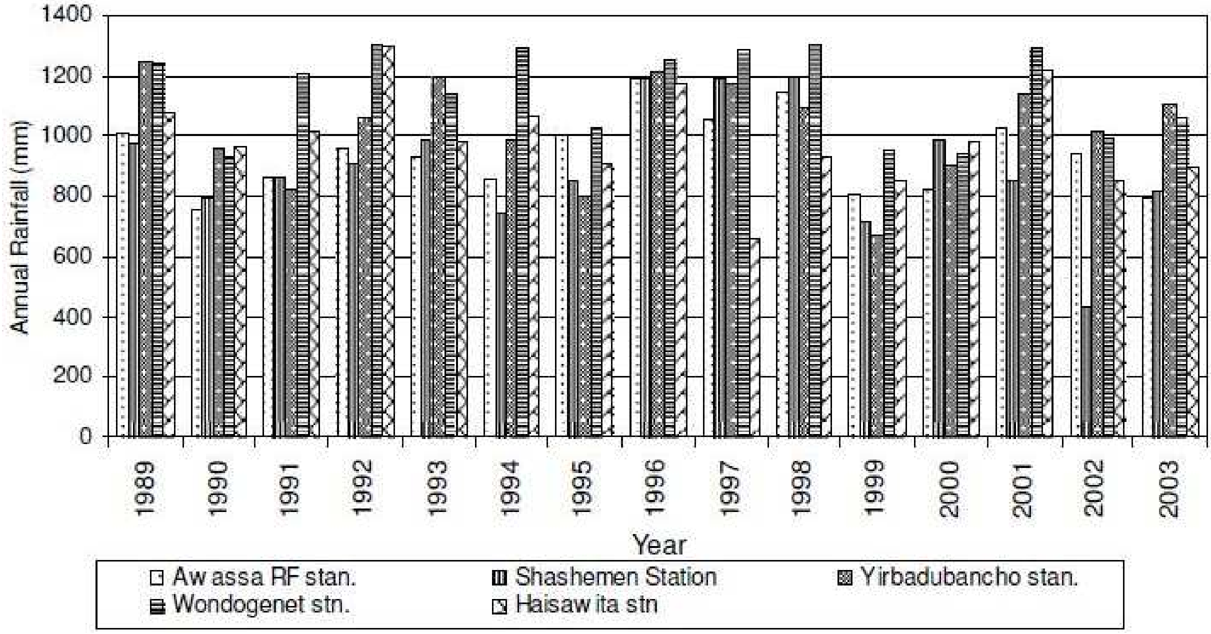

Figure 8-8. *Annual rainfall distributions at different station in Lake Hawasa catchment. (Gebreegzeibher 2004).*

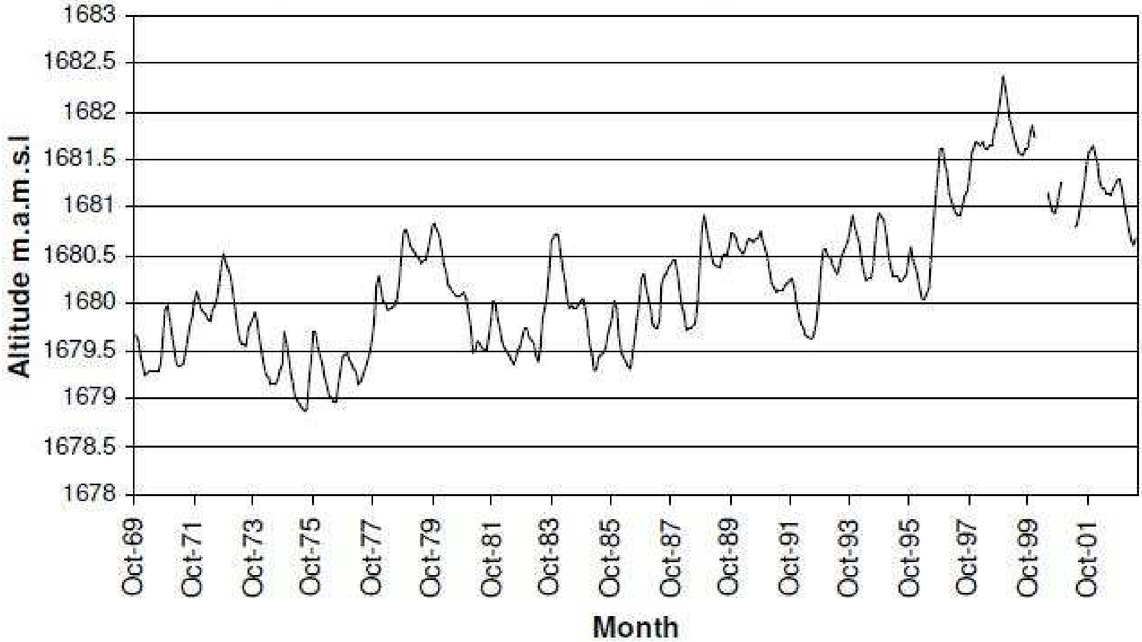

Figure 8-9. *Lake Hawasa level fluctuation from 1969 until 2003 (Gebreegzeibher 2004).*

8.3.2. FLUORIDE

The problem with the **high fluoride content** in the water of the Hawasa area is very well known and is described in many studies. The fluoride concentration frequently exceeds 3 mg/l which will cause mild fluorosis (mottling of teeth). Higher fluoride concentrations in drinking water cause both dental and skeletal fluorosis resulting in serious public health problems. The treatment of fluoride in groundwater, if viable, could resolve a number of pressing water supply problems in the Hawasa area.

Fluoride concentrations are particularly high in areas of occurrence of thermal waters or near areas of recent volcanism (e.g. around the Corbetti Caldera). There is a direct correlation between silicic volcanic rocks such as obsidian, pumiceous tuff and high concentrations of fluoride in groundwater. It is considered that leaching of water soluble Na-fluorides coating pyroclasts is the most likely source of fluoride. The rhyolitic rocks are extremely poor in phosphorus which would lead to fixing of the fluorine in apatite and they lack calcium which would react with fluorine producing non-leachable calcium fluoride. The interaction of the rhyolitic pyroclastic rocks with a large effective surface and percolating groundwater and carbon dioxide at high pH causes the release of fluoride into the groundwater. It is suggested (Rango 2009) that the fluoride concentration in groundwater is inversely related to the concentration of Ca. This permits free mobility of the fluoride ion into groundwater at lower Ca content. This effect (Ca deficiency) is magnified where cation exchange takes place within the sediments (fluvio-lacustrine, volcano-lacustrine) causing the removal of ions from the solution (mainly Ca^{2+}) and replacement with Na^{+} ions from the clay. Such hydrogeochemical processes are responsible for the evolution of Ca (Mg)–HCO_3 types of water of the highlands and the escarpment area to Na–HCO_3 types of groundwater (including the thermal water of the rift floor).

Thermal water tends to have a higher fluoride content than cold water as the water temperatures allow greater dissolution of fluoride. This probably explains the preponderance of high fluoride in waters around Hawasa town. It was also mentioned that the closed terminal lakes attain high fluoride, salinity and alkalinity as a result of evaporation and the groundwater flux that comes through the acidic rocks. High concentrations can also be observed in the north-eastern area of the Bilate River, the surroundings of Lake Hawasa as well as in the lake itself.

It was shown by Tadesse and Zenaw (2003) and by JICA (2012) that fluoride contents decrease with increasing depth of the water source (testing wells). This confirms that the main source of fluoride is related to infiltration of rain water through young deposits of silicic volcanic activity. The concentration of course can be enhanced in geothermal systems. The same is also valid for the concentration of chlorides as well as nitrates. Tadesse and Zenaw (2003) noted that the decrease of fluoride with depth in the Hawasa area indicates that the shallower lacustrine aquifer has a high concentration of fluoride (Figure 8-10).

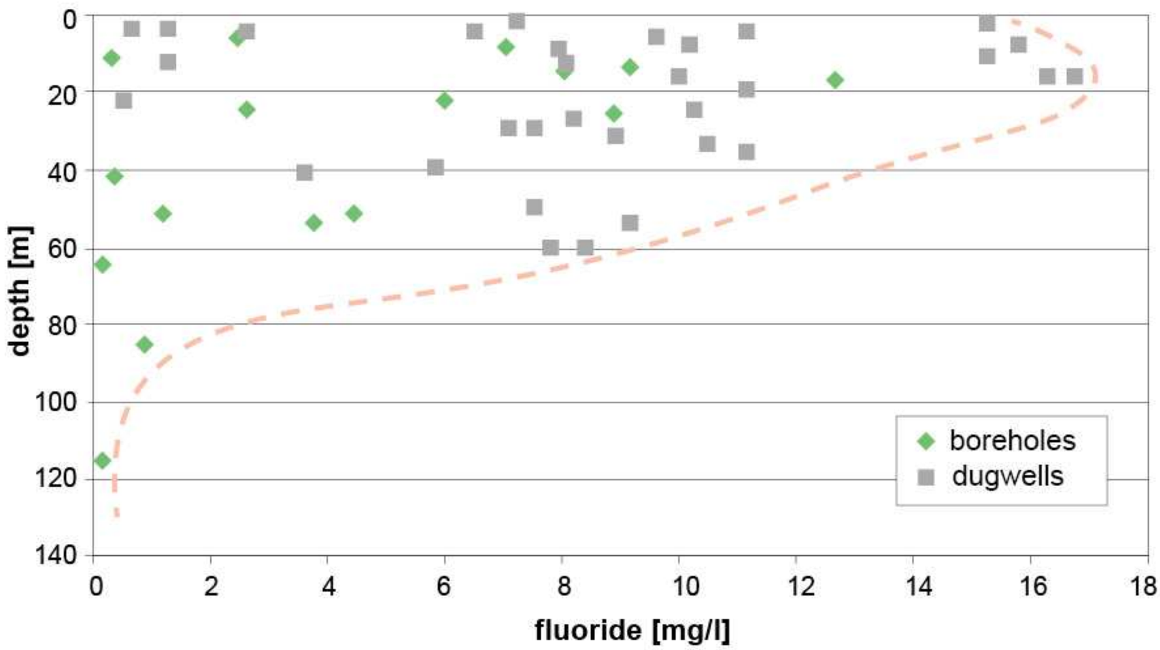

Figure 8-10. *High content of fluoride is caused by its leaching from silicic pyroclastic deposits. A decrease in fluoride content in groundwater with increasing depth is most likely the effect of depletion of older pyroclastic deposits and lacustrine sediments due to higher age and longer leaching of fluoride in the past.*

UNDP (1971) listed the content of fluoride of Chabbi obsidian of 2,500, pumice 440, obsidian 400, rhyolite 300, and ignimbrite 410 ppm. Samples of rocks were collected from the tuff and pumice of the Shashemene area during the field trip of 2012. Partial results of the chemical composition of samples analysed in the laboratory of CGS are shown in table 8-1 as well as the composition of leachate analysed in the laboratory of AQUATEST.

Table 8-1. *Chemical composition of rock samples in wt. % and chemical composition of leachate from these rocks in mg/l. See appendix 1 for details of sample location and lithology.*

Sample	**Rock sample composition**				**Leachate composition**			
	CaO	**Na_2O**	**K_2O**	**F**	**Ca**	**Na**	**K**	**F**
HSRV009	1.18	3.52	4.76	0.209	2.5	32.8	5.28	4.16
HSRVR069D	0.58	4.13	4.19	0.199	4.2	6.42	0.74	1.37
HSRVR069C	0.30	4.05	4.17	0.192	1.1	9.39	0.66	1.89
Sd007	0.28	4.96	4.39	0.218	5.4	4.25	< 0.5	0.74

A number of fluoride removal methods are practiced in basic water treatment plant design. The method of adding gypsum to the artificial sand-pack filter of a borehole and mixing of hot water with cold water was successfully tested in fluoride rich groundwater in Mexico (Carrillo-Rivera, 2002).

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