2 Geology of Ethiopia: A Review and Geomorphological Perspectives

Ernesto Abbate, Piero Bruni, and Mario Sagri

Abstract

The Ethiopian region records about one billion years of geological history. The first event was the closure of the Mozambique ocean between West and East Gondwana with the development of the Ethiopian basement ranging in age from 880 to 550 Ma. This folded and tilted Proterozoic basement underwent intense erosion, which lasted one hundred million years, and destroyed any relief of the Precambrian orogen. Ordovician to Silurian fluviatile sediments and Late Carboniferous to Early Permian glacial deposits were laid down above an Early Paleozoic planation surface. The beginning of the breakup of Gondwana gave rise to the Jurassic flooding of the Horn of Africa with a marine transgression from the Paleotethys and the Indian/Madagascar nascent ocean. After this Jurassic transgression and deposition of Cretaceous continental deposits, the Ethiopian region was an exposed land for a period of about seventy million years during which a new important peneplanation surface developed. Concomitant with the first phase of the rifting of the Afro/Arabian plate, a prolific outpouring of the trap flood basalts took place predominantly during the Oligocene over a peneplained land surface of modest elevation. In the northern Ethiopian plateau, huge Miocene shield volcanoes were superimposed on the flood basalts. Following the end of the Oligocene, the volcanism shifted toward the Afar depression, which was experiencing a progressive stretching, and successively moved between the southern Ethiopian plateau and the Somali plateau in correspondence with the formation of the Main Ethiopian Rift (MER). The detachment of the Danakil block and Arabian subcontinent from the Nubian plate resulted in steep marginal escarpments marked by flexure and elongated sedimentary basins. Additional basins developed in the Afar depression and MER in connection with new phases of stretching. Many of these basins have yielded human remains crucial for reconstructing the first stages of human evolution. A full triple junction was achieved in the Early Pliocene when the MER penetrated into the Afar region, where the Gulf of Aden and the Red Sea rifts were already moving toward a connection via the volcanic ranges of northern Afar. The present-day morphology of Ethiopia is linked to the formation of the Afar depression, MER, and Ethiopian plateaus. These events are linked to the impingement of one or more mantle plumes under the Afro-Arabian plate. The elevated topography of the Ethiopian plateaus is the result of profuse volcanic accumulation and successive uplift. This new highland structure brought about a reorganization of the East Africa river network and a drastic change in the atmospheric circulation.

E. Abbate (✉) · P. Bruni · M. Sagri
Dipartimento di Scienze della Terra, Università di Firenze, Via La Pira 4, 50121 Florence, Italy
e-mail: abbate@unifi.it

P. Billi (ed.), *Landscapes and Landforms of Ethiopia*, World Geomorphological Landscapes,
DOI 10.1007/978-94-017-8026-1_2, © Springer Science+Business Media Dordrecht 2015

Keywords
Paleogeography of Ethiopia • Ethiopian volcanites • Planation surfaces • Ethiopian highlands • Main Ethiopian Rift • Afar depression

2.1 Introduction

The spectacular landscape of the Ethiopian region (Fig. 2.1) with the typical flat-topped mountains (Fig. 2.2) (ambas) and deep-incised valleys has fascinated the European travelers since the sixteenth century when Alvarez (1540) visited the fabulous land of Priest John. This fantastic scenario is the result of geodynamic and geomorphic processes which have shaped this territory since the Oligocene. These processes, which came relatively late in the ca. one-billion-year geological history of East Africa, were triggered by the impingement of a mantle plume or plumes under the Afro-Arabian continental crust. The plume action gave rise to extrusion of huge amounts of magma, uplift, and

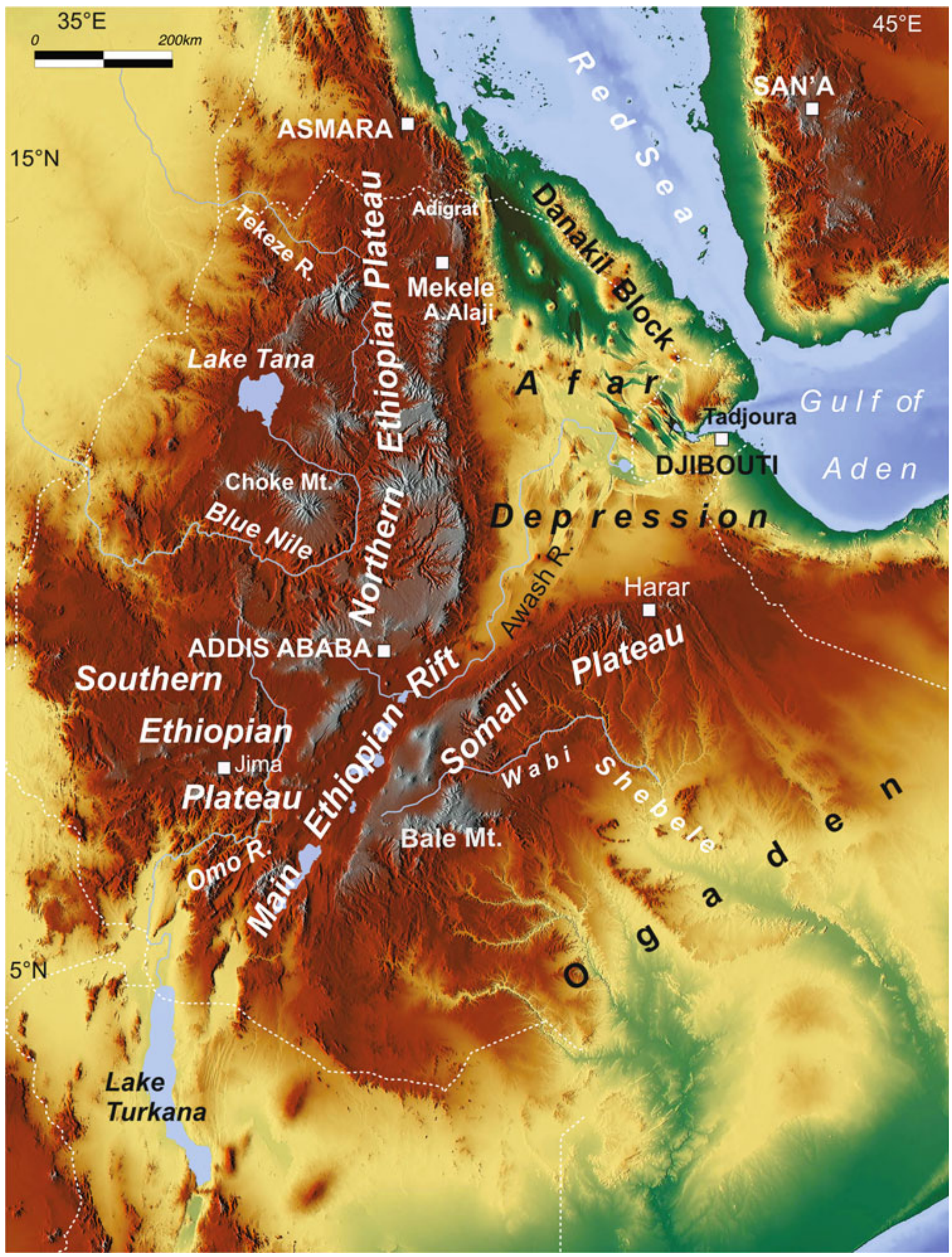

Fig. 2.1 Digital elevation map of Ethiopia (SRTM data) with the main physiographic elements

Fig. 2.2 Flat-topped mountains (*amba*) and deeply incised valleys in the Tigray region (*northern Ethiopia*) exposing Enticho sandstones capped by trap basalts

fragmentation of the continental crust and contributed to the birth of the Red Sea, Gulf of Aden, East Africa Rift valley, and the adjoining Afar depression.

In his evocative book, Mohr (2009) reports the main stages in the geological exploration of East Africa in the nineteenth and early twentieth centuries by outstanding scholars, such as Rüppell (1834), Johnston (1844), Munzinger (1864), Blanford (1870), Baldacci (1891), Dainelli and Marinelli (1912). After these pioneers, Dainelli (1943), in his great synthesis on eastern Africa geology, relied on his own investigations as well as contributions by Stefanini (1933) and Merla and Minucci (1938). Dainelli's three volumes close a research cycle based on a naturalistic approach to the regional geology. After the World War II, researches resumed with a scrupulous re-examination of the available geological data in the light of new investigations by Mohr (1962) and geomorphological contributions by Abul-Haggag (1961) and Merla (1963, and following years) (Fig. 2.3).

In the wake of the plate tectonics theory, eastern Africa has become an invaluable laboratory for understanding passive margin processes, continental fragmentation, and the first stages of oceanization. The Afar region, as a candidate for the formation of a new oceanic crust, has been studied with particular attention using updated analytical methods and facilitated field exploration (e.g., Barberi et al. 1970, 1972; Barberi and Varet 1977; Makris and Rhim 1991). The highland volcanites were investigated from a petrographical, geochemical, and geochronological point of view by Zanettin and Justin-Visentin (1974), Davidson and Rex (1980), Mohr and Zanettin (1988), Woldegabriel et al. (1990), Ebinger et al. (1993), Hofmann et al. (1997), Rochette et al. (1998), Pik et al. (1998), Kieffer et al. (2004), and Beccaluva et al. (2009). The newly collected data made possible the compilation of several geological maps at two million scale very useful for regional syntheses (Mohr 1963; Kazmin 1973; Merla et al. 1973; Tefera et al. 1996).

Information on the sedimentary successions of the Afar and Danakil Alps regions was produced by Vinassa de Regny (1931), Bannert et al. (1970), Tiercelin et al. (1980), Kalb et al. (1982), and Bosworth et al. (2005).

The geology of the Main Ethiopia Rift has been treated, among others, by Mohr (1962), Di Paola (1972), Woldegabriel et al. (1990), Ebinger et al. (1993), Chorowicz et al. (1994), Boccaletti et al. (1998), Le Turdu et al. (1999), Maguire et al. (2006), and Peccerillo et al. (2007). Many of these contributions have been reviewed and summarized by Corti (2009). Specific attention to the sedimentary filling of the Ethiopia Rift has been given by Street (1979), Le Turdu et al. (1999), and Benvenuti et al. (2002).

The possible economic importance of the Proterozoic terranes prompted regional reconnaissance and dedicated surveys (Dainelli 1943; Mohr 1962; Beyth 1972; Kazmin et al. 1978; Kröner 1985; Stern 1994; and Beyth et al. 1997). The Paleozoic to Eocene sedimentary cover of the Proterozoic terranes summarized in the general syntheses by Dainelli (1943) and Mohr (1962) has been thoroughly investigated by Dow et al. (1971), Bosellini et al. (1997, 2001), Hunegnaw et al. (1998), Kumpulainen et al. (2006), and Bussert and Schrank (2007).

The diverse morphology of the Ethiopian region with extended plains dotted by intermittent ponds and lakes, structural corridors along the rift valley surrounded by elevated plateaus, and intense climate changes since the Pliocene has favored human speciation and dispersal toward

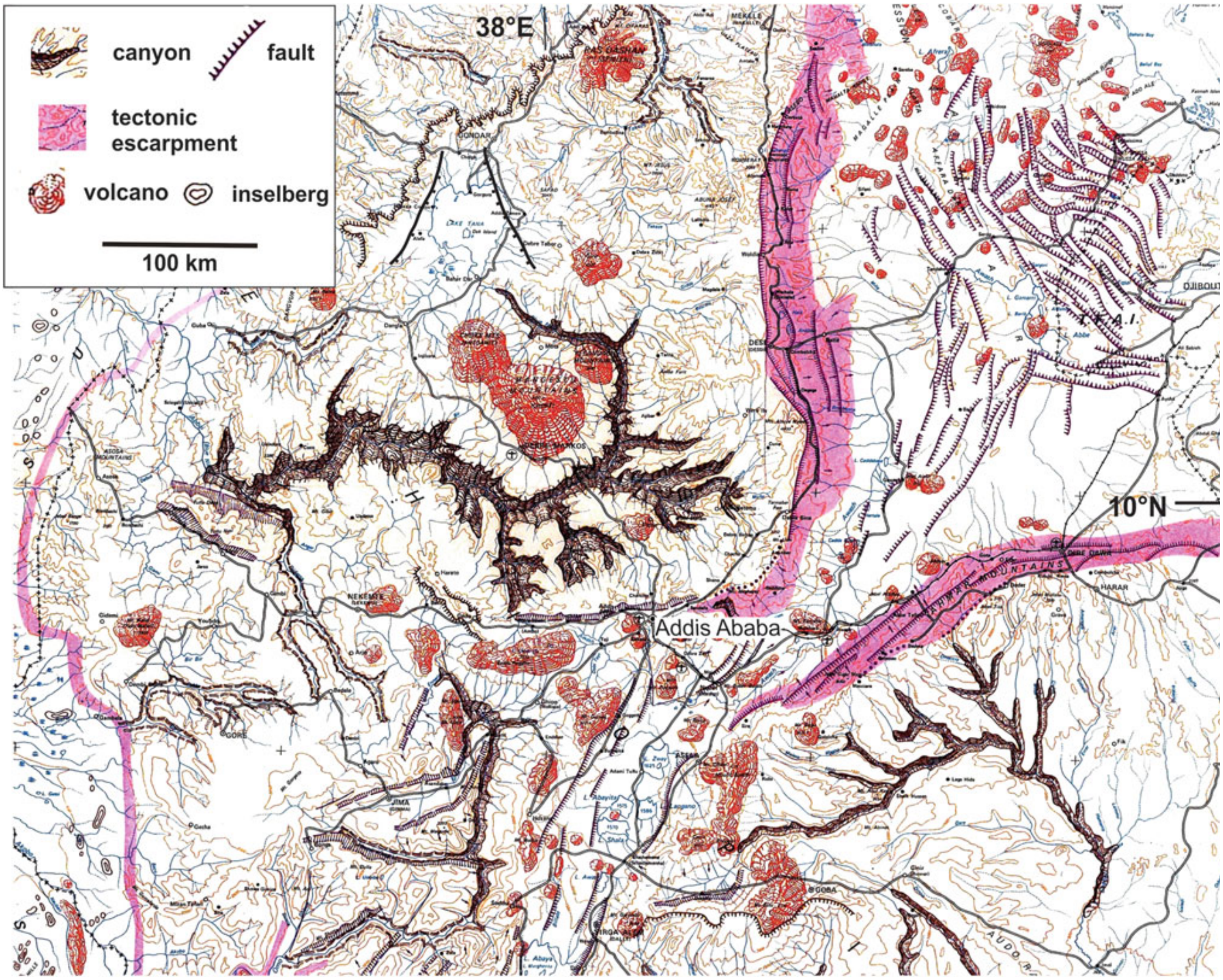

Fig. 2.3 Morphological features of the Blue Nile area, southern Afar depression, Main Ethiopian Rift, and Somali plateau. Excerpt from the "Major landform map of Ethiopia" in Merla et al. (1979), based on a morphological map in Merla (1963)

more suitable territories. The rift valley and Afar sediments contain abundant paleoanthropological evidences and lithic industries connected to these exceptional conditions during the first stages of human evolution. After a few investigations carried out before 1960, a competitive and publicized search for hominid fossils has been carried out in the Omo region since the end of the 1960s (e.g., Chavaillon 1971; Arambourg 1972; Leakey 1974; Walker and Leakey 1978; Johanson and Taieb 1976; Johanson et al. 1976; Lewin 1983), and in the Awash region (e.g., Taieb 1974; Larson 1977; Clark 1985; Kalb 1993; Tiercelin 1986; White and Johanson 1982; Walter 1994). Recent and outstanding results include the discovery of traces of possible human precursors (*Ardipithecus kadabba*, 5.5/5.8 Ma, Haile-Selassie et al. 2009) and ancestors (*A. ramidus*, 4.4 Ma, White et al. 2009) followed by various *Australopithecus* and *Homo* genera (e.g., Haile-Selassie et al. 2007; Johanson and Taieb 1976; Asfaw et al. 2002).

In the following paragraphs, we will summarize and comment on the main sedimentary, volcanic, metamorphic, and structural events recorded in the Ethiopian region. They are related to the continental fragmentation of Gondwana and Afro-Arabian plates and connected basin development, Paleozoic glaciations, and mantle plume activity. The present-day morphology results from their interaction (see chapter 2.7).

2.2 The Closure of the Mozambique Ocean and the Development of the Ethiopian Basement

A Neoproterozoic crystalline basement ranging from 880 to 550 Ma constitutes the crustal backbone of the Ethiopian region with wide exposures in the southern and western Ethiopia and, to a lesser extent, in the northernmost Ethiopia (Fig. 2.4).

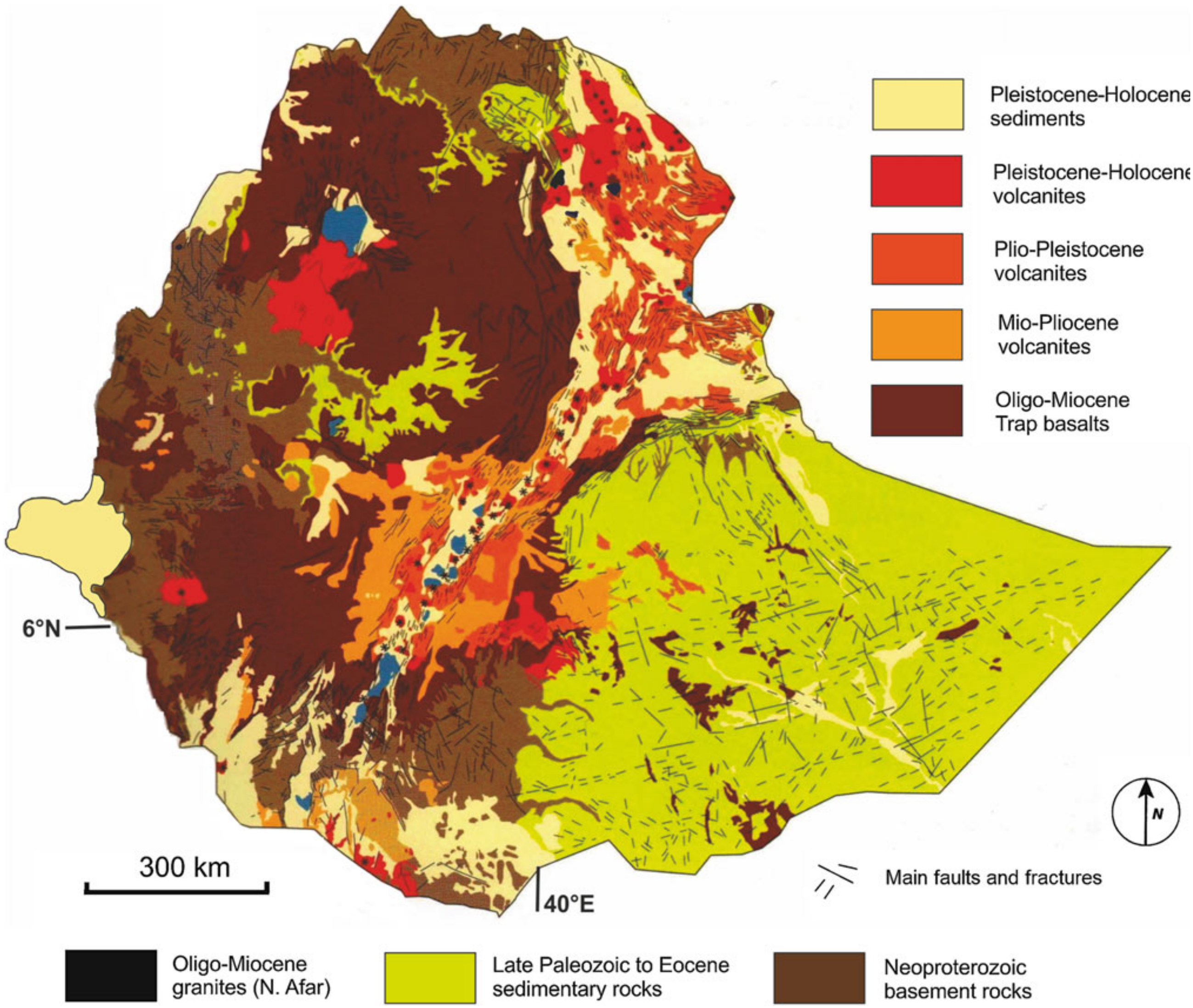

Fig. 2.4 Simplified geological map of Ethiopia modified from Tefera et al. (1996)

The Proterozoic terranes in Ethiopia are related to as the East African Orogen (Stern 1994), a N–S elongated mega-collisional structure stretching from Israel to Madagascar and produced between West and East Gondwana by the closure of the Mozambique ocean (Fig. 2.5). The N–S alignments of the East African Orogen lithic components, sometimes marked by belts of ophiolites, stand out as pronounced present-day morphological expressions. In addition, they influence the trends of the succeeding fragile structures.

In the north, the East African Orogen constitutes the Arabian–Nubian Shield, and in the south the Mozambique Belt. In northern Ethiopia, the Nubian portion of the Shield is prevalent, with dominantly low-grade volcano-sedimentary rocks overlain by metasediments (stromatolitic carbonates and diamictites) associated with "Snowball Earth" (Beyth et al. 2003). In southern Ethiopia, the Mozambique

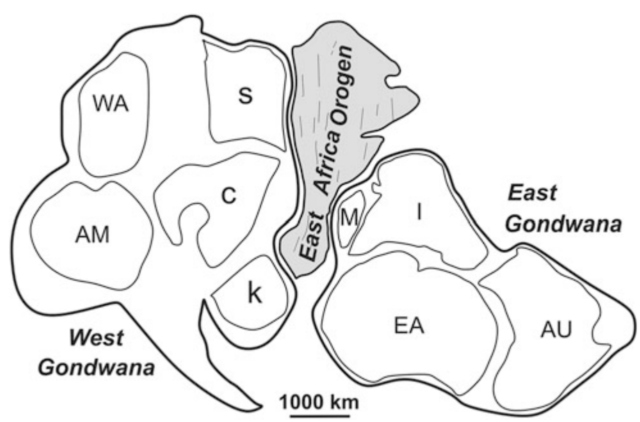

Fig. 2.5 The East Africa Orogen squeezed between West and East Gondwana. *WA* West African craton; *AM* Amazonian craton; *S* Sahara craton; *C* Congo craton; *K* Kalahari craton; *M* Madagascar; *I* India shield; *EA* East Antarctic shield; *AU* Australia craton. Modified from Meert and Lieberman (2008)

Belt exposes abundant amphibolites and granulite facies metamorphic rocks and gneiss terranes.

The tightly folded and tilted Proterozoic basement underwent intense denudation following the Early Paleozoic (first planation surface "PS 1" in Fig. 2.6; for a thorough review of planation surfaces, see Coltorti et al. 2007). Remnants of less erodible rocks, such as granites and gneisses of various age, are now inselbergs in the gently rugged basement landscape, e.g. close to the Ethiopia/Sudan border (Fig. 2.3).

2.3 The Paleozoic Glaciation

The first sediments above the Early Paleozoic planation surface are represented by a few patchy outcrops distributed throughout Ethiopia (Bussert and Schrank 2007) (Fig. 2.6). Detailed studies have been carried out close to the Eritrea/Ethiopia boundary in the Adigrat areas where greater thicknesses up to 500 m are exposed (Dow et al. 1971; Kumpulainen et al. 2006; Bussert and Schrank 2007). According to Bussert and Schrank (2007), Ordovician to Silurian fluviatile sandstones (lower Enticho Sandstone) rest beneath Late Carboniferous to Early Permian glacial fluvio/lacustrine deposits (upper Enticho Sandstone, and Edaga Arbi Glacials). When in contact with the basement, the glacial activity is manifested by striations, roches moutonnées, grooves, and chatter marks. This reconstruction, also supported by petrographic data (Sacchi et al. 2007), could supplant a former hypothesis of an Ordovician/Silurian glaciation (Dow et al. 1971).

Late Paleozoic fluviatile sandstones are also reported in the Blue Nile gorge (Jepson and Athearn 1964; Russo et al. 1994) and near Harar. Many deep oil boreholes in the Ogaden basin have intersected Late Paleozoic sediments of possible glacial to fluvial environment, unconformably resting on the basement and capped by Permian to Triassic continental clastic sediments from lacustrine, deltaic, and fluvial environment. The latter are considered to belong to the Karoo System (Hunegnaw et al. 1998). The glacial and fluvio-glacial deposits were located at the margin of the southern ice sheet of the Pangea (Martini et al. 2001).

2.4 The Jurassic Flooding of the Horn of Africa

Along with the initial breakup of Gondwana, an Early Jurassic regional marine transgression invaded the Horn of Africa from the northeast (Paleotethys) and east (India/Madagascar nascent ocean). The sea covered the NS-trending block-faulted structures connected to the Karoo rift system in southern Ethiopia (Ogaden region), and the NW-trending rift basins linked to the Central Africa shear zone in central Ethiopia (e.g., the Blue Nile rift) (Bosellini 1989; Hunegnaw et al. 1998; Gani et al. 2009) (Fig. 2.7).

The Jurassic marine sedimentation was preceded by deposition of the continental Adigrat Sandstones (Fig. 2.8). These were deposited above the partially peneplained Triassic surface (PS 2 in Fig. 2.6) that developed at the expense of the Permo-Triassic sediments as well as of the basement. The latter was intersected by positive structures and deeply subsiding intracratonic basins which constituted the source areas and accumulation sags for the Adigrat Sandstones, respectively. The Adigrat Sandstones are widespread in Ethiopia and with correlative units in the whole of East Africa and Arabia. In Ethiopia, they commonly rest unconformably on the Paleozoic and basement rocks, but in the some basinal contexts (e.g., in the Ogaden basin, Hunegnaw et al. 1998) are probably conformable with the Permo-Triassic Karoo deposits. The Adigrat Sandstones are light gray or red quartz arenites with interbeds of conglomerates and intensely pedogenized red mudstones (Fig. 2.8). Their thickness is variable even at short distances and reaches 700 m. They were mainly deposited in fluvial or piedmont zones, but also in fluviolacustrine and deltaic environments (e.g., Beauchamp 1977; Bosellini et al. 1997, 2001; Wolela 2008).

The typical facies of the Jurassic transgression is represented by shallow-water Callovian to Kimmeridgian carbonates, up to 1,000 m thick, referred to as the Antalo Limestones and the Hamanlei Formation (Figs. 2.7, 2.8 and 2.9). They conformably overlie the Adigrat Sandstones (Blanford 1870), and their earliest occurrences (Pliensbachian/Aalenian) are found in the Ogaden (Hunegnaw et al. 1998). In the Blue Nile basin, the Adigrat Sandstones are followed by the Gohatsion marls and evaporites of Aalenian to Callovian age (Russo et al. 1994). In the Dire Dawa-Harar and in the Tigray area, a younger widespread marine flooding is recorded since the Bathonian and in the Callovian/Oxfordian, respectively. Within the carbonate succession, characterized by several depositional sequences, the maximum flooding surface is marked by organic-rich marls and shales and is time-transgressive from Oxfordian (Ogaden area) to Tithonian (Tigray) (e.g., Brassier and Guleta 1993; Hunegnaw et al. 1998; Bosellini et al. 1997, 2001). In northern Ethiopia, the carbonate outcrops extend to the Mekele area and the northwestern border of the Afar depression (Figs. 2.8 and 2.9). The westernmost outcrops occur in central Ethiopia in the Blue Nile valley south of Choke Mt., and it is likely that the marine transgression did not cross the 36°E meridian and the 16°N parallel.

The carbonate deposits from Tigray to the Dire Dawa/Harar area are truncated by an erosional surface (PS 3 in Fig. 2.6) due to an Early Cretaceous tectonic event marked by faulting and tilting (Bosellini et al. 2001). The abruptly overlying Amba Aradam Sandstones are fluviatile and

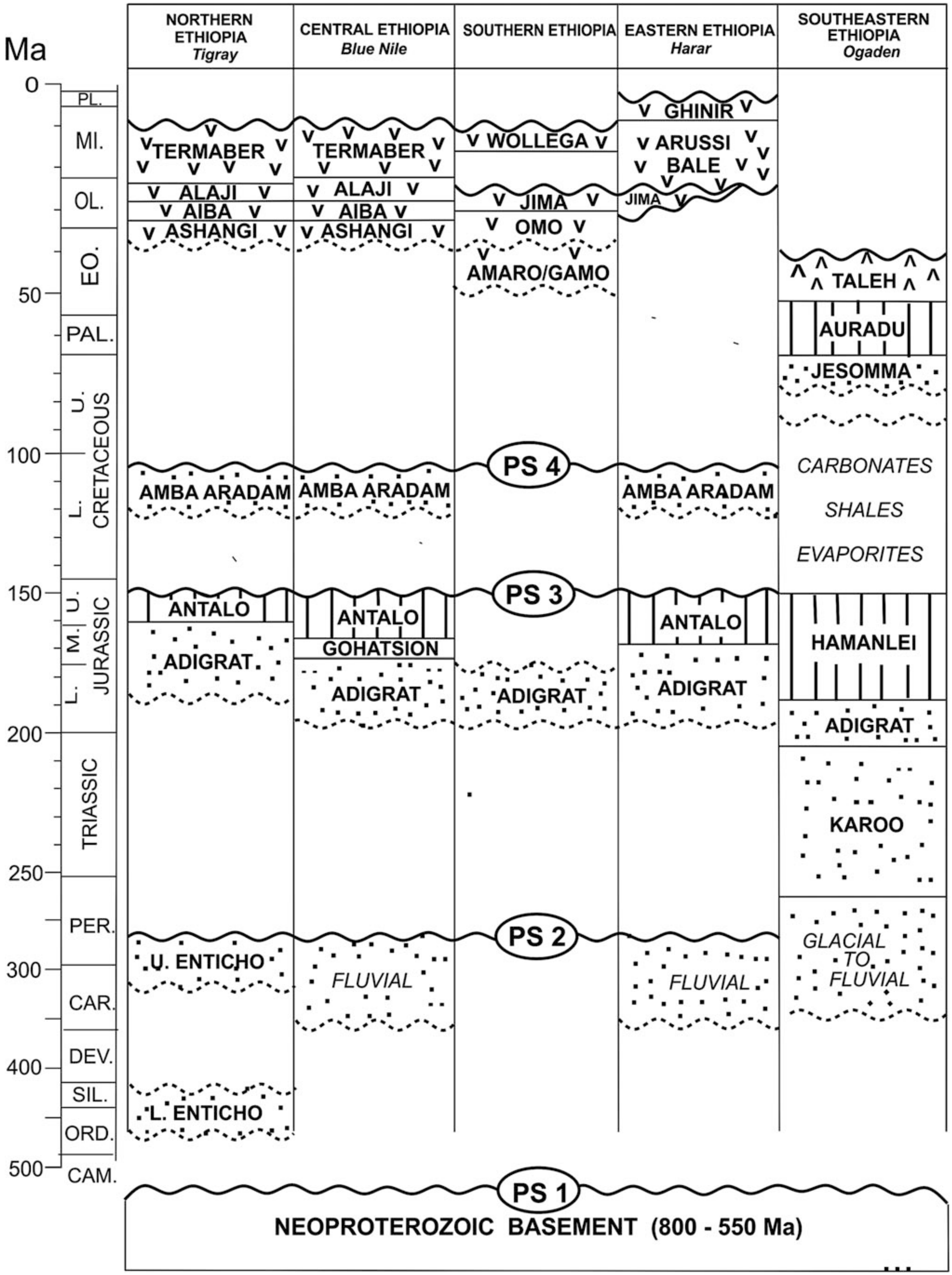

Fig. 2.6 Schematic stratigraphic chart of Ethiopia with the major planation surfaces [PS acronyms as in Coltorti et al. (2007)]

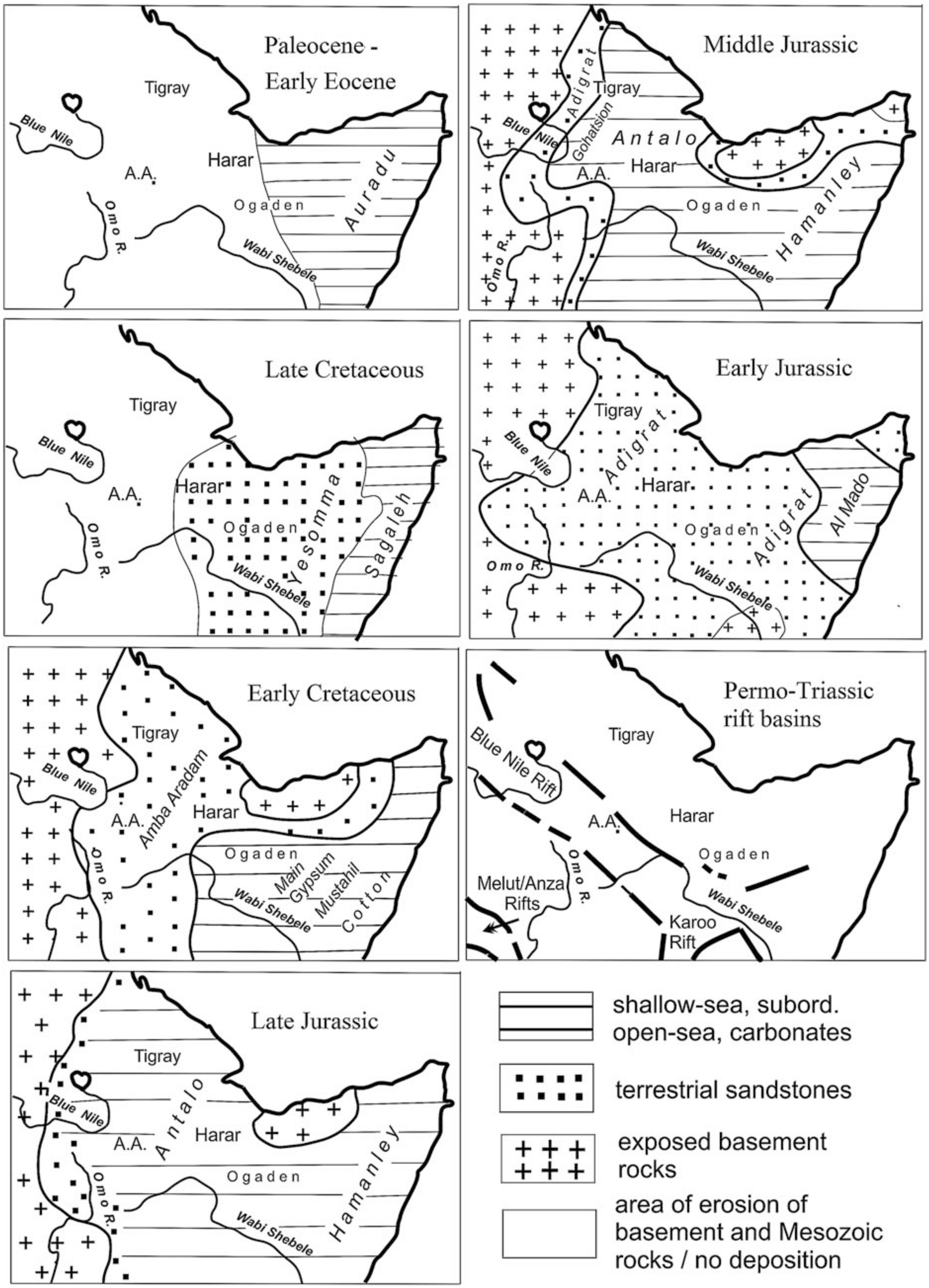

Fig. 2.7 Paleogeographic sketches for the Horn of Africa from Permian to Early Eocene

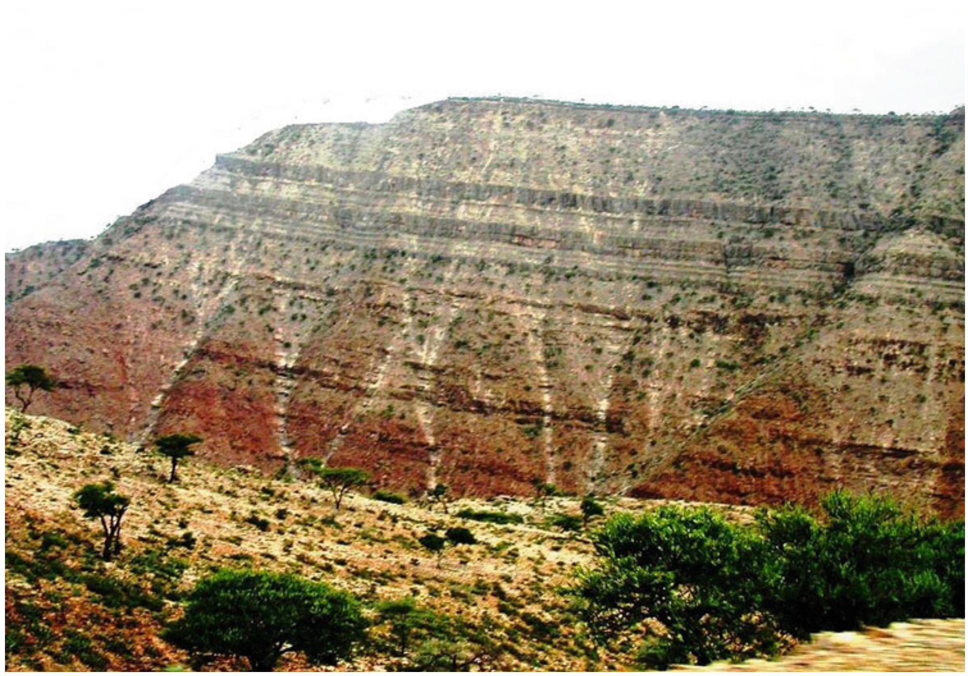

Fig. 2.8 The reddish Adigrat Sandstones conformably covered by the *gray* Antalo Limestone along the escarpment east of Mekele

Fig. 2.9 The Antalo Limestones at the foot of the escarpment east of Mekele: *horizontal* beds in the foreground and an *anticline* in the background

commonly associated with lenses of quartz conglomerates and red shales. They often exhibit laterites at their base. Their maximum thickness is 200 m, and their age determined on the base of *Orbitolina* findings in the Harar region is Aptian to Albian (Gortani 1973; Bosellini et al. 1999).

By contrast, in the Ogaden basin, marine deposition continues during the Cretaceous until the Turonian or possibly the Campanian (Fig. 2.7). It consists of ca. 1,200-m-thick alternation of transitional, shallow-water marine and open-sea deposits including shales, carbonates, sandstones, and evaporites (e.g., Main Gypsum, Mustahil, Cotton) (Barnes 1976; BEICIP 1985; Hunegnaw et al. 1998). This succession records many sea-level oscillations and represents the final stages of the Mesozoic flooding in the Ogaden basin. An erosional surface truncates the Mesozoic carbonate/evaporite sequence from south to north down to the

Middle Jurassic Hamanlei Formation (Merla et al. 1973). The overlying sediments above this erosive surface are the Jesomma Sandstones, a few-hundred-meter-thick quartzose fluvial deposit with minor conglomerates and siltstones. The age of this unit is poorly constrained and can be assigned to the upper portion of the Late Cretaceous.

A shallow-water marine deposition (Auradu Limestones, ca. 400 m thick) resumes at the beginning of the Paleocene and was connected to a new transgression recorded only in the easternmost portion of the Ogaden basin (Fig. 2.7). It lasts until the Early Eocene, and its deposits were covered by the Early to Middle Eocene Taleh Evaporites which reach 250 m in thickness.

2.5 The Cenozoic Volcanic History: Floods and Volcanoes

Concomitant with the first phases of rifting in the Afro/Arabian plate, a period of a prolific volcanic activity took place predominantly during the Oligocene in the Horn of Africa and southern Arabia which were at that time connected. These volcanic rocks, mainly represented by basalts and traditionally referred to as the trap succession, have estimated to have covered an area in Ethiopia not less than 750,000 km^2 before erosion, with a total volume of ca. 350,000 km^3 (Mohr 1983) (Fig. 2.10). Their great areal extension and volume are due to the exceptional supply of mantle material connected with hot plumes (Schilling 1973; White and McKenzie 1989).

According to Hofmann et al. (1997), the basalt activity was concentrated in the very short time of one million years around 30 Ma, and this rapid outpouring of a huge volume of volcanic rocks has been regarded as a possible cause of climatic deterioration and ensuing mass extinction on a global scale (Courtillot et al. 1988; White and McKenzie 1989; Rochette et al. 1998).

The volcanic succession rests above a peneplained surface (Blanford 1869; the pre-trappean peneplanation of Mohr 1962; PS 4 in Fig. 2.6), marked by laterites, particularly well developed in Eritrea and Tigray (Dainelli and Marinelli 1912; Merla and Minucci 1938) and in southwestern Ethiopia (Davidson and Rex 1980). The laterites are also present in similar contexts in Yemen (Baker et al. 1996) and western Arabia (Overstreet et al. 1997). This extensive pedogenesis is indicative of a long period of morphological stability of the peneplained surface marked by low elevation, little or no vertical deformations, and sediment starvation. The laterization was active until at least 40 Ma (Ar/Ar age, Andrews Deller 2006) and can be related to the Early Eocene climatic optimum.

The volcanic rocks that cover most of Ethiopia have been subdivided into five major provinces on the basis of their lithological development, type of activity, frequency of volcanic centers, and age of effusion (Abbate and Sagri 1980): (1) volcanites of the northern plateau; (2) volcanites of the southern plateau; (3) volcanites of the Somali plateau; (4) Afar volcanites; and (5) Main Ethiopian Rift (MER) volcanites.

The first three groups (Merla et al. 1979) comprise the major part of the Ethiopian volcanites (Fig. 2.10). They have collectively been referred to as “Traps” (Blanford 1870; Kazmin 1973), a general term from an old Swedish word meaning stairs (Fig. 2.11). Fine-grained stratoid fissural Paleogene basalts represent the greater portion of these volcanites. The Afar and the MER volcanites, filling two megastructures related to Neogene continental fragmentation, have a more limited extension (Fig. 2.10) and were referred to as Aden Series (Blanford 1870; Mohr 1962).

2.5.1 The Volcanites of the Northern Ethiopian Plateau

After Blanford’s (1870) attempt to subdivide the northern plateau volcanites into a lower Ashangi Group unconformably overlain by a Magdala Group, a more detailed lithostratigraphic approach was proposed in the 1970s by Zanettin and Justin Visentin (1973) and Gregnanin and Piccirillo (1974), with the distinction of the Ashangi and Aiba basalts, Alaji Rhyolites, and Termaber Basalts. These units were incorporated in the Merla et al. (1979) and Tefera et al. (1996) maps. Some authors have pointed out that the lateral heterogeneity of these volcanic rocks, the vertical recurrence of similar lithology, and the different morphological response of basalts with the same petrological or chemical characteristics (e.g., Kieffer et al. 2004) prevent the adoption of the criteria commonly used for sedimentary bodies. However, in the expectancy of further detailed field and petrographic studies, we prefer to maintain the distinctions proposed by the previous authors and also followed by Rochette et al. (1998) in their magnetostratigraphy analyses of the northern Ethiopian traps.

The Ashangi Basalts are composed of transitional to tholeitic olivine basalts, often highly zeolitized, alternating with subordinate tuffs (Mohr and Zanettin 1988). The flows are barely evident owing to their small thickness, reduced horizontal extension, and deep weathering. Their thickness is from 200 to 1,000 m. The Aiba Basalts consist of well-developed columnar massive transitional flood-basalt flows, locally with intervening agglomerate beds. The flows are 15–50 m thick reaching in some cases almost 100 m and

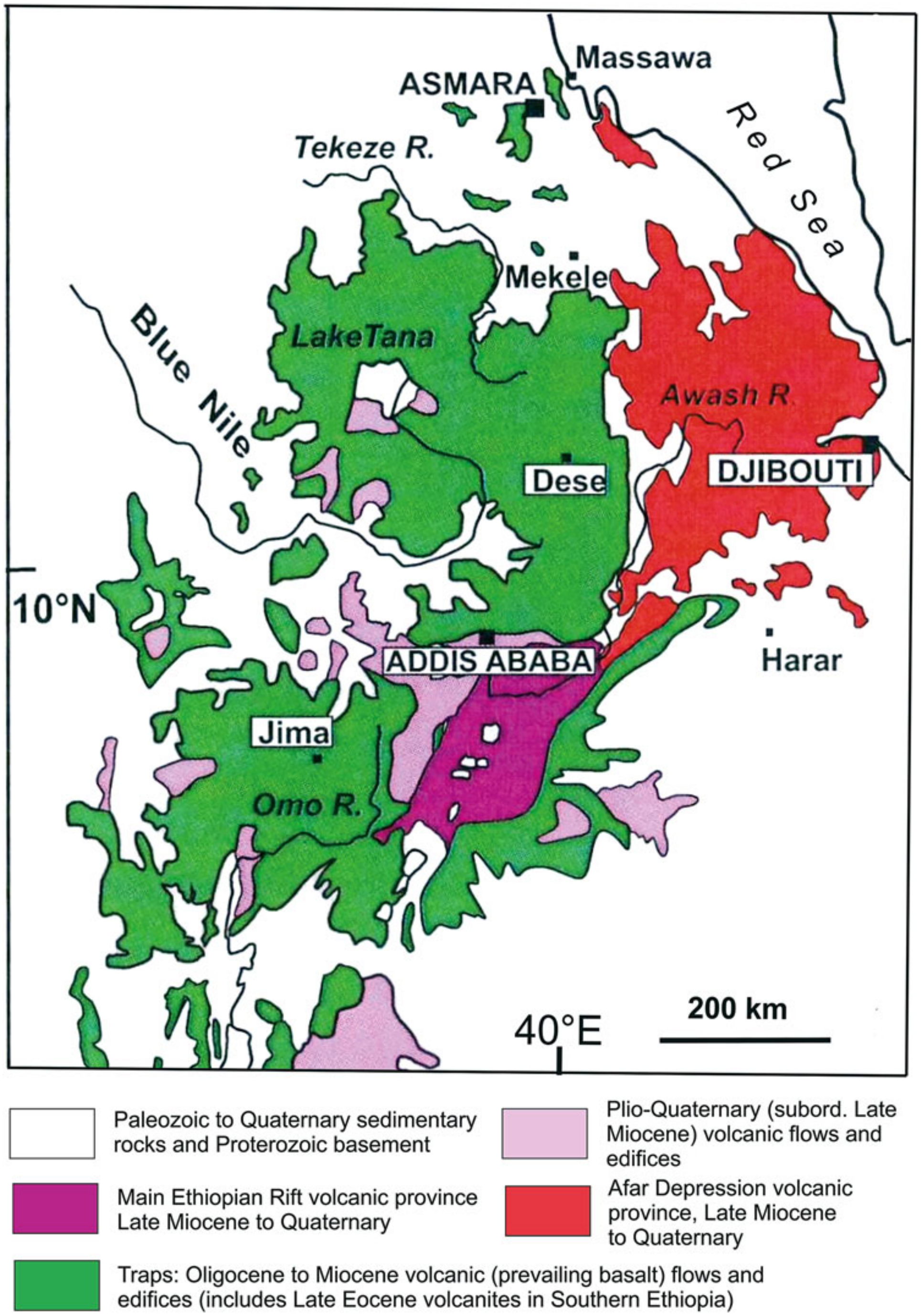

Fig. 2.10 The main volcanic provinces of Ethiopia. After Abbate et al. (2014)

can be traced over long distance. Their total thickness reaches 1,000 m. The above-described fissural basalt units constitute the bulk of the volcanic pile of the northern Ethiopia plateau, locally attaining 2,000 m in thickness. This profuse outpouring took place between 31 and 29 Ma (Hofmann et al. 1997; Pik et al. 1998; Ukstins et al. 2002; Coulié et al. 2003). The Amba Alaji Rhyolites, whose outcrops are limited to the northern portion of the northern Ethiopian plateau, are an alternation of alkaline to peralkaline rhyolites and transitional basalts. The acidic terms are mainly whitish ignimbritic tuffaceous layers that can be followed for a great distance. They form typical landscape elements, such as steep walls and pyramids, well represented in the Amba Alaji peak (Fig. 2.12). Their maximum thickness is 500 m with a decrease to nil about 100 km west of the Afar margin. Their age ranges from Late Oligocene in the northern outcrops to Early Miocene in the south (Zanettin et al. 1974).

Fig. 2.11 Felsic and subordinate basic volcanites of the Semien shield volcano overlie a thick succession of flood basalts. Semien National Park. Photograph courtesy of Frances Williams

Fig. 2.12 The outstanding pyramidal morphology of the Amba Alaji Rhyolites at the Amba Alaji peak

A peculiar feature of the northern Ethiopian plateau is the frequent occurrence of shield volcanoes, about 30 major centers according to Mohr and Wood (1976), some of which reach as much as 100 km in diameter and 1,000–2,000 m in elevation above the plateau (e.g., Semien, Guna, Choke, and Guguftu) (Figs. 2.13 and 2.14). In the regional reviews and maps, they are grouped under the name of Termaber Basalts. They are made of lenticular, often zeolitized, alkali basalts with a large amount of tuffs, scoriaceous lava flows, peralkaline rhyolites, and typical red paleosoils. Dike swarms and acidic extrusions are present. The thickness of the Termaber Basalts reaches 1,000 m close to the volcanic centers.

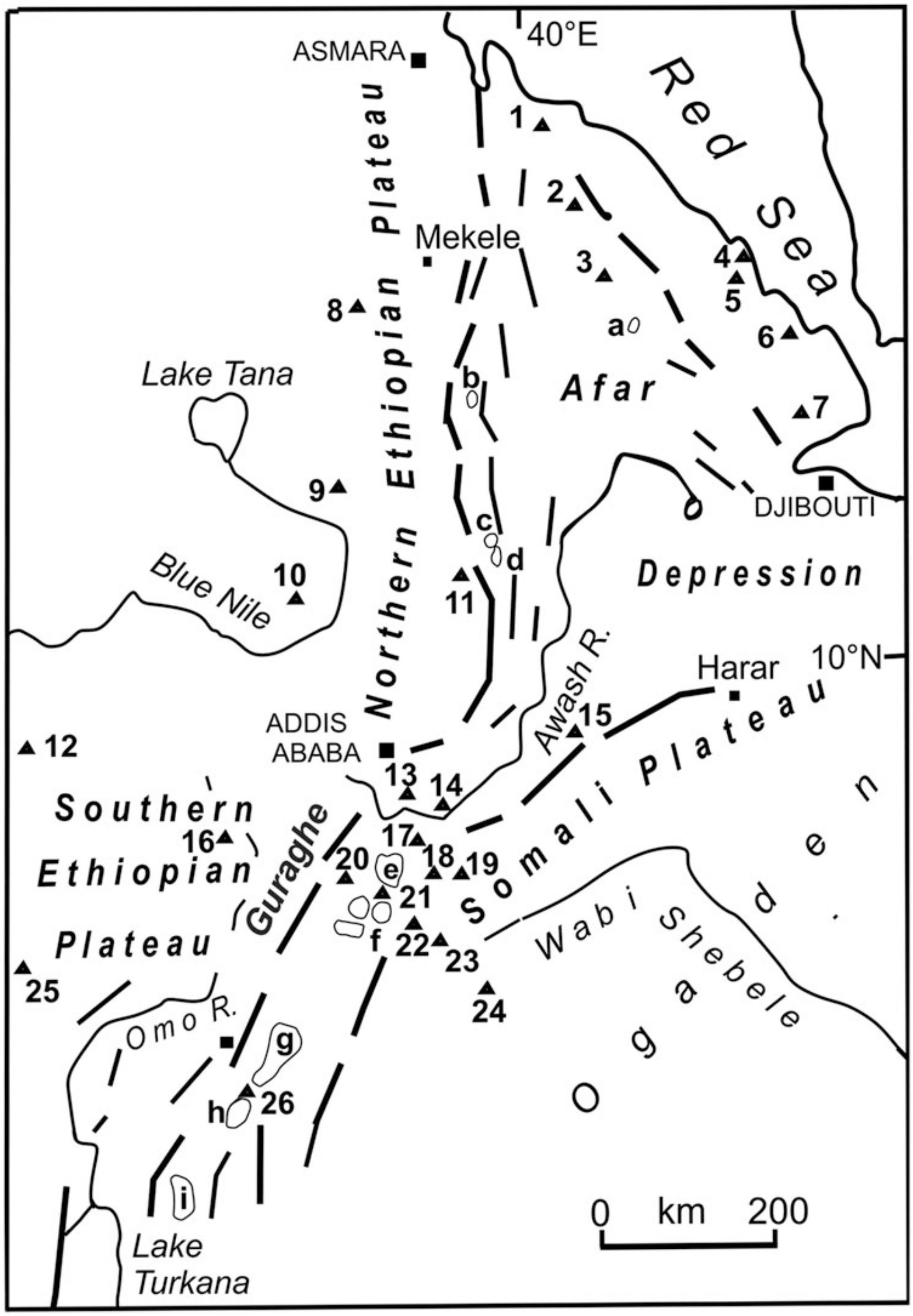

Fig. 2.13 Location map of the volcanic edifices and lakes cited in text. Volcanic edifices: *1* Alid; *2* Dallol; *3* Erta Ale; *4* Dubbi; *5* Sork Ale; *6* Ado Ale; *7* Mussa Ale; *8* Semien; *9* Guna; *10* Choke; *11* Guguftu; *12* Tullu Wellel; *13* Yerer; *14* Boseti Guda; *15* Fantale; *16* Egan; *17* Bora Bericho; *18* Chillalo; *19* Badda; *20* Gademotta; *21* Alutu; *22* Chike; *23* Kecha; *24* Bale; *25* Mizan Tefari; *26* Tosa Sucha. Lakes: *a* Afrera; *b* Ashangi; *c* Haik; *d* Ardibbo; *e* Ziway; *f* Langano, Abiyata, Shala; *g* Abaya; *h* Chamo; *i* Chew Bahir

The ages of the Termaber shield volcanoes are Early and Middle Miocene, ranging from 23 to 11 Ma (e.g., Kieffer et al. 2004), with the exception of the Semien with the base of 30 Ma and the top of 19 Ma.

In addition to the trap basalts and shield volcanoes, some subvolcanic intrusions are an outstanding feature in the Axum–Adwa area producing a landscape of cliffs, pinnacles, and domiform hills with an east–west alignment (Le Bas and Mohr 1968; Abbate and Sagri 1980). They are basalt–trachyte (syenite) plugs and domes (Prior 1900; Merla and Minucci 1938; Mohr 1962; Hagos et al. 2010) and have been dated as Mio-Pliocene by Beyth (1972), and more recently, Natali et al. (2013) determined their Ar/Ar age of 19–15 Ma. The rocks of this volcanic complex have been quarried for the famous ancient Axumite obelisks.

On the western portion of the northern Ethiopian plateau, the Tana rift basin is located in a structural complex area at the junction of three grabens (Chorowicz et al. 1999). Quaternary

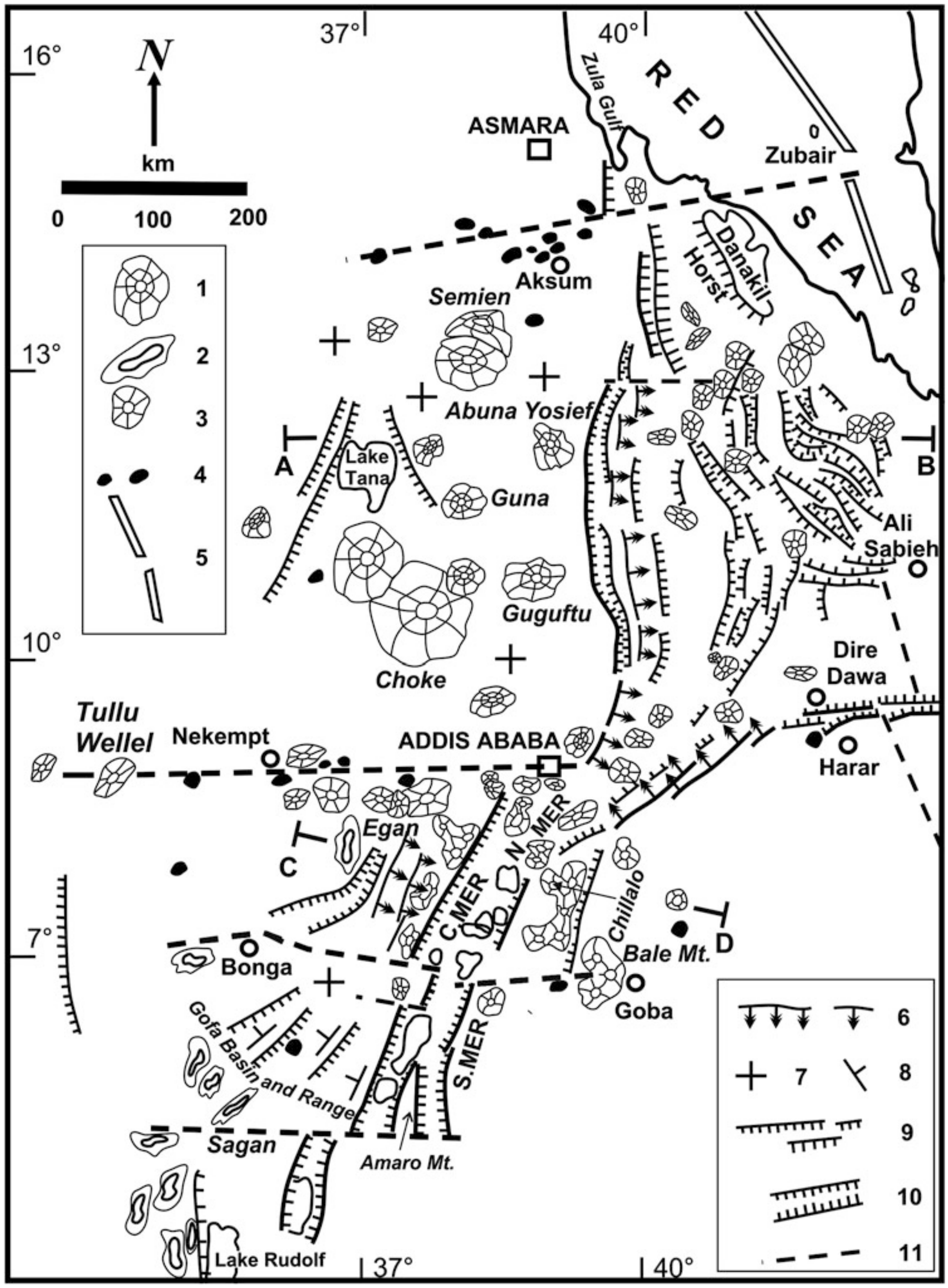

Fig. 2.14 Structural sketch map of the Ethiopian and Somali plateaus, Afar depression, and Main Ethiopian Rift (Northern, Central, and Southern MER) with the main transversal tectonic line and major volcanic edifices. Legend: *1* Miocene volcanic centers of Termaber unit in the northern Ethiopian plateau; *2* Pliocene acidic domes and plugs; *3* Plio-Quaternary volcanic centers; *4* peralkaline plugs; *5* Red Sea axis; *6* Flexures; *7* Horizontal lava flows and sedimentary sequences; *8* tilted lava flows and sedimentary sequences; *9* block faulting; *10* major graben; *11* transversal tectonic lines. A–B, C–D cross sections shown in Fig. 2.23. Modified from Abbate and Sagri (1980)

olivine–basalts and subordinate phonolites cover much of the southern portion of the Tana rift (Jepson and Athearn 1964) with well-preserved lavas, plugs, and spatter cones.

The transition to the southwestern plateau volcanites is marked by a 700-km-long and 80-km-wide east–west-trending volcano-tectonic alignment (Fig. 2.14) (Addis Ababa-Nekempt line in Abbate and Sagri 1980; Yerer-Tullu Wellel alignment, Abebe et al. 1998) consisting of a line of Late Miocene to recent volcanic centers gradually shifting in age from Late Miocene in the west to Quaternary in the east (Abebe et al. 1998). These edifices have basic lava flows at their base with acid domes, plugs, and pyroclastic deposits in their evolved end members.

2.5.2 The Volcanites of the Southern Ethiopian Plateau

For the southern plateau volcanites, there are reports of limited volumes of basalts (Amaro and Gamo basalts) with ages between 45 and 35 Ma (Davidson and Rex 1980; Ebinger et al. 1993; George et al. 1998). They predate the

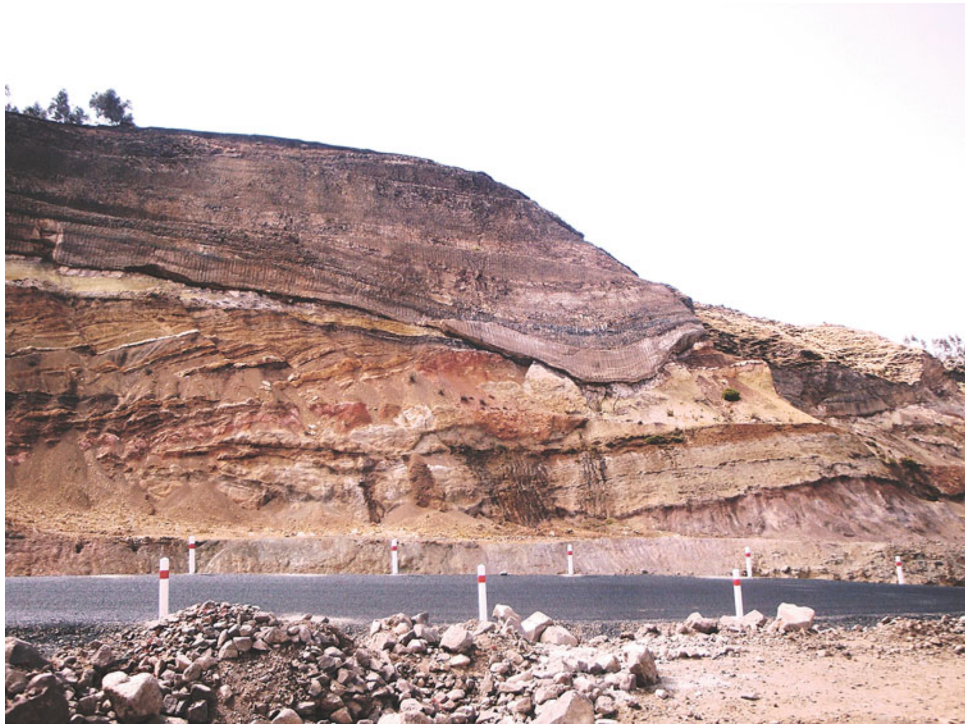

Fig. 2.15 The Jima Volcanites at the top of the Guraghe escarpment (Fig. 2.13). Gently inclined rhyolite ignimbrites incised by a channel in turn filled by horizontally laminated ignimbrite flows. New road on the western flank of the MER between Butajira and Welkite

northern Ethiopian traps by as much as 15 Ma (Rogers 2006). The southern plateau traps are less thicker than those of the northern plateau and are characterized by much thicker and more widespread siliceous rocks. For this volcanic sequence, resting directly on the crystalline basement or, more rarely, on the Eocene basalts and Mesozoic sandstones, we follow the distinctions proposed in Merla et al. (1979). The succession begins with a hundred meters of mildly alkaline basalts (Omo Basalts), capped by a thick unit, up to 1,000 m, of rhyolites, acidic tuffs, and subordinate basalts (Jima Volcanites). The Omo Basalts are commonly fine grained with columnar flows up to 10 m thick alternating with minor tuffs and red paleosols. There are some sparse dates ranging around 30 Ma (Merla et al. 1979; Davidson and Rex 1980). The Jima Volcanites, reaching one thousand meters of thickness in the Omo valley, represent most of the effusives in SW Ethiopia with a wide fringe in the southern portion of the Somali plateau NW of the Amaro Mts. and south of the west–east Bonga–Goba line (Abbate and Sagri 1980). The Jima Volcanites are mainly composed of massive, white, pinkish, and gray rhyolites, comendites, and pantellerites in thick flows alternating with tuffs and subordinate basalts (Fig. 2.15). Reliable radiometric datings are quite scarce. At the Omo village, toward the top of the succession, the Jima Volcanites gave an age of 27 Ma (Merla et al. 1979). An overall age range from ca. 30 to 27 Ma can be assigned to this unit. The Wollega Basalts, resting on the basement and on the tilted Omo Basalts and Jima Volcanites, consist of 200–400 m of predominant columnar alkaline basalt flows interbedded, particularly in the upper portion, with acidic tuff and loose fluvial lacustrine deposits. Two samples gave ages of 15 and 13 Ma.

A few huge rhyolite plugs and domes (e.g. Mt.Egan, Mt. Mizan Tafari, Fig. 2.13) constitute a prominent and peculiar feature of the southern Ethiopian plateau. According to their relationships with the surrounding volcanites, they are doubtfully assigned to the Pliocene (Merla et al. 1979).

2.5.3 The Volcanites of the Somali Plateau

Above a patch of limited extent of Jima Volcanites, the succession in the Somali plateau, assigned to the Traps, consists of the Arussi and Bale Basalts of Miocene age (K/Ar ages ranging from ca. 24 to 9 Ma, Kunz et al. 1975; Morbidelli et al. 1975; Merla et al. 1979) with variable composition from transitional to alkaline basalts (Zanettin et al. 1980) and a thickness of about 3,000 m (Juch 1975). Rhyolitic intercalations are particularly abundant and thick in the middle portion of the Arussi and Bale Basalts (Juch 1975). They become the predominant component of the overlying Ghinir Unit alternating with basalts and fluviolacustrine intercalations. From the data supplied by Juch (1975), it can be inferred that the Ghinir Unit attains several hundred meters in thickness. The radiometric ages fall in the range of 6–2 Ma (Kunz et al. 1975; Morbidelli et al. 1975; Merla et al. 1979). A lacustrine unit with abundant diatomites and rare sands and conglomerates (Chorora Formation, Sickenberg and Schoenfeld 1975) is discontinuously present beneath the Ghinir Unit at the foot of the escarpment. It is up to 200 m thick and has yielded Late Miocene mammals (Bernor et al. 2004).

A peculiar morphological feature in the Somali plateau is the huge Plio-Quaternary volcanic complex of the Bale Mts. with cones and plugs, probably connected with the Bonga–Goba line (Figs. 2.10 and 2.14). It reaches an elevation of 4,300 m (Mt. Batu, Quaternary, Merla et al. 1979), rests on the Arussi and Bale Basalts, and is covered by patches of glacial deposits.

2.5.4 The Afar Volcanites

The Afar region is a quasi-triangularly shaped depressed area at the intersection of the Red Sea, Gulf of Aden, and the Main Ethiopian Rift (MER) (Fig. 2.1). Due to its 25-million-year-long story of rifting and incipient oceanization, volcanic rocks cover wide areas of the Afar depression (Fig. 2.10).

According to Barberi et al. (1975), the Afar volcanites can be assigned to a first stage of continental rifting which lasted about twenty million years, starting from 25 Ma, and a later stage which commenced 4 Ma during which the oceanic floor in the central portion of Afar began to develop.

The older volcanites of the first stage include the Adolei Basalts, Mabla Rhyolites, and Dalha Basalts (Barberi al. 1975). They are more than 1,000 m thick and cover a time range from 26 to 6 Ma. Associated with them are alkaline and peralkaline granites aged 25–22 Ma linked to an early phase of continental breakup. The most extensive volcanic sequence connected with the second stage is the Plio-Pleistocene Afar Stratoid Series which covers about two-thirds of the Afar depression. This consists of transitional basalts, about 1,500 m thick and lies unconformably on the Dalha Basalts after a phase of magmatic quiescence. Intercalated in the top of and above the Afar Stratoid Series are the transversal volcanics and marginal rhyolitic centers (e.g., Dubbi, Ado Ale, Fig. 2.13). The axial volcanic ranges of Quaternary age are a typical morphological feature of the Afar depression from which they rise prominently up to 1,500 m. The northern range (Erta Ale) parallels the Afar axis with a NNW trend; to the south, the volcanic ranges shift gradually to WNW. They consist of fissure eruptions and shield volcanoes with basaltic flows and alkaline to peralkaline silicic rocks. Many of them have been active in historical times, and the Erta Ale volcano exhibits a spectacular lava lake.

2.5.5 The Main Ethiopian Rift Volcanites

The Main Ethiopian Rift (MER) is a NNE–SSW to N–S-trending trough 80 km wide in its central portion and 1,000 km long (Fig. 2.14). It separates the southern Ethiopian plateau to the west from the Somali plateau to the east. Northward, the MER progressively widens out into the complex Afar triple junction, while at its southern end, a 200–300-km tectonically disturbed area (Gofa basin and range, Baker et al. 1972) marks the transition to the Kenyan Gregory Rift in the Turkana depression.

The volcanic history of the MER has been dealt with in numerous papers which often take into account limited sectors of the rift. This has resulted in a proliferation of volcanic units with significant problems of correlation among the northern, central, and southern sectors.

The MER volcanic stratigraphy was summarized by Corti (2009). He envisages a lower basalt unit with trachybasalts and subordinate silicic flows from 11 to 8 Ma old followed by a widespread ignimbrite cover (e.g., Nazaret Group) ranging in age from 7 Ma in the northern sector to 2 Ma to the south and up to 700 m thick. Most of the ignimbrite layers are believed to have formed by catastrophic eruptions related to the collapse of large calderas, such as the 3.5-Ma-old Munesa caldera now buried beneath the Ziway–Shala lakes (Fig. 2.13). These two units, common to the whole MER, are followed by Late Pliocene basalts with pyroclastics fed by calderas which are limited to the northern and central sectors. The subsequent Quaternary volcanic unit, which outcrops throughout the MER, is the Wonji Group associated with the oblique Wonji fault belt (Mohr 1962). It includes basalt flows and scoria cones, and large silicic central volcanoes with calderas. These edifices and calderas rise up to 700 m above the plain (e.g., Bora Bericho, Alutu, Gademotta, Fig. 2.13), and some of them experienced phreatomagmatic activity and historical flows. They are referred to as en-echelon arranged magmatic segments connected to the Wonji fault belt (see later).

Off-axis magmatism is mainly concentrated on the Somali plateau with huge shield volcanoes of basaltic and trachytic composition and Mio-Pliocene age (Chillalo, Badda, Chike, Kecha, Figs. 2.13 and 2.16). Some of them exceed 4,000 m in elevation and have a base of 30–40 km diameter rising from the plateau level for 1,000–1,500 m. Glacial cirques and massive moraines occur at an altitude of about 4,000 m, indicating that these high mountains were glaciated during the Late Quaternary (Grove et al. 1975).

2.5.6 The Intertrappean Beds

Common intercalations in the previously described trap pile of the Ethiopian highlands as well as in the Yemen plateau are terrestrial sediments (intertrappean beds) composed of red clays, sands, diatomites, and lignite seams, generally a few tens of meters thick, but also reaching hundreds of meters (Abbate et al. 2014). Within the abrupt and steep trap

Fig. 2.16 The Main Ethiopian Rift floor with a Quaternary volcano (*hill* on the *left*) and the faulted escarpment of the Somali plateau (*light*- and *dark-colored* stripes in the *midground*) overlain by the huge Chillalo shield volcano (in the *background*)

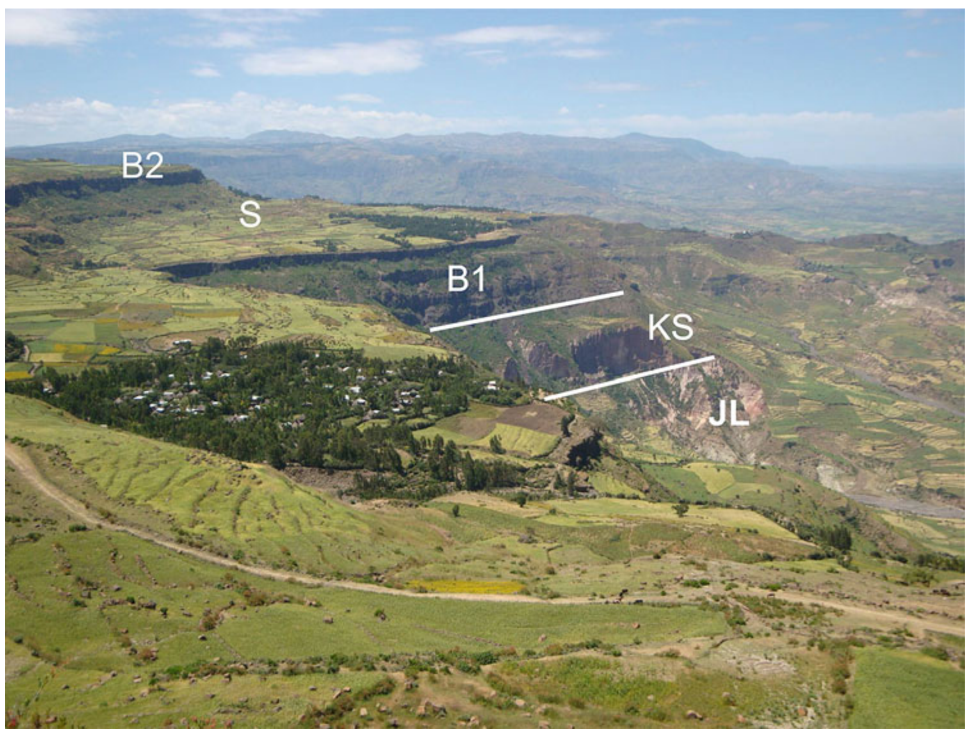

Fig. 2.17 The flat morphology of the soft intertrappean sediments (*S*) contrasting with the steep slopes cut through the trap basalts (*B1*, *B2*), the Cretaceous sandstones (*KS*), and the Jurassic limestones (*JL*). Slope of the Jema river, a Blue Nile left tributary, 100 km NNW of Addis Ababa

escarpment, these loose sediments give rise to a pronounced morphological break (Fig. 2.17). The intertrappean sediments occur in lenses which are sometimes continuous for tens of km in the middle/upper portion of the traps and span a time interval between ca. 29 and 27 Ma (Early/Late Oligocene transition). They mark a period of volcanic quiescence following a voluminous and rapid lava outpouring. The volcanic activity resumed after two/three million years but was delayed a couple of million years in the marginal areas of the trap effusion (Abbate et al. 2014). The presence of endemic proboscideans in the intertrappean sediments is particularly significant in investigating the origin of these mammals and in clarifying the relationships between African and Eurasian faunas (Abbate et al. 2012, 2014).

2.6 The Sediments in the Afar Depression, Main Ethiopian Rift, and Adjoining Areas

In addition to magmatic and pyroclastic materials, the subsiding basins of the Afar and MER host sediments which are particularly useful in reconstructing Plio-Pleistocene human evolution and climatic variations as well as the paleogeography and structural development of the region.

2.6.1 The Afar Depression

Different types of basins occur within the Afar depression and along its margins. They originated during successive phases of tectonic deformation since the Miocene and have generated a significant morphological response in the present-day topography. According to their position with respect to the Afar depression axis, we distinguish axial, peripheral, and marginal basins (Fig. 2.18). The first two types are located within the Afar depression, and the latter type characterizes the lower and upper portions of the western escarpment. This distinction holds for most of the Afar, but the occurrence of latest Oligocene sediments in the northern apex of the Afar triangle north of 13° Lat. N is related to an older incipient rifting with the development of a sedimentary basin which is not recorded southward. These older sediments, which were the first laid down in the Afar Depression, are the Red Series (Bannert et al. 1970) or Danakil Formation (Brinkmann and Kürsten 1970; Garland 1980). They are composed of violet-red to bright-red conglomerates and sands with mudstones (Fig. 2.19) locally gypsiferous, and rare freshwater gastropods-bearing limestones. Alluvial fans and high-energy streams with some swampy to lacustrine ponds were the main features of the Danakil Formation environment. Frequent basalt flows are found intercalated in this succession. Those at the base and toward the top gave K/Ar ages of 24 and 4 Ma, respectively (Bannert et al. 1970). A thickness of about 1,000 m is commonly assumed. The whitish gypsiferous Enkafala Formation, a few meters thick, unconformably overlies the Danakil Formation and marks a marine transgression in the northern Afar depression. Its marine fossils have been dated by U/Th methods at 200 to 24 ky (Lalou et al. 1970). Toward the center of the basin, the Enkafala Formation passes transitionally into the salt formation composed of halite, gypsum, potash salts, and clays (Fig. 2.20). The salts have precipitated at the surface and generate an impressive, bright-white salt plain. A thickness of 975 m has been drilled for potash exploitation, and a thickness of 2,200 m has been estimated by geophysical investigations.

Peripheral and axial basins occur south of 13° Lat. N (Figs. 2.14 and 2.18). Fluviolacustrine sediments fill peripheral basins at the foot of the western and southern Afar escarpment along the Middle Awash valley (e.g., Woramso/Mille, Hadar, Kesem/Kebena, and Chorora sub-basins). Kalb et al. (1982) include these continental sediments under the Late Miocene to Pleistocene Awash Group which is more than 1,000 m thick. Main lithological components are shales, sands, pebbles, and diatomites with intercalated ash layers and basalt flows (Fig. 2.21). The Awash Group is famed for its rich hominid content, artifacts, and mammal faunas (e.g., Hadar, Bodo, Buri, Busidima, Daka, Sidi Koma, Sagantole, Chorora, Adu Asa) (a rich bibliography on this matter can be acquired from Quade and Wynn 2008).

In central and eastern Afar, elongated graben structures (e.g., Abhe/Gob Ad, Hanle/Dobi, Tendaho/Dubti, Gaggade, Figs. 2.14 and 2.18) filled by Pleistocene fluviolacustrine deposits are related to the axial basins (Tiercelin et al. 1980). In geothermal drillings in the Tendaho basin, more than 500 m of fine-grained Pleistocene sediments have been found alternating with basalts (Battistelli et al. 2002).

The eastern margin of the Eritrean–Ethiopian plateaus is characterized by a flexure that connects the plateau to the Afar depression (see later). Such a deformation belt with a maximum width of 100 km is developed along the escarpment between Asmara and Addis Ababa for 900 km (Fig. 2.14). Connected to this flexure are a number of tectonic depressions parallel to the escarpment and mostly developed along a north–south direction ("marginal basins" Mohr 1967) (Fig. 2.18). The flexure and associated depressions form very conspicuous features due to their morphological continuity and pronounced expression.

The depressions are filled by Pleistocene fluviolacustrine sediments and volcanoclastics. Those situated close to the plateau edge with a master fault on their western flank are well developed both longitudinally and transversally (Kobo basin: 120 km by 15 km; Haik/Borkenna basin 70 km by 10 km). The sediment thickness in these basins is generally a few tens of meters. Those developed within the flexure are usually smaller and characterized by their reduced or absent sedimentary infilling. On the contrary, basins at the base of flexure host thick sedimentary successions. From north to south, they are Buia in Eritrea, and Garsat and Teru in Ethiopia. These basins are filled by up to 1,000 m of the fluviolacustrine sediments of the Early-to-Middle Pleistocene Dandiero Group (Abbate et al. 2004). The Buia section yielded a one-million-year old *Homo erectus* skull, abundant mammal faunas, and lithic industries (Abbate et al. 1998).

2.6.2 The Main Ethiopian Rift

An additional area of Late Cenozoic sediment accumulation is the MER where fluviolacustrine sediments with rare diatomites (Fig. 2.22) cover a large area. They represent the deposits laid down in a very wide lake which, in the past,

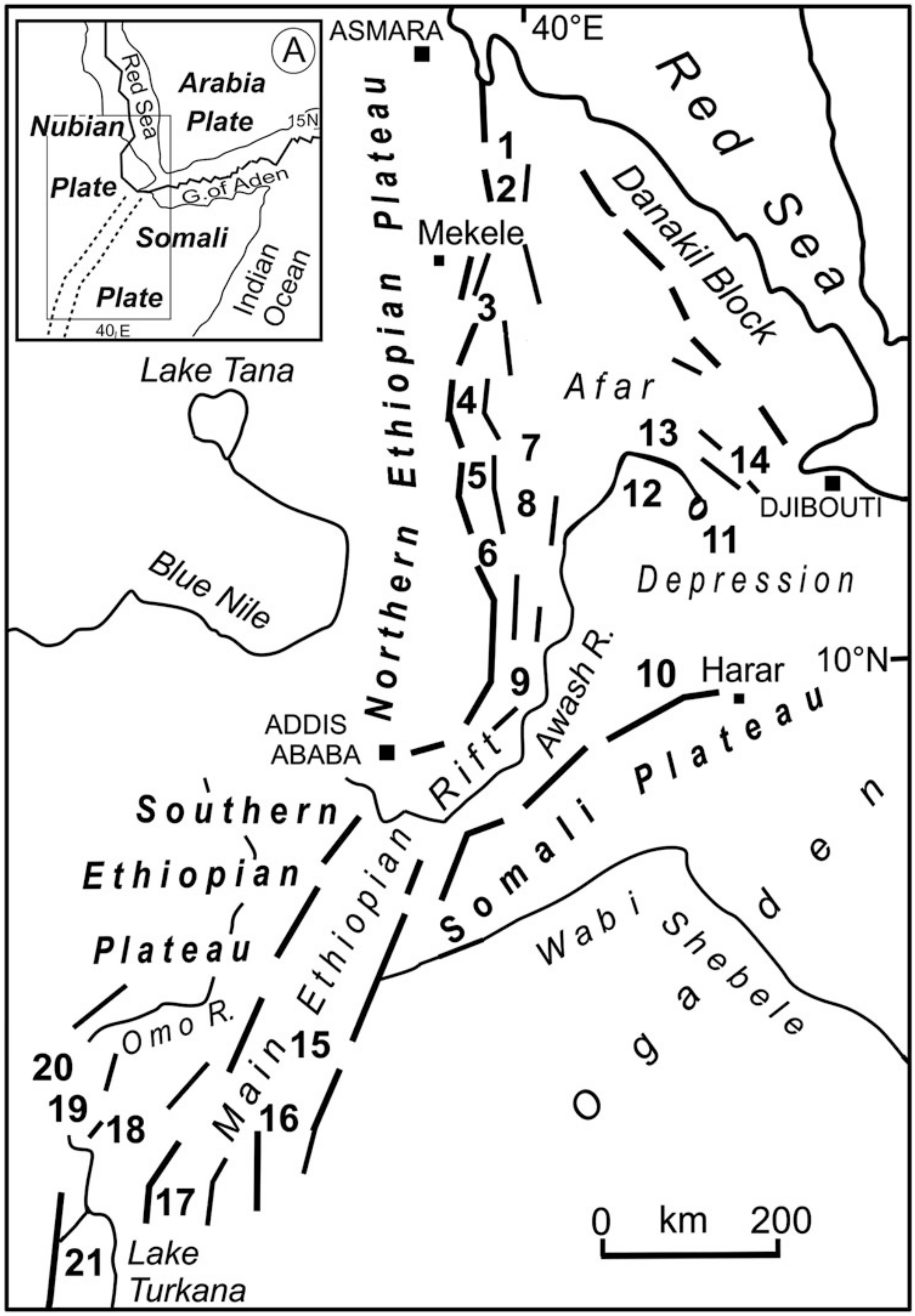

Fig. 2.18 Location map of the major Plio-Quaternary sedimentary basins (marginal, peripheral, central) according to their structural setting in the northern Ethiopia plateau escarpment, Afar depression, and Main Ethiopian Rift. Marginal basins: *1* Buia; *2* Garsat; *3* Teru; *4* Kobo; *5* Hayk; *6* Borkenna. Peripheral basins: *7* Woramso; *8* Mille; *9* Kesem-Kebena; *10* Chorora. Central basins—in Afar: *11* Abhe-Goba Ad; *12* Tendaho-Dubti; *13* Hanle-Dobi; *14* Gaggade; in the Main Ethiopian Rift: *15* Galana; *16* Konso-Gardula; *17* Chew Bahir; *18* Usno; *19* Omo; *20* Kibbish; *21* Turkana. Inset map A (*top left*) shows location of study area relative to the Nubian, Arabia, and Somali plates. Main Ethiopian Rift within *dotted lines*

occupied most of the rift floor. In the northern and central part of the MER north of the Lake Shala, only a few tens of meters of Late Pleistocene/Holocene sediments outcrop. They record at least two major phases of lake expansion separated by a prolonged period of lowstand and erosion (Fig. 2.22) (Street 1979; Le Turdu et al. 1999; Benvenuti et al. 2002). On the basis of geophysical investigations, the presence of about 600 m of sediments has been estimated by Le Turdu et al. (1999). It has been proposed that their maximum age is as old as 500 ka (Le Turdu et al. 1999).

Poorly studied similar fluviolacustrine deposits occur in the southern MER in the Abaya/Chamo Lake regions with a thickness of more than 500 m (Ebinger et al. 1993). More detailed studies have been carried out on the fluviolacustrine sediments containing *Australopithecus boisei*, *Homo erectus,* and abundant artifacts in the Konso/Gardula area (Katho et al. 2000). These sediments comprise the Konso Formation and consist of dark-gray clay, red-brown silt, sand, and gravel, with frequent intercalations of volcanic rocks and tephra. The Konso Formation is more than 200 m thick and was deposited between 1.9 and 1.4 Ma.

Fig. 2.19 *Red* fluviatile sandstones and mudstones of the Danakil Formation with a dark intercalation of a basalt flow, unconformably capped by coarse-grained Quaternary alluvial deposits

Fig. 2.20 Highly dissected salt crust hosting iron-rich brine deposits near Dallol, northern Afar depression. The mountains in the background are the Afar western escarpment at the edge of the northern Ethiopian plateau

The MER terminates to the south with the Chamo and Konso/Gardula basins and abuts the Sagan line (Baker et al. 1972; Abbate and Sagri 1980). Through the intermediate Chew Bahir, Usno, Omo, and Kibish graben structures, the deformation shifts to the Kenyan Turkana rift (Fig. 2.14). With the exception of the Chew Bahir, which is a symmetrical graben, all the others are half-graben with the master fault on the western side (Davidson 1983). All these basins are filled by fluviolacustrine deposits interbedded with volcanic rocks and ashes. The Omo basin, in the lower course of the Omo river, is the northern extension of the Turkana rift and is particularly well studied owing to the occurrence of abundant vertebrate

Fig. 2.21 Cyclically arranged lacustrine, lake margin, and fluviatile deposits with tuff horizons in the Hadar basin, Middle Awash, northern Afar (basin 8 in Fig. 2.18). This section is adjacent to the site where the 3.2-million-year-old partial skeleton of "Lucy" was discovered

Fig. 2.22 Late Quaternary lacustrine sediments consisting of massive diatomites (*whitish*) and thinly stratified, *light gray* volcanoclastic deposits. A deep erosional surface separates the Holocene from the Late Pleistocene successions. Central Main Ethiopian Rift. Photograph courtesy of Marco Benvenuti

fossils including hominids (e.g., Howell 1969; Arambourg 1972). It is filled by one thousand meters of sediments, and most of them are represented by the fossiliferous Plio-Pleistocene Shungura formation (deHeinzelin 1983). The development of this basin dates back to the Early Pliocene (Kidane et al. 2007; McDougall and Brown 2008).

2.7 The Morphological Responses to the Cenozoic Geodynamic Events

Three main physiographic provinces characterize the Ethiopian region: the highlands, represented by the northern and southern Ethiopian plateaus and Somali plateau, the Afar depression, and the MER (Fig. 2.1). The birth, evolution, and present-day morphology of these provinces, although not achieved at the same time, are linked to the uplift and rifting of the Afro-Arabian plate since the Oligocene.

2.7.1 The Ethiopian Plateaus and their Uplift

Using observations from along the Gulf of Aden, Dainelli (1943) assumed an Eocene age for the main uplift of the whole Horn of Africa and claimed that has occurred prior to the trap outpouring and rifting episodes. He was also the first to visualize the uplift by drawing contours of the present surface of the crystalline basement.

The issue of the exact time of uplift is still strongly debated. Mohr (1967) and Mohr and Zanettin (1988) assumed that the major uplift of the Afro-Arabian swell occurred during the Pleistocene. Alternatively, Merla et al. (1979) proposed that the domal uplift started in the Oligocene with a climax at the beginning of the Miocene at about 25 Ma, inferring this timing of events from the stratigraphy of the Neogene formations in the Somali shoulder along the Gulf of Aden.

More recently, Pik et al. (2003) suggested on the basis of (U-Th)/He thermochronometry that the Ethiopian plateau has been an elevated and stable dome since the Oligocene, with its highest region along the present-day Afar escarpment. The regional high structure was the result of the combined effects of the Afar plume impingement and associated large basalt effusions (see also Ebinger and Sleep 1998). According to Pik and coworkers, steady-state erosion commenced in the Blue Nile canyon as early as 25–29 Ma and is still active. About 20 My ago, the drift of the Arabian plate and a concomitant collapse along the western Afar margin gave rise to the Afar depression (Pik et al. 2003).

The morphotectonic history of the northern Ethiopian plateau has also been assessed by Gani et al. (2007) using the long-term incision rate of the Blue Nile catchment. Their picture proposes that starting from a broad dome with slow rate of uplift from 29 to 10 Ma (phase I), a rapid rate of increase in the uplift occurred at 10 Ma (phase II) followed by a dramatic plateau rise at 6 Ma (phase III).

An episodic succession of tectonic events is also accepted by Ismail and Abdelsalam (2012) on the basis of morphotectonic analyses of the Tekeze and Blue Nile drainage systems. The first event, characterized by a low to moderate incision rate over the entire plateau, was associated with a broad and regional uplift of the plateau after the impingement of the Afar plume at ca. 30 Ma. The second event resulted in the localized increase of the incision rate controlled by the buildup of the shield volcanoes at ca. 22 Ma along the Tekeze and Blue Nile watercourses. A particularly significant increase in the incision rate took place at ca. 11 Ma, but was limited to the eastern portions of the Tekeze and Blue Nile catchments. It was the result of the rapid uplift of the eastern margin of the plateau facing the Afar depression.

Paleobotanical data can also be used to decipher the complex history of uplift of the Ethiopian plateau. Near Lake Tana, 130 m of fluviolacustrine sediments are interbedded with lavas in the middle/upper portion of the traps. They are the famous Chilga intertrappean beds renowned for their vertebrate and flora content (among others, Unger 1866; Merla and Minucci 1938; Yemane et al. 1987; Kappelman et al. 2003; Currano et al. 2011; Abbate et al. 2014). Their Ar/Ar age of 27.4 Ma has been obtained from an intercalated ash layer (Kappelman et al. 2003). The Chilga beds with their Guineo-Congolean wet forest trees and palynoflora devoid of gymnosperms were deposited at an altitude much lower than the 1,950 m of their present-day elevation (Yemane et al.1987). On the basis of this broad indication, we tentatively assume that the Chilga beds were deposited at an altitude not higher than 900–1,000 m. Thus, the difference from the present-day elevation would be ca. 1,000 m and has to be ascribed to the uplift of this plateau segment after 27 Ma. The Chilga beds also provide constraints relevant to the height of the pre-trappean surface above the sea level. Since they lie above ca. 600 m of trap basalts and were deposited, as we assumed, at ca. 1,000 m, we deduce a modest (ca. 400 m) elevation for the pre-trappean surface. This argues against a pronounced pre-trappean regional doming.

As to the age of the uplift, the Ethiopian plateau began to rise at ca. 20 Ma according to Moucha and Forte (2011) who applied a numerical model of mantle flow to reconstruct the uplift amount and time in East Africa.

For the southern Ethiopian and Somali plateaus, detailed morphotectonic data are scanty apart from cursory mentions within general papers on the Horn of Africa.

The southern Ethiopian plateau reaches its highest elevations along the eastern margin close to the MER (over 3,000 m in the Guraghe region) and progressively slopes westward to the Sudan lowlands and southward to the Turkana depression. A low elevation peneplained pre-trappean surface, continuously covered by laterites, is suggested by Davidson and Rex (1980). Conversely, a pre-trappean doming stage is tentatively put forward by Woldegabriel et al. (1990) on the basis of a tilted Mesozoic sequence unconformably overlain by Oligocene basalts in the Kella horst (Guraghe region), but fission-track analyses in the same region indicate that updoming and concomitant denudation of the Kella horst did not begin before the Late Miocene (Abebe et al. 2010).

To these conflicting hypotheses, we add that, as in the case of the northern plateau (Chilga), palynological data are also available for the southern plateau for paleoaltitude assumptions. Samples collected by Wolela (2007) in the Oligocene intertrappean sediments in the Jimma region at altitudes between 1,700 and 2,200 m proved to lack gymnosperms. As in the northern plateau, this absence points to an altitude much lower than that of the present day and, consequently, to an uplift substantially after the accumulation of the main trap effusion.

The Somali plateau, another sector of the Ethiopian highlands, reaches elevations of more than 3,000 m along its margins facing the Afar depression and the MER. It gradually slopes down toward the southeast (Ogaden and Indian Ocean). The scarce available data on the time and amount of its uplift derive from these margins. Juch (1980), who has studied a large extent of the Somali plateau escarpment, proposes a major uplift of 1,500 m younger than 2–3 Ma. Near the margin of the plateau, this uplift was accomplished along large normal faults cutting previous flexure-like structures.

In a wider regional analysis, many authors, beginning with Pickford (1990), have pointed out that the uplift of the East Africa plateaus caused a drastic reorganization of atmospheric circulation. This induced strong hydroclimatic changes and heavy impacts on ecosystems with a trend toward more arid conditions. The first event of the East African aridification, marked by an expansion of savanna grassland replacing the wet forests, occurred around 8–10 or 13.5 Ma (Sepulchre et al. 2006; Bonnefille 2010; Wichura et al. 2010).

From the discussion presented above, we conclude that the uplift of East Africa occurred essentially during the Middle/Late Miocene after the trap accumulation. By the Early/Late Oligocene transition, these volcanic successions had produced a wide bulge, particularly pronounced in the eastern portion of the northern Ethiopian plateau. At that time, the drainage was poorly defined due to the reorganization of the African river network (Goudie 2005; Stankievicz and De Witt 2006). Beginning in the Early Miocene, shield volcanoes were superimposed on the northern Ethiopian highland and began to control the courses of the Blue Nile and Tekeze rivers with their circular bases (Fig. 2.1). The courses of these rivers became annular and stable through pronounced erosional action enhanced by the rise of the highland. Incised valleys developed in their upper reaches and have gradually evolved into the present-day canyons to 1,600 m deep. Starting from the Miocene, in addition to the updoming, the Ethiopian region experienced the Afar rifting and, successively, the development of the MER. These tectonic events affected the plateau margins and caused further uprise due to flexural deformations. These marginal uplifts have firmly established the present-day fluvial systems. In the Somali plateau, the consequence was a pronounced dendritic drainage toward the Indian Ocean with canyons in the upper reaches of the Juba and Webi Shebeli rivers (Fig. 2.1).

2.7.2 The Afar Depression and Adjacent Plateau Margins

The Afar depression is bounded to the west by the N–S-trending, 700-km-long northern Ethiopian escarpment, to the south by the W–E trending, 350-km-long Somali plateau escarpment, and to the east by the NNW–SSE trending, 700-km-long Danakil/Ali Sabieh block (Fig. 2.14). Its minimum elevation reaches 120 m below sea level in the northern sector where the axial volcanic ranges of the volcanic shield complexes dominate the landscape.

As previously discussed, the northern Ethiopian and Somali escarpments are characterized by a continuous flexure (Figs. 2.14 and 2.23) (Mohr 1962; Abbate and Sagri 1969, 1980; Justin-Visentin and Zanettin 1974; Zanettin and Justin-Visentin 1975; Morton and Black 1975; Juch 1975; Beyene and Abdelsalam 2005) with the exception of short segments north of 13°N and in the Harar-Dire Dawa area which show block tilting toward Afar (e.g., Abbate and Sagri 1980; Beyene and Abdelsalam 2005).

The onset of the escarpment formation along the western margin of Afar varies in age from north to south (Zanettin and Justin-Visentin 1975): latest Oligocene (24 Ma) in the northern sector, and between 13 and 8 Ma southward. The foot of the escarpment along the whole margin was affected during the Plio-Pleistocene by major normal faults dipping east.

The westernmost escarpment of the Somali plateau underwent a downflexing toward Afar during the Miocene with important normal faults activity in the Pliocene (Juch 1975). In the remaining portion of the Somali plateau escarpment, near Dire Dawa, block faulting becomes predominant and involves mainly Mesozoic sediments and, subordinately, trap basalts of latest Oligocene to Miocene age. Horizontal Afar Stratoid basalts of Late Miocene to Pliocene age seal the block-faulted structures (Juch 1975; Ethiopian Institute of Geological Survey, Dire Dawa sheet 1985).

Both the flexural structures and block faulting, involving a deformed belt 50–100 km wide, produced rugged slopes at the margins of the tabular Ethiopian highlands (Fig. 2.1). The deformation is most pronounced parallel to the margins with closely spaced faults and dikes. Morphological features characteristic of the edge of the northern Ethiopian plateau and associated with the marginal graben are long river reaches parallel to the margin (from north to south, Gabala in the Garsat plain, Alomata in the Kobo plain, Borkenna in the homonymous basin) locally giving rise to endorheic lakes (Ashangi, Haik-Ardibbo) (Fig. 2.13).

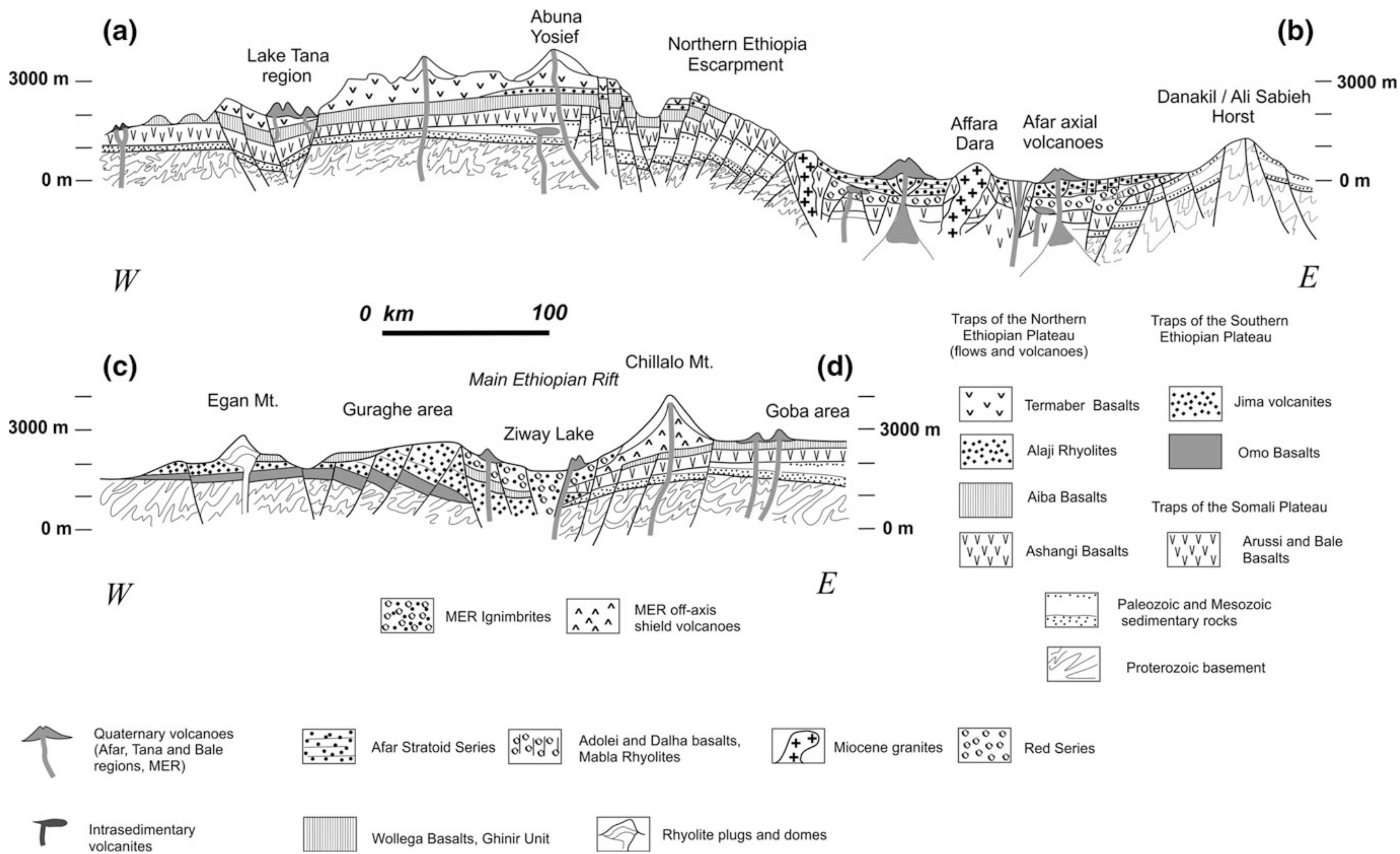

Fig. 2.23 Cross sections across northern (*A–B*) and southern (*C–D*) Ethiopia; location in Fig. 2.14. Modified after Merla et al. (1979) and Abbate and Sagri (1980)

The eastern margin of the Afar depression lies against the so-called Danakil block. This continental microplate stretches from the Gulf of Zula to the Gulf of Tadjoura and is interposed between the Afar depression and the southern Red Sea. It is composed of Proterozoic basement covered by Mesozoic sediments, trap basalts, and southward by Neogene volcanites including large edifices. The Danakil block reaches an elevation of 1,300 m in its northern portion and more than 2,000 m to the south (Sork Ale and Mussa Ale volcanoes, Fig. 2.13). No recent structural data are available for this Afar margin facing the Danakil block. According to the geological map by Brinckmann and Kürsten (1970) and in Bannert et al. (1970), flexures seem to affect most of it.

The youthful morphology of the Afar depression is substantially the result of Plio-Pleistocene events connected with the thinning of the crust and the first oceanization episodes. The magmatic and tectonic processes produced wide areas covered by the flood basalts of the Afar Stratoid Series, imposing axial shield volcanoes, and, in the central and southern sector mainly, an intricate network of fractures and faults (CNR-CNRS 1971, 1975) (Fig. 2.14).

The morphotectonic features vary from north to south. Over a distance of 200 km at the triangular apex of the Afar depression, between the Gulf of Zula and Lake Afrera, the Erta Ale axial shield volcano dominates an inhospitable, but fascinating, landscape. This segment of the Afar depression has a maximum width of ca. 100 km along 13° Lat. N and hosts at its margins the exclusive occurrences of the bright-red Miocene Danakil Formation. At its extreme north, the depression merges into the 10-km-wide Gulf of Zula bounded by Proterozoic basement rocks and terminates at the Alid axial volcanic range.

South of 13° Lat. N, the regional picture changes abruptly, probably in connection with a W/E regional tectonic alignment. The morphotectonic scenario becomes particularly complex and dominated by a series of narrow graben (often half-graben, e.g., Abbate et al. 1995; Acocella 2010) a few km wide and some tens of km long. Their sedimentary filling has been referred to as the axial basins. According to Hayward and Ebinger (1996) and Beyene and Abdelsalam (2005), three divisions can be recognized in central and southern Afar (Fig. 2.14). The east-central area is affected by a diffuse rifting, trending from NNW–SSE to W–E, and in many cases forming curvilinear structures (e,g., Immino graben). This area is bounded to the SW and south by the Tendaho-Goba Ad rift, a major structure with a length of ca. 300 km and a width up to 50 km (Acocella et al. 2008). The southeastern area is characterized by a W–E fault system parallel to the Somali plateau escarpment. In the southwestern area, the NNE–SSW fault trend of the MER, which propagates in this sector of Afar, is dominant.

Toward the west and south of this complex tectonic region, peripheral basins developed at the base of the Ethiopian and Somali escarpments in connection with intense downfaulting, subsidence, and crustal stretching.

The structural complexity of the Afar depression, particularly evident in the central and southern sectors, is the result of the interactions of geodynamic events affecting the Afro-Arabian plate since the Early Miocene. The structural history began with the anticlockwise rotation of the Danakil microplate (Baker 1970; Burek 1970; Sichler 1980) which caused it to detach from the Nubian plate with a later northward movement (Chorowicz et al. 1999; Beyene and Abdelsalam 2005). This was also facilitated by the NE drift of the Arabian plate.

By ca. 10 Ma, the Gulf of Aden propagator with its active spreading axis progressively invaded the southern Afar region between the Somali plateau and the southern portion of the Danakil block. Subsequently, the extension of the MER propagated northward into the southern Afar depression giving rise to a full-fledged triple junction (Wolfenden et al. 2004). Within the Afar east-central area, rotation of small blocks resulted in curvilinear grabens cut into the Afar Stratoid Series (e.g., Barberi and Varet 1977; Manighetti et al. 1998).

2.7.3 Morphotectonic History of the Main Ethiopian Rift

The MER is the salient morphotectonic feature that together with the southern Ethiopian and Somali highlands constitutes the spectacular scenery of the southern Ethiopia landscape. This depressed area hosts beautiful lakes, also famous for their bird life. They have a tectonic or volcanic origin and are variously colored, from the blue of Shala, the green of Bishoftu, the whitish of Abiyata, and the pink of Langano and Abaya, to the pearl gray of Chamo. All these lakes form endorheic systems connected by outlet–inlet fluvial reaches or by groundwater infiltration (Street 1979). The southern end of this endorheic system is located in the present-day ephemeral Chew Bahir lake, described at the end of nineteenth century as a wide stretch of permanent water pool. During the Late Quaternary wet periods, Lakes Abaya and Chamo were connected to Lake Turkana through the Sagan river and Lake Chew Bahir. In turn, Lake Turkana overspilled via the Akobo–Sobat rivers into the White Nile river system (Butzer et al. 1972; Street 1979). This Mediterranean connection is testified by the occurrence of the typical Nilotic Nile perch (Tilapia) in Lakes Abaya and Chamo.

The MER is confined between the uplifted shoulders of the southern Ethiopian and Somali highlands (Figs. 2.1 and 2.23). The escarpments can be very steep with a difference in altitude of 1,000–1,500 m from the plateau margin to the rift floor (e.g., Guraghe) and narrow (5–7 km) and are marked by major border normal faults. In other places (e.g., east of Langano), the shoulder is less steep and the difference is up to 1,000 m. Also the width of the escarpments varies between 10 and 20 km and is characterized by a series of steeply dipping faults with individual vertical displacement of 200–300 m, covered by a veneer of ignimbrites (Di Paola 1972).

From a morphological and geological point of view, the MER has been subdivided into three main segments: the northern, central, and southern (Mohr 1983; Woldegabriel et al. 1990; Hayward and Ebinger 1996; Bonini et al. 2005) (Fig. 2.14). The northern MER funnels from the Afar depression, where it is about 100 km wide, to the 80-km-long Dubeta Col sill (north of Ziway lake). The central MER, which is 80 km wide, includes most of the lake region and extends southward up to the W/E Goba–Bonga line (Fig. 2.14). This portion of the MER has an average elevation of 1,600 m, and the lowest altitude is at Lake Abiyata (1,580 m). At the Bonga–Goba line, the southern MER narrows up to 60 km, shifts to a N–S trend, and reaches an elevation of 2,000 m, decreasing southward to 1,000 m. From its middle portion to the south, the southern MER bifurcates into two branches (the Lake Chamo and Galana river rifts) separated by the 3,000-m-high Amaro horst ("a small Ruwenzori" according to Mohr 1967). The southern MER keeps its morphological identity until the Sagan line. To south and west of this, a wide basin and range structure connects the MER with the Kenyan rift (Fig. 2.14).

The rift floor is not uniformly flat but is occupied by recent volcanic edifices rising some hundreds of meters above the plain (e.g., Fantale, Boseti Gudda, Alutu, Tosa Sucha) and calderas (e.g., Gademota, lake Shala O'a caldera) (Fig. 2.13). Furthermore, the strongly deformed Wonji fault belt (see later) is characterized by rough and irregular morphology with narrow uplifted blocks, valleys, lava fields, spatter cones, and swampy depressions.

The origin of the MER, a continental rift with an average crustal extension rate of about 2.5 mm/a (Wolfenden et al. 2004), or 6.0 mm/a according to Corti (2009), is still a matter of debate. It has been related to pure tensional deformation by McKenzie et al. (1970), Di Paola (1972), and Le Pichon and Franchetau (1978). A sinistral shear component has been postulated by Mohr (1968), Gibson (1969), Kazmin (1980), and Boccaletti et al. (1992). According to Bonini et al. (1997) and Boccaletti et al. (1998), a sinistral oblique rifting related to an E–W extension followed a pure extension orthogonal to the rift trend, whereas Chorowicz et al. (1994) maintain that a right-lateral component of motion along the rift structure produced a NW-to-NNW-oriented extension.

The MER development was characterized by an early phase (Mio-Pliocene, Corti 2008) of activity of a series of large boundary fault-formed local asymmetric basins (e.g., Abbate and Sagri 1980; Kazmin et al. 1980; Woldegabriel et al. 1990; Boccaletti et al. 1992; Corti 2009) (Fig. 2.23). The total vertical displacement across the boundary faults reaches some thousand meters. Above the pre-Cambrian basement and Mesozoic sediments, the rift is floored by ca. 1,000 m of syn-rift Miocene to Recent volcanoclastic and sedimentary deposits (Cornwell et al. 2010).

This early phase was followed during the Pleistocene by a rift-in-rift stage, in which volcanic and tectonic activity was concentrated riftward with right-stepping en-echelon magmatic segments, the Wonji fault belt (Mohr 1962; Gibson 1969; Kazmin et al. 1980; Boccaletti et al. 1992; Chorowicz et al. 1994; Ebinger and Casey 2001; Wolfenden et al. 2004; Bonini et al. 2005; Corti 2009). In this phase, the bordering faults were no longer active and the deformation was magma assisted with diffuse diking (Ebinger and Casey 2001; Ebinger 2005). According to Bonini et al. (1997), Boccaletti et al. (1998), and Wolfenden et al. (2004), the first and second phases were related to rift orthogonal and oblique extension, respectively. However, Corti (2008) showed that both phases may have resulted from a constant post-10-Ma oblique rifting in line with early suggestions by Gibson (1969).

There is a general consensus that rifting was diachronous along the whole MER. Woldegabriel et al. (1990) recognized a 18–15-Ma rifting initiation in the southern and central MER with extension in the northern MER commencing after ca. 11 Ma (see also Ebinger and Casey 2001; Wolfenden et al. 2004). Bonini et al. (2005) propose a different picture with the onset of rifting in the southern MER between 20 and 11 Ma connected to the deformation of the Kenyan rift. At that time, no major tectonic activity was affecting the central and northern MER sectors. At the northern end of the MER, the southward rift propagation started from the Afar depression and progressively affected the northern MER in the Late Miocene (11 Ma), the central MER in the Pliocene (5.6–3 Ma), and, eventually, joined the southern MER in the Late Pliocene/Pleistocene (3–0 Ma). For the central MER, the timing is consistent with the thermochronology data provided by Abebe et al. (2010).

2.8 Conclusions

After the Neoproterozoic orogenic cycle, the cratonic history of the Ethiopian region was dominated by phases of vertical motion and rifting recorded by various erosional cycles. They are marked by regional planation surfaces (Fig. 2.6) which constitute geomorphological features useful in deciphering the different stages of the geological history of the Ethiopia (see also Coltorti et al. this volume).

The oldest and particularly significant planation surface (PS 1) results from the intense erosion which destroyed any relief of the Precambrian orogeny across the whole of East Africa. Some occurrences of more resistant granites and gneisses escaped this peneplanation and presently stand as inselbergs along the Ethiopia/Sudan boundary (Fig. 2.3).

The PS 1 records a time gap of at least one hundred million years (between the emplacement of the post-orogenic batholiths and the deposition of the Ordovician sediments), during which planation and lateritization took place.

The Triassic planation surface (PS 2) is mainly limited to northern Ethiopia where it intersects a few preserved patches of Paleozoic fluvial and glacial deposits. This surface marks a relatively short period of erosion and/or non-deposition, and in some basins, it is lacking with a continuous succession from Paleozoic to Jurassic (e.g., in the Ogaden).

The Cretaceous planation surface (PS 3) cuts across the Middle-to-Late Jurassic marine sediments and is most evident in northern Ethiopia where it represents a key marker (Coltorti et al. 2007) and is overlain by continental Cretaceous (Aptian–Albian) sandstones. The development of this surface spans a period of a few tens of million years.

After the Late Jurassic marine regression and deposition of Cretaceous continental deposits, the Ethiopian region was an exposed land affected by tectonic deformation and regional uplifts for a period of about 70 Ma. A planation surface (PS 4) developed before the trap outpouring, cutting the previous sedimentary successions, in some cases, down to the basement. It is recognizable over all the Ethiopian region and could correspond on a continental scale to the African Surface of Burke and Gunnel (2008). The topographical elevation of PS4 at the time of the traps outpouring was modest, a few hundred meters above sea level, according to the information provided by the palynoflora assemblages preserved in the intertrappean sediments of the northern plateau (Chilga, Tana lake area) as well as the southern (Jima area) Ethiopian plateaus. This is good evidence against the hypothesis of a prominent pre-trappean updoming affecting the whole Ethiopian region.

The Tana and Jima areas also provide constraints on the amount and timing of their uplift. Indications from there suggest that uplift reached a maximum of one thousand meters and was achieved after the major volcanic outpouring. Similar relationships between uplift and time were probably common to both Ethiopian plateaus. The volcanic activity, particularly prolific around 30 My, and the uplift of the Ethiopian region were essential in producing a bulge which resulted in high elevated plateaus. This new topographic barrier induced the reorganization of the eastern Africa river network with a shifting of the regional divide eastward. Rivers, originally flowing toward the Indian Ocean, were gradually captured by the Mediterranean-directed paleo-Nile system (Said 1993; Goudie 2005).

As to the role of a mantle plume in the morphogenesis of the Ethiopian region, the local impingement of a rising mantle plume has been considered as a possibility since the 1970s by Morgan (1971). Ebinger and Sleep (1998) proposed a model with a single large plume beneath the Ethiopian plateau with lateral flows exploiting preexisting lithospheric thinnings. A different reconstruction was provided by George et al. (1998) who envisage a Kenya plume initiating at 45 Ma and a 15 Ma younger Afar plume. More recent authors (e.g., Furman et al. 2006; Meshesha and Shinjo 2008) reconsidered the African superplume hypothesis of Ritsema et al. (1999) and assumed multiple plumes stemming from this large-scale thermal upwelling.

The impact of the plume (or plumes) was concomitant with the dismembering of the Nubia/Arabian continental block. During the Oligo-Miocene transition, the Danakil block began to separate from Nubia leaving behind the Afar region, and after a few million years, the Somali plate began to separate from Nubia with the development of the MER.

In addition to its salient morphological features, the Ethiopian region records some of the most important events of the Earth history since the Neoproterozoic:

(i) The aggregation of the East and West Gondwana continental blocks to form the Gondwana supercontinent and the development of the East Africa Orogen.
(ii) The long plate stillness of the southern portion of Gondwana during the Paleozoic with the erosion of the Late Proterozoic mountain chains and development of a wide planation surface.
(iii) The major, widespread, and long-lasting glaciation during the Carboniferous to Early Permian with Ethiopia located at the margin of the southern hemisphere ice sheet of Pangea.
(iv) The beginning of the breakup of Gondwana and the related Jurassic sea-level highstand resulting in the East Africa marine ingression from the Paleotethys and the India/Madagascar nascent ocean.
(v) The profuse and rapid basaltic activity which contributed to the Oligocene climatic deterioration and ensuing mass extinctions at a global scale.
(vi) The uplift of the East Africa plateaus which resulted in a drastic reorganization of atmosphere circulation and river pattern during the Late Neogene.
(vii) The development of a variegated landscape with well-defined rift valleys which prompted the birth, evolution, and radiation of the human species later impelled to colonize more suitable territories in nearby continents.

Acknowledgments Constructive commentaries and careful editorial suggestions by Frances Williams (Adelaide University, Australia) greatly improved the manuscript. The authors have benefited from helpful discussions in the field with Abebe Tsegaye (MASSA Spin off, Pisa, Italy) and Miruts Hagos (Mekele University, Ethiopia) and in the office with Marco Bonini, Giacomo Corti, and Federico Sani (Department of Earth Sciences, Florence University, Italy). Special thanks to World Geomorphological Landscapes Series Editor Piotr Migoń (University of Wrocław, Poland) for his precious editorial assistance. We are grateful to Volume Editor Paolo Billi (Ferrara University, Italy) who prompted our contribution and gave valuable suggestions.

References

Abbate E, Sagri M (1969) Dati e considerazioni sul margine orientale dell'altopiano etiopico nelle province del Tigrai e del Wollo. Boll Soc Geol It 88:489–497

Abbate E, Sagri M (1980) Volcanites of Ethiopian and Somali Plateaus and major tectonic lines. Atti Convegni Acc Lincei Roma 47:219–227

Abbate E, Passerini P, Zan L (1995) Strike-slip faults in a rift area: a transect in the Afar Triangle, East Africa. Tectonoph 241:67–97

Abbate E, Albianelli A, Azzaroli A, Benvenuti M, Tesfamariam B, Bruni P, Cipriani N, Clarke RJ, Ficcarelli G, Macchiarelli R, Napoleone G, Papini M, Rook L, Sagri M, Tecle TM, Torre D, Villa I (1998) A one-million-year-old *Homo* cranium from the Danakil (Afar) depression in Eritrea. Nature 393:458–460

Abbate E, Woldehaimanot B, Bruni P, Falorni P, Papini M, Sagri M, Girmay S, Tecle TM (2004) Geology of the Homo-bearing Pleistocene Dandiero basin (Buia region, Eritrea Danakil Depression). Riv It Paleont Strat 110:5–34

Abbate E, Bruni P, Coppa A, Aria D, Ferretti MP, Libsekal Y, Rook L, Sagri M (2012) A new Oligocene-Miocene mammal-bearing site from a sedimentary intercalation in the Trap basalts of central Eritrea. Riv It Paleont Strat 118:545–550

Abbate E, Bruni P, Ferretti MP, Delmer C, Laurenzi MA, Hagos M, Bedri O, Rook L, Sagri M, Libsekal Y (2014) The Oligocene intertrappean beds: regional distribution, depositional environments and Afro/Arabian mammal dispersal corridors. J Afr Earth Sci 99:463–489

Abebe T, Mazzarini F, Innocenti F, Manetti P (1998) The Yerer-Tullu Wellel volcanotectonic lineament: a transtensional structure in central Ethiopia and the associated magmatic activity. J Afr Earth Sci 26:135–150

Abebe T, Balestrieri ML, Bigazzi G (2010) The Central Main Ethiopian Rift is younger than 8 Ma: confirmation through apatite fission-track thermochronology. Terra Nova 22:470–475

Abul-Haggag Y (1961) A contribution to the physiography of Northern Ethiopia. University of London Athlone Press, London, 153 pp

Acocella V (2010) Coupling volcanism and tectonics along divergent plate boundaries: collapsed rifts from central Afar, Ethiopia. Geol Soc Am Bull 122:1717–1728

Acocella V, Abebe B, Korme T, Barberi F (2008) Structure of Tendaho Graben and Manda Hararo Rift: implications for the evolution of the southern Red Sea propagator in Central Afar. Tectonics 27 (TC4016). doi:10.1029/2007TC002236

Alvarez F (1540) Verdadeira Informação das Terras do Preste João das Indias. 458 pp

Andrews Deller ME (2006) Facies discrimination in laterites using Landsat Thematic Mapper, ASTER and ALI data—examples from Eritrea and Arabia. Int J Remote Sens 27:2389–2409

Arambourg G (1972) Expedition internationale de rechérche paléontologique dans la vallèe de l'Omo, Ethiopie, en 1967. Proc Pan Afr Congr Prehist 6:135–140

Asfaw B, Gilbert WH, Beyene Y, Hart WK, Renne PR, WoldeGabriel G, Vrba ES, White TD (2002) Remains of *Homo erectus* from Bouri, Middle Awash, Ethiopia. Nature 416:317–320

Baker BH (1970) The structural pattern of the Afro-Arabian rift system in relation to plate tectonics. Phil Trans Roy Soc London A267:383–391

Baker BH, Mohr PA, Williams LAJ (1972) Geology of the eastern rift system of Africa. Geol Soc Am Spec Pap 136:67 pp

Baker J, Snee L, Menzies M (1996) A brief Oligocene period of flood volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the Afro-Arabian triple junction. Earth Planet Sci Lett 138:39–55

Baldacci L (1891) Osservazioni fatte nella Colonia Eritrea e pubbl. a cura del R.Ufficio Geologico con una carta. Tipografia Nazionale Roma 110 pp

Bannert D, Brinckmann J, Käding KCh, Kretsch G, Kürsten N, Mayrhofer H (1970) Zur Geologie der Danakil Senke (Nördliches Afar Gebiet), NE Aethiopien. Geol Rund 59:409–443

Barberi F, Varet J (1977) Volcanism of Afar: small-scale plate tectonics implications. Geol Soc Am Bull 88:1251–1266

Barberi F, Borsi S, Ferrara G, Marinelli G, Varet J (1970) Relations between tectonics and magmatology in the northern Danakil depression (Ethiopia). Philos Trans R Soc Lond A267:293–311

Barberi F, Tazieff H, Varet J (1972) Volcanism in the Afar depression: its tectonic and magmatic significance. Tectonoph 15:19–29

Barberi F, Ferrara G, Santacroce R, Varet J (1975) Structural evolution of the Afar triple junction. In: Pilger A, Roesler EA (eds) Afar Depression of Ethiopia. Schweizerbart, Stuttgart, pp 38–54

Barnes SU (1976) Geology and oil prospects of Somalia, East Africa. Am Assoc Pet Geol Bull 60:389–413

Battistelli A, Yiheyisb A, Calore C, Ferragina C, Abatnehb W (2002) Reservoir engineering assessment of Dubti geothermal field, Northern Tendaho Rift, Ethiopia. Geothermics 31:381–406

Beauchamp J (1977) La série sédimentaire en Ethiopie central and oriental. Ph.D. thesis, University Claude Bernard Lyon, 419 pp

Beccaluva L, Bianchini G, Natali C, Siena F (2009) Continental flood basalts and mantle plumes: a case study of the Northern Ethiopian Plateau. J Petrol 50:1377–1403

BEICIP (1985) Geological map of Ogaden and surrounding area, scale 1:1,000,000. Ministry of Mines and Energy Addis Ababa

Benvenuti M, Carnicelli S, Belluomini G, Dainelli N, Di Grazia S, Ferrari GA, Iasio C, Sagri M, Ventra D, Atnafu B, Kebede S (2002) The Ziway-Shala lake basin (main Ethiopian rift, Ethiopia): a revision of basin evolution with special reference to the Late Quaternary. J Afr Earth Sci 35:247–269

Bernor RL, Kaiser TM, Nelson SV (2004) The oldest Ethiopian Hipparion (Equinae, Perissodactyla) from Chorora: systematics, Paleodiet and Paleoclimate. Cour Forsch Inst Senckenberg 246:213–226

Beyene A, Abdelsalam MG (2005) Tectonics of the Afar depression: a review and synthesis. J Afr Earth Sci 41:41–59

Beyth M (1972) The geology of central and western Tigray. Ph.D. thesis, Reinische Friedrick-Wilhelm University of Bonn, 200 pp

Beyth M, Stern R, Matthews A (1997) Significance of high-grade metasediments from the Neoproterozoic basement of Eritrea. Precambr Res 86:45–58

Beyth M, Avigadb D, Wetzelc HU, Matthewsb A, Berhe SM (2003) Crustal exhumation and indications for Snowball Earth in the East African Orogen: north Ethiopia and east Eritrea. Precambr Res 123:187–201

Blanford WT (1869) On the geology of a portion of Abyssinia. Q J Geol Soc London 25:401–406

Blanford WT (1870) Observations on the geology and zoology of Abyssinia, made during the progress of the British expedition to that country in 1867–68. Macmillan, London, 487 pp

Boccaletti M, Getaneh A, Tortorici L (1992) The main Ethiopian Rift: an example of oblique rifting. Ann Tectonicae 6:20–25

Boccaletti M, Bonini M, Mazzuoli R, Abebe B, Piccardi L, Tortorici L (1998) Quaternary oblique extensional tectonics in the Ethiopian Rift (Horn of Africa). Tectonoph 287:97–116

Bonini M, Souriot T, Boccaletti M, Brun JP (1997) Successive orthogonal and oblique extension episodes in a rift zone: laboratory experiments with application to the Ethiopian Rift. Tectonics 16:347–362

Bonini M, Corti G, Innocenti F, Manetti P, Mazzarini F, Abebe T, Pecskay Z (2005) Evolution of the main Ethiopian Rift in the frame of Afar and Kenya rifts propagation. Tectonics 24:TC1007. doi:10.1029/2004TC001680

Bonnefille R (2010) Cenozoic vegetation, climate changes and hominid evolution in tropical Africa. Glob Planet Change 72:390–411
Bosellini A (1989) The continental margins of Somalia: their structural evolution and sequence stratigraphy. Mem Sci Geol Padova 41:373–458
Bosellini A, Russo A, Fantozzi PL, Assefa G, Solomon T (1997) The Mesozoic succession in the Mekele outlier (Tigrai province, Ethiopia). Mem Sci Geol Padova 49:95–116
Bosellini A, Russo A, Schroeder R (1999) Stratigraphic evidence for an Early Aptian sea-level fluctuation: the Graua Limestone of south-eastern Ethiopia. Creta Res 20:783–791
Bosellini A, Russo A, Assefa G (2001) The Mesozoic succession of Dire Dawa, Harar Province, Ethiopia. J Afr Earth Sci 32:403–417
Bosworth W, Huchon P, McClay K (2005) The Red Sea and Gulf of Aden Basins. J Afr Earth Sci 43:334–378
Brassier M, Geleta S (1993) A planktonic marker and Callovian-Oxfordian fragmentation of Gondwana: data from Ogaden basin, Ethiopia. Palaeogeogr Palaeoclimatol Palaeoecol 104:177–184
Brinkmann J, Kürsten M (1970) Geological sketch map of the Danakil Depression, scale 1:250,000. Bunderanstalt für Bodenforschungen, Hanover
Burek PJ (1970) Paleomagnetic evidence for an anti-clockwise rotation of the Danakil Alps, Ethiopia. Eos Trans Am Geophys Un Abs 51:271
Burke K, Gunnell Y (2008) The African erosion surface: a continental-scale synthesis of geomorphology, tectonics, and environmental change over the past 180 Million Years. Geol Soc Am Mem 201:66 pp
Bussert R, Schrank E (2007) Palynological evidence for a latest Carboniferous-Early Permian glaciations in Northern Ethiopia. J Afr Earth Sci 49:201–210
Butzer KW, Isaac GL, Richardson JL, Washbourn-Kamau C (1972) Radiocarbon dating of East Africa lake levels. Science 175:1069–1076
Chavaillon J (1971) Les habitants acheuleens de Melka-Kontoure. Proc PanAfr Congr Prehist 230:17–25
Chorowicz J, Collet B, Bonavia FF, Korme T (1994) Northwest to north-northwest extension direction in the Ethiopian Rift deduced from orientation of the extension structures and fault slip analysis. Geol Soc Am Bull 105:1560–1570
Chorowicz J, Collet B, Bonavia FF, Korme T (1999) Left-lateral strike-slip tectonics and gravity induced individualization of wide continental blocks in the western Afar margin. Eclogae Geol Helv 92:149–158
Clark JD (1985) Découvertes effectuée dans le middle Awash en 1981. L'Anthropologie 88:129–130
CNR-CNRS (1971) Geological map of the northern Afar, scale 1:500,000. Geotechnip, La Celle St. Claude
CNR-CNRS (1975) Geological map of the central and southern Afar, scale 1:500,000. Geotechnip, La Celle St. Claude
Coltorti M, Dramis F, Ollier CD (2007) Planation surfaces in northern Ethiopia. Geomorphology 89:287–296
Cornwell DG, Maguire PKH, England RW, Stuart GW (2010) Imaging detailed crustal structure and magmatic intrusion across the Ethiopian Rift using a dense linear broad band array. Geochem Geophys Geosyst 11. doi:10.1029/2009GC002637
Corti G (2008) Control of rift obliquity on the evolution and segmentation of the main Ethiopian rift. Nature Geosci 1:258–262
Corti G (2009) Continental rift evolution: from rift initiation to incipient break-up in the main Ethiopian Rift, East Africa. Earth Sci Rev 96:1–53
Coulié E, Quideleur X, Gillot PY, Courtillot V, Lefevre JC, Chiesa S (2003) Comparative K–Ar and Ar/Ar dating of Ethiopian and Yemenite Oligocene volcanism: implications for timing and duration of the Ethiopian traps. Earth Planet Sci Lett 206:477–492
Courtillot V, Féraud G, Maluski H, Vendamme D, Moreau MG, Besse J (1988) Deccan flood basalts and the Cretaceous/Tertiary boundary. Nature 333:843–846
Currano ED, Jacobs BF, Pan AD, Tabor NJ (2011) Inferring ecological disturbance in the fossil record: a case study from the late Oligocene of Ethiopia. Palaeogeogr Palaeoclimatol Palaeoecol 309:242–252
Dainelli G (1943) Geologia dell'Africa Orientale. (3 vols. text, 1 vol. maps). Reale Accademia Italia, Roma, 1916 pp
Dainelli G, Marinelli O (1912) Risultati scientifici di un viaggio nella Colonia Eritrea. Pubblicazioni Regio Istituto di Studi Superiori Pratici e di Perfezionamento Firenze, 601 pp
Davidson A (1983) Reconnaissance geology and geochemistry of parts of Illubabor Kefa, Gemu Gofa and Sidamo, Ethiopia. The Omo River Project, Ministry of Mines and Energy, Ethiopian Institute of Geological Survey Bull, 289 pp
Davidson A, Rex CD (1980) Age of volcanism and rifting in southwestern Ethiopia. Nature 283:657–658
deHeinzelin J (ed) (1983) The Omo Group. Koninklijk Muesum voor Midde-Afrika, Tervuren Belgie Annalen 85:365 pp
Di Paola GM (1972) The Ethiopian Rift Valley (between 7° 00′ and 8° 40′ lat.). Bull Volcanol 36:517–560
Dow DB, Beyth M, Hailu T (1971) Paleozoic glacial rocks recently discovered in northern Ethiopia. Geol Mag 108:53–60
Ebinger CJ (2005) Continental breakup: the East African perspective. Astronomy and Geophysics 46:2.16–2.21
Ebinger CJ, Casey M (2001) Continental breakup in magmatic provinces: an Ethiopian example. Geology 29:527–530
Ebinger CJ, Sleep NH (1998) Cenozoic magmatism through east Africa resulting from impact of a single plume. Nature 395:788–791
Ebinger CJ, Yemane T, Woldegabriel G, Aronson JL, Walter RC (1993) Late Eocene-Recent volcanism and faulting in the southern main Ethiopian rift. J Geol Soc London 150:99–108
Ethiopian Institute of Geological Survey (1985) Geological map of the Dire Dawa Sheet, scale 1:250,000, NC 37-12 Ethiopian Government Addis Ababa
Furman T, Bryce J, Rooney T, Hanan B, Yurgu G, Hayalew D (2006) Heads and tails: 30 million years of the Afar plume. In Yurgu G, Ebinger CJ, Maguire PKH (eds) The Afar volcanic province within the East Africa rift system. Geological Society Special Publications No 259, pp 95–119
Gani NDS, Gani MR, Abdelsalam MG (2007) Blue Nile incision on the Ethiopian Plateau: pulsed plateau growth, Pliocene uplift, and hominin evolution. GSA Today 17:4–11
Gani NDS, Abdelsalam MG, Gera S, Gani MR (2009) Stratigraphy and structural evolution of the Blue Nile Basin, Northwestern Ethiopia Plateau. Geol J 44:30–56
Garland CR (1980) Geology of the Adigrat Area. Geological survey of Ethiopia, Addis Ababa, 51 pp
George R, Rogers N, Kelley S (1998) Earliest magmatism in Ethiopia: evidence for two mantle plumes in one continental flood basalt province. Geology 26:923–926
Gibson IL (1969) The structure and volcanic geology of an axial portion of the main Ethiopian rift. Tectonophysics 8:561–565
Gortani M (1973) La fauna mesocretacea degli Stati di Graua. In Missione Geologica dell'AGIP nella Dancalia Meridionale e sugli Altopiani Hararini (1936–1938). Acc Naz Lincei Roma 4:3–98
Goudie AS (2005) The drainage of Africa since the Cretaceous. Geomorphology 67:437–456
Gregnanin A, Piccirillo AM (1974) Considerazioni sulle serie vulcaniche e sulla struttura dell'Altopiano Etiopico centrale. Mem Mus Tridentino Sci Nat 20:79–100
Grove AT, Street FA, Goudie AS (1975) Former lake levels and climatic changes in the rift valley of southern Ethiopia. Geogr J 141:177–202
Hagos M, Koeberl C, Kabeto K, Koller F (2010) Geochemical characteristics of the alkaline basalts and the phonolite-trachyte

plugs of the Axum area, northern Ethiopia. Austrian J Earth Sci 103:153–170
Haile-Selassie Y, Deino A, Saylor B, Umer M, Latimer B (2007) Preliminary geology and paleontology of new hominid-bearing Pliocene localities in the central Afar region of Ethiopia. Anthropol Sci 115:215–222
Haile-Selassie Y, Suwa G, White TD (2009) *Ardipithecus Kadabba*: late miocene evidence from the Middle Awash, Ethiopia. In: Haile-Selassie Y, WoldeGabriel G (eds) The middle awash series. University of California, Berkeley, pp 159–236
Hayward NJ, Ebinger CJ (1996) Variations in the along-axis segmentation of the Afar Rift system. Tectonics 15:244–257
Hofmann C, Courtillot V, Féraud G, Rochette P, Yirgu G, Ketefo E, Pik R (1997) Timing of the Ethiopian flood basalt event and implications for plume birth and global change. Nature 389:838–841
Howell FC (1969) Remains of Hominidae from Plio/Pleistocene formations in the lower Omo basin, Ethiopia. Nature 223:1234–1239
Hunegnaw A, Sage L, Gonnard R (1998) Hydrocarbon potential of the intracratonic Ogaden Basin, SE Ethiopia. J Petrol Geol 21:401–425
Ismail EH, Abdelsalam MG (2012) Morpho-tectonic analysis of the Tekeze River and the Blue Nile drainage systems on the Northwestern Plateau, Ethiopia. J Afr Earth Sci 69:34–47
Jepson DH, Athearn MJ (1964) Land and water resources of the Blue Nile Basin. Appendix II Geology US Dept Interior, Addis Ababa, p 221
Johanson DC, Taieb M (1976) Plio-Pleistocene hominid discoveries in Hadar, Ethiopia. Nature 260:293–297
Johanson DC, Splingaer M, Boaz NT (1976) Paleontological excavation in the Shungura Formation, lower Omo basin, 1969–1973. In: Coppens Y et al. (eds) Earliest man and environments in the Lake Rudolph basin: stratigraphy, paleoecology, and evolution. University Chicago Press, Chicago, pp 402–420
Johnston C (1844) Travels in southern Abyssinia through the country of Adal to the Kingdom of Shoa. Madden, London, 492 pp
Juch D (1975) Geology of the south eastern escarpment of Ethiopia between 39° and 42° long, East. In: Pilger A, Roesler EA (eds) Afar depression of Ethiopia. Schweizerbart, Stuttgart, pp 310–316
Juch D (1980) Tectonics of the southeastern escarpment of Ethiopia. Atti Convegni Acc Lincei Roma 47:407–418
Justin-Visentin E, Zanettin B (1974) Dike swarms, volcanism and tectonics of the western Afar margin along the Kombolcha-Eloa traverse (Ethiopia). Bull Volcanol 38:187–205
Kalb JE (1993) Refined stratigraphy of the hominid–bearing Awash Group, middle Awash valley, Afar depression, Ethiopia. Newsl Stratigr 29:21–62
Kalb JE, Oswald EB, Tebedge S, Mebrate A, Tola E, Peak D (1982) Geology and stratigraphy of Neogene deposits, Middle Awash valley, Ethiopia. Nature 298:17–25
Kappelmann J, Rasmussen DT, Sanders WJ, Faseha M, Bown T, Copeland P, Krabaugh J, Fleage J, Glanz M, Gordon A, Jacobs B, Maga M, Muldoon K, Pan A, Pyne L, Richmond B, Ryan T, Selffert ER, Sen S, Todd L, Wlemann MC, Winkler A (2003) Oligocene mammals from Ethiopia and faunal exchange between Afro-Arabia and Eurasia. Nature 426:549–552
Katho S, Nagaoka S, Woldegabriel G, Renne P, Snow MG, Beyene Y, Suwa G (2000) Chronostratigraphy and correlation on the Plio-Pleistocene tephra layers of the Konso formation, southern main Ethiopian Rift, Ethiopia. Quat Sci Rev 19:1305–1317
Kazmin V (1973) Geological map of Ethiopia, scale 1:2,000,000. Geological Survey of Ethiopia, Addis Ababa
Kazmin V (1980) Transform faults in the east African Rift system. Atti Convegni Acc Lincei Roma 47:65–73
Kazmin V, Shiferaw A, Balcha T (1978) The Ethiopian basement, stratigraphy and possible manner of evolution. Geol Rund 67: 531–546
Kazmin V, Seife MB, Nicoletti N, Petrucciani C (1980) Evolution of the northern part of the Ethiopian rift. Atti Convegni Acc Lincei Roma 47:275–292
Kidane T, Otofuji YI, Brown FH, Takemoto K, Eshete G (2007) Two normal paleomagnetic polarity intervals in the lower Matuyama Chron recorded in the Shungura Formation (Omo Valley, Southwest Ethiopia). Earth Planet Sci Lett 262:240–246
Kieffer B, Srndt N, Lapierre H, Bastien F, Bosh D, Pecher A, Yirgu G, Ayalew D, Weis D, Jerram DA, Keller F, Meugniot C (2004) Flood and shield basalts from Ethiopia: magmas from the African superswell. J Petrol 45:793–834
Kröner A (1985) Ophiolites and the evolution of tectonic boundaries in the late proterozoic Arabian–Nubian shields of northeast Africa and Arabia. Precambr Res 27:277–300
Kumpulainen R, Uchman A, Woldehaimanot B, Kreuser T, Ghirmay S (2006) Trace fossil evidence from the Adigrat sandstone for an Ordovician glaciation in Eritrea, NE Africa. J Afr Earth Sci 45:408–420
Kunz K, Kreuzer H, Muller P (1975) Potassium-argon age determinations of the Trap Basalts of the SE part of the Afar rift. In: Pilger A, Roesler EA (eds) Afar depression of Ethiopia. Schweizerbart, Stuttgart, pp 370–374
Lalou C, von Nguyen H, Faure H, Moreira L (1970) Datation par la method Uranium-Thorium des hautes niveaux de coraux de la dépression de l'Afar (Ethiopie). Rev Géo Phys Géol Dyn 12:3–8
Larson PJ Jr (1977) Matabaietu, an Olduwan site from the Afar, Ethiopia. Nyame Akuma 11:6–10
Le Bas MJ, Mohr PA (1968) Feldspathoid rocks from the Cainozoic volcanic province of Ethiopia. Geol Rundsch 58:273–280
Le Pichon X, Francheteau J (1978) A plate-tectonic analysis of the Red Sea-Gulf of Aden area. Tectonoph 46:369–406
Le Turdu C, Tiercelin JJ, Gibert E, Travi Y, Lezzar K, Richert J, Massault M, Gasse F, Bonnefille R, Decobert M, Gensous B, Jeudy V, Tamrat E, Mohamed MU, Martens K, Balemwal A, Chernet T, Williamson D, Taieb M (1999) The Ziway-Shala lake basin system, main Ethiopian rift: influence of volcanism, tectonics, and climatic forcing on human formation and sedimentation. Palaeogeogr Palaeoclimatol Palaeoecol 150:135–177
Leakey REF (1974) Further evidence of lower Pleistocene hominids from East Rudolf, North Kenya. Nature 248:653–656
Lewin R (1983) Fossil lucy grows younger, again. Science 219:43–44
Maguire PKH, Keller GR, Klemperer SL, Mackenzie GD, Keranen K, Harder S, O'Reilly B, Thibo H, Asfaw L, Khan MA, Amha M (2006) Crustal structure of the Northern Main Ethiopian Rift from the EAGLE controlled source survey: a snapshot of incipient lithospheric break-up. In: Yirgu G, Ebinger CJ, Maguire PKH (eds) The Afar volcanic province within the East African rift system. Geol Soc Spec Publ 259:269–291
Makris MJ, Rhim R (1991) Shear-controlled evolution of the Red Sea: pull apart model. Tectonophysics 198:441–466
Manighetti I, Tapponnier P, Gillot PY, Jacques E, Courtillot V, Armijo R, Rurgg JC, King G (1998) Propagation of rifting along the Arabia–Somalia plate boundary into Afar. J Geophys Res 103:4947–4974
Martini IP, Brookfield EM, Steven S (2001) Principles of glacial geomorphology and geology. Prentice-Hall, New Jersey, 380 pp
McDougall I, Brown FH (2008) Geochronology of the pre-KBS Tuff sequence, Omo Group, Turkana Basin. J Geol Soc London 165:549–562
McKenzie DP, Davies D, Molnar P (1970) Plate tectonics of the Red Sea and East Africa. Nature 226:243–248
Meert JG, Lieberman BS (2008) The Neoproteozoic assembly of Gondwana and its relationship to Ediacaran–Cambrian radiation. Gondwana Res 14:5–21
Merla G (1963) Missione geologica nell'Etiopia meridionale del Consiglio Nazionale delle Ricerche 1959–1960. Notizie geomorfologiche e geologiche. Giorn Geol 31:1–56

Merla G, Minucci E (1938) Missione geologica nel Tigrai. Volume primo: La serie dei terreni. Reale Accademia, Italia Roma, 363 pp
Merla G, Abbate E, Canuti P, Sagri M, Tacconi P (1973) Geological map of Ethiopia and Somalia, scale 1:2,000,000. Consiglio Nazionale delle Ricerche, Roma
Merla G, Abbate E, Azzaroli A, Bruni P, Canuti P, Fazzuoli M, Sagri M, Tacconi P (1979) A geological map of the Ethiopia and Somalia and comment with a map of major landforms (scale 1:2,000,000). Consiglio Nazionale delle Ricerche, Roma, 95 pp
Meshesha D, Shinjo R (2008) Rethinking geochemical feature of the Afar and Kenya mantle plumes and geodynamic implications. J Geoph Res 113. doi:10.1029/2007JB005549
Mohr P (1962) The geology of Ethiopia. University College of Addis Ababa Press, Ethiopia, 268 pp
Mohr P (1963) Geological map of Horn of Africa, scale 1:2,000,000. Philip and Tacey, London
Mohr P (1967) The Ethiopian rift system. Bull Geoph Obs Addis Ababa 11:1–65
Mohr P (1968) Transcurrent faulting in the Ethiopian rift system. Nature 218:938–941
Mohr P (1983) Ethiopian flood basalt province. Nature 303:577–584
Mohr P (2009) Africa beckoning. Explorers of eastern Africa, its rift valleys and geology, in the 19th and early 20th centuries. Millbrook Nova press, Tóin An Ghárrain, Corr an Dola, Co na Gaillime, 192 pp
Mohr P, Wood CA (1976) Volcano spacings and lithospheric attenuation in the Eastern Rift of Africa. Earth Planet Sci Lett 33:126–144
Mohr P, Zanettin B (1988) The Ethiopian Flood Basalt Province. In: Macdougall JD (ed) Continental flood basalts. Kluwer Academic Publisher, The Netherlands, pp 63–110
Morbidelli L, Nicoletti C, Petrucciani C, Piccirillo EM (1975) Ethiopian south-eastern plateau and related escarpment: K/Ar ages of the main volcanic events (Main Ethiopian Rift from 8° 10' to 9° 00' lat. N). In: Pilger A, Roesler EA (eds) Afar depression of Ethiopia. Schweizerbart, Stuttgart, pp 362–369
Morgan WJ (1971) Convection plumes in the lower mantle. Nature 230:42–43
Morton WH, Black R (1975) Crustal attenuation in Afar. In: Pilger A, Roesler EA (eds) Afar depression of Ethiopia. Schweizerbart, Stuttgart, pp 55–65
Moucha R, Forte AM (2011) Changes in African topography driven by mantle convection. Nature Geosci 4:707–712
Munzinger W (1864) Ostafrikanische studien. Schaffhausen, p 584
Natali C, Beccaluva L, Bianchini G, Siena F (2013) The Axum-Adwa basalt-trachyte complex: a late magmatic activity at the periphery of the Afar plume. Contr Min Petrol. doi:10.1007/s00410-013-0879-0
Overstreet WC, Stoeser DB, Overstreet EF, Goudarzi GH (1977) Tertiary laterite of the As Sarat mountains, Asir Province, Kingdom of Saudi Arabia. Min Res Bull Saudi Arabia Direct Gen Min Res 21:1–30
Peccerillo A, Donati C, Santo AP, Orlando A, Yirgu G, Ayalew D (2007) Petrogenesis of silicic peralkaline rocks in the Ethiopian rift: geochemical evidence and volcanological implications. J Afr Earth Sci 48:161–173
Pickford M (1990) Uplift of the roof of Africa and its bearing on the evolution of mankind. J Hum Evol 5:1–20
Pik RD, Coulon C, Yirgu G, Hofmann C, Ayalew D (1998) The Northwestern Ethiopian plateau flood basalts: classification and spatial distribution of magma types. J Volc Geoth Res 81:91–111
Pik R, Marty B, Carignan J, Lavé J (2003) Stability of the Upper Nile drainage network (Ethiopia) deduced from (U-Th)/He thermochronometry: implications for uplift and erosion of the Afar plume dome. Earth Plan Sci Lett 215:73–88
Prior GT (1900) On Aegirite and Riebeckite Anorthoclase rocks related to the "Grorudite-Tinguaite" series, from the neighborhood of Aodowa and Axuma, Abyssinia. Min Mag 12:255–273
Quade J, Wynn JG (Eds) (2008) The geology of early humans in the Horn of Africa. Geol Soc Am Spec Publ 446:234 pp
Ritsema J, van Heijst HJ, Woodhouse JH (1999) Complex shear wave velocity structure imaged beneath Africa and Iceland. Science 286:1925–1928
Rochette P, Tamrat E, Féraud G, Pik R, Courtillot V, Ketefo E, Coulon C, Hoffmann C, Vandamme D, Yirgu G (1998) Magnetostratigraphy and timing of the Oligocene Ethiopian traps. Earth Planet Sci Lett 164:497–510
Rogers NW (2006) Basaltic magmatism and the geodynamics of the East Africa rift system. In: Yrgu G, Ebinger CJ, Maguire PKH (eds) The Afar volcanic province within the East Africa rift system. Geological Society London Special Publication, London, 259, pp 77–93
Rüppell WE (1834) Skizze der geologischen Formation Abyssiniens. Abhandlungen Museum Senkenbergianum 1:286–288
Russo A, Getaneh A, Atnafu B (1994) Sedimentary evolution of the Abbai River (Blue Nile) Basin, Ethiopia. N J B Geol Palaeo Mh 5:291–308
Sacchi R, Alene M, Barbieri M, Conti A (2007) On the Paleozoic Tillite of the Adigrat Group (Tigrai, Ethiopia). Periodico Mineralogia 76:241–251
Said R (1993) The River Nile geology, Hydrology and Utilization. Pergamon Press, Oxford, p 320
Schilling JG (1973) Afar mantle plume: rare earth evidence. Nature 242:2–5
Sepulchre P, Ramstein G, Fluteau F, Schuster M, Tiercelin JJ, Brunet M (2006) Tectonic uplift and eastern Africa aridification. Science 313:1419–1423
Sichler B (1980) La biellette danakile. Bull Soc Geol Fr 6:925–933
Sickenberg O, Schoenfeld M (1975) The chorora formation—lower pliocene limnical sediments in the southern Afar (Ethiopia). In: Pilger A, Roesler EA (eds) Afar depression of Ethiopia. Schweizerbart, Stuttgart, pp 277–284
Stankiewicz J, de Wit MJ (2006) A proposed drainage evolution model for the Central Africa—did the Congo flow east? J Afr Earth Sci 44:75–84
Stefanini G (1933) Carta Geologica dell Eritrea, della Somalia e dell'Etiopia alla scala di:2.000.000. Istituto Geografico Militare Firenze
Stern RJ (1994) Neoproterozoic (900–550 Ma) arc assembly and continental collision in the East African Orogen. Ann Rev Earth Planet Sci 22:319–351
Street FA (1979) Late quaternary lakes in the Ziway-Shala basin, Southern Ethiopia. Ph.D. thesis, University of Cambridge, Cambridge, 457 pp
Taieb M (1974) Evolution quaternaire du basin de l'Awash (rift éthiopienne et Afar). Doctoral Univ Paris, 442 pp
Tefera M, Chernet T, Haro W (1996) Geological map of Ethiopia, scale 1:2,000,000. Ethiopian Mapping Authority, Ethiopia
Tiercelin JJ (1986) The pliocene hadar formation; Afar depression of Ethiopia. In: Frostick LE, Renaut RW (eds) Sedimentation in the African Rifts. Geological Society Special Publication No 25, pp 221–240
Tiercelin JJ, Taieb M, Faure H (1980) Continental sedimentary basins and volcano-tectonic evolution of the Afar Rift. Atti Convegni Acc Lincei Roma 47:491–504
Ukstins IA, Renne PR, Wolfenden E, Baker J, Ayalew D, Menzies M (2002) Matching conjugate volcanic rifted margins: 40/39Ar chrono-stratigraphy of pre-and syn rift bimodal flood volcanism in Ethiopia and Yemen. Earth Planet Sci Lett 198:289–306

Unger F (1866) Notiz über fossile Hölzer aus Abyssinien. Sitzungenesberichte der Kaiserlichen Akademie der Wissenshaften Math. Naturwissenshaft Klasse, Wien 54:289–296

Vinassa de Regny P (1931) La geologia delle Alpi Dancale. Boll Soc Geol It 50:1–24

Walker A, Leakey REF (1978) The hominids of East Turkana. Sci Am 239:54–66

Walter RC (1994) Age of Lucy and the First Family: Single crystal $^{40}Ar/^{39}Ar$ dating of the Denen Dora and lower Kada Hadar members of the Hadar Formation, Ethiopia. Geology 22:6–10

White RS, McKenzie DP (1989) Magmatism at rift zones: the generation of a continental margins and flood basalts. J Geoph Res 94:7685–7729

White TD, Johanson DC (1982) Pliocene hominid mandibles from the Hadar Formation, Ethiopia; 1974–1977 collections. Am J Phys Anthropol 57:501–544

White TD, Asfaw B, Beyene Y, Haile Selassie Y, Lovejoy CO, Suwa G, WoldeGabriel G (2009) *Ardipithecus ramidus* and the paleobiology of early hominids. Science 326:75–86

Wichura H, Bousquet R, Oberhäusli R, Strecker MR, Trauth MH (2010) Evidence for middle Miocene uplift of the East African Plateau. Geology 38:543–546

WoldeGabriel G, Aronson JL, Walter RC (1990) Geology, geochronology, and rift basin development in the central sector of the Main Ethiopia Rift. Geol Soc Am Bull 102:439–458

Wolela A (2007) Fossil fuel energy resources of Ethiopia: coal deposits. Int J Coal Geol 72:293–314

Wolela A (2008) Sedimentation of the Triassic–Jurassic Adigrat sandstone formation, BlueNile (Abbai) basin, Ethiopia. J Afr Earth Sci 52:30–42

Wolfenden E, Ebinger C, Yirgu G, Deino A, Ayalew D (2004) Evolution of the northern Main Ethiopian rift: birth of a triple junction. Earth Plan Sci Lett 224:213–228

Yemane K, Taieb M, Faure H (1987) Limnologic studies on an intertrappean continental deposit from the northern Ethiopian Plateau (37° 03′E, 12° 25′N). J Afr Earth Sci 6:91–101

Zanettin B, Justin-Visentin E (1973) Serie di vulcaniti etiopiche: 1—La serie dell'altopiano etiopico centro-orientale. Boll Soc Geol It 92:313–327

Zanettin B, Justin-Visentin E (1974) The volcanic succession in central Ethiopia. 2—The volcanics of western Afar and Ethiopian rift margins. Mem Ist Min Univ Padova 31:1–19

Zanettin B, Justin-Visentin E (1975) Tectonical and volcanological evolution of the western Afar margin (Ethiopia), In: Pilger A, Roesler EA (eds) Afar depression of Ethiopia. Schweizerbart, Stuttgart, pp 300–309

Zanettin B, Gregnanin A, Justin-Visentin E, Nicoletti M, Petrucciani C, Piccirillo EM, Tolomeo L (1974) Migration of the Oligocene-Miocene ignimbritic volcanism in the Central Ethiopan Plateau. NGB Geol Palaeo Mh H 9:567–574

Zanettin B, Justin Visentin E, Nicoletti M, Piccirillo EM (1980) Correlations among Ethiopian volcanic formations with special references to the chronological and stratigraphical problems of the "Trap Series". Atti Convegni Acc Lincei Roma 47:231–252

Springer

http://www.springer.com/978-94-017-8025-4

Landscapes and Landforms of Ethiopia
Billi, P. (Ed.)
2015, VIII, 389 p. 350 illus., 319 illus. in color.,
Hardcover
ISBN: 978-94-017-8025-4