The Landscape and Landforms of the Ogaden, Southeast Ethiopia

19

Daniel Mège, Peter Purcell, Stéphane Pochat, and Thomas Guidat

Dedication This chapter is dedicated to the memory of hydrogeologist Dr. Costantino Faillace, who worked extensively on the basalt aquifers of Somalia and India, among many other countries, in a life dedicated to providing clean water supplies to remote communities. He died in 2012.

Abstract

The Ogaden region is located on the Somali Plateau, in southeast Ethiopia. Originally a clan-based term, the Ogaden is now commonly used for the entire region below about 1,500 m a.s.l., an area of some 300,000 km^2 that encompasses most of the Somali Regional State and includes the southwest portion of Oromia. The climate is hot, arid to semiarid, corresponding to the Ethiopian *bereha* and *kolla* climatic zones. Three basic physiographic provinces are recognized: the Genale and Shebele drainage basins and the Eastern Slope and Plains. The two drainage basins include spectacular upstream canyons that witness the vertical movements that have accompanied the succession of rifting events in the Ethiopian Rift, Afar, and the Gulf of Aden. In strong contrast, the Eastern Slopes and Plains is dipping less than 0.4° on average over hundreds of kilometers to the southeast and is mantled by red sands. Several remarkable Ogaden landforms are described and analyzed, including volcanic, fluvial, and gravitational features, some having few equivalents in other areas on Earth. A variety of volcanic landforms are present across the region, reflecting the complex Cenozoic history of the Ogaden's margins. For instance, meandering basalt hills provide a textbook example of inverted topography by fossilizing paleodrainage networks of various ages. The modern drainage network provides information on the genesis of the mega-geomorphology of the Ogaden and documents its uplift history. In western Ogaden, the deep incision has exposed the Cretaceous evaporites and triggered the development of one of the largest gravitational spreading domains on Earth, the Audo Range.

D. Mège (✉)
WROONA Research Group, Institute of Geological Sciences, Research Centre in Wrocław, Polish Academy of Sciences, ul. Podwale 75, 50-449 Wrocław, Poland
e-mail: daniel.mege@univ-nantes.fr

D. Mège · S. Pochat · T. Guidat
Université de Nantes, CNRS UMR6112, , Laboratoire dePlanétologie et Géodynamique de Nantes, Nantes, France

P. Purcell
P&R Geological Consultants, 141 Hastings Street, Scarborough, WA 6019, Australia

D. Mège · S. Pochat
Observatoire des Sciences de l'Univers Nantes Atlantique (OSUNA, CNRS UMS 3281), Nantes, France

P. Billi (ed.), *Landscapes and Landforms of Ethiopia*, World Geomorphological Landscapes,
DOI 10.1007/978-94-017-8026-1_19, © Springer Science+Business Media Dordrecht 2015

Keywords
Ogaden • Wabe Shebele • Audo Range • Marda Range • Basalt • Topographic inversion • Rift flank uplift • Incision rate

19.1 Introduction

The landscape and landforms of Ethiopia, and the peoples and cultures that evolved there, have captured the imagination since biblical times. This dramatic topography is the creation of earth forces uplifting and splitting apart the Afro-Arabian continent for more than 30 Myr. A vast rift complex now cleaves south through the uplifted dome of Ethiopia, separating western (Ethiopian) and southeastern (Somali) plateaus, and creating a landscape that has profoundly influenced the history and culture of the region. The high and dissected western plateau, long known as Abyssinia, sheltered the Coptic Christian kingdom from Islamic and European expansionism. Conversely, the southeastern plateau's easy access to the Islamic coast saw early conversion of Sidama, Oromo, and Somali clans and the establishment of Harar in the thirteenth century as the religious center of the Horn of Africa.

In this chapter, we describe the landscape and landforms of the lower regions of the southeastern plateau, the area known informally as the Ogaden (Fig. 19.1). This poorly accessible and seldom visited region is not as well known or studied as the Ethiopian Plateau and is often dismissed as 'desert.' Certainly, the region has vast red soil plains, but it also has the grand canyons of the Wabe Shebele and its tributary rivers, the spectacular Audo Range gravitational spreading complex, and a variety of landforms, soils, and vegetation that reflect the changing elevation of the plateau. We summarize the geographical and geological information and then focus on three major features of the Ogaden landscape: the volcanic landforms, the drainage system and its evolution, and the very large-scale gravitational spreading structures of the Audo Range. These landforms are described and also discussed from a mega-geomorphology perspective.

There is no formal definition of 'the Ogaden' but, in popular usage, it corresponds approximately to the area of the Somali Plateau from about 1,500 m elevation to the Somalia and Kenya borders. The Ogaden takes its name from the Ogaden clan (Somali, Ogaadeen), a subclan of the Darod, who live in the region. The term originally referred only to the Ogadeni lands but is now commonly used for the entire Somali region, even, albeit rather imprecisely, as an alternative for the Somali Administrative Region (Hagmann and Khalif 2006; Temin 2006). Climatically, it corresponds to the hot arid region of the Ethiopian *bereha* and *kolla* climatic zones. In geological terms, it is the area where sedimentary rocks occur on or near the surface, underlain by a deep sedimentary basin.

The modern use of the Ogaden name is opposed by some people in the region because they feel it implies Ogadeni political leadership, both in general and specifically over non-Ogadeni lands (Hagman 2007). However, there is no useful alternative term and it is now widely used and accepted in many fields of study.

19.2 Landscapes

19.2.1 Human Geography

The Ogaden occupies the southern portion of the Somali Regional State of Ethiopia, and the southeastern portion of the Oromia State. Jijiga is now the regional capital of the Somali State and the administrative center for the region. Adama (or Nazret) is the capital of Oromia. Figure 19.1 shows the Ogaden region, as described in this paper, with the main towns, rivers, and roads. Important towns include Aware (Teferi Ber), Daghabur, Gode, Kebri Dehar, Fik, Filtu, and Werder (Harar, the historical capital of the region, is now designated as a separate state, as is Dire Dawa). The Jijiga/Ferfer road coincides with a major topographic and geological divide between eastern and western Ogaden regions.

The Ogaden region encompasses about 300,000 km^2 and has a population of the order of 5 million, predominantly Somali and Oromo clans, with each constituting near 90 % of the population in their state (Ethiopian Government Portal 2014). Historically, the people of the Ogaden have been primarily nomadic pastoralists, but the population is increasingly gathered into the large and small towns across the region. Agriculture predominates at higher elevations and along the lower Wabe Shebele.

Major roads provide access to the Ogaden from the national capital Addis Ababa (Fig. 19.1). In the north, where numerous major river canyons occur, secondary roads extend south from the main road to Jijiga. Access to southwestern areas is limited from the north by the Wabe Shebele canyon and is primarily via roads linking to the Imi-Gode-Mustahil road. A main road from Jijiga southeast through Kebri Dehar to Ferfer on the Somalia border links with secondary roads in the central and eastern region and provides the road link to Somalia capital, Mogadishu. Secondary roads in the Ogaden, as well as some of the main

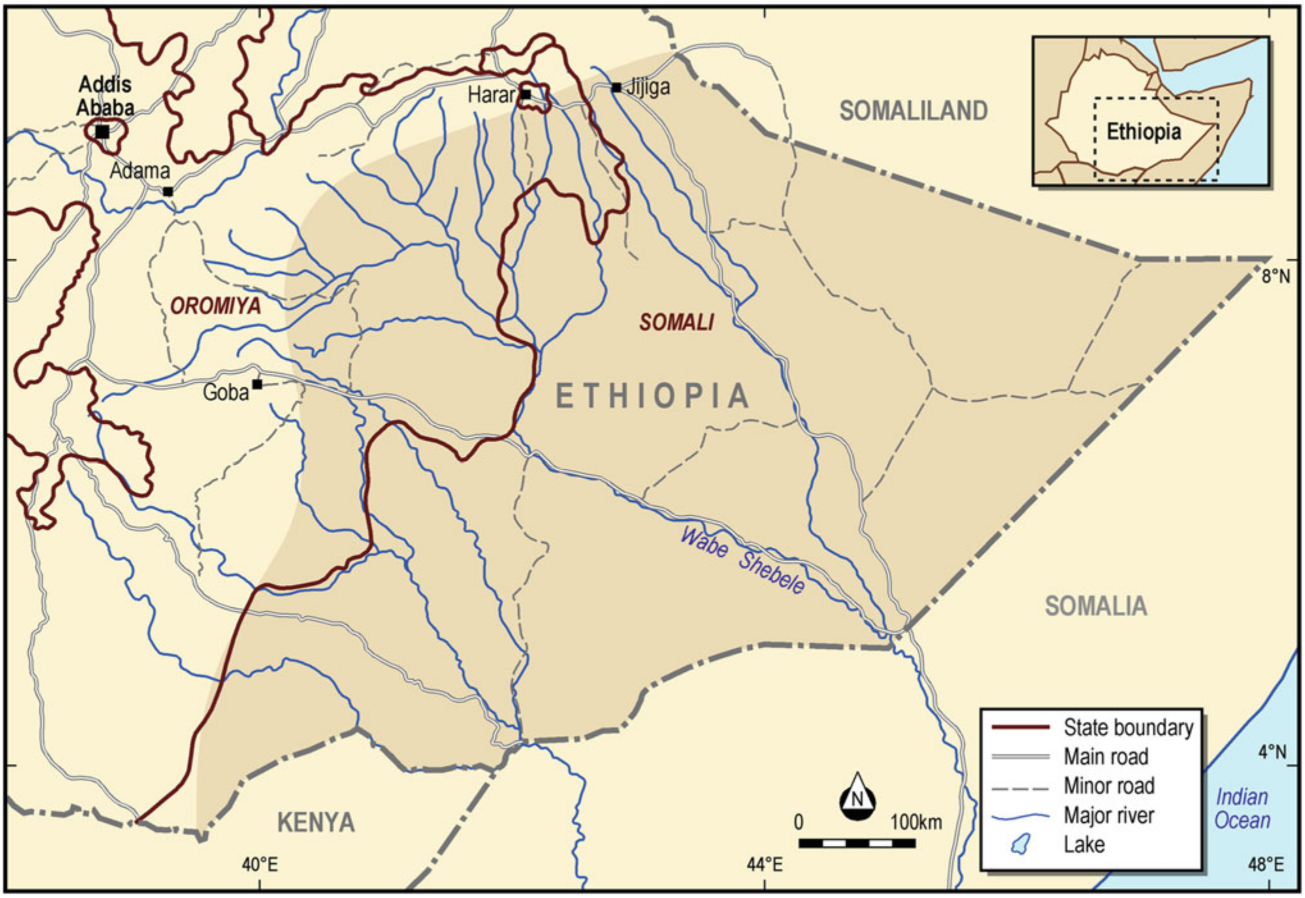


Fig. 19.1 Location map, Ogaden region, Ethiopia

roads, are unsealed and can be in poor condition, with river crossing very difficult, especially in the wet seasons.

19.2.2 Physical Geography

The digital elevation model of southeastern Ethiopia of Fig. 19.2 shows the main features of the Ogaden landscape and the clear subdivision into highly dissected western and subdued eastern regions. The boundary is relatively abrupt, along the eastern side of the uplifted Marda Range, a prominent NW/SE-trending structure thought to have formed by Phanerozoic multiphase reactivation of a Precambrian shear zone (Purcell 1976). In the western Ogaden, the high plateau rises to the rift margin rim and is dissected by the steep canyons of south- and east-draining rivers, creating a rugged topography. The steep river canyons and profiles are evidence of the recent relative uplift along the plateau rim. These rivers join the Wabe Shebele, which flows southeast across the central Ogaden into Somalia, its valley slowly diminishing from a steep-walled high canyon to a broad flood plain. Pronounced NW-trending features, such as the Marda Range complex, are clearly seen.

By contrast, the eastern Ogaden is a very gentle slope, on average dipping less than 0.4° to the southeast, with no major rivers or high topographic features. Comprehensive geomorphological studies remain to be conducted; nevertheless, an analysis of the most prominent landforms, the scattered low basaltic hills, has been undertaken and is discussed in Sect. 19.3.2. Rock outcrops are relatively rare and the plain is covered with alluvial and eolian red sand, commonly a few meters thick but locally as deep as 13 m, based on the results of oil and water bores (Walsh 1976; Faillace 1993).

The main physiographic provinces and features of the Ogaden are shown in Fig. 19.2. The basic subdivision recognizes the main provinces of the Wabe Shebele and Genale watersheds and the Eastern Slopes and Plains. The further subdivision into regions is clearly defined in some areas, such as the Audo Range, but in other cases, the boundaries between regions are diffuse. Figure 19.3 illustrates typical landscapes from several of the physiographic regions,

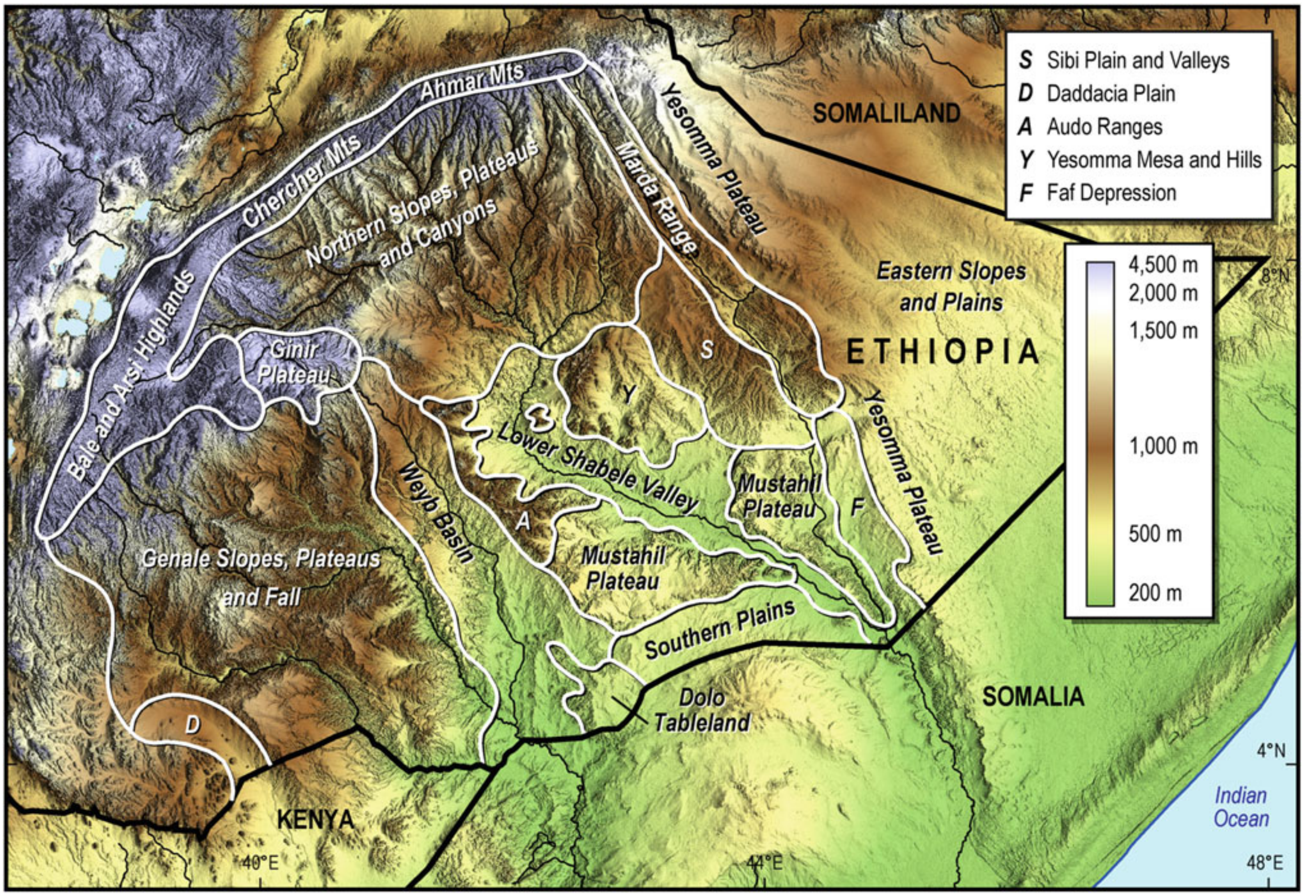


Fig. 19.2 Digital elevation model, southeast Ethiopia, showing informal physiographic subdivisions

including the Mustahil Plateau, the Eastern Slopes and Plains, and the Wabe Shebele valley.

19.2.2.1 Elevation

The Somali Plateau has its highest elevation along the uplifted faulted margins of the Afar Depression and the Main Ethiopian Rift (MER), reaching over 4,000 m a.s.l. in the Arsi and Bale mountains in the west and over 3,000 m a.s.l. in the Chercher and Ahmar mountains in the north/northwest. Except in the west, the areas above 3,000 m in elevation occur only relatively near the plateau edge and, in all areas, are associated with volcanoes or thick Tertiary basalt flows. The elevation declines to the south and east and is about 300 m along the Somalia border (Fig. 19.4).

The present elevation of the Somali Plateau is the result of geodynamic events that produced vertical movements of the crust over the Cenozoic. The Ogaden is located at the edge of a dynamic mantle plume, upwelling for more than 30 million years in eastern Africa and western Arabia (Moucha and Forte 2011). Flood lava eruption in the Ethiopian-Yemenite province, which peaked at 30–29 Ma (Hofmann et al. 1997), was accompanied by vertical displacements in the region, though whether and where it resulted in uplift or subsidence depends on an interplay of parameters (Olson 1994), details of which are limited by the scarcity of adequate geological observations (see, however, Juch 1975). On the northern side of the Ogaden, rifting of the Gulf of Aden (Leroy et al. 2012) started as early as Late Eocene, while uplift peaked at 20–18 Ma and stopped around 16 Ma, when oceanization started (Watchorn et al. 1998; Fournier et al. 2010). Northward propagation of the Main Ethiopian Rift and initiation of the southern Afar started at 11–10 Ma (Wolfenden et al. 2004; Bonini et al. 2005), and rifting has proceeded until the present. Rift-flank uplift at the western edge of the Ogaden is thought to have occurred during this interval. The overall southeastward slope of the Ogaden seems primarily a consequence of the topographic evolution of this tectonism along the northwestern edge of the Somalia Plate, although it does appear that the region had a preexisting southward slope dating to

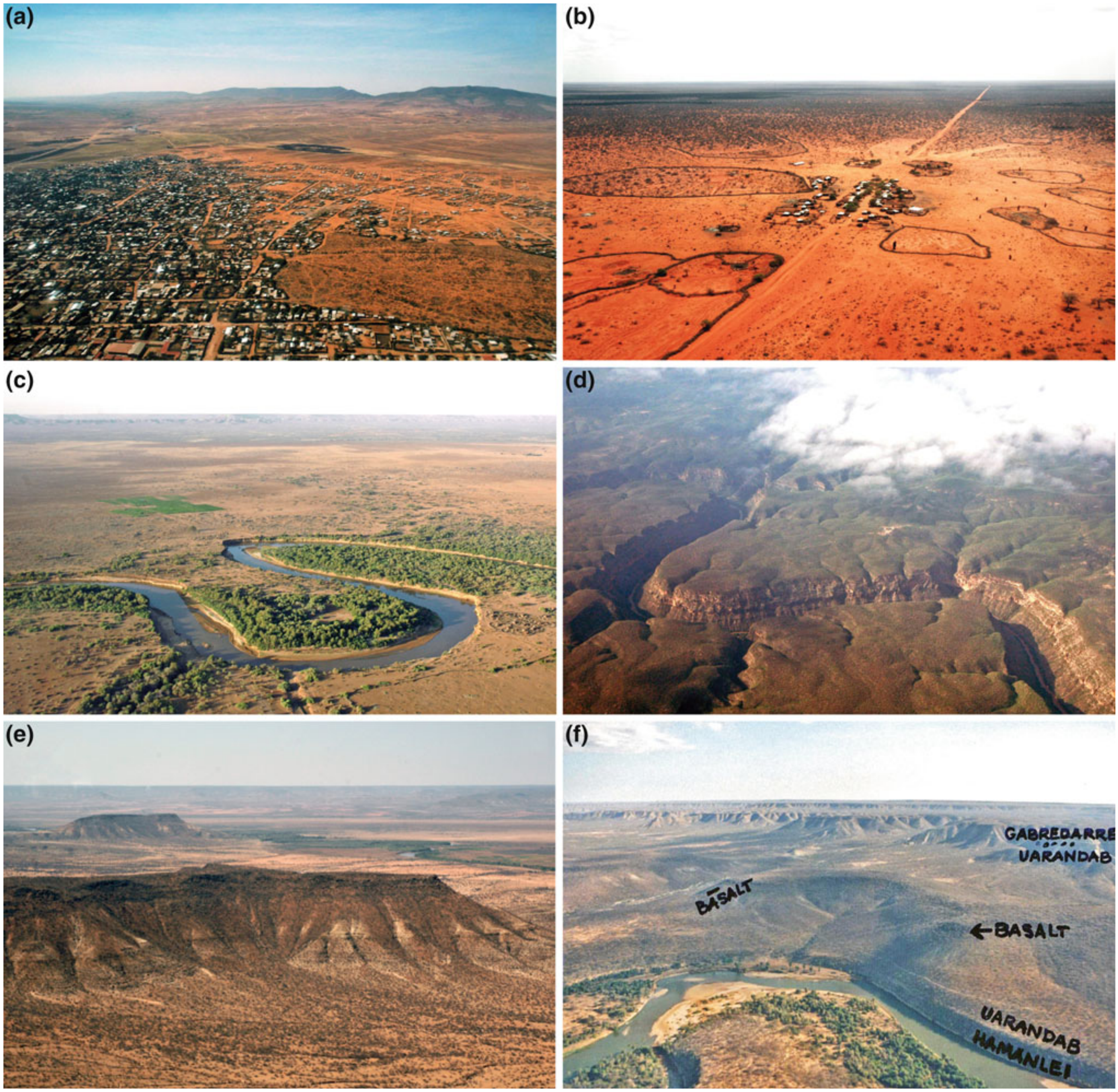


Fig. 19.3 Selected Ogaden landscapes. **a** Somali state capital Jijiga, looking southwest toward Marda Range; **b** Red sand plains in eastern Ogaden, with village in foreground; **c** Wabe Shebele near Gode; **d** Canyons of the Wabe Shebele incising Uarandab Shale plateau, south of Wabe/Ramis junction; **e** Mustahil Plateau, south-central Ogaden, looking across Wabe Shebele floodplain; and **f** Genale Plateau on Gabredarre limestone above Genale River (*Photos* by P. Purcell except **e** which is courtesy of Hunt Oil Company)

the Late Jurassic, as revealed by the thinning and transition to less marine facies of the Upper Jurassic sediments outcropping in the northern and western areas (Purcell 1981).

19.2.2.2 Climate

The climatic zones in the Ogaden and adjacent region are shown using traditional Amharic terminology on Fig. 19.5 (Ethiopian Mapping Authority—EMA 1988; Lemma 1996). The *bereha* zone (hot arid) covers the region below 500 m elevation, where annual rainfall is less than 400 mm, resulting in sparse vegetation with extensive bare ground. The *kolla* zone (warm to hot semiarid) covers the region between 500 and 1,500 m in elevation, where the average annual rainfall is generally around 600–800 mm. The higher regions of the Somali Plateau are classified as *weyna dega* (1,500–2,500 m a.s.l.; warm to cool semihumid) and *dega* (>2,500 m a.s.l.; cool to cool humid). Under the Köppen classification, the Ogaden is classified as hot arid (Bwh) and hot semiarid

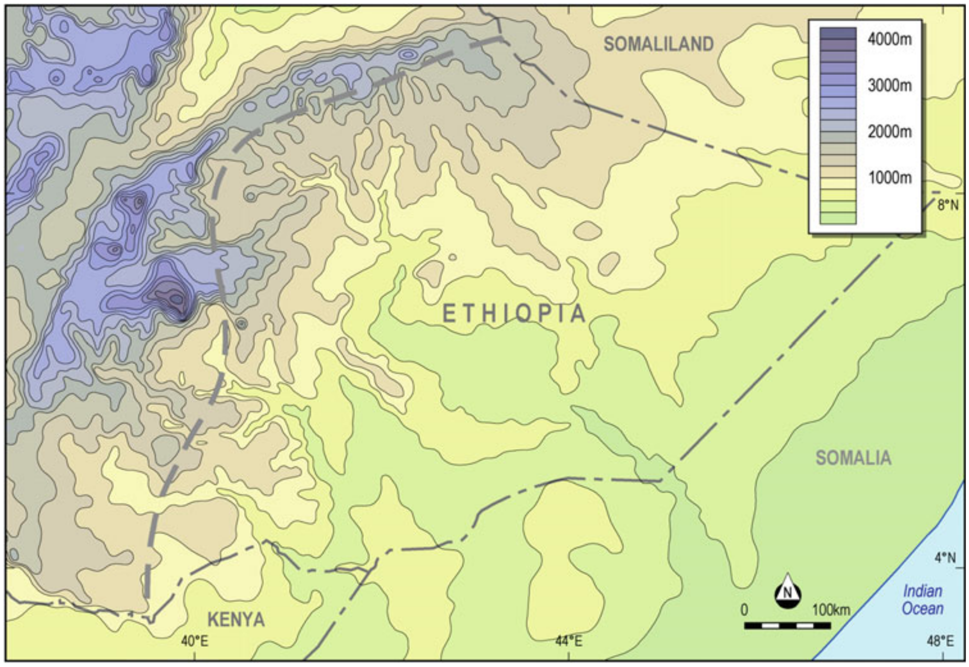


Fig. 19.4 Simplified elevation map, southeast Ethiopia

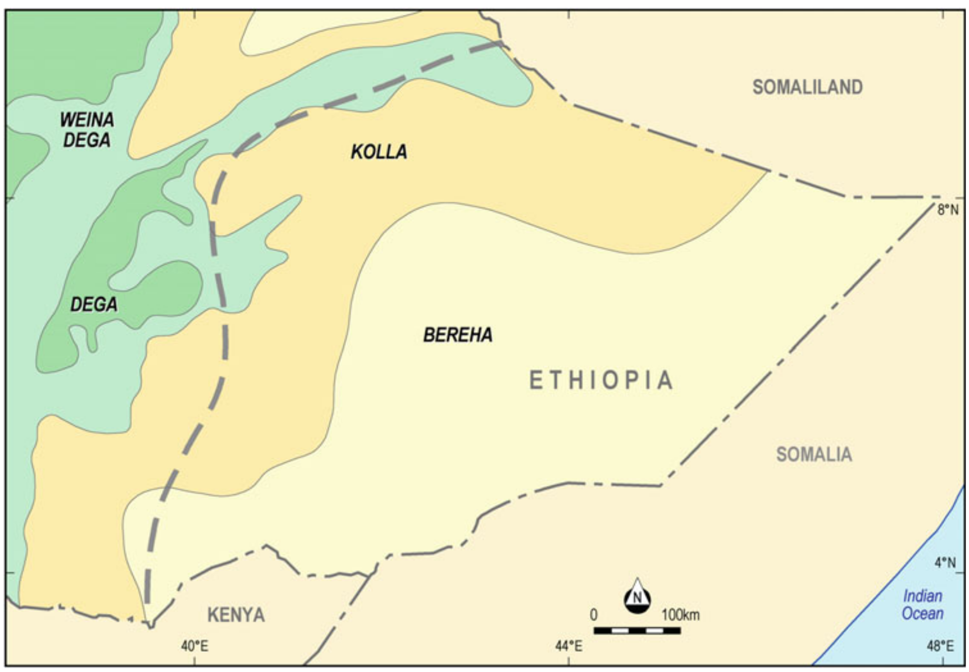


Fig. 19.5 Climate zones, southeast Ethiopia (after Lema 1996; EMA 1988)

(Bsh). In the high country above 2,000 m (beyond the Ogaden sensu stricto), the climate is warm temperate (Cwb). For all intents and purposes, Koppen zones Bwh and Bsh correspond to the *bereha* and *kolla* zones.

Ogaden aridification dates back to Late Miocene, when, after the Eocene optimum, the Sahara desert formed (Micheels et al. 2009) and the Messinian salinity crisis in the Mediterranean region occurred (Feakins 2013). Aridity has been globally maintained until modern times. The main causes in the Ogaden are, firstly, that the NE and the SE monsoons that blow across the region are relatively dry and carry little rain and, secondly, that the Ogaden is in the rain shadow of the Ethiopian highlands as regards Atlantic moisture carried east by the unstable Congo airstream (Nicholson 1996; Sepulchre et al. 2006). The rainfall over most of the Ogaden falls mainly during the transition period between the monsoons, giving a bimodal rainfall distribution (EMA 1988), with rainy seasons in March–June (main) and September–November (minor), known in Somali as Dehr and Gu, respectively.

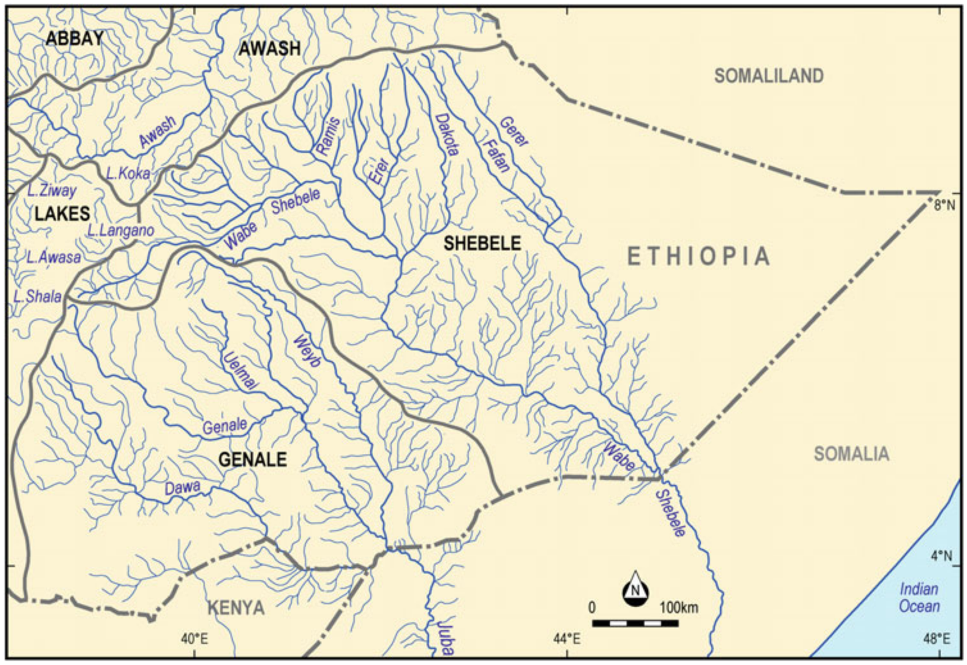


Fig. 19.6 Drainage basins, southeast Ethiopia (after EMA 1988)

Annual rainfall is between 400 and 800 mm over much of the Ogaden (refer to *bereha* and *kolla* zones on Fig. 19.5) but is very irregular and variable in the extreme east and southern areas, often 200 mm or less. Annual variability can be considerable within and between local areas, mainly linked to variability in Gu rains, but recent analyses show no overall decline in annual rainfall in the period 1965–2002 (Cheung and Senay 2008).

19.2.2.3 Hydrology

The Ogaden region contains two vast drainage systems, the Wabe Shebele basin in the northeast and the Genale basin in the southwest, as shown in Fig. 19.6 (EMA 1988). Both systems drain into the Indian Ocean.

The Wabe Shebele (Somali, River of Leopards), known as the 'Second Nile' to early Arabian geographers, is over 1,300 km long in Ethiopia (about 2,000 km overall) and has a catchment area of over 205,000 km^2. The river rises in the Arsi highlands in the west and flows initially northeast in spectacular deep canyons, reaching over 900 m deep near the ancient town of Sheik Hussein, before abruptly swinging southeast and meandering across the Ogaden into Somalia. Near Mogadishu, it is deflected southwestward by coastal dunes and, in the wet season at least, joins the Juba River and enters the ocean near Kisamayo. The main tributaries of the Wabe Shebele are the Galeti, Ramis, Erer, and Dakota rivers, rising in the north in the Ahmar Mountains and cutting deep narrow gorges in the northern slopes of the plateau, as discussed further in Sect. 19.3.3. The easternmost major river in the region is the Fafan, which, with its main tributary, the Gerer (or Yerer), flows southeast along the Marda Range and then southward, drying into the desert, except in heavy wet seasons when it flows into the Wabe Shebele.

The Genale catchment area covers about 168,000 km^2 and contains three main rivers, the Genale, Weyb (or Webi Gestro), and Dawa, all of which meet near Dolo on the Somalia border and continue south as the Juba River. The topographic divide between the Wabe Shebele and Genale watersheds runs through the Audo Range, an alignment of gravitationally unstable mesas, further discussed in Sect. 19.3.4.

In terms of landscape evolution, the rainfall regime is responsible for the development of temporary streams and small river channels throughout the Ogaden lowlands. They are dry most of the time, but are reactivated during the short and intense rainfalls, washing out the surface of the hills and accumulating the erosional products downstream in pan-type depressions. Such depositional areas are easily identified downstream from basaltic hills, because the dark clay accumulations contrast with the surrounding red sands. In the vast Wabe Shebele basin, intense rainfall in the upper catchment produces flash floods that periodically cause loss of life and destruction of buildings, crops, and livestock, by the strength of the flow of the crocodile-infested waters. At the same time, these waters and the soil they carry play a considerable role in the local agro-pastoral economy by making possible flood-recession agriculture in the riverbed in the Gu and Dehr seasons (UNDP 1999). Other major rivers, such as the Fafan and Gerer, are subject to intense floods lasting hours or days (Bauduin et al. 1973) but of much lower dramatic consequences than the Shebele floods.

19.2.2.4 Vegetation and Soils

The changing elevation of the Ogaden region and its rim of highlands, and the rainfall pattern they influence have a marked impact on the pattern of soils and vegetation across the Ogaden landscape.

Fluviosols are present along the lower reaches of several rivers, notably the Wabe Shebele, and can support large irrigated agricultural programs. In many valleys, however, the alternating wet periods and long dry spells have created heavy clay-rich vertisols that are less useful for agriculture. Over most of the Ogaden, the predominant soils are xerosols and yermosols, the latter often gypsiferous, and generally not suitable for agriculture. The soils are alluvial and vulnerable to wind and water erosion (EMA 1988).

Botanical description of the Ogaden flora is still very limited, as illustrated by the recent discovery of probably hundreds of thousands of specimens of a newly described acacia species, *Acacia fumosa*, on the Cretaceous Mustahil limestone hills in eastern Ogaden (Thulin 2007). The basic vegetation pattern reflects the soils and moisture conditions. While a complex interfingering of zones is determined by local conditions, there is an overall change from SE to NW, from desert vegetation to steppe to grassland to woodland and savannah and, finally, in the high country to coniferous forests. Xeromorphic thorny plants and grasses, often salt resistant species, and low acacias dominate the desert and semidesert scrubland in the southeast. In the steppes, between 200 and 1,400 m a.s.l., the vegetation is similar but with larger and more dense growth. The grasslands in the Ogaden, covered by short to medium, fire-resistant grasses, occur between about 400 and 2,000 m a.s.l. and interfinger with the savannahs and woodlands that are dominated by acacias and juniper trees (EMA 1988).

19.3 Remarkable Landforms

19.3.1 Geological Background

The landscape and landforms of the Ogaden are a product of the stratigraphic and structural evolution of the region. The surface today consists of sediments, Mesozoic to Neogene in age, as well as Precambrian basement rocks and Cenozoic volcanics (Fig. 19.7). Jurassic and Cretaceous sediments are

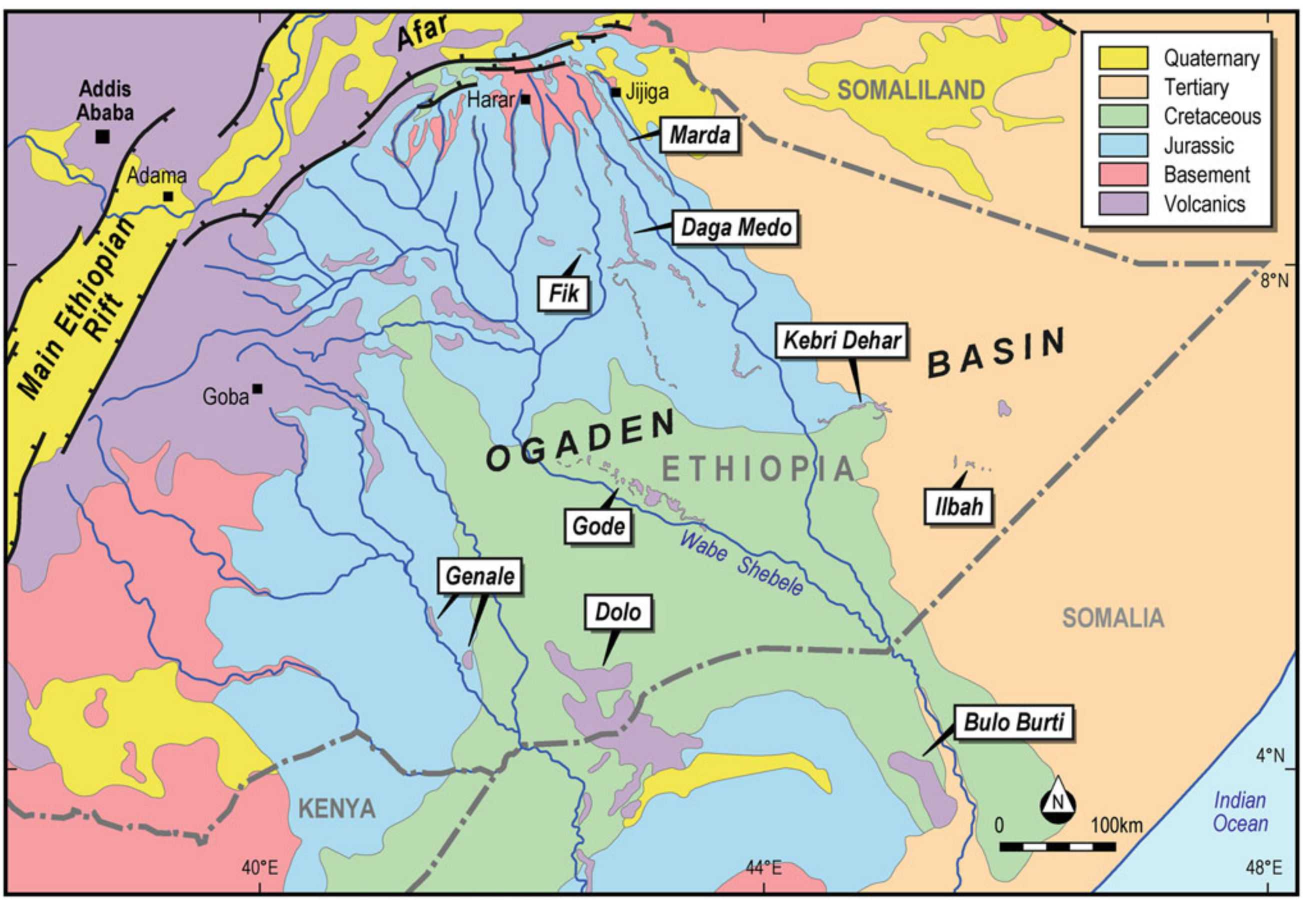


Fig. 19.7 Geology map, southeast Ethiopia, showing location of volcanic features discussed in text

the predominant outcrop in the western Ogaden, while Cenozoic sediments occur in the east; the contact between the two provinces being roughly coincident with the Marda Fault Zone. The underlying Ogaden Basin contains about 8 km of sediments deposited from Permian to Eocene time, approximately 260–35 million years ago.

The Ogaden Basin formed initially as part of the Karoo rifting in the Permian (Purcell 1981). In the Late Triassic to Early Jurassic, it developed into a sag basin and marine waters from the newly opening Indian Ocean flooded across the region, extending to northern Ethiopia, and depositing some 1,500 m or more of predominantly carbonates and evaporates in a vast shallow sea. In the Oxfordian, the seas reached their maximum flooding level and the Uarandab Shale developed. It was overlain, as the seas shallowed, by the carbonate Gabredarre Formation. The alternating cliff-forming limestones and softer shale and evaporite units result in a cliff-and-terrace topography in the eroded valleys in the northern and western Ogaden.

In the Early Cretaceous, silling of the basin, probably by a barrier reef trend near the present coastline, established a broad sabhka environment over the Ogaden, where the thick evaporites (1,600 m) of the Gorrahei Formation (previously, the Main Gypsum) were deposited in the basin center, thinning to the north and west. A marine transgression in the Aptian reestablished open marine conditions and deposited the dense limestones of the Mustahil Formation. Regional uplift in the Santonian exhumed the western Ogaden and reoriented the eastern basin to a NE-trend along the newly formed continental margin (Purcell 1981). During the Maastrichtian–Paleocene, the continental Yesomma Formation was deposited over much of the Ogaden, becoming more marine in the east. The Mustahil and Yesomma formations were to collapse later into the underlying Gorrahei evaporites by block tectonics of gravitational origin, as discussed further in Sects. 19.3.4 and 19.4.

An Eocene transgression deposited the carbonates and evaporities of the Auradu, Karkar, and Taleh formations in the eastern Ogaden and, thereafter, sedimentation was limited to the coastal Somalia area. Further widespread erosion occurred in the Oligocene, driven by uplift of the Somali Plateau and creating a landscape of eroded Tertiary, Cretaceous, and Jurassic sediments, similar in general terms to the present surface.

The early plume volcanism along what is now the Somali Plateau margin is relatively undocumented, but probably commenced during the Oligocene around 30 Ma, as on the Ethiopian Plateau (Hofmann et al. 1997), since the two regions were not then separated by the Afar and the Main Ethiopian Rift (MER). In the eastern Ogaden, the $^{40}Ar/^{39}Ar$ age of volcanic rocks geochemically akin to the plume basalts covers a time span of $\sim$8 million years, between 30 and 22 Ma (Mège et al. 2012a), encompassing the onset of rifting in the Red Sea and Gulf of Aden. Excluding the 2,000 m or more of accumulations at major volcanic centers along the plateau rim, basalt and associated volcanics on the plateau proper are 200–500 m thick in the north and west and more commonly 50 m or less in southern and eastern areas. While not comparable volumetrically with the Ethiopian Plateau volcanics, the Ogaden basalt flows were extensive, reaching over 600 km into coastal Somalia, as revealed by the widely scattered remnants seen on the surface and identified in the subsurface by aeromagnetic surveys and intersections in water bores and oil exploration wells (Purcell et al. 2011). Low viscosity lavas, that flowed for 100–200 km or more, filled river canyons and are preserved today as the inverted topography of basalt hills meandering across the landscape. The volcanic features of the Ogaden are discussed in detail in Sects. 19.3.2 and 19.3.3. A major feature of the Ogaden magmatism was the Late Oligocene Ogaden Dyke Swarm, which can be traced across the Ogaden on outcrop and magnetic data from the Afar margin to the Somalia border (Mège et al. in press).

The tectonic activity at the northern and western edge of the Somalia plate since the Miocene, the volcanic activity since the Oligocene, and contrasts in rheology and strength of the Meso-Cenozoic cover are the main geological influences on the geomorphological evolution of the Ogaden. In particular, they are key to understanding the three prominent landforms of the Ogaden discussed below: the volcanic landforms, the exhumed canyon-filling lava flows and the gravitational spreading structures.

19.3.2 Volcanic Landforms

The geomorphology of the volcanic outcrops in southeast Ethiopia have been discussed by Purcell et al. (2011), based primarily on mapping of the entire region on Landsat Geocover mosaics 1990 and 2000, high-resolution satellite images available on Google Earth™, and helicopter-supported field work in the eastern and southern Ogaden. Volcanics in southeast Ethiopia occur as broad volcanic plateaus, linear outcrops, isolated hill complexes, and meandering ribbons of exhumed paleocanyon basalt fill. The locations of various outcrops discussed in this chapter are shown in Fig. 19.7. Selected examples of Ogaden volcanic landforms are shown in Fig. 19.8. It is interesting to note that the volcanics have locally influenced settlement patterns in the region. The rolling basalt hills at Fik (Fig. 19.8b), for example, provide a natural shelter for the town. At nearby Daga Medo, the town has been built atop a recent flow, protecting residents from flash flooding during occasional heavy rains.

Fig. 19.8 Selected volcanic landforms of the Ogaden. **a** Ilbah Hills, a dyke-related volcanic complex in east central Ogaden; **b** volcanic hills near Fik town; **c** part of a Landsat ETM+ image (Geocover 2000) of basalt hills formed by inversion of canyon-filling lava flows in the ancestral Shebele river. *Arrow* shows direction of view in (**d**); **d** Wabe Shebele and flanking volcanic hills near Gode. North to the upper right; **e** Arid land farming around volcanic cones, east of Jijiga near the Somaliland border; and **f** view southeast down the Marda Range from quarry in hillside above the Marda Pass (*Photographs* by P. Purcell)

19.3.2.1 The Main Ethiopian Rift Shoulder

The most extensive basalt features occur in the west as eroded plateaus flanking the upper Wabe Shebele (Fig. 19.7). These plateaus are considered to be remnants of flows that originally extended continuously from the rift margin far into the Ogaden. The ages of the basalts are not well constrained. The older Trap volcanics overlying Jurassic sediments were dated in the early 1970s using K–Ar as Oligocene to Miocene (Megrue et al. 1972) and need reevaluation. Dating ($^{40}Ar/^{39}Ar$) of a sample from the Gara Mulata area was attempted by the authors; a well-defined but depressed plateau indicates obvious argon loss, which compromises the age determination; nevertheless, an emplacement age for the first basalts >24 Ma can be inferred. The Pliocene (2.2 Ma) age obtained for the overlying Ginir Formation rhyolites (Merla et al. 1973) also needs reevaluation. The columnar-jointed Ginir rhyolite, rising sharply above the eroded slope of the Garbaharre sandstones, forms a prominent north-facing cliff known as the Bilka Ridge (Kibrie and Yirga 2008). The multilayered flows are commonly over 100 m thick and reach a maximum of 365 m and are a prominent landform of the plateau adjacent to the Wabe Shebele canyon.

19.3.2.2 The Genale and Dolo Basaltic Tablelands

Several large, undated basaltic tables occur in southwest Ogaden and adjacent Somalia. Lava flows originating close to the Main Ethiopian Rift shoulder flowed down the Uelmal River, a tributary of the Genale River, and accumulated downstream on the Genale valley floor east of Filtu. They are now manifest as two basaltic tables, both 150 km^2 in surface area (Fig. 19.7). The northern table stands 100–150 m above the Genale River and is dissected into mesas by numerous antecedent rivers. About 20 km downstream, the southern table culminates 300 m above the Genale River. Nearly 100 km to the southeast, the Dolo basaltic table is 100–150 m high and covers some 6,500 km^2. Basaltic outliers, now separated by rivers, testify to an original much broader extent. The Dolo basalt table forms a cliff above the Weyb river on its western side, while on the eastern side its edge is masked by extensive Quaternary deposits and its true extent is not known; aeromagnetic data suggest that it could extend more or less continuously below the Quaternary mantle to the Bulo Burti basalt outcrop in Somalia, and then as far as the Indian Ocean (Bosellini 1989; Purcell et al. 2011). In the south, the geometry of the present outcrops suggests that the Dolo basaltic table could have fed the meandering basalts that filled the Juba paleo river channel, as discussed in Sect. 19.3.3.

19.3.2.3 The Marda and Jijiga Volcanics

The best known volcanic outcrop in the region is the Marda Range, a chain of uplifted and eroded hills of Jurassic limestone, capped by a linear basaltic layer, 150 km long and up to 2 km wide, trending SSE from Afar to the central Ogaden, parallel to the first order drainage pattern (Fig. 19.8f). In tectonic terms, it is referred to as the Marda Fault Zone and described as a Precambrian mylonite zone that has been reactivated several times during the Phanerozoic (Purcell 1976; Boccaleti et al. 1991). In the north, near Jijiga, the Marda basaltic layer is about 200 m thick and consists of a number of thick, columnar basaltic flows (Fig. 19.8f). There is no evidence of a feeder dyke within the limited outcrop area, but recently cut quarries nearby reveal numerous hypovolcanic basaltic intrusions, ranging to over 10 m in width and from which narrow dykes (<1 m) have propagated upward. The rare earth element spectra for the intrusives and the Marda extrusives are similar enough to suggest the same parental magma, in agreement with a similar $^{40}Ar/^{39}Ar$ age of 23–25 Ma (Mège et al. in press).

East of the Marda Range, several complexes of basaltic hills rise prominently above the red sand plains (Fig. 19.8a). Volcanism has been dated using the $^{40}Ar/^{39}Ar$ method, evidencing a 30–24 Ma age range (Mège et al. in press). The hills are generally broad mounds covered with rounded basalt cobbles, and actual outcrops are few and scattered. The topographic linearity of the hills suggest the presence of emergent dykes, but the poor quality of the outcrops makes identification difficult, except at Ilbah Hills where a dyke has been confirmed from its chilled margins (Mège et al., in press). Satellite images and SRTM topography reveal widespread NW/SE-trending lineaments associated with several volcanic hills and confirmed by field studies to be shallow depressions, 100–300 m wide and a few meters deep, marked by contrasting vegetation density and occasional calcrete exposures, but without any surface evidence of associated volcanic activity. Many are coincident with high-frequency linear magnetic anomalies (Purcell et al. 2011, Mège et al. in press) and are considered to be the product of hydrothermal alteration and limestone or gypsum karst development along dykes and dyke-parallel fissures (Mège et al. 2012b).

19.3.3 Inverted Basalt-Filled Paleo River Channels

A prominent feature of Ogaden and Somali volcanism is the presence of long (>100 km) basaltic flows in paleo river channels. In the central western Ogaden, an elegant chain of meandering hills extends south for 120 km from the Daga Medo flow. No recent age dating has been done on this flow; however, Maxus Ethiopia (1993) obtained 27.4 ± 1.4 Ma using the K-Ar method (Table 19.1). Another flow, albeit more eroded, can be seen northwest of Mustahil. It is 90 km long, but with eroded 'gaps' between the basaltic remnants and originally flowed in a gently meandering succession of narrow valleys in the Cretaceous Mustahil limestones.

The Gode lava flow (Fig. 19.8c, d) can be traced for more than 200 km and appears to have flowed into the large meandering channel of the paleo-Wabe Shebele. The Gode and Mustahil flows were sampled during the 2008 helicopter survey. Locally, this flow appears to overflow the main channel to form overbank basaltic pods. The Juba River in Somalia has meandering basaltic outcrops, following a paleo-Juba River channel (Abdirahim et al. 1993; Ali Kassim et al. 1987, 1993), which are geomorphologically very similar to the Gode flow outcrops. Initially thought Oligocene, the geomorphology of both the Juba and Wabe Shebele basalt outcrops argues in favor of a much younger age of emplacement. A 7.5 ± 0.4 Ma ^{40}Ar-^{39}Ar age has been determined for the Wabe Shebele basalts (Table 19.1).

Table 19.1 Location and age of the basalt samples used in this work

Volcanic site	Sample ID	Type	Coordinates (WGS84)		Age	Method	Material	References
			Latitude N	Longitude E	(Ma ± 2σ)			
Marda (north)	MA03	Flow	9°21′52.13″	42°41′57.74″	23.68 ± 0.54	$^{40}Ar/^{39}Ar$	Groundmass	Mège et al. (in press)
Marda (north)	MQR7	Dyke	9°21′48.51″	42°42′7.68″	25.04 ± 0.65	$^{40}Ar/^{39}Ar$	Groundmass	Mège et al. (in press)
Marda (south)	L-2-3	Flow	8°43′50″	43°4′20″	25.5 ± 1.3	K–Ar	Whole rock	Maxus Ethiopia (1993)
Daga Medo	K-2-1	Flow	8°25′40″	42°54′30″	27.4 ± 1.4	K–Ar	Whole rock	Maxus Ethiopia (1993)
Mustahil	20	Flow	5°32′22.12″	44°35′37.80″	28.09 ± 0.81	$^{40}Ar/^{39}Ar$	Whole rock	Mège et al. (in press)
Fik	A-3-1	Flow	8°12′	42°40″	28.4 ± 1.4	K–Ar	Whole rock	Maxus Ethiopia (1993)
Kebri Dehar	K3.2	Flow	6°49′38.00″	44°56′49.45″	27.64 ± 0.40	$^{40}Ar/^{39}Ar$	Whole rock	Unpublished*
Kebri Dehar	K1.6	Flow	6°45′18.34″	44°26′3.39″	27.61 ± 0.59	$^{40}Ar/^{39}Ar$	Whole rock	Unpublished*
Gode	WS	Flow	6° 1′12.79″	43°21′55.28″	7.46 ± 0.47	$^{40}Ar/^{39}Ar$	Groundmass	Mège et al. (in press)

*The ages yet unpublished have been obtained from this chapter's team of contributors. Sample K3.2 has a 78 % plateau age with MSWD (mean square of weighted deviates) 0.61, and sample K1.6 an inverse isochron with intercept 289.3 ± 8.6 and MSWD 1.15

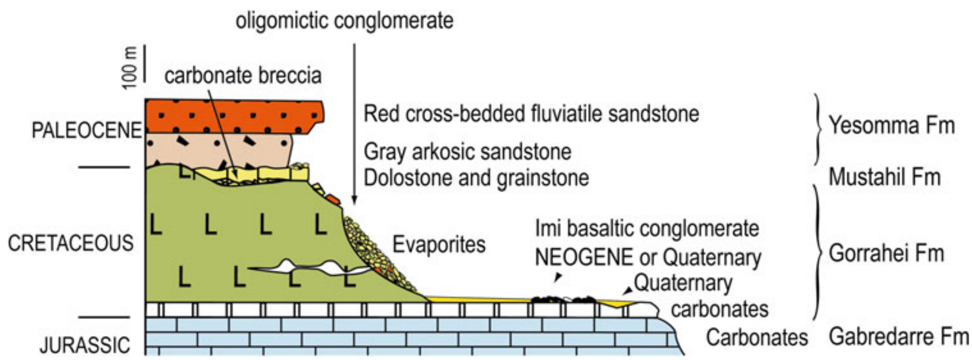


Fig. 19.9 Simplified stratigraphy of the northern Audo Range (Mège et al. 2013)

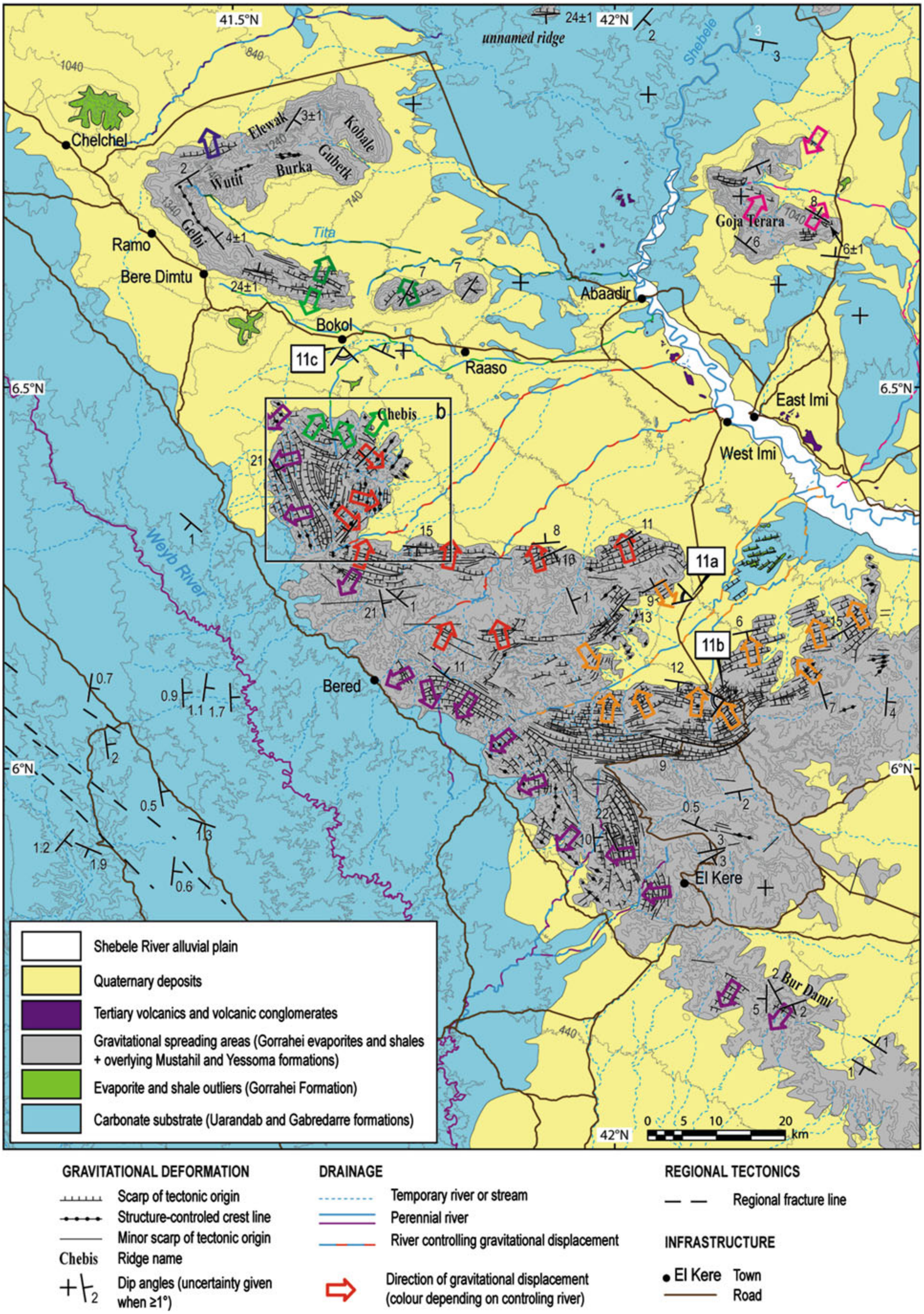
The current outcrops of the Gode and Juba basalts suggest an original total lava flow length of several hundreds of kilometers, similar to the length of lava flows in other flood basalt provinces, for example, the Columbia River flood basalts (Tolan et al. 1989). Surprisingly, however, and contrary to the other very long basaltic flows, which appear to have formed as part of the main flood basalt emplacement event, the age of the Gode flow very significantly postdates the age of the main Ethiopian flood basalt events. The Juba basalts, which have a similar morphology and similar relationships with the Juba river, might also be of Upper Miocene age, as might the Dolo volcanic table, given the good geomorphological evidence that the Juba basalts flowed from it.

19.3.4 Gravitational Spreading Structures

19.3.4.1 Manifestation and Geographical Extent

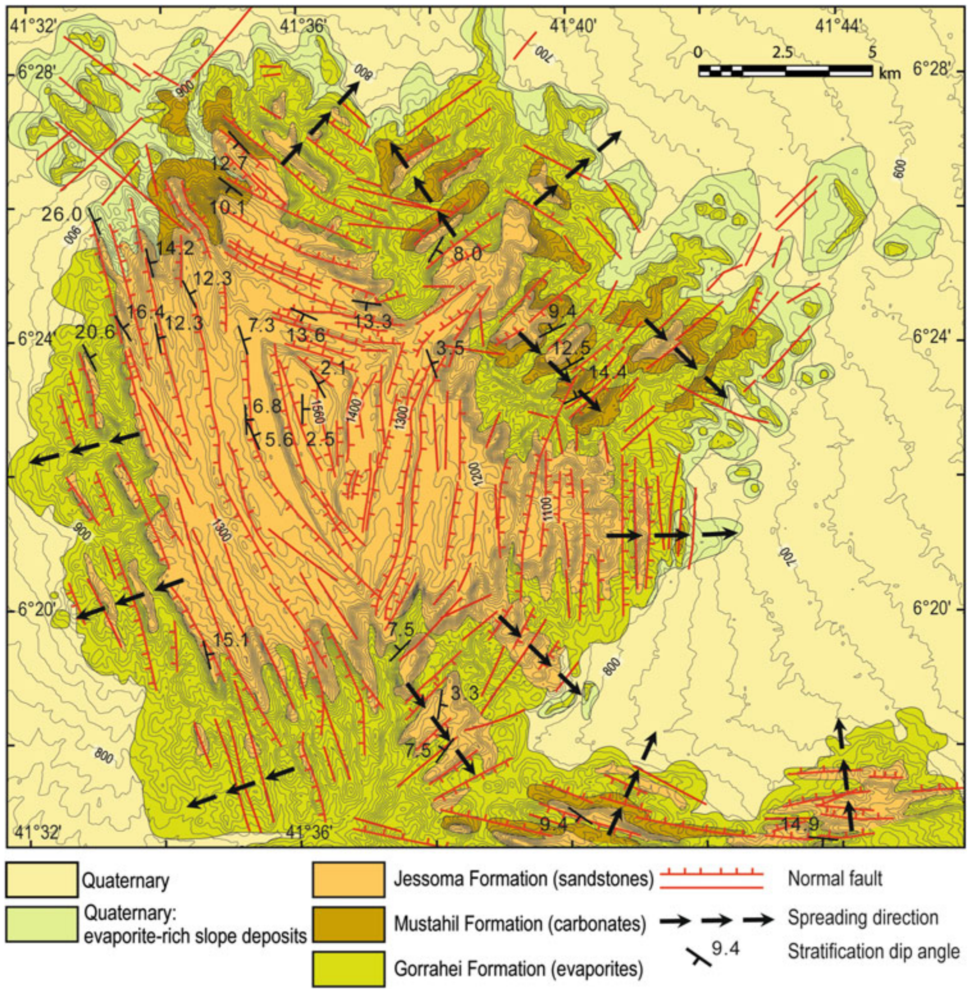
The Portlandian–Neocomian Gorrahei Formation outcrops extensively in western Ogaden, where it is dominantly evaporites alternating with shales and over 150 m thick (Fig. 19.9). It overlies the Kimmeridgian–Portlandian Gabredarre Formation inner shelf limestones, which provides a rigid basement on which the spreading has occurred: the Mustahil Formation (limestone) and the Yesomma Sandstone overlying the Gorrahei Formation have spread spectacularly by block faulting and tilting (Figs. 19.10 and 19.11), forming one of the world's largest gravitational spreading domains. Presently covering about 5,000 km^2, the Ogaden complex is 25 times larger than the Canyonlands grabens area in Utah, another spectacular continental-spreading domain.

The spreading zone extends from the Weyb River to the Wabe Shebele (Fig. 19.10a) and is mainly manifest in the Audo Range, an element of the water divide between the Genale and Wabe Shebele basins. The Audo Range is markedly asymmetric, with the most dramatic topographic relief and best-preserved gravitational features along the Weyb River, and more eroded and attenuated landscapes on the Wabe Shebele side. An unnamed ridge north of the Audo Range also displays evidence of normal faulting, producing tilting of post-Gorrahei sedimentary layers up to 25° (Figs. 19.10a and 19.11). East of the Wabe Shebele, the Goja mesa displays tilted blocks bounded by downhill- and uphill-facing normal fault scarps on the


41.5°N
42°N
6.5°N
6°N
unnamed ridge
Shebele
Chelchel
Elewak
Kobale
Gubetk
Burka
Wutit
Gelbi
Ramo
Bere Dimtu
Tita
Abaadir
Goja Terara
Bokol
11c
Raaso
Chebis
b
East Imi
West Imi
Weyb River
11a
11b
Bered
El Kere
Bur Dami
Shebele River alluvial plain
Quaternary deposits
Tertiary volcanics and volcanic conglomerates
Gravitational spreading areas (Gorrahei evaporites and shales + overlying Mustahil and Yessoma formations)
Evaporite and shale outliers (Gorrahei Formation)
Carbonate substrate (Uarandab and Gabredarre formations)
0 5 10 20 km
GRAVITATIONAL DEFORMATION
Scarp of tectonic origin
Structure-controled crest line
Minor scarp of tectonic origin
Chebis Ridge name
Dip angles (uncertainty given when ≥1°)
DRAINAGE
Temporary river or stream
Perennial river
River controlling gravitational displacement
Direction of gravitational displacement (colour depending on controling river)
REGIONAL TECTONICS
Regional fracture line
INFRASTRUCTURE
El Kere Town
Road

◄ **Fig. 19.10** **a** Geomorphological map of the Audo Range, based on field work at the Kebenawa Ridge and along the Imi–el Kere road complemented by Landsat ETM+ images and high-resolution satellite images available through Google Earth and Bing Maps. Block displacement arrows have a color that reflects the color pattern of the controlling stream or river. Dip angle is given with an accuracy of 1°, except for dip angles in nearly horizontal areas when a higher precision was thought to be significant. **b** Geomorphological map of the Chebis Ridge. In (**a**) and (**b**), error on dip angles is <0.1, except when given

Fig. 19.10 (continued)



east and a huge rotational landslide on the west. Both the Goja mesa and the unnamed ridge indicate that the initial extent of the gravitational spreading zone may have been much larger than presently observed.

19.3.4.2 Previous Work

The Audo Range and surrounding area have been little studied, as illustrated by the confusion in the reported stratigraphy. The rocks overlying the Gorrahei Formation are the Aptian Mustahil Formation limestones and the Maastrichtian–Paleocene Yesomma Formation sandstones (Fig. 19.9), but are shown in many documents as Tertiary basalts. Unrecognized on the earliest geological maps of Ethiopia, where it appears as Jurassic ('Antalo') limestone (Dainelli 1943; Mohr 1963), the Yesomma Formation was correctly identified on the first edition of the Geological Map of Ethiopia (Kazmin 1972) and a contemporary hydrogeological map of the Shebele drainage basin by ORSTOM (Bauduin et al. 1973). However, these sediments were mapped subsequently as volcanics of unknown age by Merla et al. (1973) and, reflecting this, Beicip's (1985) Geological Map of Ogaden reported them as either the Yesomma sandstone or 'volcanics.' This indecision was not reflected on the second edition of the Geological Map of Ethiopia (Tefera et al. 1996) where they are shown as Eocene basalts (Ashangi Formation).

Evidence of halokinetic deformation predating gravitational spreading was found at the Kebenawa Ridge in the northern Audo Range (Mège et al. 2013). Gravitational spreading—in the form of tilted blocks surrounding mesas—was documented at the Chebis Ridge (Lopez-Gonzalez 2006), with faults dipping outward in most cases (Fig. 19.10b). Mège et al. (2013) suggested that gravitational spreading commenced after the Yesomma regression (Bosellini 1989; Purcell 1981), when erosional incision of the uplifted Ogaden surface reached the level of the Gorrahei evaporites. Topographic debuttressing and evaporite rheology then triggered fragmentation and spreading of the overlying formations, similar to the spreading of the Honaker Trail Formation and the Cutler Group over the evaporite Paradox Formation in the Needles district of the Canyonlands Park in Utah (Mège et al. 2013). A significant difference, however, is that the Canyonlands topography was incised by the Colorado River only on one side, leading to a single spreading direction, whereas the Audo Range is wholly surrounded by rivers incising the evaporite formation, leading to multidirectional spreading. Another difference is that spreading has promoted the development of half graben tilted up to 25° in the Audo Range, whereas spreading in the Canyonlands produced nearly symmetric grabens (Moore and Schultz 1999).

19.3.4.3 Landform Development

The direction of displacement of the tilted blocks in a gravitational spreading complex provides important insights into the development of the structure. Because gravitational spreading occurs in response to debuttressing of the evaporite layer, displacement is predictably perpendicular to the orientation of the 'free' boundary, that is, to the side where the river has cut down through the gypsum layer. Comparison between block displacement and the drainage system at the Audo Range suggests that gravitational spreading has occurred in response to incision by tributaries of the Wabe Shebele and by the Weyb River, but not by the Wabe Shebele itself. A correlation between stream or river incision and block displacement direction is proposed on Fig. 19.10a.

The gravitational spreading features are much better preserved on the western side of the Audo Range than on the eastern side, where the tilted blocks are much more dissected by the Wabe Shebele tributaries. This indicates that gravitational spreading is older in the east and that topographic debuttressing of the western side by the Weyb River occurred later. From the fluvial nature of the Cretaceous–Paleocene upper Yesomma Formation sandstones and the paleodeltaic deposits downstream in southern Somalia, the Shebele basin has been dated as old as the Cretaceous–Paleocene in western Ogaden (Bosellini 1989). Hence, there has been considerable time for erosion of the eastern side of the Audo Range. No evidence for such an age has been reported for the Weyb drainage basin, which could be a recent component of the Juba Basin—though the Juba Basin itself is thought to be of similar age to the Shebele Basin, based on the same sedimentary criteria. Fracture lines in the SW corner of the Audo Range map (Fig. 19.10a) which are parallel to the Weyb River and some Genale River tributaries (see Fig. 19.6) may testify to recent moderate tectonic movement related to the opening of the Main Ethiopian Rift (Gani et al. 2009), possibly controlling the incision of the Weyb River and triggering the more recent gravitational spreading on the western side of the Audo Range.

Dip angles were measured at 196 sites in the Audo Range area. The dip angle of the tilted layers is proportional to the quantity of stretching (e.g., Angelier and Colletta 1983) and provides additional information as to the spreading mechanisms. Dip angles were measured using the Orion™ structural analysis software from Pangaea Scientific (Fueten et al. 2005) applied to a co-registered SRTM90 digital elevation model and a Landsat ETM+ image (14.25–28.5 m/pixel). SRTM90 data (87–89 m/pixel) have an error of 5 m in southeast Ethiopia (Farr et al. 2007). A best-fit plane was computed from multilinear regression from manually selected points of known horizontal coordinates and elevation, picked out along a stratigraphic plane on the satellite image. The validity and accuracy of the computed plane is controlled by a series of statistics (see Fueten et al. 2005) and 3D visualization tools in OrionTM, and cross-checked with the high-resolution (0.5–2.5 m/pixel) 2D and 3D views using Google Earth and Bing Maps. Geologically speaking, each reported dip angle corresponds to the mean dip angle of a given strata of constant dip angle, averaged over a measurement site varying in length from a few to several hundred meters (7–30 measurements). Dip errors correspond to a 95 % confidence level and are reported only when >0.1°. Representative dip angles are reported on Fig. 19.10a. Figure 19.10b gives all the dip angles measured on the Chebis Ridge.

Dip angles measured in the tilted layers of the Mustahil and Yesomma formations are in the range 0–26°. The uppermost tilted blocks are connected to remnant Yesomma plateau fragments, which are either horizontal (north of El Kere) or more frequently, tilted by a few degrees (e.g., Elewak Ridge, Chebis Ridge). Dip angles could not be measured in the Gorrahei Formation, due to the difficulty in identifying continuous layers on the satellite imagery. Dip angles measured from the top of the Chebis Ride to its western foot (Fig. 19.10b) increase from the top to the bottom, suggesting that spreading proceeded inward.

Dip angles in the underlying Gabredarre Formation are usually close to zero and were never found to exceed 2–3°. In the southernmost area, dip angles were found to be consistently 0.4–0.7° to the east, accordant with the general 0.8°E dip angle calculated for the underlying Jurassic sequences from seismic reflection data (Line 93-GR-07E) about 70 km south of Fig. 19.10a (Beicip-Franlab 1998). These low dip angles show that gravity gliding along a regional structural slope (in the sense given by Schultz-Ela

Fig. 19.11 Tilted block in the eastern Audo Range: **a** in the Yesomma sandstones; **b** in the Mustahil carbonates; **c** at the Chebis Ridge. Location on Fig. 19.10

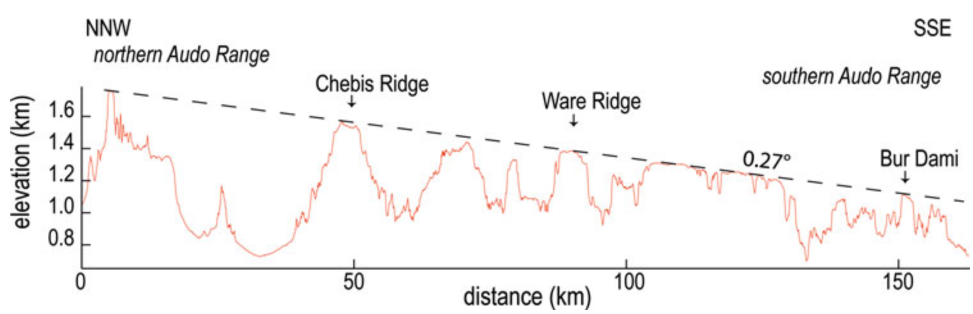


Fig. 19.12 Topographic profile along the Audo range water divide

2001) over the rigid pre-Cretaceous substrate did not play a significant role in the development of the observed landscape.

It is significant to note that the various plateaus of sub-horizontal Yesomma sandstone that constitute the summit blocks of the Audo Range Yesomma are fragments of the same dipping surface. A topographic profile along the water divide shows a linear decrease of plateau surface elevation from NNW to SSE, with an inclination of 0.27° (Fig. 19.12). An analysis of thirty-one points on the summit plateau surfaces throughout the Audo Range, plus 3 points on the Goja mesa, shows they fit a single plane of strike N003°E ± 016 and dip 0.4 ± 0.2° (at a 95 % confidence level), with a goodness of fit of 98.2 %. This remarkable fit indicates that the many geodynamic events that occurred in the Cenozoic after Yesomma sandstone deposition, including flood lava emplacement, and the rifting in the Gulf of Aden, Ethiopian Rift, and Afar, had very little influence on deformation in western Ogaden, beyond the uplift of the plateau itself.

19.4 Landform Evolution at Regional Scale

19.4.1 Adaptation of Rivers to Topography

Analysis of drainage systems provides valuable information regarding vertical motions of the surface at a regional scale (Snyder et al. 2000; Schumm et al. 2002; Duvall et al. 2004; Whipple 2004; Whipple et al. 2013) and can help understanding of the evolution of landforms in relation to geodynamics. In this section, the development of the present drainage network and the current topography is analyzed.

The general organization of the Ogaden basin shows large-scale structural and geodynamic control. The regional geometry of the Genale and Wabe Shebele river systems indicates two main directions of flow (Fig. 19.13). A dominant N130E orientation is exemplified by the main orientation of both the Genale and Shebele basins and by tributaries such as the Gerer, Fafan, and Dawa rivers. A second dominant orientation is N050-060E and is especially exemplified by a 350-km-long segment of the upper Wabe Shebele in the Arsi highlands. It is also observed in the lower part of the Dakota river. The N130°E trend is the orientation of the tilt of the Somali Plateau. The N050°–060°E trend is the orientation of the Main Ethiopian Rift

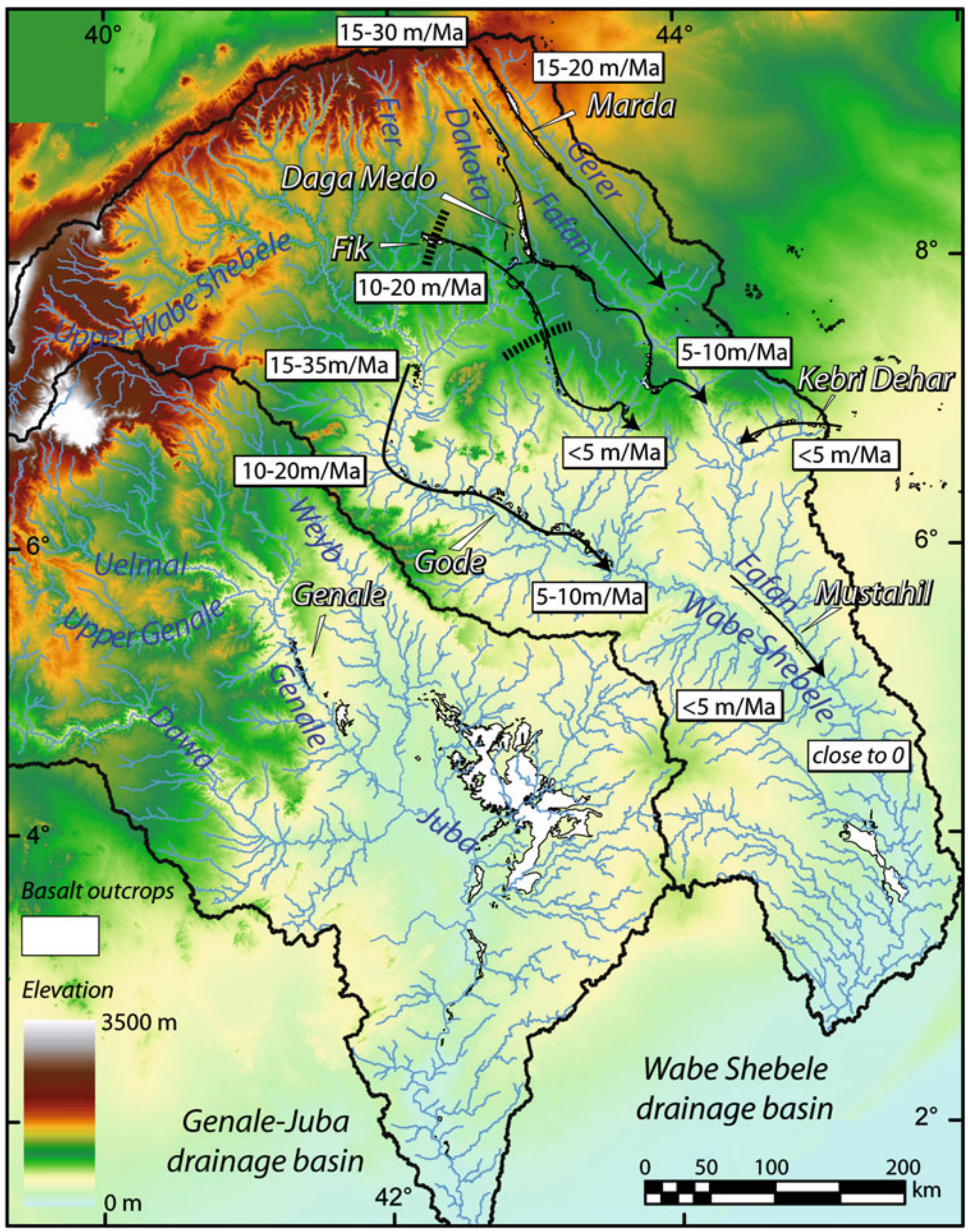


Fig. 19.13 Drainage system map, with the location of the basalt outcrops in the Ogaden (*white* surrounded with *black line*). The rivers are in *blue* and the watersheds in *dark grey*. The basalt flows used in the morphometric analysis are named. The *black arrows* indicate lava flow directions. Local mean incision rates since basalt outpouring are indicated in the *boxes*

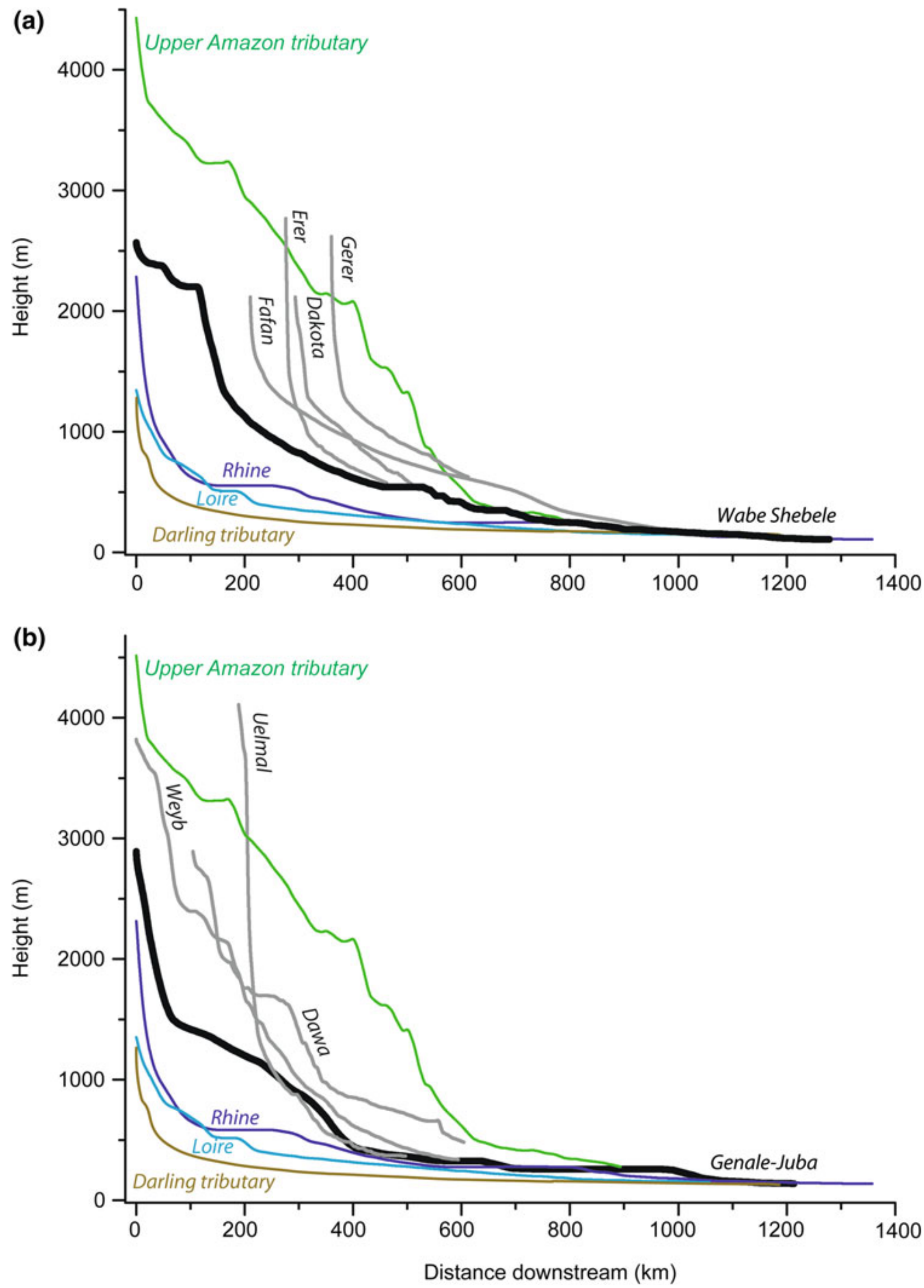


Fig. 19.14 Longitudinal profiles of rivers of the Wabe Shebele and Genale systems discussed in the text, and comparison with profiles of rivers at equilibrium (Darling river tributary, Australia); in equilibrium except in localized segments, where they are slightly disturbed by tectonics or localized abrasion (Rhine and Loire rivers, respectively, Europe); and in disequilibrium owing to active tectonic uplift and resulting strong fall of base level (Amazon tributary, Andes). The profiles were extracted from ASTER GDEM with RiverTools® (Peckham 1998). **a** Wabe Shebele system; **b** Genale system. The profiles are leveled at the elevation value at the end of the Wabe Shebele and Genale

axis. The faults guiding the rivers could originate from the early stage of rift development, before strain concentrates on a limited number of fractures (e.g., Olson 1993).

The longitudinal profiles of nine riverbeds overlain by basaltic flows were analyzed (Fig. 19.14). These rivers were selected as representative of their location compared to the main geologic features of the Ogaden. In the Wabe Shebele system (Fig. 19.14a), the Wabe Shebele does not show the characteristic fully concave longitudinal profiles of rivers in equilibrium. Profile equilibrium is usefully described with the concavity index (Langbein 1964), given in Table 19.2 for the studied rivers. This index is zero for a straight river profile; −1 is for strongly unequilibrated (convex) profile; 1 is for fully equilibrated (concave) profile. For the Wabe Shebele, the concavity index cumulated over the whole profile length (cumulative concavity index, CCI) is 0.83 (Table 19.2). The Wabe Shebele is characterized over its upper half by a succession of vertical-step knick-points. Between elevations ~2,600 and ~2,300 m a.s.l. in the Arsi highlands, it is characterized by an alternation of relatively

Table 19.2 Geomorphometric parameters for the rivers on Figs. 19.14 and 19.15 (graphical definition on Fig. 19.15)

River name	h_{max}	h_{min}	l	Concavity indexes	h			
	(m)	(m)	(km)		25 %	50 %	75 %	100 %
Main Ethiopian rivers								
Genale	2,825	50	1,315	*D*	*2 %*	*5 %*	*23 %*	*100 %*
				CCI	0.04	0.27	0.48	0.87
				ICI	0.04	0.3	**−0.2**	0.54
Wabe Shebele	2,685	165	1,505	*D*	*8 %*	*10 %*	*23 %*	*100 %*
				CCI	**−0.12**	**−0.49**	0.42	0.83
				ICI	**−0.12**	**−0.01**	0.16	0.63
Tributaries								
Uelmal	4,040	300	305	*D*	*6 %*	*13 %*	*10 %*	*100 %*
				CCI	**−0.42**	**−0.82**	0.29	0.87
				ICI	**−0.42**	0.34	0.32	0.68
Dakota	2,735	740	250	*D*	*0.8 %*	*4 %*	*22 %*	*100 %*
				CCI	0.48	0.58	0.81	0.72
				ICI	0.48	0.32	0.60	0.12
Dawa	2,825	415	500	*D*	*8 %*	*24 %*	*46 %*	*100 %*
				CCI	**−0.48**	0.43	0.11	0.60
				ICI7	**−0.48**	0.18	**−0.71**	0.07
Weyb	3,750	220	700	*D*	*10 %*	*25 %*	*35 %*	*100 %*
				CCI	**−0.49**	0.56	0.17	0.69
				ICI	**−0.49**	0.28	0.18	0.74
Erer	2,235	615	250	*D*	*4 %*	*8.5 %*	*44 %*	*100 %*
				CCI	0.24	**−0.05**	0.59	0.57
				ICI	0.24	**−0.13**	0.1	0.2
Fafan	2,230	280	800	*D*	*1 %*	*12 %*	*45 %*	*100 %*
				CCI	0.5	0.65	0.6	0.53
				ICI	0.5	0.47	0.2	0.26
Gerer	1,875	855	300	*D*	*11 %*	*33 %*	*66 %*	*100 %*
				CCI	0.27	0.23	0.32	0.22
				ICI	0.27	0.16	0.04	0.004
Other rivers								
Darling (Australia)	1,245	105	1,225	*D*	*0.4 %*	*2.5 %*	*7 %*	*100 %*
				CCI	0.67	0.52	0.75	0.91
				ICI	0.67	0.25	0.43	0.78
Rhine (Europe)	1,360	0	2,170	*D*	*0.07 %*	*2 %*	*7 %*	*100 %*
				CCI	0.18	0.36	0.7	0.82
				ICI	0.18	0.21	0.25	0.54
Loire (France)	1,200	0	1,055	*D*	*2 %*	*8 %*	*20 %*	*100 %*
				CCI	0.27	0.33	0.53	0.81
				ICI	0.27	0.53	0.53	0.44
Amazon tributary (Andes)	4,490	255	890	*D*	*11 %*	*33 %*	*55 %*	*100 %*
				CCI	0.69	0.16	0.11	0.33
				ICI	0.69	**−0.19**	**−0.51**	0.74

h_{max} = maximum river elevation a.s.l.; h_{min} = minimum river elevation a.s.l.; l = river length; h = river height decrease since its source; D = horizontal distance along the river taken from its source; CCI = Cumulative concavity index; ICI: Incremental cumulative index. Cumulative index (Langbein 1964) is defined as 2A/H, with A the vertical difference between the profile midterm and a straight line joining the two ends (or any point) of the longitudinal profile; H is the elevation difference between the uppermost and lowermost points of the straight line. CCI measures concavity of a river profile from its source to a given D. ICI measures concavity between two given D's, as illustrated in the insert of Fig. X.15. The indexes are 0 for straight river profile; −1 is for strongly unequilibrated (convex) profile; 1 is for fully equilibrated (concave) profile. Indexes are bold when convex. In each category, the rivers are ranked by cumulative concavity index, from higher to lower

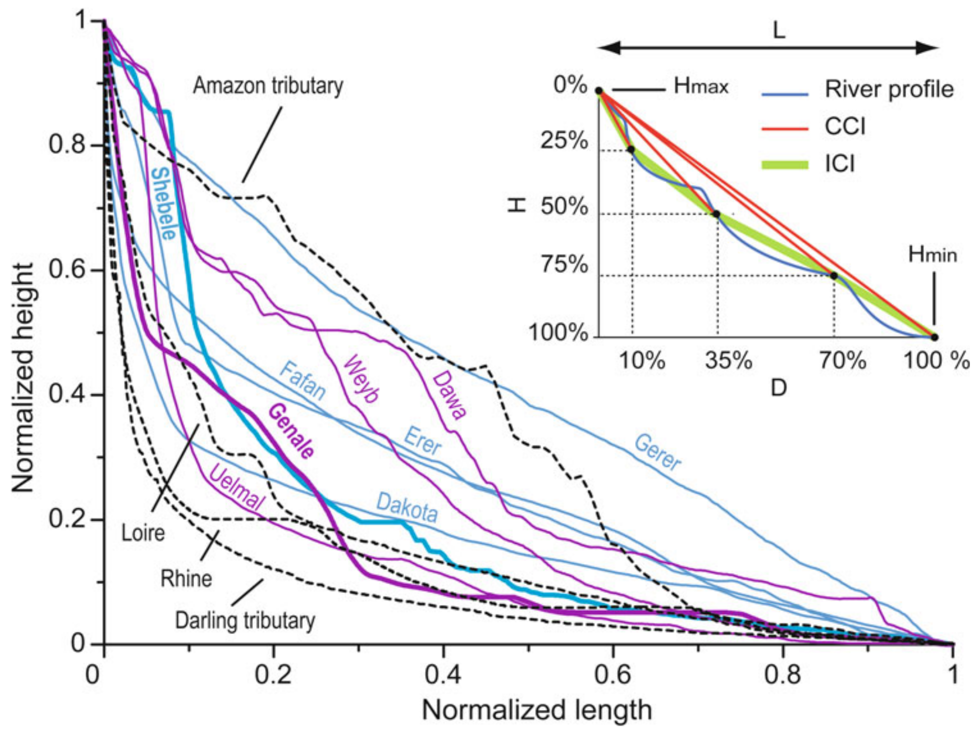


Fig. 19.15 Normalized river profile plot for the rivers displayed on Fig. 19.14. The *inset* shows relationships between geomorphometric parameters used in Table 19.2

flat areas and slopes with a gradient of 5–7 m/km, giving an overall gradient of about 3 m/km. However, at about 110 km, the slope increases abruptly to 20 m/km over several tens of kilometers and only recovers its average slope of 3 m/km after 340–350 km, at 660 m of altitude. This huge vertical-step break in slope creates the spectacular deep canyons for which the river is famous (Fig. 19.3d). In its lower reaches, the Wabe Shebele is again marked by a succession of vertical-step knick-points but of one order of magnitude less prominent. Eventually, the Wabe Shebele ends its Ethiopian course in a wide floodplain (10–20 km) with a slope of only 0.2 m/km. Even if its upper part is highly disrupted by knick-points, its overall profile is close to those of Rhine or Loire rivers, being smooth concave with irregularities: a near equilibrium profile (Fig. 19.15), with a CCI of 0.82 and 0.81, respectively (Table 19.2).

The Fafan River has a much lower CCI (0.53), denoting a significantly different evolution. Except in the uppermost 20 km, where a high slope (25 m/km) is manifest (incremental cumulative index ICI = 0.5), the Fafan has a linear profile for approximately 700 km, with a slope of 1.5 m/km and without any remarkable knick-points (ICI = 0.2–0.26). The same evolution is observed for the Gerer (linear profile at 3 m/km along 300 km), Dakota (2.5 m/km along 200 km) and Erer rivers (3.5 m/km along 225 km). High-gradient slopes of ~35–40 m/km are present in these rivers only in the initial 25 km. None of those valleys show an equilibrium profile. The Fafan and Gerer valleys are spectacularly linear and long compared to the other tributaries of the Wabe Shebele, which is attributed to the structural control of the Marda Range.

In the Genale system (Fig. 19.14b), the Genale River (1,300 km) has a linear profile upstream (20 m/km upstream, CCI = 0.04, Table 19.2) but changes abruptly at km 70 to a spectacular convex profile, with the slope decreasing sharply to 2 m/km and then increasing regularly to 5 m/km between km 350 and 400 (ICI = −0.2). Another abrupt change occurs downstream, with the slope decreasing to around 0.3 m/km and staying constant for the next 900 km.

The Weyb and Dawa rivers are both marked by very irregular profiles, with a succession of major slope breaks in their upper reaches giving convex profile sections (ICI ≤ −0.48) and very high average slopes: 10 m/km for the upper 300 km for the Weyb (CCI = 0.69) and 12 m/km during the upper 250 km for the Dawa (CCI = 0.6). In contrast, the Uelmal River is close to an equilibrium profile (ICI = 0.87). Its slope decreases gradually from the very high value of 100 m/km down to 1 m/km during the 300 km course, albeit marked by knick-points at km 50 and km 100 (CCI ≤ −0.42).

The highland part of both Genale and Wabe Shebele is not in equilibrium with their base level. Comparison with profiles from the Andes, where uplift is active (CI = 0.33 but negative over much of its profile ICI), and Australia, where the selected river is in equilibrium (Fig. 19.15) (CCI = 0.91), reveals that the Wabe Shebele, Genale, and Uelmal are close to an equilibrium profile, but the presence of irregularities indicates that none of them is a perfect equilibrium profile.

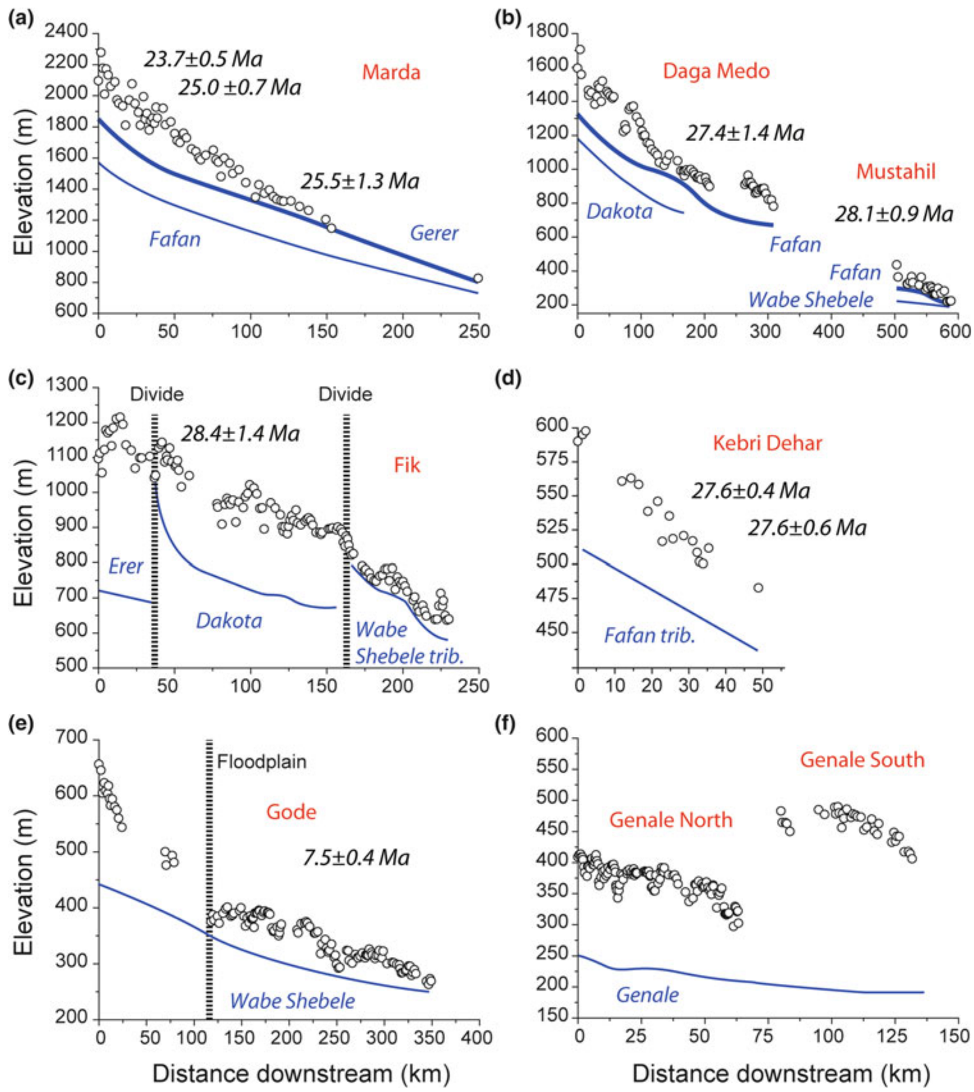


Fig. 19.16 Profiles of modern rivers (*blue lines*) and the base of basalt flows (*black dots*, names in *red*). Age details are on Table 19.1. The water divides in (**c**) are located on Fig. 19.13. The two data clusters in (**f**) are for the two Genale basalt tables located on Fig. 19.7. The difference in elevation reveals the depth of incision

The Dawa and Weyb profiles are closer to the Andean profile, whereas the Erer, Dakota, and Fafan show exotic bimodal linear profiles, and the Gerer has a unimodal linear profile, the latter being very uncommon. This analysis of the profiles of the Genale, and Wabe Shebele and their tributaries suggests a major base-level fall in the Ogaden, most likely due to tectonic uplift of one of its margins. In the next section, we discuss the use of age-dated basalts in paleo river valleys to help constrain uplift amplitude and timing.

19.4.2 Insight into the Evolution of Ogaden Topography Since the Upper Oligocene

The presence of age-dated basaltic flows, which filled paleo river valleys and presently are only a short distance from the modern river valley, allows the determination of average incision rates. For example, the elevation of the base of the Marda volcanics can be compared with the elevation of the beds of the Gerer and Fafan rivers, and the Gode flow, with the Wabe Shebele (Fig. 19.13).

This difference in elevation reveals the depth of incision since the basalt outpouring and that can be converted to a mean incision rate. The reliability of such an analysis requires that the horizontal distance between paleo- and present rivers is minimal and both sites are located in the same geological domain, without intervening deformation subsequent to the lava flow.

The elevation of the longitudinal profiles of six basalt-filled paleo river channels in the Wabe Shebele drainage basin was analyzed and compared with the elevation of the present river profiles. In addition to the Marda and Gode flows mentioned above, the Daga Medo volcanics were compared with the Fafan river, and the Fik volcanics with the Erer and Dakota rivers in the north and a Wabe Shebele tributary in the south. The elevation of the two Genale basaltic tables was also compared with the elevation of the Genale River (Figs. 19.13 and 19.16). In all cases, the area between the volcanic flow and the modern river valley has been geologically stable since the time of eruption. The Marda volcanic flow, being located on the eastern side of the prominent Marda Precambrian deformation zone, warrants some caution in that regard but the excellent and continuous rock exposures through the Marda volcanics and across the neighboring Fafan and Gerer rivers on the Harar-Jijiga road show no significant postflow deformation.

The elevation of the base of every basalt outcrop was measured using elevation data from ASTER DEM, with geographical control from Landsat ETM+ images and high-resolution images available on Google Earth™. Uncertainty in elevation control is estimated to 10–15 m. Some of these flows (Marda, Mustahil, Kebri Dehar, Gode) have been dated recently using argon radiochronology and their age is considered reliable. The Marda, Daga Medo, and Fik flows were dated in the 1990s by the K-Ar method but have the same age span as most of the argon-dated samples, suggesting these ages are plausible. The Genale tables have not been dated. More details are given on Table 19.1.

Figure 19.16 presents the results of these comparisons and shows clearly that incision is intense at the river head and decreases downstream. This is true for the older basalts at Marda, Daga Medo, Fik, and Kebri Dehar (Fig. 19.16a–d), and also for the younger Gode flow. Moreover, the Fafan has incised faster than the Gerer (Fig. 19.16a); the Dakota than the Gerer (19.16b), and the Erer than the Dakota (19.16c), revealing that the mean incision rate has increased from east to west. The incision rate has also increased from south to north, mean incision rate for the middle and upper Dakota being 7–11 m/Myr. (Figure 19.16c) and 13–20 m/Myr, respectively (Fig. 19.16b). For the Fafan it has increased, south-to-north, from 10–13 m/Myr. (Figure 19.16b) to 16–36 m/Myr. (Fig. 19.16c). The maximum mean incision rate of about 30 m/Myr (Fig. 19.16e) was obtained for the Wabe Shebele in its upstream course at the northernmost outcrop of the Gode flow. Incision rates calculated for the different rivers and the age of the associated lava flows are given on Fig. 19.17.

The base of the Fik flow has a linear profile but crosses two water divides (Fig. 19.16c), showing that the drainage network has changed since the basalt outpouring, with the Erer and Dakota rivers achieving their present geometry more recently than the Fafan and Gerer. This is well illustrated on the comparative river profile plot (Fig. 19.15), in which the Erer and Dakota river profiles are close to recently equilibrated profiles, in contrast to the linear Fafan and Gerer profiles, which indicate a relict transient profile (Kirby and Whipple 2012 and references therein). The Erer and Dakota have their convergence point with the Wabe Shebele much

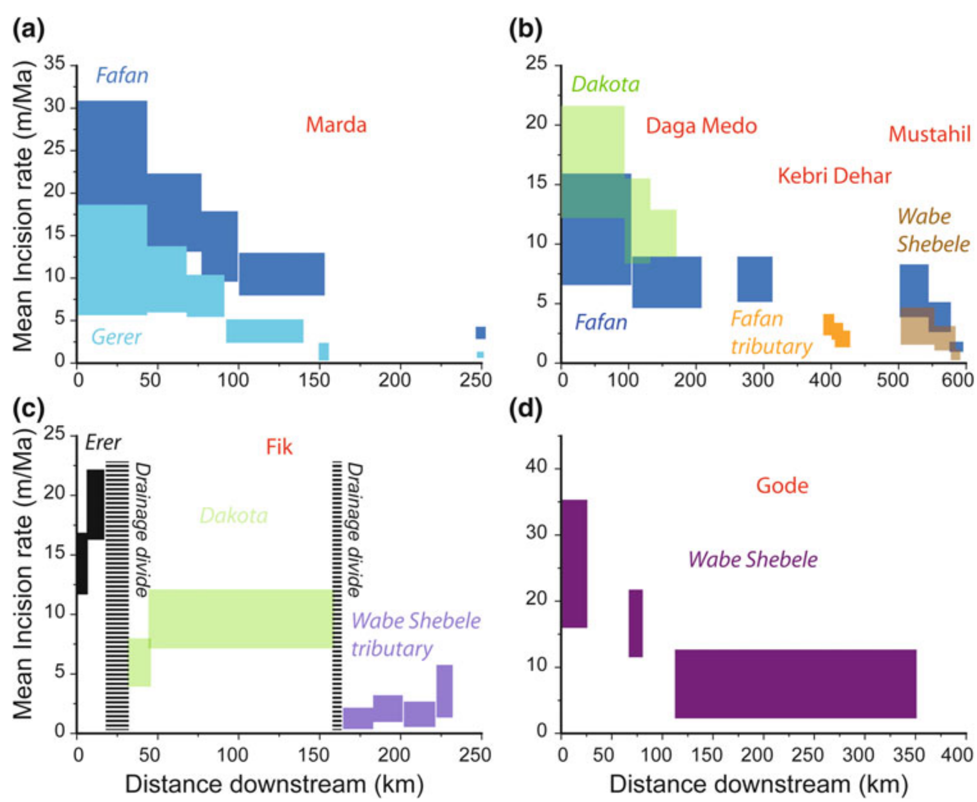


Fig. 19.17 Mean incision rate calculated from the data presented in Fig. 19.16. Incision after the Marda (**a**), Daga Medo, Kebri Dehar, and Mustahil (**b**), and Fik flows (**c**), starts at 28–22 Myr, i.e., as soon as the lavas are erupted. For Gode (**d**) erosion starts at 8–5 Myr

higher upstream than the Fafan and have been therefore more sensitive to the geodynamic events occurring in the upper Shebele region.

Downstream, the Fik flow follows a Wabe Shebele tributary with a constant vertical base-difference of 50 m. This tributary converges on the Wabe Shebele 100 km southward, cutting through the Gode basalt outcrops. This moderate incision reflects the lower uplift rate of this area.

Similarly, in the easternmost Shebele basin, where the Kebri Dehar flow is located, incision in the Fafan tributary that parallels the Kebri Dehar flow is slow (2.5 m/Myr) and nearly constant. This is consistent with the general incision pattern in the basin, with the mean incision rate increasing from east to west and south to north, toward the upper Wabe Shebele (Fig. 19.13). An extreme and remarkable case is the Mustahil flow (Fig. 19.16b) on the southeasternmost border of the Ogaden (that is, as far as Ogaden can be from Afar), which, in spite of its 28 Ma age, ends at the Wabe Shebele–Fafan confluence, at appreciably the same elevation as the present Wabe Shebele, pointing to the vertical stability of this confluence. This specific location along the Wabe Shebele may be close to the point in the river profile where incision stops and deposition starts. Perhaps not coincidentally, with the exception of the northeastern Ogaden (Mège et al. in press), the Cenozoic volcanic rocks in the Ogaden are outcropping and being eroded, whereas further east in Somalia the volcanic rocks are covered by Miocene to Quaternary sediments (e.g., Bosellini 1989; Faillace 1993). More generally, there is a marked absence of Neogene rocks throughout the Ogaden, except its northeastern part, while sediments of this age are widespread in Somalia (Abbate et al. 1994).

The Wabe Shebele floodplain begins near the latitude of Gode town. Its beginning is apparent on Fig. 19.16e, at the convergent point between the upstream profile, with a steep longitudinal slope (2 m/km) and a high mean incision rate (30 m/Myr), and the downstream profile, where the slope is gentle (0.5 m/km) and the mean incision rate is between almost 15 m/Myr and zero, the latter occurring at the convergence point with the Fafan River.

Floodplains usually develop in subsidence areas (Syvitski et al. 2012), in which detrital deposits accumulate, elevating the slope profile. As a result, the Wabe Shebele incision may be underestimated. The sharp transition in the slope profile of the base of the Gode basalts observed on Fig. 19.16e may be due to either a variation in the ancestral Wabe Shebele profile, or a difference in uplift rate, with an increasing mean uplift gradient from south to north.

The analysis of the paleotopography preserved by the basalts indicates that the present-day Wabe Shebele catchment is divided into two main parts that had contrasting responses to uplift. In the west, river profiles of Wabe Shebele-type have nearly completed a return to an equilibrium state, even though the entire profile is not yet smooth and concave. In the east, Fafan-type rivers have preserved a tilted slope in the uppermost part of the profile, but most of the profile has not changed. The Gerer River is an extreme case in which the tilted slope is atrophied and much of the remaining slope is constant, denoting geodynamic stability and probably an increasingly dry climate and subsequent lower erosion rate since the Miocene (e.g., Feakins 2013).

19.4.3 Uplift Rates

Commonly, large-scale river incision is the result of base-level fall, which can be caused by either tectonic uplift or sea-level (or lake-level) fall. In the Wabe Shebele valley, the geomorphological analyses indicate that the Wabe Shebele valley profile has nearly reached its equilibrium profile downstream. All the perturbations in valley profiles are located in the very upstream part of the system. Consequently, the calculated mean incision rates (Fig. 19.17) can be taken to approximate the uplift rates, with only minor, if any, contribution coming from sea-level variations.

Vertical movements of the surface (and underpinning crust) in the Ogaden region are a result of the complex geodynamics in the Horn of African since the Oligocene. The calculation of river incision rates helps in the understanding of the present topography at a regional scale, but does not inform regarding the uplift rate variations. On the Somali Plateau, such variations were probably not negligible, as discussed above in Sect. 19.2.2 with regard to the origin of the plateau elevation, and mean uplift rates need to be interpreted with caution when reconstructing paleotopographic evolution stages. Nevertheless, for young ages, additional information is given by the slope break in the paleo-Wabe Shebele profile (Fig. 19.16e), which shows that at least part of the uplift postdates 7 Ma. Since that time, the mean incision rate has been ~30 m/Myr upstream, decreasing to zero downstream near the Somalia border. This incision and the causative uplift (as argued above) are related to the development of the Main Ethiopian Rift. These measurements have been obtained at a minimum distance of 250 km from the rift margin, and the uplift rate of the westernmost Ogaden along the rift shoulder must have been much higher, given the usual rift-flank concave curvature. Furthermore, if rift-flank uplift has been the dominant mechanism of topographic building, then visco-elastic models predict that this ~30 m/Myr uplift rate could have been relatively constant since the beginning of rifting (Sachau and Koehn 2010). The mean incision rates obtained for the Wabe Shebele would correspond to a constant uplift rate since that time.

The Fafan River is located on the western side of a major crustal discontinuity, now manifest at the surface in the Marda Range; the Gerer River is located on its eastern side, and both rivers are parallel to it. The Marda Range serves, therefore, as the boundary between the northern uplifted Ogaden, with its rivers responding according to their setting, and the eastern stable Ogaden for which the evolution of the Main African Rift appears, perhaps deceptively, to have been only a remote influence.

19.5 Concluding Remarks

The landscape and landforms of the Ogaden reflect the geological development of the region. This is clearly manifest at a regional scale: the steep, nearly impenetrable canyons in the north, for example, are a consequence of the relative uplift of the Somali Plateau margin. Similarly, the contrast between the eastern and western Ogaden landscapes owes much to the pattern of Jurassic and Cretaceous sedimentation in these areas, and the impact of erosion during Cretaceous, Tertiary and Recent times. This interplay of Mesozoic sediments and Tertiary–Recent erosion is also seen on a local scale in the Audo Range, where erosional debuttressing of the Gorrahei evaporites has triggered gravitation collapse and spreading of blocks of the overlying Mustahil and Yesomma formations.

In spite of its diversity of landforms, somewhat amazingly, the Ogaden forms a continuous and coherent mega-geomorphological unit: a long eastward-dipping slope of dominantly thermal origin that docilely recorded the tectonic jolts from its neighborhood, mainly the many volcanic and rifting events. These resulted in dramatic upwarping on the western and northern side of the region, while the eastern and southern regions underwent negligible deformation. Vertical motions aside, the huge size of the area has allowed landforms to develop over broad surfaces: many identified lava flows are >100 km long and the Audo Range gravitational spreading complex could be the largest gravitational spreading domain on Earth. Other landforms not described in this chapter include the karstic landscape of the Gabredarre limestones south of Ginir, where the splendid Sof Omar caves are located.

A better understanding of the geomorphology of Ogaden will require considerably more exploration and study, perhaps especially the easternmost region. That the landscape of the Ogaden and its flora and fauna have not been better studied to date is, in part at least, a product of the remoteness and limited infrastructure but also of the difficult security conditions that have prevailed over large areas for many years. Current issues are the modern guise of conflicts centuries old and have their origins in that landscape and the rift that developed between the cultures on the Somali and Ethiopian plateaus.

Acknowledgments Part of this work was funded by the CNRS/INSU Marges programme. Field work in 2008 was conducted in cooperation with Pexco Ethiopia Exploration (East Africa) N.V. ^{40}Ar/^{39}Ar dating for this project is performed by Dr Fred Jourdan at the Western Australian Argon Isotope Facility, Curtin University, Perth, Western Australia. ASTER GDEM is a product of METI and NASA.

References

Abbate E, Sagri M, Sassi FP (1994) Geological map of Somalia, 1:1,500,000. Somali National University, Mogadishu

Abdirahim MM, Ali Kassim M, Carmignani L, Coltorti M (1993) The geomorphological evolution of the upper Juba valley in southern Somalia. In: Abbate E, Sagri M, Sassi FP (eds) Geology and mineral resources of Somalia and surrounding regions. Florence, Italy, vol 113 (Ist. Agron Oltremare Relaz E Monogr), pp 241–250

Ali Kassim M, Carmignani L, Fazzuoli M (1987) Geology of the Luuq-Mandera basin, geology of Somalia and surrounding regions, excursion A, GEOSOM 87. Somali National University, Department of Geology, Mogadishu, pp 1–43

Ali Kassim M et al (1993) Flood basalts of the Gedo Region (Southern Somalia): geology, petrology and isotope geochemistry. In: Abbate E, Sagri M, Sassi FP (eds) Geology and mineral resources of Somalia and surrounding regions. Florence, Italy, (Ist. Agron. Oltremare, Relaz. E Monogr) vol 113, pp 311–334

Angelier J, Colletta B (1983) Tension fractures and extensional tectonics. Nature 301:49–51

Bauduin D et al (1973) Projet du Wabi Shebele: étude hydrologique. ORSTOM, fdi:06586, Paris

Beicip (1985) Geological map of the Ogaden and surrounding area, 1:1,000,000. Geological Survey of Ethiopia, Addis Ababa

Beicip-Franlab (1998) Petroleum potential of Ethiopia. The Ministry of Mines and Energy of Ethiopia, Addis Ababa

Boccaleti M, Getaneh A et al (1991) The Marda fault: a remnant of an incipient aborted rift in the paleo-African Arabian plate. J Pet Geol 14:79–92

Bonini M et al (2005) Evolution of the main Ethiopian rift in the frame of Afar and Kenya rifts propagation. Tectonics 24, TC1007. doi:10.1029/2004TC001680

Bosellini A (1989) The continental margins of Somalia: their structural evolution and sequence stratigraphy. Mem Sci Geol 41:373–458

Cheung WH, Senay GB (2008) Trends and spatial distribution of annual and seasonal rainfall in Ethiopia. Int J Climatol 28 (13):1723–1734. doi:10.1002/joc

Dainelli G (1943) Geologia dell'Africa orientale. Centro Studi per l'Africa Orientale Italiana, Rome

Duvall A, Kirby E, Burbank D (2004) Tectonic and lithologic controls on bedrock channel profiles and processes in coastal California. J Geophys Res 109(F3). doi:10.1029/2003JF000086

Ethiopia Government Portal (2014) www.ethiopia.gov.et/stateoromia & /statesomali. Accessed Jan 2014

Ethiopian Mapping Authority (1988) National atlas of Ethiopia. Addis Ababa, Ethiopia

Farr T et al (2007) The shuttle radar topography mission. Rev Geophys 45:1–33

Faillace C (1993) Hydrogeological importance of the sub-surface basalts in the Mudug-Galgadud plateau. In: Abbate E et al (eds) Geology and mineral resources of somalia and surrounding regions, vol B, Mineral and water resources. (Ist Agro l'Oltremare, Rel Mon, Firenze, Italy) vol 113, pp 649–664

Feakins SJ (2013) Pollen-corrected leaf wax D/H reconstructions of northeast African hydrological changes during the late Miocene. Palaeogeogr Palaeoclimatol Palaeoecol 374:62–71. doi:10.1016/j.palaeo.2013.01.004

Fournier M et al (2010) Arabia-Somalia plate kinematics, evolution of the Aden-Owen-Carlsberg triple junction, and opening of the Gulf of Aden. J Geophys Res 115, B04102. doi:10.1029/2008JB006257

Fueten F, Stesky RM, MacKinnon P (2005) Structural attitudes of large scale layering in Valles Marineris calculated from mars orbiter laser altimeter data and mars orbiter camera imagery. Icarus 75:68–77

Gani NDS, Abdelsalam MG et al (2009) Stratigraphic and structural evolution of the Blue Nile Basin, Northwestern Ethiopian Plateau. Geol J 44:30–56

Hagmann T (2007) The political roots of the current crisis in region 5. Social Science Research Council, Web forum Crisis in the Horn of Africa, New York

Hagmann T, Khalif MH (2006) State and politics in Ethiopia's Somali Region since 1991. Bildhaan. Int J Somali Stud 6:25–49

Hofmann C, Courtillot V et al (1997) Timing of the Ethiopian flood basalt event and implication for plume birth and global change. Nature 389:838–841

Juch D (1975) Geology of south-eastern escarpment of Ethiopia between 39° and 42° long. East. In: Pilger A, Rosler A (eds) Proceedings of an international symposium on the afar region and related rift problems. Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung

Kazmin V (1972) Geological map of Ethiopia, 1st edn, 1:2,000,000. Geol Surv Ethiopia, Addis Ababa

Kibrie T, Yirga T (2008) The geology of Bedesa area (NC37-16) Geol Surv Ethiopia Memoir 10, Addis Ababa

Kirby E, Whipple KX (2012) Expression of active tectonics in erosional landscapes. J Struct Geol 44:54–75

Lemma G (1996) Climatic classification of Ethiopia. National Mapping Authority, Addis Ababa

Leroy S et al (2012) From rifting to oceanic spreading in the Gulf of Aden: a synthesis. J Arab Earth Sci 5:859–901. doi:10.1007/s12517-011-0475-4

Langbein WB (1964) Profiles of rivers of uniform discharge. US Geol Surv Prof Pap 501-B:119–122

Lopez-Gonzalez T (2006) L'étalement gravitaire de la ride de Chebis dans le bassin de l'Ogaden, Ethiopie. MSc. Thesis, Laboratoire de Planétologie et Géodynamique, Nantes University

Maxus Ethiopia (1993) Ogaden concession final report. Addis Ababa, Ethiopia

Mège D, Le Deit L, Rango T, Korme T (2013) Gravity tectonics of topographic ridges: Halokinesis and gravitational spreading in the western Ogaden, Ethiopia. Geomorphology 193:1–13

Mège D, Purcell, PG, Jourdan F (2012a) Volcanism in southeast Ethiopia and the Ogaden Dyke Swarm. Magmatic rifting & active volcanism conference, Addis Ababa, Abstract

Mège D, Purcell P, Jourdan F (2012b) Dykes and linear troughs: new observations on the Somali Plate. Lunar and planetary science conference 43, Lunar and Planetary Institute, Houston, Texas, Abstract 1317

Mège D, Purcell P et al A major dyke swarm in the Ogaden region south of afar and the early evolution of the afar triple junction. In: Wright TJ, Ayele A et al (eds) Magmatic Rifting and Active Volcanism. Special Publication Geological Society of London, 420, in press

Megrue GH, Norton E et al (1972) Tectonic history of the Ethiopian rift as deduced by K-Ar ages and palaeomagnetic measurements of basaltic dykes. J Geophys Res 77(29):5744–54

Merla G, Abbate E et al (1973) Geological map of Ethiopia and Somalia, 1:2,000,000. Consiglio Nazionale Della Ricerche, Florence

Micheels A, Eronen J, Mosbrugger V (2009) The late Miocene climate response to a modern Sahara desert. Glob Planet Change 67:193–204. doi:10.1016/j.gloplacha.2009.02.005

Mohr P (1963) Geologic map of African Horn of Africa. Philip and Tacey, Fulham

Moore JM, Schultz RA (1999) Processes of faulting in jointed rocks of Canyonlands National Park, Utah. Geol Soc Am Bull 111:808–822

Moucha R, Forte AM (2011) Changes in Africa topography driven by mantle convection. Nat Geosci 4:707–712. doi:10.1038/NGEO1235

Nicholson SE (1996) A review of climate dynamics and climate variability in East Africa. In: Johnson TC, Odada E (eds) The limnology, climatology and paleoclimatology of the East African lakes. Gordon and Breach, Amsterdam, pp 25–56

Olson JE (1993) Joint pattern development: effects of subcritical crack growth and mechanical crack interaction. J Geophys Res 98 (B7):12,251–12265

Olson P (1994) Mechanics of flood basalt magmatism. In: Ryan MP (ed) Magmatic systems. Academic Press, New York, pp 1–18

Peckham SD (1998) Efficient extraction of river networks and hydrologic measurements from digital elevation data. In: Barn-dorff-Nielsen OE et al (eds) Stochastic methods in hydrology: rain, landforms and floods. World Scientific, Singapore, pp 173–203

Purcell P (1976) The Marda Fault Zone, Ethiopia. Nature 261 (5561):569–571. doi:10.1038/261569a0

Purcell P (1981) Phanerozoic sedimentary history and petroleum potential. In: Chewaka S, de Wit MJ (eds) Plate tectonics and metallogenesis: some guidelines to Ethiopian mineral deposits. Ethiopian Inst Geol Surv Bull 2:97–114

Purcell P, Mège D, Jourdan F (2011) Volcanic geomorphology of Southeast Ethiopia. In: Asrat A et al (eds) Geomorphology for human adaptation to changing tropical environments. IAG/IAG regional conference, Addis Ababa, 127

Sachau T, Koehn D (2010) Faulting of the lithosphere during extension and related rift-flank uplift: a numerical study. Int J Earth Sci 99:1616–1632. doi:10.1007/s00531-010-0513-6

Schultz-Ela DD (2001) Excursus on gravity gliding and gravity spreading. J Struct Geol 23:725–731

Schumm SA, Dumont JF, Holbrook JM (2002) Active tectonics and alluvial rivers. Cambridge University Press, Cambridge

Sepulchre P, Ramstein G, Fluteau F, Schuster M, Tiercelin J-J, Brunet M (2006) Tectonic uplift and eastern Africa aridification. Science 313:1419–1423

Snyder NP, Whipple KX, Tucker GE, Merritts DJ (2000) Landscape response to tectonic forcing: digital elevation model analysis of stream profiles in the Mendocino triple junction region, northern California. Geol Soc Am Bull 112:1250–1263

Syvitski JPM, Overeem I, Brakenridge GR, Hannon M (2012) Floods, floodplains, delta plains—a satellite imaging approach. Sedim Geol 267–268:1–14

Tefera M, Chernet T, Haro W (1996) Geological map of Ethiopia, 2nd edn, 1:2,000,000. Geol. Survey Ethiopia, Addis Ababa

Temin J (2006) Grassroots conflict assessment of the Somali Region, Ethiopia. CHF International

Thulin M (2007) Acacia fumosa sp. nov. (Fabaceae) from eastern Ethiopia. Nordic J Bot 25:272–274

Tolan TL, Reidel SP et al (1989) Revisions to the estimates of the areal extent and volume of the Columbia River Basalt Group. In: Reidel SP, Hooper PR (eds) Volcanism and tectonism in the Columbia River Flood-Basalt Province, US Geol Surv Sp Pap 239:1–20

UNDP (1999) Drought and floods stress livelihoods and food security in the Ethiopian Somali Region. UNDP Emergencies Unit for Ethiopia report

Walsh J (1976) Oil and gas in Ethiopia. Geol Surv Ethiopia Min Circ 4

Watchorn F, Nichols GJ, Bosence DWJ (1998) Rift-related sedimentation and stratigraphy, southern Yemen (Gulf of Aden). In: Purser

BH, Bosence DWJ (eds) Sedimentation and tectonics of rift basins: red Sea-Gulf of Aden. Chapman and Hall, London, pp 165–189

Whipple KX (2004) Bedrock rivers and the geomorphology of active orogens. Ann Rev Earth Planet Sci 32:151–185

Whipple KX, DiBiase RA, Crosby BT (2013) Bedrock rivers. In: Shroder J Jr, Wohl E (eds) Treatise on geomorphology, vol 9., Fluvial Geomorphology. Academic Press, San Diego, pp 550–573

Wolfenden E, Ebinger C et al (2004) Evolution of the northern Main Ethiopian rift: birth of a triple junction. Earth Planet Sci Lett 224:213–228

Author Biographies

Daniel Mège Daniel Mège obtained a M.Sc. degree in geophysics and internal geodynamics in 1991 in Paris at University of Paris-Sud, Orsay, Ecole Normale Supérieure-Ulm, and Pierre and Marie Curie University. In 1994, he obtained a Ph.D. degree in planetary sciences at University Paris-Sud, Orsay, France. In charge of the NASA Regional Planetary Image Facility at University of Paris-Sud in 1995–96, he was also a postdoc at DLR and at University of Nevada, Reno. He was then appointed as assistant professor at Blaise-Pascal University, Clermont-Ferrand, France, before obtaining an associate professor position at Pierre and Marie Curie University in 1997. In 2001, he obtained his habilitation in comparative planetology and moved to University of Nantes, France, in 2004. Since 2011, he is a Visiting Professor at the Institute of Geological Sciences at the Polish Academy of Sciences, where he is in charge of developing a research group working on planetary sciences. He conducts research on the geology of the Gojjam lowlands in western Ethiopia and the Ogaden in order to contribute to document the evolution of the Ethiopian Large Igneous Province and the Afar triple junction, and of various bodies of the solar system. Daniel is a member of the Geological Society of America, the American Geophysical Union, the Geological Society of Africa, and IEEE.

Peter Purcell Peter Purcell is an Australian geologist with an MSc from the University of Sydney. He is General Manager of P&R Geological Consultants Pty Ltd, with over 40 years experience working in Australia, SE Asia, and East Africa. Peter first worked in Ethiopia in 1973–1977 and continues to be involved with exploration and research there. He has edited several books on Australian geology and is the author of numerous articles on geology and petroleum exploration in Australia and East Africa, as well as environmental and social issues. Peter is a fellow of the Geological Society of London and a member of AAPG, PESA, and ASEG.

Stéphane Pochat Stéphane Pochat received the MSc degree in sedimentology and paleoclimatology in 1999 and a PhD degree in sedimentology and tectonics at University of Rennes 1 (Geosciences Rennes), France. He was appointed as assistant professor, then associate professor in 2007 at University of Nantes (LPG Nantes), France. He shares his time between paleoclimatic and sedimentary basins dynamic during the Paleozoic, the study of marine terraces, fluvial geomorphology in Ethiopia and Somalia, and fluvial and glacial geomorphology on Mars.

Thomas Guidat Thomas Guidat is a geomorphologist who obtained a MSc degree in planetology in 2013 at University of Nantes (LPG Nantes), France. He worked on geomorphometric analysis of basalt-filled paleorivers in Ogaden and Somalia, and glacial evolution of Isidis Planitia on Mars. He is currently involved in the PhD program at Trinity College, Dublin, where he is studying eolian dynamics on Mars. Thomas is a member of the British Society of Geomorphology.