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Morphological Landscapes of Ethiopia

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Abstract—We give an outline of the topographic features of the Main Ethiopian Rift and the Afar Triangle as well as of the Ethiopian Highlands. We highlight the role played by the active tectonics and young volcanism which have largely determined the appearance and morphological diversity of contemporary landscapes of Ethiopia. A brief description of several unique natural sites is provided.

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INTRODUCTION

Ethiopia is located in Northeastern Africa; it is bordered by Eritrea, Djibouti, Somalia, Sudan and Kenya (Fig. 1) [1]. Ethiopia is the second-most populous nation on the African continent (with 88 million inhabitants as of 2010).

The geological history of the region under consideration can be subdivided into four stages corresponding to the Pre-Cambrian, Palaeozoic, Mesozoic, and Cainozoic. Each of them is represented by respective ensembles of rocks [2]. The Cainozoic era is the most prominent as regards the magnitude of geological events; at that period the territory of Ethiopia was experiencing active tectonic processes: overall uplifting of the territory, active volcanism, rifting, etc. Those processes were responsible for the shaping of the region's contemporary relief that includes forms of endogenous and exogenous genesis of a great variety.

We were able to familiarize ourselves with the structural and evolutionary features of the geomorphological areas of Ethiopia during scientific excursions before and after the IAG/AIG Regional Conference on Geomorphology "Geomorphology for Human Adaptation to Changing Tropical Environments" held in Addis Ababa, Ethiopia, February 18–22, 2011 [3], as well as during field observations organized on our own. The total length of the routes was about 6.5 thou km.

The uniqueness of the morphological landscapes of Ethiopia is characterized by an excellent pronouncedness in the relief of differently directed tectonic movements, an abundance of structural forms, and by active erosion processes. This paper outlines the most interesting geological and geomorphological features of this territory and of its major regions – the Main Ethiopian Rift, the Afar Triangle, and the Ethiopian highlands.

THE MAIN ETHIOPIAN RIFT

The Main Ethiopian Rift (MER) has its origin in the Late Miocene. It is a classical intracontinental rift structure (see Fig. 1). It is about 500 km in length and up to 80 km in width. The rift valley cuts into two parts the largest (in the East-African rift system) upwarping whose formation started in the Oligocene. The southeastern and the northwestern shoulders of the rift are represented by the Somalian highlands and the Ethiopian (Abyssinian) highlands, respectively. The two highlands from the surface are largely comprised of eruptive products and constitute a volcanic plateau. Its surface is dominated by numerous young volcanoes, including those having their origins in the Late Holocene. The mountains surrounding the Main Ethiopian Rift reach 4000 m above the sea level.

The steep (weakly affected by erosion processes) normal fault side scarps of the rift are located at an altitude of 1000–1500 m above the level of the bottom. They are complicated by numerous tectonic steps and seismic dislocation structures and are characterized

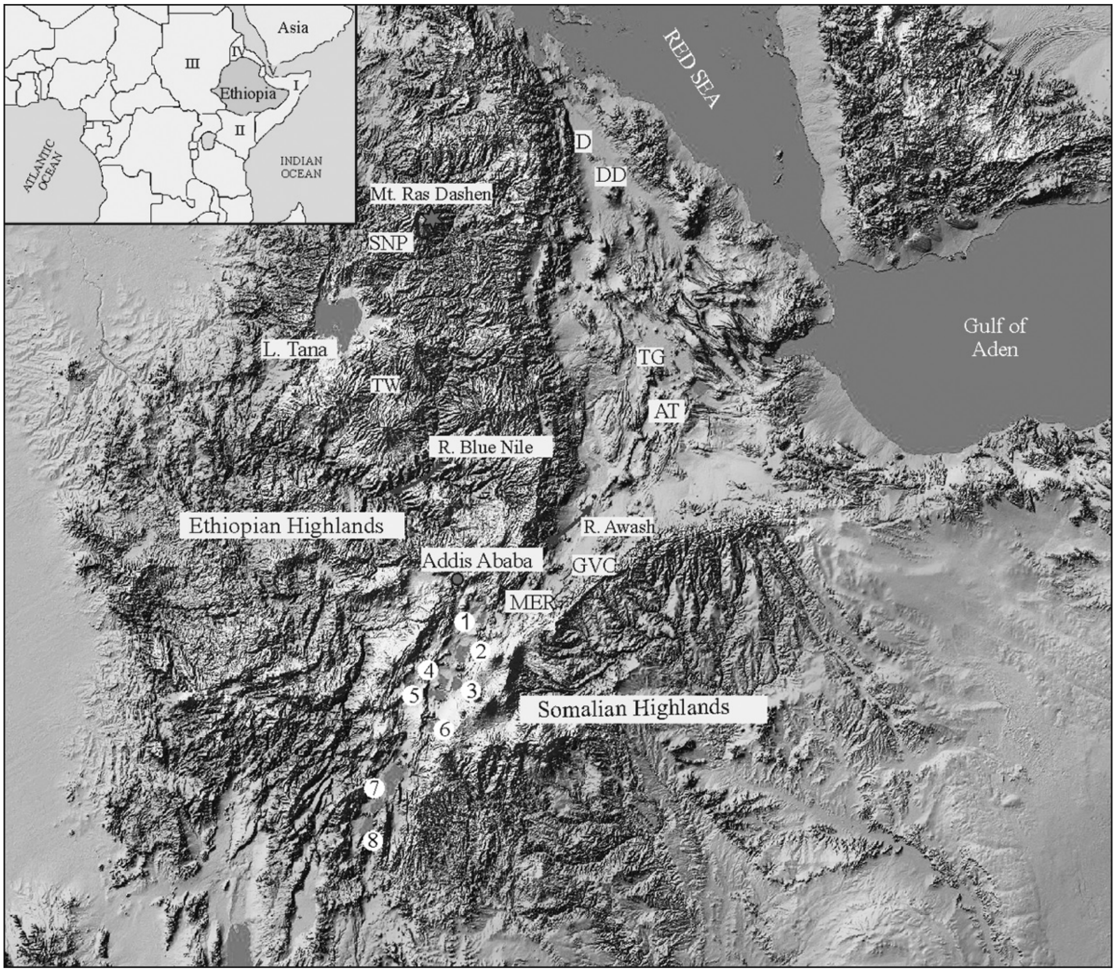

Fig. 1. Digital terrain model of Ethiopia.
MER – Main Ethiopian Rift, GVC – Gariboldi Volcanic Complex, AT – Afar Triangle, TG – Tendaho graben, D – Dallol, DD – Danakil depression, SNP – Simen National Park, TW – Tis Ysat waterfall. Lakes in the MER bottom: 1 – Koka, 2 – Ziway, 3 – Langano, 4 – Abijatta, 5 – Shala, 6 – Awasa, 7 – Abaya, 8 – Chamo. Map inset: countries bordering on Ethiopia: I – Somalia, II – Kenya, III – Sudan, IV – Eritrea, V – Djibouti.

by high tectonic activity of their respective governing faults. The narrow echeloned intermediate tectonic steps are virtually devoid of the faceted shape of the scars which is usually brought about by erosional dissection of the shoulders-counter-upwarpings of the rift basins. These steps are all characterized by a monolithic structure and a clear morphological pronouncedness of tectogenic facets.

The spurs of the MER's northwestern flank show inversionally upwarped and dissected by erosion (to a state of badland) tracts of the margin of the rift basin, in the neighborhood of the settlement of Warabey, for example (Fig. 2, a). The presence of young inversional transformations of the intra-depression structures here makes the peculiarities of the MER's morphotectonics similar to the Baikal Rift Zone where the inversional tectonic movements constitute a characteristic feature of the neogeodynamics of the depressions and complicate considerably their development [4, 5].

The bottom of the rift valley itself (abs. alt. 1200–1600 m above the sea level) largely comprises eruptive products, exceeding 500 m in thickness. This area is home to large calderas 10–25 km in diameter, some of which are occupied by lakes (Shala and Awasa). The northern part of MER is dominated by maars. Furthermore, the rift bottom is broken by young low-amplitude normal faults. This is particularly clearly seen in its axial portion and nearer to its southeastern side where a closeness of tectonic discontinuities reaches its maximal concentration. These faults intermittently "remind of themselves" by cutting the fresh roadbed with deep cracks (in the vicinity of Lake Ziway, for example). This same zone, the so-called Wonji Fault Belt (WFB), is also home to earthquakes epicenters and to an active manifestation of Pleistocene-Holocene volcanism. The last eruption was recorded here about 230 years ago [6]. Maximum extension rates of the rift basin, 4–6 mm/year, are also associated with the WFB [7].

In the Late Pleistocene – Early Holocene, a large

Fig. 2. The Main Ethiopian Rift.
(a) marginal parts of the rift, inversionally upwarped and dissected by erosion to a state of badland; (b) the largest volcanic structure of the central type in the rift bottom — Zuqualla volcano (abs. alt. 2989 m above the sea level).

portion of the rift bottom was occupied by an extensive lacustrine water body which gradually degraded with the passage of time. To date its relicts have only persisted in the calderas occurring in the axial Wonji belt. Lacustrine deposits persisting in the central portion of the Main Ethiopian Rift (between Lake Shala and Lake Langano) bear witness to the numerous reconfigurations of the ancient lacustrine basin.

Some lakes, such as Abijatta, had existed long before the beginning of the Last Pluvial Period in Africa [8]. Situated in the central portion of the Ethiopian rift, the water bodies occupy an area of a few hundred square kilometers (Lake Ziway – up to 442 km^2) and depths ranging from 7 (Lake Ziway) to 257 m (Lake Shala). They differ greatly in water turbidity and salinity. Elevated hydrothermal activity was recorded in the neighborhood of the calderas. Hot springs (with temperatures of up to 65–85 ºC) are rather numerous; they enjoy wide use among the local population for therapeutic as well as sanitary-hygienic purposes.

The Zuqualla volcano (abs. alt. 2989 m above the sea level) (see Fig. 2, b), situated to the south of the city of Addis Ababa, is the largest volcanic edifice of the central type in the MER bottom with an almost ideal geometry of the cone. The volcanoes of this part of the rift occurring in the Wonji zone of faults are the youngest (from the Late Holocene). Many of them are currently in the fumarole stage.

THE AFAR TRIANGLE

In the eastern part, the MER joins with the Red Sea rift and with the rift of the Gulf of Aden thus forming the sol-called Afar Triangle, It is the most complex and interesting place from the geological and geomorphological perspective, with an overlapping of rift structures of a different orientation [9]. In the Red Sea and Aden rift zones which are closely linked to the system of mid-ocean ridges, the riftogenic process has reached a maximum magnitude, leading to a fragmentation and thinning of the continental crust and, in its central portions, even to its fracture and neoformation of the oceanic crust [10]. According to the latest data, some incipient oceanic crust also occurs in the northern part of the Afar Triangle (in the Danakil depression) [7].

The extension rate of the Aden and Red Sea rifts is 11 and 20 mm/year, respectively, or far in excess of the rate of MER [11]. Therefore, it comes s no surprise that the morphological landscapes of the Afar region are clearly controlled by active tectonics and young volcanism. This is dramatically exemplified by the Tendaho graben with traces of differently directed dislocations corresponding to the orientation of the different rift zones [12]. The lifeless lava fields and almost black mantles of basalts, which are not infrequently characterized by spheroidal weathering, impart a special severity to this region.

The northern part of the Afar region includes the Danakil depression – one of the hottest and inaccessible places on Earth, with elevations up to 126 m below the sea level. A chain of active shield volcanoes surrounded by hardened lava flows, and salt lakes are aligned along the axis of the depression. In the neighborhood of Lake Assal there is a series of maars, and the largest of them is Dallol (48 m below the sea level) which formed in 1926. Its crater is home to a lake of viridian-yellow color, which is due to high sulfur content ($pH < 1$); because of an abundance of iron oxides, the lake's shores are ochreous reddish-brown in color. The crater features the most bizarre shapes of fumaroles and solfataras (Fig. 3, a).

In the southern portion of the Afar region, in the neighborhoods of Fantale Volcano (the last eruption occurred in about 1820), lava flows with blisters (lava grottos up to 3 m in height) have persisted in very good condition to date; they are partly flooded by the advancing waters of Lake Metehara (Basaka). The extensional processes within the rift zone are evidenced here by a series of subparallel open faults up to 1–2 m in width, an apparent depth of up to 12 m or more [13] and several kilometers in length on the lake's western shore. In some tracts, the faults are

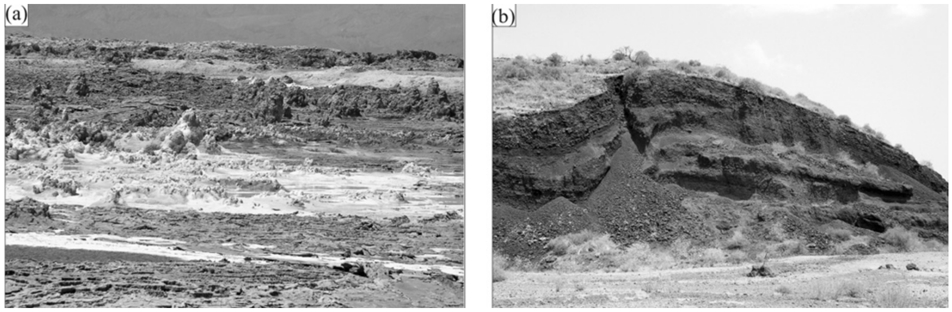

Fig. 3. The Afar Triangle.
(a) bizarre shapes of fumaroles and solfataras in the Dallol crater (maar) (48 m below the sea level); (b) deformed cone of a young volcano comprising interbedded basalt lavas and their tuffs (Gariboldi volcanic complex).

not rectilinear but have a zigzag shape.

The whole of Ethiopia and this region in particular are characterized by high seismicity, and most earthquakes here are shallow-focus, crustal earthquakes, with M > 5. One such earthquake (M 5.9) in 1969 razed to the ground the city of Serdo – the former capital of the Afar region. Traces of tectonic movements here can be seen everywhere: young movements led to displacements of large blocks on the sides of the Tendaho graben, deformed the volcanic cone comprised of interbedded basaltic lavas and their tufas (see Fig. 3, b), the bottom of the small caldera of the Gariboldi volcanic complex, etc.

In the northern part of the Somalian plateau, active tectonics caused in many tracts some reconfigurations of the river system: the formation of a step bench of the rift basin resulted in the beheading of the southward oriented valley heads belonging to the drainage basin of the Shebelle river (Somali: Webi Shabeelle) by reversing their runoff (toward the rift) to produce in the place of the contemporary watershed a series of closed lakes in the saddles – fragments of the ancient valleys. Traces of numerous reconfigurations are also seen along the eastern margin of the Ethiopian highlands traversed by the watershed between the drainage basins of the Red Sea and the Mediterranean.

In spite of the extremely arid contemporary conditions, the southern periphery of the Afar region in places of limestone outcrops is characterized by the presence of traces of karst processes, more specifically groove karren which, according to data reported by N.A. Gvozdetskii [14], are produced under the effect of atmospheric precipitation. The occurrence of karsting rocks was also responsible for the formation of calcareous (phytoclastic) tufas which are widely distributed along the river valleys and are interbedded by sandy and gravelly deposits of the terraces. In some cases, they were also recorded at the foot of the slopes. Accumulation of tufas was taking place within the time interval 12–16 thou years ago [12]. The character of precipitation bears witness to the existence of the more humid conditions and the presence of vegetation on the slopes at that period, which did cause an intensification of solution of carbonate rocks. By dating phytoclastic carbonate Neoformations, it is possible to determine the deepening rates of the river valleys which reach 1 mm/year in the vicinities of the city of Dire Dawa as well as the age limits of pediment formation. Within the chalky limestones of the Ethiopian and Somalian highlands, rather extensive caves were also recorded; the longest of them is Sof Omar Cave more than 15 km long [15].

THE ETHIOPIAN HIGHLANDS

A large role in the contemporary morphogenesis of the Ethiopian (Abyssinian) highlands played the tectonic faults having their origins in the Cainozoic; the process was accompanied by the outpouring of basaltic lavas to form trap plateaus (the Oligocene–Miocene) as well as separate stratovolcanoes, and various intrusive forms (sills and dikes). Nowadays, the highlands has the form of an extensive gently rolling plain (abs. alt. 2200–2700 m above the sea level) which is cut in some places by deep erosional-tectonic valleys, with separate, sometimes rather large isolated mountain massifs. An active action of the processes of erosion and denudation led to exposure of previously buried peneplanation planes in the northern section of the highlands. The most ancient and the youngest of them date back to the Early Palaeozoic and the Early Cainozoic, respectively [16].

The largest mountain massif – Simen – in the northern part of the highlands (at about 1000 km from Addis Ababa) is a Miocene-aged shield volcano [17]. Among the mountains of the massif is the tallest peak of Ethiopia, Mt. Ras Dashen (4620 m above the sea level), with the height of the mountain ranges averaging 3000–3500 m above the sea level (this place is called the "Roof of Africa") [18]. The impressive morphological landscapes of the Simen mountain massif (Fig. 4, a), which we can observe today, were also formed through active tectonic processes and the manifestati9ons of intense erosion and denudation of Cainozoic basalts and tuffs (totaling up to 300 m in thickness) comprising the massif [18]. The most spectacular landforms are represented by deep (reaching 2000 m) canyon-like gorges, perpendicular benches up to 1500 m or more

Fig. 4. The Ethiopian Highlands.
(a) view of the Simen mountain massif in the area of Chennek Camp (abs. alt. from 3600 to 4000 m or higher above the sea level); (b) canyon-like gorge of the Blue Nile; (c) Tis Ysat waterfall.

in height, farewell rocks that were reconfigured by denudation to bizarre shapes, etc.

In 1969, most of this mountain massif (about 220 km^2) was declared the Simen National Park; the Park was inscribed on the List of UNESCO World Natural Heritage Sites in 1978.

One of the most impressive places of the Ethiopian highlands is the gorge of the Blue Nile. The Blue Nile (Amharic – Abbay) is the largest river of Ethiopia and one of the most brilliant natural attractions of the country. The river has its origin in Lake Tana in the northwestern part of the highlands, initially heading southeastward, then southward, and then westward thus describing a gigantic loop and skirting the lake on the southern side. Next, it flows across the territory of Sudan where, in the area of Khartoum, joins with the White Nile.

Over a length of 800 km the Blue Nile flows in a deep canyon-like gorge (see Fig. 4, b). In the middle part of the highlands, it reaches its maximum depth – 1500 m. In the perpendicular walls of the gorge, one can read almost the entire geological history of the region: Tertiary basalts outcrop in the upper part of the profile, with a thick layer of Mesozoic and Palaeozoic sedimentary rocks occurring below; metamorphic rocks of the Pre-Cambrian foundations outcrop in the river bed. The gorge produces an equally spectacular impression upon the observer as does, for example, the famous Grand Canyon carved by the Colorado river in the USA.

For the most part, the contemporary morphology of the Ethiopian highlands is represented by different structural landforms. They include tracts of flat-top plateaus, rocky high-mountain massifs, separate volcanic domes that have been transformed by weathering processes, and sills and dikes reconfigured in a bizarre manner. The slopes of the highlands have a step profile – also the result of action of selective denudation. The same step profile in some areas is also characteristic for the river valleys, with waterfalls occurring on occasion [2]. Thus, flowing out from the southeastern part of Lake Tana, the Blue Nile is initially calm and full-flowing; however, 30–35 km downstream, when crossing basalt layers, it terminates at a most beautiful waterfall with a free fall of about 40 m and up to 400 m in width at a humid period, and only 100 m in width during a dry season. It is Tis Ysat, or Tis Abbay (in Amharic, meaning "smoking fire" and "smoking water", respectively) (see Fig. 4, c).

Waterfalls of this type usually come into existence due to a river-mediated reworking of geological substratum whose structural-lithological properties are responsible for the creation of steep benches in the thalwegs of water courses. In the first place, these waterfalls occur in places where a river intersects young basalt blankets [19]. Given the local climate, however, much more stable rocks than basalts are represented by Mesozoic sandstones, the outcrops of which do form the tables and ideally flat tracts of the highlands, whereas basalts are more likely to be characterized by gently rolling surfaces of more subdued outlines.

Lake Tana is one of the largest and picturesque lakes of Ethiopia; it is situated at an altitude of 1830 m above the sea level. The lake's water table measures about 2156 km^2; its area increases considerably in rainy seasons; its maximum depth reaches 15 m. The water body was formed at the Quaternary period as a result of intense volcanic activity and the blocking of the streamflow by lava flows. Young eruptive rocks can be seen everywhere – on the shores, and on the islands.

The lake has about two tens of islands. In the heart of many of them there still remain medieval Orthodox cloisters and churches. The interior of the churches boasts remarkably beautiful wall-paintings on evangelical themes as well as other Christian relics, such as marvelous icons, ancient manuscripts, etc. They are all kept with much care. For that reason, in addition to its indubitable natural value and attractiveness, the lake has an important cultural and historical significance; clearly it attracts a large number of tourists.

Nowadays, seismotectonics continues to determine in many respects the morphogenesis of the Ethiopian highlands [20, 21]. In some areas, as many as several tens of earthquakes are recorded every year. At regular intervals the strongest of them (> M 6) lead to destruction of roads and buildings as ell as generating rock falls and landslides [16].

The slipping of earth materials is also caused by significant amounts of atmospheric precipitation (most of which corresponds to the summer season of rainfall) in areas with badland topography largely comprising the most yielding sedimentary rocks with sparse vegetation cover as well as experiencing anthropogenic impacts. Because of some of the largest landslides, several tens of inhabitants had to move to new places of residence [16].

Water erosion processes during summer floods are highly hazardous and unpredictable. On occasion they are so intense that they are capable of causing substantial damage to the country's economy by destroying bridges and undercutting the river banks. An essential contribution to the ongoing morphogenesis processes is also made by the anthropogenic factor. High population density, extensive methods of management of the economy, and forests' destruction occurring everywhere (and, not infrequently, extermination of herbaceous vegetation) on the slopes, combined with extremely unevenly distributed rainfall, bring about an intensification of soil erosion and degradation processes evolving on a staggering scale, causing a real challenging problem for the entire country.

CONCLUSIONS

Rifting and accompanying processes – volcanism and tectonics – are responsible for the specifics of Ethiopia's contemporary relief. They produced the largest morphological features of the region – the Ethiopian and Somalian highlands and the rift valleys as such as well as determining the location of many lakes and river valleys, and their subsequent reconfigurations. The morphogenesis has actively continued till the present: traces of recent vertical and horizontal movements, captures of river systems leading to a shifting, including of the main African divide, are almost universal in occurrence. Considerable rates of contemporary morphogenesis processes are characteristic for each of the regions outlined above. Within the rift valleys, they are associated with contemporary tectonic movements, and with young volcanism; on the Ethiopian highlands – with depth of dissection of relief, unevenly distributed rainfall, and with active anthropogenic impacts which have been steadily increasing over the last four millennia to gradually become one of the leading factors of morphogenesis.

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