12 Geomorphic Processes in Late-Pleistocene and Holocene Environments

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Late-Pleistocene and Holocene environmental changes in Dogu'a Tembien are evidenced by cyclic alternation of stable and active morphogenetic periods. Stable phases correspond to periods of longitudinal river profile stabilisation through the development of river tufa dams (see Chap. 8), by (1) development of forest vegetation, protecting soil against erosion and by (2) formation of soils with swell-shrink crack patterns suggestive of Vertisols or vertic horizons. Active morphogenetic phases comprise seasonal river flood-related vertical and lateral channel incisions, active erosion processes such as landsliding, gullying, sheet- and rill-wash on hillslopes, creating eroded zones in uplands, and the development of

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colluvial and alluvial deposits at foot slopes and in valley bottoms. Cyclicity of active and stable environmental phases is generally believed to correspond to climatic cycles in which the precession movement of the earth axis, the orbital characteristics of the earth around the sun and cycles of sun spot activity play a role. Such astronomically induced cyclicity should be of regional to (sub) continental importance. This was the case during most of the Pleistocene. Since ca. 7000–5000 years ago, however, local climates become out of phase with the regional cycle (Fig. 12.1). Scientific literature reports that human interventions in the local water balance are the explanation of this phenomenon. This marks the beginning of significant geomorphological change by humans in Ethiopia. The first three sections of this chapter address landforms and their genetic processes in Dogu'a Tembien that evidence stability, followed by several sections on landforms related to instable periods, up to today. Finally, the influence of humans on the environment is discussed.

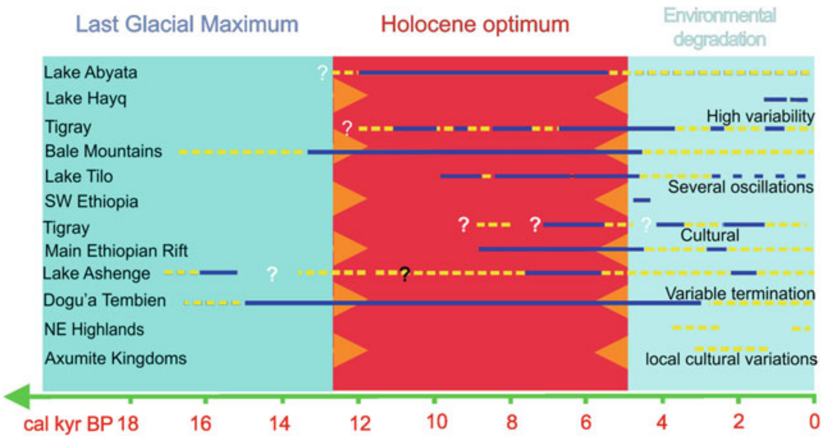

Fig. 12.1 Recent palaeoclimatic interpretations for Ethiopia. Yellow lines: relatively moist; blue dashed lines: relatively arid; ?: uncertainty about extent in time. Blue belt to the left: generally accepted LGM-arid conditions; light blue belt to the right: often considered as late-Holocene climatic aridification with environmental degradation. Out of phase oscillations are obvious. Horizontal scale in thousands of years before present. After Moeyersons et al. (2010), upgraded with information by Marshall et al. (2009), Lanckriet et al. (2015) and Terwilliger et al. (2011)

12.1 Tufa Dam Development, an Environmental Indicator of Stable Phases

Tufa dams in Dogu'a Tembien are found in Agula shale and Antalo limestone domains. Typically, they occur where a river crosses a knickpoint in the longitudinal profile corresponding to a harder layer in the Antalo limestone or a dolerite sill. In such favourable areas, successions of up to seven tufa dams can be found along the same river channel over a distance of 1–2 km. Remnants of older generations of dams sometimes exist in the same valleys at higher levels, corresponding to older terraces. In a 1200 km^2 area comprising Mekelle and Hagere Selam (Fig. 12.2), nine large inactive river tufa dams and several dozens of disintegrated remnants of dams dispersed all over the area are to be found. Although inactive today, these nine dams are still spectacular features (Photos 7.7, 12.1, 12.2, 24.3 and 38.14).

Freshwater tufa deposits are the sedimentary response to karstic system activity. They develop during relatively wet and warm conditions, in areas with dense plant cover and with nearly continuous surface water flow and percolation. Tufa dams preferentially start to develop in river rapids or small chutes, because better water aeration there favours the evacuation of carbon dioxide and hence high rates of $CaCO_3$ precipitation. Also essential for tufa build-up is underwater growth of algae

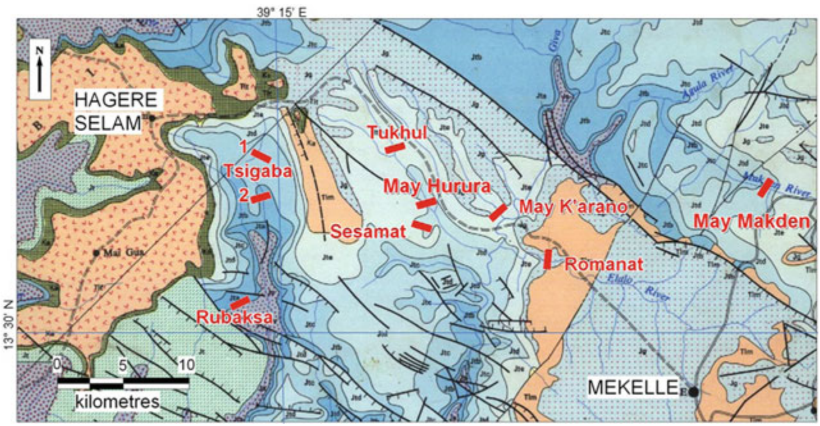

Fig. 12.2 Location of the most important inactive tufa dams in the Mekelle—Hagere Selam area. The underlying geological map shows that tufa dams coincide with the extension of Antalo limestone (blue tones) domain

Photo 12.1 Tufa dam in valley bottom between Tsigaba and Rubaksa (location on Fig. 12.2). The dam has been incised by the river after tufa growth stopped. Photo Jan Nyssen (2015)

Photo 12.2 The tufa dam of Sesamat (location on Fig. 12.2) is ca. 100 m wide, more than 15 m high in the centre of the valley and is ca. 200 m long in upstream direction. Remnants of an older tufa dam are visible high on the valley slope (clear patch just under the crestline on the left, indicated by arrow). Photo Jan Moeyersons (2000)

and mosses. This means that photosynthesis is needed in the building process, which necessitates clear water (with a very low turbidity). These environmental conditions offer supplementary evidence for a river flow regime with much smaller peak flow discharges than today and thus with a continuous base flow and a high vegetation cover in the catchment that limited or even prevented surface runoff. In other words, the river regime is typically perennial during tufa dam development.

If river tufa dams originate primarily as a response to wet environmental conditions in the catchment, their further development, in turn, induces moist conditions to develop. This is explained by the natural lake development upstream of river tufa dams, accompanied by a supplementary rise of the local groundwater table, independent of the environmental forcing to river tufa dam origin.

12.2 Weathering Processes During Stable Phases

Dogu'a Tembien is a stepped highland where flat lands alternate with prominent cliffs. This morphology reflects the horizontal arrangement of geological strata with different hardness, undergoing differential erosion. The flat steps of the landscape are covered up by materials derived from the next cliff. At the foot of Antalo limestone and Agula Shale cliffs, this colluvium can be described as decalcified sand, loam and clay, containing limestone and shale fragments of different size (1 mm–1 m). At the foot of the cliffs of volcanic rock, especially at the foot of both tertiary basalt formations on top of the Amba Aradam sandstone, a large volume of black and red coloured deposits exists. The same type of weathering products is present, but in smaller quantities, at the foot of dolerite sill cliffs. Deposits at the foot of volcanic rocks also contain abundant rock fragments, again of very different size, but many fragments are core stones still showing a laminated weathering mantle. The blackish or reddish soil matrix shows a rhombohedral or prismatic structure and patterns of desiccation cracks. The presence of clays and basalt core-stones strongly suggests that this Vertisol-like material is a chemical weathering product of the basalts at the highest elevations in the landscape, and of dolerite sills, at lower altitude in the stratigraphic succession. The coupling between phases of intense rock weathering and phases of tufa dam development is suggested because chemical weathering is more active during wet environmental conditions and below a well-developed vegetation cover.

12.3 Age of the Last Stable Phase with Tufa Dam Formation

The humid conditions required for tufa dam formation started at least 15,000 years ago. In order to obtain the age of $CaCO_3$ precipitation, tufa samples have been taken from three dams (Tsigaba, Qarano, Romanat, Fig. 12.2) for Uranium-Thorium dating (a radiometric method in which the proportions of ^{230}Th and ^{234}U isotopes are measured). Due to generally high tufa porosity and the presence of non-calcareous debris most tufa samples were difficult to analyze. Especially the presence of ^{232}U can lead to an important overestimation of the dam age. However, one sample taken in the fresh part of the centre of a stalactite speleothem from a collapsed cavity in Tsigaba dam is an exception. The low content of ^{232}Th makes its age of 12.7 kyr (thousand years) very reliable. This gives confidence that the age range obtained for the post-LGM (Last Glacial Maximum) tufa deposits (14.1 and 15.8 kyr) in Tsigaba and May K'arano is reliable. Moreover, it is also very logical to find at Tsigaba for the primary calcite precipitation, which is at the origin of the cavity, an older age (14.1 kyr) than for the speleothem of secondary precipitation developed in the cavity (12.7 kyr). Since both samples were taken near the top of the tufa dam, the start of tufa dam build-up should be older. Although the Tsigaba dam contains a few calcified three trunks and twigs, the biohermal construction mainly contains moss and algal tufa. Laminations, known to reflect seasonal changes in growth, can be distinguished in all tufa dams and plugs (Photo 12.3). Analysis of tufa deposits from Australia shows that such laminations have a growth rate in the order of a few mm per year. At Tsigaba dam, laminations mostly have a thickness of less than one cm. Considering a yearly growth of the dam by 1 cm, the 15-m thick dam body thus represents 1500 years. This results in a minimum age of 15 kyr for the onset of humid conditions.

In the speleothems from Tsigaba, the analysed calcite is quite pure, indicating that it was precipitated in a period with low rain variability and relatively good and continuous vegetation cover, ensuring high CO_2 partial pressure in the soil, hence very aggressive soil water percolating down the soil profile into the bedrock. In this way, the speleothems in the river tufa dams indicate warm and humid conditions. The occurrence of long-lasting moist conditions well before 10–11 kyr BP (before present; i.e. before 1950) has also been found at Lake Ashenge (Fig. 12.1).

Let us now turn to high-energy deposits before and after the tufa-dam building phase and incisions that indicate environmental degradation rather than stability.

Photo 12.3 Tufa lamination at Ab'aro. A cave in the tufa plug has been enlarged to construct a rock-hewn church. Laminations, steeply dipping to the left and almost parallel to the church wall are clearly visible. Photo Jan Nyssen (2017)

12.4 Morphological Activity in the Pleistocene and Its Causes

At the bottom of the sedimentary sequence, and below almost all tufa dams, gravelly river bed deposits are present, containing even larger boulders than the ones in the present-day river beds. It points to ancient river floods, more powerful than today (Photo 12.4). Dating of the Tsigaba speleothems suggests that drastic change in river flow regime from highly seasonal to nearly perennial base flow took place before 15 U/Th kyr BP. This is 4000–5000 years before the first signs of post-LGM humid conditions deduced from former lake extensions in the

Photo 12.4 High energy flow deposits at the base of alluvium in the river bank, near Rubaksa (at right). Such coarse deposits systematically occur at the bottom of the alluvial succession, at the contact with in situ material. The small terrace where the persons are standing is composed of the same material that has been reworked by the current river. Photo Jan Nyssen (2015)

Ethiopian and Kenyan rift. There are presently no data suggesting alternative scenarios to climatic forcing. Also, the age at which the period of tufa dam building started is not clear. One tufa sample from Sesamat (Fig. 12.2) yields a date of 262 kyr. This date, much older than the other dates, has been furnished by a sample from river tufa remnants, located on a high terrace of the Sesamat river (Photo 12.2, at the back). In this case, morphological evidence supports a pre-LGM age. Most probably, throughout the Pleistocene, stable and dynamic phases did alternate.

12.5 Timing and Characteristics of the Holocene Activity Phase

In Tsigaba, speleothem growth continued over a long period. Organic matter rich sediment inclusions in one of the outer growth rings of another stalactite from the same collapsed cave were radiocarbon dated 3560 BP, which gives a calibrated date of 3983–3693 cal. yrs BP.

In the Dogu'a Tembien and surroundings, the gradual disappearance of forest just before the end of tufa dam build-up is evidenced by the following combination of arguments: (1) the change in dominance from dicotyledon phytoliths (preserved rigid parts of plant tissues) to monocotyledons in the final period of tufa growth; (2) the accelerated sediment infilling of the lakes upstream of the tufa dam since that time and several gravel layers in the sediments deposited in these barrier lakes, confirming high runoff and soil erosion rates on the hillslopes due to a low vegetation cover; (3) bush fires of grasses in Tukhul, stratigraphically equivalent to or younger than the top of the tufa dam. These arguments suggest that the area became gradually deforested by fires and that locally agriculture activities started.

This environmental change went hand in hand with a change in river flow regime which sheds some light on the changes in hydrological response of the landscape. In many parts of Africa, including Ethiopia, relicts exist of the ancient valley network characterized by small valleys without river channels, commonly called 'dambos', 'tropical valley bottoms' or 'inland valley swamps' (Photo 12.5).

The valley bottom Vertisols (Chap. 24) which are now commonly incised, were originally formed in such dambos. They also occur as palaeosols (buried below Holocene colluvium) in landscape hollows (Photo 12.6). The hydrograph of a dambo shows a relatively constant perennial base flow discharge with retarded and

Photo 12.5 Non-incised dambo in Era at the fringe of Des'a forest (NE of Mekelle). The presence of rock fragments at the soil surface and the polygonal structures, gilgai undulations micro-relief, suggest the presence of a thick Vertisol in this valley bottom. Despite ongoing forest degradation, the runoff is not (yet) strong enough to cut the dambo surface, though incipient gullying is apparent at mid-left. Photo Jan Nyssen (2007)

restricted flood response to rains, either individual storms or a rainy season (Fig. 12.3a). This delay is explained by the absence of channels in the valleys which are mainly spring fed. This type of river was hydrologically compatible with the humid conditions of northern Ethiopia until late Holocene times. Today, rivers in Dogu'a Tembien are characterized by very important flash floods and only restricted base flow. This change in river regime is explained by a change in the hydrological behaviour of the landscape with river flow discharges fed directly by overland flow from the hillslopes. The current contribution of direct runoff from the hillslopes to the river flow is much more important than in the past. Figure 12.3b lists the processes which generally contribute to much higher soil erosion rates on

Photo 12.6 Remnants of dambo Vertisols (black colour, at several spots along the river) that are incised and in most places covered by colluvium in the upper Tanqwa valley near Sewuhi Tekkay. The reader may imagine this catchment more than 5000 years ago, when all slopes were covered with forest, having a valley bottom like that of Photo 12.5. Photo Jan Nyssen (2008)

the hillslopes, sediment redistribution and increased environmental hazards, during an active compared to a stable morphodynamic phase.

The flat morphology of valley bottoms is no longer in equilibrium with high-energy peak flows: flow discharges have strongly increased, especially when the valley bottoms are devoid of the original flow-retarding vegetation, mainly grasses. In many places, farmers report how, starting from the 1950s onwards, small swampy valley bottoms without river channels developed into well-established river channels (Photo 12.7) after runoff coefficients increased as a result of deforestation and agricultural intensification on the surrounding hillslopes. Sometimes soil cracking induced by Eucalyptus plantation in the valley bottom

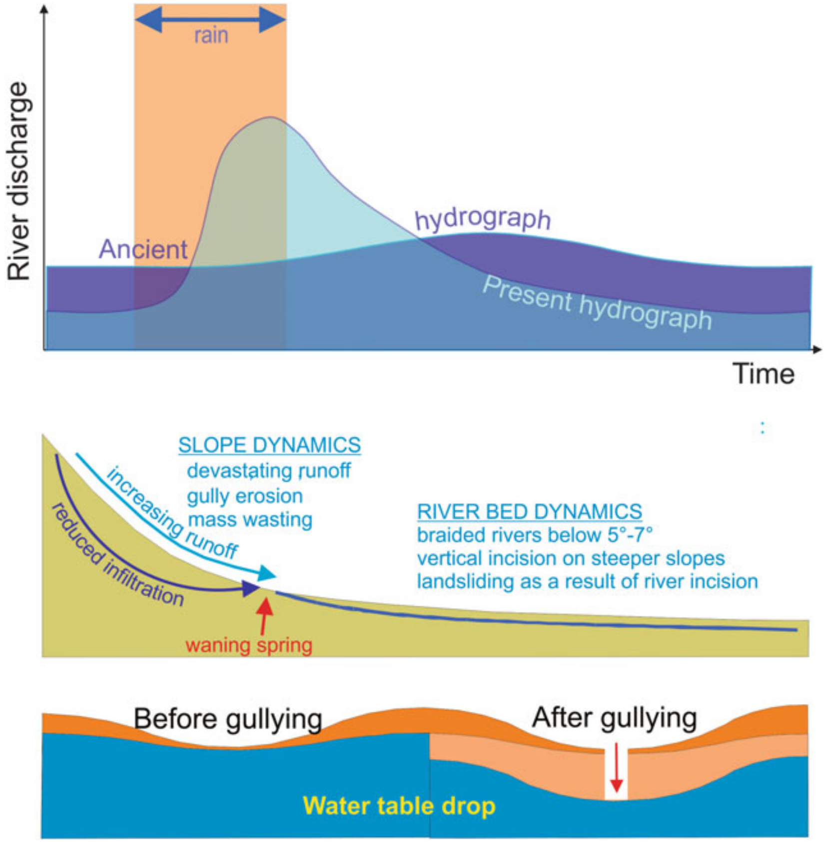

Fig. 12.3 Changes in a dambo due to a transition from the Early and Mid-Holocene stable conditions to a Late Holocene environmental degradation phase. Top: conceptual rain event-related hydrographs for the stable phase with tufa dam development (ancient situation) and present river regime as a result of increased surface runoff Bottom: increase in hydrological risks as a result of runoff increase at the partial expense of the infiltration-exfiltration water circulation. The water table drops after gully channel incision. After Moeyersons et al. (2010)

resulted in piping erosion and channel formation. The current gully erosion dynamics are further discussed in Chap. 22.

Strong geomorphic activity occurred in Dogu'a Tembien after tufa dams ceased to grow at around 3500 cal. yrs BP. Even today rock fall and debris flows

Photo 12.7 Incised Vertisol in dambo at Addi Selam due to increased runoff response after deforestations. Since the photo was taken (1998), the area has been smoothened and stabilised by check dams and woody vegetation. Photo Jan Moeyersons

(Photo 12.8) form a threat for road and house infrastructure as well as for people and cattle in the field. Most of the debris flows dating from Holocene times start from the top of Amba Aradam sandstone mesas, where large volumes of weathering products from Tertiary basalts are piled up. The matrix of this debris consists of swelling clays. As indicated in Chap. 20, argilliturbation, which becomes active when rainfall seasonality increases, is the trigger of this type of movement.

In addition to gully erosion, mass movements (Chap. 20) and sheet and rill erosion (Chap. 21) are active geomorphic processes that result in significant soil losses from farmland, in sediment redistribution within the landscape and in colluvial deposits at the footslopes. They are another evidence of the ongoing environmental degradation phase.

Photo 12.8 The debris flow of Melfa Maryam, has temporary blocked the river channel during the landslide event by forming a landslide dam on the valley bottom. Parts of the breached cliff have been transported far downslope. In a later stage, the river re-incised the debris flow material. Photo Jan Moeyersons (2006)

12.6 Human Influence and Control

Dogu'a Tembien has only a few small forest relicts, and forest regression is sometimes ascribed to the onset of arid conditions. But forest disappearance was not only the result of the climate becoming drier. Ample evidence exists that forests can still survive and even develop under the current environmental conditions. Pollen diagrams and some forest stands evidence local natural reforestation in northern Ethiopia, which indicates that the evolution of the forest cover was not always towards degradation. Moreover, the strongest arguments for a non-climatic driven deforestation in the Ethiopian Highlands in the last 5000 years are that the actual climate can still easily support forest, that forest recovery can be quick in exclosure areas where free grazing for cattle is forbidden, that reforestation operations are made by foresters and that these can be successful (Chap. 16).

Human-induced land cover changes during the last 7000 years started about a thousand years before the first local manifestations of the dry to arid conditions. This is probably one of the earliest proven impacts of humans in Africa on the hydrological cycle.

Field observation sites: valley bottom Vertisols along treks #6, #8, #11V and #23; tufa dams along #10, #12, #13, #14, #16, #17, #24 and #Gh2; incised tufa dam backfill with fire levels along #13, #14 and #17; and coarse boulders at the bottom of incised alluvium along rivers that are crossed by treks #3, #6, #8, #9V, #10, #12 and #20.

Further Reading

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