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Palaeogeography, Palaeoclimatology, Palaeoecology 230 (2006) 165–181

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Age and backfill/overfill stratigraphy of two tufa dams, Tigray Highlands, Ethiopia: Evidence for Late Pleistocene and Holocene wet conditions

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Received 3 January 2005; received in revised form 19 July 2005; accepted 21 July 2005

Abstract

Geomorphological mapping of parts of the Mekele outlier reveals the presence of numerous river tufa dams, spring tufas and old landslides, indicating high groundwater levels and karstic activity in the area during former times. U/Th dating of river tufa dams indicates that wet conditions prevailed in the highlands as early as 15,000 BP. This is 4 to 5000 years before the first signs of post-last glacial maximum (LGM) humid conditions deduced from former lake extensions in the Ethiopian and Kenyan rift. Tufa build-up and the corresponding wet conditions in the highlands gradually came to an end from 5000 BP onwards. In the study area, environmental deterioration started around 3000 BP and is explained as a result of forest recession. Evidence is presented, showing that forest retreat and land degradation in the area is not climate-driven but the result of human activities.

Keywords: Ethiopian Highlands; Groundwater; Holocene; Land degradation; Palaeoenvironment; River tufa dams

1. Introduction

Because local evidence is poor or lacking, Late Pleistocene and Holocene environmental conditions in the Ethiopian Highlands are currently deduced from data, mainly gathered in the Rift Valley and other low-lying areas, hydrologically controlled by the highlands. Since the early work by Grove et al. (1975), Gasse and Street (1978) and Gillespie et al. (1983), Late Quaternary lake-level fluctuations in the Ethiopian rift became the standard reference for palaeoclimatic reconstruction in East Africa, including the Ethiopian Highlands. Lake level fluc-

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doi:10.1016/j.palaeo.2005.07.013

tuations in the East African rift valley are in phase with lake extensions in the whole Western African subcontinent, pointing to overall changes, obviously of climatic origin. Nevertheless, reports start slowly to accumulate, showing that high regions in Africa were not much affected by extreme drought during the LGM. The Bamenda volcanic highlands are one example wherein the Bafochu Mbu caldera at 1650 m a.s.l. forests remained in place during the LGM (Moeyersons, 1997). On the vegetation map of Africa during the LGM (Ray and Adams, 2001), based on all available literature, the Ethiopian Highlands appear as partly capped by permanent ice and carrying, below 4000 m asl (Höverman, 1954; Hastenrath, 1977), an open woody vegetation, strongly in contrast with the less than 10% cover of tropical semi-desert grassland in the lower-lying areas.

This article reports on the presence of numerous river tufa dams and other geomorphological evidence, pointing to long-lasting wet conditions in the highlands of Ethiopia. Brancaccio et al. (1997) estimate that the period of build-up of the May Makden tufa dam in the highlands (Fig. 1A,B) started during the more humid and mild climatic

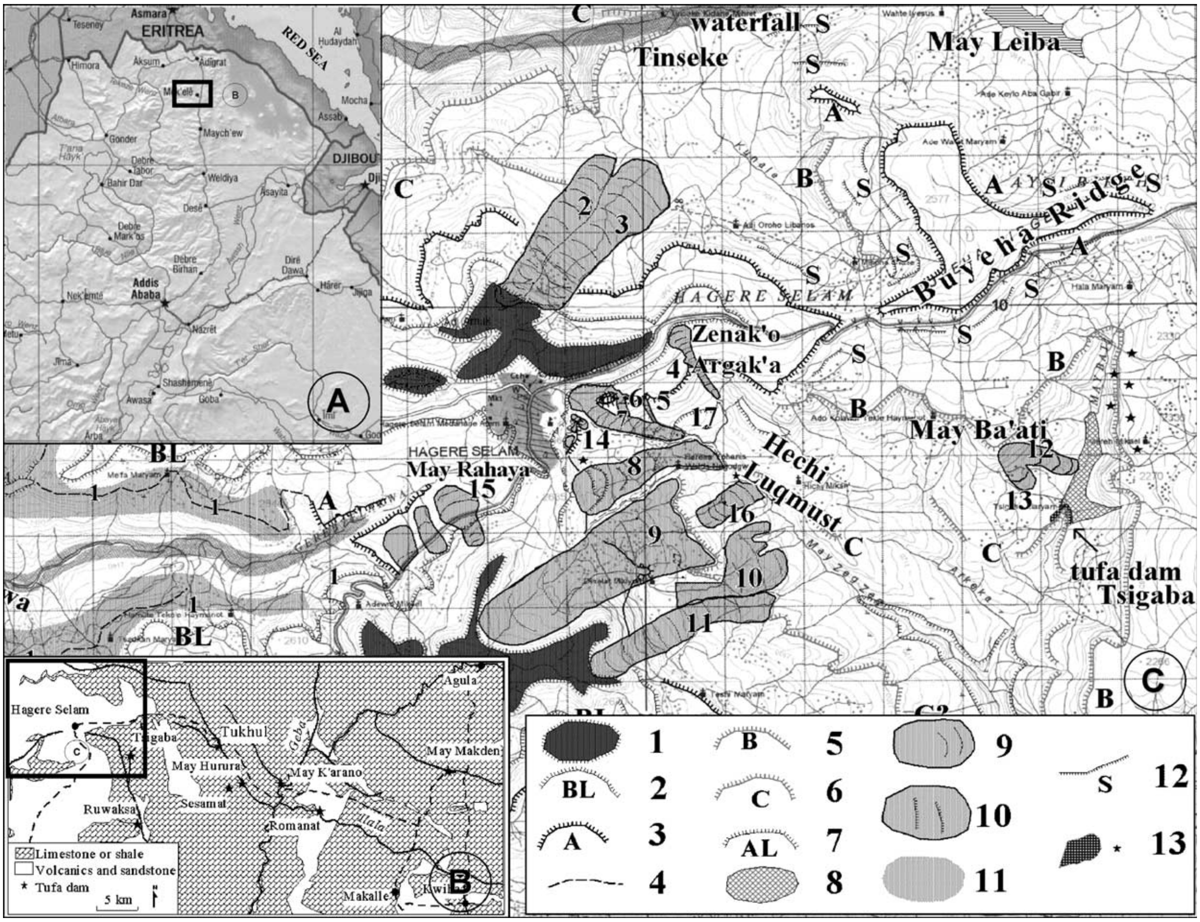

Fig. 1. A: Location in Ethiopia of map B. B: location of inactive tufa dams on the Arkin et al. (1971) geological map. Makalle = Mekele. C: Geomorphological map of Hagere Selam. Legend: 1, upper basalt extension with cliff; 2, lower basalt cliff; 3, Amba Aradam sandstone cliff; 4, Amba Aradam sandstone cliff covered by landslide debris; 5, May Ba'ati aquiclude cliff; 6, Tinseke–Hetchi–Tsigaba aquiclude cliff; 7, cliff in lower part of Antalo limestone; 8, Tsigaba alluvia; 9, landslide moving from left to right; 10, deep serial slumping from left to right; 11, unindividualized landslides; 12, deep slumpings; 13, fossil river and spring tufas. The numbers on the map refer to the number of landslides. Scale in km^2.

post-LGM conditions, which gave rise to high strandlines in the Rift Valley lakes. As to the reasons for the end of tufa growth, several hypotheses have been forwarded. Dramis et al. (1999) and Dramis (2001) link the end of tufa build-up in Ethiopia, Northern Africa and Europe to a lag in groundwater temperature rise after the last glacial maximum. Ogbaghebriel Berakhi et al. (1998) expect that the build-up of the May Makden tufa dam (Fig. 1B) ended with deforestation and concomitant increase of river turbidity, which inhibits growth of algae provoking decreased $CaCO_3$ precipitation. This way of tufa decay has also been described by Ford and Pedley (1996) in NW Europe. Finally, Virgo and Munro (1978) assume that a recent shift from perennial to seasonal stream flow decreased the length of the yearly period of build-up and increased the power of flash floods eroding tufa dams.

Voigt et al. (1990), in Northern Somalia, radiocarbon dated the oldest post LGM tufa deposits at 11 535 ± 105 BP (Hv 16032), 10 800 ± 80 BP (Gd 5515), 9105 ± 105 BP (Hv 16019), and obtained a U/Th age of 9200 ± 4800 years. They also refer to Brandt and Brook (1984) who reported U/Th ages of 5000–7600, 9500–9700, 11 800 for the oldest post LGM deposits.

Field work in a 1200 km^2 area, in the Northern Ethiopian Highlands (Fig. 1A), comprising Mekele and Hagere Selam (13°39′N, 39°10′E), has revealed that, besides the well-known May Makden tufa dam (Ogbaghebriel Berakhi et al., 1998), six other important river tufa barrages occur (Fig. 1B). These dams, given the important palaeoenvironmental information they hold, have been visited and sampled for the purpose of their dating.

This paper presents U/Th and ^{14}C dates for these newly visited tufa dams, adds other geomorphological evidence for the wet conditions during tufa growth and describes tufa dam back- and overfill deposits, giving more information about the reasons for the gradual environmental deterioration since 5000 BP. Consequently, this paper aims (1) to date both the beginning and ending of the period of tufa growth in the Ethiopian Highlands, (2) to specify the type of wet environment during tufa dam growth, and (3) to evaluate and amend the current hypotheses concerning the environmental conditions which led to the end of tufa growth.

2. Materials and methods

2.1. The study area

Geologically speaking, the study area (Fig. 1B) belongs to the Mekele outlier, an 8000 km^2 polygonal area on the western shoulder of the Ethiopian Rift. It is a depression in the Precambrian basement (Bosellini et al., 1997), filled by a succession of Palaeozoic to Cainozoic subhorizontal sedimentary layers (Beyth, 1972; Tesfaye and Gebretsadik, 1982). Antalo Limestones and Agula Shales cover most of the area. In the vicinity of Hagere Selam (Fig. 1C), the highest points reach 2800 m asl and are formed by two series of Tertiary basalts, separated, like in the Adigrat Area, North of the Mekele outlier (Garland, 1980), by silicified lake deposits of limestone and diatomites with gastropods.

Seen from the West (Fig. 2A), the Mekele outlier rises abruptly out of the surrounding Tigray Plateau with a highly dissected escarpment of nearly 1 km high. This situation is depicted in Fig. 2B, showing the double escarpment, made up respectively by Adigrat sandstones and Antalo limestones and Hagere Selam, located nearly on top of this escarpment. At Shiket the outlier is down faulted towards the Ethiopian Rift. Since this tectonic event, the part of the Geba basin East of Arakohila Pond has been tapped to the Rift. The general dipping of layers to the East confirms former work on the geological structure of the Mekele outlier (Beyth, 1972). The section (Fig. 2B) follows the WNW–ESE axis of the Mekele fault block.

In Hagere Selam, basalts and lake deposits have a combined thickness of about 300 m. The lower basalt series rests upon the Amba Aradam sandstone, Cretaceous in age and of continental origin, and about 25 m thick at Hagere Selam. This laterized sandstone disconformably overlays the near shore marine Antalo limestones, dating from Jurassic times. In the deepest gorges of the May Zeg Zeg River at the southern edge of the map (Fig. 1C), the underlying Adigrat sandstone, Triassic–Middle Jurassic in age, locally outcrops at 1840 m a.s.l. Due to tectonic uplift of the whole area (Fig. 1B) since early Tertiary times, the remnants of the assumed peneplain of the Amba Aradam sandstone currently occur at an altitude above 2000 m a.s.l. and subsequent vertical river

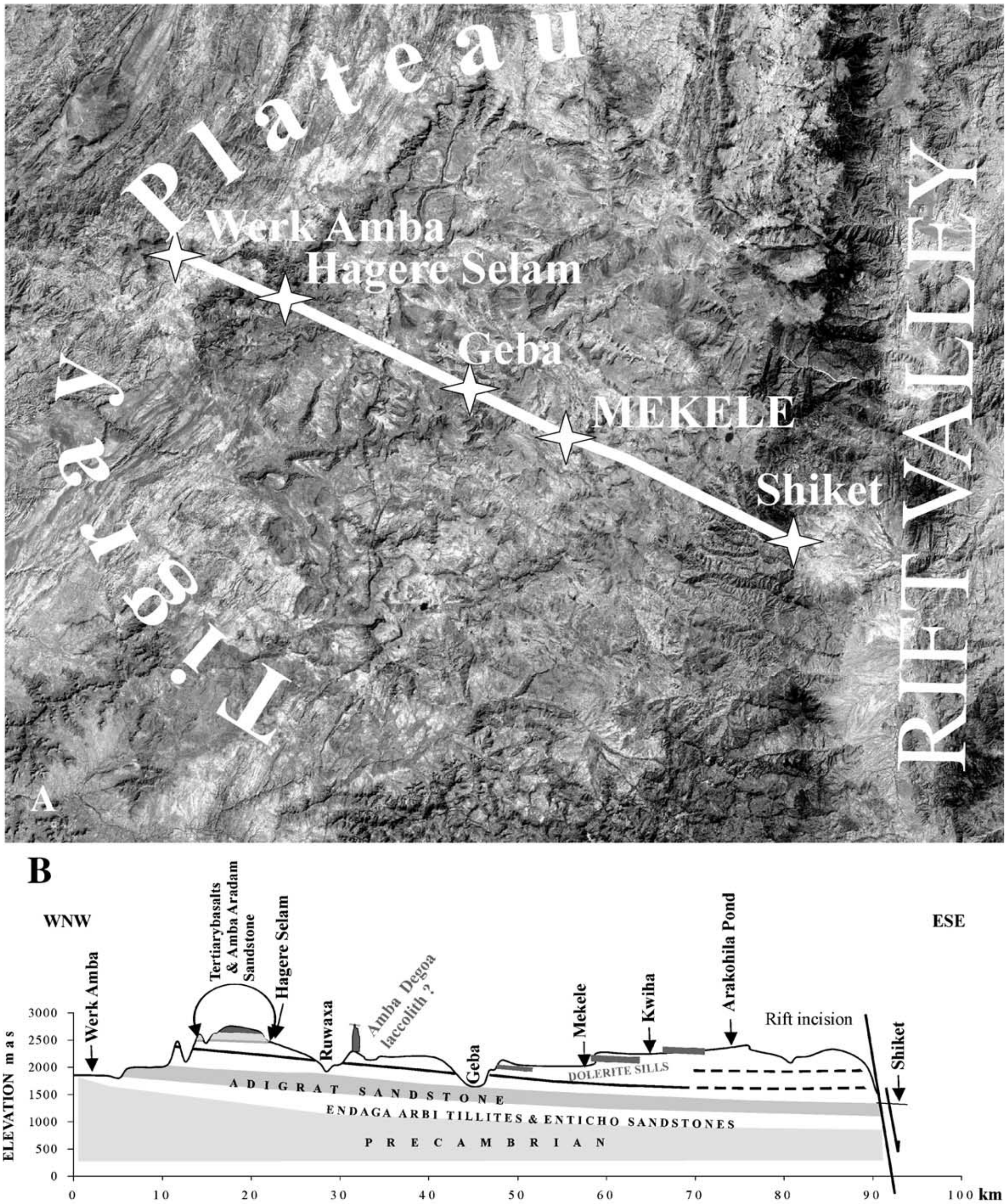

Fig. 2. A: ETM image bands 123 of the Mekele outlier. Scale: Distance between Werk Amba and Shiket is 90.47 km. B: Simplified geological section through the Mekele outlier from Werk Amba to Shiket. The whitish layers between Adigrat and Amba Aradam sandstones form the Antalo super sequence with Antalo limestones and Agula shales. Dolerite sills are indicated. Elaboration on the base of geological work mentioned in this article and on own field observations.

incision eroded an impressive and complicated canyon network in the Ethiopian Highlands.

The western part of the study area, around Hagere Selam, comprises subhorizontal series of alternating hard and soft Antalo Limestone layers, 5 to 600 m thick, overlain by Amba Aradam Sandstone. The geology of the region around Mekele comprises mainly calcareous Agula shale, and locally sills of Mekele dolerite within this formation (Arkin et al., 1971; Merla et al., 1979). This subhorizontal geologic structure controls the stepped topography of the study area. The tectonic uplift explains the altitude of 2800 m a.s.l. of its summits.

Hydrogeological exploration of the Mekele outlier (Tesfaye and Gebretsadik, 1982) has shown the presence of water tables, perched upon layers acting as aquicludes or aquitards. No mention is made of the occurrence of a regionally important perched water table within the Antalo limestone domain, over which the study area extends. The Antalo limestones are generally considered as highly permeable, due to their high secondary porosity.

The Hagere Selam–Mekele region receives 500 to 900 mm of annual precipitation, depending on slope orientation and altitude (Nyssen et al., in press-b). Most of it falls between June and September, but small 'Belgh' rains irregularly occur from March onwards. Average total yearly precipitation is 778 mm year^{-1} in Hagere Selam (2650 m a.s.l.) and 593 mm year^{-1} in Mekele/Kwiha (2070 m a.s.l.). If the landscape is nowadays largely deforested, small patches of forest around churches as well as in places, which are difficult to access, are secondarized remnants of the former climax vegetation (Descheemaeker et al., in press).

Typical for the area is the occurrence of Vertisols in most flat bottomed valleys. Superposed Vertisols or other colluvial valley sequences are generally thought to evidence oscillations of secondary forest recession and extension during the general deforestation in the area since 5000 years ago (Nyssen et al., 2004).

2.2. Geomorphological mapping and laboratory methods

Geomorphological mapping of a 200 km^2 area centered on the village of Hagere Selam (Fig. 1C) was mostly done by stereoscopic interpretation of the aerial photograph 1:50 000 cover of the area. Mapping was manually transferred to a 'geomorphology layer' in a MAPINFO 5.5 GIS-system, built upon the 1:50 000 topomap (Ethiopian Mapping Authority, 1994) basic layer. The geomorphological map contains essentially lines of ruptures of slopes like cliffs or piedmont knickpoints, which combine to express the existing landforms. In the case of landforms, too small to be represented on the 1:50 000 scale of the geomorphological map, symbols have been used.

The fieldwork included not only the verification of the mapped relief forms but also the gathering of evidence for their origin, evolution and age. For this purpose geological and soil sections have been described, mapped and sampled for laboratory analysis. Phytohermal (autochthonous) tufa deposits from tufa dams were dated by U/Th method (alpha-spectrometry—Ivanovitch and Harmon, 1992) at the "Centre d'Etudes et de Recherches Appliquées au Karst", Mons, Belgium (Quinif, 1989, 1998). The applicability of this method to our study will be analysed in Section 3.1.

Charcoal, as well as organic matter included in speleothems, was dated by ^{14}C method at the "Centrum voor Isotopenonderzoek", Groningen, Netherlands (Van der Plicht, 1993). Obtained conventional radiocarbon ages, reported with $\pm 1\sigma$ of uncertainty, were calibrated using OxCal v 3.5 software (Bronk Ramsey, 2000). Calibrated date intervals have a probability of 95.4%.

Sediment samples were analysed by optical microscopy for phytolith composition (Department of Agriculture and Forest Economy, Royal Museum for Central Africa, Tervuren, Belgium).

Samples from old landslides were analysed for their textural and geotechnical properties (Laboratory Experimental Geomorphology, K.U. Leuven).

3. Results

The geomorphological map of the Hagere Selam area (Fig. 1C) shows first of all the presence of cliffs, plateaus, table mountains and stepped valley sides. They reflect the horizontal arrangement of geological layers undergoing differential erosion. In the legend, the resisting plateau and cliff forming layers are indicated. But special attention is given here to landscape elements which clearly indicate moister conditions than to today during recent geological times.

3.1. Mass movements as indicators for former wet conditions

Mass movements of varying size and form occur. In the 200 km^2 area, covered by the geomorphological map (Fig. 1C), not less than 17 individual landslide lobes, some more than 2 km long, could be distinguished on the aerial photographs and have been checked in the field. Moreover a belt of intermingled mass movement deposits garnishes both sides of the Gerebzelakwa river valley to the West of Hagere Selam.

The age of landslides is often not easy to determine but the relatively young age of their last important reactivation is confirmed by their lobe forms, still recognizable, and by the fact that several landslides are younger than, or contemporaneous to, Vertisol deposits, considered as Holocene in age (Brancaccio et al., 1997). Therefore, a Late Pleistocene to Middle Holocene age has been put forward (Nyssen et al., 2002a). Landslide 4 (Fig. 1C) is shown (Fig. 3).

Landslide activity is not necessarily an indicator for wet soil conditions, especially not in the East African rift valley area where neotectonics and earthquakes are common. But in the case of the Ethiopian landslides, a number of arguments against the seismic hypothesis can be forwarded. First, there is the morphological argument that most of the landslides in the study area are much longer than wide (Nyssen et al., 2002a). In a recent study of landslides in Bukavu, it was found that landslides, triggered by earthquakes, are proportionally much wider than those simply induced by hydrostatic soil water or seepage pressure (Moeyersons et al., 2004a). The forms of the landslides in Bukavu town reflect the rectangular form of the fault blocks on which the lay. These fault blocks oscillate during earthquakes. Also a tectonically induced landslide along the shore of Lake Langano (Main Ethiopian Rift) is about 800 m wide but much shorter (Coltorti et al., 2002b). The second argument is the finding that during Holocene times there has been an intensification of landsliding in places far apart such as Rwanda, Ethiopia and Malawi (Moeyersons et al., 2001; 2004b). It would be a big coincidence that seismic activity had increased during the same period at different places along the western as well as the eastern branch of the East African rift. Geological literature does not mention a general increase of seismic activities during Late Pleistocene and Holocene times in the area.

Therefore, the massive occurrence of ancient landslides in the study area can only be adequately explained as a result of peaking hydrostatic soil pressures, resulting from perched water tables being more developed in the recent geological past than today. Special attention is called to the example of deep-seated serial slumps, generally to be found at the

Fig. 3. The May Nteb Nteb landslide #4 (Fig. 1C) is a mass of Vertisol material surged over the Amba Aradam sandstone cliff, visible to the left. Tree in the right upper corner is 8 to 10 m high.

plateau edges and sitting on top of cliff forming massive limestone layers within the Antalo limestone domain. These serial slumps, although still recognizable by their morphology, are easily detectable during pedological mapping in the field because of the repetition in downslope direction of soils typical for Amba Aradam sandstone and Antalo limestone. In the surrounding piedmont plains of the Buyeha Ridge (Fig. 4), these serial slumps have their base on top of two massive and cliff forming Antalo limestone layers. As these slumps are not active anymore today, it is concluded that they provide strong evidence the former presence of important water tables, standing above each of both massive limestone formations. Today, these water tables are too low to remain driving forces for this type of slump movements, but they still form springs in places, including the two last remaining forests in the area, the May Ba'ati and Luqmust forests. There exists experimental evidence that at least the lower massive Antalo limestone layer acts as an aquiclude or aquitard with respect to infiltrating water. Since the construction of the May Leiba microdam (Figs. 1C and 4) in April 1999, the Tinseke waterfall regime changed from seasonal to perennial.

The hypothesis of perched water tables, more important in thickness and lateral extension than today, is supported by the frequent occurrence of spring tufa on cliff edges and slopes, where spring activity is strongly reduced or non-existent. Such spring tufa are indicated on the geomorphological map (Fig. 1C).

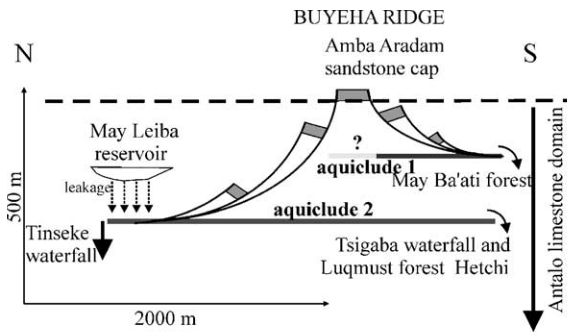

Fig. 4. Schematic N–S section from the Tsalet to the May Zeg Zeg basin with representation of serial slumpings, May Leiba reservoir, May Ba'ati and Luqmust forests and Tinseke waterfall in relation to two aquicludes in the Antalo limestone. Aquiclude 1 corresponds with cliff B and Tsigaba–Tinseke–Luqmust with cliff C in Fig. 1C. Place names: see Fig. 1C.

3.2. River tufa dam evidence for past wet conditions

Freshwater tufa deposits are the sedimentary response to karstic system activity (Vaudour, 1984; Magnin et al., 1991; Peña et al., 2000). Their presence is related to relatively wet and warm environmental conditions, with significant plant cover and with nearly continuous surface water flow and percolation (Pazdur et al., 1988; Andrews et al., 1993; Goudie et al., 1993).

Inactive river tufa dams in the study area are generally located in Agula shale and Antalo limestone areas, where a watercourse crosses a cliff corresponding to a hard layer in the Antalo limestone or a dolerite sill. In such favourable areas, successions of up to seven breached dams exist along the same river over 1 or 2 km. Generally speaking, these dams have respectable dimensions. Their cross-valley length is often of the order of one to several hundreds of meters and their length in upstream direction can even be longer, especially in cases like Ruwaksa and May Makden where several successive cross-valley bioherm constructions are interlinked by clastic tufa sand bodies. Their height often exceeds 10 m. Remnants of older dams sometimes exist in the same valleys at higher levels, corresponding to older terraces (Catlin et al., 1973; Virgo and Munro, 1978). Inactive tufa dam locations were mapped from aerial photographs (± 1:50,000) and at the occasion of field visits during the period 1998–2001. May Makden was the only dam mapped before this study started (Ogbaghebriel Berakhi et al., 1998). Today several dozens of other inactive dams have been located. River tufa dam development has been a very common feature in the study area. This renders its indicator value for moist environmental conditions in the recent geological past more reliable.

If river tufa dams originate in first instance in response to wet and warm conditions, their further development, in turn, causes moist conditions further to develop. This is due to the fact that natural lakes often develop upstream of river tufa dams. This creates a supplementary rise of the local groundwater table, independent of the environmental forcing to river tufa dam origin. In this way, landslides 12 and 13 have been observed to intermingle stratigraphically with the ancient marsh and lake deposits, upstream of the Tsigaba tufa dam (Fig. 2). These landslides appar-

Fig. 5. Location of soil samples, indicated by sample number, on Tsigaba dam. The dam is approximately 15 m high.

ently have been triggered by the secondary water table rise behind that dam.

Of course, the major part of the landslides mentioned in Section 4.1 is located outside the areas of secondary water table rise and remains as indicators for primary moister conditions than today, just as the inactive tufa river dams do. But the case of landslides 12 and 13 shows again the concurrency of tufa river dam development and landslide activity, as shown already by Nyssen et al. (2002a).

3.3. Tufa dam build-up: U/Th and ^{14}C dates and their reliability

In order to get more information about the timing of the Late Pleistocene and Holocene wet period, eight dams were studied, from West to East: Ruwaksa, Tsigaba (Fig. 5), Tukhul, Sesamat, May Hurura, May K'arano, Romanat and May Makden (Fig. 1B). Although care was taken to sample the most pure rocks of the parts of the dam, judged to be the youngest, the tufa samples were generally difficult to analyse by U/Th datings. This difficulty is due to the high porosity of the samples and presence of non-calcareous detritals. Table 1 shows the generally low ratio between isotopes ^{230}Th and ^{232}Th. In the U/Th method, the ratio between isotopes ^{230}Th and ^{234}U allows to calculate the age of the $CaCO_3$ precipitation. However, the presence of ^{232}Th, which belongs to a different radioactive decay chain, indicates possibly that part of the ^{230}Th does not originate from ^{234}U, hence a great probability that the obtained age is false, generally overestimated (Quinif, 1998).

However, sample 6604 taken in the fresh part of the core of a stalactite speleothem from a collapsed cavity in Tsigaba dam (Fig. 5) is an exception. Its low content of ^{232}Th makes its age of 13.7 ka very reliable. This gives confidence that the age range obtained for the post-LGM phytohermal tufa deposits (14.1 and 15.8 ka) in Tsigaba and May K'arano is reliable. It is further also very logical to find at Tsigaba for the primary calcite precipitation, which

Table 1
U/Th determinations by alpha-spectrometry (CERAK, Mons)

Location	Sample	$[U]_{ppm}$	$^{234}U/^{238}U$	$^{230}Th/^{234}U$	$^{230}Th/^{232}Th$	$[^{234}U/^{238}U]_{t=0}$	Age (in ka)
K'arano	6382	0.364 ± 0.003	1.534 ± 0.011	0.137 ± 0.009	5.0 ± 0.8	1.558	15.8 [+1.1/−1.1]
Sesamat	6383	0.158 ± 0.003	1.158 ± 0.024	0.946 ± 0.040	1.63 ± 0.09	1.329	261.9 [+61.3/−38.8]
Romanat	6391	0.130 ± 0.001	1.683 ± 0.022	0.236 ± 0.011	1.61 ± 0.11	1.740	28.7 [+1.4/−1.5]
Tsigaba	6384	0.545 ± 0.003	1.263 ± 0.009	0.188 ± 0.004	1.99 ± 0.05	1.280	22.5 [+0.4/−0.5]
Tsigaba	6387	0.436 ± 0.006	1.245 ± 0.019	0.256 ± 0.008	1.23 ± 0.05	1.267	31.8 [1.1/−1.2]
Tsigaba	6419	1.205 ± 0.007	1.239 ± 0.007	0.123 ± 0.004	1.11 ± 0.05	1.249	14.1 [+0.6/−0.5]
Tsigaba	6420	0.431 ± 0.003	1.193 ± 0.008	0.339 ± 0.006	1.00 ± 0.09	1.219	44.4 [+1.0/−1.0]
Tsigaba Stalact.	6604	0.728 ± 0.004	1.266 ± 0.007	0.119 ± 0.005	11 ± 2	1.276	13.7 [+0.6/−0.5]

is at the origin of the cavity, an older age (14.1 ka, sample 6419, Table 1) than for the speleothem of secondary precipitation developed in the cavity (13.7 ka, sample 6604, Table 1). Because both samples come nearly from the top of the tufa dam (Fig. 5), the start of tufa dam built 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 (Fig. 6). Laminations, known to reflect seasonal changes in growth, can be distinguished in the Tsigaba dam. Measurements in Australia have shown that such laminations have an annual growth rate of the order of a few millimetres/year (Drysdale and Gillieson, 1997). At Tsigaba dam, laminations mostly have a thickness of less than a centimetre. Taking into account a yearly growth of the dam by 1 cm the 15-m-thick dam body represents 1500 years. This brings us at a minimum age of 15 ka for the start of humid conditions.

Speleothem formation is generally attributed to the same karstic environment (Quinif et al., 1994), or at least to conditions with slowly but constantly percolating water (Ayalon et al., 1999). In the case of the speleothems from Tsigaba, the analysed calcite is quite pure which tends to indicate that it was precipitated in a period with low rain variability and relatively good and continuous vegetation cover, ensuring high CO_2 pressure in the soil, hence a very aggressive seepage water (Genty and Quinif, 1996). In this way the speleothem confirms the indicator value of river tufa dams for warm and humid conditions.

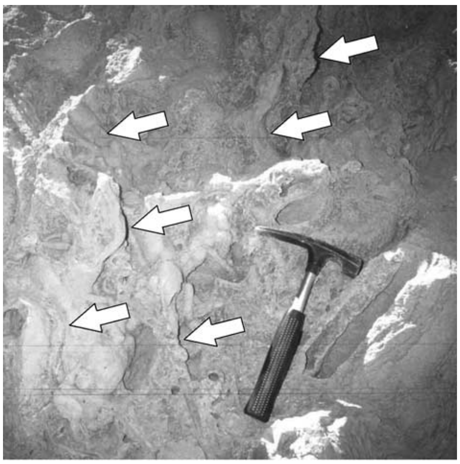

Fig. 6. Tufa facies in Tsigaba dam. Many impressions and inclusions of plant remain completely calcified. The arrows indicate depositional laminae in the moss and algal tufa.

In Tsigaba, speleothem growth continued over a long period. Organic matter rich sediment inclusions in one of the outer grow rings of another stalactite from the same collapsed cave were radiocarbon dated 3560 ± 50 BP (GrA-18722), which gives a calibrated date of 2030–1740 BC.

3.4. Environmental conditions and age of the end of Tufa dam build-up

Back- and/or overfill deposits of the Tsigaba and Tukhul dams (Fig. 1B) yield detailed information about the timing and reasons for the end of tufa dam build-up. In Tsigaba, during and after the precipitation of tufa, the upstream basin was filled by alluvium and well-stratified colluvium was deposited on the sides of the valley bottom. In the last 20 years, a deep gully incised the alluvial–colluvial deposits of the eastern valley side, over a depth of 8 m, down to the bedrock in some places. A synoptic view of gully and tufa dam and the localisation of the sections A to C is given (Fig. 7). The stratigraphical correlation, especially the stratigraphical level in B and A, corresponding with the top of the weathered phytohermal tufa (C1) in C, could be established using the presence of two petrocalcic horizons in the overfill and several levels of burnt earth, stone-lines and fine laminations, used as guide horizons. The main information obtained from the sections is as follows:

1. The radiocarbon age of a charcoal sample taken in layer A99 was 3090 (± 30) BP (GrN-25665), which gives a calibrated age of 1430–1260 BC. Radiocarbon dating of $CaCO_3$ precipitated on this charcoal samples yields an age of 2690 (± 90) BP (GrN-25792) (interval: 1150–500 BC). Stratigraphically the sample corresponds to the top of the backfill and thus approximately dates the end of tufa dam growth. This corresponds in order of magnitude with the date obtained from sample GrA-18722, mentioned in Section 4.3.
2. In Profile A, overfill deposits, stratigraphically above the tufa dam, are more than 4 m thick while the thickness of backfill deposits, stratigra-

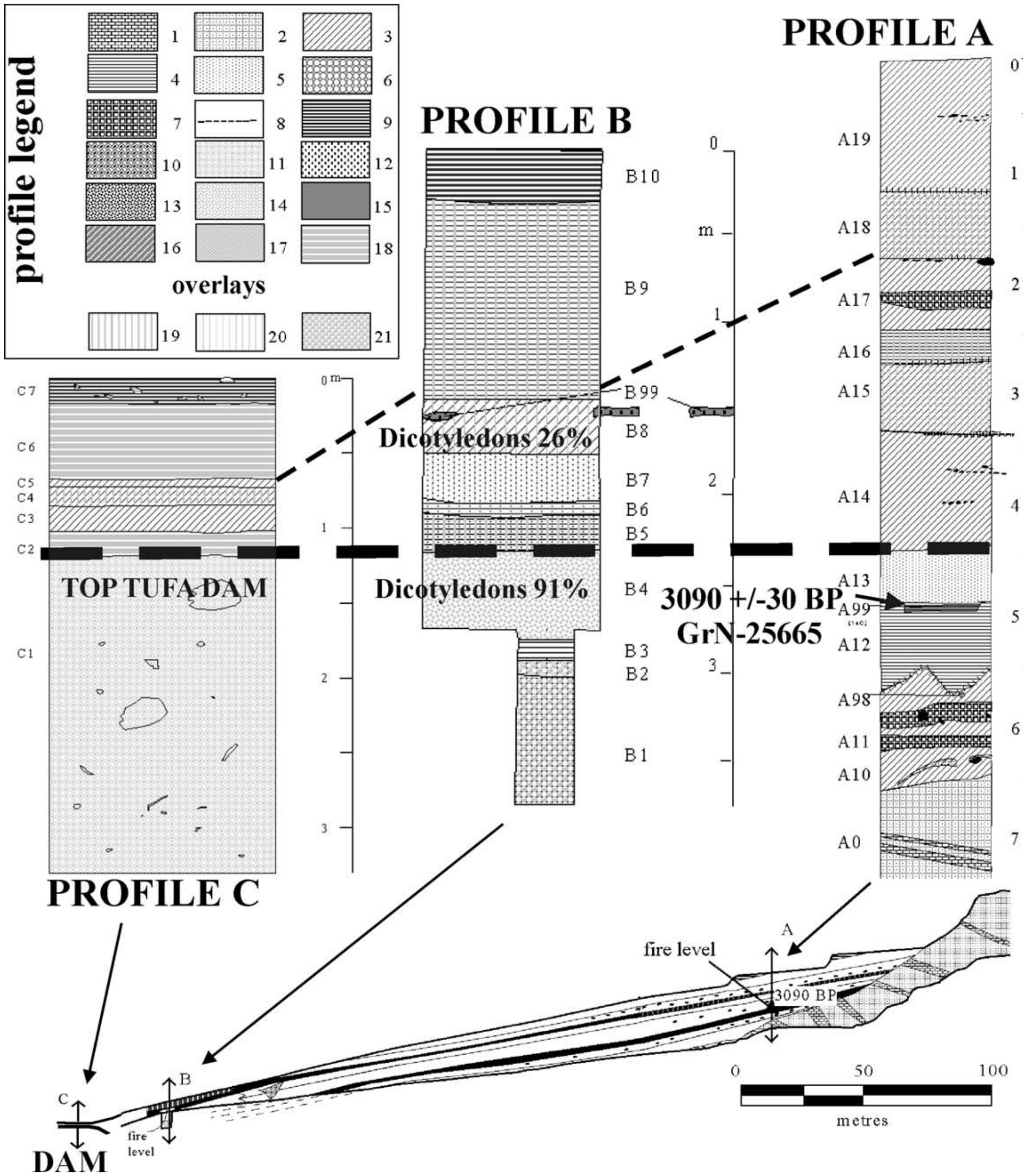

Fig. 7. Synoptic presentation of back- and overfill of Tsigaba tufa dam and location of sections A to C. 1, limestone; 2, marl; 3, loamy sediment; 4, clayey sediment; 5, sandy sediment; 6, river terrace; 7, other coarse material; 8, stone-line; 9, recent colluvium; 10, tufa; 11, weathered tufa; 12, tufa gravel; 13, phytoclastic tufa sand; 14, weathered phytoclastic tufa sand; 15, burnt soil in situ; 16, reworked burnt soil; 17, ash layer; 18, petrocalcic horizon; overlays: 19, calcic horizon; 20, calcium precipitation; 21, gleyic properties.

phically below the tufa dam top, reaches only ± 2 m because the A0 layer consists of in situ weathered Antalo limestone. Also in profile B the overfill is thicker than the backfill. In as much as the backfill covers a much longer time span than the overfill, this difference in thickness indicates a

Table 2
Profiles Tsigaba B and C, phytolith content

Sampled layers	Monocotyledons		Dicotyledons	
	n	%	*n*	%
B9	290	80	71	20
B8A	227	76	70	24
B8U	346	74	122	26
B4	46	9	442	91
C6	387	73	141	27
C3	90	74	31	26
C1	65	70	28	30

pronounced intensification in sediment redistribution by runoff processes since the end of tufa river dam growth.

3. In Profile B, monocotyledon phytoliths dominate (74–80%) in the overfill deposits while the backfill is characterized by a great proportion (91%) of dicotyledons, corresponding to more woody vegetation in the lower sample B4 (Table 2).
4. In the slope deposits of section A, at a depth of 5.05 m, there is a 70-cm-thick burnt horizon (A99) with ash on its top, probably an anthropogenic fireplace. However, no artefacts or bones were found. This layer has a lateral extension in the gully of more than hundred meters and, therefore, is interpreted as the result of a bush fire. Stratigraphically it belongs to the upper part of the backfill, chronologically very close to the top of the tufa dam. Several traces of fire occur higher in the section.

In Tukhul, the alluvial plain behind the tufa dam is deeply incised by the May Shimbula river (Fig. 1B). In the backfill of the tufa dam, different layers of burnt soil and ash are present (Fig. 8). The last lake deposit related to the top of the dam is a greyish layer (a), capped by pure black clay. Both layers, when moving upstream, first dip (Fig. 8) and then become more or less horizontal. After some 60 m, they disappear. Layer (a) contains a mixture of four different types of small gastropods, some ostracods and abundant phytoliths (burnt fragments of Poaceae) (Table 3), but no macro- or microscopic char-

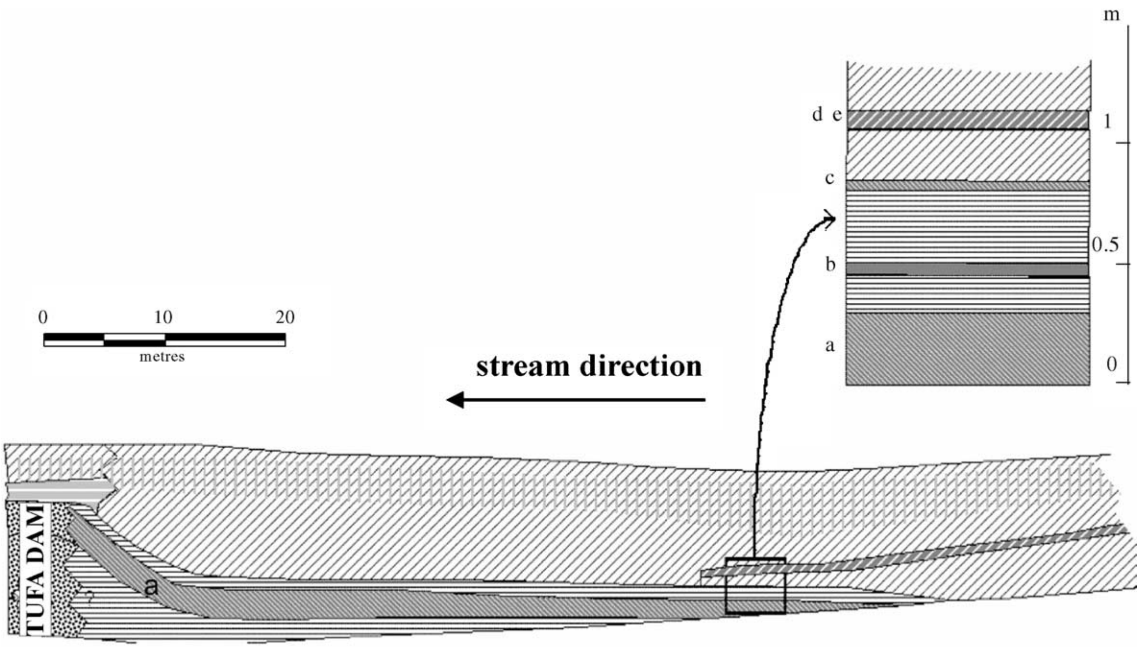

Fig. 8. Backfill of Tukhul dam. Ash layer (a) gives evidence for a widespread grassland fire in the catchment. Its reverse slope just behind the dam and its correspondence with the top of the dam identifies the ash layer and its black clay top as the last lake deposit. No tufa build-up occurred after the deposition of this ash layer. Inset: See legend of Fig. 7 and Table 3: predominance of phytoliths of monocotyledons deposited above (a).

Table 3
Phytolith content of fire levels in Tukhul

Sampled layers	Monocotyledons		Dicotyledons	
	n	%	*n*	%
e	706	80	175	20
d	193	74	67	26
c	144	82	32	18
b	457	80	115	20
f	492	86	83	14
g	823	92	72	8

coal fragments. This is a deposit of ash settled in the lake behind the tufa dam, as witnessed by its reverse slope just behind the dam. It gives evidence for a widespread grassland fire in the catchment. No tufa build-up occurred after the deposition of this ash layer.

The gradual disappearance of forest since a short time before the end of tufa dam build-up is evidenced by the following combination of arguments:

(1) the change in dominance by dicotyledon to monocotyledon phytoliths at the period of tufa growth ending, around 3000 BP in Tsigaba;
(2) the accelerated sediment redistribution since that time and several gravel layers above the lower fire horizon in section A at Tsigaba, confirming a low vegetation density and soil truncation by runoff;
(3) bush fires of *grasses* in Tukhul, stratigraphically equivalent to or younger than the top of the tufa dam.

Highly increased sediment mobility was probably not the consequence of forest retreat alone. Also the frequent bush fires recorded from the moment that tufa build-up ended might be a cause (Meyer et al., 2001). However, it is assumed that the increase in sediment mobility is a strong indication for increasing river turbidity inhibiting photosynthesis by algae and thus also precipitation of tufa, as shown by Ford and Pedley (1996) in NW Europe.

The age of the forest disappearance period and of the end of tufa build-up varies from one locality to another. Ancient soils, related to the presence of the primary forest (Brancaccio et al., 1997), were covered by colluvium after 5160 ± 80 (May Makden, Tigray) to 300 ± 60 ^{14}C years BP (Adi Kolen, Tigray). The ^{14}C age of 3090 BP for the degradation phase in Tsigaba fits within this range. Both the presence of layered slope deposits and of burnt soil underneath the analysed charcoal in profile A tend to indicate that deforestation in that area locally started before 1430–1260 BC. Finally, the end of tufa build-up in May Makden is estimated to have occurred after 4230–3760 BC (calibrated age) (Ogbaghebriel Berakhi et al., 1998).

3.5. Further land degradation and desertification in more recent times

Deforestation over three millennia resulted in decreased infiltration, increased surface runoff and soil erosion on the hillslopes, as witnessed by the thick colluvial layers on the footslopes in the area (Fig. 2). Tufa dam incision as a result of stream erosion necessarily ended with the release of the upstream lake waters. Both are the indirect result of human activities and contribute to a general lowering of groundwater levels. In the study area, gully incision accelerated since the first half of the 20th century, due to agriculture intensification, to draining of the formerly perennially wet valleys (Nyssen et al., in press-a) and, more recently, to large-scale infrastructural works like road building (Nyssen et al., 2002b). Gully incision leads to lowering of groundwater levels. While the human impact on land degradation is likely since the end of tufa dam growth and obvious since the 20th century, arguments in favour of climatic forcing of land degradation can hardly be found.

3.6. Pre-LGM humid environments

As discussed in Section 4.3, the majority of U/Th ages (Table 1) might be (slightly) too old. Therefore, there is a slight chance that most dates are of post-LGM age. But this assumption is doubtful for sample CERAK-6382, giving an age of 261.9 [+61.3 / −38.8] ka. This date, much older than the other dates (Table 1), has been furnished by a sample from river tufa remnants, located on a high terrace of the Sesamat river. The morphological evidence supports in this case a pre-LGM age. Inactive river tufa dams older than the LGM exist in the lower parts of the region (Voigt et al., 1990).

4. Discussion

4.1. Wet conditions in the highlands out of phase with high strandlines in the rift

The U/Th and ^{14}C datings in Section 4.1 suggest that humid conditions in the Tigray Highlands started at least at $\pm$15 ka ago. This is some 4 to 5000 years before the first high lake levels in the rift. These lake levels are known to have been low up to less than 12,000 years ago. For instance, Le Turdu et al. (1999) showed that Lake Abijata had a low stand up to 10,050 $\pm$ 100 BP (calibrated age: 11.6 ka) (Lab. no. Orsay H1416 on total organic matter). Also the so-called pluvial lake 'Galla' in the Ziway–Shala Lakes basin came into existence only around 10 ka ago (Coltorti et al., 2002a). Moreover, this late high stand corresponds to the first post-LGM high stands of most of the lakes in the East African rift (Butzer et al., 1972) and even of the lakes Albert, Kivu and Tanganyika in the Albertine rift (Goudie, 1996; Haberyan and Hecky, 1987; Gasse et al., 1989; Vincens et al., 1993). Many of the endoreic lakes in the Gregory rift have been proven to show a large-amplitude response to long-term climatic (or runoff) fluctuations (Street, 1980). The difference of 4–5000 years, at least, between the onset of humid conditions in the Tigray Highlands and the lake extensions in the rift, renders high lake levels in the rift an invalid proxy for wet soil conditions in the highlands.

4.2. The end of tufa dam development and deforestation

Crucial to this discussion is the interpretation of erosional phases, recognized by several research teams in different parts of northern Ethiopia (Brancaccio et al., 1997; Machado et al., 1998; Dramis et al., 2003). These erosional phases are currently related to relatively dry climatic oscillations, including the present-day land degradation phase. According to this hypothesis forest disappearance is climatically induced. The climatic interpretation is evidenced by the occurrence, like in phases, of wet/dry oscillations over a rather large area of Northern Ethiopia, related even with ancient lake strandlines in the Main Ethiopian Rift (Dramis et al., 2003).

Several arguments can be forwarded in favour of the alternative hypothesis that deforestation by man, more than forest disappearance as a climatic result, led to the erosional phases, recognized. First of all, the cyclicity evidence should be used with caution. It is known since long by archaeologists that technical innovations during the Iron Ages and the Neolithic economic-agraric revolution in Africa spread fast, like in phases, over considerable distances (Van Noten, 1982). In this way, cyclic forest disappearance around 3000 BP in Rwanda (Roche, 1996) and West Cameroon (Moeyersons, 1989) has been linked in both cases to human activities. But also in Ethiopia, cyclic deforestation and forest regrowth is not always interpreted as climatically induced. Around lakes Hayk and Hardibo in Welo province, forest recession and extension has been interpreted in terms of immigration and depopulation emigration (Darbyshire et al., 2003). Furthermore, the cyclic character of deforestation is not always evident. Palaeosols in the Adwa area, indicating post-deforestation wetter periods (Ogbaghebriel Berakhi et al., 1997; Machado et al., 1998), provide calibrated radiocarbon dates with important overlap during the period 1400–1960 AD. This makes it impossible to decide whether one or two humid phases occurred (Nyssen et al., 2004).

Finally, the strongest argument for a non-climatically driven deforestation in the Ethiopian Highlands since 5000 BP is that the actual climate still easily supports forest. Relict forests, like the Des'a forest on the rift shoulder northeast from Mekele or the thousands of church forests survive. Moreover, there is overwhelming evidence from throughout the country that arborescent vegetation develops very quickly in exclosures, areas where free grazing for cattle is forbidden.

In the study area, the evidence suggests that large bush fires are linked to the ending of tufa dam build-up and forest retreat. Taking into account that bush fires are an agricultural practice, still in use today in many places in Africa, it can be hypothesized that deforestation in the Ethiopian Highlands corresponds to the first arrival of agriculture.

4.3. What about climate forcing?

One of the questions open for discussion is the role of climate change, mainly changes in the very long-term yearly precipitation mean. As a matter of fact, we are unable to argue that water table rise in the period +15 to ±3 ka should be due to more annual rain than today and/or during the LGM. Most evidence, put forward here, shows that humid conditions were essentially periods with higher water tables. Hence water table level changes do not necessarily reflect changes in amounts of rainfall. Especially for the last 3–5000 years, the general drop in water table level and river base flow can be due to deforestation. It is generally accepted that woody vegetation causes the highest infiltration capacity of water in soil for all land uses. Deforestation, especially when it is followed by other land use, like e.g. agriculture, can lead to such reduction of the soil infiltration capacity that water table recharge during the wet season is incomplete. This leads to a reduction in river base flow and even intermittent flow (Bruijnzeel, 2004). It should be added that active gully incision, often following deforestation, is another reason for a reduction in the water table potential (Moeyersons et al., 2004c) and river base flow.

5. Conclusions: the Late Quaternary in the Tigray Highlands

(1) The Tigray Highlands provide clear and abundant geomorphological evidence that Late Pleistocene to Mid-Holocene environmental conditions were wet. Environmental descriptive elements are a regular hydrograph with perennial base flow for most streams, lakes retained by tufa dams, high groundwater, abundant vegetation and occurrence of mass movements mobilized by soil water pressures.

(2) Due to the unreliability of most of the U/Th datings, the time of onset of this period cannot be correctly assessed. However, wet conditions prevailed at least since 15 ka. This is nearly 5000 years before the first lake extensions in the rift. Therefore, the high strandlines in the rift should not be used anymore as a climatic proxy for conditions in the northern highlands. The latter, as a matter of fact, do not feed the high strandline Rift lakes, South of Addis Ababa, nor the more northward located lake Abhé, but are hydrologically connected to the Danakil depression.

(3) In Tigray this period ended between 5000 BP and today. In Tsigaba, the end of tufa dam growth and the start of severe soil erosion, somewhat more than 3000 years ago, are attributed to forest disappearance. Arguments, forwarded above, indicate a human responsibility for massive deforestation. The strongest argument for a non-climatically induced forest disappearance is the present survival of important climactic forests, like e.g. Des'a, the existence of luxuriant church forests and the quick arborescent development in exclosures.

(4) Deforestation, and gullying in the last century, apparently provoked a gradual fall of the groundwater levels. Data about the evolution of the annual precipitation since the last 3000 to 5000 years are lacking.

Acknowledgements

This study is part of research programme G006598N funded by the Fund for Scientific Research—Flanders, Belgium. Financial support by the Flemish Interuniversity council (VLIR, Belgium) is acknowledged. Sample analyses by Yves Quinif, CERAK, Mons (Belgium), by CIO, Groningen (The Netherlands) and by Hugues Doutrelepont, Royal Museum for Central Africa (Belgium). Discussions held at the occasion of the Symposium of the International Association of Geomorphologists (Addis Ababa, 9–10 December, 2002), as well as constructive comments by Mauro Coltorti helped to improve this paper.

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