Morphometric terrain analysis to explore present day geohazards and paleolandscape forms and features in the surroundings of the Melka Kunture prehistoric site, Upper Awash Valley, Central Ethiopia

Michael Maerker[1,2,*], Calogero Schillaci[2,3], Jan Kropáček[4]

[1] Dipartimento di Scienze della Terra e dell'Ambiente, University of Pavia, Italy
[2] Heidelberg Academy of Sciences and Humanities, Germany
[3] Department of Agricultural and Environmental Sciences, Universita degli Studi di Milano, Italy
[4] Department of Applied Geoinformatics and Spatial Planning, Czech University of Life Sciences Prague, Czech Republic
* Corresponding author: michael.maerker@unipv.it

ABSTRACT

Morphometric Terrain Analysis was successfully applied in different sectors of environmental studies. However, other disciplines, such as archaeology, might also profit from spatially distributed high-resolution terrain information. In this paper, we show how detailed topographic analysis and simple hydrological modelling approaches help to explain complex terrain pattern and to assess geohazards affecting archaeological sites. We show that Melka Kunture, a cluster of Pleistocene sites in the Upper Awash valley of Ethiopia, is affected by flooding and erosion/sedimentation processes. Moreover, we identified paleo-landscape features, such as changes in drainage pattern and evidences of tectonic activity. The topographic indices indicate especially a different paleo-drainage pattern with a lake or palustrine environment in the upstream areas. Furthermore, a different drainage of the paleo-lake via the Atabella tributary is likely and might be also stressed by the dimensions of the lower Atabella valley with quite large cross sections not corresponding to the present-day drainage situation.

KEYWORDS

Melka Kunture; palaeolithic sites; Upper Awash Valley; morphometric analysis; digital elevation models; storm flow model

Received: 23 August 2017
Accepted: 2 January 2018

Maerker, M., Schillaci, C., Kropáček, J. (2018): Morphometric terrain analysis to explore present day geohazards and paleolandscape forms and features in the surroundings of the Melka Kunture prehistoric site, Upper Awash Valley, Central Ethiopia. AUC Geographica 53(1), 10–19
https://doi.org/10.14712/23361980.2018.2

1. Introduction

The area of Melka Kunture, in the Upper Awash valley of central Ethiopia, is one of the most important clusters of Palaeolithic sites in Eastern Africa. The archaeological record spans from ca. 1.7 Ma onwards, with a number of stratified occurrences of Oldowan, Acheulean, Middle Stone Age and Late Stone Age industries, together with faunal remains and human fossils (Piperno 2001; Chavaillon, Berthelet 2004; Raynal et al. 2004; Morgan et al. 2012). Furthermore, Melka Kunture also represents the earliest known example of obsidian utilization, which outcrops north of the site and was widely redistributed by the drainage system (Piperno et al. 2009). Recently, this cluster of sites was included in the Tentative List for Ethiopia (http://whc.unesco.org/en/tentativelists/5788/), as a first step towards a nomination in UNESCO's World Heritage List. Landscape forming processes such as flooding, soil erosion and sediment transport as well as tectonic activity affected the archaeological sites in the past, leading to the specific find location context that was excavated in the last decades. None the less, these processes may affect the archaeological sites in future and hence, could lead to severe damages of the heritage sites. However, the analysis of present day processes also provides information about landscape evolution and therefore, may help to deduct information and/or hypothesis on the archaeological context of the larger surroundings of Melka Kunture.

A proper assessment of the afore-mentioned processes requires a detailed study not just of the closer surroundings of the Melka Kunture sites but rather of the whole Upper Awash River draining the area. To get a better understanding of dominating processes, controlling factors and the related forms and features, we propose a screening of the area based on a detailed terrain analysis and a concentrated field work campaign to validate the analysis.

One of the aims of this paper is to investigate the specific present-day hydro-erosive process related to geo-hazards. These processes are mainly triggered by climatic conditions, present day land use/land cover, soil characteristics and specific paleo-landscape forms and features in the surroundings of Melka Kunture and in the upper Awash basin. Furthermore, we analyse and detect paleo-landscape patterns in the wider surrounding of Melka Kunture in order to get additional environmental information for the interpretation of the archaeological setting.

2. Study Area

The Prehistoric area of Melka Kunture is located close to the Awash village (latitude: 8°41′0″N; longitude: 37°38′0″E) (see Fig. 1). The core area, where archaeological excavations and research focused over the last 50 years, is centred on Garba and Gombore gullies, on the right bank of Awash River. It is an area of 0.7 km^2 at an elevation of ca. 2010 m a.s.l.. The climate is semiarid to sub-humid with a main precipitation period between May and October. Mean annual precipitation is about 875 mm/a. The maximum precipitation event registered in the period 1970–2010 at the Station Boneja, 10 km Northeast of Melka, amounts to 120.9 mm/day (registered on 08.09.1987). The annual distribution of the precipitation is shown in Fig. 2. The mean annual temperature is about 17 °C (Ethiopian Meteorological Service).

Fig. 1 Study area of the upper Awash River basin and location of Melka Kunture.

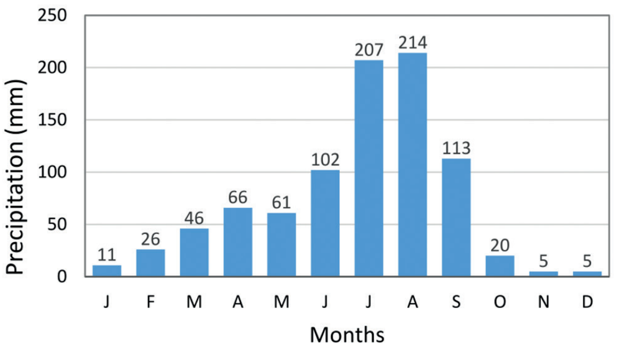


Fig. 2 Monthly precipitation means calculated from daily measurements at Boneya station operated by the National Meteorology Agency. Monthly means are based on measurement records from the period 1974–2014. Boneya station is located about 5 km north-east of the study area at an elevation of 2251 m a.s.l.

Since the beginning of the excavations in the Sixties of last century, the investigations led to the discovery of ca. 70 archaeological horizons. About 30 of them have been since extensively excavated (Piperno 2001), with more research currently going on (Mussi et al. 2016).

Geologically, since the Upper Miocene volcanic activity interrupted frequently the erosion and sedimentation cycles (Chavaillon, Taieb 1968). This activity is closely related to the Rift Valley evolution documented by several fault systems, uplift and tilting. Effusive volcanic products such as tuffs, which are of Quaternary age, are interbedded with fluvial sediments (Raynal et al. 2004). The tephra deposits, including tuffs which have been dated by $^{40}Ar/^{39}Ar$ (Morgan et al. 2012), allow stratigraphic correlation among archaeological layers outcropping in different gullies (Piperno 2001). The area is characterized by a horst and graben structure which runs parallel to the structural Rift pattern (Salvini et al. 2012), denoted as semi-graben fault system (Gallotti et al. 2014). Morphological evidences of the tectonic structures can be identified in the Melka Kunture area (Raynal and Kieffer 2004; Salvini et al. 2012). The so called 'Awash Sill' which is a border fault delimiting the graben from SE due to its periodic reactivation controlled the cycles of sedimentation and erosion in the area (Raynal and Kieffer 2004). Especially the colluvial and alluvial depositional areas in the study area are affected by severe gully evolution in the last 50 years (Kropáček et al. 2016). The main soil types of the area are Vertisols and Fluvisols (Berhanu Debele 1985). Vertic Umbrisols and Vertisols can be found on gentle sloping and flat areas, while flood plains are characterized by clay rich Fluvisols (Gleysols). Vertisols have active layer clays that produce cracks of more than 20 cm depth, which develop preferentially during the dry season. Moreover, these soils are prone to tunnelling and erosion processes (Nyssen et al. 2000).

3. Materials and Methods

Based on a detailed DEM analysis and fieldwork we assessed the geomorphological processes, forms and features of the Melka Kunture area. We focused our investigation on the major hydro-erosive processes as well as the neotectonic activity using GIS based models together with a detailed terrain analysis. For this study, we tested different digital elevation models (DEM) based on diverse sources and with different resolution as shown in Tab. 1.

The SRTM DEMs and the ASTER GDEM are public domain models with global coverage (Rabus et al. 2003; Farr et al. 2007; Tachikawa et al. 2011) while the other two models were generated specifically for the study area by means of digital stereo-processing following Kropáček et al. (2015). The ALOS/PRISM DEM from an image triplet acquired by PRISM optical instrument composed of three cameras with back, nadir and forward looking direction, which was carried by the ALOS satellite in the period 2006–2011. We used a feature matching technique implemented in the LPS photogrammetry software package. A robust technique of 3D reconstruction was applied for the derivation of the Airphoto DEM from aerial photographs acquired in 1971 and 1972 using a Structure from Motion Approach (SfM) in Agisoft Photoscan software package. Softcopies of the aerial photographs were provided by the Ethiopian Mapping Agency. The Shuttle Radar Topographic Mission (SRTM) accomplished in 11 days in February 2000 resulted in an almost global interferometric acquisitions of the Earth's surface in the microwave bands C and X. Two DEMs were produced from SRTM data: the first is based on C-band data denoted as SRTM-C and the second is based on X-band data denoted as SRTM-X. The advantage of the SRTM data lies in its almost global availability, temporal homogeneity and absence of processing "artefacts".

The DEMs were georeferenced using UTM projection. Subsequently, we performed a quick screening to evaluate the quality of the DEMs following Carlton and Tennant (2001).

A quality check was performed consisting in: i) checking if the maximum and minimum values are realistic, ii) creating a histogram of elevation values to check for "artefacts" and irregularities such as peaks or outliers, iii) deriving a hillshade to get a 3D-like visualization of the surface, and iv) delineating the slope as first derivative of the DEMs to check for errors which normally increase with the level of derivative. Thereafter, we hydrologically corrected the DEMs in order to eliminate sinks using the algorithm proposed by Planchon and Darboux (2001). The latter procedure guarantees that the surface is completely drained and that there are no pits or sinks remaining in the DEM impeding the drainage of surface runoff. Especially the hydrologic terrain indices need a hydrological corrected DEM.

Based on the available DEMs we performed a detailed terrain analysis to explore the potential of the terrain surface concerning certain hydro-erosive hazards, neotectonics and Palaeo-geomorphology. The potential for surface runoff was estimated using a simple storm flow model based on a weighted multiple flow accumulation algorithm according to Freeman (1991). In this study, we utilized the precipitation

Tab. 1 Sources and resolution of DEMs utilized in this study.

Sensor	Product	Date	Resolution
SRTM-C	NASA SRTM-C DEM 3 arcsec	02.2000	90 m
SRTM-X	NASA SRTM-X DEM 1 arcsec	02.2000	25 m
ASTER DEM	ASTER GDEM2	10.2011	25 m
ALOS PRISM	Level 1B1	24.05.2008/15.07.2010	10 m
Airphoto DEM	1965_HCP46; 1971_123ET9	1965/1971	2.5 m

event of the 08.09.1987 amounting to 120.9 mm/day to calculate the maximum surface runoff of a storm event supposing that there was no infiltration. This precipitation event has a return period of 40 years. Hydro-erosive processes in the area of Melka Kunture are mainly linked to deep linear erosion processes like gullies and deep rills as well as surficial sheet erosion processes also called rill-interrill erosion processes. We assessed the linear erosion processes using the Stream Power Index (*SPI*) following Moore et al. (1991). The SPI is the product of specific catchment area (Freeman 1991) and slope (Zevenbergen, Thorne 1987). We identified the rill-interrill erosion potential applying the Transport Capacity Index (*TCI*) according to Moore and Wilson (1992). The *TCI* corresponds to the LS-factor of the RUSLE (Renard et al. 1997) and thus, describes the potential for surficial erosion processes just based on the topography. The Topographic Wetness Index (*TWI*) was derived following Beven and Kirkby (1979) (see also Moore et al. 1991; Moore et al. 1997) to identify areas of high soil moisture and hence, saturation excess overland flow.

$$SPI = A_s \times \text{slope} \qquad (1)$$

$$TWI = \ln(A_s/\text{slope}) \qquad (2)$$

$$TCI = (A_s/22.3)^m \times (\text{slope}/0.09)^n \qquad (3)$$

With A_s = specific catchment area; Slope in degree; m and n are constants. For prevailing rill erosion $m = 1.6$, $n = 1.3$ while for prevailing sheet erosion, $m = n = 1$.

Neotectonic structures as well as Palaeogeomorphological forms and features can be identified using information about the drainage network base-level (*DNBL*) (Golts, Rosenthal 1993). As stated by Grohmann et al. (2011) base-level maps are constructed from an initial map of valley orders, classified according to the Strahler (1952) system. Roughly spoken, the elevation of the channel segments greater than a specific order are selected to interpolate the *DNBL* elevation according to Filosofov (1960). The streambeds designate the erosional base surface. In geological terms, *DNBL* surfaces relate to similar erosional stages and should be regarded as manifestations of regional erosional-tectonic events and especially of young movements of the crust (Golts, Rosenthal 1993).

If we subtract the *DNBL* from the selected DEM we yield a surface that is normalized by the erosion base level. The Altitude Above Stream Channel Network (*AACN*) gives information on the elevation above the base level. Thus, features like fluvial terrace systems, palaeo river courses, planation surfaces as well as erosion and deposition zones (e.g. Haider et al. 2015) can be identified. Moreover, also neotectonics such as faulting, uplift and downshift processes may be detected (Gary et al. 1973). We calculated also the relative height that describe the vertical offset of a grid cell to its according drainage line considering the local relief energy in relation to the local erosion base level following Dietrich and Böhner (2008). This index emphasizes landscape structures and forms even more than the AACN index due to the fact that the local relief and hence the related noise is considered.

We also organized an extended field work mapping geomorphological forms and features and assessed also the dominant soil characteristics.

4. Results and Discussion

4.1 DEM assessment and selection

The terrain analysis requires a good quality DEM in order to provide proper information about the terrain surface and the related processes. Moreover, additional criteria such as acquisition costs, large or better worldwide coverage and preparation efforts may play a role. For this study, we required the DEM coverage of the entire Upper Awash River Basin and a good quality to assess the relevant geomorphological processes. As shown in Tab. 1 and Fig. 3 the quality of the DEMs is very heterogeneous. The DEMs are based on different sensors and systems. However, the SRTM 90 m having the coarsest resolution gives only a vague idea of the terrain surface. Much better is the SRTM 30 X band data performing, showing also smaller geomorphological features such as linear erosion forms. The ASTER GDEM has a slightly higher resolution with 25 m but also a lot of noise and "artefacts". The latter is always a problem for passive optical sensors since the DEM reflects the vegetation surface. Similarly, the ALOS PRISM DEM is based on optical data and even though it has the higher resolution of 10 m a lot of "artefacts" resulting from larger vegetation features disturbs the terrain surface. The highest resolution with 2 m was obtained with the aerial-photograph-based DEM that was generated using a structure from motion algorithm (Agisoft Photoscan). However, the stereo images do not cover the entire basin and also vegetation disturbs a proper analysis. Especially the large trees close to the river network have major effects on the delineation of an accurate drainage network.

The quality check reveals that the best compromise between a good quality providing enough terrain details and low noise resulting in small preparation efforts is the SRTM-X 30 m. Hence, we utilized the SRTM-X 30 m for the further detailed terrain analysis. Figure 3 shows the hillshades of the DEMs we considered in this study.

4.2 Assessment of surface runoff and soil erosion processes

We estimated the surface runoff volumes using a weighted multiple low algorithm supposing an exceptional precipitation event of 120.9 mm/day. We

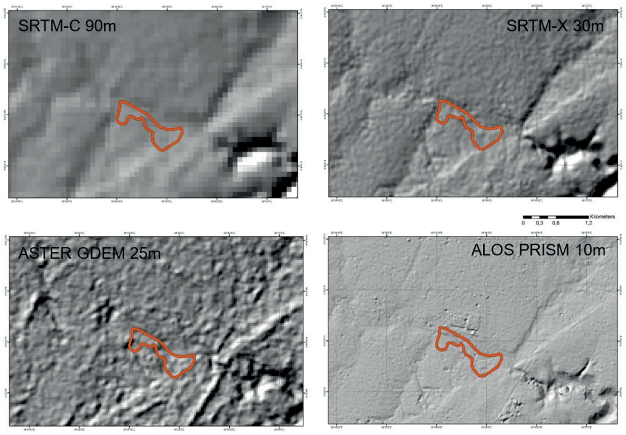


Fig. 3 DEMs considered in this study: upper left: SRTM 90 m C-band; lower left: ASTER GDEM 25 m; upper right SRTM 30 m X band; lower right: ALOS PRISM 10 m

do not consider evapotranspiration processes nor soil infiltration. The latter hypothesis allows us to calculate the maximum runoff of a 40 years return period event. Such an event may occur under different conditions: i) after long dry seasons when due to effects like surface crusting and hydrophobicity infiltration is very low, or ii) after preceding rainfall events that saturated the soils leading to saturation excess runoff. Figure 4a illustrates the runoff volumes for the 40 years return period. Zones with higher runoff are illustrated in blue colors whereas dryer zones in light green colors. Moreover, we highlight the zones prone to flooding risk in yellow and purple color indicating medium and high flooding risk respectively. Figure 4a shows that the lower parts of the core archeological area, including Gombore and Garba gullies, will be completely flooded during the selected event. Low *TWI* values (brown color) correspond to dry or well drained zones whereas high *TWI* values (blue color) represent high soil moisture and thus, soil saturation risk (see Fig. 4b). Consequently, the mayor flooding zones are those with high *TWI* values corresponding to the modeled runoff shown in Figure 4a. Specifically, the surroundings of the core archeological area are very prone to soil saturation and consequently, related surface runoff. Of particular interest is the upper Atabella tributary area, that shows very high *TWI* values and thus, much higher moisture conditions.

Soil erosion processes are assessed using the *TCI* (rill-interrill erosion) and *SPI* (deep linear erosion). Figures 4c and 4d illustrate the spatial distribution of these processes. Figure 4c exposes the more areal or sheet erosion features. The yellow and lighter blue areas are characterized by sheet (rill-interrill) erosion processes, whereas the dark blue areas indicate stable conditions. According to Eq. 3, very high *TCI* values are related to steep slopes and/or very large catchment areas. Here especially the steep slopes along the rift shoulder incision of the Awash River and the steeper mountain areas show very high *TCI* values. However, also the tectonic lineaments are revealed by the *TCI*, e.g. the major fault system crossing the area of Melka Kunture from southwest to northeast (see also Raynal, Kieffer 2004). In the sub-basins of the Atabella and Kella tributaries as well as in the upper parts of the Awash River some larger sheet erosion areas occur. They are often related to tectonic fault systems (see also Fig. 4). Figure 4d describes the deep linear soil erosion processes such as gully erosion (e.g. Zakerinejad, Märker 2015) using the *SPI* following Eq. 1. The yellow and red colors highlight incision zones. These incisions reproduce well the existing gully systems we mapped during fieldwork in 2014 (Fig. 4e). High *SPI* values are also related to knickpoints in the longitudinal profiles of higher Strahler-order drainage basins and may indicate neotectonic activities. In 1st order drainage basins, knickpoints are often related to gully headcuts. These headcuts seem to be lined along the fault systems running in south-west to north-east direction through the study area (Fig. 4f). Dendritic pattern like in the upper Kella Tributary can be related to retrogressive erosion. In the western parts of the archaeological park we identified major gully systems with the *SPI* approach that were later also detected and mapped during the field-campaign.

4.3 Neotectonics and paleo-landscape features

SPI and *TCI* already indicate linear tectonic activity. However, the *AACN* (Fig. 5) shows in red and orange areas that are subject to erosion/ incision processes and in light blue and blue areas where deposition processes prevail. In terms of neotectonics we might differentiate between uplift and downshift areas. The core archaeological area of Melka Kunture is constrained by tectonic faults as already indicated in Figure 4c and 4d. These faults act as local erosion bases and hence, drive erosion/incision and deposition/ sedimentation processes. The *AACN* shows mainly strong erosion processes in the Southeast and Northeast of the Melka Kunture Archeological Park. The Kella tributary for example seems to be affected by retrogressive fluvial erosion processes triggered by the main incision of the Awash River into the rift valley shoulder. The core archaeological area seems to be only slightly affected by erosion or tectonic downshift processes. In the western part of the study area upstream the Awash River again incision prevails between two fault lines (Fig. 5). Further upstream similar conditions to those of the core archaeological area can be identified. Due to the low erosion and/or tectonic activities that come along with a higher risk of flooding and ponding as demonstrated in Figures 4a and 4b, we hypothesize a major sedimentation and deposition zone in the core archaeological area as well as in a section ca. 10 km upstream. This locally led to the preservation of deposits including archaeological horizons. Consequently, the other sedimentation/deposition zone, further up the Awash River, might represent also a certain potential for archaeological investigations.

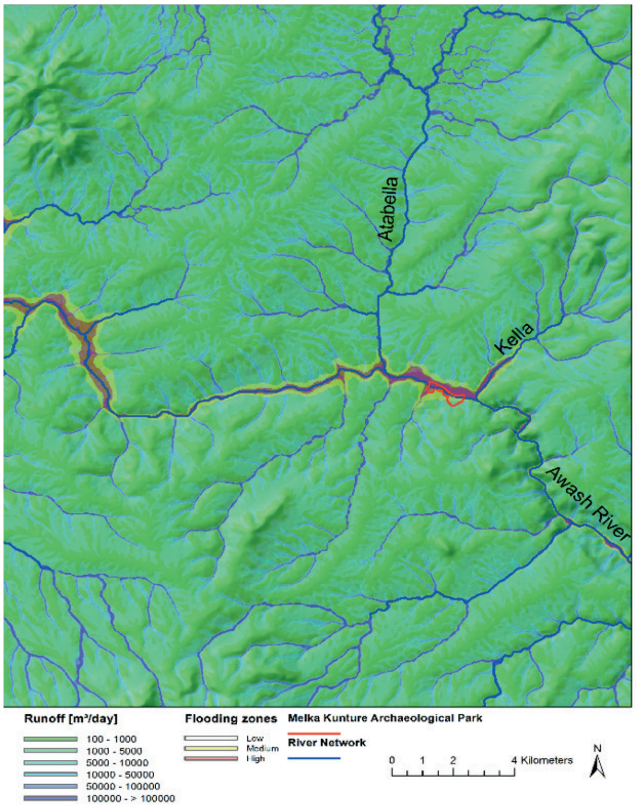


Fig. 4a Surface runoff for a 40 years return period and areas prone to flooding (blue = high runoff, light green = low runoff values. In yellow zones of lower flooding risk and in red-purple those with high risk of flooding.

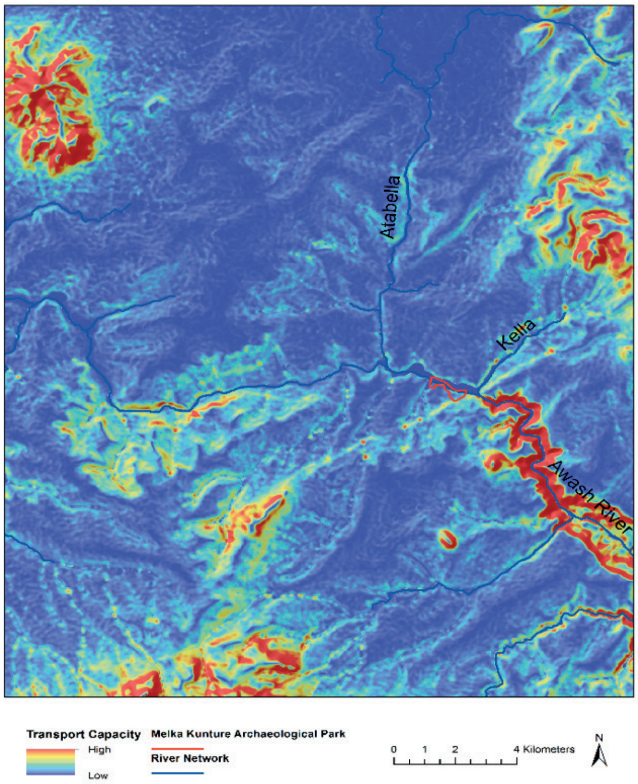


Fig. 4b Topographic Wetness Index (TWI) showing soil moisture distribution (brown = dry; blue = wet).

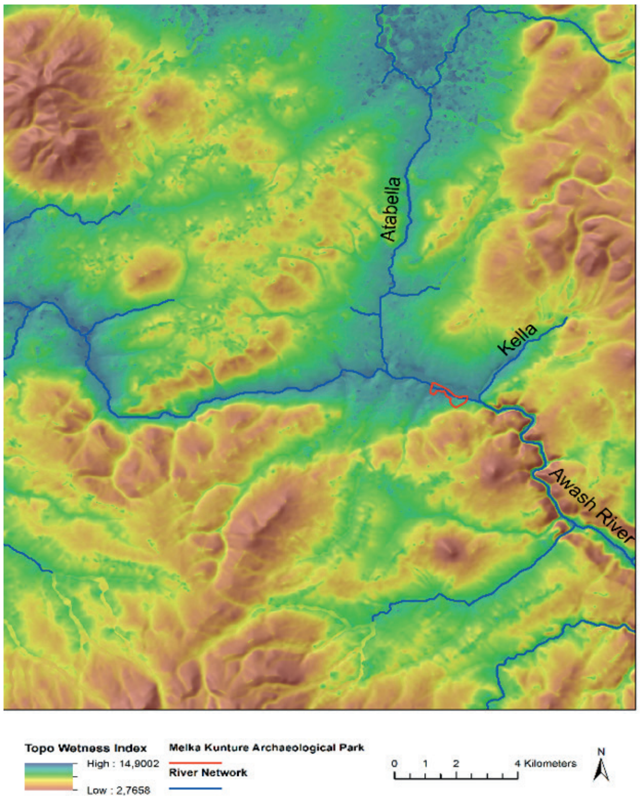


Fig. 4c Transport Capacity Index (TCI) characterizing sheet erosion processes (yellow and red = moderate and high risk).

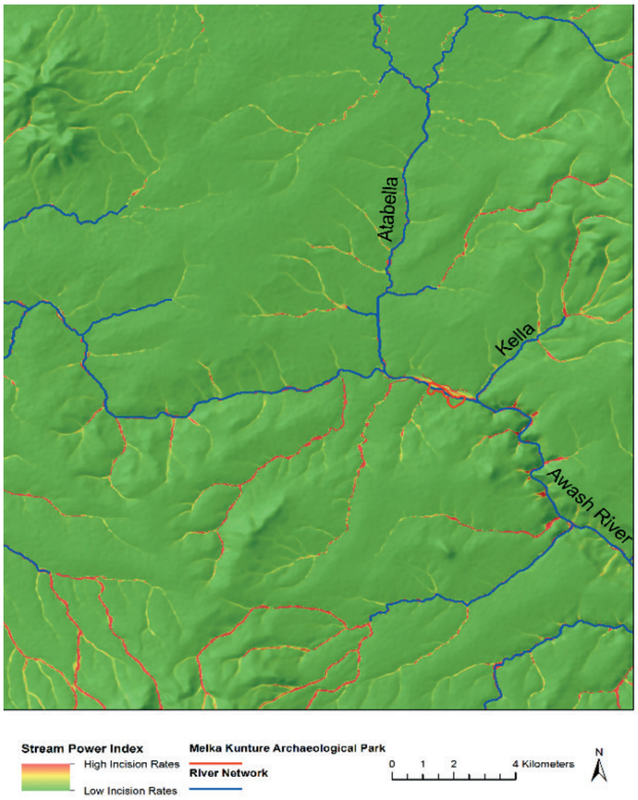


Fig. 4d Stream Power Index highlighting deep linear erosion processes (red = strong incision; green = no or low linear erosion).

Fig. 4e Gully erosion in the area south of Tefki.

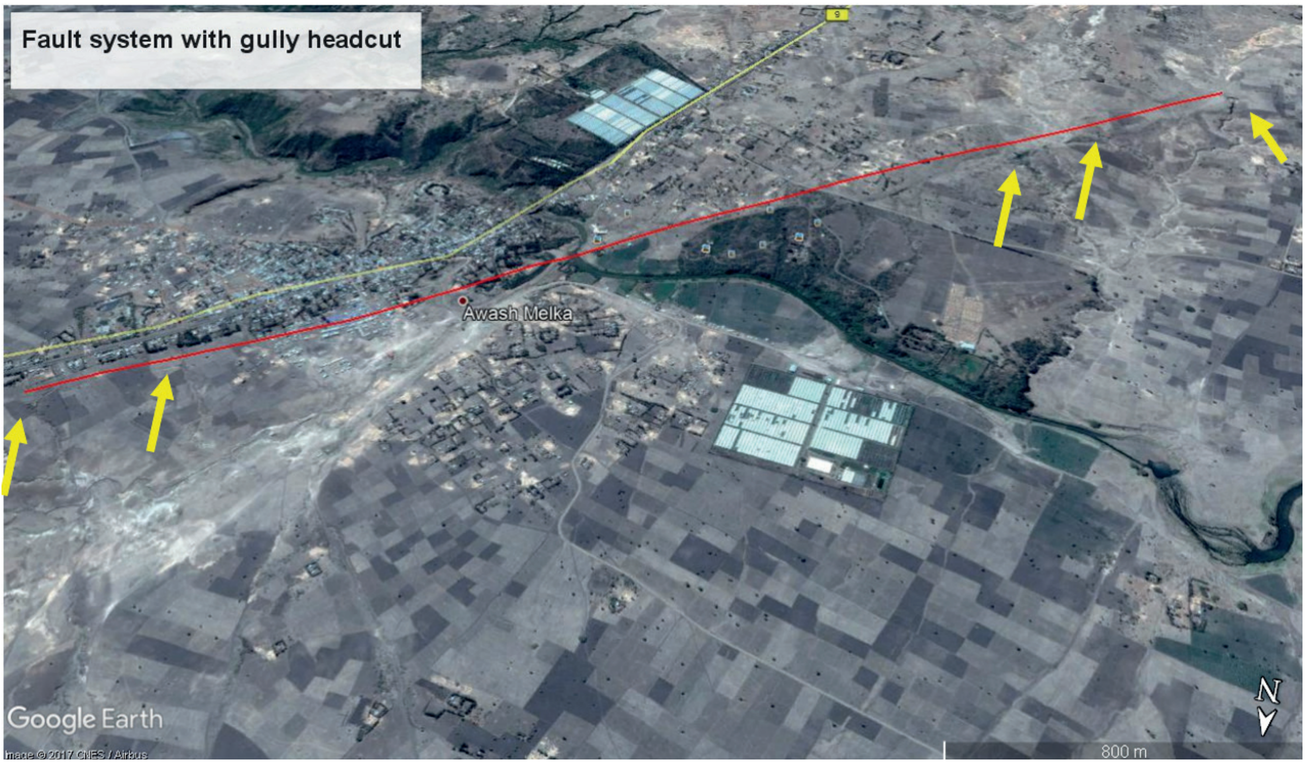
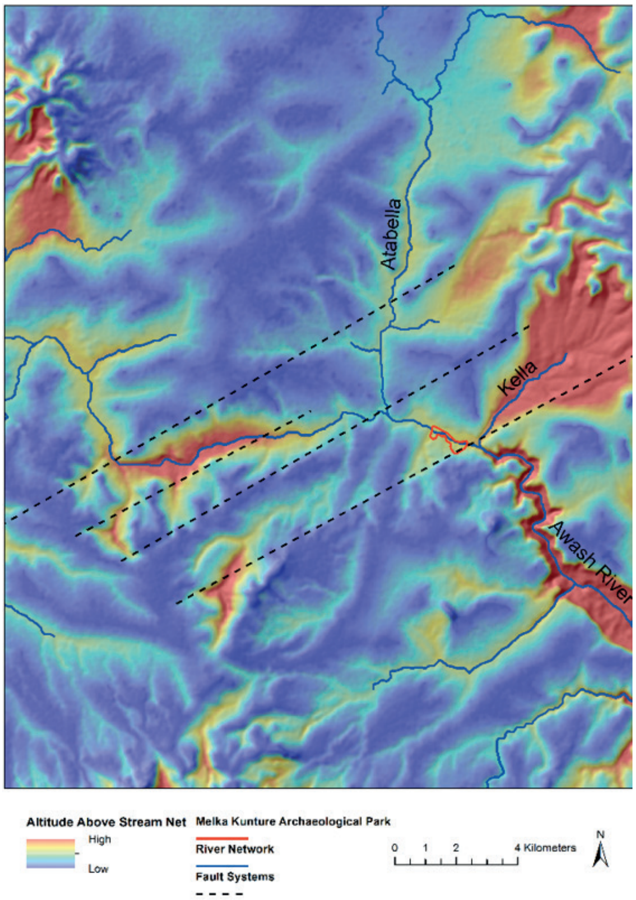
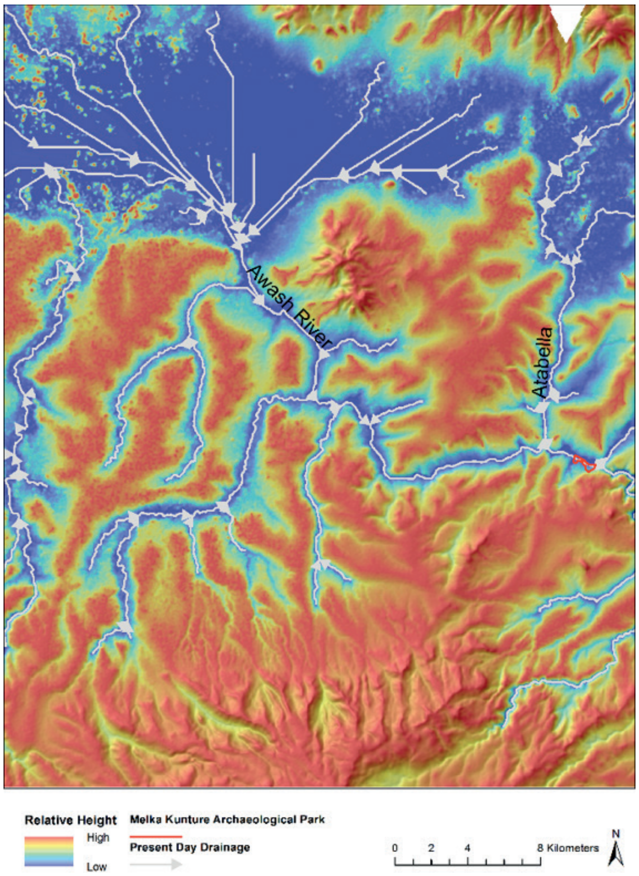


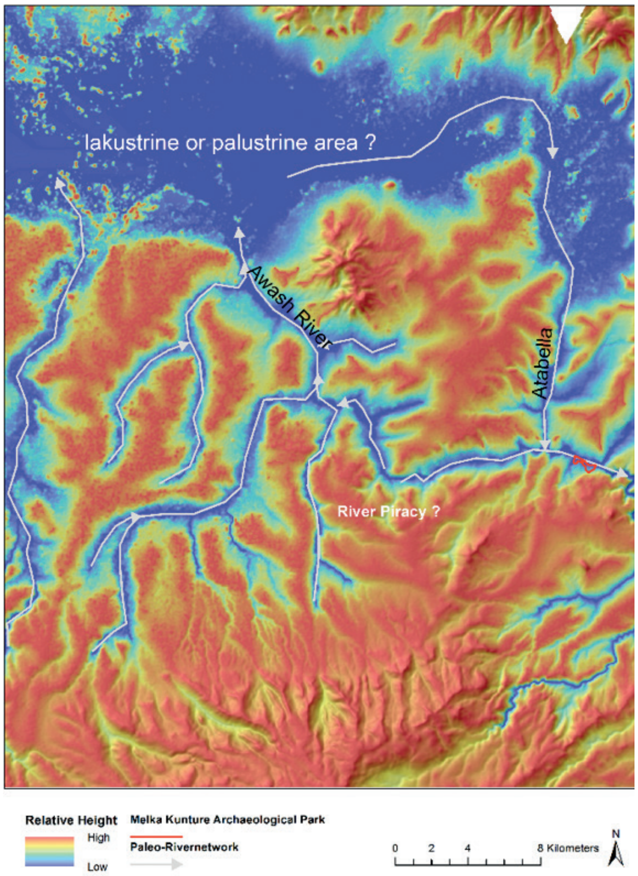
Fig. 4f Fault system (red) at the Melka Awash town with associated gully headcuts (yellow arrows) (looking towards the South).



↑ **Fig. 5** Altitude Above Stream Channel network (*AACN*) and supposed tectonic lineaments.



↑ **Fig. 6** Relative Height with the present-day drainage network and related flow directions.



← **Fig. 7** Relative height and the supposed Paleo-Drainage Network. Indicated potential river piracy zones and Palustrine or Lacustrine environments.

4.4 Drainage network and Paleodrainage

Figures 6 and 7 reveal the drainage conditions of the larger study area. Shown is the upstream part of the Awash River above the core archaeological area including a large flat basin in the North, today drained by the Awash towards the Southeast (Fig. 6). However, northern drainage directions of the smaller tributaries in the southwest indicate modifications of the drainage network in the past. The change of the drainage pattern, the so called 'river piracy' might occurred in the past likely due to tectonic movements and/or quickly propagating backward erosion of the today Awash river. Figure 7 shows a hypothesized Paleo-drainage according to the geomorphological settings. Thus, the larger depression in the north receives much more water and hence, might have been characterized by Palustrine or Lacustrine environments. The basin was potentially drained on its eastern margin towards South via the present day Atabella river valley. This could also explain the large valley pattern that is not in line with the present-day catchment area of the Atabella tributary. Finally, a potential zone for river piracy was identified ca. 8 km upstream the core archaeological area.

5. Conclusions

This study reveals the spatial distribution of present day landscape forming processes. Surface runoff and soil erosion processes were analysed in detail using Topographic Indices and simple hydrological modelling approaches. The analysis shows that large parts of the core archaeological area Park is prone to flooding caused by extreme events coming along with erosion and deposition processes, as confirmed during high Awash floods at the time of last century excavations (Chavaillon, Berthelet 2004). Moreover, we evidence specific paleo-landscape patterns in the surroundings of Melka Kunture. In part, these features can be explained with the tectonic activity revealed by the Topographic Indices (e.g. *AACN*, *TCI*). Larger features like the depression in the upper parts of the study area indicate environmental conditions, that up to present time are related to large areas of ponded water bodies, thus implying lacustrine or palustrine conditions in the past. Moreover, the Topographic Indices reveal information about the paleo-drainage of the Upper Awash System. As shown, river piracy is a highly probable explanation of the present day drainage pattern. This provides a further evidence for the impact of tectonic activity on the landscape evolution in the area. Finally, this analysis shows the potential of topographic indices and simple modelling approaches to reveal paleo-landscape information and thus, contributes to archaeological investigations and interpretations of the whole area. In future, we plan more detailed studies with concerted fieldwork to further evaluate the hypothesis developed in this paper using a pure Terrain Analysis approach.

Acknowledgements

We are grateful to the Ethiopian authorities and namely to the Authority for Research and Conservation of the Cultural Heritage for research permits and assistance during fieldwork. This study was carried out in the framework of the German Science Foundation (DFG) project “Integrated assessment of geomorphological process dynamics on different spatio-temporal scales in the Ethiopian Highlands using remote sensing and advanced modelling approaches” (HO1840/11-1). The ALOS/PRISM data were provided by the ESA in the framework of the project ID13160. The aerial photographs were provided by the Ethiopian Mapping Agency in Addis Ababa.

References

Beven, K. J., Kirkby, M. J. (1979): A physically-based variable contributing area model of basin hydrology. Hydrology Science Bulletin 24(1), 43–69, https://doi.org/10.1080/02626667909491834.

Chavaillon, J., Taieb, M. (1968): Stratigraphie du Quaternaire de Melka-Konturé, vallée de l’Awash, Ethiopie. Premiers résultats. C. R. Acad. Sci., S. D 266, 1210–1212.

Chavaillon, J., Berthelet, A. (2004): The archaeological sites of Melka Kunture. In: Chavaillon, J., Piperno, M. (eds.): Studies on the Early Palaeolithic Site of Melka Kunture, Ethiopia (25–80). Origines, Instituto Italiano di Preistoria e Protostoria, Firenze.

Carlton, D., Tenant, K. (2001): DEM Quality Assessment. In: Maud, D. F. (ed.): Digital Elevation Model technologies and applications: The DEM users manual (395–440). American Society of Photogrammetry and remote sensing, Bethesda USA.

Debele, B. (1985): The Vertisols of Ethiopia Their properties, classification and management. 5th Meeting of the Eastern African Soil Correlation and Land Evaluation Sub-Committee, 4–10 December 1983, Wad Medani Sudan. World Soil Resources Report 56. FAO (Food and Africulture Organization of the United Nations), Rome, 31–54.

Dietrich, H., Böhner, J. (2008): Cold air production and flow in a low mountain range landscape in Hessia (Germany). Hamburger Beiträge zur Physischen Geographie und Landschaftsökologie,19, 37–48.

Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L. (2007): The shuttle radar topography mission. Rev. Geophys., https://doi.org/10.1029/2005RG000183.

Freeman, G. T. (1991): Calculating catchment area with divergent flow based on a regular grid. Computers and Geosciences 17, 413–22, https://doi.org/10.1016/0098-3004(91)90048-I.

Filosofov, V. P. (1960): Brief guide to morphometric methods in search of tectonic structures, Saratov, Saratov Univ. Publ. House. (in Russian).

Gallotti, R., Raynal, J. P., Geraads, D., Mussi, M. (2014): Garba XIII (Melka Kunture, Upper Awash, Ethiopia): A new Acheulean site of the late Lower Pleistocene. Quaternary International 343, 17–27, https://doi.org/10.1016/j.quaint.2014.04.039.

Gary, M., McAfee, R., Wolf, C. (1973): Glossary of Geology. 2nd ed. Am. Geol. Inst.,Washington.

Golts S., Rosenthal E. (1993): A morphotectonic map of the northern Arava in Israel, derived from isobase lines. Geomorphology 7, 305–315, https://doi.org/10.1016/0169-555X(93)90060-F.

Grohmann, C. H., Riccomini, C., Chamani, M. A. C. (2011): Regional scale analysis of landform configuration with base-level (isobase) maps. Hydrol. Earth Syst. Sci. 15, 1493–1504, https://doi.org/10.5194/hess-15-1493-2011.

Haider, V. L., Kropáček, J., Dunkl, I., Wagner, B., Von Eynatten, H. (2015): Identification of peneplains by multi-parameter assessment of digital elevation models. Earth Surface Processes and Landforms 40(11), 1477–1492, https://doi.org/10.1002/esp.3729.

Kropáček, J., Vařilová, Z., Baroň, I., Bhattacharya, A., Eberle, J., Hochschild, V. (2015): Remote Sensing for Characterisation and Kinematic Analysis of Large Slope Failures: Debre Sina Landslide, Main Ethiopian Rift Escarpment. Remote Sensing 7(12), 16183–16203, https://doi.org/10.3390/rs71215821.

Kropáček, J., Schillaci, C., Salvini, R., Märker, M. (2016): Assessment of gully erosion in the Upper Awash, Central Ethiopian highlands based on a comparison of archived aerial photographs and very high resolution satellite images. Geogr Fis e Din Quat. 39, 161–170, https://doi.org/10.4461/GFDQ2016.39.15.

Moore, I. D., Garson, R. B., Ladson, A. R. (1991): Digital terrain modelling: a review of hydrological, geomorphological and biological applications. Hydrological Processes 5, 3–30, https://doi.org/10.1002/hyp.3360050103.

Moore D., Wilson J. P. (1992): Length-slope factors for the revised universal soil loss equation: simplified method of estimation. Journal of Soil and Water Conservation 47, 423– 428.

Moore, I. D., Garson, R. B., Ladson, A. R. (1997): Digital terrain modelling: a review of hydrological, geomorphological and biological applications. Soil Science Society of America Journal 57, 443–452, https://doi.org/10.2136/sssaj1993.03615995005700020026x.

Morgan, L. E., Renne, P. R., Kieffer, G., Piperno, M., Gallotti, R., Raynal, J. P. (2012): A chronological framework for a long and persistent archaeological record: Melka Kunture, Ethiopia. Journal of Human Evolution 62, 104–115, https://doi.org/10.1016/j.jhevol.2011.10.007.

Mussi, M., Altamura, F., Macchiarelli, R., Melis, R. T., Spinapolice, E. E. (2014): Garba III (Melka Kunture, Ethiopia): a MSA site with archaic Homosapiens remains revisited. Quaternary International 343(1), 28–39, https://doi.org/10.1016/j.quaint.2013.08.028.

Mussi, M., Altamura, F., Bonnefille, R., De Rita, D., Melis, R. T. (2016): The environment of the Ethiopian highlands at the Mid Pleistocene Transition: Fauna, flora and hominins in the 850–700 ka sequence of Gombore II (Melka Kunture). Quaternary Science Reviews 149, 259–268, https://doi.org/10.1016/j.quascirev.2016.07.033.

Nyssen, J., Moeyersons, J., Deckers, J. A., Haile, M., Poesen, J. (2000): Vertic movements and the development of stone covers and gullies, Tigray Highlands, Ethiopia. Zeitschrift für Geomorpologie 44, 145–164.

Planchon, O., Darboux, F. (2001): A fast, simple and versatile algorithm to fill thedepressions of digital elevation models. Catena 46, 159–176, https://doi.org/10.1016/S0341-8162(01)00164-3.

Piperno, M. (2001): The prehistory of Melka Kunture (Ethiopia). Bulletin du Centre de recherche français à Jérusalem 8, 135–145.

Piperno, M., Collina, C., Gallotti, R., Raynal, J. P., Kieffer, G., Le Bourdonnec, F. X., Poupeau, G., Geraads, D. (2009): Obsidian exploitation and utilization during the Oldowan at Melka Kunture (Ethiopia). In: Interdisciplinary approaches to the Oldowan, Springer.

Rabus, B., Eineder, M., Roth, A., Bamler, R. (2003): The shuttle radar topography mission, a new class of digital elevation models acquired by spaceborne radar. ISPRS Journal of Photogrammetry Remote Sensing 57, 241–262, https://doi.org/10.1007/978-1-4020-9060-8_10.

Raynal, J. P., Kieffer, G. (2004): Lithology, dynamism and volcanic successions at Melka Kunture (Upper Awash, Ethiopia) 2004, 111–135.

Raynal, J. P., Kieffer, G., Bardin, G. (2004): Garba IV and the Melka Kunture Formation. A preliminary lithostratigraphic approach. In: Chavaillon, J., Piperno, M. (eds.): Studies on the Early Palaeolithic Site of Melka Kunture, Ethiopia (137–166). Origines, Istituto Italiano di Preistoria e Protostoria, Firenze.

Renard, K. G., Foster, G. R., Weesies, G. A., McCool, D. K., Yoder, D. C. (1997): Prediction soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation. Agricultural Handbook 703. U.S. Dept. of Agriculture, p. 404.

Salvini, R., Riccucci, S., Francioni, M. (2012): Topographic and geological mapping in the prehistoric area of Melka Kunture (Ethiopia). Journal of Maps 8, 169–175, https://doi.org/10.1080/17445647.2012.680779.

Strahler, A. N. (1952): Hypsometric (area-altitude) analysis of erosional topography. Geological Society of America 63,1117–1142, https://doi.org/10.1130/0016-7606(1952)63[1117:HAAOET]2.0.CO;2.

Tachikawa, T., Hato, M., Kaku, M., Iwasaki, A. (2011): Characteristics of ASTER GDEM version 2 Geoscience and Remote Sensing Symposium (IGARSS), 2011 IEEE International (3657–3660): IEEE.

Zakerinejad, R., Märker, M. (2014): Prediction of Gully erosion susceptibilities using detailed terrain analysis and maximum entropy modeling: a case study in the Mazayejan Plain, Southwest Iran. Geogr Fis Dinam Quat 37(1), 67–76.

Zevenbergen, L. W., Thorne, C. R. (1987): Quantitative analysis of land surface topography. Earth Surface Processes and Landforms 12, 47–56, https://doi.org/10.1002/esp.3290120107.