# Volcaniclastic sedimentation in a closed, marginal rift basin: The case of the Melka Kunture area (Upper Awash, Ethiopia)

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**Abstract**
The Upper Awash runs across a volcano-sedimentary sequence dated from Late Miocene to Middle Pleistocene and is located on the western margin of the Main Ethiopian Rift (MER). The sequence formed within a fluvial system which developed within transversal rift faults. The Pleistocene stratigraphy consists of primary volcanic deposits interbedded with reworked sediments emplaced in a low energy floodplain environment developed in a subsiding area. The Lower part of the sequence is dominated by a low aspect ratio, complex, pyroclastic density current deposit (Kella Unit), 1.2 Ma old. This eruption was followed by an eruptive stasis and reorganization of drainage system. Tephra sedimentation in the floodplain climaxed again in between 0.9 and 0.7 Ma ago and was associated with extensive tephra reworking. Sedimentation rates significantly decreased after 0.6 my ago, probably due to declining volcanic activity in the nearby MER sector. Dynamic interaction between tectonics and volcanic activity created a complex sedimentary environment constituting an exceptional fossil trap which preserved numerous artifacts and fossil remains. Stratigraphic correlation is based on the interpretation of the basin history and evolution and has a crucial relevance not only for the reconstruction of the paleoenvironment and interpretation of the paleontological and archeological data.

Keywords: Main Ethiopian Rift, tephra erosion, fossil trap

Running title: *Volcaniclastic sequence of Melka Kunture*

Because of the high sedimentation rates, high probability of fast burial and permineralization by silica rich fluids, volcaniclastic sequences are ideal fossilization environments. As a consequence, several volcaniclastic sequences are also hosting significant and detailed fossil records, preserving key information on the evolutionary history of the Earth and of hominins (e.g. Lune river, Tasmania: Bromfield et al., 2007; John Day Formation, Oregon, USA: Robinson et al., 1984; Olduvai Gorge, Tanzania: Ashley et al., 2010). The study of such exceptional fossil records requires accurate stratigraphic and chronostratigraphic

reconstruction of the hosting sequence, understanding the effect of volcanic activity on the environment and life development.
The impact of volcanic activity on the environment depends on eruption magnitude, intensity, and frequency (Payne and Egan, 2019; Ayris and Delmelle, 2012; Sadler and Grattan, 1999). The impact of explosive eruptions does not only depends on primary processes of tephra formation and dispersal, but is also associated with tephra reworking and re-sedimentation, developing a volcaniclastic cycle which is active during, in between and after eruptions. Because of the interplay between timescales of eruption (constructive phases) and erosion, the impact of volcanic activity on landscape is variable. For example, small eruptions with short (hours to months) repose times can disperse significant masses of tephra over small areas (tens of $km^2$) which are redeposited over larger areas by erosion and rain or stream-controlled transport. On the opposite side, volcanoes responsible of large events do erupt rarely but disperse large volumes of fine tephra (ash) on wider areas in very short times which, by creating an impermeable cover increases water runoff, erosion and epiclastic sedimentation even at tens of km from the vent. In the case of large volcanic provinces, epiclastic sedimentation is extremely significant, because of the large volume of material involved and its duration(the same tephra can be subjected to several erosion/sedimentation cycles) which is larger than the volcanic activity itself (Cas and Wright, 1997). Interpretation of volcaniclastic sequences in terms of volcanic and sedimentary cycles requires understanding the balance between primary volcanic sedimentation, tephra erosion and re-sedimentation, and how both are affected by tectonic activity. It requires understanding how very different superficial processes (tephra deposition, erosion and transport) interacted with each other in the specific environment considered in the study.

The most striking example of fossil and cultural history preserved and documented in a volcaniclastic context is the East African Rift system, a key area for reconstructing hominin evolution (Maslin et al., 2015). Understanding the value and representativity of these archeological succession requires interpreting the eruptive history of the rift and how it affected the preservation potential of the remains. Among the various tectonic settings marked by extensive volcanism, rifting areas appear the most challenging because of the extensive faulting which forms interconnected or isolated small basins, each one potentially exhibiting significant facies variability and stratigraphy (Mathisen and McPherson, 1991; Baker, 1986). This condition, associated with a high spatial concentration of active volcanoes and limited magmatic compositional changes make tephra correlation a particularly challenging task. For this reason, reconstruction of rift volcanic activity is either based on large, regional scale events (Di Paola, 1972; Woldegabriel et al., 1990) or on the collection of studies of single volcanic sequences of proximal and very proximal areas (e.g. Boccaletti et al., 1999; Katoh et al., 2000; Siegeburg et al., 2018).
In this article we document and reconstruct the general stratigraphy of the Melka Kunture basin (fig. 1), which hosts a cluster of prehistoric sites from Oldowan to Late Stone age (Chavaillon and Piperno, 2004). Melka Kunture (MK) is a marginal basin in the west side of the northern portion of the Main Ethiopian rift (MER). It is currently crossed by the upper Awash river, whose valley connects it to the rift floor and is actively eroding sediments and exposing exceptional archaeological and paleontological sequences.

## Geology of Melka Kunture

The basin of MK is located 30 km south of Addis Ababa (fig. 1a). It is about 3000 $km^2$ wide, and is bounded by two major lineaments (Yerer-Gugu and Chilalo-Gurage; Mohr, 1967) and by a system of faults, parallel to both lineaments and major rift faults (fig. 1b). The geological history of MK is associated with the Late Cenozoic evolution of the MER, characterized by tectonic and magmatic activity (WoldeGabriel et al., 2000, Raynal and Kieffer, 2004; Corti, 2009). Rifting began during Middle Miocene with the formation of grabens and half-grabens with a dominant NE orientation (Davidson and Rex, 1980; WoldeGabriel et al., 1990; Corti, 2009). Voluminous silicic eruptions in the central MER were associated with rifting 5-3 My ('Nazareth series' Bonini et al., 2005). Extensive pyroclastic deposits, formed by large magnitude eruptions associated with caldera collapses, filled the grabens and covered the adjacent plains ('Dino Formation' of Kazmin, 1981; Corti, 2009). In particular, the MK area was a site of widespread volcanic activity until late Miocene. The activity consisted in sparse effusive eruptions defining monogenetic centers localized along faults (Kieffer et al., 2004) and occasionally by more explosive activity with formation of pyroclastic density current (PDC) deposits building minor small volcanic edifices (fig. 1). The Early Pleistocene stratigraphy consists of a sequence of primary (fall and flow) volcanic deposits interbedded with reworked sediments emplaced in a floodplain environment developed in the subsiding area (Melka Kunture Formation, Raynal et al. 2004). In the Early Pliocene the activity moved eastwards to the current rift floor, and volcanic activity in the area ceased and was followed by further faulting and development of an axial system of horst and grabens (Mohr, 1967). From this point on, volcaniclastic sedimentation associated with primary deposition, local erosion and redeposition of medial/distal tephra (Taieb, 1974; Raynal and Kieffer, 2004). The total visible thickness of volcaniclastic deposits is about 30 m, but it likely reaches up to 100 m (Taieb, 1974).

The volcaniclastic Pleistocene sequence is overlapped by a large, poorly welded ignimbrite tuff ('Kella Formation' of Raynal et al. 2004; Raynal and Kieffer, 2004) dated at 1.2 Ma (Morgan et al, 2012). After this volcanic event, sedimentation was mainly characterized by fluvial processes interbedded with distal ash fall and reworked volcano sediments emplaced in a low energy floodplain environment (Gelasian-Chibanian) (Chavaillon and Taieb, 1968; Taieb, 1974; Raynal and Kieffer, 2004). The fluvial sedimentation of the Awash river and tributaries was controlled by the level of the Awash sill at the SSE border of the basin. The paleo-landscape of the area around MK was geomorphologically active and complex. It was reconstructed from detailed stratigraphic logs from several localities (Chavaillon and Taieb, 1968; Taieb, 1974; Raynal and Kieffer, 2004).

The first general stratigraphic reconstruction of the area of the upper Awash valley was assessed by Taieb (1974); he distinguished, combining stratigraphy with archeological data, 6 units:

1) 'Volcanic unit' ('Miocene- Early Pleistocene'), a succession including lava flows, domes and ignimbrites
2) 'Gomborean unit' ('Early Pleistocene'), a volcanoclastic succession emplaced in a fluvial setting

3) ‘Garbian unit’ (‘Middle Pleistocene’) a volcaniclastic succession emplaced in fluvial and lacustrine settings
4) ‘Tabellen unit’ (‘Late Pleistocene’) a volcaniclastic succession emplaced in fluvial and lacustrine settings, including upper vertisols
5) ‘Recent deposits’ (Holocene), located on the Awash valley, reworking the older sediments

Later, the first geological map was published by Salvini et al. (2012), together with a cartography at 1:10000 scale. They identified 4 units, following the previous work of Raynal and Kieffer (2004) listed in stratigraphic order from oldest to most recent:

1) Basalt’ and ‘Acidic to Intermediate Lava’ (Late Miocene)
2) (old) Ignimbrites (Late Miocene)
3) Melka Formation (Early-Middle Pleistocene)
4) Kella Formation (Middle Pleistocene), an up to 4 m thick, non-welded to incipiently welded, PDC deposit.
5) Tuka Meja Formation (Late Pleistocene- Holocene)

**Archeological significance of the area**

The volcaniclastic and sedimentary fossil trap preserved archaeological sites at remarkable density, even by African standards. Along the Awash River, more than 70 archaeological layers are so far recorded in the gullies of the tributaries on right side, and in the Atebella and Kella valleys on the left side (Chavaillon and Piperno 2004; Mussi et al., 2021 and 2022). Many have been archaeologically tested over up to $20m^2$, and six extensively excavated over up to $250m^2$. The record begins at 2 million years with the Oldowan at Garba IV, Karre I, Gombore I (Gallotti and Mussi, 2015; Perini et al., 2021). Before elsewhere in Africa or Eurasia, the emergence of the Acheulean is documented at c. 1.9 My at Garba IV, lev. D, and then at Gombore I, level B. The Acheulean is then extensively found before 1 My at Garba XII, Simbiro III, Atebella II, continuing at 1 My at Gombore II and Garba XIII, then at 0.75 My at Gombore II-2, and at 0.6 My at Garba I (Sánchez-Dehesa Galán et al., 2022) and Garba III. Fossil hominin remains were also discovered in sealed deposits and in direct association with lithic technocomplexes, which is far from the rule in the Early Pleistocene (the hemimandible of a *H*. cf. *erectus* child at Garba IV; a humerus fragment of *H*. cf. *erectus* at Gombore I; two *H*. cf. *heidelbergensis* skull fragments at Gombore II). Recently, animal and hominin footprints, including young children, were documented at Gombore II and at Gombore II-2. They date back between 1.2 and 0.7 Ma (Altamura et al, 2018; 2019; 2020).

After 0.5 My the record is much affected by erosion and quite patchy. At c. 0.2 Ma, Garba III is an early Middle Stone Age site, where fragmented remains of an archaic *Homo sapiens* were also found (Mussi et al. 2014). In many places the Late Stone Age outcrops at the surface in a disturbed position. The uppermost LSA level are dated to the Holocene. At Balchit, 7 km north of the modern Awash River course (fig., 2), obsidian exploitation is impressively documented until historic times by accumulations of hundreds of thousands of flakes, blades, cores, and débris, which litter the landscape.

**METHODS**

The stratigraphy of the Melka Kunture area was assessed during several fieldtrips conducted annually from 2011 up to 2019 within the framework of the Italian archeological Mission at Melka (since 2019 Italo-Spanish Archaeological Mission at Melka Kunture and Balchit). In parallel, sampling and grainsize studies were performed to characterize and correlate sedimentary and volcanic facies. Detailed stratigraphic reconstructions were also made in archeological areas with the aid of total GPS stations.
Correlation of volcaniclastic beds was attempted only at very short /outcrop scale. Stratigraphic correlations across the entire area were made based on the identification of the main unconformities and major volcanic layers. Facies variability across volcaniclastic layers was described and used to define basin evolution and spatial heterogeneity.
Stratigraphic correlation implied several steps (implemented in a recursive sequence):

- Identification of the main unconformities in the succession
- Identification of the main volcanic events /marker layers)
- Reconstruction of the tectonic evolution of the area
- Reconstruction of the sedimentary basin in time and space

Finally, bulk rock geochemistry of the main volcanic units cropping out in the area was assessed by XRF for major elements and ICP-MS for trace elements by Actlabs. Rock specimens (tab. 1 of supplementary material) were cleaned and prepared in the volcanology laboratory of the department of Chemical and Geological Sciences of the University of Cagliari. Prior to fusion, the loss on ignition (LOI), which includes $H_2O^+$, $CO_2$, S and other volatiles, were determined from the weight loss after heating the sample at 1000°C for 2 hours. The fusion disk is made by mixing the roasted sample with of a lithium metaborate and lithium tetraborate with lithium bromide as a releasing agent. Samples are fused in platinum crucibles using an automated crucible fluxer and poured into platinum molds for casting. Samples are finally analyzed on a wavelength dispersive XRF.

## RESULTS

### Stratigraphy

*Basal succession*

The oldest rocks of the area are of late Miocene to early Pliocene age, and correspond to lava flows and domes, erupted from local volcanic centers dispersed all around the area, and could be correlated with the Nazareth Series which constitute the floor of the MER (Meyer et al., 1975, fig. 2). At MK least 12 vents have been identified and mapped suggesting that this is a monogenetic field (fig. 2). The two closest volcano edifices are located S of the Awash Melka village, and at about 15 km distance, to the NE (fig. 1b; Tinishu Muti and Debel volcanoes) They are small volume cones, reaching a height of a few hundred m above the plain. Among the lava complexes, the most important one is the Balchit obsidian lava flow, whose material has been used to make obsidian artifacts since Oldowan (fig. 4a Gallotti e Mussi 2015). This lava flow is dated at 4.37 ±0.07 My (Chernet et al., 1998). The sequence is well visible along the Awash gorge (fig. 4b) Moreover, at least two large ignimbrite sheets are visible, separated by a paleosol. The topmost one is a crystal-rich, welded ignimbrite with regional distribution

and little variability across the entire area. It has a high phenocryst content (sanidine and quartz, and subordinate orthopyroxene and biotite) and consists of at least two flow/cooling units and present an up to 60 cm thick, laminated basal vitrophyre (fig. 4c). The units show reomorphic features (embricated fiamme and vesicles) typical of a high-grade ignimbrite; the top of the upper unit, also characteristically shows decimetric degassing pipes. The ignimbrite covers all lava flows excepting the thickest coulees (fig. 2). Its total visible thickness ranges from 2 to 6 m and is always eroded on top. Attempted correlation by Raynal and Kieffer (2004) associates the deposit either to the 4.5 Ma old Balchit rhyolite tuff of Wachacha volcano or to a 5.2 Ma old tuff erupted from the same volcano. However, the stratigraphic position relative to the Balchit obsidian flow does not support this hypothesis. We correlate it with the Munesa tuff, erupted about 3.5 my ago as also suggested by Woldegabriel et al., (1992, 2000). This ignimbrite reaches a maximum thickness of 300 m in the Munesa area, and it was found in drillings across the rift floor at a depth ranging from 1.5 to 2.5 km (Woldegabriel et al., 2000). Composition of the lavas is bimodal, ranging from basalt to rhyolite (table 1, fig. 1 of supplementary material), similarly to contemporaneous volcanism in other sectors of the MER (Trua et al., 1999). Data from drillings made for geothermal explorations in 1964 in the area suggest that volcanic units from the basal sequence lie from 30 to 80 m below the current topography (fig. 82 of Taieb, 1974) in the upper Awash river valley. The depth of the contact increases from NW to SE.
A large depositional gap and widespread erosion of the top of all units mark the limit of this succession with the ash-dominated volcaniclastic deposits which make up the main Plio-Pleistocene sequences (fig. 4d).

*Lower Succession*
The Lower Succession consists in an alluvial/volcaniclastic sequence of flood plain, river channel, bar, and overbank sediments interlayered with debris flows, hyperconcentrated flows, ash fallout layers (also including coPDCs) and PDC deposits. The sequence shows very variable thickness and stratigraphy across the area suggesting a complex paleotopography within a flood plain associated with active faulting. The thickness ranges from 10 m to about 30 m and is maximum in the Gombore area and in the SW portion of the MK basin; thickness variability is coupled with significant variability of facies association of both reworked and primary deposits, making detailed stratigraphic correlations very difficult. The basal layers of the sequence always lie in unconformity with both lava flows and ignimbrite sheets, either separated by an erosional surface or and/or a paleosol from the basal succession. The basal beds consist of coarse conglomerate layers with silt matrix. Pebbles consists of fragments of the Munesa tuff, obsidian and crystalline lavas of variable compositions (Basal Succession). A similar componentry marks both debris flows and conglomerate lenses intercalated in the entire succession, and is a diagnostic feature of this succession. Primary volcanic deposits are usually fine grained, with none or very little lapilli component, and often contain diffuse accretionary lapilli (vesiculated tuffs sensu Rosi, 1992). Along the Kella river (fig. 2) the succession is exposed along a paleo-high; it is reduced to three PDC deposit separated by paleosols; they have thicknesses ranging from 1 to 2.5 m and are separated by paleosols or erosional surfaces. The Lower PDC deposit contains accretionary lapilli and lies above a conglomerate layer in contact with the top of the Balchit lava flows. When thickest (Garba area) the succession

comprises tens of discontinuous, massive ash layers with thickness ranging from a few up to 20 cm (fig. 5a, b) intercalated to riverbed sediments and hyperconcentrated flow deposits (i.e. lahars). We interpreted them as both distal plume ash fallout and coPDCs fall deposits. Dating of tuff layers and sediments intercalated in the sequence range from 2.0 to 1.2 Ma (Morgan et al., 2012; Perini et al., 2021); however, no analyses were done on the very basal clay layers cropping out in the Gombore area (i.e. the Gomborean unit of Taieb et al., 1974) which mark the first sediments above the Basal Succession.

The most detailed dating of the Lower succession beds was based on magnetochronology methods in the Gombore area and suggest that the oldest exposed sediments have an age of about 2.1 my (Perini et al., 2021). Geochronology on glass and sanidine crystal identified, in the same area, and in the Awash village area, identified eruptions at 1.87, 1.67, 1.71 1.39, 1.28 Ma.

The top of the Lower Succession is marked by the largest single eruption deposit of the Pleistocene sequence, also visible along the Kella river ('Kella Unit' of Raynal et al., 2004, fig. 2, 4a). At the base, a discontinuous pumice lapilli fallout layer up to 3 cm thick is only locally preserved. The Kella unit consists of three flow units. The lowermost one is a cross stratified, a few cm thick, coarse ash, lithic poor deposit; above, separated by an erosional surface, lie an up to 60 cm thick, massive deposit consisting of pumice lapilli and rare lithic fragments (obsidian, lava, tuffs) dispersed in a coarse ash matrix, overlain by a cm-thick coarse ash bed. In erosional contact lies the topmost bed, which is also the thickest unit reaching up to 6 m in the Kella butte area (fig. 5a). This layer is incipiently welded and presents a characteristic but poorly developed, columnar jointing. It carries tubular pumice lapilli of up to 2 cm diameter. The base of this unit is enriched in lithic fragments with diameters up to 13 cm (obsidian, lava and tuffs). It is best exposed N of the MK village, where it reaches its maximum thickness of 7 m; the top portion, rarely exposed, is non welded. It was dated at 1.25 ma (Morgan et al, 2012) and has a dacite composition (Taieb, 1974; Reynal et al., 2004, Table 1 of supplementary material). This is the most significant primary volcanic deposit of the sequence and a stratigraphic marker in the MK area. Bulk rock compositions of the tuffs range from andesite to dacite (fig. 1. supplementary material), with relatively limited variability.

*Upper Succession*

The Upper Succession is a volcaniclastic sequence of sediments deposited in a flood plain, river channel, bar, and overbank settings; it also comprises hyperconcentrated flows, and at least 3 large PDCs deposits, a lapilli fallout layer and several minor ash layers (fig. 5d). At many locations (fig. 4) the contact with the Lower Succession is marked by a major erosional surface which cuts the sequence below the Kella unit (fig 5c). In the Melka area, the erosional surface was dated at about 1 Ma (Perini et al. 2021; Morgan et al. 2012). When the erosional surface is not present, the basal layers lie on a paleosol up to 30 cm thick on the top of the Kella unit and consists of reddish fine sand with plane parallel stratification also including rare large lava pebbles; otherwise, the same beds are directly above the erosional surface. Above this characteristic marker layer, the succession consists of an alternance of PDC deposits intercalated with paleosols and fluvial/lacustrine sequences, and a dm thick, stratified fallout deposit consisting of up to 5 cm long tubular pumice lapilli, which is a significant stratigraphic marker in the area and is dispersed across the entire area (fig. 5d). Three massive, fine grained

PDC deposits were recognized along the Kella valley (fig 2) below the lapilli fallout layer they have thickness ranging from 20 to 120 cm. A fourth PDC deposit above the lapilli fallout is visible in the Kella butte outcrops (log 5 of fig. 5). The volcaniclastic sequences intercalated to the PDCs change significantly across the area and comprise numerous cm-thick ash beds which could correspond to coPDC or distal plume fallout deposits from large magnitude eruptions from the rift floor (Mussi et al., 2021; Altamura et al., 2019; Raynal et al., 2004). This units thickens from N to S exposures. Tuff compositions are very variable ranging from andesite to rhyolite (fig. 1. supplementary material)

Dating was made on material from various ash layers in the sequence; they revealed ages ranging from 1.04 to 0.70 Ma (the age of the topmost PDC deposit and the tubular lapilli fallout bed) (fig. 5d, Morgan et al., 2012; Perini et al 2021). Dates cluster in between 0.89 and 0.70 Ma (Morgan et al., 2012). Diagnostic feature of this succession are small tubular pumice lapilli dispersed in most of the volcaniclastic layers and some ignimbrites. Layers are generally lithic poor with rare obsidian fragments. The thickness of this succession ranges from 5 to 15 m. This is the most widespread unit and is exposed also in the Tinishu Muti area (fig. 1b, 2, 5d).

## Geomorphological and tectonic setting

The Pleistocene stratigraphy is exposed along the Awash valley and minor tributaries. Active escarpments are visible in the southern area along main faults parallel to the main rift direction (fig. 2). Escarpments on the western side of the basin are instead stable (fig. 3d)

High areas consist of dome/lava coulees and volcanic edifices (fig. 1b). The present morphology is mainly characterized by wide glacis affected by sheet, gullies, and fluvial erosion, responsible for vigorous incisions and for the fast destruction of soil cover (Bardin et al., 2004). The landscape is dominated by the Washasha volcano located just south of Addis Ababa, active from Miocene to Early Pleistocene, at about 30 km north of the valley (fig. 1b). The Awash river, characterized by a low gradient meandering river morphology, reflects the main direction of the rift fault systems (fig. 2). Sheet and gully erosion processes contribute to the landscape evolution and are mainly triggered by anthropogenic activities (farming and pastoralism). Rockfalls occurs in the lithological discontinuities undercutting of the middle Pleistocene ignimbrites and tuffs.

Tectonic structures, in turn, determine lithological contacts between large ingimbrites and lavas as well as the contacts to the volcano sedimentary deposits (Märker et al., 2019). The major escarpments are formed on welded ignimbrite sheets.

Three major high angle faults have been recognized in the area; they are parallel either to the main rift axis or the Chilalo-Gurage lineament (fig. 2). The oldest one, transversal to the rift axis, cuts only lava flows and large Pliocene ignimbrites of the Basal Succession and controls the Awash river path in the MK area. This fault is cut by two high angle normal faults parallel to the rift axis; they are isolating a smaller graben structure where the thickness of the Pleistocene volcaniclastic succession reaches its maximum values. These faults are cutting all deposits of the Lower Succession. The Upper Succession shows more homogeneous thickness in the MK area and complex relationships with the same faults. It covers the western faults but is cut by the eastern one (fig. 2). This evidence suggests a Late Pliocene age for the transversal fault which controlled the path of the paleo-Awash river, and Pleistocene age for the parallel faults, resulting in subsidence (and enhanced sedimentation) of the graben in between them, likely associated with temporary deviation of the river path to a SW-NE direction. Stratigraphic relationships with the Upper Succession layers also suggest that movement along the western fault ceased at about 1.2-1 Ma while the eastern fault remained active until end of the volcaniclastic cycle. In Upper Pleistocene/Holocene times the Awash river resumed its original NW-SE path resulting in the opening of the river gorge.

**DISCUSSION**

The geomorphologic evolution of the MK landscape has been strongly affected by Plio-Pleistocene volcanism and tectonic factors, as well as fluvial processes and the climate change (Chavaillon and Taieb, 1968; Taieb, 1974; Bonnefille, 1976, 2018; Raynal and Kieffer, 2004; Märker et al., 2019). After the end of Late Miocene-Early Pliocene graben stage the volcanic activity moved towards the central rift and assumed the characteristic bimodality we see now. After having being site of volcanic activity in pre-rift stages, at the beginning stages of MER formation (Pliocene), the area of MK became a distal deposition site for the very large ignimbrites associated with a magmatic flareup from the rift floor (Woldegabriel, 2000) which, with progression of subsidence and activity in the rift floor, are now exposed only at its margins. Further tectonic activity isolated MK from the rift floor isolating the upper Awash valley. In parallel, volcanic activity from the closest magmatic segment of the rift (i.e the Gedemsa one) shifted to very large explosive fissural eruptions emitting trachyte to rhyolite magmas and associated with domes and flows (Abebe et al, 2010; Corti, 2009) to formation of central edifices built by both effusive and large explosive activity (Le Turdu et al., 1999). Several authors suggest that the Pleistocene activity in the different sectors of the MER was episodic rather than continuous (Siegburg et al., 2016; Hutchinson et al., 2016; Abebe et al., 2007). This was reflected clearly in the MK volcaniclastic successions, which points to clusters of distal strongly explosive eruptions from the MER in between 1.9 to 1.2 Ma and at 0.8 to 0.7 Ma. We notice that a very similar sequence to the one observed at MK is also preserved on the Melka Wakena basin, located on the eastern MER margin, at about 150 k south of Addis Ababa (Hovers et al., 2021), suggesting that these two periods could be associated to very significant flare up of volcanic activity. As for MK, we can tentatively correlate volcanics of the Lower Succession with a phase of major volcanic activity occurred between 2 and 1 Ma ago, with major eruptions at 2- 1.9 Ma (ignimbrites of the Asela escarpment) and around 1.3 Ma ago (ignimbrites of the Asela escarpment and caldera eruptions of Gademota and Tulu respectively; Abebe et al., 2007). As for the volcanism associated with the Upper Succession, published data suggest association with the late silicic activity of the Wonji group, possibly in the Aluto, Nazret areas (Kazmin et al., 1981; Boccaletti et al., 1999).
Sedimentation processes and the stratigraphic records of the Pleistocene basin of MK were controlled by the interplay between several processes such as frequency, intensity, style and source localization of volcanic activity, associated with the tectonic evolution of the area. Sediment accumulation was primarily controlled by eruption parameters (fallout tephra) combined with paleotopography (PDC), and by surface processes (mainly fluvial erosion, transport, and sedimentation). The fluvial dynamics was strongly affected by influx of volcanic

material which considerably augmented the river load. After each volcanic episode, the paleo-Awash regularly re-established its course with a new basal level of erosion, but faulting and subsidence further controlled the distribution of river tributaries (fig 6).

In the MK area the paleo-Awash developed along transverse faults opening at the end of Pliocene magmatic flareup. Channel and overbank sedimentary sequences formed by dismantling of the exposed rocks of the Basal Succession deposited before the onset of a renewed volcanic phase in the MER, starting at about 2 Ma. From this time onwards the river dynamics coexisted with ash sedimentation and was also affected by formation of faults parallel to the rift axis. The river channeled along primary tephra deposits and migrated laterally. Further subsidence occurred contemporaneously with volcanic activity enhancing local sedimentation. All these processes resulted in sedimentation rates variable in time and space which affected the burial and preservation of artifacts and fossil remains. Almost all layers of both Pleistocene successions are laterally discontinuous and marked by lateral facies variability, making detailed stratigraphic correlation quite challenging. Correlations are possible only based on major volcanic events/deposits, which present much smaller lateral facies variability with respect to volcaniclastic layers. Volcaniclastic sedimentation could occur at both syneruptive times (i.e. lahar formation during short eruptive paused) and in between eruptions. Because of their fine grainsize (Raynal et al., 2004) even thin tephra layers at MK had very poor permeability and enhanced superficial runoff and erosion of the preexisting stratigraphy. Rain-triggered lahars typically remobilize huge quantities of sediments up to several decades after explosive eruptions, eroding not only fresh tephra but also older beds (Bauman et al., 2019; Perrotta et al., 2006; Newhall and Punongbayan, 1996). Such phenomena correspond to hyperconcentrated flow deposits which are ubiquitous in the successions. On the other hand, conglomerate and coarse layers interbedded throughout both successions suggest active channel dynamics possibly associated with overbank sedimentation of a meandering (i.e. low energy) river within a closed basin, The fauna was diverse and abundant (Geraads et al., 2004), and hominin groups also settled there. The interplay of volcanism, deposition, tectonism and limited erosion allowed a substantial preservation of deposits recording hominin life and Pleistocene environments.

## CONCLUSIONS

Large volumes of fine tephra were supplied in the Awash Melka basin during Pleistocene times from the MER floor activity. In parallel, tectonic dynamics of the rift margin formed a closed basin and a floodplain environment. Fluvial sedimentation was affected by rate and intensity of volcanic activity and reworking of tephra; tectonic structures controlled erosion and distribution of epiclastic sedimentation. MER volcanic activity was discontinuous, with major pulses in between 2 and 1.2. Ma and 0.9-0.7 Ma. The interplay between fluvial activity and variable volcanic sediment input (distal plume and co-PDC fallout, and about 6 major PDC events) created an exceptional, but discontinuous fossil/archeological record which is now retrieved in the area. Further faulting after about 0.7 Ma determined the opening the basin, formation of the Awash gorge and consequent erosion of the Pleistocene fluvial volcanic sequence. Depocenters shifted with time because of new faulting and subsidence in the Melka area.

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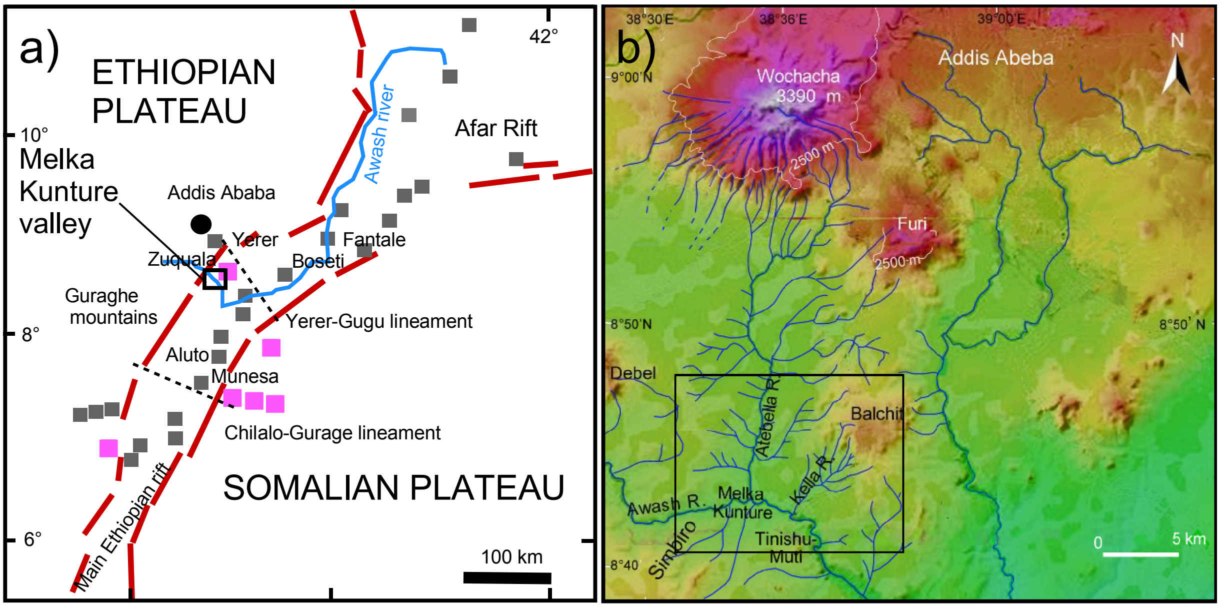


Fig. 1. a) Main structure and volcanic centers of the Main Ethiopian Rift. Grey squares: rhyolite centers; pink squares: trachytic centers. Location of the Melka Kunture basin shown by the open square. Red lines: main escarpments (rift margins); b) Relief map of the Melka Kunture basin, red lines are faults

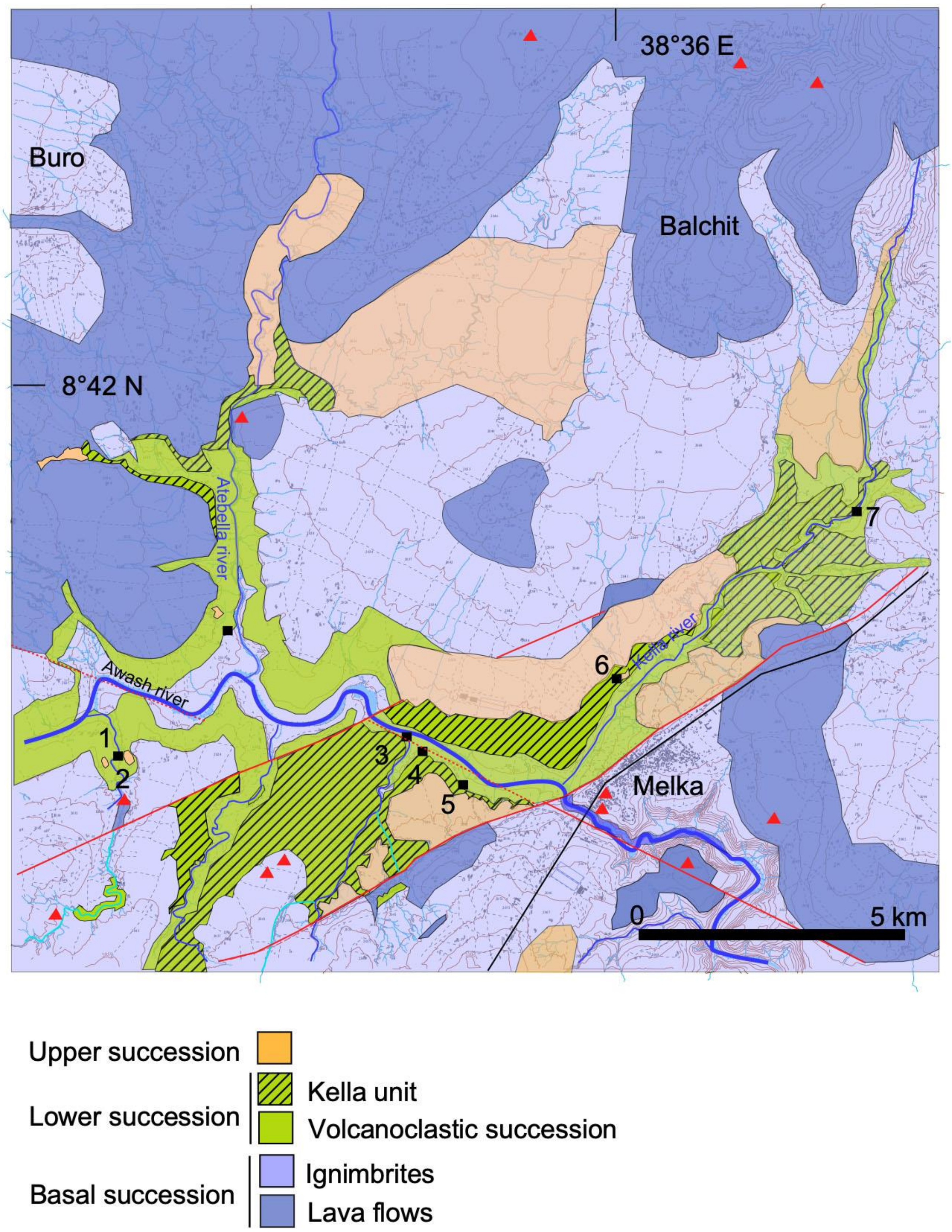


Fig. 2. Geological map of the Melka Kunture area with schematic profile. Red lines: faults dottered line: buried faults. Black line: national road. Holocene deposits/soils are not represented. Numbers refer to sites of fig. 4. Triangles: volcanic vents


Fig. 3. a) Ramp structure in Balchit obsidian lava flow b) Awash gorge at Melka Kunture village area, exposing the fault escarpment and lava flows and coulees of the Basal succession c) Welded crystal rich ignimbrite, d) Landscape over the basin: on the top, deposit of the Upper Succession below, Kella unit and volcanoclastic beds of the Lower Succession

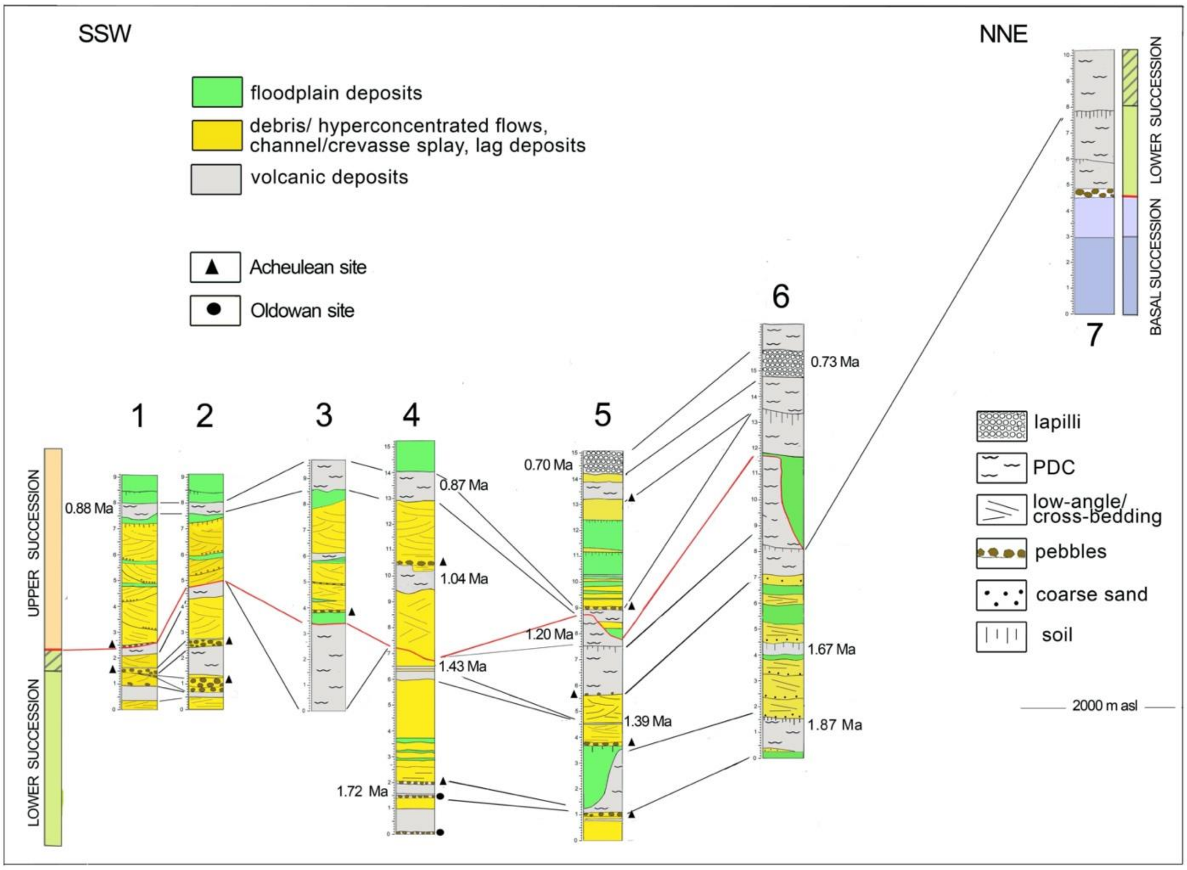


Fig. 4. Schematic stratigraphic logs of exposed and excavated succession in the MK basin. Ages are from Morgan et al. (2012).

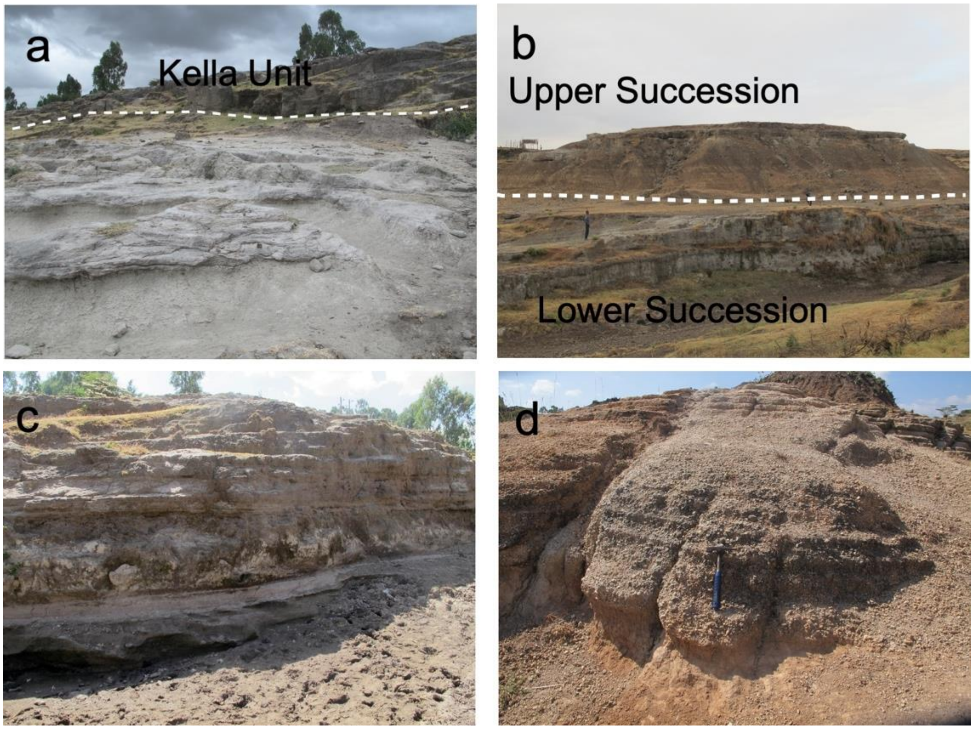


Fig. 5. a) Close up of topmost part of the Lower Succession at Kella butte b) Unconformable contact between Lower and Upper Succession, Kella butte c) Close up of basal beds of the Lower Succession, Kella river d) Lapilli Fallout bed at its thickest exposure, Upper Succession, Tinishu Muti area

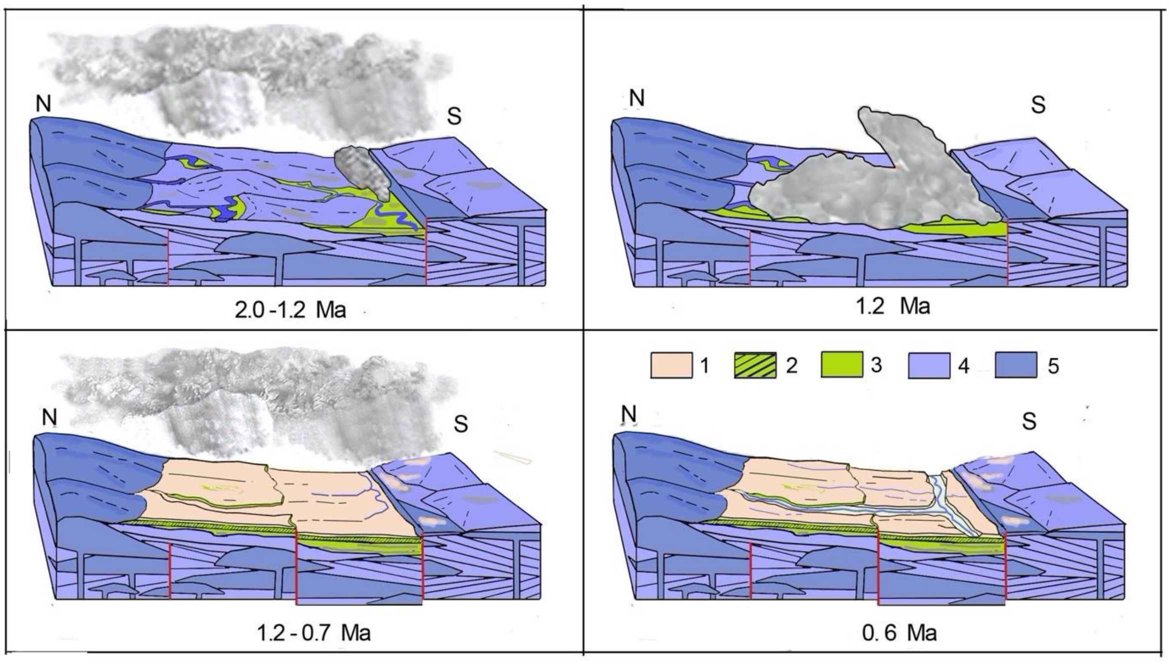


Fig. 6. Reconstructed morphological evolution of the MK area. 1= Upper Succession, Lower succession: 2= Kella unit, 3= bottom layers. Basal Succession: 4: ignimbrites and 5: lava flows and domes