



Afromontane forests and human impact after the African Humid Period: wood charcoal from the Sodicho rock shelter, SW Ethiopian highlands

Stéphanie C. Bodin¹ · Katharina Neumann¹ · Elena A. Hensel² · Ralf Vogelsang³ · Sebsebe Demissew⁴ · Manuel Casas-Gallego^{1,5} · Karen Hahn⁶

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Abstract

The SW highlands of Ethiopia are a key component in the evolution of modern humans. Yet, palaeoecological studies, essential to understand past human-vegetation relationships, are almost inexistent in this region. In this paper, we present an anthracological study of the Sodicho rock shelter, located at 1,930 m a.s.l. in the SW Ethiopian Afromontane forest zone, reconstructing the past woody vegetation since the end of the African Humid Period (ca. 5,000 cal BP). Our results show that the vegetation around the rock shelter from ca. 4,750 to 1,750 cal BP was an ecotone between Afromontane forest and wooded grasslands of the lowlands, maintained open by the use of fire, although the climatic conditions were favourable for closed forest. The charcoal assemblage also demonstrates strong wood selection, with *Syzygium guineense*, *Acacia* and Proteaceae as the preferred taxa, even during a volcanic event when human occupation had been assumed to be absent. We therefore suggest that the rock shelter might have been visited more continuously than previously thought. Finally, under less intense occupation activities from ca. 1,700 to 300 cal BP, forest taxa became comparatively more dominant than before, as documented in the charcoal record. This demonstrates that the forest can recover under reduced human impact. The fact that the Afromontane forest is resilient is of utmost importance, indicating that reforestation is still possible despite the strong agricultural and demographic pressures the Ethiopian highlands are currently facing.

Keywords Anthracology · Palaeovegetation · Hunter-gatherer · Fire · Late Holocene

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✉ Stéphanie C. Bodin
stephanie.bodin@senckenberg.de

- ¹ Department of Paleoanthropology, Senckenberg Research Institute, Senckenberganlage 25, 60325 Frankfurt am Main, Germany
- ² Institute for Ecosystem Research, Geoarchaeology and Environmental Hazards, Kiel University, Olshausenstraße 75, 24118 Kiel, Germany
- ³ Department of Prehistoric Archaeology, University of Cologne, Weyertal 125, 50931 Cologne, Germany
- ⁴ Department of Plant Biology and Biodiversity Management, College of Natural and Computational Sciences, National Herbarium, Addis Ababa University, Addis Ababa, Ethiopia
- ⁵ Department of Geodynamics, Stratigraphy and Palaeontology, Complutense University of Madrid, Madrid, Spain
- ⁶ Institute of Ecology, Evolution and Diversity, Goethe University Frankfurt, Max-Von-Laue-Straße 13, 60438 Frankfurt am Main, Germany

Introduction

SW Ethiopia is one of the most ecologically and culturally diverse regions of Africa and therefore of special historical and prehistorical interest. A large part of the area consists of highlands, with Afromontane forest as the main potential natural vegetation above altitudes of 1,800 m (Friis et al. 2010). The SW Ethiopian Afromontane forest is discussed as a refugium for prehistoric populations during arid phases of the late Quaternary, especially after the end of the African Humid Period (AHP, 11 to 5 ka; DeMenocal and Tierney 2012; Foerster et al. 2015). However, excavated archaeological sites in the Ethiopian Afromontane forest zone are rare (Gutherz et al. 2002; Lesur et al. 2007; Hildebrand and Brandt 2010; Hildebrand et al. 2010; Brandt et al. 2012, 2017; Arthur et al. 2019; Schepers et al. 2020; Hensel et al. 2021, 2022). Only a few sites with preserved bones of wild animals provide palaeoenvironmental information (Lesur et al. 2007, 2014; Schepers et al. 2020). Pollen profiles that

might shed light on vegetation changes in the past are only available from higher altitudes above 3,000 m or from the lowlands, while non-existent from the Afromontane forest zone (Casas-Gallego et al. 2023). Therefore, data on palaeoenvironment and natural resources are currently insufficient to support any anthropological model of human agency, mobility and landscape utilization in the past (Wright and Forman 2016). More site-specific environmental information from the Afromontane forest zone is necessary to understand vegetation changes and human responses in the late Quaternary, in particular after the end of the AHP.

Evidence for human occupation during the Early Holocene in the Ethiopian Afromontane forest zone is very sparse (Foerster et al. 2015) but becomes more abundant after 5,500 cal BP in the southwestern highlands (Hildebrand et al. 2010) and after 6,000 cal BP in the Gamo highlands (Arthur et al. 2019). This roughly coincides with the end of the AHP and a rapid drop in Rift Valley lake levels at Chew Bahir (Foerster et al. 2015; Trauth et al. 2015, 2018) and Lake Turkana (Garcin et al. 2012). The post-AHP sites in the highlands are rock shelters occupied by hunter-gatherers, whereas lowland sites of the same period are most often associated with pastoral populations (Lesur et al. 2014; Wright et al. 2015; Hildebrand et al. 2022).

The Sodicho rock shelter is exceptional with a stratigraphic sequence from roughly 27,000 BP to subrecent times (Hensel et al. 2021, 2022). The strata younger than 4,800 years, above the archaeologically sterile deposits of the AHP, provided abundant and well-preserved archaeobotanical remains, including phytoliths and macroscopic wood charcoal. Both are local proxies from a restricted depositional area, making them ideal for a reconstruction of the past vegetation around the sites. This is much needed given the complex climate-altitude-vegetation interactions that can lead to a variety of vegetation types in a limited area (Hildebrand et al. 2019). Wood charcoal identification has already shown its reliability to reconstruct past African woody environments, especially in the Sahara, West and South Africa (e.g. Neumann 1989, 1992, 1999; Ballouche and Neumann 1995; Höhn 1999, 2022; Allott 2006; Höhn and Neumann 2012, 2016; Cartwright 2013; Hubau et al. 2013, 2014; Eichhorn and Neumann 2014; Höhn et al. 2021). Anthracological studies are much rarer for Eastern Africa and so far, in Ethiopia, have only been applied in the Tigray region (Gebru et al. 2009; Ruiz-Giralt et al. 2021) and the Bale Mountains (Beldados et al. 2022).

The aim of this paper is to elucidate how the Afromontane forest around Sodicho developed in relation to climate change and human impact during the last 4,800 years. Our research questions are: (1) Did the Afromontane forest persist during human occupation or was there a more open vegetation? (2) If there was an opening of the vegetation, were the main drivers anthropogenic, climatic or both? To

answer these questions, we analysed wood charcoal dated between 4,750 and 300 cal BP. We interpret them in terms of human activities, such as firewood selection or landscape modifications, in the context of increasing aridity after the end of the AHP.

Regional setting and archaeological context

The Sodicho rock shelter (7°15'21"N-37°36'44"E) is located about 40 km NW of Sodo, Wolayta, in the SW Ethiopian highlands, on the southern flanks of Mount Sodicho (max. altitude 2,025 m a.s.l.), a volcano belonging to the major trachytic volcanic complexes formed along the Rift's margins during the Plio-Pleistocene (WoldeGabriel et al. 1992). At an elevation of 1,930 m a.s.l., the shelter is located only a few meters below the edge of the plateau and offers an excellent view over the surrounding landscape (Fig. 1A–B) (Hensel et al. 2021). The mountain is flanked by two streams that drain into the Omo River about 11 km to the Southwest. The highlands are characterised by a complex rainfall regime (Friis et al. 2010; Kassa et al. 2017; Hildebrand et al. 2019) varying according to the regions. The SW highlands are part of the temperate dry summer–warm summer climate after the Köppen-Geiger classification (Csb climate, Peel et al. 2007; Beck et al. 2018). The rainy season occurs between March and November and the dry season between December and February (Kassa et al. 2017). Mean annual rainfall and mean annual temperature recorded in Sodo are 1,125 mm and 14 °C, respectively (World Weather Online 2012).

The rock shelter is located near the lower limit of the Afromontane forest, which is now highly impacted by human pressure throughout Ethiopia. Since the 1970s, the population of Ethiopia has more than tripled (Ringheim et al. 2009; United Nations Population Fund 2022), and agricultural expansion has led to dramatic deforestation (Friis et al. 1982; Woldu 1999; Holden and Shiferaw 2004; Nysen et al. 2004; Kassa et al. 2017; Tolessa et al. 2017). As a result, the Afromontane forest is degraded and has turned into woodlands and wooded grasslands in many areas, forming a mosaic landscape. The different vegetation types that would occur without such human pressure are referred to as the potential natural vegetation of Ethiopia and were mapped by Friis et al. (2010), based on topography, rainfall data and field surveys. The potential vegetation types around Sodicho are the Dry Afromontane Forest (DAF), the *Combretum-Terminalia* woodland and wooded grassland (CTW) and, further down in the lowlands to the East, the *Acacia-Commiphora* woodland and bushland (ACB) (Fig. 1A–B). The DAF is potentially present between 1,800 and 3,000 m a.s.l. and grows under precipitation between 700 and 1,700 mm/year (Friis et al. 2010). But today, the area around Sodicho is heavily impacted by crop cultivation and grazing, and almost no remnants of the natural DAF can be found (Fig. 1C–D).

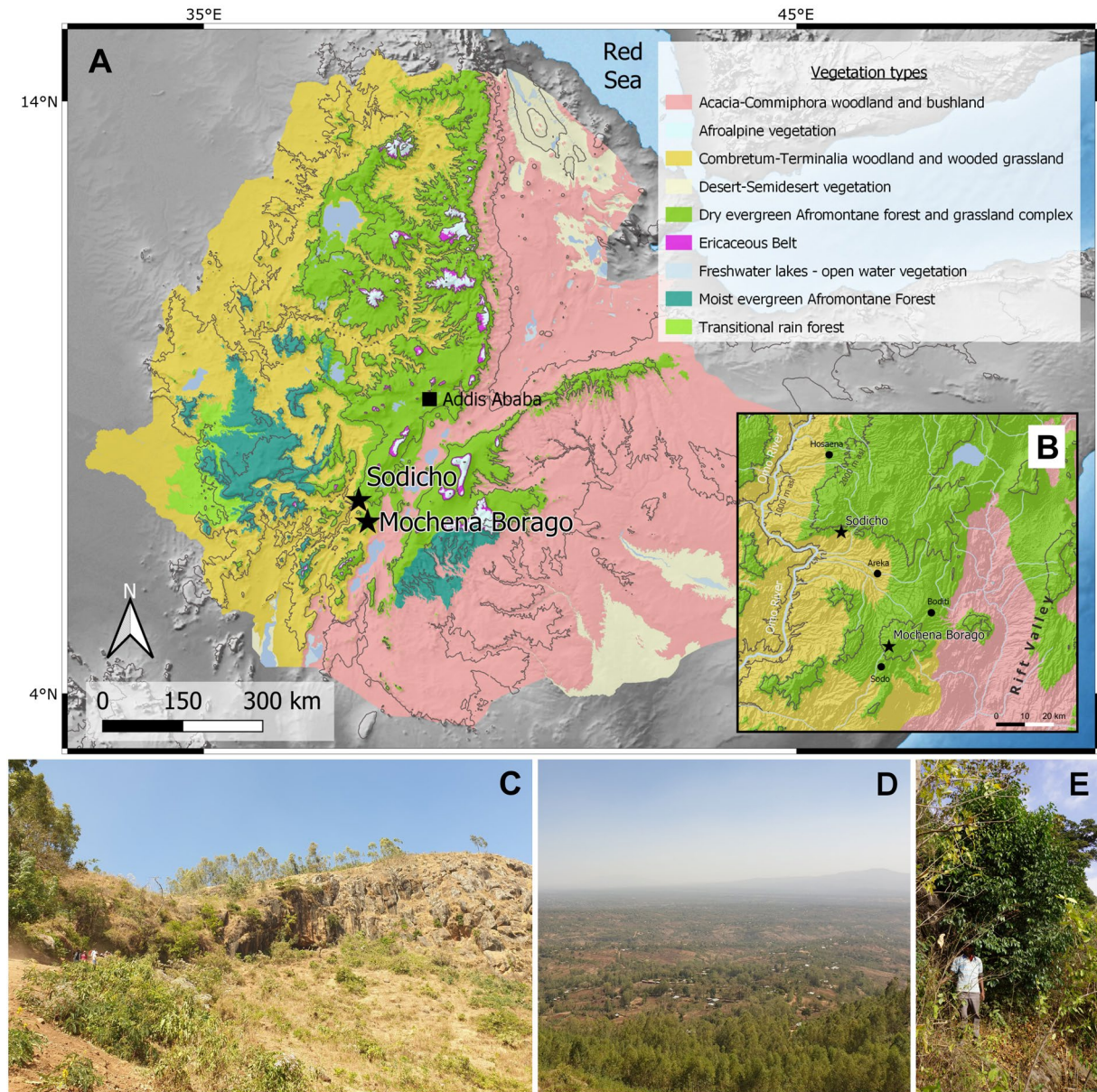


Fig. 1 The Sodicho rock shelter. **A** Map of Ethiopia showing the different vegetation types according to Friis et al. (2010), location of Sodicho and Mochena Borago. **B** Zoom on the vegetation types around the two rock shelters. **C** Sodicho, and the degraded vegetation in the surrounding. **D** Landscape as seen from Sodicho, showing

the cultivated areas downhill. **E** *Syzygium guineense* growing next to the rock shelter, behind a local resident. Maps by M. Casas-Gallego, modified from Friis et al. (2010); photos by S. Bodin and R. Vogel-sang

Instead, the current vegetation is a mosaic of agricultural plots, grazing areas, barren land and plantations of introduced tree species, mainly *Eucalyptus camaldulensis*.

The DAF comprises two subtypes: the undifferentiated Afromontane Forest (DAF/U) and the Afromontane woodland, wooded grassland and grassland (DAF/WG), which is (partly) a degraded state of the DAF/U (Friis et al. 2010). A floristic survey in the surrounding of Sodicho comprised some single specimens of DAF/U and/or DAF/WG species,

such as *Syzygium guineense* (Fig. 1E), *Croton macrostachyus*, *Teclea nobilis*, *Ritchiea albersii*, *Maesa lanceolata*, *Ekebergia capensis*, and *Maytenus arbutifolia* (Wondafrash pers. comm. 2023), indicating that the DAF could grow there. The CTW potentially grows on the western escarpment of the highlands; while the ACB potentially occurs on the eastern escarpment and down to the Rift Valley, both vegetation types with an altitudinal range between 400 and 1,800 m a.s.l. (Friis et al. 2010).

Past human occupation in Sodicho is evidenced by potsherds and tool assemblages from the Later Stone Age. These are dominated by segments (curved backed forms), representative of typical hunting equipment (Lombard 2008; Lombard and Pargeter 2008; Mazzucco et al. 2012). The stratigraphy of Sodicho is divided into natural sedimentary units (SUs). SUs I (450–300 cal BP), III (2,090–1,750 cal BP), V (4,750–4,360 cal BP), VII (17,000–4,960 cal BP) and IX (27,000–21,000 cal BP) are considered anthropogenic according to their content in lithics and features such as hearths and pits. The scarcity of cultural remains in SU I, consisting mainly of potsherds and few obsidian stone artefacts, indicates only sporadic use of the shelter by small groups, such as hunting expeditions of farming and/or herding people, settling in the lowlands. Evidence of human occupation is much stronger in SU III and especially in SU V, which are both characterised by microlithic stone tools, mainly segments. SU VI, which had been formed during the AHP, is archaeologically sterile (Fig. 2; Hensel et al. 2021). SUs II, IV and VIII correspond to allogenic tephra deposits (Hensel et al. 2021). We presume that during the Holocene, Sodicho was never a long-term settlement site, but rather a hunting camp used by small groups of hunters for repeated short-term stays. Indeed, while food-producing societies settled in large parts of the Horn of Africa during the late Holocene, the highlands of Ethiopia seem to have offered a retreat for hunter-gatherers.

Material and methods

Charcoal sampling

Charcoal was sampled during excavations in 2015, 2016 and 2017 in the framework of the CRC 806 “Our Way to Europe” (Hensel et al. 2021). Four 50 × 50 cm quadrants were investigated for charcoal: F34, F35, G34 and G35. Sampling was done according to the SUs which were subdivided into arbitrarily defined 5 cm thick layers (see detailed protocol in Hensel et al. 2021). No identifiable charcoal was recovered from the tephra unit VIII and the anthropogenic unit IX. The sediment was dry-sieved in the field with 10, 5 and 2.5 mm meshes to recover archaeological remains including charcoal (Hensel et al. 2021). In the laboratory, we sorted charcoal pieces suitable for anatomical identification, i.e. big enough, using a 4 mm mesh (Chabal et al. 1999; Scheel-Ybert 2001; Kabukcu and Chabal 2021). The majority of pieces are dispersed charcoal fragments and only a few come from identifiable archaeological features (several pits and one hearth). Dispersed charcoal is the best indicator of the palaeovegetation as these fragments are the residuals of different types of burning activities over time; while charcoal from features like hearths is more likely to give only a picture of a specific use or a short-term activity and, therefore, often leads to a poor representativeness (Chabal 1992; Kabukcu and Chabal 2021). Nevertheless, we can reasonably assume that all of the dispersed charcoal comes from fireplaces. Big charcoal fragments (from ca. 1.5 to more than 2 cm) were also recovered among the dispersed charcoal from units III and V. These large fragments most

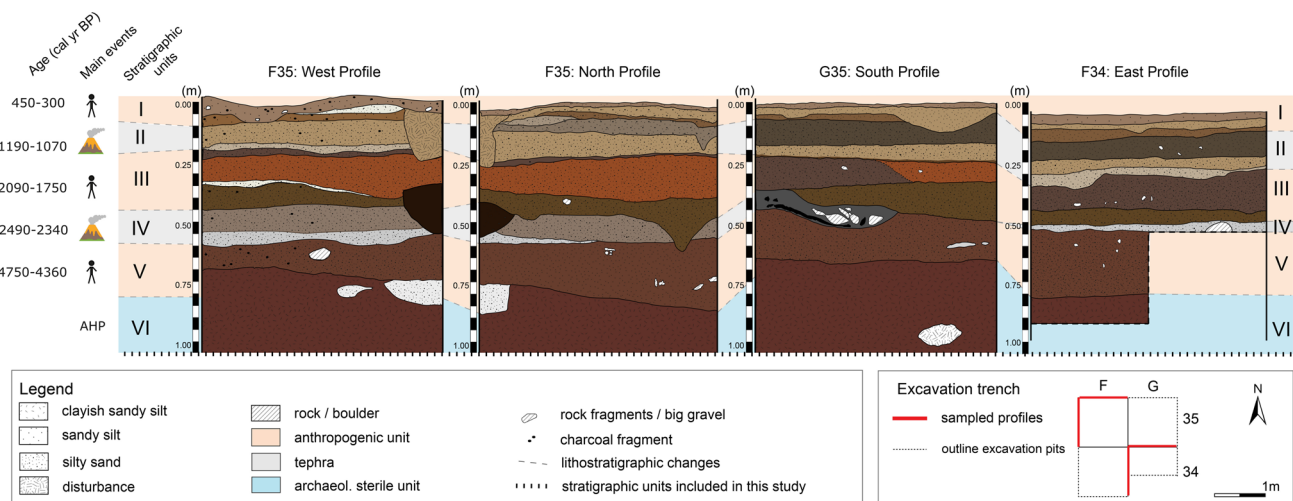


Fig. 2 Illustration of sampled excavation profiles F35 West and North, G35 South, and F34 East from Sodicho. Profiles are displayed to a depth of 1 m to indicate which sediment units are in the focus of this study. Locations of the illustrated profiles are marked in red

within the excavation trench (box bottom right). Major stratigraphic units are highlighted in the background by different colours (mod. after Hensel et al. 2022)

probably indicate fireplaces as suggested by Hensel et al. (2021), and were scattered after trampling and sweeping processes (Hensel et al. 2022). Therefore, the charcoal from archaeological features assigned to specific units are thereafter interpreted together with the dispersed charcoal from the same sedimentary units.

Charcoal identification

Charcoal anatomical features were observed with a ZEISS Axio Imager A2.m reflected light microscope equipped with dark and bright field devices at $\times 100$, $\times 200$ and $\times 500$ magnifications. The anatomy of each charcoal taxon was described and images were taken with a JEOL JSM-6490LV Scanning Electron Microscope in the SGN-SF-Hi-res-SEM laboratory. Taxonomic identifications were done by comparing archaeological charcoal to the wood slides of the African reference collection from the Institute of Archaeological Sciences of Goethe University (JWG) Frankfurt am Main (Germany), mainly on duplicates of the Ethiopian wood collection of Addis Ababa University. The online database InsideWood (Wheeler et al. 1989; Wheeler 2011) and specific literature (Metcalf and Chalk 1950; Neumann et al. 2001 and see references for specific taxa in the SI 1) were also used to help the identification process. The taxonomic nomenclature used in this paper follows that of Friis et al. (2010) to allow easy comparison. Naming of charcoal taxa was done in small capitals according to Höhn and Neumann (2018). We used the prefix “cf.” when the specimen was very similar to the assigned taxon but badly preserved and/or when one of the diagnostic features was not clearly visible. The unidentifiable pieces were those too badly preserved (e.g. vitrified, presenting many cracks, twisted) to provide any good anatomical description. Finally, we evaluated the number of knots and twigs present in the charcoal assemblage; the former being characterised by a distortion of the anatomical planes of wood and the latter recognizable by the growth-ring curvature and/or the non-parallelism of the rays in cross section. We did not undertake any qualitative measurements but simply counted the number of charcoal fragments presenting such features. The list of the charcoal taxa and their anatomical description, as well as the raw data containing the charcoal counts and information on the stratigraphy are available in the online resources (SI 1 and SI 2).

The basis of the anthracological diagram was made on RStudio v. 2022.7.2.576 (RStudio Team 2022) with the *strat.plot()* function from the package Rioja (Juggins 2022). Additional information (e.g. counts, dates and pie charts) was then added using Inkscape v. 1.2.1 (Inkscape’s Contributors 2022).

Radiocarbon dating

A total of 31 radiocarbon dates made on charcoal, seeds, soot and organic material was already available for Sodicho (Hensel et al. 2021). Four additional radiocarbon dates were obtained from charcoal for this study (Beta Analytic). Calibration was done using the IntCal20 calibration curve (Bronk Ramsey 2009; Reimer et al. 2020). We chose twigs from different taxa to ensure that we do not date charcoal pieces from the same specimen and that there is no ‘old wood effect’ (Schiffer 1986; Carcaillet and Talon 1996). Dated specimens are from SU II where no date had been available before, SUs III and IV where the dating was unclear and SU VI, the archaeologically sterile unit deposited during the AHP (Hensel et al. 2021), where a few charcoal pieces had also been recovered.

Results

Additional ^{14}C dates to Hensel et al. 2021 for four stratigraphic units

The four dates obtained are consistent with the stratigraphy and with the dates previously obtained by Hensel et al. (2021). Charcoal from SU II (tephra deposit) delivered a date of 1,192–1,070 cal BP, SU III (anthropogenic) of 2,007–1,872 cal BP, SU IV (tephra deposit) of 2,490–2,338 cal BP, and SU VI (archaeologically sterile) of 4,772–4,612 cal BP (Table 1).

Given the date obtained for SU VI, the charcoal found in this sterile unit probably originates from the unit above. Indeed, SU VI is a mixture of allochthonous and autochthonous sediments (Hensel et al. 2022). Therefore, the charcoal found in SU VI can be reasonably interpreted together with those from SU V.

Table 1 Radiocarbon dates obtained from identified charcoal of the Sodicho rock shelter

Lab. code	Sample code	Material dated	Stratigraphic unit	Conv. age (BP)	Cal. range (cal BP)
Beta-628478	F35_SE_L4_2	Charcoal	II (tephra)	1,240 \pm 30	1,192–1,070
Beta-628479	G34_NE_L12_1	Charcoal	III (anthropogenic)	2,020 \pm 30	2,007–1,872
Beta-628480	F35_NW_L11_8	Charcoal	IV (tephra)	2,370 \pm 30	2,490–2,338
Beta-628481	F34_NW_L19_2	Charcoal	VI (sterile)	4,170 \pm 30	4,772–4,612

Anthracological results

A total of 1,907 charcoal fragments was analysed from SUs I to VII, including transitional units (e.g., SU I/II and so on), corresponding to a total of 26 charcoal taxa (Fig. 3, SI 1). Older units did not provide any charcoal or fragments big enough for identification, except a single piece from quarter G35, SE, level 38. It is identified as *JUNIPERUS PROCERA*/*PODOCARPUS FALCATUS* and the level is dated to 27,107–26,392 cal BP (Hensel et al. 2021). All fragments were analysed except in the richest units SU III and V: there, we stopped the identification at the 438th and 740th piece, respectively, because the accumulation curves of these SUs reached a plateau in the taxonomic identification after a substantial number of identified fragments. Out of these 1,907 charcoal fragments, 61 come from archaeological features, mainly pits. One hearth from SU V provided 11 charcoal pieces representing three

different taxa, *FAUREA ROCHETIANA*/*PROTEA* spp., *COMBRETUM* 2 and *PRUNUS AFRICANA*, which are also present in dispersed charcoal samples.

As expected, the richest SUs are the anthropogenic ones; they provided the highest number of charcoal pieces and taxa. In SUs I, III and V, a total of 15, 19 and 13 charcoal taxa were identified out of 159, 438 and 740 charcoal pieces, respectively. Hereafter, we provide percentages that take into account the number of unidentified pieces. The assemblages from SUs III, V and the SU interface III/V are dominated by *SYZYGIUM GUINEENSE* (29, 53 and 79%, resp.), *ACACIA* spp. (19, 11 and 13%, resp.) and *FAUREA ROCHETIANA*/*PROTEA* spp. (11, 14 and 6%, resp.). If the pieces confidently identified as *FAUREA ROCHETIANA* are added to the latter percentages, the Proteaceae account for 14, 25 and 6% of the charcoal pieces, respectively. A number of burned kernels from *Syzygium guineense* were found in SU V, three of them dated to 4,617–4,765 cal BP,

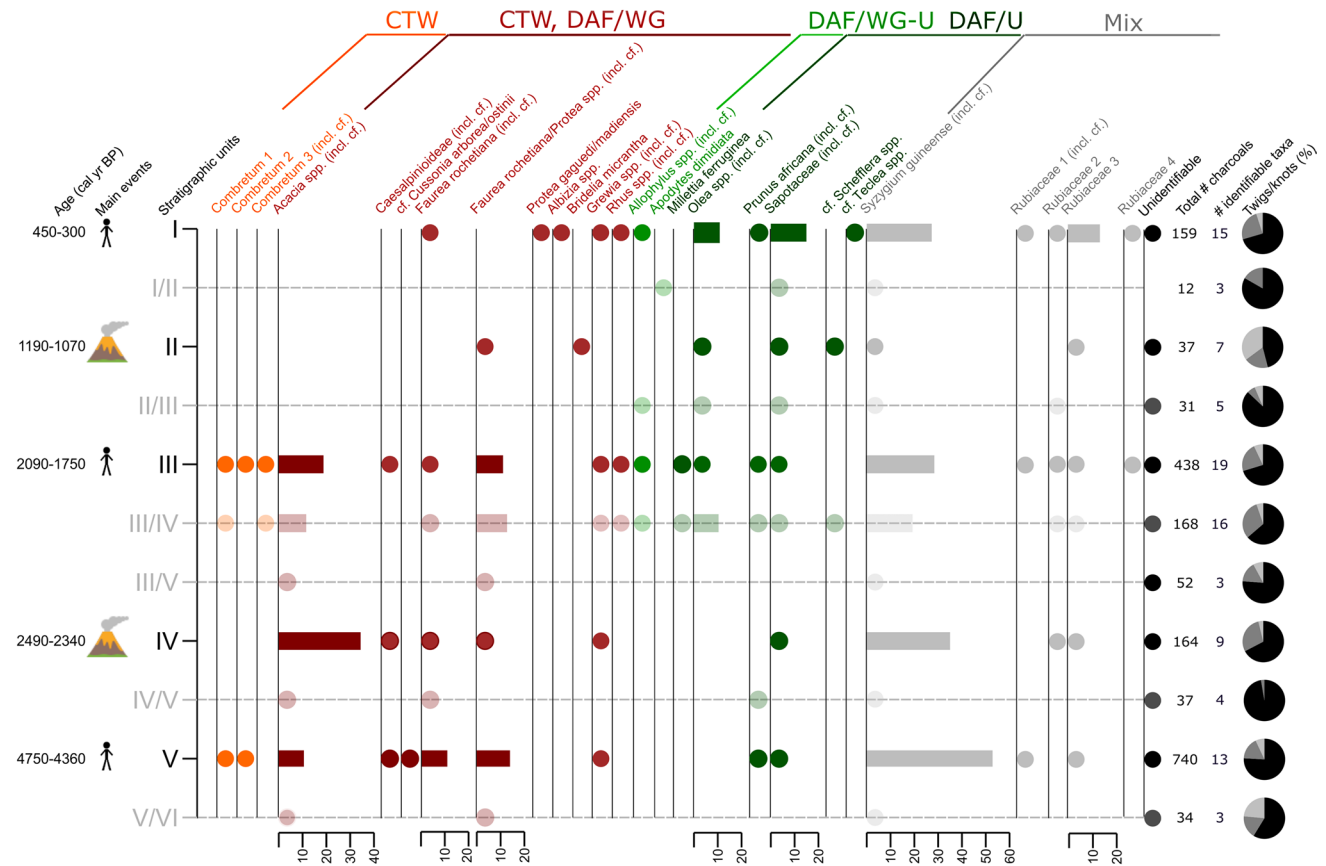


Fig. 3 Anthracological diagram showing the charcoal taxa identified. Vertical axes on the left: stratigraphic units, radiocarbon ages and the main events occurring: volcanic activity, human occupation. Vertical axes on the right: total number of analysed charcoal fragments, number of identifiable taxa and percentages of twigs (dark grey), knots (light grey) and the remaining charcoal pieces (black). Lower horizontal axis: percentage of taxa in the charcoal-rich units (bars). Col-

oured dots indicate the presence of taxa in charcoal-poor units and for taxa with abundance < 10%. CTW: *Combretum-Terminalia* woodland and wooded grassland; DAF/WG: Afromontane woodland, wooded grassland and grassland; DAF/U: Undifferentiated Afromontane Forest (Friis et al. 2010); Mix: for taxa growing in several vegetation types

4,567–4,729 cal BP and 4,610–4,828 cal BP. Local residents of Mt Sodicho indicated that the fruits are still eaten today.

SU I shows a different pattern and is dominated by *SYZYGIUM GUINEENSE*, SAPOTACEAE, RUBIACEAE 3 and *OLEA* SPP., which account for 28, 15, 14 and 10% of the charcoal pieces, respectively.

In occupation Unit VII, most charcoal pieces were unidentifiable due to poor preservation, and only 15 fragments of a single taxon, *SYZYGIUM GUINEENSE*, were found. Unit VII has a very broad chronological range of 17,000–14,960 cal BP, with two intrusive radiocarbon dates from younger units. Because it is not known how old the charcoal pieces are and because they are very few, we exclude them from our discussion on the palaeoecological significance.

The tephra units SU II and IV were overall less rich in charcoal fragments (37 and 164, respectively) but contained similar taxa as in the anthropogenic units, with *SYZYGIUM GUINEENSE*, *FAUREA ROCHETIANA*/PROTEA SPP, SAPOTACEAE, ACACIA SPP. and *OLEA* SPP. being the most abundant. The transitional units SU I/II, II/III, III/IV, III/V, IV/V and V/VI provided the same dominant taxa as the tephra and anthropogenic units.

Among the fragments analysed, there was a high proportion of knots and twigs. Together, they represent 27% of the whole record and an average of $21 \pm 14\%$ per anthropogenic unit and of $39 \pm 21\%$ per tephra unit. In the archaeologically sterile unit VI, where the charcoal dates correspond to the anthropogenic SU V, 45% of the fragments are twigs or knots.

Discussion

Wood selection and human fire activity

One of the most striking results is that three taxa strongly dominate the charcoal sequence, from the end of the AHP to roughly 2,000 cal BP: *SYZYGIUM GUINEENSE*, the Proteaceae *FAUREA ROCHETIANA* and *FAUREA ROCHETIANA*/PROTEA SPP., and ACACIA SPP. Especially significant is their strong abundance in SU V, dated between 4,750 and 4,360 cal BP, where the highest number of fragments was counted. The dominant representation of some taxa in the charcoal record may simply reflect their abundance in the environment (Chabal 1992; Kabukcu and Chabal 2021), but they may have also been preferred for their usefulness. Charcoal fragmentation depends on many factors and is not always dependent on the species. Nevertheless, as it has already been widely discussed in anthracology, these fragmentation issues do not impact the palaeoenvironmental representativeness, provided that the assemblage is composed of dispersed charcoal and is large enough (see for example Asouti and Austin 2005; Lancelotti et al. 2010; Théry-Parisot et al. 2010). The

dominance of only three taxa, in an assemblage of 740 fragments, provides a strong argument for wood selection by past people. Although only few fragments were identifiable in occupation unit VII, the fact that *SYZYGIUM GUINEENSE* was the only taxon also speaks for selection.

Wood selection is indeed often observed in charcoal records from archaeological sites (Bachelet and Scheel-Ybert 2017; Bodin et al. 2020; Robledo 2021; Ruiz-Giralt et al. 2021) and it is supported by ethnographic and modern-day observations (Picornell Gelabert et al. 2011; Teklay et al. 2014; Picornell Gelabert 2020).

Nowadays, *Syzygium guineense*, *Olea* (*O. capensis*, *O. europaea* ssp. *cuspidata*) and *Acacia* (e.g. *A. abyssinica*) are commonly used as firewood and charcoal in Ethiopia (Bekele-Tesemma 2007; Maroyi 2008; Bekele and Girmay 2013; Teklay et al. 2014; Feyisa et al. 2017; Bahru et al. 2021; Gebre and Seboka 2021; Tropical Plants Database 2022). *Faurea rochetiana* is not currently known as being used as firewood or charcoal in Ethiopia, though it has a high calorific potential (Gebremedhin 2021). PROTEA MADIENSIS (one of the two *Protea* species present in Ethiopia) and SYZYGIUM SP. have been reported in all levels from the hunter-gatherer site Shum Lake in Cameroon, dated between 1,000 and 8,000 cal BP (identification by H. Doutrelepon, Lavachery 2001), illustrating their high value as firewood. Selection of certain taxa for fuelwood was also observed in several other charcoal assemblages from tropical Africa, although they come from different environmental contexts. ACACIA and OLEA were abundant in the charcoal record from Ona Adi, Tigray, and interpreted as selected taxa (Ruiz-Giralt et al. 2021). SYZYGIUM GUINEENSE was the dominant charcoal taxon in Ounjougou, Mali, throughout the Holocene sequence (Eichhorn and Neumann 2014). An additional argument for wood selection comes from the low number of taxa found in the hearth from Unit V, which was probably used only once given its poor taxonomic richness. The hearth contained the abovementioned FAUREA ROCHETIANA/PROTEA SPP., a COMBRETUM and PRUNUS AFRICANA, the two latter also known to provide good firewood in Ethiopia (Bekele-Tesemma 2007).

Syzygium guineense, *Faurea rochetiana* and several *Acacia* and *Olea* species are also known to have medicinal properties (Bekele-Tesemma 2007; Glen 2008), to provide edible fruits (e.g. *Syzygium guineense*), or are used for mouth care (*Olea europaea*), among other uses. We can therefore assume that plant parts of these species were not only harvested for fire making but also for other activities and that the wood wastes served to light fires, explaining why they are so abundant in the charcoal record.

The high number of twigs and knots (Fig. 3) indicates that small calibre wood and twigs were preferred. It makes sense, as these parts would be easier to collect and transport. In fact, shrubs are mainly used for firewood and charcoal

production (Bahru et al. 2012) as this was also observed in anthracological assemblages from various sites around the world (Bodin et al. 2021; Kabukcu et al. 2021; Robledo 2021).

It is noteworthy that the emblematic DAF gymnosperms *Juniperus procera* and *Podocarpus falcatus* are not present in the Sodicho assemblage, just as it was noticed for the Ona Adi and Mezber sites in Tigray, dating from ca. 3,550 to 1,950 BP and then located in the DAF (Ruiz-Giralt et al. 2021). Both are assigned to the DAF/U and usually not present in the secondary DAF/WG (Friis et al. 2010, p 178). The absence of *Podocarpus falcatus* charcoal correlates with its absence in several modern Afromontane forest inventories of Ethiopia (Friis et al. 1982; Friis 1986) and thus needs no further explanation. But the absence of *Juniperus procera* in the assemblages of Sodicho is striking. Almost all available vegetation surveys of Ethiopian DAF include *J. procera* (Friis et al. 1982, 2010; Friis 1986; Bekele 1993), which also has a strong regeneration capacity after fire (Bussmann 2001). Maybe the open DAF/WG was much more extended than the closed DAF/U, and the occupants of the rock shelter may have avoided *Juniperus* as firewood because it grows in closed forest, as proposed for the sites Mezber and Ona Adi in northern Ethiopia where *Juniperus* charcoal was also very rare (Ruiz-Giralt et al. 2021). *Juniperus procera* may also have been avoided because only tall trees were present in the landscape. According to Friis et al. (2010), *J. procera* has a tree habit and can grow up to 40 m, while almost all other taxa present in the assemblage can also grow as shrubs. If hunter-gatherers came to the rock shelter for short visits (see the archaeological context section), then they would have avoided cutting off large calibre trees. The almost complete absence of the dominant taxa ACACIA and PROTEACEAE in SUs I and I/II, dated after 1,100 cal BP, might be explained either by a change in collection behaviour, or, especially in SU II, by the low number of counted fragments. However, in the assemblage from SU I, 159 fragments were counted, excluding sampling size as the reason for the absence of certain taxa. The dominance of forest taxa in SU I can indeed be interpreted as real change in the vegetation.

Palaeoecological significance

Past vegetation around the rock shelter during human occupation

The vegetation composition during human occupation can be best described thanks to the assemblages of SUs V, III and I from where the majority of the charcoal pieces were recovered. As most taxa in the charcoal assemblages cannot be identified to species level, several options for assigning them to vegetation types must be considered. We base our interpretation mainly on the Atlas of the Potential Vegetation

of Ethiopia (Friis et al. 2010) with its general description of the Ethiopian vegetation types. Most important for our reconstruction is the information on the undifferentiated Dry Afromontane Forest (DAF/U) and the Afromontane woodland, wooded grassland and grassland (DAF/WG). The latter includes primary edaphic woodlands with several *Acacia* species on black cotton soils, and secondary woodlands resulting from the deforestation of the “proper” DAF/U and subsequent intensive human land use. These secondary woodlands are especially relevant for our reconstruction. We also include more general literature on East African montane forests in other countries (Friis 1992; African Plant Database 2022), as well as personal observations gained during three field trips in SW Ethiopia.

In SU III, dated between 2,090 and 1,750 cal BP, there is the highest charcoal taxonomic diversity, suitable for a detailed vegetation reconstruction. The taxonomic composition in SU V, dated between 4,750 and 4,360 cal BP, is fairly similar to that of SU III, except that there is proportionally a higher number of open vegetation taxa. Several forest taxa that are present in SU III are absent from SU V, such as the emblematic OLEA SPP.

The majority of the taxa in SU III depict an open vegetation: COMBRETUM SPP., RHUS SPP. (now *Searsia*), GREWIA SPP., ACACIA SPP. and the Proteaceae FAUREA ROCHETIANA and FAUREA ROCHETIANA/PROTEA SPP. Most of the *Combretum* species of Ethiopia occur in the CTW (Friis et al. 2010, p 186, 2022). However, *C. adenogonium*, which would anatomically correspond to our COMBRETUM SPP. 2, can also be found in the DAF/WG (Friis et al. 2010, p 186; African Plant Database 2022). *Rhus* occurs mainly in dry vegetation types and along forest margins (Friis 1992; Friis et al. 2022, p 297). Ethiopian *Grewia* species have a wide distribution, including the lowlands, but *G. ferruginea* also occurs at higher altitudes in the DAF/WG (Friis et al. 2010, p 187, 2022, p 225). *Faurea rochetiana* and *Protea* are typical secondary vegetation taxa, growing in the CTW and the DAF/WG (Friis et al. 2010, p 184, 2022, p 211).

The charcoal taxon ACACIA, so dominant in the occupation units III and V, poses a special challenge for the interpretation due to the wide distribution of the genus in Africa (nowadays divided into two genera *Senegalia* and *Vachellia*). The majority of the Ethiopian *Acacia* species are found in the *Acacia-Commiphora* woodland and bushland (ACB) (Friis et al. 2010, p 198), which is distributed more to the East. This is why we do not consider it for our reconstruction. It is much more likely that the charcoal taxon ACACIA represents either CTW or DAF/WG. Some *Acacia* species grow in the CTW, but they are not a dominant element. On the black cotton soils of the primary DAF/WG, *Acacia* species are well represented, but they are much rarer in the secondary DAF/WG. A probable candidate is *Acacia abyssinica*, described by Friis (1992, p 143) as a forest tree

with an altitudinal range of 1,500–2,900 m a.s.l., but hardly occurring in closed forest. *Acacia abyssinica* rather grows along forest edges; it is a pioneer in secondary woodlands (Friis 1986), and its thick bark is probably an adaptation to fire resistance (Friis et al. 2022, p 242). Finally, the presence of CAESALPINIOIDEAE in the charcoal assemblage may also be indicative of an open environment as most of them are found in the CTW or DAF/WG (Friis et al. 2010, pp 196–197).

In addition to these open vegetation taxa, the assemblages of unit III and V also comprise several ones typically associated with the DAF/U proper (Friis 1992; Bekele-Tesemma 2007; Friis et al. 2010): ALLOPHYLUS SPP. (e.g. *A. abyssinicus* which can be found in the DAF), SAPOTACEAE (e.g. *Mimusops* and *Sideroxylon* occurring in the DAF), and especially PRUNUS AFRICANA and OLEA SPP., both typical forest taxa of the DAF/U.

The high proportion of CTW and DAF/WG taxa in comparison to those of DAF/U is at first glance surprising. At an altitude of 1,930 m a.s.l., Sodicho is located in the Afromontane forest zone, although today no forest remnants are found around the site, due to intensive land-use and population pressure. The picture emerging from the charcoal assemblages of the anthropogenic units III and V might be best interpreted in terms of an ecotone, a transition zone between closed DAF, secondary DAF/WG and CTW woodlands. The ecotone would comprise a mosaic of open woodland and closed forest, existing side-by-side, the distribution of them determined by edaphic factors, solar exposition, and human impact. An example of an ecotonal situation can be observed in the Kure Forest, near Jinka, 178 km southwest of Sodo, at an altitude of ca. 1,500 m a.s.l. There, small patches of forest with *Olea europaea* ssp. *cuspidata*, *Syzygium guineense*, *Teclea nobilis*, and *Diospyros* sp. are alternating with patches of open woodland, according to the topography of the terrain. In the open woodland, fire-resistant Proteaceae (*Faurea rochetiana* and *Protea madiensis*) were observed. A similar mosaic is probable for the area around Sodicho between 4,750 and 1,750 cal BP. Although at 1,930 m a.s.l., the exposition of the rock shelter, facing south, might have contributed to a drier type of DAF in a mosaic with CTW.

Fire would have been an important factor for the equilibrium between the three vegetation types in the ecotone. Bushfires occur regularly in the CTW, due to a distinct precipitation seasonality, resulting in a bulk of inflammable biomass during the dry season (Friis et al. 2022, p 41). By contrast, the closed DAF/U is usually not affected by fire (Eriksson et al. 2003; Teketay 2005; van Breugel et al. 2016). That fire was a constant factor in the landscape around Sodicho through its complete occupation history from 27,000 cal BP to the present, is indicated by burnt phytoliths in the soil samples of the site (Hensel et al. 2022). Although most of the burnt phytoliths are attributed to fireplaces within the rock shelter, they also occur in natural tephra deposits of aeolian

origin, the phytoliths of which represent the surrounding vegetation. Furthermore, high percentages of phytolith morphotypes from the grass subfamily Panicoideae in the soil samples attest the presence of large savanna grasses that are dominant constituents of CTW and are regularly prone to fire (Neumann ongoing laboratory work; White 1983, p 168). The strong representation of fire-resistant Proteaceae charcoal in occupation units III and V provides a further argument for regular bushfires between 4,750 and 1,750 cal BP (White 1983, p 169; Friis 1992, p 99). Proteaceae, as well as many Combretaceae, are typical fire-tolerant taxa with thick barks (Gilbert and Gebregziabher 1975; Bond et al. 1990; Midgley 2019; Makumbe et al. 2020; Friis et al. 2022, p 211). Regular bushfires would favour the CTW with its panicoid grass layer at the expense of forest and contribute to a relative openness of the landscape.

It is highly probable that humans contributed to the openness around Sodicho and the maintenance of the ecotone through fire activity. Human-induced bushfires are a central element of human niche construction, associated with the expansion of *Homo sapiens* from Africa to Europe and Australasia at least from 50,000 BP onwards (Summerhayes et al. 2010; Boivin et al. 2016). For Africa, Archibald et al. (2012, p 849) assume high fire probability from 40,000 to 4,000 cal BP, ‘when the effect of humans on ignition frequency and season were pushing fire into landscapes previously rarely burned’. If, as the vegetation model by Casas-Gallego et al. (2023) shows, Sodicho was located in an area with climatic conditions suitable for DAF throughout the Holocene, although not far from the adjacent CTW, it would have been easy for humans to increase the extension of open CTW and DAF/WG through regular burning.

Hunter-gatherers visited Sodicho at least for 27,000 years, albeit, according to the archaeological record, not continuously. Probably these hunter-gatherers were highly mobile and used a large range of different habitats along an altitudinal gradient from the hot lowlands to alpine grasslands. Hunting and gathering economies persisted in SW Ethiopia longer than in other regions of the Horn of Africa, and livestock and ceramics only appear around 2,000 cal BP (Hildebrand et al. 2010; Lesur et al. 2014). For hunter-gatherers, an ecotonal situation with several vegetation types would have been favourable, increasing the availability of resources, such as wild animals, plants and honey. Hunting of wild animals is still a major activity of the few remaining modern hunter-gatherers in the East African montane forests, such as the Okiek of Kenya (Kratz 1999), and the Chabu of SW Ethiopia (Dira and Hewlett 2017). There is also early evidence for hunting at high altitudes in the Bale Mountains around 47,000 cal BP (Ossendorf et al. 2019). As numerous examples around the world have shown, human-induced fires are a regular element for hunting wild animals (e.g., Bliege Bird et al. 2008; Bird et al. 2016).

In the anthropogenic unit I of Sodicho, dated to 450–300 cal BP, a different vegetation pattern emerges. The CTW and DAF/WG taxa *ACACIA* SPP. and *COMBRETUM* SPP. are not present anymore and only a few fragments from *FAUREA ROCHETIANA* and *PROTEA GAGUEDI/MADIENSIS* were found. The forest taxa *OLEA* SPP. and *SAPOTACEAE* are the most abundant, together with *RUBIACEAE* 3 and *SYZYGium GUINEENSE*, which can either grow in a closed or open vegetation (Bekele-Tesemma 2007; Friis et al. 2010). *APODYTES DIMIDIATA*, found in the transitional unit I/II (i.e. it can belong either to SUs I or II), may be added to the forest taxa list. The reconstructed vegetation would be a denser DAF/U, whereas the DAF/WG and the CTW would have retreated and were probably only found at lower altitudes, explaining why people were less relying on their firewood.

How can the development of an open ecotone with a mosaic of DAF/U, DAF/WG and CTW during occupation periods V and III (4,750 and 1,750 cal BP), towards a closed DAF in occupation period I (450–300 cal BP) be explained? As the distribution of the Ethiopian potential vegetation types is largely dependent on climatic factors (Friis et al. 2010; Casas-Gallego et al. 2023), climate change might provide an answer. In the Holocene, after the end of the AHP, the modelled vegetation maps by Casas-Gallego et al. (2023) for 5,000 cal BP to the present indicate a gradual retreat of the DAF to higher altitudes and an expansion of CTW and ACB. The Chew Bahir record (Foerster et al. 2015) shows a distinct increase in precipitation between 2,200 and 1,300 cal BP for SW Ethiopia that might have favored the expansion of the DAF, but a return to drier conditions afterwards. Thus, the expansion of the DAF during the last millennium in a former ecotone around 1,900 m a.s.l. cannot be explained by climate change. This leaves decreasing human impact as the most probable factor.

It is remarkable that almost all SW Ethiopian rock shelter sites show only weak signs of human presence for the last two millennia (Hildebrand et al. 2010). At Mochena Borago, the most recent occupation phase is dated around 1,500 cal BP (Lesur et al. 2007). It seems that with the arrival of domesticated animals around 2,000 cal BP in SW Ethiopia, residential activity shifted from the montane forest areas to the lowlands. If pastoralism became the main economic basis in the lowlands, then the upland forests might have become less attractive and were only visited sporadically for specific tasks, such as hunting and honey collection. This would have contributed to the regeneration and expansion of the DAF/U during the last two millennia, a development that was only reversed in the 20th century through massive settlement activities and land use.

Human occupation at Sodicho during volcanic events (tephra units) and the AHP

The charcoal assemblages from the tephra units (SUs II, IV) are taxonomically similar to the anthropogenic units, though much less diverse. Only two new taxa were found in unit II, namely *BRIDELIA MICRANTHA* and *CF. SCHEFFLERA* SPP. (now *Astropanax*). The habitat of *Bridelia micrantha* includes forest margins and moist CTW habitats (Friis et al. 2022, p 233), while *Schefflera* is a forest plant (Friis 1992; Friis et al. 2010). Charcoal fragments from these tephra units are probably too big to have been transported over long distances (> 4 mm) (Clark 1988) even in an eruption context (see for example Loughlin et al. 2018).

No evidence of human occupation, including lithics and features such as combustion areas (which would have led to concentrated charcoal lenses), were found in the tephra units (Hensel et al. 2021). Black carbon analyses (Hensel et al. 2022) show a very low content for the upper part of SU IV when compared to the higher black carbon values in the surrounding anthropogenic units. The lack of black carbon signals rather points to an absence of humans, as black carbon particles would have spread throughout, even if human fire activity had occurred at a different spot within the rock shelter.

Nevertheless, in SU IV, three taxa dominate the charcoal assemblage: *SYZYGium GUINEENSE* (37%), *ACACIA* SPP. (36%) and the *Proteaceae* *FAUREA ROCHETIANA* and *F. ROCHETIANA/PROTEA* SPP. (17%), just as in the anthropogenic units III and V. Such high percentages of dominant taxa in the charcoal assemblage from unit IV, as in anthropogenic units, depict a strong wood selection. This suggests that the charcoal was also produced by humans, but that the rock shelter was visited for short stays without tool making as no obsidian artefacts were found (Hensel et al. 2021). The absence of features such as combustion areas might be explained simply because they were not present in the excavated squares or by the reworking of charcoal fragments. Our new ¹⁴C dates indicate that charcoal was produced between 2,490–2,338 cal BP (Table 1), so even if some may have been reworked, fire activity did occur in the rock shelter during these volcanic events.

There is a gap of at least 1,700 years between SUs V and IV (Fig. 2), for which archaeological evidence is missing. One could first think that people were simply not around in this interval; but the similarity of the anthracological assemblages from SUs IV and V challenges this assumption. If humans had abandoned the rock shelter for such a long time, according to the environmental setting favourable for the DAF, the forest would have recovered. It would be the case even if volcanic eruptions occurred in the meantime, as it takes only decades to centuries for the forest to recover (Clarkson 1990; Tsuyuzaki 1995; Zobel and Antos 1997).

The fact that the CTW charcoal taxa are still present in SU IV, pointing to identical wood selection as observed in SU V, suggests that visits by humans occurred rather continuously. Thus, the gap might be explained by weathering processes and sediment erosion. This is evident from the micro-morphological observations of thin sections from SU IV. According to Hensel et al. (2022), the thin sections indicate a multi-stratification of the tephra, allowing division into subunits. The stratigraphically lower homogeneous subunit contains a high proportion of volcanic glass, which can be considered as the initial ash fall. Overlying subunits also contain mainly volcanic glass, but also non-continuous laminations (fine grading) of volcanic glass with clay and appear redeposited. These observations suggest increased moisture and weathering intensity along with sediment redeposition. As Unit IV is not comparatively well preserved in all excavation squares (Fig. 2), the processes involved confirm that sediment was subsequently eroded.

Further work comparing anthracological and black carbon analyses would be needed to disentangle such potential contradictory signals. Keeping that in mind, the anthracological results have shown that (1) the same main taxa occur along almost the whole sequence; (2) the same taxa dominate the charcoal assemblages even in tephra layers (with a different pattern in unit I); and (3) there is evidence of fire activity given by both charcoal and phytoliths in an environment naturally not prone to fire. Based on these evidences, we suggest that human presence at and around Sodicho was actually more continuous than previously thought since the end of the African Humid Period ca. 5,000 cal BP until 1,750 cal BP.

The charcoal pieces identified in the archaeologically sterile unit VI, associated with the AHP, are attributed to *SYZYGIUM GUINEENSE*. As one of them was dated to 4,772–4,612 cal BP, which falls in the range of the dates from the overlying anthropogenic unit V, they are probably allogenic and of anthropogenic origin. Furthermore, several charcoal pieces from this unit come from twigs – and one was a very big piece (> 2 cm), probably indicating a fire-place (Hensel et al. 2021) – as observed in anthropogenic units. Shrink and swell processes as well as bioturbation, which were identified in this unit (Hensel et al. 2022), may have reworked them. Therefore, the general conclusion by Hensel et al. (2021, 2022) that Sodicho was not visited during the AHP, is still valid.

Conclusions

The anthracological study of Sodicho allows us to provide new insights into wood selection, human occupation, human-vegetation relationships and Afromontane forests dynamics in the SW highlands of Ethiopia since the end of the AHP. In contrast to expectations regarding the environmental

conditions, Sodicho was not located in a closed DAF/U between 4,750 and 1,750 cal BP. The charcoal record clearly shows that CTW and DAF/WG were part of the picture, suggesting that the site was actually in the ecotone between CTW and DAF, constituting a mosaic with DAF/WG. This brings new perspectives into potential economic activities of the late Holocene hunter-gatherers. It seems that they preferred a more open landscape, most probably due to its better resource potential, and that the closed DAF/U was only one element among others. The presence of DAF/WG and CTW in an environment not prone to their development indicates that humans were the main factor conditioning their maintenance by using fire. This illustrates the significant impact that hunter-gatherers can have on the vegetation.

The charcoal record clearly shows consistent firewood selection from 4,750 to 1,750 cal BP. *ACACIA* spp., *SYZYGIUM GUINEENSE* and the Proteaceae *FAUREA ROCHETIANA* and *PROTEA* spp. were the preferred taxa. As these charcoal taxa were also the most abundant in the tephra unit IV, where no archaeological evidence was found, this challenges the interpretation that humans were not present. It rather suggests that hunter-gatherers visited the rock shelter for different purposes than living and tool making. Continuity of human presence around Sodicho can also be assumed for the chronological gap between units V and IV (4,360 and 2,490 cal BP), indicated by the persistence of open vegetation taxa in unit IV. If no people had been there before, a closed DAF would have developed, which was obviously not the case.

Finally, the regeneration and expansion of the DAF during the most recent periods (from 1,750 cal BP onwards), when human interference was decreasing, demonstrates that the Afromontane forests are resilient. This is of utmost importance knowing the challenge these forests are facing nowadays due to very high demographic and land use pressure.

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Declarations

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

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