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Living the Holocene in the Kassala region of Eastern Sudan
A geoarchaeological perspective

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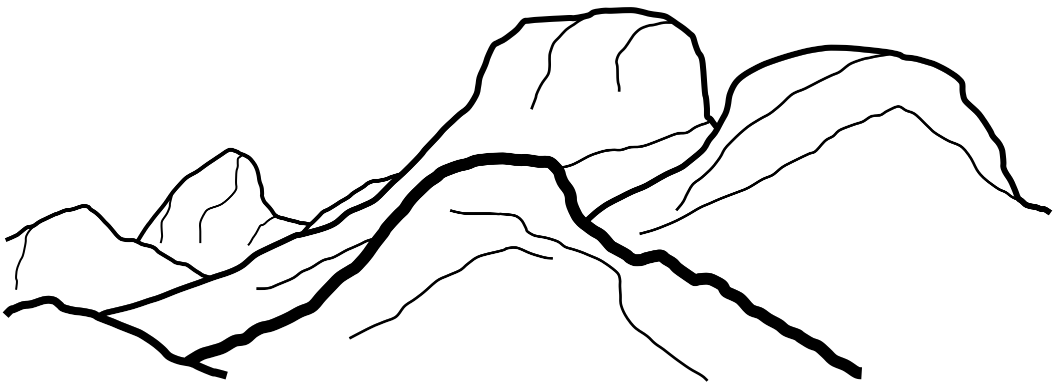

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Living the Holocene in the Kassala region of Eastern Sudan

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This geoarchaeology PhD Thesis is the outcome of years of research carried out by the author in the scheme of the Italian Archaeological Expedition to the Eastern Sudan (IAEES), funded by the University of Naples "L'Orientale", the ISMEO (International Association for Mediterranean and Oriental Studies), the Italian Ministry for Foreign Affairs, and supported by the Sudanese National Corporation for Antiquities and Museums (NCAM) and the local authorities of the Kassala State of the Republic of Sudan.

The research was carried out on field in Eastern Sudan and in the sedimentology and micromorphology lab facilities kindly allocated by the Earth Science Department of the University of Milan "La Statale".

Research supervision was provided by Professor Andrea Manzo of the University of Naples "L'Orientale" - Department of Asian, African and Mediterranean Studies (Main Supervisor), and by Professor Andrea Zerboni of the University of Milan "La Statale" - Earth Science Department (Co-Supervisor).

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Preface

Eastern Sudan is not an easy place to reach. Only one paved road stretches across the open plains for nearly 600km to connect Khartoum, Sudan's capital city, to the growing borderland city of Kassala, counting nearly half a million inhabitants. Visitors of the region are welcomed by an unforgiving dry heath and a peculiar intricate landscape of seasonal streams, rocky domes and thorny vegetation - manifestation of the encounter between the very outskirts of the vast plains of the Nile River's basin and the crystalline outcrops of the Eritrean Highlands.

Archaeological research groups, and early explorers before them, are not spared by such geographical constraints: logistics are complicated, the right period for visiting has to be cautiously selected to avoid chance of rainfall and scorching temperatures as well, and car breakdowns in the middle of nowhere must be accounted for - just to name a few. Moreover, academic research operates in the real world, and the real world dictates the movement of people.

The work presented in this Doctoral dissertation was carried out between late 2019 and middle 2022, surely not the easiest of times in the early 21st century. As soon as I started my PhD program, Covid-19 broke out and disrupted all movements for more than a year. Just when things seemed to be resuming, political instability and revolution led by citizens longing for a newly found democratic Nation ran throughout the country, delaying academic exchanges for several more weeks. Adding to that, the Kassala State was also impacted by Ethiopian internal conflicts, which has caused a still-standing humanitarian crisis with thousands of people fleeing across the border into neighbouring States.

In the end, only one field season was carried out at the very beginning of my three-years PhD program, before visiting became impossible. Even so, data gathered were sufficient for setting up the successful framework that is presented here. All observations, soil samplings and radiometric dating provided meaningful results over a very large area, thanks to the advantages offered by remote-sensing applications and an extensive production of cartographic material.

This dissertation, therefore, is structured in such a way that the impact of each result and finding is maximized in relation to the regional context and archaeological significance: most of the reported data have already been peer-reviewed and published on international journals, and are used here to create a documentary that deviates slightly from traditional science reporting in favour of a mellower narration that integrates hard science and humanities. The final purpose of this work is to present state-of-the-art knowledge upon the Holocene natural history and human journey of the Eastern Sudan, with both natural scientists and archaeologists in mind, and the full awareness that it represents but a springboard for much more learning to come.

Stefano Costanzo, 2023

1. Introduction

Northern Africa, and the Nile Valley in particular, have always sparked interest among explorers, archaeologists and common people alike. The direct proximities of the Nile River, luscious and fertile even through the most depriving Saharan droughts, have been playground throughout human history for early mankind and historical civilizations alike, giving life and sustainment to astounding forms of early societies that acted as crucial bridges between the Mediterranean and Levantine worlds, and the deep African interior. The wealth of monumental loci disseminated along the Egyptian and Nubian course of the Nile River attracted generations of scholars, but the very same monumentality and artistry of what sparked more interest - pyramids, temples, statues and, most crucially, written documents and tales -, in truth, represented the biggest limitation to the very same field of studies for decades, or even centuries. It is a relatively newer realization, in fact, that the study of monuments and written sources of the Nile Valley should not be just a self-sustaining purpose of research (Welsby, 2004), but rather be used as a gateway towards the discovery and comprehension of hidden societal facets and deeper human past, whose remains are more than often lying just beneath the surface of the much more glaring historical civilizations (Fattovich, 2010; Usai et al., 2010; Usai et al., 2014; Usai & Salvatori, 2019). Additionally, understanding the everyday life of the past Nile Valley societies in relation with the natural environments and climates respective to each period in history, stimulated reflections upon the actual role of far, marginal regions and their inhabitants in the shaping of supra-regional dynamics. In truth, the very concept of geographic and ethnographic marginality stems from a set of biased perceptions created and perpetrated by early western scholars. In fact, they had limited knowledge and cognition of the African archaeological and environmental past in general, and the operative constrains posed by the more remote and environmentally challenging areas only aggravated the circumstances, causing the peripheries to remain excluded from the literature because they simply could not be explored enough. Moreover, the deep-rooted belief that civilization can only stem from surplus agriculture – meaning living close to the Nile –, paired with an excessive fondness towards philological and epigraphic ancient sources that depicted people living in the desert as barbaric and uncivilized (Manzo, 2017), prevented overall attempts to establish unbiased research lines aiming to seek out the real complexity of the archaeological mosaic until relatively recent times. This shift of paradigm kickstarted many projects that were able to generate new discoveries and information upon the very peripheries of the Nilotic world, such as the InterLINK project in Northern Kordofan (Eger & Karberg, 2019), the explorations of the Egyptian and Sudanese Eastern Desert (Krzywinski, 2012; Davies & Welsby, 2020; Cooper, 2020), and the excavations of Jebel Moya in the Sennar region (Brass et al., 2019), just to name a few from recent years. Their successful frameworks led to relevant findings that not only provided missing links that were long sought after for a complete comprehension of supra-regional dynamics, but are also empowering local communities in the recognition of a tangible and shared archaeological past (Näser & Tully, 2019).

1.1 The activity of the Italian Archaeological Expedition to the Eastern Sudan

The IAEES (Italian Archaeological Expedition to the Eastern Sudan), formerly known as IAMSK (Italian Archaeological Mission to Sudan, Kassala), is one of the projects that are treasuring peripheral areas.

Drawing from previous but discontinuous works by a few British and American isolated expeditions (Crowfoot, 1928; Shiner, 1971; Clark, 1976; Phillipson, 1977), the IAMSK's program of systematic archaeological exploration of Eastern Sudan, intended as the vast flat territory known as Southern Atbai, extending east of the middle Atbara river up to the Gash river and the Eritrean border, started in 1980 with a research project led by the Istituto Universitario Orientale - presently University of Naples 'L'Orientale' - and the Butana Archaeological Project, jointly sponsored by the University of Khartoum and Southern Methodist University (Dallas, TX). The project set the aim of studying the relationships between Eastern Sudan and the Nile Valley in the 'Neolithic' phase, without overlooking other potential links to southerly regions in prehistoric times (Fattovich, Marks & Mohammed Ali, 1984). The teams conducted an extensive systematic survey across thousands of square kilometres in the Southern Atbai, discovering 256 sites that contributed to establishing a long regional cultural sequence starting in the 6th millennium BCE and ending in the 2nd millennium CE with a practically continuous human presence throughout eight millennia. Despite a long halt to the expeditions caused by the Eritrean-Ethiopian War of 1998-2000 and its international implications in the neighbouring countries (Murphy, 2016), the works of the IAMSK and associated teams were resumed in 2010 by the IAEES, yet again co-directed by the University of Naples "L'Orientale" and the Sudanese National Corporation for Antiquities and Museums (NCAM). The newly produced data added plentiful insights upon the Late Quaternary cultural sequence of the region, reinforcing older theories and paving new roads thanks to the possibilities offered by current scientific advance, particularly regarding GIS-based analyses of environs and terrain, radiometric dating, geochemistry applied to physical anthropology, and computational geospatial analysis.

The IAMSK's and IAEES's findings tell a story of human adaptation and thrive in a land that is archaeologically not as remote nor isolated as previously thought, surely characterized by long distances and severe environments, but whose people were able to provide a bridge between the two worlds of the inner Nile Valley and the upper Ethiopian Highlands.

The occupation of the region is continuous from the Early/Middle Holocene up to the present day. Most of the archaeological sites date to the Butana Group (4th–3rd mill. BCE), the Gash Group (3rd - 2nd mill. BCE), and the Jebel Mokram Group (2nd–1st mill. BCE), but, in truth, occupation spans from the Pre-Saroba Phase (6th - 5th mill. BCE) to the Gergaf Group (mid-2nd mill. CE) (Fig 1.1 and 1.2) (Manzo, 2017). The archaeological sites, found in hundreds, are located in the open savanna along the paleochannels of the Gash River, although their temporal relationship with them is still debated (Manzo, 2019: pp. 270–271), and will be object of discussion within this dissertation (Chapter 4.1). Sites consist of deflated scatters of micro- and macrolithic artefacts, potsherds, ephemeral semi-nomadic structures, shell middens, and simple or small mound burials, with stratifications that rarely exceed a thickness of a few centimetres due to intense wind deflation, although some of them reach a depth of over 1 m as result of particularly intense and continuous occupation. Fewer known sites are located at the foothills of the rocky outcrops east of the alluvial plain; among these, the largest and most important one (~100'000 m^2), is Mahal Teglinos (archaeological site K1) (Manzo, 2017 and references cited therein).

In the region, the onset and spread of agriculture started in the 4th millennium BCE, with what appears to be one of the earliest occurrences of domesticated *Sorghum sp.* in the world (Beldados et al., 2018; Winchell et al., 2017), introduced by the Butana Group. Butana ceramics, in fact, often bear remarkably well-preserved imprints of sorghum seeds and stems, possibly included as temper in the ceramic paste. The recovery of allochthonous ceramic artefacts from the Gash Group strata in Mahal Teglinos suggests that the region has also been part of a supra-regional commercial intersection between the Nile Valley, the Horn of Africa and Arabian Peninsula since as early as the 3rd mill. BCE (Manzo, 2020). For example, potsherds of Egyptian production are relatively common, alongside with administrative sealings and shell-made jewellery from the Red Sea. Moreover, the incredible number of grindstones recovered both from living areas and burials is indicative of a prominent importance and ritual significance of agriculture among the Gash Group (Rega et al., 2021). Agricultural and pastoral land use persisted up to present times, with a steep increase in the extension of cultivated surface since the introduction of the spate irrigation system by the British in 1924 (Barbour, 1961) and the construction of the Khashm el Girba Dam along the Atbara River in 1964 (Woodward et al., 2020). As a result of such practices, many archaeological sites have been irredeemably compromised by artificial floods and ploughing - implying for the IAEES a conspicuous duty in recording and salvaging as much archaeology as possible before agricultural expansion takes over.

SOUTHERN ATBAI				***NORTHEAST AFRICA***		
	Phase		***Group***	***Middle Nile***	***Egypt***	***N. Ethiopia***
			Gergaf			
1000				CHRISTIAN		
				POST-MEROITIC	ROMAN	AXUMITE
AD 0 BC	TAKA		Hagiz	MEROITIC	PTOLEMAIC	PRE-AXUMITE
			Late Mokram	NAPATAN	LATE DYNASTIC	
1000	*LATE*	KASSALA	Mokram		NEW KINGDOM	
2000	*MIDDLE*	KASSALA	Gash	LATE NEOLITHIC		
					OLD KINGDOM	
3000	*EARLY*	KASSALA			EARLY DYNASTIC	
			Butana	KHARTOUM NEOLITHIC	PRE-DYNASTIC	
4000	TRANSITIONAL		Site KG28			
	SAROBA		Malawiya	KHARTOUM MESOLITHIC		
5000	PRE-SAROBA		Amm Adam Site KG14			

Figure 1.1 *Regional cultural sequence as it was reconstructed after the investigations conducted in the Eighties compared with the cultural sequence of the Middle Nile Valley, Egypt and northern Ethiopia (modified from Sadr, 1991).*

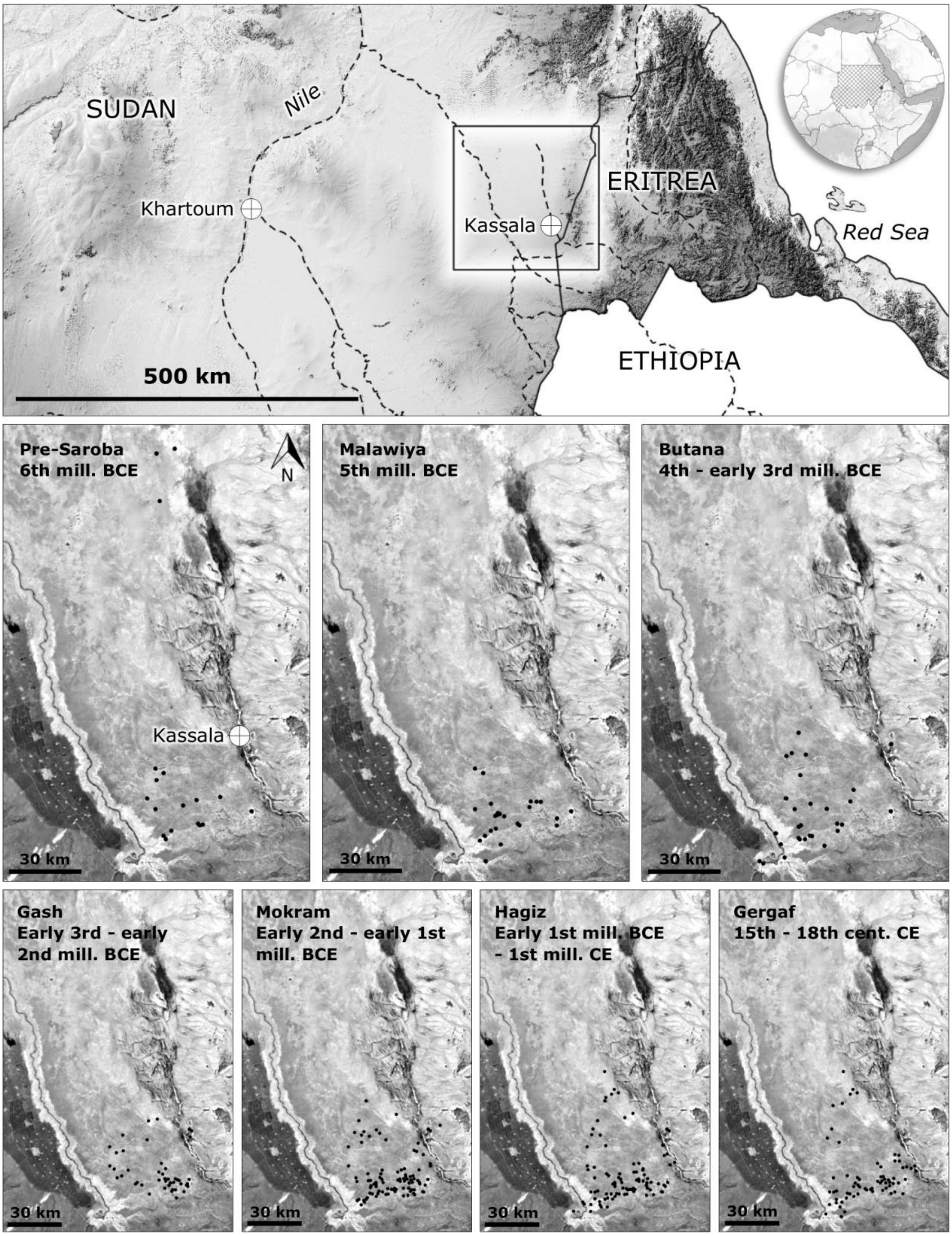


Figure 1.2 *Sites found in the Southern Atbai by the IAMSK, IAEES and NCAM surveys (modified from Manzo, 2017). Scantiness of older sites (Pre-Saroba, Malawiya, Butana and, to some extent, Gash Groups) may be more related to preservation issues rather than actual lesser abundance.*

1.2 The contribution of geoarchaeology

Geoarchaeology, in Karl W. Butzer's words, "*implies archaeological research using the methods and concepts of the earth sciences*" (Butzer, 1982). As such, it is a discipline that is not auxiliary to archaeology in its most common sense, but rather fully complementary in the same extent as archaeobotany, zooarchaeology and archaeometry are. By employing techniques and approaches that were originally developed in spheres of research belonging to hard sciences such as, for example, solid geology, sedimentology, geomorphology, pedology, and geochronology, the geoarchaeologist's duty is to master a balance of activities that can critically contribute to the understanding of each archaeological context in its own individuality. Taylor-made geoarchaeological analyses are, therefore, crucial for understanding several facets of the complex archaeological picture such as:

- the landscape context at the microenvironmental (single strata), mesoenvironmental (local geomorphology and topography) and macroenvironmental (regional physiography and ecosystem) scale;

- the stratigraphic context intended as the outcome of accretional and erosional pedosedimentary processes acting at the local and regional scale;

- the site formation processes, in their complex alternations of anthropogenic and natural inputs to the material (i.e. soil, artefacts, organic remains) that composes the mass of the pedostratigraphic bodies themselves;

- the site modification processes, defining phases of deposition and differentiating pristine and tainted stratigraphies;

- the landscape modifications, intended as features at the local and regional scale that are not natural, but rather the outcome of anthropogenic modifications of the natural settings (e.g. earthworks, ditch systems, hydrography regimentation) may they be unintended or deliberate.

In the area of the Nile Valley, pioneering works in the direction of collaborative frameworks between archaeologists and geoscientists started to during the 1920's thanks to the revolutionary foreseeing of the archaeologist Gertrude Caton Thompson and the geologist Elinor Wight Gardner (Nicoll et al., 2021; Butzer, 2011), and of Karl W. Butzer himself, who promoted the study of the valley's Quaternary geology using hominin artefacts as guide fossils (Butzer, 1959; Butzer, 1980), and the idea that the analysis of extant geomorphological settings is key to understanding the geography of prehistoric settlements (Butzer, 1960).

Even so, systematic involvement of geoscientists in archaeological projects did not immediately catch on, possibly as an influence of the deeper roots that archaeology shares with art history, philology and epigraphy.

Nevertheless, over time an increasing number of scholars from either side - archaeology and geosciences - started to undertake cross studies on their own account, until a recognition of geoarchaeology as a self-worth discipline in the archaeological "toolbox" was achieved. In this sense, the IAMSK was relatively ahead of its time. Since the beginning of the Italian explorations in the Eastern Sudan, there has been recognition of the importance of the geological and environmental context of the region as a key component for understanding its archaeological past. Efforts towards the comprehension of the evolving environment in which the human communities settled were put in from the start of the investigation, and paramount observations were published as early as 1984 by Professor Mauro Coltorti (Coltorti et al., 1984), shortly followed by

Professor Mauro Cremaschi (Cremaschi et al., 1986), two geologists who immediately identified the presence of buried soils in Mahal Teglinos and a fossil river system in the open Southern Atbai plain, two natural vestiges that bear cardinal significance for the reconstruction of past environments and climate change. Despite the long halt to the investigations caused by the Eritrean-Ethiopian war of 1998-2000, and the delayed resume of the geoarchaeological work after the reprise of the IAEES in 2010 (Cremaschi, 2014), enough content was laid out to contextualize the Holocene climate evolution of Eastern Sudan within that of North Africa at large, with the identification in the geological record of a long period of wetter climate in the Early and Middle Holocene - corresponding to the African Humid Period (deMenocal & Tierney, 2012) -, followed by the period of aridity that is still in place.

The work started by Professor Cremaschi was reprised by myself in 2017 for my MSc final dissertation. Plenty of data from Mahal Teglinos, such as thin sections of undisturbed soil samples and sedimentological analyses of the site's rich stratigraphy, had been kept for future study and publication, which happened some time later (Costanzo et al., 2020a). In the study, for the first time was presented a radiocarbon dating of the buried organic soil horizon underlying the aeolian dust accumulation, providing a first impression of the region's paleoenvironmental dynamics based on the spatially limited case-study delivered by the site.

Drawing on those introductory data, the scope of this doctoral project was to expand the geoarchaeological surveys to as wide as a territory as possible, with the prospect of producing new results on the regional scale. The idea is to provide a backbone for future location-specific surveys and archaeological interventions, which will pivot on freshly produced regional-scale cartography and geoarchaeological assessments. Contextually to the surveys and investigations conducted for the territorial analyses and paleoenvironmental reconstructions, very preliminary observations on the petrographic nature and location of rock bodies and outcrops were carried out to provide introductory data on raw material supplying for the plentiful macrolithic tools found in the archaeological assemblage. In fact, several lithotypes with a high degree of variability are found within the assemblage, with some elements being absolutely anomalous to the regional geology and therefore deserving attention aimed at defining very specific commercial or migration routes.

Despite the limitations imposed by the Covid-19 pandemic, which forced us to call two field seasons off, enough data were collected for fulfilling the scope: new radiocarbon dates, sedimentological samplings, geomorphological surveys and desk-based GIS analyses of the territory allowed us to draw a picture of the Holocene palaeoenvironment over a region of nearly 30000 km^2, stretching from the Khashm el Girba dam on the Atbara river in the south west to the meta-sedimentary outcrops of the Jebel Maman hills in the north east.

The presentation of the results is organized as follows: after a layout of the general methodology and research's workflow (Chapter 2), the present-day physical geography of the region is presented (Chapter 3). The very outline of the current physiography is the springboard for Chapter 4, "Vestiges: locations of interest for the reconstruction of past climates and landscapes". Locations that were surveyed and deemed relevant for the reconstruction of past climates and environments are presented individually, displaying the findings for each one separately, regardless of the archaeological time period that their analyses unveiled. Chapter 5 "Zooming back: the human-environmental nexus during the past 8000 years", in turn, unifies all contexts to propose the unified Holocene timeline zooming out on the regional scale, based on the results yielded by each previously presented context. Chapter 6, finally, addresses perspective future research by presenting open questions and outlining possible solutions.

As an addition, *Appendixes* integrate the manuscript with cartographic material (A and B), and micromorphological description tables of the soil thin sections presented within the following chapters (C).

2. Methodology of research

The employed methodologies, workplan and resources are tailored around the main aim of this research, which is to provide paleoenvironmental data *extensively* - i.e. on the regional scale and for the widest possible time brackets - rather than *intensively* - i.e. producing ultra-high resolution data on just one or a few sites -. This choice is dictated by a twofold constraint: on one hand, it is the scope of this doctoral work to provide a geoarchaeological backbone for future studies in the wider region, thus working extensively is strategically more convenient than prematurely focusing on small-scale contexts; on the other hand, the extensive surveys tackle the issue of site preservation, which is relatively poor for known locations, making it a priority to assess the existence and status of still unknown ones.

The approach pivots around field survey and regional geomorphological cartography, upon which promising locations are selected for further analysis such as local-scale high resolution geomorphological characterizations, radiometric dating, and soil sampling for sedimentological and micromorphological analyses.

2.1 Cartographic production – QGIS and Spatial Analysis

The cornerstone of the whole project was the field survey and the production of cartography. Over three field seasons, several locations spread over a region of nearly 30000 km^2 were visited, described, and used as control samples for the creation of satellite images-based cartography in GIS environment. The sparseness of the vegetation cover makes this workflow entirely reliable, as it has been thoroughly proven by several research teams working in arid lands who, over the years, produced abundant cartographic material using the very same approach (Azzoni et al., 2017; Forti et al. 2021; Perego et al., 2011; Zerboni et al., 2015, 2020).

In particular, the geomorphological aspect of the region's physiography was favoured in the analysis as the most significant indicator of natural and anthropogenic processes that bear potential archaeological significance, both as a *driver* and an *outcome* of human agency. This choice was conditioned by my firm belief that there can be no true understanding of archaeological sites, archaeological landscapes, and the general archaeological past, without a full comprehension of the extant physiographic settings and sedimentary palimpsest imprinted therein.

The detailed procedure for the drawing of the regional cartography (*Appendix A*) is as follows:

The mapping process relied on satellite images and open access Digital Elevation Models (DEM) analysed within QGIS 3.4 (QGIS Development Team, 2019). Observations were carried out using several available datasets. Multispectral images (visible and infrared) from USGS Landsat8-OLI-TIRS (earthexplorer.usgs.gov) were projected to UTM Zone 37N reference system. Late summer images with a <5% cloud coverage were chosen because the blooming ephemeral vegetation highlights several large-scale landforms such as active and fossil river channels, splays and patches of land altered by agricultural exploitation. The spectral bands were combined in false colours to focus on the vegetation and the distribution of moisture-retaining alluvial sediments (RGB bands 4, 5, 2 and 6, 5, 2 respectively). Free-open access high-resolution satellite imagery collections were manual explored through the QGIS plugin QuickMapServices (NextGIS, 2019) to identify small-scale landforms. A TanDEM-X DEM with 3 arcsec horizontal resolution (~90 m at the equator) released by the German Aerospace Center (download.geoservice.dlr.de/TDM90) was projected to UTM Zone 37N and used for extracting contour lines and a hillshade representation, providing a 3D ruggedness effect. An elevation-dependent colour scale was applied to the DEM and superimposed over the hillshade, in order to easily observe landforms and elevations. An Aspect model - i.e. cardinal direction of the exposure of slopes - was created to aid the visualization of subtle slope variations of flat areas tilted by Late Quaternary sub-regional tectonics. This is effective in interpreting the trajectory of elusive and poorly preserved paleochannels as in the case of the Gash river's fossil system. The legend is structured to illustrate lithologies, structural landforms, residual surface and aeolian landforms, active and fossil hydrology and fluvial landforms, anthropogenic features, and topography, with the use of flat coloured polygons superimposed to the hillshade relief. The ephemeral channel network was manually drawn from satellite images. In addition to topographical and satellite visual information, the 1:2,000,000 geological map of the Sudan (Geological Research Authority of the Sudan, 2004) was used as a control for the interpretation of lithologies for non-surveyed distant areas. A contoured buffer around the coloured area is used to provide a visual clue of the surrounding geography, with regards to the continuation of the Eritrean mountains.

The small-scale cartography of the archaeological site of Mahal Teglinos (*Appendix B*) was created with the same desk-based procedure, but some minor differences apply. The field survey was carried out across the entire site, leaving no portion to postdictive inferred interpretation. The DEM used was ALOS World 3D - 30m (AW3D30) by JAXA (2015), because it has a better resolution than TanDEM-X. The map's legend and colours are organized according to process chronology rather than landform category, in order to provide a glaring distinction between ancestral features, Late Quaternary deposits and active landforms. This choice was driven by the very scope of the map, which is to provide graphic reference to the paleoenvironmental evolution of the valley in relation to its phases of human occupation and abandonment (discussed in chapter 4.2). Occasionally, test pits and trenches were employed for assessing localized stratigraphic relationships between depositional features in archaeologically negligible (i.e., not pristine and/or poor in artefacts).

2.2 Radiometric dating

Radiometric dating was used, when possible, to anchor landforms and relevant portions of stratigraphy to calendar dates, thus making it possible to correlate the data obtained from the study area to known supra-regional processes and chronologies, such as - to provide an appropriate example - the Holocene African Humid Period (deMenocal & Tierney, 2012).

Radiocarbon dating was the preferred method, thanks to its ease of sample collection and logistics of samples transportation. Due to the arid climate and marked morphogenetic dynamism of the interspersed archaeological and natural deposits, which are often tainted by post-depositional displacement and therefore prone to stratigraphic misinterpretation (Costanzo et al., 2022), "traditional" targets for radiocarbon dating such as charcoal and bones were avoided, favouring the collection of soil *horizon* samples instead. One of the main features of the region, as mentioned in the Introduction (Coltorti et al., 1984; Cremaschi et al., 1986), is the frequent occurrence of buried thick organic soil horizon, which, on the basis of their stratigraphic position, lateral continuity, and preservation status, can be safely considered as reliable paleoenvironmental markers. Their pedogenetic organic content, in the form of well-developed humic compounds typical of subaerial prairie soils, allowed for successful dating of three contexts, which will be discusses in chapters 4.2 and 4.3.

2.3 Pedosedimentary analyses

Due to the very nature of the currently active water-related morphogenetic erosional processes, it is extremely common to come across deep gullies cutting within the foothill Late Quaternary unconsolidated deposits. The gullies evolve by lateral migration caused by embankment collapse, a process that causes the formation of vertical cliffs on the eroded side and the subsequent exposure of freshly revealed stratigraphic sections.

Sedimentological analyses were carried out on bulk soil samples collected from the adventitious sections that were identified during the field surveys and selected for their potential information yield, such as the presence of diverse pedostratigraphic features (i.e. soils horizons, colluvium, aeolian dust, etc) and archaeological material and layers. When possible, preliminary assessments of the depositional and erosional processes were defined based on the sediment's texture and structure, and chronologies were defined based on archaeological material found therein. Samples were collected from bottom to top to avoid contamination from each layer/horizon - when identifiable – or at regular intervals of 15 cm, as in the case of the 4 m section of Jebel Haura (see chapter 4.3). The samples were labelled accordingly.

Physical and chemical lab characterization of sediments included the following analyses: (i) grain-size distribution, performed after removing organics by hydrogen peroxide (130 vol) pre-treatment; sediments were wet sieved (diameter 1.0–0.63 mm), then the fine fraction (<0.63 mm) was determined by hydrometer based on Stokes' law (Gale and Hoare, 1991); (ii) loss on ignition (LoI), used as a proxy for the evaluation of the total organic carbon content (Heiri et al., 2001) and (iii) humified organic carbon matter, performed measuring the oxidizable organic carbon through titration after chromic acid treatment (Walkley and Black, 1934); (iv) calcium carbonate equivalents, estimated from the CO2 emitted by the sample after reacting with HCl with the Dietrich–Frühling calcimeter (Gale and Hoare, 1991).Sedimentological analyses were carried out on bulk soil samples collected from a selection of these adventitious sections, identified during the field surveys because of their potential information yield - i.e. the presence of archaeological layers or buried soil horizons or pivotal interfaces between climatically opposing sedimentary processes -.

The obtained data were used to produce grain size distribution diagrams and concentration curves for each explored chemical component.

2.4 Micromorphological analyses

In support of all other analyses, micromorphology of thin section of undisturbed soil samples (i.e., lifted as blocks and kept intact) was carried out.

Micromorphology is the study of soils and sediments at the microscopic scale. The technique adds fundamental insights to the understanding of formation processes of depositional layers, soils, transformations of soils and, ultimately, the formation of archaeological sites, because it allows to see and interpret sub-millimetric features that would be otherwise unrecognizable. Everything, in an undisturbed and oriented soil sample, ultimately has a meaning towards the reconstruction of the sin- and post-depositional events that condition the formation and evolution of the stratigraphy (Goldberg, 1980; Bullock et al., 1985; Murphy et al., 1985 and Courty et al., 1989).

Samples were collected from clean sections, outlining oversized blocks using a very thin knife. The blocks were lifted and further roughed out until ~5x5x10cm parallelepipeds were obtained. These were carefully laid out on newspaper, wrapped up and secured using soft elastic bands. Orientation was reported with a marker on the external surface of the newspaper. We choose the newspaper technique because it allows the sample to desiccate slowly and naturally from the moment it is collected, preventing cracking caused by fast oven heating. Samples were wrapped in wadding for transportation and shipment.

The thin sections were manufactured by Massimo Sbrana "Servizi per la Geologia" laboratory (Piombino, Italy - serviziperlageologia.it). The preparation followed the procedure described by Murphy (1986). The finished thin section product is a 45 x 85 mm slice mounted on a glass support and covered with thinner glass for additional protection.

The thin sections were scanned at 1:1 magnification and studied employing an optical petrographic microscope (Olympus BX41) mounting a digital camera (Olympus E420) for the acquisition of high-quality images. Observation was carried out at various magnifications (20x, 40x, 100x, 400x) under plane polarized light (PPL) and cross-polarized light (XPL).

The description of the thin sections (*Appendix C*) followed the terminology suggested by Stoops (2021), and their interpretation was aided by the coloured atlases and concepts summarized in Nicosia & Stoops (2017), Macphail & Goldberg (2018), Stoops et al (2018), and Verrechia & Trombino (2021).

3. Present day physiography and landscapes: the periphery of two worlds

This chapter presents the natural and anthropogenic features of the Eastern Sudanese landscape in its present-day climatic and geomorphological settings. Using updated excerpts of the paper "*Geomorphology and (palaeo-)hydrography of the Southern Atbai plain and western Eritrean Highlands (Eastern Sudan/Western Eritrea)*" (Costanzo et al., 2021a), the study region is contextualized as part of the supra-regional climatic and environmental domain of the Sahel.

The geomorphological research was carried out concurrently with the archaeological activities of the Italian Archaeological Expedition to the Eastern Sudan, over a period of three field seasons. Sample areal units for field control were identified and selected from satellite images, and *in situ* surveys were planned accordingly. Vast part of the area of interest is in fact unapproachable due to rough terrain, sandy pits, tight shrubland and vast crops divided by steep earthworks, lacking any raised landmark anywhere west of the Gash River except for Jebel Tarerma/Erembat and Jebel Ofreik (Fig. 3.1), which are offset to the northwestern margins of the study area. Natural and anthropogenic deposits were examined from naturally exposed sections and from archaeological excavations as well. Occasionally, test pits and trenches were employed for assessing localized stratigraphic relationships between depositional features in archaeologically negligible (i.e., not pristine and/or poor in artefacts) locations (Rick et al., 2022).

The total characterized area, covering 28,500 km^2, is represented in Figure 3.1 and *Appendix A - Geomorphological and (palaeo-)hydrological map of the Southern Atbai and western Eritrean Highlands*, which provides graphic reference for all landscape features reported in the following paragraphs. The map drawing process was carried out as described in Chapter 2.1. The map's confines are arbitrary and do not represent natural or political boundaries, but a large buffer around the main geographic and archaeological features that are object of the present research.

Thorough descriptions of all features are provided, focusing on structural landforms, active and fossil fluvial landforms, residual surfaces, aeolian landforms and zoogeomorphological and anthropogenic features. The geomorphological characterization lays the foundation for the interpretation of the evolution of the local landscape, representing a powerful tool for reconstructing the spatial and temporal distribution of Late Quaternary archaeological features, and their functional relationships with the fossil fluvial system, the western foothills, and the Holocene environmental dynamics.

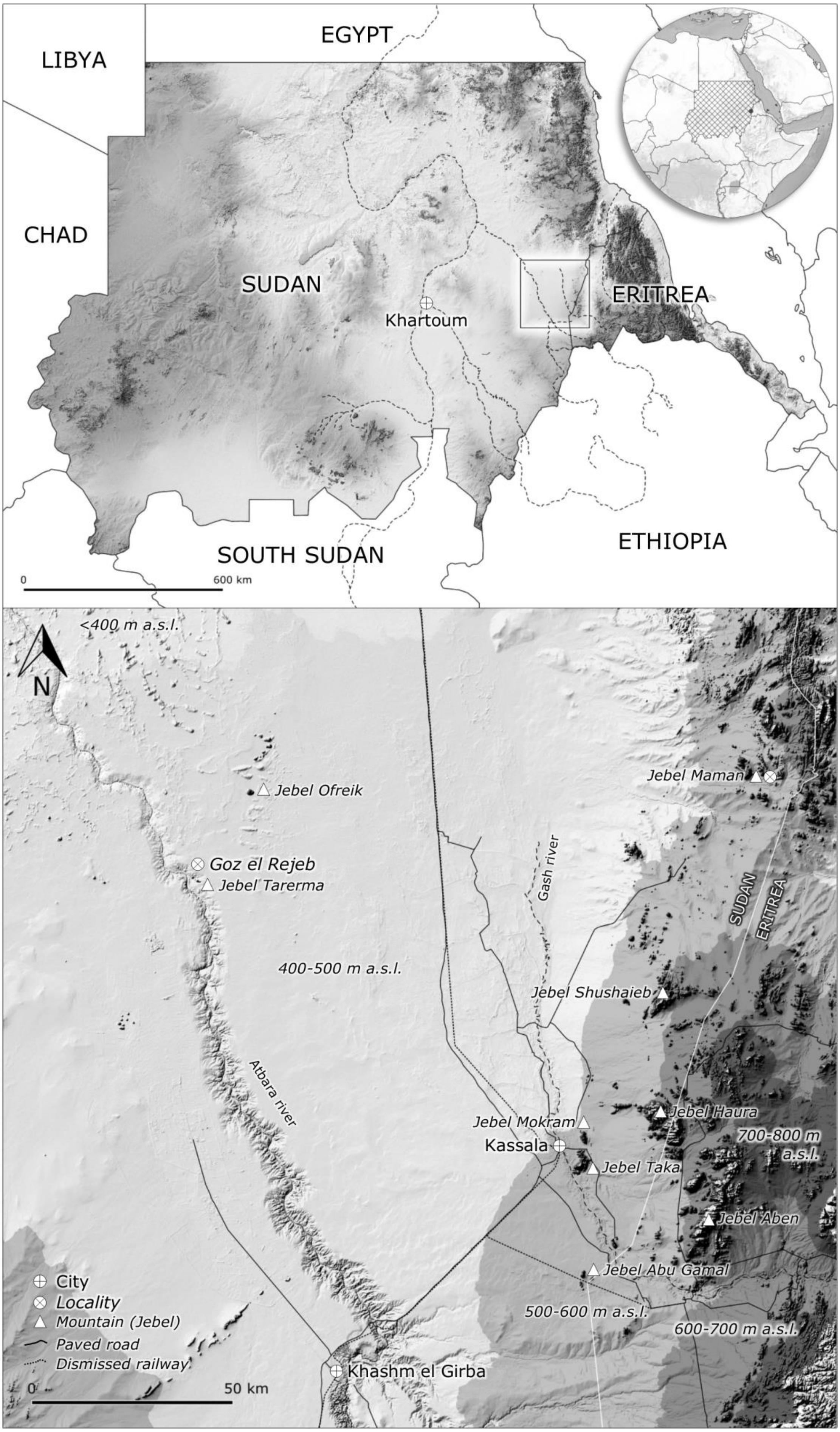


Figure 3.1 Overview of the region covered in this research.

3.1 Introduction

The Sahel is an African region corresponding to the transitional belt between the hyperarid Sahara and the peri-equatorial pluvial zone, extending for ~3,000,000 km^2 from the Atlantic Ocean to the Red Sea and bracketed between 10° and 20° latitude (Epule et al., 2017). Although receiving substantially more abundant rainfall than the Sahara, the Sahel is suffering severe desertification caused by both climate change and human agency (Huang et al., 2020). The latter is also responsible for altering the variety of landscapes that are found therein, whose formation, on the other hand, is primarily the result of complex and extensive palimpsests of natural event (Roberts, 2019). The geomorphological and ecological evolution of the Sahel was - and still is – triggered by several factors, including, most notably, the lithological and structural properties of the regional bedrock, and the contrasting past and present climatic settings, which have been oscillating throughout the Quaternary as alternating pluvial and (hyper)arid periods (Cruz Larrasoaña, 2021). Since the emergence of agriculture and husbandry in the Holocene, several anthropic interventions such as deforestation, diversion of water courses, excavation of artificial canals and alteration of topography, were put in place with the aim of satisfying an ever-growing demand of land for cultivation and pasture, however resulting, ultimately, in the disruption of natural ecosystems and progressive desertification of large regions (ArchaeoGLOBE, 2019; Huang et al., 2020; Wright, 2017).

At the easternmost low-lying fringe of the Sahelian belt, the Kassala region of Sudan is found. The Nile basin's alluvial plains terminate against the western edge of the Ethio-Eritrean Highlands, where the alluvial savanna encounters the crystalline rocky outcrops of the Arabian-Nubian Shield (Johnson et al., 2011). The region is crossed by two large rivers: the Atbara, which is the northernmost perennial tributary of the Nile, and the Gash, an impetuous endorheic sandy braided seasonal river originating in the Highlands. The region played a crucial role in the Pleistocene and Holocene human peopling of northeastern Africa, because it represents a bridge between the Nile Valley and the Horn of Africa (and beyond) (Beyin, 2013; Beyin et al., 2019; Gatto & Zerboni, 2015). Today, the area outside of the densely packed urban centre of Kassala is sparsely inhabited, but huge anthropic modifications of the hydrographic network, carried out between the 1860's (Dahl & Hjort-af-Ornas, 2006) and the 1960's (Barbour, 1961; Woodward et al., 2020) with the objective of increasing the extension and yield of cultivable patches, disrupted the region's natural savanna ecosystem irreversibly.

3.2 General climatic and physiographic settings

The position of the Kassala region, which is wedged between the Ethio-Eritrean Highlands and the open shrubland that leads to the Sahara Desert, conditions the local climate. In the south-east, the relative mitigation offered by the mountain ranges provides slightly enhanced seasonal rainfall, making for a hot semi-arid (BSh) (Kottek et al., 2006). Moving north-east, in turn, the climate gradually shifts to hot desert (BWh), with progressively decreasing presence of arboreal vegetation and increasing occurrence of seasonal grassy shrubs colonizing sand dunes. The rainy season is set between June and September, peaking in July and August, with the city of Kassala receiving an average precipitation of 250 mm/year (Hermance, 2014).

The present-day course of the Gash river further separates the region of Kassala into two contiguous physiographic sub-regions: the Southern Atbai alluvial plain to the west, and a vast glacis (i.e., a gentle slope connecting a valley bottom to a mountain range) leading up to the Highlands to the east (Plate 3.1).

The Southern Atbai plain is the portion of land outlined by the Atbara and the Gash rivers to the west and east respectively, and extending south to north from the city of Khashm el Girba to the locality of Goz Regeb. The plain is gently sloping down from SSE (560 m asl) to NNW (420 m asl), with a slope variability ranging from 0.5% (2,86°) to 0.1% (0,57°) along a 140km longitudinal transect. The land is covered with Quaternary fluvial deposits, comprising glaring evidence of an ancient network made up of multiple generations of meandering, braided and anabranching paleochannels, which converge towards the dried-up deposits of the Middle/Late Pleistocene shallow dune-interdune lacustrine environment of the Atbara Paleolake (Abbate et al., 2010). Although the Quaternary alluvium is generally unconsolidated, the upper strata were interested by hot/humid climate pedogenesis, resulting in a strong compaction and reddening of the residual clays. Today, the Atbara is a perennial, low-sinuosity river with an incised riverbed some 10–30 m lower than the surrounding area and flanked by a tributary system of ephemeral sandy streams extending for up to 4 km on each side. Downstream of the Khashm el Girba Dam, along the river, the bedrock underlying the Quaternary fluvial deposits - Precambrian crystalline basement capped by Cretaceous Nubian Sandstone and Cainozoic basalts (Abbate et al., 2010; Whiteman, 1971) - is poorly exposed and concealed by unconsolidated alluvium.

To the east of the Gash River, the gravelly and rugged deflated glacis cut by E-W aligned tributary channels (in Arabic: *khors*) gently slopes up to the edges of the Eritrean Highlands. The S-N orientation of the residual ridges, dictated by the supra-regional morphotectonic processes, creates a watershed between the Gash and the Barka rivers' catchments, separating the Nile's basin from the Red Sea headwaters. Bare rocky outcrops are very common: alternations of Paleoproterozoic (2.5-1.6 billion years) gneiss hills and Neo-Proterozoic (1.0-0.541 billion years) igneous plutons (granite and granodiorite; Geological Research Authority of the Sudan, 2004) dot the landscape in the form of imposing inselbergs and batholites, uplifted from the basement during the formation of the Arabian-Nubian Shield (Johnson et al., 2011). Inselbergs and batholites are often assemblages of many discrete domes, and are also found sparsely scattered far from the main mountain range and well within the floodplain, as it is the case of the Jebel Taka, Jebel Abu Gamal, and the small domes near Goz Regeb and along the Atbara's main paleochannel (Plate 3.2). All geological formations are fragmented by fault-induced joints and discontinuities that are consistently found throughout the study area. These are especially evident in two main families of fractures, respectively SE-NW and E-W oriented, of which the latter is more prominent and offers zones of weakness for rock weathering processes. The regional morphotectonic evolution also induced the formation of felsic (i.e. of quartz-feldspar dominant composition) dyke swarms. Dykes are hypo-abyssal, high-angle planar magmatic bodies, sometimes coming in swarms of dozens of separate elements, that extrude from fractures present in the pre-existent solid rock and are recognizable at the topographic surface as linear rock bodies, a few metres large and several tens of kilometres long. In the region they cut all crystalline granitoid formations, but are in turn segmented and displaced by the same fractures fragmenting inselbergs and batholites, revealing the exact direction and extent of strike-slip faulting. Meta-volcanic and meta-sedimentary gold-bearing assemblages are also present, always in the form of discrete inselbergs (Elsamani et al., 2001; Geological Research Authority of the Sudan, 2004) (Plate 3.2).

The Gash river (known in Eritrea as Mareb), finally, is the single, most important hydrographic feature for the subsistence of the urban economy of the open plain cities of Kassala, in Sudan, and Teseney, in Eritrea - just past the border. It is a seasonal river that originates south of the Eritrean capital city of Asmara; for the first half of its 680 km it crosses the Eritrean Highlands, flowing through steep-sided valleys and narrow gorges, often creating permanent pools where the eroded bedrock allows it. In its second half, it becomes a wide, sandy braided river fed by ephemeral networks of *khors* (long, linear incisions with steep banks and sharp edges, hosting seasonal ephemeral streams of water) and gullies. Lastly, it terminates into the open Sudanese plain with an SSE-NNW-oriented long and narrow endorheic terminal fan, drained by artificial canals that exploit its significant agronomic potential (Barbour, 1961) (Plate 3.1). The terminal fan occupies an SSE-NNW-oriented shallow tectonic sub-regional depression, probably a half-graben, that was generated by a Late Quaternary relative displacement of two parallel faults, the Atbara-Hudi Fault and the Gash Fault (Plate 3.1and *Appendix A*) (Abbate et al., 2010).

South of the Southern Atbai plain, a slightly more rugged area crossed by ephemeral tributaries of the Atbara river extends for a few tens of kilometres until it encounters the Setit/Tekeze river basin.

3.3 Morphogenesis of the region: a deeper look

Each physiographic sub-region described in section 3.2 can be further characterized by breaking them down into individual geomorphological features. The current geomorphological settings are, in fact, the ultimate result of the palimpsest of morphogenetic processes that has been shaping the land for millions of years at all scales, from regional to sub-metric. Landforms in their current shape and conservation status carry significance for the reconstruction of past environments and for the comprehension of current dynamics: their interpretation is crucial to define the extent at which human groups shaped the environment and were, in turn conditioned by it.

3.3.1 Tectonic and structural landforms

The current shape and alignment of the rocky outcrops east of the Gash River are a result of intensive uplift and shear of the Precambrian crystalline basement in the area, related to the late Neo-Proterozoic phases of the orogeny of the Arabian-Nubian Shield (Johnson et al., 2011) that also produced the pervasive fragmentation and displacement of rock masses caused by parallel strike-slip faults. Likely, the uplift of the granodioritic plutons that dot the landscape occurred after the formation of the crystalline basement, because they appear to have dragged upwards parts of the gneiss outcrops as a result of the forced intrusion. Fault systems also triggered the intrusion of felsic dykes, which form extensive swarms visible at ground level as low-lying linear reliefs or as tabular intrusions within the raised inselbergs. They reveal different generations of faults occurring; in fact, while they preferentially occupied E-W oriented discontinuities, they were later segmented and displaced by several parallel strike-slip faults that caused relative translations of up to 150m (Plate 3.3).

Solution weathering that occurred under warm and wet past climatic conditions, acted preferentially along faults and fault-related fractures, unloading-induced sheeting joints and thermally-induced fissures (Plate 3.4) (Twidale, 1982). This also influenced the continuous weathering of rocks: they are exfoliating along iso-oriented discontinuities, producing mildly sloping to subvertical flat surfaces that usually end with abrupt steps or rounded domes (bornhardts) (Plate 3.4). Exhumed inselbergs are surrounded by a chaos of detached blocks. They are either found at the bottom of the slope or scattered throughout the hillsides, depending on the smoothness and gradient of the etchplain (a smooth or slightly irregular surface that is exposed by weathering and removal of resulting detached debris) (Plate 3.4). Single granitoid blocks show varying degrees of alteration. Those at higher altitudes often preserve their original polyhedral shape and are coated with a dull orange to dark brown alteration patina, a sign of prolonged and undisturbed exposure of a rock surface to atmospheric agents (Dorn, 2009). Those at lower altitudes show exfoliation, disaggregation, and their coating is thinner and paler. Some more isolated outcrops are subject to sand-blasting of surface winds that cause rapid exfoliation and smoothing of the surface of the lowest blocks, which appear perfectly rounded. Nubbins and tors are also very common (Plate 3.4), occurring mostly atop whaleback outcrops.

3.3.2 Fluvial landforms

In the study region, an active and a fossil fluvial network are found (Fig. 3.2). The active network, although characterized by a marked seasonality that keeps it dry for eight months per year, is readily visible and identifiable in the landscape; it comprises the two main rivers of the region – the Atbara and the Gash –, a sparse distribution of discontinuous *khors* between the two main waterways, and a much denser tributary drainage network cutting the glacis east of the Gash river. The fossil network, on the other hand, is almost impossible to identify from ground level because nearly all features were levelled by wind erosion, sheet wash, xerophyte vegetation overgrowth and, most dramatically, agricultural parcelization, carried out with consistent use of heavy ploughing machinery. Nevertheless, high resolution satellite images disclose an intricate fossil fluvial network made up of dozens of paleochannels forming an intricate relict riverscape occupying the entirety of the Southern Atbai plain.

Active fluvial networks

The Atbara River, as introduced earlier, is a perennial, low-sinuosity meandering river (mean width is 300 m downstream of the Khashm el Girba dam), with a stable riverbed deeply incised into unconsolidated to cemented floodplain deposits. It is surrounded by a tributary system of ephemeral streams extending for up to 4 km on each side (mean width past the dam is 70 m, decreasing to 30 m in the northern stretches) (Plate 3.5), forming an open, low-gradient badlands drainage landscape. The badlands landscape has long been object of investigation, and has yielded plentiful evidence for riverine settlement and exploitation since the lower Palaeolithic, as attested by the discovery of a relatively continuous cultural sequence, spanning from the Acheulean to recent Arab groups, built upon artefacts collected from several buried and open-air contexts distributed from Khashm el Girba down to Goz Regeb (Shiner, 1971; Costanzo et al., 2020b) and further downstream (Masojć et al., 2019).

The Gash River is a seasonal endorheic river that originates in the Ethio-Eritrean Highlands and terminates in the Sudanese savanna as a sandy braided and weakly meandering river dissipating in a terminal fan (Plate 3.5). Its downstream activity depends on the upstream water supply, because the semi-arid climate of the Sudanese interior and the sediments underlying its riverbed are incompatible with near-surface groundwater retention. Its lowlands riverbed, up to 1200 m wide with an average of 600 m, is shallow and prone to flooding (Alredaisy, 2011). Since the

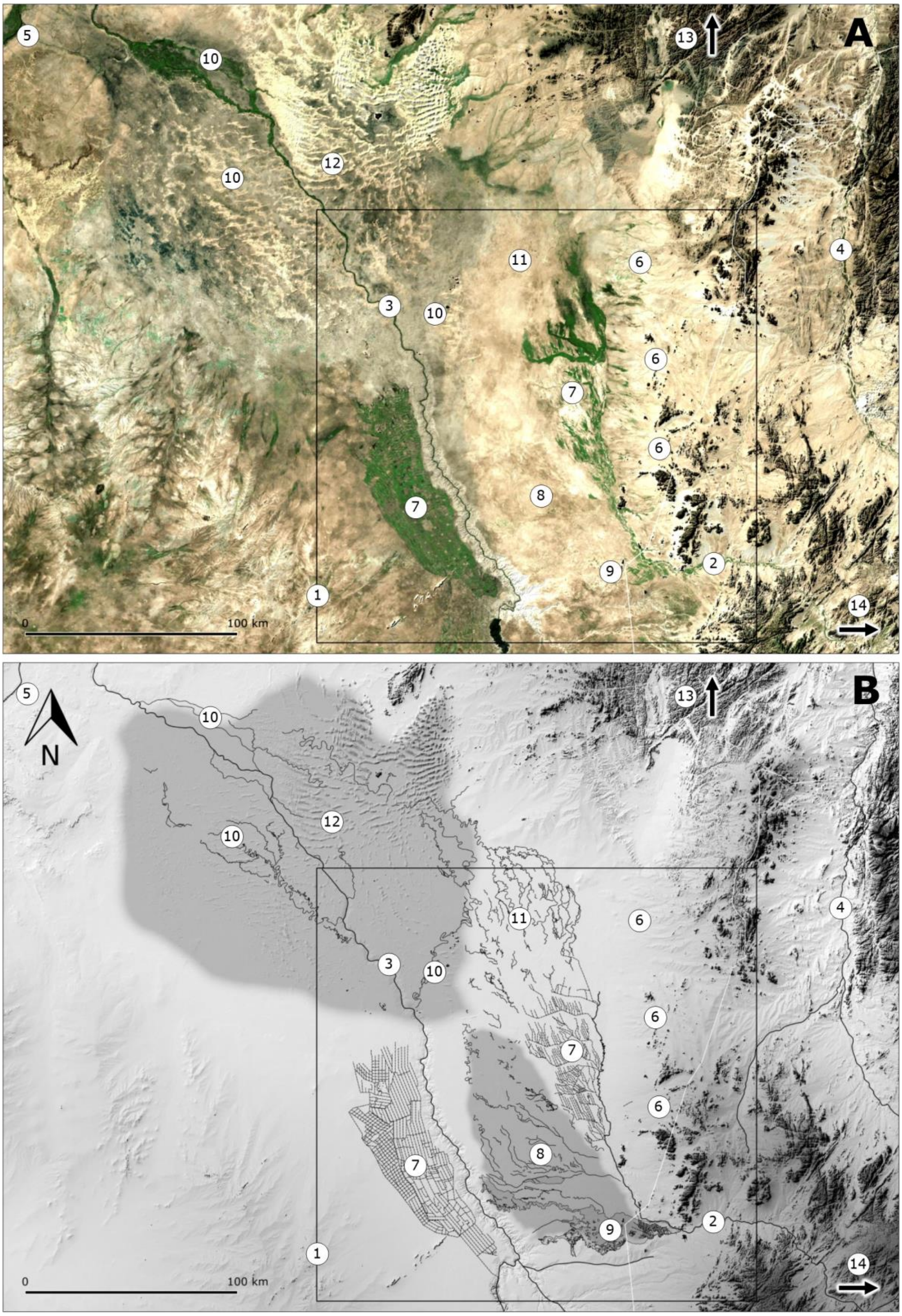


Figure 3.2 Overview of the active and fossil fluvial network of the extended region. *(A) Satellite view. (B) DEM+Hillshade view. 1) Main Study Region; 2) Gash river; 3) Atbara river; 4) Barka river; 5) Nile river; 6) Source area of the Gash's active tributary network (not represented to avoid cluttering); 7) Artificial irrigation canals; 8) Late Pleistocene Gash's fossil network and alluvial plain (dark hue); 9) Gash's fossil anastomosing system; 10) Atbara's Early/Middle Pleistocene paleochannels; 11) Gash's Early/Middle Pleistocene network; 12) Early/Middle Pleistocene Atbara paleolake hypothetical surface (dark hue); 13) Red Sea Hills; 14) Ethio-Eritrean Highlands.*

1980's, the main riverbed between 25 km to, and 10 km past, the city of Kassala, has undergone substantial infrastructural modifications. The riverbed has been straightened, enlarged and, in its urban course, constrained within tall masonry riverbanks, with the aim of regimenting the water for the maintenance of fruit orchards and non-drought resistant crops. The terminal fan is a 100 km long, 30 km wide system of natural crevasse splays and artificial canals that has been exploited for intensive agriculture since 1924, with a large spate irrigation system that drains the only remaining active branch with limited efficiency and control over the water intake and redistribution (Barbour, 1961; Ghebreamlak et al., 2018). Over time this has led to the unregimented deposition of fine alluvium and the formation of otherwise unachievable splays across its whole extension and into the currently arid northern stretches of the Southern Atbai, where dispersed irrigation sheet wash intermingles with sand dunes.

The *khor* system that extends between the Atbara and Gash rivers sets within topographic lows and softer ground left by the abandoned Gash's paleochannels. The water flows from east to west into the Atbara, or moves discontinuously until dissipation, or sets statically along larger abandoned meanders, forming oxbow lake-like stagnant depressions colonized by riparian vegetation and soft grass (Plate 3.5).

The Gash's tributary network originating from the Eritrean hills, contrarily, is very dense and tripartite (Plate 3.5): (I) precipitation is gathered by the bare rocky outcrops following drainage patterns that converge downslope into large dendritic, trellis, radial or annular systems, depending on the shape, size, slope and fracturing/fissuring condition of the underlying bedrock; (II) the collecting drainage systems merge into E-W flowing medium-sized single channels (mean width is 150 m) with gravel-dominated bedload; (III) the channels flow towards the lower plains splitting into splays and sheet flows on increasingly flatter ground, thus never reaching the Gash River as full-loaded streams (Plate 3.5). This system is responsible for consistently mobilizing new weathering products and Quaternary deposits east of the Gash River, feeding the terminal alluvial fan up to its northernmost stretches. Most of the mobilized sediments are eroded from foothill deposits by channelled runoff, triggered by the steep water convoying angle. Sharply cut gullies can reach widths of several tens of metres and depths of up to a few metres.

Fossil fluvial networks

A system of paleochannels, seemingly related to the Late Pleistocene to Holocene evolution of the Gash River (Manzo, 2017 and authors cited therein), yet as of now not anchored to any absolute radiometric dating, is located between the Atbara and the Gash rivers, forming a succession of channels and coalescent fans and splays with an SW-NE progression (Fig 3.2 and *Appendix A*). The first relict apex is located at the abrupt northward turn of the modern river; from that point, a ~550 km^2 slow water system of individually small channels originates (Plate 3.6). The feature was heavily levelled by natural and anthropogenic weathering, and the Tandem-X and JAXA DEMs shows very little slope variations. In truth, it is from natural colour and composite bands coloured satellite images that the system is most recognizable. The very toponymic of the location, *Shurab el Gash*, means *the Gash's ponds*: in fact, an active system comparison from other north African locations may be found in the Khor Abu Habl' fan (White Nile State, Sudan), or the Niger River's inland delta (Plate 3.7 A-D) - just to name two examples, but the Sahelian belt provides plenty more -, where slow moving water, splays and networks of intermingling active and relict channels create hybrid riverine-lacustrine environments, with shallow ponds sustaining riparian vegetation and drought-resistant freshwater fauna. The *Shurab el Gash* system diverges into four small single channels that were mostly erased by ploughing - their identification from satellite images requires time, dedication and a trained eye -, which seem to have been tributaries of the

Atbara. The second relict apex is located ~12 km south of the city of Kassala. At least two major channels, comparable with the present-day Gash in terms of size and morphology, originate from it (Plate 3.6). They represent the single, most evident fossil fluvial feature of the plain, still preserving portions of intact riverbed and bedload stabilized by grass overgrowth. Although, again, their conservation status is compromised by ploughing, trampling and - limited - aeolian cover, which dismantled their proximal and distal portions, leaving only the central portion relatively intact, they appear to have been endorheic as a result of the slight uplift caused by the Hudi-Atbara Fault, which produced a SE-facing tilt of the entire northern half of the Southern Atbai Plain (Plate 3.1B) preventing eastern watercourses to reach the Atbara river. The third relict apex is inferred to be situated in correspondence of the city of Kassala, but evidence is obscured by the urban expansion. The only recognizable paleochannel originating from it (~15–60 m) is a high sinuosity, laterally active (i.e., active migration of the riverbed with deposition of scroll bars and point bars) meandering channels, heavily levelled and partially erased by infrastructures or covered with modern artificial alluvium laid by the spate irrigation system (Plate 3.6).

A probably older system of paleochannels is visible to the north and north-west of the Gash alluvial plain. Its age may be compatible with recent discoveries by Tsukamoto et al (2022), who dated with Optically Stimulated Luminescence (OSL) the entire accretional sequence of the Atbara river near Khashm el Girba between 224±23ka and <17±1ka, although the location of their study may be too far from the riverine system presented here to be significative in its regard. The most prominent feature is a large SW-NE flowing Atbara paleochannel diverging from the modern riverbed north of Goz Regeb at a 60° angle from the present-day river (Figure 3.2). It follows a high sinuosity trajectory with active lateral deposition and no entrenching - as opposed to the present-day Atbara, which flows up to 20 m deeper than its surrounding plain - and runs northeast for 60 km, until it merges with an intricate system of smaller channels, often recognizable by the faint vegetation overgrowth colonizing scroll and point bars, running parallel to the eastern piedmont. The latter seem to be related to an ancient setting of the Gash river, much older than the fossil alluvial plain described above, that was able to overcome evapotranspiration, thanks to favourable climatic settings and substantial intake from the drainage of the north-eastern hills encircling the Southern Atbai, and feed the ancient Atbara Paleolake, a shallow dune-interdune lacustrine system that today occasionally gathers enough rainfall to create a few ephemeral ponds. Considering the discovery by Abbate et al. (2010) of Gilbert-type delta sedimentary structures (typical of rivers pouring into lakes) within the present-day Atbara's eroded embankments north of Goz Regeb, the combination of large paleochannels with plentiful minor feeders spreading across a large plain again finds a viable present-day comparison in the Chari river feeding Lake Chad north of N'Djamena (Chad) (Plate 3.7 E-F). Therein, one large river and hundreds of minor anastomosing channels and relict ponds gather seasonal drainage of the central Sahel, creating a vast alluvial plain that slowly pours into the shallow and discontinuous waters of Lake Chad. It is very likely that the Late Middle Pleistocene fluvial landscape of the Southern Atbai, during particularly wet and favourable periods, would have been characterized by a highly dynamic active riverine-lacustrine environment - possibly laying the foundations for human dispersal corridors – which would have still been exploitable in much more recent late prehistoric, protohistoric, and historic settings thanks to the water-retainance properties of the silty/sandy relict bedload.

3.3.3 Residual surfaces

The flat, gentle glacis east of the Gash River represents an archive of subsequent phases of accretion, weathering and erosion of deposits that derive, ultimately, from *in situ* dismantling of the crystalline geological formations that characterize the region. The pediplain shows, in fact, a rather consistent stratigraphy over its whole extension. There, the Precambrian basement and the Cainozoic sandstones are covered by a tight alternation of laterally coalescent wadi sands, slow water laminations and windblown silt layers. Pedogenesis of such deposits is evident, as buried and heavily humified thick soil horizons (up to ~4 m thick), which will be discussed further on in the following chapters, are found ubiquitously. Their formation was promoted by water availability greater than today, during periods of enhanced rainfall caused by the northerly shift of the summer monsoon that sustained grassy savanna environments. The current topographic surface, where it is not furrowed and disrupted by gullies, is sealed by a residual layer of coarse gravel and small stones that form a relatively well-developed desert pavement - a terminal surface landform created by the wind removal of smaller particles that is commonly found throughout arid lands (Knight & Zerboni, 2018) (Plate 3.8). Angular stones of the "*hamada*" type desert pavement are commonly found when approaching the hills, where they derive from short-transported weathered debris and colluvium. On the other hand, some patches of the "*serir*" type desert pavement, composed of rounded stones, are found sealing raised terraces of the Atbara river downstream of Khashm el Girba. The stones are mostly basalt pebbles eroded from the Khashm el Girba basalt outcrop and transported by the river during high flood periods. The Mahal Teglinos (K1) archaeological site, largely presented and discussed in Chapter 4.2, is a privileged location to observe aggradation, pedogenesis and erosion because recent rill erosion exposed the entire Holocene stratigraphic record therein: an Early/Middle Holocene organic paleosoil, patches of calcrete and an alterite underlying the whole 6 m thick succession, sealed by a tight desert pavement composed, almost completely, of archaeological material such as potsherds, lithics and animal and human skeletal remains (Costanzo et al., 2020a; Costanzo et al., 2022; Cremaschi et al., 1986) (Plate 3.8).

3.3.4 Aeolian landforms

Windblown sand sheets, single barchan dunes and fields of coalescing barchans can be observed at the very northern and north western edges of the Southern Atbai plain (Plate 3.9), far from the cultivated land and approaching the area corresponding with the Early/Middle Pleistocene fluvial landscape and Atbara Paleolake described in section 3.3.2. Sand sheets are very likely still remnants of the dune-interdune lacustrine system of the Atbara Paleolake. They are stabilized by patches of grass, shrubs and xerophytes growing especially along their sinuous perimeters. The barchan and coalescing barchans, on the other hand, are kept active by strong seasonal winds with opposing directions. The fine sand building the dunes likely derives from the mobilization of the unconsolidated finer sediments laid by the hundreds of channels and splays whose eroded open-air remnants are often found, coincidentally, relatively close to dune fields.

Aeolian deposits are also found as localized sand sheets leaning against the hillslopes of inselbergs and whaleback rocks, where the relief provides sheltered spurs or secluded valleys that act as wind breakers that disrupt the kinetic energy of winds favouring the deposition of sand and dust. Such is the case, for example, of the valley of Mahal Teglinos, where the aeolian dust deposit reached a thickness of almost 2 m intertwining with the colluvial pediment (more on this in Chapter 4.2), or the small reliefs outcropping from the fossil lacustrine landscape along the course of the Atbara's paleochannels, where windblown sand forms rampant dunes engulfing boulders and crevices (Plate 3.9).

3.3.5 Zoogeomorphological and anthropogenic landforms

Thousands of animal trails can be observed throughout the Southern Atbai except for its arid north-western fringe far from the Atbara River, where they become more sporadic and less erratic. Dramatic concentrations of animal trails are distributed along watercourses and in the vicinity of villages and *hafirs* - artificial watering ponds - (Plate 3.10). Vehicles leave similar marks on the rocky desert pavement and the dusty cultivated land. Animal- and human-related agency appears to be a major cause for ground instability and soil loss (Zerboni & Nicoll, 2019), especially along the hillslopes affected by severe runoff. In such geomorphological contexts trampling of flocks amplifies the retreat of existing escarpments and triggers the formation of new ones by stripping large patches of vegetation and desert pavement.

Plentiful cases of deep modifications of the landscape at the regional scale can be observed as results of agricultural activities and water harvesting practices. Some examples are the Khashm el Girba dam (Plate 3.10), the trench dam protecting Kassala from the flooding *wadis* descending from the hillslopes laying east (Plate 3.10), the massive Gash Spate Irrigation System north of Kassala and its smaller homologue west of Teseney (Eritrea) (Plates 3.1 and 3.5F), the creation of polygonal partitions of rainfed crops throughout the non-irrigable plain, created by contouring the slope with steep earthworks made of bulldozed topsoil, and the diversion of foothill streams using tree branches and mud wedges to obtain large overflooding sheet flows (Plate 3.10). The yearly maintenance of the earthworks and wedges, which dissolve and are slowly but inevitably pushed downslope by surface water movement, involves the reworking of surface deposits. This is leading to an enhanced mobilization of fine sediments that become easily removed by wind and water erosion, paired with the formation of swamped area flanked by nutrients impoverished patches.

Road and dismissed railway infrastructures contribute to further disrupting the natural morphogenetic processes and landscape of the region. Because the infrastructures are built over steep linear earthworks that are raised up to 1 m above the surrounding ground, the natural movement of surface water and ground-level winds is disrupted, triggering the formation of entrenched gullies and dust deposits along their trajectories.

In general, modern and sub-recent animal and human agency are responsible for the most pervasive modifications and disruption of the geomorphological landscape and natural ecosystem of the region, posing a threat to archaeological sites at all scales as a direct result of trampling, erosion, and soil loss.

3.4 Conclusion

In the Southern Atbai Plain and the western edge of the Eritrean Highlands, ancestral morphogenetic processes started with tectonic uplift, supra-regional twisting and faulting, and emersion of large crystalline batholites as main driving factor in shaping the area. Yet, the extant landscape started forming in the Quaternary due to deep rock weathering, fluvial and colluvial processes and phenomena, and aeolian dynamics triggered by the humid and arid alternating periods that acted around minor regional tectonic adjustments. The work presented in this chapter introduces the natural settings upon which the geoarchaeological investigation took place. The prominent role and constraints of the geomorphological settings of the region on the archaeological communities are highlighted, providing background for explaining site distribution in relation to past land habitability within the fossil fluvial plain and the rocky piedmont region. Moreover, the regional geomorphological map (*Appendix A*) provides a base for planning future archaeological surveys and interventions in unexplored areas, and, thanks to the very method used for its creation (i.e. GIS environment), allows the creation of computational archaeological and landscape evolution models (*Appendix C)*.

4. Vestiges: locations of interest for the reconstruction of past climates and landscapes

As introduced in the preface to this manuscript, the far Eastern Sudan is not an easily reachable place for doing extensive archaeological and environmental research. This is mainly due to the lack of infrastructure and the perilous nature of the landscape, which poses difficulties in reaching spots that are only a few kilometres off the paved road, let alone locations that are tens of kilometres away even from off-road tracks.

Choosing viable locations during the desk-assessment phase is crucial for optimizing time and resources on field. Even so, sometimes remote sensing falls short in presenting actual local-scale topography and geomorphological settings, and the value and magnitude of environmental and archaeological archives are only truly understood on field.

With the aid of the Geomorphological and (Palaeo-)Hydrological Map (*Appendix A*) presented in Chapter 3, and of high-resolution freely available satellite images, a list of high potential locations was compiled. Apart from the valley of Mahal Teglinos, which has been known for more than a hundred year as the most prominent archaeological site of the region (Crowfoot, 1928), the identified locations are, from an environmental value point of view, of novel consideration. They are mainly located either around large rocky inselbergs in spurs that looked morphologically similar to Mahal Teglinos itself - thus potentially comparable in their information yield -, or the open Gash river's fossil alluvial plain, where most of the archaeological evidence for seminomadic archaeological communities has been recognized in previous survey campaigns. Crucially, it must be noted that our current lack of knowledge upon prehistoric and protohistoric occupation in the land east of the Gash river's current terminal fan - i.e., whether it was as inhabited as the alluvial plain or not - is merely circumstantial, as no systematic intensive survey campaign has been carried out as of today. Nevertheless, the state of the art may be about to be brought significantly forward: as will be thoroughly presented in Chapter 4.3, a large Gash Group site, of size and artefacts yield almost comparable to that of Mahal Teglinos, has been identified at the foothill of a large inselberg some 15 kilometres east of Jebel Taka, on the Eritrean border. This may be the first of many others, constituting the true domain of the Gash Group.

The following chapters, mostly based on peer-reviewed published literature (Costanzo et al., 2020a; Costanzo et al., 2020b; Costanzo et al., 2021a; Costanzo et al., 2021b; Costanzo et al 2022; Costanzo et al., in press) present locations that were studied, albeit with different methods and at different levels of detail, for their impressive archaeological and environmental yield. Each of them contributes, thanks to a solid consistency of geomorphological settings and pedological bodies, and thanks to existent studies on faunal and botanical assemblages from dated archaeological contexts as well (Geraads, 1983; Beldados, 2015), to create a picture of the regional evolution of climates and environments. This very picture represents a lens for reading anthropological aspects of the archaeological past through happenings of the natural world, but is also a new tile of the larger, supra-regional mosaic that is the Holocene in northern Africa, a time of rising and falling of civilizations and technologies in a dynamic and inconceivably vast land – in other words, the human-environmental nexus.

4.1 The Southern Atbai

From the paleoenvironmental point of view, the Southern Atbai, i.e. the rectangular strip of land delimited by the parallel Atbara and Gash rivers that encompasses the Gash river's fossil alluvial plain, is, as of now, a still largely unexplored and only partially understood archive. Despite the plentiful data on settlement distribution on chronology produced by the archaeological surveys carried out by the IAMSK, IAEES and NCAM (Chapter 1.1), who found hundreds of open-air campsites dating as far back as the 7th – 6th millennia BCE along the banks of dried up river channels and ponds, systematic on-site evaluations of the fluvial and alluvial geomorphological palimpsest of the sub-region is still missing. In fact, only one location in the open plain (Site UA50, Manzo, 2017) was subjected to test trenching and sampling for evaluating the nature of the uppermost portion of the red-brown soil where most of the Mesolithic and later sites sit on. For this reason, geochronological data, which would be pivotal for anchoring the hypotheses drawn on the basis of remote-sensing analyses, as of now is not available. Yet, although it only yields a partial vision of an incredibly complex environment, remote-sensing itself in truth provided a way to decipher, at least, the spatial extent and surface morphology and morphometry of the active and fossil fluvial networks that provided sustainment to the archaeological communities.

4.1.1 The Gash river's fossil channel network – A geochronological open question

Ever since the beginning of the systematic explorations in the Southern Atbai carried out by Shiner (1971), Clark (1976) and Phillipson (1977) in the 1960's and 70's, later on followed by the expeditions of the IAMSK and IAEES, a conundrum has afflicted the interpretation of the spatial distribution of the archaeological sites found in the open plain between the Gash and Atbara rivers, specifically their temporal and functional relationship with the fossil riverscape of the region.

Early interpretations provided a most classic model of "site-water duality" (Fattovich et al, 1984; Fattovich, 1990), i.e. settlements would exist in correspondence of active water bodies - preferably rivers, lakes or fresh ponds. In effect, the vast majority of all sites discovered by the IAMSK and IAEES in the open plain (a total of 378 mapped locations, many of which bearing diachronic occupation) (Fig. 1.2 and Plate 4.1.1A), is found more or less in proximity of ephemeral or completely relict *khors* and ponds. Additionally, a rudimental understanding of the presence, within the open plain, of fossil channels crossing the land from East to West, was already available to the early scholars (Fattovich et al, 1984; Fattovich, 1990); this added a further layer of misinterpretation about the archaeological settings of the Southern Atbai, according to which the cultural sequence of the region, i.e. the people residing therein, would have moved over time following hypothesized subsequent phases of channel migration. Today, conversely, thanks to the availability of high-resolution satellite images paired with GIS instruments, and more on-field dedicated surveys and observation, the model can be revised and properly amended to fit a more accurate interpretation of the archaeo-environmental dynamics of the subregion.

One mega-fan, many riverscapes

As introduced in Chapter 3.3.2 "Fluvial landforms – *Fossil fluvial networks*", the Southern Atbai's interior hosts an incredibly complex palimpsest of relict riverscapes (Fig. 1.2, Plates 3.6 and 4.1.1, *Appendix A*), created by former trajectories of the Gash river during former climatic and tectonic settings. Such riverscapes are characterized by a common characteristic, which is a tendency towards a SW-NE migration of the transient drainage trajectory, i.e. the creation of a fluvial megafan, at the river's outlet from its narrow Highland canyon, whose age decreases northwards.

Despite the complete lack of geochronological anchorage for any of the channels constituting the relict riverscape, the age model is supported by the presence of a regional-scale half graben created by the relative movement of the Hudi-Atbara Fault and the Gash Fault, located at the western outskirt of the strike-slip fault systems of the Arabian Nubian Shield. The tectonic control forced the Gash river to gradually migrate northeast, eventually assuming its present-day trajectory within a linear depression that traps all water making the river endorheic. Additionally. the tectonics-forced migration was very likely mitigated or aided by transient local and supra-regional climatic regimes, providing abundance or causing scarcity of water availability from the headwaters down to the lower and terminal valley.

Former perennial rainfall availability across the Ethio-Eritrean Highlands and within the lower valley interior may have been crucial for feeding the Gash river and its tributaries with moderate flows, promoting the formation of the slow water inland splay starting from the first relict apex (Chapter 3.3.2 and Plate 3.6B) at the southern end of the megafan, the oldest of the three main fossil riverscapes. The resulting relict system that is visible today consists of pale well-drained sandy loamy sediments occupying the former anastomosing branches of the inland delta. The loam is in stark chromatic and spectral contrast with the surrounding host substrate (Plate 3.6B and 4.1.1B), and is subjected to slight localized subsidence where current seasonal precipitations gather and sustain dense patches of mixed shrubland-woodland savanna. The local toponymic for the area is Shurab el Gash, a dialectal modification from the Arab Sharāb al-Qash (شراب القاش), which can be roughly translated with "the Gash's ponds"; this is evocative of the environmental seasonality of the location, still subjected to mild transient swamping during particularly rainy seasons - a characteristic that is also reported as *«pools after rains»* on Sheet 56-A of the Sudan Survey 1940 cartography. The tectonic push eventually forced the anastomosing system to channel up and progressively move northwards, with the formation of at least four, probably diachronic wandering shallow main riverbeds, today almost completely levelled and erased by agricultural activity. The southernmost of the four channels currently hosts an underfitted watercourse named Khor Marmareb (largely discussed in Chapter 4.2.1), and all four channels appear to have been tributaries of the Atbara river.

More tectonic push, joined with a possible shift in upland climate towards an enhanced monsoon regime, gave way to the second riverscape. A few large channels bisect the Southern Atbai from the second relict apex down to the Atbara river's proximities (Chapter 3.3.2, Plate 3.6C and *Appendix A*), showing morphological characteristics that are completely different from the preceding settings. At least two major channels belonging to this system are comparable with the present-day Gash river in terms of size and morphology, with large meandering riverbeds (up to 700m wide) that, however, don't show prominent lateral migration (i.e. no scroll bars or point bars appear to have been deposited) (Plate 4.1.1C). The channels are remarkably well-preserved in the traits that were not affected by ploughing, with an overgrowth of vegetation within the riverbed that acted as a bedload stabilizer. Satellite images suggest a remarkable similarity with the present-day Gash river, thus it can be inferred, until more on-field data become available upon deep sediment stratigraphy, that these were sandy braided channels fed by intermittent large discharges during upland rainy seasons. Nowadays, a few segments of their ancient beds host thick riparian vegetation and muddy pools (Plate 3.5D), representing a potentially astounding environmental archive that may host pivotal highly resolute information upon the river's geochronology as well as the faunal, botanical and even human past of the immediate and extended surroundings.

A further tectonic push, coupled with a hypothetical renewed steadiness of uplands rainfall regime, created a third riverscape (Plate 3.6D) characterized by smaller channels prone to lateral migration across large areas with very convoluted meanders and active deposition of levees, scroll bars and point bars - easily visible from satellite pictures. Current vegetation overgrowth is lesser than the one stabilizing the other two systems, possibly as a consequence of its more northern location - thus lesser annual precipitation compared to the southern stretches of the plain. Nevertheless, late summer Landsat satellite images reveal vast blooming of ephemeral grasses, which provide surface protection to a certain extent.

A later and final phase of tectonic-climatic push forced the Gash river into its present course, occupying the long S-N linear depression constituting the eastern margin of the Southern Atbai's half-graben. The current settings are those of a large but relatively shallow entrenched sandy braided endorheic river fed by highly seasonal upland monsoon climate, flowing intermittently for a few summer weeks. Floods can be disruptive, causing banks collapses and, occasionally, overflows that bring destruction to nearby settlements. The river remained unregimented until 1924, when a large spate irrigation system created by the British started draining its distal stretches for intensive agriculture (Barbour, 1961). It must be noted that before 1924 there appeared to have existed two main terminal branches, the Eastern Gash and the Western Gash, of which only the latter still exists. The Eastern Gash was silted up to divert all water into the spate irrigation system, but its splays remained vivid enough to be represented into regional maps up to, at least, the 1940's, as reported on Sheet 56-A of the Sudan Survey 1940 cartography. An additional feature reported by the Sudan Survey 1939 on Sheet 45-P is the capacity of the Eastern Gash's floods to reach locations as far north as 16.74°N, 35.95°E, not far from the present-day settlement of Eriba, before dissipating into ephemeral pools at the outskirts of the fossil Paleo Atbara dune-interdune basin. This, in my opinion, is a cartographic mistake caused by the unavailability, at the time, of extensive aerial imagery and the subsequent limited - if not completely absent - comprehension of the fossil riverscape. Nonetheless, the reported feature more likely represents the furthest possible stretches of the Western Gash's floods (thus the present day's river) during times of great water availability from its upland course and, most crucially, from the dense network of ephemeral tributaries flanking its right bank. Such events, as reported on the same Sheet, were last recorded in 1916 and 1920, before the agricultural scheme enforced in 1924 siphoned all the potential flood water 100 km southeast.

Spatio-temporal relationship between riverscapes and archaeological sites

Almost all recorded sites within the Southern Atbai lie in correspondence of the described fossil riverscapes, with very few exceptions that are, however, still at manageable walking distance from relict channels in any direction (Plate 4.1.1A). Additionally, the Kernel Density Estimation (KDE) shows that the majority of sites, regardless of their age, is found in the area of Shurab el Gash and along Wadi Marmareb (Fig. 1.2 and Plate 4.1.1D). Nevertheless, certain geomorphological settings of the sites suggest temporal and functional relationships between them and the riverscapes that differ from the earliest interpretations of the regional pre- and protohistory (Fattovich et al, 1984; Fattovich, 1990).

Sites, consisting of thin surface scatters of lithics (knapped agate, granite pestles, basalt hammerstones and grinders – sometimes vesicular), ceramics, faunal remains and occasional inhumations, are usually found within the area covered by riverbeds or in their direct proximity, sitting above residual surfaces of levelled bedforms or over levee alluvial loam, regardless of the original geomorphological properties of any of the described riverscapes where they may be found. In some exceptions, i.e. the sites located along the active Khor Marmareb, older archaeological strata belonging to Pre-Saroba, Malawiya and occasionally Butana Groups intermingle with synchronous loamy flood laminations laid by minor overflows.

This very property, observed consistently for all recorded sites no matter their preservation status, opens for the most crucial geochronological inference upon the age of the Gash river's fossil alluvial plain, i.e. when the relict riverscapes were created by the past supra-regional tectonic and climatic settings. In the absence, for now, of absolute radiometric datings of the paleochannels, the surface finding of relatively intact sites starting as early as Pre-Saroba Group (7th-6th mill. BCE) all across the plain (Fig. 1.2), suggests that any fluvial activity of the past riverscapes was already ceased by the time said archaeological communities settled in the area. If the contrary was true, archaeological evidence would only be constituted by chaotic and partially buried scatters of completely shattered material, consequence of the periodic floods that would have affected the river's active plain. This is particularly true for the second relict riverscape where riverbeds as large as the present-day Gash river are found. Today, monsoon pulses over the river's upland valley cause disruptive floods that cause devastation of modern facilities all along the river's lowland course (NASA Earth Observatory, 2003; Alredaisy, 2011), but no trace of such disruption is recorded in the archaeological record of the Southern Atbai's interior. On the contrary, as previously stated, sites are found within what would have been the active range of the coalescing splays building the relict floodplain.

In the area of Shurab el Gash, where the evidence consists mainly of Gash (mid-3rd – early 2nd mill. BCE), Mokram (early 2nd – early 1st mill. BCE), Hagiz (mid 1st mill BCE – early 1st mill CE) and Gergaf (mid-1st – mid 2nd mill. CE) Groups, sites are found flanking denser vegetation patches and ephemeral pools, and show inter-site distance that never exceeds 5 km, measuring generally an average of 2-2.5 km, making the settlement network an easily walkable and safe environment for groups and individuals moving in any direction across the relict anastomosing riverscape.

Proceeding west towards the Atbara river, sites cluster along Khor Marmareb, an ephemeral intermittent entrenched water stream that sets with the topographic low left by an almost completely levelled Gash relict main channel. Therein, as introduced earlier, archaeological strata are engulfed in modestly thick loamy deposits (max 30cm) extending a few dozen metres each side of the stream, but are never found dismantled as it would be the case were they affected by large-scale floods. Some of the best studied and biggest sites of the open plain are found in these settings, such as UA50, discussed in the next subchapter, UA53, very similar to UA50 in terms of size, chronology and morphology, and UA14/KG23 (Plate 4.1.5 for the locations of the mentioned sites), a very large but still underexplored site whose diachronic occupation, spanning from the earliest Butana phases up to the present day, was so intensive that it caused the growth of a stratigraphically complex tell-like structure, wedged between Khor Marmareb and a small tributary, raising almost 150 cm above the surrounding plain.

Northern locations related to the second relict riverscape differ slightly in terms of number and conservation status, although this is likely caused by the prominent agricultural exploitation of the area, which was ploughed and scarred with heavy machinery since the introduction of intensive sorghum, millet and cotton production in the first half of the 20th century. Nonetheless, inter-site networks replicate those found in Shurab el Gash in terms of diachronicity, spatial organization and average distances. Again, sites are mostly found in correspondence of woodland-shrubland patches colonizing loamy splays and the fossil riverbed itself, which remained remarkably intact over a length of ~30 km possibly due to the inconvenience of ploughing and cultivating over excessively sandy and drained soil.

Further north, in correspondence of the third relict riverscape, occupation is again diachronic, starting with evidence dating as far back as the Gash Group (3rd mill. BCE), but evidence is too scanty to infer observation upon site networks and local economy. Nevertheless, it is evident that overall site frequency and distribution, of any age, within the Southern Atbai's interior follows a peculiar fan-like pattern. This not only reflects preference for locations providing arboreal shelter and availability of food and water resources deriving from the former riverine settings of the region, but is probably also connected with the inland penetration capacity of East African monsoon rainfall front. Still to these days, the cloud cover radiates northwest above the Southern Atbai with a circular sector geometry pivoting approximately in correspondence of the valley outlet of the Gash river, discharging most of its yield in the first tens of kilometres and progressively dying out as it moves farther from the Ethio-Eritrean Highlands.

It should also be remarked that, thanks to the GIS analysis of Landsat multispectral satellite images, a solid correlation emerged between areas with no recorded occurrence of archaeological sites and areas where the building of infrastructures, i.e. railways replaced with paved roads in recent decades, and the enforcement of intensive agriculture completely disrupted the pristine soil cover. This is readily visible in Plate 4.1.1E, where RGB spectral band combination 4, 5, 7 highlights blooming vegetation in bright green and unvegetated areas in grey. Sites are mostly found in area lesser affected or completely untouched by ploughing, and conversely affected areas where it would be reasonable to expect occurrence of sites show no recordings. Extant surviving archaeological record still allows plentiful data to be produced, but appropriate reflections upon lost record should be included when considering regional-scale settlement patterns and economies.

4.1.2 Site UA50 – A crossroad for a territorial network?

Site UA50 (15.120779° N, 36.217877° E) is a small multiphase campsite located along the left bank of Khor Marmareb, in the completely flat open plain halfway between Jebel Abu Gamal and the confluence of Khor Marmareb itself and the Atbara River (Fig. 3.1 and Plate 4.1.2). Khor Marmareb is a ~50km long creek that is relatively narrow and shallow for most of its length, not exceeding 8m width per 2m depth, flanked by thorn bush tunnel vegetation extending only for a few tens of metres across the surrounding dusty ground. It sets within the topographic low created by the southernmost of the four relict Late Pleistocene emissary channels belonging to the southernmost of the Gash river's relict riverscape of *Shurab el Gash* (chapter 4.1.1) (Plate 4.1.2), and follows a mildly wandering path that presents no significative lateral migration nor active bank erosion and scroll bar deposition except for its last 10km, where it enlarges within the loosened Quaternary fluvial deposits of the Atbara River assuming a sandy-braided behaviour with a 100m wide riverbed. The *khor*'s banks are, however, prone to the formation of badlands and piping, which find a likely trigger in the fossil burrows (Plate 4.1.3A) created by large fossorial animals such as warthogs. These would have colonized the riparian bushland during past environmental settings, and their dental remains are commonly found scattered near archaeological sites and along the riverbanks. The original riverbed sediments of the Gash's fossil emissary channel, fine/loamy in nature as a result of the slow-water anastomosing headwater riverine environment, underwent long-standing ancestral (Late Pleistocene – Early Holocene) pedogenetic cycles and erosion, which brought them to a state of oxidized plinthite soil. Plinthites in arid lands are characterized by strong compaction, angular prismatic aggregation (plinths), general light yellow-orange chromatic appearance caused by the presence of iron oxides, and little to no presence of a topsoil. In the area, plinthites originated over ancient riverbed sediments are homogenized with the surrounding plain (Plate 4.1.2 and 4.1.3). The typical rusty colour is, in fact, recognizable from the satellite pictures in correspondence of unmanaged land patches and freshly ploughed fields both near the *khor* and well within the unflooded plain (Plate 4.1.2), and in-situ from within the spontaneously carved *khor* riverbed (Plate 4.1.4A). Thin section micromorphology (*Appendix C*, Plate 4.1.4C-D) further supports the model, showing presence of well-rounded clasts and bone fragments, resulting from consistent water transport, included within a dense clay matrix containing abundant oxidized papules (inherited small clay particles deriving from erosion of pre-existent heavy soils) and goethite particles, an iron mineralization commonly found in the upper portion of strongly oxidized tropical soils.

The site is one of the most studied locations investigated by the IAMSK and IAEES. Despite being severely affected by ploughing, seasonal camping by local nomadic communities, and natural erosion, evidence found therein tells a story of prolonged and continuous occupation through several millennia. Large shell middens date as early as the late 6th millennium BCE - late Pre-Saroba Phase - (Manzo, 2016; Manzo, 2017; Cesaro, 2017), and contain, along with occasional lizards, wild game and cattle remains, hundreds of terrestrial and freshwater gastropods species such as *Achatina fulica, Pila ovata*, and *Pila wernei*, water-reliant snails that are today found at much lower latitudes – although they are capable of aestivation under drought conditions. The bases of the shell middens sit on a compact reddish clay surface that, while in the surrounding ploughed fields bears a thin superficial dark anthrosol - i.e. an artificially produced topsoil created by intentional enrichment with fertilizer and reiterated incorporation of harvested stalks, manure and other organics -, in correspondence of the archaeological site presents no buried topsoil horizon (Plate 4.1.3A). Contrarily, the rusty clay is covered by a pale ~30cm thick thinly layered pale loamy alluvial deposit that engulfs the shell middens hiding their very large bases. In turn, the loamy deposit is cut by subsequent pits and graves of the Butana Group, dating to the 4th millennium BCE, which however are partially exposed at surface (Plate 4.1.3B). This very feature is the outcome of late Holocene dry climate aeolian morphogenetic processes that removed the finer fraction of the loamy alluvial sediment, concentrating several millennia worth of archaeological stratification into an almost singular residual surface horizon of coarse material such as ceramics, lithics, shell and faunal remains and, as reported, inhumations.

Archaeological significance of the position and natural settings of UA50

Despite the slight paucity of pedostratigraphic data and geochronologic anchorages available from its surroundings, site UA50, together with other comparatively similar sites located downstream along Khor Marmareb such as UA53 and UA14 - to cite the largest and most studied, but in truth they are several more - (Manzo, 2017; Cesaro, 2017), bears a great significance towards the comprehension of the regional pre- and protohistoric subsistence economies.

Its position is strategic under several points of view: the stable and reliable presence of a seasonally active and non-dangerous watercourse would have provided water and abundant protein food sources in the form of molluscs and terrestrial animals year-round, making it a good hunting-gathering spot with reduced associated hydric risk. Moreover, the very trajectory of Khor Marmareb would have represent an easily walkable path for reaching Jebel Abu Gamal (Plate 4.1.5), a peculiar granite outcrop whose shape against the horizon is unmistakable and visible from afar in the flat alluvial plain, constituting a necessary landmark towards the Gash River's upland canyon and Ethio-Eritrean Highlands. Lastly, the occasional floods of Khor Marmareb, providing spreads of water-retaining loamy sediments, would have represented a naturally favourable ground for early domestication attempts of *Sorghum sp.* crops, frugal cereal species that don't require particularly rich substrates and can withstand prolonged droughts. Finds of domesticated sorghum are, in fact, found in Butana Group ceramics mostly as negative impressions of seeds and spikelets, dating back as far as the 4th millennium BCE (Winchell et al., 2017).

These three conjugated factors created in Site UA50 an effectively advantageous spot for short to medium-term permanence throughout the millennia. Early settlers would have found abundance of readily available food, and changing location along Khor Marmareb to allow resources regeneration and turnover would have been easy. Later on, the same locations would have also been favourable for people moving for trade between the Nile Valley and the Highlands, thanks to the geographical importance of Khor Marmareb's trajectory and, again, to the accessible food sources available throughout its course. Despite the onset of aridity in the mid-3rd millennium BCE, which diminished the annual flow of Khor Marmareb ultimately leading to exacerbated hyper-seasonality and consequent loss of wildlife and water-reliant species, the location remained a favoured campsite through the millennia, and still at the present day it hosts regular occupation in its direct proximities by seminomadic pastoral communities of the region.

On the basis of the much higher concentration of sites found along Khor Marmareb and within the contiguous area of *Shurab el Gash* against the rest of the Southern Atbai Plain - which is, however, still far from being an empty space – (Fig. 1.2), it is reasonable to hypothesize that this would have been one of the most used and most reliable routes followed from the late prehistory up until sub-recent times in the region. All aspects of its settings depict an ideal scenario for crossing the Southern Atbai, which most likely was an open bushland savanna teeming with wildlife, including predators and herbivorous megafauna. Nomadic communities crossing the plain from the Atbara river to the Highlands, would have followed a fortuitously short path dotted with settlements and campsites that provided shelter and may have even been inhabited by residents year-round as if they were designated checkpoints, especially in later times (Gash Group onwards) characterized by systematized long-distance supra-regional trading networks.

4.1.3 Goz Regeb, Jebel Tarerma and Jebel Erembat – Towards the Middle Atbara Valley

Goz Regeb is the toponymic of a locality situated ~115 km NW of Kassala, along the Atbara river (Fig. 3.1), where a ford traditionally used for crossing the river is found, representing a crucial intersection for the routes connecting the Butana plains (the land comprised between the Nile/Blue Nile and the Atbara river) to the regions east of it. The area, roughly located at 16.05°N, 35.56°E, is characterized by two small whaleback granite outcrops - isolated outcrops resembling whales at the sea surface - called Jebel Tarerma and Jebel Erembat, emerging from the alluvial plain of the Atbara river less than 1 km east of the present-day riverbed, within the locally mildly eroded strip of badlands flanking the river (Chapter 3.3) (Plate 4.1.6).

In this setting, a high density of archaeological remains is found (Crawford, 1951; Costanzo et al., 2020b). Evidence of a remarkable streak of continuous occupation is found in the form of Pre-Saroba ceramics associated with badly eroded small shell middens, followed by Butana Group ceramics, generic Middle Nubian tradition ceramics (possibly related to the Gash and Mokram Groups), Hagiz Group ceramics, and Gergaf Group ceramics, with each group yielding high enough amounts of material to infer consistent use of the location. Because all the recovered cultures are related to mobile seminomadic economies (Manzo, 2017), it is plausible that Goz Regeb represented a very important node in their patterns of seasonal mobility due to its proximity to the Atbara river and the presence of Jebel Tarerma and Jebel Erembat, topographic landmarks that are visible and unmistakeable from far away, being the only two outcrops emerging in direct proximity of the river's entire lowland trajectory. Moreover, the occurrence of possible Meroitic ceramic materials confirms that Goz Regeb, most likely because of the nearby ford on the Atbara, was an important link between Eastern Sudan and the Butana Plain during that time. Bricks with Christian iconography were also recovered on site (Ferrandino, 2019; Monneret de Villard, 1935), together with some subrecent Islamic burials and ~340 stone and earth mounds/tumuli of uncertain age at various degrees of preservation, conferring to the site a certain degree of ceremonial value as well (Plate 4.1.7 and 4.1.8A).

Extant natural settings of the area and archaeological implications

Jebel Tarerma and Jebel Erembat are two Neoproterozoic (~600 million years) granite plutons that were shaped as small whaleback inselbergs by chemical solution and erosional weathering. They sit a few hundred metres from each other, and are separated by a *khor* belonging to the dense drainage system of the badlands flanking the Atbara river. Like all the granite inselbergs characterizing the regional geology, Jebel Tarerma and Erembat evolved by insurgence of unloading etchplains that caused the formation of tors and nubbins atop the pluton's main body and accumulation of boulders all around its sides and base. Due to the current climatic conditions of the arid Southern Atbai's interior, the jebels are also exposed to strong dust-bearing ground winds that blast and strip the granite surface consistently, modelling their NE sides into chaotic amasses of crumbly exfoliating spherical boulders immersed into coarse fresh gravel (Plate 3.4F). The dusty winds blast any surfaced archaeological evidence on the NE sides of the jebels as well, compromising its preservation while also generating sterile blankets that engulf artefacts and boulders alike.

Underlying the loose aeolian sand cover that engulfs the wind blasted outcrops' skirts, and exposed by hydric erosion and the very presence of the Atbara's canyon-like incision, the complex palimpsest of riverine, deltaic (Gilbert type) and lacustrine sediments identified by Abbate et al. (2010) is found. This is a remnant of Late Middle/Late Pleistocene wetland environments connected with the presence of the intricate network of channels created by the wandering riverbeds of the ancient Atbara, Khashm and Gash rivers, in a phase of anastomosing coalescing branches that characterized the region before the regional tectonic uplift separated the eastern and western watercourses gradually leading to the present-day's riverscape (Fig. 3.2, Chapter 3.3 and Chapter 4.1.1).

Attempts at a precise OSL and ^{230}Th/U dating of the Atbara's accretional succession have been carried out 120 km to the south of Goz Regeb, just north of the Khashm el Girba dam (Tsukamoto et al., 2022), demonstrating that the entire fluvial sequence was created between 224±23 ka and <17±1 ka without significative depositional hiatuses. Despite the distance between the two areas, which may invalidate such dating in regard to Goz Regeb, the results obtained by Tsukamoto et al

(2022) provide the first well-grounded Quaternary high-resolution absolute geochronology of the fluvial setting of the region.

Other glaring remnants of relatively recent past morphologic and kinetic settings of the Atbara river consist of surface patches composed of tightly juxtaposed imbricated cobbles ranging in size from a few millimetres up to ~10cm, mainly consisting of granitoid/gneissic and basaltic lithologies, commonly found as regional Proterozoic crystalline basement and localized Tertiary extrusions respectively. The imbricated cobbles armour pseudo reliefs along the raised fluvial terraces of the Khashm el Girba Synthem 3 (KGS3), the uppermost of four main chronostratigraphic units (Butana Bridge Synthem – BBS -, KGS1, KGS2, KGS3) that have been identified along the Atbara, defining sub-regional bodies of sediments bounded by unconformities and representing cycles of sedimentation responding to changes in climatic regimes and regional tectonics (Abbate et al., 2010; Tsukamoto et al., 2022) (Plate 4.1.8). The pseudo reliefs, in truth, are residual mounds created by migration of the river, desiccation of the abandoned high-energy riverbed, and subsequent aeolian deflation of the fine-grained fraction of the engulfing bedload sediment, which kept being removed until the imbricated cobbles sat close enough to stop the erosional process upon limited mound-like areas. Because such stony terraces are in direct contiguity with the present-day riverbed, i.e. there hasn't been a drastic diversion since their formation, it is reasonable to hypothesize that they may in phase with the Middle Holocene cultural sequence of the area and extended region. The dating proposed by Tsukamoto et al (2022), in fact, only provides an upper limit of <17±1 ka for the undisturbed stratigraphy, but doesn't account, of course, for stages of subsequent erosion that may have erased significant portions of younger sediments. Consequently, during the Early and Middle Holocene the Atbara river's riverbed could have been several metres higher than present, and the paleocurrent would have been stronger, steadier and more reliable than today due to the wetter north African climatic settings of the African Humid Period. The shell middens associated with Pre-Saroba ceramics, which find a comparison in the better-preserved occurrences of Site UA50, substantiate this hypothesis. Later climatic deterioration towards aridity and, later, hyper seasonality, caused a severe change in the current regime of the river, whose flow decreased causing the river to entrench and form the shallow canyon observed today. At the same time, aeolian deflation started to remove fine-grained alluvium from the abandoned terraces creating the armoured mounds now visible at surface, and concomitant episodic rains triggered the formation of badlands and gullies, with retreating knickpoints spreading away as much as 5 km each side of the main riverbed.

The extant landscape, therefore, is the result of Late Quaternary cycles of fluvial deposition, aeolian deflation, and hydric erosion, triggered by humid/arid climatic shifts, terminating with the current settings of an entrenching large river flanked by short ephemeral tributaries. The interpretation well-fits with the evidence found at Site UA50, where 6th mill. BCE water-reliant faunal remains buried in loamy alluvium are now brought to light by deflation and erosion. During the Early/Middle Holocene, the area of Goz Regeb would have appeared very different from now, with a non-entrenched river flowing at the same altitude of its surrounding alluvial plain and a biotic environment likely characterized by luscious grassland/wetland and water-reliant wildlife nowadays characteristic of much lower latitudes. The model is convincingly substantiated by Geraads (1983)'s findings of kobs, reedbucks, hippos and buffalos within the faunal assemblages from Pre-Saroba archaeological sites (7th-6th mill. BCE) of the Gash river's fossil alluvial plain, and Abbate et al (2010)'s findings of buffalos and elephants within the sublithified KGS2 and KGS3 terraces of the Atbara river. Later climatic shifts, abundantly documented in all pedosedimentary archives of the extended region (see the following subchapters), gradually led the landscape to assume the settings that we see today. Nevertheless, despite the aridity and apparent barrenness of the surroundings, Goz Regeb remained a crucial station for human transit and possibly even stable occupation, as testified by the remarkable abundance of archaeological finds from Jebel Tarerma and Erembat and due to the fact that the Atbara river, thanks to the highland climatic settings of its headwater and the wetland transit of its upper valley, was never an ephemeral river but rather a generally reliable source of water and food resources through the millennia and until the present day, despite its decreased flow and bed entrenchment.

The archaeo-environmental significance of the area, with its remarkable cultural sequence and sedimentary palimpsest, well-deserves the attention earned ever since its first explorations. Although its understating is still embryonal (Costanzo et al, 2020b), several observations were still possible thanks to the pioneering chronostratigraphic works of Abbate et al (2010) and Tsukamoto et al (2022), who provided detailed reference upon the Quaternary riverine dynamics of the middle Atbara valley with reliable absolute datings for the entire depositional succession.

Future archaeological excavations at the foothill sites of Jebel Tarerma and Erembat, and targeted geoarchaeological surveys along the Atbara river's tributary badland network will surely provide even more detail to the Holocene human and natural transformations of this remarkable locality.

4.1.4 Past Jebel Ofreik – Terra Incognita

Jebel Ofreik (16.247116°N, 35.690234°E) is a small conical granitoid outcrop, only measuring ~1.3 km in diameter and a few tens of metres in height, located 25 km NE of Goz Regeb (Plate 4.1.9). 10 km to its north, another cluster of 8 outcrops of similar size and lithology is found. They rise abruptly from the open plain close to a very large meandering fossil channel of the Atbara river; the exact age of the paleochannel is not known, but due to the size and convolution of the point bars delimited by its wide meanders (Plate 4.1.9), and the fact that is so levelled to the ground surface to be unrecognizable from Digital Elevation data, it is probably referable to one or more Middle-Late Pleistocene long phases of high water discharge from its upper valley. The area of Jebel Ofreik was briefly surveyed during 1980's expeditions and yielded sporadic ceramic material of Christian and Post-Meroitic production, as well as evidence of possible Amm Adam Group (Pre-Saroba) presence (Manzo, 2017; Fattovich, 1989; Fattovich, 1990; Fattovich, 1991). Even so, its excessive remoteness and complete lack of infrastructures hindered extensive work, making it virtually unknown - *terra incognita* - if compared with the other locations investigated by the IAMSK and IAEES.

Nonetheless, currently available high-resolution satellite images and remote sensing applications can help evaluating the effective archaeological potential by disclosing the occurrence of structures and monuments, as well as being fundamental for recognizing local and supra-local active morphogenetic processes and relict landforms and landscapes.

Desk-based analysis of satellite images disclosed plentiful occurrence of raised funerary structures encircling the majority of the rocky outcrops in the area, with Jebel Ofreik itself hosting 98 out of the 226 recorded tumuli. Crucially, satellite images also reveal active wind- and water-driven morphogenesis of the unconsolidated deposits around the foothills of all outcrops. Seasonal rains, despite being relatively meagre, are channelled on the steep hillslopes causing the insurgence of short but pervasive gullies at the foothills, while strong winds lift dust and sand from the surrounding open plain that impact against the outcrops engulfing rocks, vegetation and archaeological evidence. As a consequence, perspective field surveys may reveal the existence of hidden well-preserved archaeological structures that cannot be detected by satellite imaging, whilst evaluating the effective conservation status of visible monuments.

Jebel Ofreik, the Jebels to its north, and Jebel Tarerma and Erembat from the Goz Regeb area as well, have always been crucial topographic landmarks of the region, as testified by the abundance of funerary culture found therein. Yet, such plentiful funerary evidence surrounding the outcrops is not paired, as of now, by any data upon settlements and ancient roads networks. Nonetheless, satellite imaging once again provides hints and suggestions for a tentative definition of how ancient ways might have been. For example, the large paleochannel of the Atbara river, although to a much lesser extents than the Gash's paleochannels from the lower Southern Atbai, seasonally adsorbs enough rainwater to provide ground for flash cropping (Plate 4.1.10A). This water retention capacity of the paleochannel may have provided the same sustainment for archaeological communities moving along the SW-NE route from Goz Regeb to Jebel Ofreik and beyond, towards the northern stretches of the Gash river's terminal fan. Additionally, the apparently barren plain blooms seasonally with bushland thanks to the brief reactivation of some pools belonging to the Atbara paleolake's dune-interdune lacustrine environments (Fig. 3.2 and Plate 4.1.10B), whose SE stretches flank the left bank of the Atbara paleochannel, making it an environmentally favourable route aided by the presence of several topographic landmarks and the relatively straight trajectory of the paleochannel.

At the current state of knowledge of the area, any more hypotheses could swerve too much from reality, but its remarkable archaeological potential is undeniable and hopefully will be addressed in the future with adequate resources and from cross-disciplinary points of view, in order to define the calibre of the finds in their relationship with the paleoenvironments and past landscapes.

It is also worth mentioning that the area of Goz Regeb and Jebel Ofreik, is close to the region of competence of the EDAR (*Eastern Desert Atbara River*) Project (Nassr & Masojć, 2018), an international cooperation that is investigating hominin occupation in the middle Atbara valley. The main concentration of finds by the EDAR Project is located along the eroded banks of the present-day Atbara river and in correspondence of the El Helgi Depression, a pseudo-island located 60 km upstream of the river's confluence with the Nile delimited by the Atbara's active channel and a large former channel that is still subject to static swamping during rainy seasons, but some surveys found evidence of Early Stone Age much closer to the Southern Atbai, still in area belonging to the Atbara paleolake dune-interdune lacustrine system (Masojć et al., 2019; Masojć et al., 2021; Michalec et al., 2021; Ehlert et al., 2022). It should not be ruled out that the Southern Atbai, with its remarkably complex fluviolacustrine environmental palimpsest and proven evidence of Palaeolithic human presence all along the course of the Atbara river downstream of the Khashm el Girba dam (Abbate et al., 2010), belonged to green corridors of early to late human dispersal.

4.2 Mahal Teglinos – An open book in a hidden valley

The small valley of Mahal Teglinos (archaeological site K1) is, without doubt, the most studied and the most representative archaeological site of the wider region, both in terms of intensity and continuity of the human occupation (Manzo, 2017 and references therein). Moreover, the location was recognized as pivotal for the comprehension of the paleoenvironmental evolution of the region ever since the earliest archaeological interventions by the IAMSK (Coltorti et al., 1984; Cremaschi et al., 1986), and the first time that the geomorphological dynamism of the site was addressed dates back to almost one hundred years (Crowfoot, 1928).

Mahal Teglinos is a privileged location for carrying out archaeological research in the region thanks to its proximity to the city of Kassala - which is only a few hundred meters away - and its protected settings. Despite being close to the urban area, the valley is almost completely encircled within steep granite domes and is recognized by heritage regulations (Ministry of Tourism and National Heritage, 1999); this ensures protection from excessive anthropic interference – although, as will be discussed later in this Chapter, a certain degree of misuse is inevitable.

This chapter presents the natural and cultural palimpsest disclosed by the valley's current settings, using excerpts from the published works "*Active surface processes at Mahal Teglinos (Kassala, Eastern Sudan): archaeological implications for an endangered protohistoric site in Sahelian Africa*" (Costanzo et al., 2022) and "*Geoarchaeological Investigations at Mahal Teglinos (K1, Kassala). New Insights into the Paleoenvironmental History of Eastern Sudan*" (Costanzo et al., 2020a).

As will be widely explained in the chapter, the success of the fieldwork seasons carried out in Mahal Teglinos, and the abundancy of the archaeological and environmental data that the valley yielded throughout the years, ultimately boil down to a dangerous double-edged condition of the site: active morphogenesis, particularly connected to water-induced erosion, is currently and continuously shaping the topography, revealing previously sealed contexts while, on the other hand, dismantling and destroying others. This worrying feedbacking cycle is the very motor of the formation and revelation of the archaeological stratigraphy that we investigate - but will also be, in truth, the very death of it.

For this reason, this presentation of the archaeology and paleoenvironment of Mahal Teglinos is also taken as an opportunity to highlight problems related to erosion and endangered archaeology in arid lands in general and widely applicable terms. Mahal Teglinos is used as a seminal case study for the comprehension of disruptive morphogenetic processes, and their mitigation towards an enhanced discernment of pristine and damaged archaeological contexts.

4.2.1 Erosion, arid lands and archaeological sites

Erosional processes and their influence on soils and landscapes is a foremost matter that is recurrently addressed by many scholars belonging to different fields - bioecologists, agronomists, climate scientists, just to name a few - and working in diverse regions of the world characterized by highly dynamic environments. All parts agree that sheet wash, linear erosion and, most of all, gully entrenchment, swift in their onset and extremely harmful for crops, built land and cultural heritage, must be appointed as some of the most prominent manifestations of land degradation in all environments where intensive rainfall and agriculture occur (Dotterweich, 2003; Valentin et al., 2005; Montgomery, 2007; Vanwalleghem et al., 2017; Azareh et al., 2019; Busch et al., 2021; Yang et al., 2021). In the case of cultural heritage, and specifically regarding the archaeological record - which is inherently embedded within the younger, least consolidated geological strata and pedological bodies -, some scholars have been proposing mitigation techniques promoting conservation policies. Such policies either aim to the active prevention and containment of gullies (Pederson et al., 2006), or focus on their evaluation for prioritizing archaeological investigations, by modelling and predicting the evolution of the landforms (Howland et al., 2018; Ames et al., 2020). Yet, the shared conclusion is that gullying, mostly driven by the joint action of anthropogenic land overuse and extreme climatic events, cannot be avoided unless long-term prevention and control techniques are enforced worldwide (Valentin et al., 2005).

Gully erosion happens in a vast array of environments worldwide, but crusting and sandy soils with scarce vegetation cover are the most prone to the phenomenon (Valentin et al., 2005), especially where climatic regimes alternate dry and rainy seasons or bear occasional intense rainstorms, which result in a short corrivation time (García-Ruiz et al., 2015). This is the case, for example, of the Sahelian belt of Africa.

Even though the region receives enough rainfall to be classified as hot semi-arid climate (BSh – Beck et al., 2018), human-induced climate change and dust displacement dynamics originating in the neighbouring Sahara Desert are accepted to be major causes of ongoing desertification and droughts within Sahelian territories (Epule et al., 2014; Huang et al., 2020). Despite the existence of debated opposing trends such as the "West African re-greening paradoxes" (Descroix et al., 2018), land degradation, gully erosion and soil loss related to natural processes and unregimented land exploitation and husbandry are largely investigated conspicuous drivers of environmental alteration that have been affecting the planet since prehistoric times (Wright, 2017; ArchaeoGLOBE, 2019; Roberts, 2019; Zerboni & Nicoll, 2019).

With such premises, it is likely that numerous and elusive Sahelian open-air archaeological sites, whose formation was structurally linked to past climates and balanced with formerly active morphogenetic processes, are today endangered by regional-scale landscape alterations and direct dismantling of their locations and direct proximities, with repercussions on societal wellbeing as well (Brooks et al., 2020; Rayne et al., 2020).

The valley site of Mahal Teglinos (15.44358°N, 36.43085°E) is a noteworthy example of such dynamics. In fact, despite being relatively protected from agricultural/grazing parcelization by its secluded location and heritage conservation norms, it is prone to severe gully erosion, mainly promoted by trampling and violent seasonal flash floods. Ancestral geological features, Holocene stratigraphy, and sub-recent and active surface erosion processes are hereafter reported in the high-resolution geomorphological characterization of the valley, which is accompanied by a 1:1500 geomorphological map (*Appendix B*). This study showcases the potential of in-depth geomorphological assessments of natural and archaeological contexts in integrating novel archaeological and paleoenvironmental understanding as well as in mitigating misinterpretations driven by elusive soil/sediments displacement processes, constituting a solid reference case study of endangered heritage in arid lands from the far eastern mountainous outskirts of the Sahelian belt.

4.2.2 Geographical and archaeological background of Mahal Teglinos

The city of Kassala, capital of the homonym administrative division of the far Eastern Sudan, lies in the shadow of the Jebel Taka, the most famous and characteristic of the hundreds of bare-rock granitic and gneissic outcrops and inselbergs that dot the pediplain east of the Gash river (Johnson et al., 2011; Costanzo et al., 2021a). The Jebel Taka, a fundamental topographic landmark for residents and foreign travellers alike, is composed of several dome-shaped steep bornhardts - some reaching heights of 500 metres above the surrounding landscape - that adjoin each other forming narrow secluded valleys filled with boulders, debris and fine colluvial/aeolian sediments. Mahal Teglinos is the largest (~100.000 m^2) and most accessible of such valleys, with a wide opening to the south-east that leads to a small village in the open plain and a narrow gorge to the north that leads to the densely urbanized area of Kassala (Plate 4.2.1).

The sheltered position of the valley favoured the preservation of a thick bottom pediment (in geomorphology, a gently sloping body of sediment that connects the hillside of a mountain with the surrounding plain) that bears evidence of former climates and pre-protohistoric human occupation. The archaeological potential of the valley was first recognized in the early 20th century by John Winter Crowfoot, who published a detailed note on his survey collections (Crowfoot, 1928). In the 1980's the site was re-discovered by IAMSK, attracted by its considerable size, the peculiar position within the region and the exceptionally rich archaeological palimpsest that could - and effectively proved to – be a missing link for the comprehension of the entire Horn of Africa's archaeological past. The occupation of the valley spans from the Mesolithic, testified by sparse findings of Butana Group remains in the lower strata (4th - early 3rd mill. BCE), to historic and late occupation phases represented by a few surface tumuli and artefacts belonging to the Hagiz Group (1st mill. BCE – mid-1st mill. CE) and Khatmiya Group (3rd - 6th cent. CE) (Manzo, 2017). Nevertheless, the valley hosted its most intensive occupation with the Gash Group and Mokram Group between the mid-3rd mill BCE and the early 1st mill BCE (Manzo, 2017). These Groups occupied the entire valley with large cemeteries, living areas (Plate 4.2.1) and possibly a ceramic production site with tight chronological continuity. They practiced husbandry and agriculture on a substantial scale with possibly even ritual connotations, as testified by zooarchaeological and botanical remains (Geraads, 1983) and the hundreds of large granite mortars and pestles found both in living areas and inhumations (Rega et al., 2021), and used eye-catching body ornaments such as lip plugs and intricate jewellery - e.g. cowrie shells, animal teeth, ostrich egg and faience beads and possibly other perishable materials -. Moreover, findings of Egyptian ceramics and copious administrative sealings led to the well-substantiated hypothesis that the site may have been a prominent federal administrative centre within the debated land of Punt (Manzo, 2020). In general, the site's richness and the discovery of large cemeteries counting thousands of individuals with peculiar sets of grave goods revealed, over the years, extremely complex social dynamics and commercial links with the Nile Valley, Horn of Africa, Red Sea, and Arabian Peninsula (Manzo, 2017 and references cited therein).

The permanent occupation of the Gash and Mokram Groups, together with the transitional humid-to-arid climatic settings of their specific period (Costanzo et al., 2020a), formed a deposit of anthropic, colluvial and aeolian layers exceeding a thickness of 2 m. Interestingly, the Hagiz Group, despite partially preserving stylistic continuity with the ceramics and lithics of the preceding Mokram Group, lacks almost completely of grinding stones, which represented a major component of the earlier groups' material culture (Manzo, 2017). This may be related to a regional shift from a partly agricultural economy, which benefited from the world's earliest domestication of *Sorghum sp.* (Winchell et al. 2017), to a semi-nomadic pastoral economy. The shift in the subsistence economy, and subsequent sparser occupation of the valley and its surroundings, are most probably connected with the Late Holocene aridification of north Africa, which contributed to reshape the supra-regional distribution of people and power balance (Gatto & Zerboni, 2015). Present-day occupation of the region is the outcome of the interaction between Beja groups - pastoral semi-nomadic people historically present in the region (Dahl & Hjort-af-Ornas, 2006; Krzywinski, 2012; Costanzo et al., 2021b) - and cyclic waves of invasions from neighbouring African regions and from far, oversea lands. Land use related to medieval gold mining (Elsadig, 2000), local battles for the "Scramble for Africa" (Bellavita, 1930; Raugh, 1993) and the implementation of extensive cotton, sorghum and fruit plantations within the Gash river's endorheic fan, ultimately led to the uncontrolled sprawling of the modern city of Kassala (Barbour, 1961; Costanzo et al., 2021a) and irreversible disruption of the region's natural ecosystem and the Beja's traditional economy.

4.2.3 Morphogenesis of Mahal Teglinos: a palimpsest of accretional and erosional cycles

The newly created geomorphological map (*Appendix B*) delivers a clear view of the identified landforms and processes, and offers a graphic thread for a full understanding of the following descriptions.

Bedrock and ancestral processes

The bedrock that constitutes the domes of the Jebel Taka is one of the Neo-Proterozoic granodioritic plutons that emerged in the region during the Arabian-Nubian Shield's orogeny (Geological Research Authority of the Sudan, 2004). As for the entire regional orogenic context described in Chapter 3, the Jebel Taka pluton pierced and uplifted a portion of the Precambrian gneiss basement, and was later twisted and fractured by intensive regional orogenic shear (Johnson et al., 2011). The pluton and its gneiss cap subsequently underwent numberless climatic cycles, whose weathering action mainly affected fault-related fractures, sheeting joints and thermally-induced fissures, ultimately producing the bornhardt assemblage that is visible today (Twidale, 1982) (Plate 4.2.2). The individual bornhardts are covered by tors and nubbins (residual columns and towers of split granite boulders, forming by in-situ weathering of original larger rock masses) that gradually detach and fall from the etchplain and accumulate along the slopes or at their bottom depending on the hillside gradient, forming a foothill chaos of boulders (Costanzo et al., 2021a) (Plate 4.2.2). Some of the boulders are very large - up to ~30 m^3 - and emerge from the valley's Holocene pediment and active talus (an outward sloping and accumulated debris of any size or shape lying at the base of a cliff or very steep rocky slope, formed by gravitational falling, rolling, or sliding), where they are being further dismantled by erosion and meteoric weathering. At high altitudes, small angular stones and very coarse gravel occupy inter-boulder voids, forming patches of stabilized colluvium that are seasonally overgrown with grass and thin shrubs. In the valley bottom, a thick granite alterite (sublithified arenitic sedimentary rock derived from in-situ terminal weathering and partial re-cementation of bedrock) that formed within the basin-shaped solid crystalline bedrock underlies the Holocene pediment deposit (Plate 4.2.3). The alterite is composed of densely packed cemented angular gravel and coarse sand resulting from advanced in-situ saprolitization of the underlying granite bedrock.

Late Quaternary natural and archaeological deposits, soils and processes

The valley of Mahal Teglinos is filled with a bottom pediment that reaches a thickness of ~6 m in its westernmost portion. The pediment overlies the bedrock and basal alterite and is a record of aggradation, pedogenesis and erosion that took place during diverse climates and human occupation phases of the Late Quaternary (Plate 4.2.3), as reported by recent precursory works (Costanzo et al., 2020a) and older accounts from the pioneering field seasons of the 1980's (Fattovich et al., 1988).

Above the alterite and occasionally in direct contact with the bedrock, underlying the archaeological deposit, a buried isohumic soil horizon (A horizon) is found. The soil horizon developed in the Early/Middle Holocene under humid climate on a thick gravelly colluvial deposit that likely formed during the Late Pleistocene. The isohumic soil horizon is best represented in the western half of the valley, where it preserves a thickness of ~1.5 m. Its formation was promoted by environmental settings wetter than today, under a grassland/savanna environment of the Middle Holocene's African Humid Period (Claussen, 2017). This is suggested by observed vertical and lateral homogeneity, strong evidence of pedoturbation, and an AMS-^{14}C dating result of 6410±25 uncal years BP (UGAMS #29354) (Costanzo et al., 2020a; Costanzo et al., 2022) (Plate 4.2.3).

A calcareous horizon (Bk horizon) (*Appendix C*, Plate 4.2.4A-C) is found in patches overlying the alterite and underlying the archaeological deposit as well, but its discontinuous preservation and unclear stratigraphic relationship with the organic horizon prevents further interpretation at the current state of knowledge. However, it may relate to post-depositional alteration driven by rainwater leaching of carbonate-rich dust of aeolian origin and groundwater stagnation dynamics that happened between the Late Pleistocene and Middle Holocene, similarly to what has been observed along the Nile River (McCool, 2019).

Stratigraphically above the isohumic and calcareous soil horizons, the up-to-2 m thick archaeological deposit is found. The deposit is composed of a tremendous volume of ceramics, lithics and faunal remains, found in dozens of sub-horizontal barely compacted strata, each representing a former, transient topographic surface. Micromorphological analyses on selected stratigraphic units from trench K1 VI, investigating a living area, provides even further insights into the intensity of the occupation (*Appendix C*, Plate 4.2.4D-G). Negative units - i.e. cuts and pits - occur rarely within living areas, and are usually related to simple hearths or storage of small jars. Contrarily, cemeterial areas are composed of hundreds of intercutting inhumations, some of which have burial pits reaching more than 1 m in depth. The archaeological deposit shows almost no tangible traces of pedogenesis, and blankets the entire valley. Except for the Butana Group finds (4th - early 3rd mill. BCE), which in the valley are sparse and confined to the lowest strata in contact with the isohumic soil horizon, the archaeological record of Mahal Teglinos is preserved within a loose admixture of colluvial gravel and aeolian carbonate-rich dust layers. Such layers were deposited during a time of progressive aridification of the regional climate, which can be inferred by the upwards reversal of the colluvial/aeolian sediment intake ratio. In fact, greater amounts of coarse colluvial sand and gravel (whose formation requires gravity- and water-related processes) are found in the lower strata, whereas very fine aeolian dust layers prevail in the upper strata (Plate 4.2.3). Nevertheless, despite the prevailing aeolian dynamics, the steep gradient of the surrounding hillslopes still promoted a significant colluvial intake throughout the formation of the archaeological deposit (Costanzo et al., 2020a; Costanzo et al., 2022). The archaeological deposit is ultimately sealed by an armoured desert pavement (a layer of coarse clasts formed by differential removal, usually due to wind deflation, of the fine fraction constituting a deposit), whose clastic components consist of a palimpsest of archaeological remains - potsherds, lithics and bones - (Plate 4.2.5A) (Knight & Zerboni, 2018). The wide-ranging diachronicity of the artefacts found within the desert pavement, several hundred years apart, reveals that the pristine archaeological and aeolian sequence reached a greater thickness than today, but eventually wind deflation prevailed on aeolian accretion. Further evidence of sediment removal seems to be given by the differential intensity of desert varnish (a thin but deep hued patina that forms on quiescent rock surfaces from the accumulation of meteoric clays and iron and manganese oxides) coating the boulders and bedrock that are partially submerged in the pediment: a paler strip runs parallel to the ground, revealing what seems to be a widespread loss of sediments that previously acted as a protective layer against the formation of varnish.

Raised ancient backfilled gullies are visible in one of the cliff-exposed tall sections of the western sector of the valley, where they form an intricate gravelly body of interbedding cut-and-fill channels that converge towards the centre of the valley forming a pseudo-braided drainage network with a general SW-NE direction. The feature overlies and partially cuts the isohumic horizon, but its stratigraphic relationship with the aeolian-archaeological deposit cannot be investigated as their main point of contact is concealed by a present-day Islamic cemetery. Nevertheless, the onset of water-related erosional phase is likely to have occurred after the end of the aeolian aggradation process.

A chaotic talus covers the outskirts of the archaeological deposit and occasionally intertwines with its upper strata, tainting the pristine contexts. Albeit very similar to the patches of stabilized debris that are found at higher altitudes, the talus is regularly displaced and re-shaped by strong present-day flash floods, which also create deep cut-and-fill incisions and displace heavy stones that impact against the delicate aeolian deposit causing localized collapses (Plate 4.2.5B).

Active water-related surface processes

Rainfall gathers on the bornhardts during the summer monsoon and forms powerful streams, quickly weathering the granite bedrock pushing stones and gravel downhill (Plate 4.2.6 A and B). The streams converge into a dendritic system of gullies that dissect the pediment, revealing the stratigraphic features described in the preceding paragraphs.

The size of the gullies ranges variously, from thin surface rills to large ravines up to 20 m large and 4 m deep, which evolve by erosion and collapse of their cliff embankments (Plate 4.2.7). The bedload of the gullies differs according to their size, depth and position within the valley. The large western gullies, which reveal the pediment's stratigraphy from top to bedrock, contain a coarse admixture of sandy gravel, eroded archaeological material and some large angular stones. The largest clasts are found near the streams' foothill origin and within tight meanders; the finer suspended load, eroded from the aeolian strata, is washed out the valley's northern exit. The shallow rills that furrow the pediment's surface are filled with loosened archaeological material and ultimately converge into the larger gullies. Rainwater channelling causes severe erosion of the talus as well: therein, steep gorges are cyclically cut and backfilled with angular boulders and coarse gravel, deriving from secondary displacement of older deposits and direct dismantling of the steep hillside's bedrock (Plate 4.2.5 C and D).

The pediment is also affected by badland erosion (badlands are terrains characterized by extensive erosion of unconsolidated sediments with by a very large number of deep drainage channels, separated by short, steep ridges), which is promoted by surface stripping of the loose deposits and triggered by intense rainfall. Badlands are mostly found in the western portion of the valley as deep, V-shaped, retreating recesses stemming from the sides of the gullies (Plate 4.2.6 C), but can also be observed as low, straight fronts in the valley's central portion, where the deposit is marginally more compacted and deep gullying isn't as pervasive.

Gullies and badlands reach hazardous heights, with cases of 4 metres tall overhanging cliffs found especially in correspondence of the largest ravine's meanders (Plate 4.2.7). Therein, channelled flash floods undercut the escarpment's base for up to half a meter before the vertical load overcomes the bearing capacity of the more compacted lower strata, causing catastrophic collapse events of several m^3 of sediments that gets steadily washed away by the intense waterflow (Plate 4.2.7). The total length of the endangered embankments throughout the site exceeds 200m.

During the 2019 field season, a 12x0.3m test trench was excavated perpendicularly to a system of seemingly ancient relict cut-and-fill gullies at the interface between the archaeological stratigraphy and a deeply eroded portion of the active talus, at the north-western end of the valley, in order to assess their age and spatial relationships (Plate 4.2.8). Unexpectedly, 1990's plasticized playing cards were found within their gravelly fill, providing evidence of marked severity of the erosional processes of – at least – the last three decades (Plate 4.2.9). This set of active processes may represent a comparative example of those that created the ancient interbedding channels identified in the above-described cliff-exposed Holocene stratigraphy.

Biogeomorphological processes and human agency

Human occupation of the area has been continuous up until present days, but local heritage conservation authorities issued a building ban over most the site's area (Plate 4.2.10). Indeed, the expansion of the city of Kassala and its satellite villages has had a severe impact on the archaeological area and its surroundings, with the construction of disposable huts, livestock corrals, waste dumps and newly built paved roads still representing a major cause of ground destabilization and soil loss.

The building ban did not prevent the religious use of the site, as testified by the presence of an expanding Islamic cemetery placed deep within the valley. It is noteworthy that the Islamic cemetery itself is threatened by the retreating cliffs and badlands as much as the actual archaeological record.

Despite the building ban and the general heritage awareness of the citizens nearby, who participate proactively in site keeping and archaeological excavations, site disruption triggered by biogeomorphological and human agency is inescapable (Zerboni & Nicoll, 2019). Burrowing rodents (*Xerus sp*) and arthropods such as beetles (*Pimeliinae*) and camel spiders (*Solifugae*) are very common and responsible for widespread and irreversible hidden damage to the archaeological stratigraphy (Plate 4.2.10) (Zerboni, 2011). Similar damage is caused by the sparse acacia bushes (*Mimosoideae*), whose roots disturb the archaeological record for several cubic metres underneath (Plate 4.2.10). Packs of wild dogs (*Canis lupus familiaris*) and a troop of olive baboons (*Papio anubis*) often cross the valley scavenging for waste and leftovers. Small flocks of goats graze on the acacias and the grassy hillsides, stripping patches of desert pavement and destabilizing the rocky talus.

4.2.4 Archaeological implication of the valley's morphogenetic events

Our investigation suggests that the extant topography and 6 m thick stratigraphy of Mahal Teglinos is the result of Late Quaternary accretional, pedogenetic and erosional cycles, including human contribution to sedimentation. Encircled by Neoproterozoic granite bornhardts and relatively protected by the secluded setting and heritage regulations (Ministry of Tourism and National Heritage, 1999), the site reveals a Late Pleistocene/Early Holocene phase of colluvial accumulation of coarse sediments, which underwent pedogenesis under an open savanna environment, supported by the higher water availability of the Early-Middle Holocene's African Humid Period. At the end of this phase, the gradual onset of aridity interrupted pedogenesis and promoted aeolian dust infilling of the valley. The intertwining archaeological and colluvial/aeolian dust strata reached a thickness of more than 2 m and blanketed the valley, sealing the older environmental record and preserving an even topographic surface. A later climatic shift towards unstable hyper seasonality (long dry vs. short wet season), together with readjusting supra-regional power balances, pushed the regional economy to adapt to full semi-nomadic pastoralism leaving the large administrative settlements such as Mahal Teglinos, where a feedback mechanism of site abandonment, grazing and flash floods likely caused hydrogeological instability and the onset of the pervasive gullying that we see today. The main effect of such changes in surface dynamic and their consequences of the local paleo-record are discussed in the following sections.

Onset, pace and implications of the gully erosion

The geomorphological assessment at Mahal Teglinos shows that hydric erosion is, indeed, the current main driver of soil loss and associated destruction of the paleoenvironmental and archaeological record. Although the onset of the current erosional phase could not be addressed through radiometric dating techniques due to the recurrent sediment displacement, turnover and removal that is inherent to small-scale active morphogenesis (Thomas, 2013), an assessment on its age and evolution rate was achieved by analysing written sources, relative chronology of laterally continuous cliff-exposed strata, archaeological chrono-typology of artefacts and finding of recent plastic items within patches of stabilized bedforms (Plate 4.2.11).

During his 1917 survey, J.W. Crowfoot (1928) described the site as "[...] *seamed with deep-cut watercourses, and the pottery is particularly abundant on the higher ridges and close to the boulders of rock which have fallen from the mountain.*", thus giving an image that is substantially like the present-day landscape. This means that the large gullies that dissect the pediment started forming long before the early 20th century, yet any guess on their precise onset remains speculative at the present state of knowledge. Nevertheless, radiometrically dated alluvial contexts from Erkowit (Sudanese Red Sea Hills) and the Khor Abu Habl's fan (White Nile State) (Mawson & Williams, 1984; Williams et al., 2010) provide a chronological reference of Late Holocene humid pulses affecting the eastern Sahelian plains and mountainous region. Therein, clay-rich and gastropod-bearing freshwater sequences give evidence of a transient return of humid conditions throughout the 1st millennium CE, which caused a reactivation of water-related surface processes. In the case of Mahal Teglinos, these humid pulses may have been the ancestral trigger of the current erosional processes. The lateral continuity of the isohumic soil horizon and the severed Gash Group's and Jebel Mokram Group's pristine archaeological strata, which crop out from cliffs and badlands throughout the valley, supports this hypothesis: the site possessed a general topographic evenness, free of pervasive gullying, from the Middle Holocene's humid period until at least the arid early 1st millennium BCE. This *terminus* is provided by the stratigraphically substantiated hypothesis that the Jebel Mokram Group were the last people to produce occupation layers of sufficient thickness and lateral extension to allow the correlation of cliff-cut stratigraphy throughout the valley, thus representing the latest reliable means of relative dating for the local hydrographic system. The ancient water-related processes, observed in Mahal Teglinos in the form of raised, interbedded cut-and-fill channels, may thus match with the observations reported by Mawson & Williams (1984) and Williams (2010) upon a Late Holocene east Sahelian climate shift. From the predominantly arid conditions of the post-African Humid Period (Shanahan et al., 2015), characterized by aeolian intake and accretion of the pediment within the valley, the climate of Eastern Sudan - as inferred by the environmental *proxies* presented in Chapter 4.2.4 as well - likely shifted to higher water availability during the summer monsoon. This kickstarted the onset of occasional flash floods and their consequent erosional processes affecting the loose aeolian upper strata. Such newly set climatic constraints, added to the influence of the powerful kingdoms of the Nile Valley (Manzo, 2017), may have been a contributing factor to the still unclear disappearance of the Jebel Mokram Group and the later sparse occupation by predominantly pastoral semi-nomadic groups, which protracted up until recent historical times (Manzo, 2017). Despite their well-documented presence in the Gash river's alluvial plain, the pastoral groups didn't produce any substantial evidence of settling within the valley, except for a few burials and negligible rock shelter scatters. Scarce use of foothill locations is also observed for other localities within the surroundings of Kassala, where the open plains become preferred after the disappearance of the Jebel Mokram Group (Manzo, 2017). This choice was likely driven by husbandry-oriented land use constraints. In fact, due to their aeolian/colluvial origin and loose compaction, dusty foothill pediments and gravelly taluses of the region had probably already become unsuitable for intensive grazing and human occupation due to scarce yield in wild grass and marked hydrogeological instability - a condition that is still valid nowadays despite the ever-increasing sprawling of the city of Kassala. Even so, Mahal Teglinos was never completely abandoned, and to these days the site remains susceptible to consistent ground stripping caused by herding, wild fauna and people crossing the valley as a shortcut to reach the city, to visit the Islamic cemetery to bury their kin or simply recreationally. Moreover, there is a possibility that in the late 19th and middle 20th century, armed conflicts between colonial occupants around the area of Kassala (Bellavita, 1930; Raugh, 1993) may have brought cavalry, machines and explosives inside Mahal Teglinos, with obvious consequences for the archaeological site's preservation.

Finally, the discovery of the 1990's plasticized playing cards embedded within relict foothill gullies (Plate 4.2.8 and 4.2.9) raised concerns about the possibility that an increase of the discharge volume of flash floods has been taking place for, at least, the past few decades. This observation matches with the findings of current climate and drought studies, which found a general contraction trend of the wet season of the eastern Sahel without a directly equivalent reduction of the annual rainfall yield (Zhang et al., 2012; Hulme & Tosdevin, 1989). This means that, despite current data points to the unequivocal aridification trend of the Sudanese Sahel, individual rainfall episodes have been yielding more discharge, resulting into more disruptive flash floods that in some cases were even able to briefly reactivate the fossil drainage network (Williams & Nottage, 2006).

Interpretative issues related to mass sediment displacement

The palimpsest of morphogenetic processes identified in Mahal Teglinos stimulated questions and concerns about the ease of formulating misinterpretations upon the archaeological and environmental records of highly dynamic contexts in arid lands. Mass displacements (i.e., colluvium, gullying, sheet flows) of artefact-bearing strata may create localized or widespread arrangements of artefacts and sediments that can resemble, at first glance, former topographic surfaces, deliberate cuts, living floors and refuse dumps. The risk of misinterpretation is further magnified by the remarkable similarity that ancient and recent erosional landforms may present in shape, size and sediment compaction. The age of the recently formed gullies containing the plasticized cards, for example, was only possible to estimate thanks to those findings. Their shape and fill composition and compaction, otherwise, would have been almost undistinguishable from those of the fossil interbedding channels forming the gravelly body whose eroded remains sit among the pristine archaeological stratigraphy. The very same fossil drainage system, in turn, was only possible to identify from the adventitious section exposed by the largest active gully in Mahal Teglinos, as it would otherwise have been barely recognizable from the dusty and littered topographic surface. As a matter of fact, the chance of repeated displacing and intermingling of natural sediment and anthropic remains at any time after the primary deposition, cannot be ruled out before investigating. Our reported analysis highlights the necessity and advantages of carrying out geomorphological assessments as part of any archaeological investigation, especially when the archaeological context is but a mere component of dynamic natural landscapes.

4.2.5 The importance of Mahal Teglinos

The high spatial resolution of this geomorphological assessment of the valley of Mahal Teglinos contributes valuable insights upon the human-environmental nexus of one of the most important protohistoric sites of the far Eastern Sudanese Sahel. While substantiating pre-existent archaeological and paleoclimatic knowledge with *ad hoc* cartographic material, the study provided new data on the late Holocene to recent morphogenetic processes that kickstarted landscape evolution towards the current setting of the area. Moreover, we presented a pondered projection of the future evolution of the site and, by climatic and environmental proxy, of the wider region, providing a reference point for future studies and fieldwork planning.

Seasonal flash floods were identified as the site's main morphogenetic process for at least the past 3000 years, acting preferentially on anthropogenically- and biogeomorphically-induced disruptions of the loose deposits such as stripped/trampled surface patches and burrows. Furthermore, the identification of ancient gully gravels concealed by surface dust and scatters, and the finding of contemporary plastic objects within seemingly ancient gully fills, raised faceted concerns. On one hand, it shows that the remarkable similarity between old and young displacement deposits formed during rhexistasy phases (*sensu* Erhart, 1956) may cause misinterpretation of chronological attribution of stratigraphies, especially in the case that no radiometric dating can be carried out or no glaring artefactual evidence is found. On the other hand, our assessment revealed the serious hydrogeological threat to the site's heritage and the inhabitants of the valley's outskirts caused by a seemingly increasing pace of the gully erosion within the valley, an observation supported by current supra-regional climate studies on climate change and soil loss.

In general, Mahal Teglinos represents a small but noteworthy case study on soil loss and heritage conservation in the arid Sahelian regions, because it outlines the effects of hyper seasonality and climatic pulses on fragile landforms and their embedded archaeological record. Because the damage is currently driven by an admixture of hardly manageable human activities (small-scale husbandry, mundane trampling) and *de facto* unavoidable extreme weather events (strengthening flash floods), it is appropriate to speculate that other similar contexts of the

Sudanese Sahel – which is dotted with countless inselbergs and foothills entirely similar to the Jebel Taka and Mahal Teglinos – are undergoing very similar erosional processes, with major losses for known and yet-to-be-discovered archaeological sites. With reasonable certainty, the same argument may be applied to all regions of the Sahelian belt where climate change and land overexploitation are disrupting the original settings in which known and novel archaeological sites may be found. This not only represents a potential enormous damage for the world's cultural heritage, but a substantial and inevitable issue of *loss of evidence* that, if added to the many plausible erosional cycles that may have happened in the archaeological past, could lead to highly biased misinterpretations for future archaeological research as well. In this picture, meticulous geomorphological assessments could represent a viable mitigation and a source of added value for any archaeological venture, regardless of time period, geographical region and site conservation status.

4.3 At the foothills – Eastern archives of grass and dust

The portion of the Kassala region of Sudan laying east of the Gash River (Plate 4.3.1), is a drastically understudied geographical area, both from an archaeological and paleoenvironmental point of view. This section provides kickstarting data on the Holocene climatic and environmental evolution of the area, framing and contextualizing it within the wider - and better represented - supra-regional picture. By means of field survey, pedosedimentary analyses, micromorphological analyses and absolute datings, results are provided for three sites spread over an area that extends from the outskirts of the city of Kassala to the southern stretches of the Sudanese Red Sea Hills (Plate 4.3.1). All sites are located close to the foothill of imposing rocky outcrops, where complex polygenic palimpsests of aeolian, colluvial, and hydric landforms, intertwined with pedological bodies, encapsulate the paleoenvironmental history of the region and, occasionally, host rich archaeological remains. The main identified features include African Humid Period buried isohumic soil horizons in lower flat grounds, which are legacy of water-reliant prairie environments, and later accretional dusty aeolian deposits intermingled with colluvial gravels close to the outcrops' eroded foothills, testimony of a climatic deterioration towards aridity and erosion driven by hyper seasonality. Results are of great importance as a contribution to a more holistic understanding of past human dynamics of the region, as well as being a newly added tile to the recent climatic history of the continent.

4.3.1 Jebel Haura - Site JH1

Jebel Haura is a large inselberg composed of steep granodioritic bornhardts, located 20 km east of the city of Kassala (Plate 4.3.1). Its highest peaks reach ~1200m a.s.l., with a prominence of ~650m. Ancestral Quaternary and recent morphogenetic processes acting on the inselberg and its skirt are completely analogous to those identified at Mahal Teglinos. Slopes at high altitudes are either bare rock etchplains or covered with stabilized gravelly debris. At lower altitudes, a chaos of detached boulders and coalescing gravelly taluses accumulate and gradually intertwine with the foothill pediment matching its gradient (Plate 4.3.2A). At the very outskirts of the pediment, a deeply weathered paleosoil, likely related to older hot and humid Pleistocene climatic phases, is found underlying the Holocene sequence. The pediment is composed of interlayered, very fine to coarse unconsolidated sediments. A general in-situ understanding of its sedimentological features was made possible by the widespread occurrence of large gullies (Plate 4.3.2A-B), which scar the deposit with retreating vertical cliffs reaching heights of 4-6 metres, exposing adventitious sections that disclose the geomorphological palimpsest. The examined section (Plate 4.3.2C) was chosen considering cliff stability, i.e. absence of undercuts or overhangs, accessibility and presumed information yield. The section (15.508054°N, 36.582317°E) is 4 m tall, and reveals two main sedimentary units: (i) a ~1.5m thick sand-dominated deposit characterized by faint cross- and planar-beddings, likely created by chaotic high-energy water runoff, superimposed with (ii) a 2.5m thick dust-dominated deposit characterized by a generally massive structure, enriched with coarse sand and gravel and interspersed with lenses of gravelly colluvium containing rich protohistoric archaeological layers (Plate 4.3.2D).

Results from the pedosedimentary analyses substantiate the field observations. Grain size distribution (Plate 4.3.2D) show sand-dominated sediments throughout the deposit, but a closer examination on the nuances of the coarser and finer fractions is diagnostic of different morphogenetic processes underlying the formation of the two main units. The lower portion of the deposit (samples B26 - B19 in Plate 4.3.2D) is characterized by poor sediment sorting, with large amounts of medium-sized sand but relatively abundant silt and clay as well, identifiable in thin section micromorphology (JH1 TS4) as a ubiquitous fibrous and powdery coating of all aeolian and colluvial quartz and granodioritic grains, which are loosely arranged in a pellicular grain/spongy microstructure with a chitonic to close porphyric C/F related distribution and faintly layered structure (*Appendix C* and Plate 4.3.3B-C). Samples B20 and B19, in particular, are enriched with gravel and coarse sand, consistent with the turbulent foothill water-lain strata geometry observed on field. Samples B18 to B1, conversely, show an overall prevalence of finer sand, silt and clay, although a general poor sediment sorting and a significant fraction of gravel is present throughout. Particularly, gravel-enriched extensive strata and lenses are recurrent (samples B16, B14, B8 and B5), and two of these (samples B16 and B5) also encase significant amounts of archaeological material, which in a portion of the section located a few tens of meters closer to the foothill is so abundant that it can be safely considered a large, still yet-to-be-explored archaeological site (Giancristofaro, 2021). The analysis of total organic carbon, and that of CaCO3 content also provide meaningful result upon the formation processes of the deposit. Carbon content peaks, in fact, fit positively with the gravelly lenses and layers, with greater concentrations in correspondence with the richer archaeological strata and close to the upper surface of the deposit, where live grass roots taint the results. Conversely, CaCO3 concentration peaks fits negatively against the organic carbon, suggesting the existence of periods of environmental stasis associated with intensive human frequentation alternating with periods of aeolian deposition associated with temporary abandonment. Micromorphology of samples JH1 TS2 and JH1 TS1 (*Appendix C*), taken in correspondence with low-carbon/high CaCO3 layers, yields results that are consistent with the sedimentological analyses, showing chaotic loose assemblages of dominant loessic quartz sand and swelling biotite flakes interspersed and faintly layered with hornblende and magnetite-rich granodioritic gravel. All mineral grains are coated with fibrous and powdery micrite, and are arranged in pellicular grain microstructures with chitonic C/F related distribution, with very scanty occurrence of bioturbation and illuvial pedofeatures, and almost no presence of anthropogenic/organic material (Plate 4.3.3A/D-I). On the contrary, micromorphology of sample JH1 TS5 (*Appendix C* and Plate 4.3.3J-L), lifted a few metres downstream at a quote corresponding to B16, albeit revealing no substantial difference from sample JH1 TS4 in terms of C/F related distribution and microstructure, disclosed the presence of organic remains such as bone fragments, charcoal fragments and localized ash enrichment of the groundmass.

The upper surface of the stratigraphic sequence is sealed by a tight desert pavement composed of granodioritic gravel stabilized by a thin seasonal vegetation cover.

Archaeological remains from the gravel-enriched layer corresponding to sample B16 provided dating for the lowermost portion of the aeolian/colluvial deposit. Although the organic carbon yield of the layer did not reach measurability threshold for radiocarbon dating, the artefacts - mostly represented by ceramics fragments – belong unequivocally to the Middle and Classic/Late phases of the Gash Group culture (Manzo, 2019), therefore dating to the late 3rd and early 2nd mill. BCE. This means that almost the entirety of the aeolian/colluvial deposit is coeval or younger than the Gash Group, representing a perfectly fitting chronostratigraphic analogue with the palimpsest of the valley of Mahal Teglinos (Manzo 2017; Costanzo et al., 2020a; Costanzo et al., 2022).

4.3.2 Jebel Tareg quarry - Site JT1

The gneiss quarry of Jebel Tareg is a commercial facility located a few hundred metres southeast of the city of Kassala, just east of the Jebel Taka (15.438268°N, 36.452442°E) (Plates 4.3.1 and 4.3.4A). The quarrying activity exposed a Quaternary - or possibly older - cover sitting directly on the underlying subhorizontal crystalline basement (Plate 4.3.4B). The Quaternary succession is composed of 4-6 metres of unconsolidated to weakly consolidated pedosedimentary features: the deeper portion, which was not sampled, comprises several alternating bleached and iron-rich silty clay layers and horizons, likely related to ancestral fluvial deposition followed by hydromorphism and pedogenesis; the upper portion is a ~70 cm thick, laterally extensive dark organic horizon characterized by strongly expressed, very hard small and medium-sized (3-10 cm) equilateral plinths. The organic horizon is in turn covered and masked by a layer of unsorted debris, deriving from quarry soil disposal and several other infrastructural and agricultural works carried out in the surroundings.

The organic horizon was sampled ~30cm beneath the upper surface for radiocarbon dating (sample JT20198/DSH9576_HA) and micromorphological analyses. Radiocarbon dating yielded a radiocarbon age of 5802±40, calibrated with the IntCal 20 curve (Reimer, 2020) to 6730-6490 years BP (2σ). Micromorphology (*Appendix C* and Plate 4.3.5) discloses a mature deposit, rich in small (~100μm) equilateral, subangular to subrounded quartz clasts, accompanied by less abundant same-sized feldspars and occasional larger granitoid clasts, all included with an open porphyric C/F-related distribution within a dense, massive dark brown clay matrix showing argillopedoturbation with incipient fragmentation into smaller plinths (1^{st} order decimetric plinths split into 2^{nd} order centimetric chaotic angular polyhedrons) and occasional bioturbation. Occasional $CaCO_3$ clasts, equilateral and well rounded, are also present; these may have been inherited as load features from older riverine systems or from eroded calcretes/Calcisols that are still present in small, degraded patches in the outskirts of the larger inselbergs (Costanzo et al., 2022). The matrix shows widespread humus enrichment, widespread unaltered dendritic Fe/Mn nodules, oxide hypo-coating of the $CaCO_3$ clasts, and debris infilling of planar voids separating plinths. Such features, considering the radiocarbon dating ascribable to a wet period of the middle Holocene, are compatible with a polycyclic soil formation that started with the establishment, atop of the ancestral laterites, of a Kastanozem-type soil (WRB, 2015) that formed under a warm prairie environment during a period of slightly higher water availability, followed by a transition to a Vertic Kastanozem-type soil promoted by rainfall hyper seasonality under a warm semi-arid climate (Eitel & Eberle, 2001; Eitel et al., 2002).

4.3.3 Jebel Maman - Site JM1

Jebel Maman is the name of a group of gold-bearing hills and inselbergs located at the very southern periphery of the Red Sea Hills, ~100km northeast of the city of Kassala (Plate 4.3.1 and Plate 4.3.6A). The local assemblage of bedrock lithologies differ slightly from the other two locations, including metasedimentary hills - namely greenschists (Geological Research Authority of the Sudan, 2004) - along with gneiss basement outcrops and granodioritic plutons. The Quaternary pediments and cover in the area are moderately more consolidated than in the area of Kassala, and covered with coarser angular debris forming a tight hamada surface (Knight & Zerboni, 2018). Nevertheless, the deposits are still subjected to pervasive gullying, although the depth and size of the gullies are smaller than those found, e.g., around Jebel Haura. This may be due to the reduced thickness of the unconsolidated pediments, as well as the smaller dimensions of the rocky outcrops, which convey lesser rainwater over shorter altitude gradients, resulting in weaker and less disruptive flash floods. The extended area surrounding the site, being far from cities and stationary settlements that subsist with the agricultural land to the west of the Gash river's endorheic terminal fan, is not cultivated and receives lesser visitors, preserving a glimpse of the present day's potential natural landscape of the region, dominated by seasonal short-grass hot steppe stabilizing the unconsolidated substrate, and xerophyte tunnel vegetation flanking the ephemeral watercourses and wadis.

The section chosen for analysis (16.279882°N, 36.836680°E) is a 70cm spontaneous exposure of a very dark organic horizon covered and sealed by a 30cm thick paler silty layer (Plate 4.3.6B). The same stratigraphy is observed throughout the surroundings, suggesting an extended lateral continuity covering, at least, the lower land at the lobes of the coalescing pediments of the encircling hills. The lower dark horizon, dull grey in colour, is a mildly consolidated deposit forming small and brittle equilateral polyhedrons or weakly expressed small prisms, with no macroscopic archaeological, faunal, or botanical remains. The soil was radiocarbon dated (sample Beta-594956) to 6260±30, calibrated with the IntCal 20 curve (Reimer, 2020) to 7270-7020 years BP (2σ). The upper layer, light brown in colour, is a massive, non-stratified unconsolidated fine deposit, again with no macroscopic archaeological, faunal, or botanical remains except for the roots of the live grass cover, which disrupt the already fragile aggregation making it impossible to collect undisturbed samples for thin section micromorphology. The sequence is topped by a loose discontinuous hamada surface composed of scatters of fine gravel.

Sedimentological analyses carried out on two bulk samples (Plate 4.3.6C), one for each layer/horizon, reveal a relatively similar grain size distribution, dominated by fine sand and silt with almost no coarse sand and gravel content (Φ<-0.5: B1=0.53%, B2=0.27%). Conversely, analyses of the organic substance and %CaCO3 content yielded results that differed vastly between the two samples: the pale upper layer, although containing more organic substance compared with any of the sampled collected at Jebel Haura (Site JH1, Plate 4.3.2D), has less than half of that contained in the lower darker soil, which reaches just short of 0.5%. CaCO3 content, on the other hand, shows an exactly opposite trend, with the upper layer being vastly richer in carbonate content (B1=3.17%, B2=0.62%).

Micromorphological analysis of the dark lower deposit (*Appendix C* and Plate 4.3.7A-H) add details on the colour and internal structure of the soil. Similarly to Site JT1, rather than a uniform dark mass, the sample shows argillopedoturbation, with several chaotically arranged paler and darker patches, faintly plinthic or angular polyhedral in shape, of comparable coarse grain composition. These are differentiated by the aspect and composition of the groundmass, which is clay-like in the pale patches, and more fibrous in the dark ones. Pale and dark patches may be welded together (Plate 4.3.7D and G), or juxtaposed along thin planar voids (Plate 4.3.7F), or, again, gradually fading into each other (Plate 4.3.7A), and are all disrupted by bioturbation (Plate 4.3.7B, C and E). Rare amorphous CaCO3 powdery concentrations, result of dissolution and rapid evapotranspiration, are found within the common structural voids and vesicles. Additionally, micromorphology offers a further insight on the source of the mineral fraction composing the parent material. In fact, the shape and weathering of the quartz clasts that compose most of the mineral fraction, paired with the analysis of the grain size distribution, indicates a loessic origin of the sediment (see Cremaschi et al., 2018). The soil's patchy colour and general spongy structure with faint angular aggregates, paired with the analytical results, suggest a relatively intense pedogenesis under a warm steppe environment with higher water availability than today, which led to isohumism (Duchaufour, 1982a) and the formation of a Chernozem-type soil, again compatible with the loess substrate, with subsequently established moderate vertic properties prompted by the gradual decrease of rainfall in the last millennia.

4.3.4 Paleoenvironmental significance of the pedostratigraphies of JH1, JT1 and JM1

The stratigraphic, pedosedimentary and micromorphological analyses of the three selected sites, paired with the radiocarbon dating of significant contexts identified therein, provided noteworthy insights into the Holocene environmental evolution of the eastern portion of the Sudanese very outskirt of the Sahelian belt, at the transition between the alluvial plains of the Nile's basin and the Ethio-Eritrean Highlands. Therein, natural and anthropically enhanced surface erosional processes are causing a prominent fragmentation of an understudied Quaternary record (Costanzo et al., 2022). Even so, fragmentation was overcome by retrieving data from different natural archives that, when fitted together, define a model of Holocene paleoenvironmental evolution that is consistent and valid across the study region. In turn, results insert the region in the vast, yet still geographically discontinuous, archive of North African territories that are pivotal for the comprehension of Holocene human dynamics, and whose physiographic and paleoenvironmental study are key to a full awareness of processes of the human-environmental nexus.

The three study sites evidence the existence of several pedosedimentary features, whose formation was triggered by site-specific settings because of morphogenetic agents acting on different local topographies and pre-existing substrates. Nonetheless, their holistic examination shows a rather clear picture of the processes, climatic trends, and environmental transitions the happened in the region since the Early Holocene and up to present days (Plate 4.3.8).

Pre-Holocene

In two of the three locations, namely Site JT1 and Site JH1, ancestral deposits are found underlying the Holocene succession (Plate 4.3.8A). In Site JT1, quarrying activities exposed them down to the crystalline basement, revealing a thick succession of banded hydromorphic alluvial sediments. These were not studied in detail, but their deep desiccation, plinthic structure and general rusty colour suggest, at least, one or more phases of deep weathering (Duchaufour, 1982b) of the deposit. At Site JH1, just outside of the distal fringes of the pediment, satellite images and field survey revealed a reddened soil that represents the upper residual surface of the ancestral deposit, exposed subaerially as early as the 1st millennium CE as testified by archaeological scatters of grinding stones and ceramic bowls found in pristine position partially buried within very shallow pits (Manzo, 2019).

Early/Middle Holocene

The most glaring feature from sites JT1 and JM1 is the preservation of buried isohumic soil horizons. In both cases, as proven by radiocarbon dates calibrated to 6730-6490 years BP (2σ) for JT1 and 7270-7020 years BP (2σ) for JM1, isohumic horizons formed in the Middle Holocene and are pedological remnants of environments that are no longer compatible with present-day climatic settings. In fact, they are referable to the Early/Middle Holocene phases of enhanced water availability that could sustain the prairie environments responsible for the formation of such deep and well-expressed organic profiles (Plate 4.3.8B). The same feature was observed in the well-studied valley of Mahal Teglinos (Costanzo et al., 2020a; Costanzo et al., 2021a; Costanzo et al., 2022), where a similar buried soil horizon was radiocarbon dated to 7430-7260 cal BP (2σ). The prairie environment model is further supported by the faunal assemblages from the Amm Adam archaeological sites (7th-6th mill. BCE) of the Gash river's fossil alluvial plain, which comprise kobs, reedbucks, hippos and buffalos (Geraads, 1983), all water-dependent species. Although the lateral extension of each patch of isohumic soil is not yet known, it is safe to assume that they may extend continuously interrupted by large rocky outcrops, only being truncated by active natural erosional processes or extensive modern cultivation (Costanzo et al., 2022).

At Site JM1, the isohumic soil is also associated with a peculiar parent material. In fact, as revealed by micromorphology and grain size distribution analysis, the fine-grained parent deposit appears to be of loessic origin (Yaalon, 1987). Further analyses shall be carried out in this respect, because this would represent a newly found sink location of peri-desert loess deposition (Whalley et al., 1982; Tsoar & Pye, 1987; Crouvi et al., 2010; Smalley et al., 2019; Li et al., 2020; Lancaster, 2020), adding context to a much debated phenomenon that only has few and spread-apart case studies for Northern Africa (Coudé-Gaussen & Rognon, 1988; Coudé-Gaussen, 1990; Stockes & Horrocks, 2020). Interestingly, case studies of great similarity are found at the same latitudes in the southern Arabian Peninsula, where desert loess has been documented at the northern slopes of the Dhofar Mountains in the Sultanate of Oman (Cremaschi & Negrino, 2005; Cremaschi et al., 2015), at Ras Al Khaimah in the United Arab Emirates (Goudie et al., 2000), and in the area of Sana'a in Yemen (Nettleton & Chadwick, 1996), where the loess sequence also promoted the formation of isohumic soil with a radiocarbon age very similar to the one measured for JM1 and then buried in the Late Holocene.

While at Sites JT1 and JM1 water availability and topographic settings were promoting the maturation of stable organic soils, at Site JH1 the topography of the overlying bornhardts was causing the formation of chaotic thick sand-dominated deposits created by turbulent water discharge. Likely, the kinetic energy of the discharge and the quick sediment turnover was the primary cause for the lack of diffuse pedogenesis therein.

Middle - Late Holocene transition

Both isohumic soils from JT1 and JM1, together with the one from Mahal Teglinos, show secondary vertic properties that testify the climatic transition towards aridity that took place after the humid Middle Holocene. In fact, shrink-swell cycles of the groundmass, which are the primary cause of argillopedoturbation, are better expressed in a climatic regime of alternating wet and dry seasons. It is known that Middle Holocene's enhanced water availability, even though with still-debated timing and severity, eventually came to a halt (deMenocal & Tierney, 2012; Shanahan et al., 2015), leading north Africa into a different climatic regime, which in turn promoted a new set of surface processes different from those acting in the previous several millennia.

For the Kassala region, this mainly meant aeolian deflation of open plains, with associated aeolian accretion of the pediments surrounding the large inselbergs that constitute wind breaks becoming dust traps (Plate 4.3.8C) (Middleton, 1985). This is particularly evident at Site JH1, where aeolian quartz and biotite dust contributed to the formation of the 2.5 m thick massive deposit sitting above the water-lain sands. Crucially, dust deposition is accompanied by equally present colluvial intake, i.e. granitoid and granodioritic sand and gravel chaotically mixed with the fine aeolian sediment. Because in the entire deposit only four well-distinguishable gravel-enriched layers are found, it is reasonable to consider the aeolian and colluvial processes to be acting with equal intensity in tight alternance. This alternance, rather than leading to the formation of a manifestly layered deposit, promoted the growth of a chaotic admixture driven by gravitative redistribution during mild water-led colluvial events. In truth, the four gravel-enriched layers are associated with Gash Group archaeological remains or peaks of organic substance (Plate 4.3.2D), meaning that they formed during periods of relative stasis of the aeolian accretion possibly associated with transient humid episodes. Interestingly, Mahal Teglinos and JH1 are mutually visible well within the horizon (Plate 4.3.9). The copious amount of Gash Group archaeological material, spread over laterally continuous wide layers within the deposit, may suggest that JH1 is, in effect, a large settlement of size almost comparable with that of Mahal Teglinos, possibly an outpost towards the Highlands rising just behind Jebel Haura. Nevertheless, surveys in that sense are still at their primary stage, thus it is impossible to speculate any further on this aspect of the Gash Group's effective regional domain. In general, the stratigraphy of site JH1 is the result of aeolian-led processes in hot semi-arid climate and a local environment characterized by short ephemeral grasses, which protracted for ~2000 years between the end of the Middle Holocene's humid conditions and the onset of later climatic settings that underlie the origin of the widespread gullying affecting the region's pediplains. Substantiation for the hypothesis of the hot steppe environment comes from the faunal assemblages of Mahal Teglinos (Gautier & Van Neer, 2006; Manzo, 2017), namely from Gash Group and Mokram Group archaeological strata (mid-3rd - early 1st mill BCE), which comprise, along with domesticated bovids and ovicaprines, buffalos from the inundated Gash river, and gazelles and dikdiks from the drying up eastern open plains.

The top layer from site JM1 is, again, an aeolian fine-sand deposit. Micromorphology for this layer is missing, but the massive sedimentary structure of the deposit, the almost total lack of gravel and coarse sand, and its markedly centre/right skewed grain size distribution is compatible, as for the underlying horizon, with wind-driven processes. If observed from a wider regional perspective, and considering the CaCO3 concentration measured in the sample (Plate 4.3.6C), its formation may be explained as a result of a twofold condition: (i) scarce colluvial intake caused by lesser seasonal rainfall compared to the southern locations (Fig. 1) and by the relatively lower gradient and greater distance of the overlying inselberg's hillslope, and (ii) the presence, ~150km northeast, of a vast source area of wind-blown sand and limestone dust that is the dried up dune-interdune basin system of the Middle Pleistocene Atbara Paleolake (Abbate et al., 2010). By extension, due to the consistency of the regional's physiography (Costanzo et al., 2021a), every rocky spur of the northern hinterland of Kassala could meet the criteria to be a peri-desert loess sink for dust intake coming from neighbouring source locations, therefore representing potential high-resolution paleoclimatic and paleoenvironmental archives especially if hosting buried soil horizons as in the case of Site JM1.

Late Holocene and present days

A subsequent climatic transition is not registered in accretional sedimentary record, but rather in the loss of it (Plate 4.3.8D). In fact, the pervasive gullying that exposed the very sections considered in this research, is the result of a shift from the stable aridity of the Middle to Late Holocene transition to hyper seasonality, characterized by dry spells alternating with increasingly powerful and disruptive flash floods that taint the pristine unconsolidated deposits, especially the pediments encircling the inselbergs. As emerged from the in-depth study of the valley of Mahal

Teglinos (Chapter 4.2 and Costanzo et al., 2022), whose environmental and archaeological records are particularly rich and well-preserved, and from other studies from localities of adjacent regional contexts (Mawson & Williams, 1984; Williams & Nottage, 2006), such shift happened supra-regionally somewhen around the middle/late 1st millennium BCE. Nevertheless, the geomorphological outcome that can be observed today cannot be attributed solely to climate and rainfall dynamics. In fact, deeper causes are found in the human-environmental nexus of the region, which underlies feedback looping morphogenetic processes that are, still to present-day, responsible for soil loss and erosion in the region. By the mid-1st millennium BCE, supra-regional shifting power balances pushed changes on the regional subsistence strategies and settlement patterns, and large foothill settlements such as Mahal Teglinos and Site JH1 were abandoned, with people scattering across the open plains. Pastoralism became widespread across the land with seasonal camps and flocks of ovicaprines (Manzo, 2017), and zoogeomorphological processes were triggered as the delicate hamada surfaces, which offer protection to the summit of the unconsolidated pedostratigraphies such as that of Site JH1, were stripped by trampling and grazing, exposing weakened surfaces to the action of splashing raindrops and hillside channelled water, which started eroding the ground creating, in turn, more erodible surface (Zerboni & Nicoll, 2019). Still to present days, with an even increasing intensity of the summer monsoon caused by a contracting relapse period unmatched by the total rainfall yield, which remains unvaried (Zhang et al., 2012; Hulme & Tosdevin, 1989), zoogeomorphologically and anthropogenically enhanced processes acting on the delicate pediments are in place. Intensive agriculture eroded and masked the natural archives across very large areas, and vehicles and large flocks move from the exhausted harvested crops to unmanaged grassy raised ground in search of food resources year-round, causing instability and ultimately irreversible loss and fragmentation of archaeo-environmental archives.

In general, isohumic soils, typical of warm prairie/open savanna environments, are commonly found and date radiometrically to the Middle Holocene, adding new land to the records of present-day North African arid regions that used to host wetter habitats. The isohumic soils, in turn, are buried under a sedimentary cover, deposited between the late-3rd and mid-1st millennia BCE, composed of unconsolidated fine-grained sands, silts, and gravel. This is especially true nearby tall granitoid inselbergs, which act both as topographic traps for wind-blown dust and source for colluvial gravel. Therein, unconsolidated pediment deposits can reach a thickness of a few metres, encasing archaeological strata and archiving short-term compositional variations that are diagnostic for morphogenetic processes at the local scale but, again, are consistent between sites that are far apart. Regional consistency is found for late and contemporary Holocene erosional processes as well. These are driven by a conjunction of hyper seasonal climate and zoogeomorphologically and anthropogenically enhanced processes, that have been causing pervasive gullying and soil destabilization since the mid-1st millennium BCE.

5. Zooming back: the human-environmental nexus during the past 8000 years

The discovery and analysis of the extant physical geography of the Kassala region of Eastern Sudan and its embedded archaeo-environmental archives, revealed a picture of extreme complexity under every point of view.

The sedimentary succession sitting atop of the Precambrian crystalline basement underlying the Southern Atbai Plain, comprised between the Atbara and Gash rivers, may encapsulate the entire Quaternary sedimentary history of the region. Therein, buried palimpsests of former riverine environments have been dated back at least 200,000 years (Abbate, 2010; Tsukamoto, 2022), although more realistically they may be several million years old. Crucially, the uppermost portion of the plain itself, given the available field-collected and remote-sensing data, represents a mosaic of relict riverscapes that may refer to widely diachronic periods (Chapter 3 and 4.1, and Costanzo et al., 2021a). Paleochannels, fluvio-lacustrine deposits, alluvial loams, eroded and levelled plinthites and laterites, and sparse topsoil patches belonging to spread-apart paleoclimatic and paleoenvironmental phases, coexist at the current topographic surface as a result of composite outcomes of supra-regional and regional morphotectonic adjustments and Late Holocene regional climatic conditions. During a still undefined timespan likely referable to the Late Pleistocene, relative movements of the parallel Hudi-Atbara and Gash Faults, aided by climatic pulses that would enhance the kinetic energy of lowland floods, induced channel avulsions and gradually forced the wandering path of the Gash river into a linear tectonic endorheic depression running parallel to the Atbara river, thus isolating the Southern Atbai from any further build-up of alluvium. Today, the Southern Atbai hosts vast expanses of agricultural parcelization, with the vast majority of the land being dedicated to rainfed Sorghum cultivation or irrigated cotton cultivation, as well as fruit orchards close to the major rivers. The hot semiarid (BSh) climate (Beck et al., 2018) sustains few remaining strips of wild seasonal shrubland between non-cultivated areas, as well as tunnel vegetation along ephemeral watercourses and patches of woodland savanna in areas where sandy loamy substrates - remnants of paleochannels and old alluvium – offer topographic lows with enhanced water-storing capacity.

In parallel, to the east of the Gash river, other morphogenetic processes were shaping the landscape leading up to the Ethio-Eritrean Highlands. In a setting characterized by numerous granitoid outcrops piercing a wavy gravelly expanse furrowed by narrow ephemeral waterways, which is the result of hundreds of millions of years of erosion acting on the outcrops themselves, the action of countless regional and supra-regional biostasy-rhexyistasy cycles (Erhart, 1956) and source-sink alternations of sediment input and output, resulted in the creation of the composite sedimentary palimpsests that are visible today. The characteristics of the topographic surface, which varied over time, and the subsequent differential erosion acting on the sedimentary record, produced an extant landscape that, like in the case of the Southern Atbai, hosts records from widely diachronic time periods of the Quaternary - and possibly even older. Pleistocene deep stratified laterites, Holocene buried organic soils, coalescing pediments, and thick colluvial/aeolian/archaeological deposits coexist within stratifications only a few metres thick, unveiled by deep pervasive gullying that was put in motion by Late Holocene climatic pulses and is still in motion nowadays. Again, the land is subjected to rainfed and irrigated agriculture, although to a much lesser extent than the Southern Atbai and only in correspondence of minor waterways that can be split into sheetwash with systems of hedges and mud wedges (Costanzo et al., 2021a), due to the impoverished and mostly gravelly and stony nature of the uppermost substrate. Most of the landscape is colonized by thin ephemeral grassland and xerophyte vegetation, especially along waterways and at the foothills of the inselbergs where cracks in the rock and hypoabyssal buried bedrock offer humid hotspots and phreatic water tables for shrubby vegetation to bloom year-round.

In this extant geographic, environmental and climatic setting, the research presented in this dissertation focused on the Holocene archaeo-environmental archives, stratigraphically located in the uppermost and most fragile portions of the sedimentary record.

The array of investigations carried out on the territory - remote sensing, field survey, geomorphological assessments and cartographic production, pedosedimentary analyses, micromorphological analyses, radiocarbon dating, archaeological excavations - brought to light a picture that fits within well-known supra-regional archaeological and paleoenvironmental narratives concerning the North and NE African Holocene climatic and environmental evolution and relative settlement patterns of archaeological communities. Notably, the most glaring paleoenvironmental sedimentary features are those encapsulating pedological evidence of the existence of fossil prairies belonging the Early-Middle Holocene. These formed during the African Humid Period, an extended time frame of increased monsoon penetration and water availability over North Africa (Moeyersons et al., 1999; Cremaschi et al., 2014; Vermeersch et al., 2015; Tierney et al., 2017; Henselowsky et al., 2022) that started roughly 14800 years ago (deMenocal & Tierney, 2012) and ended with a centuries-long diageographic fade-out of the humid conditions towards an increasingly arid continental climate (Shanahan et al., 2015). The peculiarity of these features, which also makes them easy to recognize even from a distance, is their stark chromatic contrast against the overlying and underlying sediments. In fact, they are rich organo-mineral buried soils of the Kastanozem category (WRB, 2015), characterized by a thick isohumic topsoil of greyish brown colour, developed over pale-coloured foothill colluvial/aeolian sediments or open-plain alluvium, and subsequently buried and preserved by newly produced pale colluvium and aeolian dust at the transition from the African Humid Period into the arid phase of the Late Holocene.

This specific pedostratigraphy, i.e. buried dark topsoils “sandwiched” between pale deposits, is found nearly unvaried from the area of Jebel Taka, where it is exposed at Mahal Teglinos (Chapter 4.2) and Jebel Tareg (Chapter 4.3), up to the area of Jebel Maman 100 km north. Interestingly, it doesn’t seem to be present in the open plain of the Southern Atbai, although it might have been eroded and masked by agriculture. Therein, nonetheless, surviving patches of Fluvisols (WRB, 2015), i.e. organic soils developed on water-retaining fluvial sediments and occasionally in fluviolacustrine and tidal depressions, are easily spotted from satellite pictures, especially in the Shurab el Gash area where they sustain the denser woodland and shrubland vegetation occupying the loamy paleochannels.

The cumulative collected pedological and geomorphological evidence, ascribable to the African Humid Period as well as the following phase of aridity, offers landscape-scale interpretative foundation for the archaeological, archaeobotanical and faunal evidence recovered in the region. Pre-Saroba and Butana Group communities would have settled in a land characterized by the presence of two large rivers, of which one would have been perennial (the Atbara) and one likely semi-perennial but still characterized by standing ponds in between high floods, and by vast

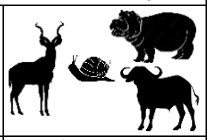
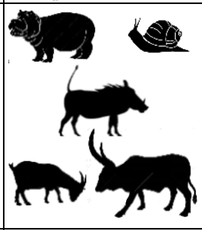
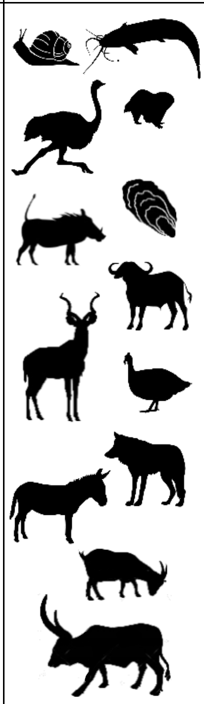
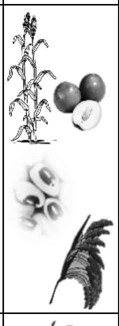
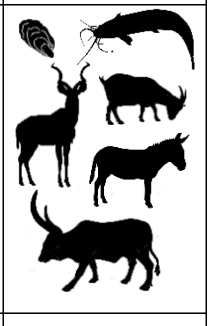
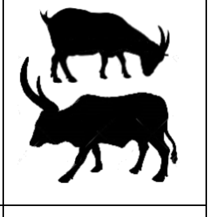
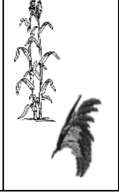
Group	Chronology	Site(s)	**Plant species** (Beldados, 2015)		**Animal species** (Geraads, 1983; Manzo, 2017)	
Amm Adam	6th mill. BCE	Amm Adam Station (site 1), Eriba Station (site 2, 3, 4)	*Unspecified millet*		*Unspecified antelopes* *Syncerus cafer* *Hippopotamus amphibious* *Achatina fulica,* *Pila ovata*	
Malawiya	5th mill. BCE	Various sites	*No data*		*Unspecified antelopes* *Land snails*	
Butana	4th - early 3rd mill. BCE	UA53, UA50, UA14, Khasm el Girba 96	*Panicum sp.* *Setaria sp.* *Echinochloa sp.* *Sorghum sp.* *Hordeum sp.* *Triticum sp.*		*Achatina fulica* *Pila ovata* *Pila wernei* *Lanistes carinatus* *Limicolaria cailliaudi* *Hippopotamus amphibius* *Phacocerus aethiopicus* *Bos primigenius* *Unspecified ovicaprines*	
Gash	Early 3rd - early 2nd mill. BCE	Kassala (site 1)	*Sorghum bicolor* *Sorghum verticilliflorum* *Panicum sp.* *Hordeum sp.* *Triticum sp.* *Eleusine sp.* *Phalaris sp.* *Ziziphus spina-christi* *Celtis integrifolia* *Vigna unguiculata* *Grewia bicolor Juss* *Echinochloa sp* *Setaria sp* *Adansonia digitata*		*Pila wernei* *Lanistes carinatus* *Limicolaria cailliaudi* *Spathopsis wahlberg* *Clarias sp.* *Synodontis sp.* *Tilapiini* *Protopterus aethiopicus* *Polypterus sp.* *Cercopithecus guereza* *Felix caracal* *Canidae sp.* *Redunca redunca* *Kobus kob* *Tragelaphus strepsiceros* *Varanus niloticus* *Python sebae* *Strutio camelus* *Numida meleagris* *Lepus capensis* *Vulpes ruppellii* *Orycteropus afer* *Procavia capensis* *Phacocerus aethiopicus* *Syncerus cafer* *Gazella rufifrons/dorcas* *Madoqua saltiana* *Equus africanus* *Bos primigenius* *Rodentia* *Unspecified ovicaprines,birds and antelopes*	
Jebel Mokram	Early 2nd - early 1st mill BCE	Kassala (site 1), Jebel Mokram (site 2), EG (site 3), Jebel Abu Gamal (site 1), Shurab el Gash (site 9), UA53, Khashm el Girba 20	*Sorghum bicolor* *Panicum sp.* *Pennisetum sp.* *Eleusine sp.* *Setaria sp.* *Vigna unguiculate* *Ziziphus sp.* *Lolium sp.* *Eleusine sp.*		*Mutela dubia* *Spathopsis wahlbergi* *Clarias sp.* *Synodontis sp.* *Tilapiini* *Chelonia* *Numida meleagris* *Syncerus cafer* *Gazella rufifrons/dorcas* *Madoqua saltiana* *Equus africanus* *Bos primigenius* *Unspecified birds, antelopes and ovicaprines*	
Hagiz	Early 1st mill. BCE-1st mill. CE	Shurab el Gash (site 42), UA129	*Panicum sp.* *Eleusine sp.* *Sorghum bicolor*		*Bos primigenius* *Unspecified ovicaprines*	
Gergaf	15th-18th cent CE	UA 126	*Sorghum sp.* *Panicum sp.* *unspecified millet*		*No data*	

Table 5.1. Results of botanical and faunal analyses on selected sites. *Adapted from authors cited therein.*

wilderness expanses where wild game would roam in a lush grassland/woodland savanna. The richness of the environment provided favourable ground for Mesolithic mixed hunting-gathering and agropastoral economies, as the faunal and botanical record from various sites demonstrate (Table 5.1).

Therein, in fact, several unspecified small-seeded wild tall grass species belonging to the Millet family (Pre-Saroba phase), later joined by other wild cereals and domesticated Sorghum sp. (Butana Group) (Beldados & Costantini, 2011; Beldados, 2015; Winchell et al., 2017), were recognized, mostly as seed impressions on ceramics. Along with the cereal species, several animal species were identified within early phases as well; these belong to assemblages of domesticated bovids and unspecified ovicaprines (introduced by the Butana Group), flanked by abundant consumption of malacofauna (snails and freshwater bivalves) and various species of antelopes and buffaloes, warthogs, and, perhaps most notably, hippopotamus. It must be remarked that the pre-Butana sites are very few and generally small and poorly preserved, therefore the real picture is likely far more complex than what can be grasped from the available data. Nonetheless, flora and fauna associated with the archaeological contexts that existed - as per radiometric dating (Manzo, 2017 and previous chapters) - during the African Humid Period show unequivocal characteristics of water-dependency. Of all identified species, the hippopotamus is the most indicative of the water availability of the period, because it is a very large mammal that requires full body coverage in still water and lives in large pods of up to ~100 individuals. The hypothesis of the year-round persistence of large water ponds in Shurab el Gash and the other sunk paleochannels, as well as within the active riverbeds of the Gash and Atbara, fits entirely with the presence of hippopotamus in the area, while the presence of small-seeded wild tall grass advocates for a general substantial rainfall yield over the entire plain.

At the transition from the Butana Group to the Gash Group, whose radiometric dating coincides with the gradual end of the African Humid Period, the number of identified plants and animals increases, providing a more detailed picture mainly thanks to the very well-studied site of Mahal Teglinos (Chapter 4.2). Interestingly, although the hippopotamus disappears from the record, some species advocate for a certain degree of environmental resilience, which ultimately supports the time-transgressive model of climatic transition proposed by Shanahan (2015) and others. In fact, remains of several varieties of catfish and tilapias, together with freshwater bivalves, suggests residual presence of ponds until, at least, the initial presence of the later Mokram Group. All the other identified animal and plant species are compatible with a dry/seasonal savanna environment which, however, would have been consistently subject to dry spells and episodes of dust intake, which remained included into the pedosedimentary record as loose deposits that blankets and seals the organic topsoil belonging to the previous period. It is reasonable to hypothesize that, despite the increasing aridity, the Gash and Mokram Groups became socially highly stratified, centralized and prosperous thanks to their adaptivity to a changing territory, their ability to exploit sugary fruit (mainly jujubes and dates) and cultivate drought-resistant crops such as sorghum and millet to a capacity that reached almost ceremonial values (Rega et al., 2021), and, most importantly, thanks to their political and commercial connections with the Nile Valley, which promoted the movement of food, luxury goods and commodities (Manzo, 2017; Manzo, 2020). Growing complexity of social structures and trade networks as a response to Late Holocene deteriorating and challenging climates has been observed for the entirety of North Africa (Gatto & Zerboni, 2015), and for other notable locations of the Near East proto- and early history (Flohr et al., 2017; Sinha et al., 2019).

Nonetheless, the inescapable drying up of the environment at the supra-regional scale eventually became unmanageable, and delicate geopolitical balances came to an end causing substantial readaptations of local economies. In the Kassala region, this meant that the centralized archaeological communities had to split up in small groups and leave the large foothill settlements, which became engulfed in loose dust and were subject to hydrogeological instability, in search for pastureland back into the open plains. The Mokram Group transitioned into Hagiz Group, with a new economy characterized by almost exclusive consumption of domesticated bovids, ovicaprines and sorghum. Hagiz people would no longer inhabit sites such as Mahal Teglinos and JH1 (Chapters 4.2 and 4.3), probably due a feedbacking soil erosion mechanism triggered by overgrazing flocks and exacerbated by the onset of hyperseasonal rainfall that was causing rill erosion and gullying all across the region (Chapter 4.2) (Henry et al., 2017; Costanzo et al., 2022). The foothill locations likely became simply too inconvenient for settling, as the continuous mass waste of sediment and the formation of gullies would threaten huts and corrals. Thus, the open plains went back to hosting most of the population, and at some point were even visited by Meroitic, Post-Meroitic and Christian groups venturing to the south following the Atbara river, possibly reaching south east as far as Jebel Haura and beyond.

The dispersal of seminomadic pastoral groups across the plain registered in the archaeological record of the surroundings of Kassala, may also be ancestrally related to the rise of the so-called "Nomadic State" of the Beja People (Cooper, 2020). The Beja are a multifaceted composite ethnic group that has been inhabiting the region since "time immemorial" (Dahl & Hjort-af-Ornas, 2006: 1), mentioned as elusive desert dwellers and navigators in ancient written sources that date their existence to well before 2000 years ago. The area examined in this research is but a narrow window on their much larger geographical expansion, which extends from the far eastern stretches of the Sudanese Sahel to the north in the Egyptian Eastern Desert and to south in the lower piedmont of the Ethio-Eritrean Highlands all the way to the Red Sea coast between Berenice and the Tokar delta. Beja economy is historically associated with cattle, sheep, and camel breeding, along with flash-crop agriculture along wadi splays and large riverbeds. Pastoral activities protracted for centuries contributed to ever prevent a soil recovery, thus meaning that the process of desertification and, most of all, soil loss that contributed to the transition from Mokram Group to Hagiz Group is still in place. The overconsumption of natural resources by grazing domesticated animal was probably also at the root of the disappearance of large wild fauna from the open plains.

The very late Holocene and the present-day environment, thus, is still characterized by a complex semiarid climate mitigated by the NW incursion of the Ethiopian Monsoon, but the regional economy was drastically manoeuvred towards modern-world export policies since the Ottoman dominion on the area starting in the first half of the 19th century (Dahl & Hjort-af-Ornas, 2006), with the foundation of the ever-growing city of Kassala in the 1830's. Centralized agglomerates of population required surplus production for direct consumption and trading; the first cotton scheme in the Gash Delta was put in place by the Ottomans in the 1860's (Dahl & Hjort-af-Ornas, 2006), and was later brought to its maximum extension with the construction of the spate irrigation system by the British in 1924 (Barbour, 1961). Despite the brief economic advantages derived from cotton cultivation that the system brought, consequences on the natural environment quickly became catastrophic, and the aftermaths are still matter of delicate social policies. The spate system, apart from erasing any archaeological evidence found within and beyond its expanse, forced local communities operating small scale production of food crops out of their territory, creating disparities and cancelling traditional knowledge (Ngirazie et al., 2015; Fadul et al., 2019). Moreover, the extreme water consumption required by cotton (Voll, 1978) forced crop production for food consumption outside of the spate system; this policy underlies the fact highlighted in Plate 4.1.1E and associated Chapter, i.e. the recorded archaeological evidence is inversely correlated with the agricultural parcelization.

In general, the relationship between people and territory in the Kassala region of Sudan across the Holocene, is characterized by dynamics that are comparable with supra-regional and continental trends. The climatic and environmental conditions of the Early and Middle Holocene were favourable for hunting-gathering subsistence strategies in which husbandry and cultivation were only complementary to the exploitation of wild game and readily available food sources granted by the lush prairies and abundant ponds that characterized the landscape for millennia. Later on, at the transition from Middle to Late Holocene, a slow but steady climatic deterioration induced a power centralization and a social stratification that allowed local archaeological communities of the Gash Group and later Mokram Group to become part of complex trade routes between the Nile Valley and the Horn of Africa. The environment, as showed in Table 5.1, still sustained flora and fauna typical of woodland savanna, but some heavily water-dependent species such as the hippopotamus already disappeared from the region. Further climatic deterioration at the continental scale (Vermeersch et al., 2015; Mologni et al., 2021) caused a few centuries of extreme aridity and environmental disruption, which led to drastic shifts in power balances and subsequent inversion of trade routes and participation of peripheral communities. In the lower Nile Valley, installed Ptolemaic dominion directed the attention of its exchange economy towards the Mediterranean, only reaching south as far as the Meroitic Kingdom in Upper Nubia. The far Eastern Sudan, consequently, remained cut out from the trade of luxury goods, and the transition from Mokram Group to Hagiz Group meant for a total switch to local agropastoral subsistence in an isolated and hostile geographical setting, giving way to the accounts of "barbarians" and "desert dwellers" reported by Ptolemaic and Arab scouts (Dahl & Hjort-af-Ornas, 2006; Cooper, 2020). Finally, a further and final climatic shift saw the onset of hyperseasonality across the Egyptian and Sudanese Eastern Desert, both in the open plains and deep within the rocky mountain ranges of the Red Sea Hills (Mawson & Williams, 1984; Williams & Nottage, 2006; Costanzo et al., 2022). These climatic conditions, summed with the disrupting action of overgrazing, caused the severe erosion and hydrogeological instability of foothill localities that used to represent preferential sites for settlement. As a consequence, settlement patterns in the form of temporary campsites set along the large rivers during dry seasons, and sparse across the open plain during wet seasons in an obligated alternation (Salih, 1994), constrained the Hagiz Group (later Gergaf Group, all likely ethnically Beja) into small-scale agropastoral subsistence economies, entertaining reduced supra-regional political relationships with the surrounding kingdoms in a way of life that remained substantially unvaried until the present day.

Final remarks

The results of this study offer several hints upon the ideal course of action in paleoenvironmental and archaeological research. On one hand they show how, for novel research endeavours, obtaining data over extensive areas, rather than intensive insight on a single isolated site, provides a baseline for future reference and a clear picture of the potential of a region under diverse points of view. Integrating well-established archaeological knowledge with radiometric anchorage of pivotal pedostratigraphic newly found contexts, creates new and fundamental data on the areal extension of paleoenvironmental trends and phenomena and, most crucially, raises awareness on extant widespread morphogenetic processes that need be addressed for the institution of sustainability policies. On the other hand, hints emerged on the importance of Late Quaternary pedosedimentary palimpsests in marginal (and understudied) areas that lack remarkable high-resolution archives (Forti et al., 2023). Pedosedimentary palimpsest are, for their nature, complex bodies of sediment characterized by phases of accretion and erosion that may carry low temporal resolution and high areal fragmentation. By considering every feature of the natural landscape as a potential missing link in the reconstruction of its complete paleoenvironmental history, low temporal resolution and areal fragmentation are overcome by cross-referencing. Hence, accurate interpretations of the complex succession of regional morphogenetic processes and climatic trends are obtained and can subsequently be inserted into supra-regional and continental dynamics.

6. Future perspectives

This research aimed to define the best possible picture of the regional paleoenvironments and its embedded human nexus. As much as plentiful new information was created on the basis of the available collected data, several questions remain, nonetheless, still open, and require future supplementary intervention.

The most notable case in these regards, as emerged in Chapter 4.1, concerns the absolute dating of the Gash river's relict channels and riverscapes. Optically Stimulated Luminescence (OSL) dating shall be operated for at least one paleochannel for each system, or at least the southernmost riverscape where the Shurab el Gash area is found, and the large paleochannel crossing the plain perpendicularly (Plate 4.1.1A-B). Ideally, nevertheless, OSL should be carried out also at the northern outskirts of the plain, in correspondence of the large levelled paleochannel of the Atbara. OSL dating would provide the age of the burial of quartz- and feldspar-bearing sediments subject to erosion, transport and deposition emplaced by the riverine processes. In the case of sandy-braided paleochannels in semiarid climates, an age estimate of the upper portion of the depositional sequence would date the last flood event, thus the moment before the main riverbed, in practice, dried up forever because its trajectory changed and/or the climate would no longer provide enough rainfall yield at the headwaters. Obtaining such age would confirm - or confute - the hypothesis expressed in Chapter 4.1.1, for which all the discovered Holocene archaeological sites (Pre-Saroba onwards) are located along, around and within riverbeds that were already inactive at the beginning of the Holocene, existing as relict features that would only sustain static water bodies such as ponds or confined palustrine environments.

Contextually to the OSL dating, coring activity is recommended for a high-resolution identification of the natural paleobotanical record. Locations such as the residual ponds that are still nowadays seasonally flooded (Plate 3.5D), encapsulate an enormous potential under every point of view. Therein, it is likely to be found a great concentration of paleoenvironmental faunal and botanical proxies such as macroscopic remains (bones, wood, seeds), pollen, and microscopic remains (plant mineralizations, microfossils), as well as preserved DNA and other organic diagnostic compounds embedded within the biotic soil.

Moreover, further activities to be carried out in the Southern Atbai will be directed at reprising excavations at topical large sites such as KG23/UA14, which were investigated in the '70s and '80s by the early expeditions illustrated in Chapter 1. Early and incomplete analytical capacity employed at that time prevented such sites from providing full potential of their archaeological and paleoenvironmental information yield, prompting us to plan new interventions with the objective of contextualizing previously lifted archaeological material stored in museum facilities (mostly ceramics and lithics) and collecting an adequate record of faunal, archaeobotanical, and geoarchaeological data.

To the east of the Gash river, the predictability of the regional physical geography lays foundation for targeted investigations aimed at finding new archaeological sites across the land delimited by the outskirts of Kassala, the area of Jebel Maman and the Eritrean border. The area is, in fact, almost completely unexplored, but aerial images unveiled several thousands of features among tumuli, ancient Islamic tombs, and composite structures that may be remnants of ancient settlements. Based on the findings from Mahal Teglinos (Chapter 4.2) and Jebel Haura (Chapter 4.3.1), which are multiphase sites intimately connected with the morphogenesis of their foothill settings, there is an extremely high probability of finding evidence of Holocene occupation in the stratigraphy underlying the larger clusters of open-air funerary monuments scattered across the land. Furthermore, the survey would be facilitated by the ubiquitous active erosional morphogenesis of the loose sedimentary cover that, as found in Mahal Teglinos and Jebel Haura, exposes thousands of years' worth of stratigraphic history without the need for test trenching. Several locations, reachable with ordinary means of transport and easy trekking, have been identified as high potential sites and will be visited during the upcoming field expeditions. Attention will also be placed in identifying buried organic soil horizons comparable with those found and dated in Mahal Teglinos, Jebel Tareg and Jebel Maman, with the aim of understanding the extent of territorial continuity and effective areal occupied by woodland savanna and relative faunal population during the African Humid Period, in order to formulate hypotheses upon the role of the region as a green corridor linking far apart regions of the northeast of the African continent. Moreover, should the eventuality arise, earlier archaeo-environmental evidence - i.e. Early to Late Palaeolithic – will be duly documented and contextualized with the findings from the neighbouring Ethio-Eritrean Highlands and Middle Atbara Valley, as well as with continental early human dynamics.

Contextually to the activities aimed at investigating the fluvial geochronology west of the Gash river and at finding new archaeological sites east of it, a systematic study of all available lithologies will be prompted. The sources of raw materials employed by the archaeological communities for the production of macrolithic tools such as grindstones, pestles, mace heads and hammerstones, commonly found in the lithic assemblages, are still mostly undefined, except for the granitoid elements which are the only ones really widespread and readily available in the region. As illustrated in Chapter 3, the entire region is affected by shearing and faulting associated with the orogeny of the Arabian Nubian Shield, which in turn caused the emersion of basalt intrusions in the area of Khashm el Girba and of felsic dykes that are now visible as low-standing linear and fractured rock bodies reaching lengths of several kilometres to the east of the Gash river. None of such rock sources present on Sudanese territory has yet been rigorously surveyed and sampled, but there is an extremely high chance of finding effective lithological correspondence with the archaeological assemblage. Even more interestingly, some artefacts such as the vesicular basalt grindstone recovered from a site in the open plain, mentioned in Chapter 4.1.1, may not be regional at all, opening to the possibility of long range movements not only of commercial commodities, as it has been largely displayed in all cited literature, but of everyday domestic goods as well.

Colour Plates

Chapter 3 - Present day physiography and landscapes: the periphery of two worlds

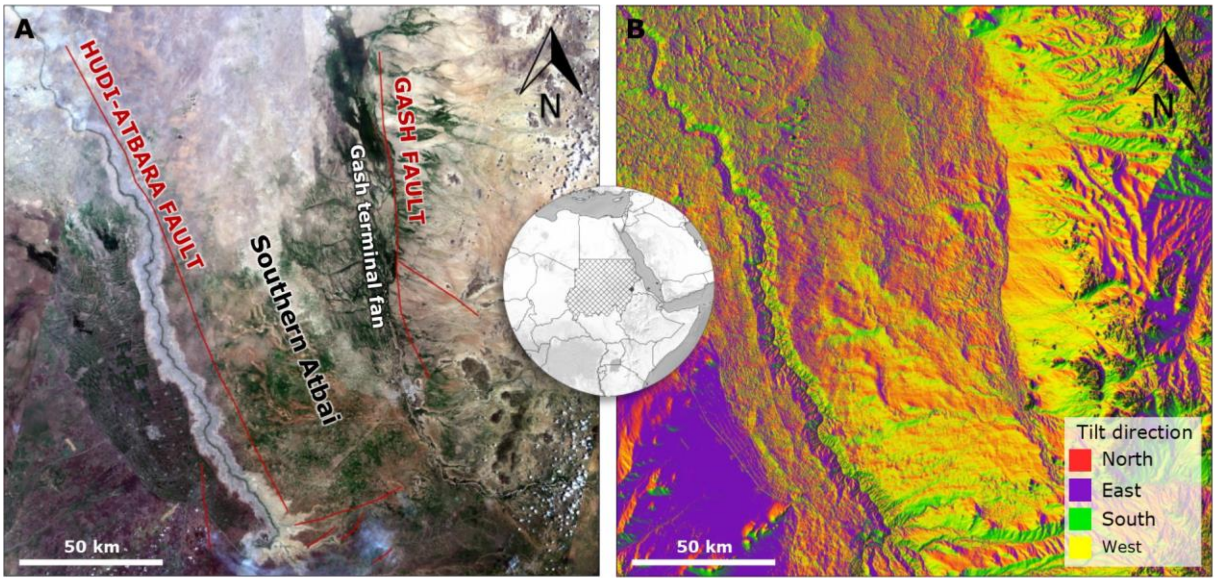


Plate 3.1. (A) Satellite image (LANDSAT8-OLI-TIRS, RGB bands 4, 3, 2) of the study region. The area is the same reported in Fig. 3.1, Chapter 3. (B) The Aspect model, using colours as indicators of the cardinal exposure of the topographic surface, shows the invertion from a NW- to a SE-facing tilt of the plain (reddish yellow to greenish purple), likely caused by tectonic uplift along the Hudi-Atbara fault and responsible for the Late Quaternary diversion of the Gash river towards its current endorheic terminal fan.

Plate 3.2. Some panoramic views of the study region. (A) The Southern Atbai Plain as it appears near Khor Marmadeb. (B) Inselbergs emerging from the shrubland and hamada-covered glacis, facing south from Jebel Maman. (C) The imposing granite domes of the Jebel Taka south of the archaeological site of Mahal Teglinos. (D) The meta-sedimentary outcrop of Jebel Maman seen from a dry wadi-bed. (E) The sharp granite domes of Jebel Haura.

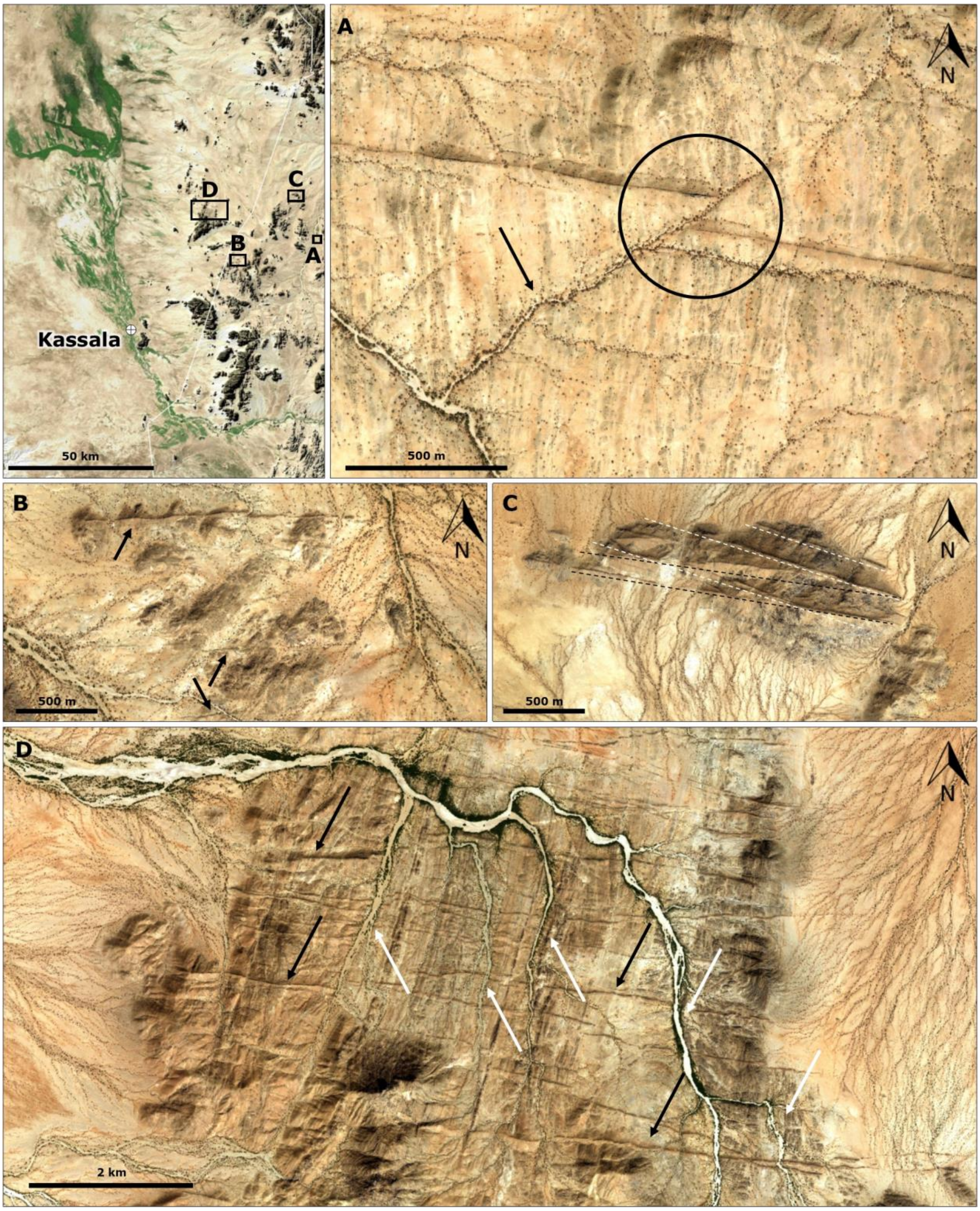


Plate 3.3. Satellite views of dykes and dyke swarms. (A) A large dyke is split and displaced by a strike-slip fault (black circle), which in turn hosts an entrenched ephemeral stream (black arrow). (B) Parallel dykes (black arrows) emerge from strongly weathered residual granite hills. (C) A relatively small gneiss whaleback outcrop is sectioned by, at least, two generations of dykes (white and black dashed lines). (D) A large gneiss outcrop is split and cut by dozens of dykes (black arrows) and fractures. Entrenched ephemeral streams (white arrows) are hosted within the strike-slip faults.

Plate 3.4. Examples of granite landforms and weathering. (A, B, F) Granite weathering (fissuring, patina coating, exfoliation) along small inselbergs at Goz Regeb. (C) The southern domes of the Jebel Taka, seen from SW; boulders detach from large sheeting surfaces and slide downslope according to the gradient of the resulting etchplain. (D) Heavily weathered bedrock exposed by linear erosion of unconsolidated Holocene sediments at Mahal Teglinos. (E) Runoff convoying channel carved in granite bedrock in Mahal Teglinos. (F) Sand-blasted blocks and tors along the slope of an inselberg at Goz Regeb.

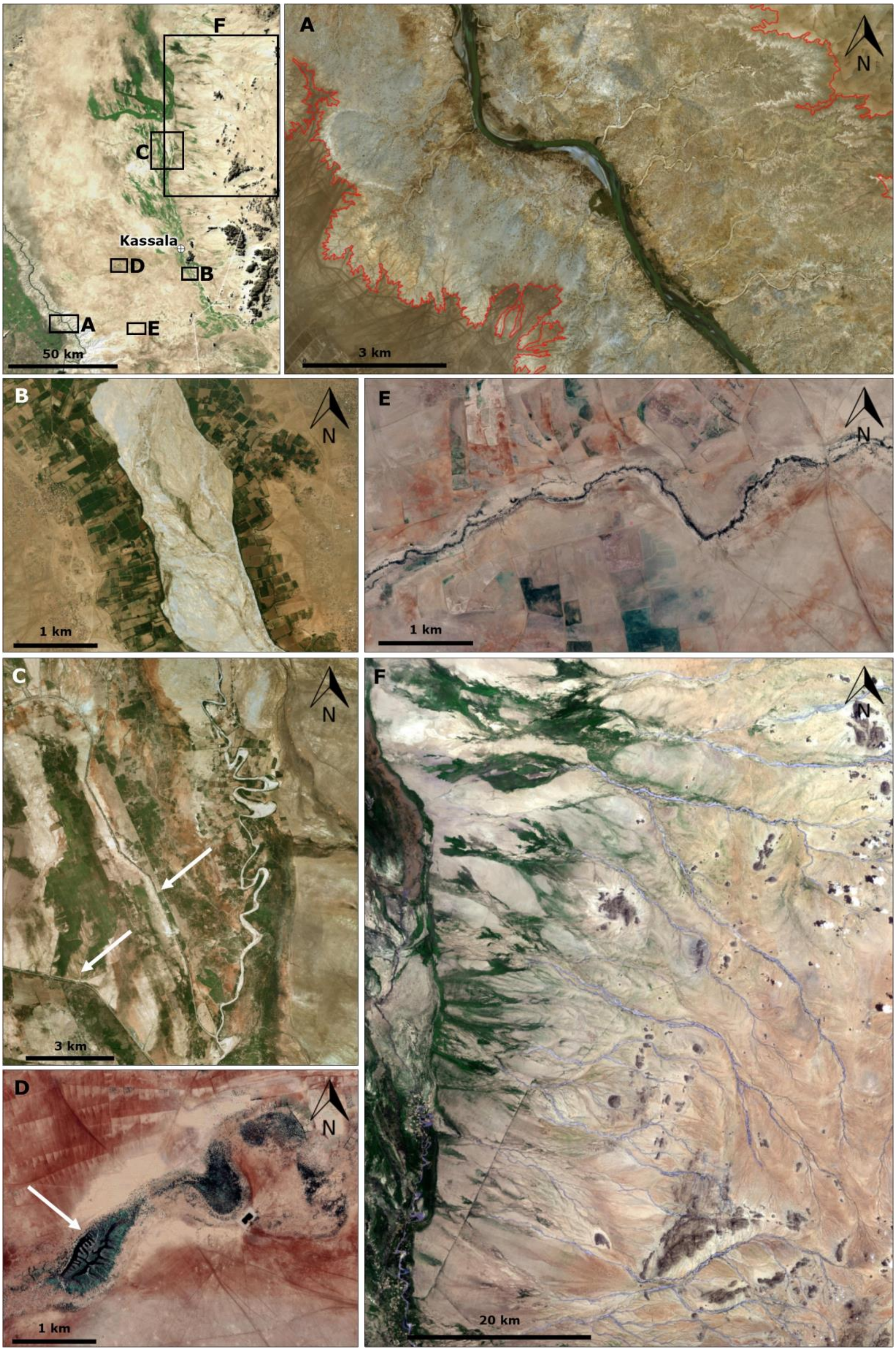


Plate 3.5. Satellite views of active fluvial landforms. (A) The Atbara River and its surrounding badlands. (B) The Gash River at its widest braided stretch 12 km SE of Kassala and (C) at its meandering stretch 45 km north of Kassala. The arrows in (C) indicate spate irrigation canals. (D) The arrows indicate oxbow-like pools colonized by riparian vegetation within a well-preserved Gash's paleochannel. (E) The thin Khor Marmareb in the plain between the Atbara and Gash rivers. (F) The dense tributary network to the east of the Gash river's endorheic fan.

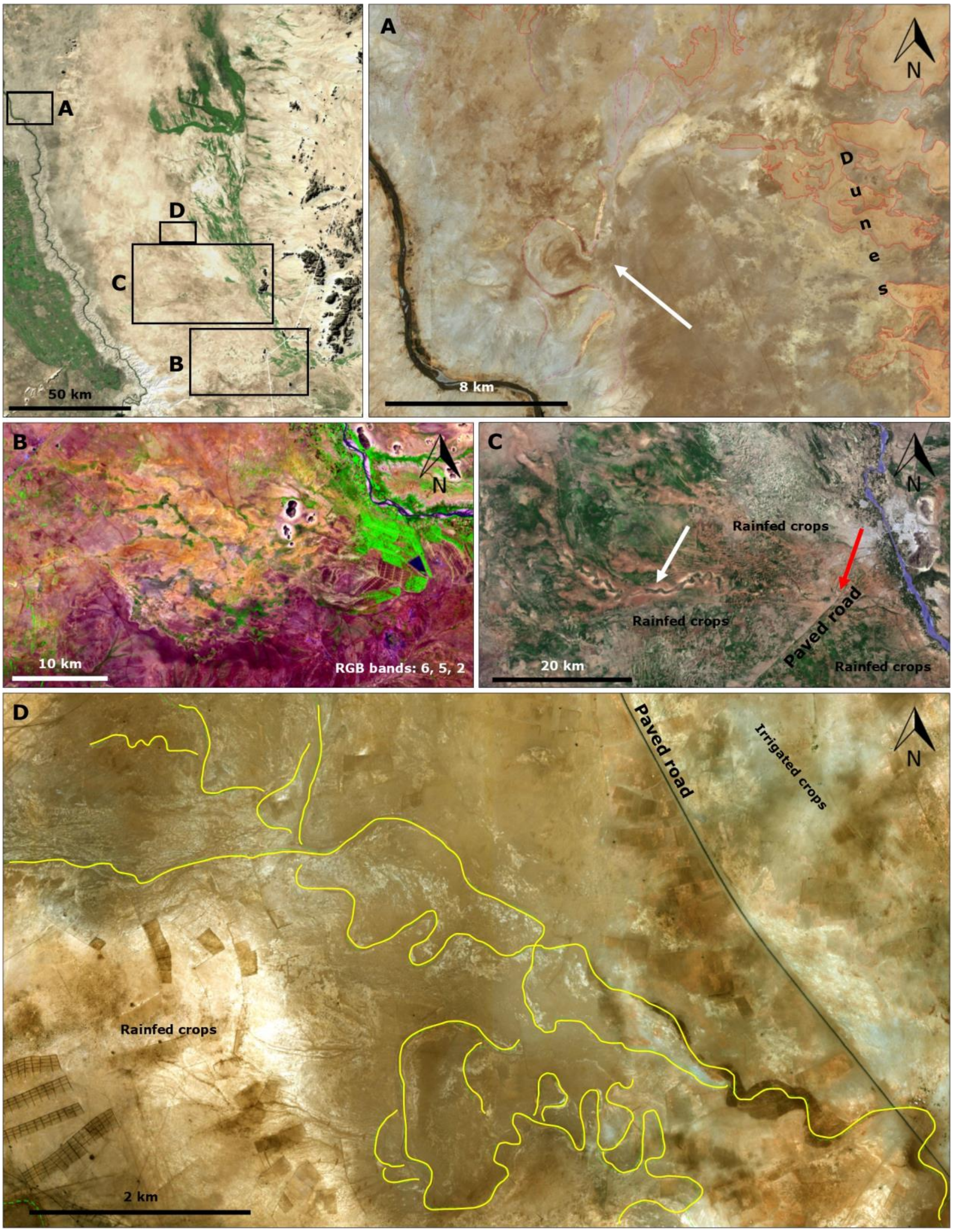


Plate 3.6. Satellite views of relict fluvial landforms. (A) The Atbara River past Goz Regeb. The arrow indicates its main Pleistocene paleochannel. (B) Landsat8 false colour composition of the Gash's relict anastomosing system (yellow hued). (C) The large Gash's paleochannel (white arrow) originating from the second relict apex. Agriculture and infrastructures badly affected the preservation of the first half of the feature (red arrow). (D) 40 km NW of Kassala, the small meandering paleochannels of the Gash (yellow lines), originating from the third relict apex.

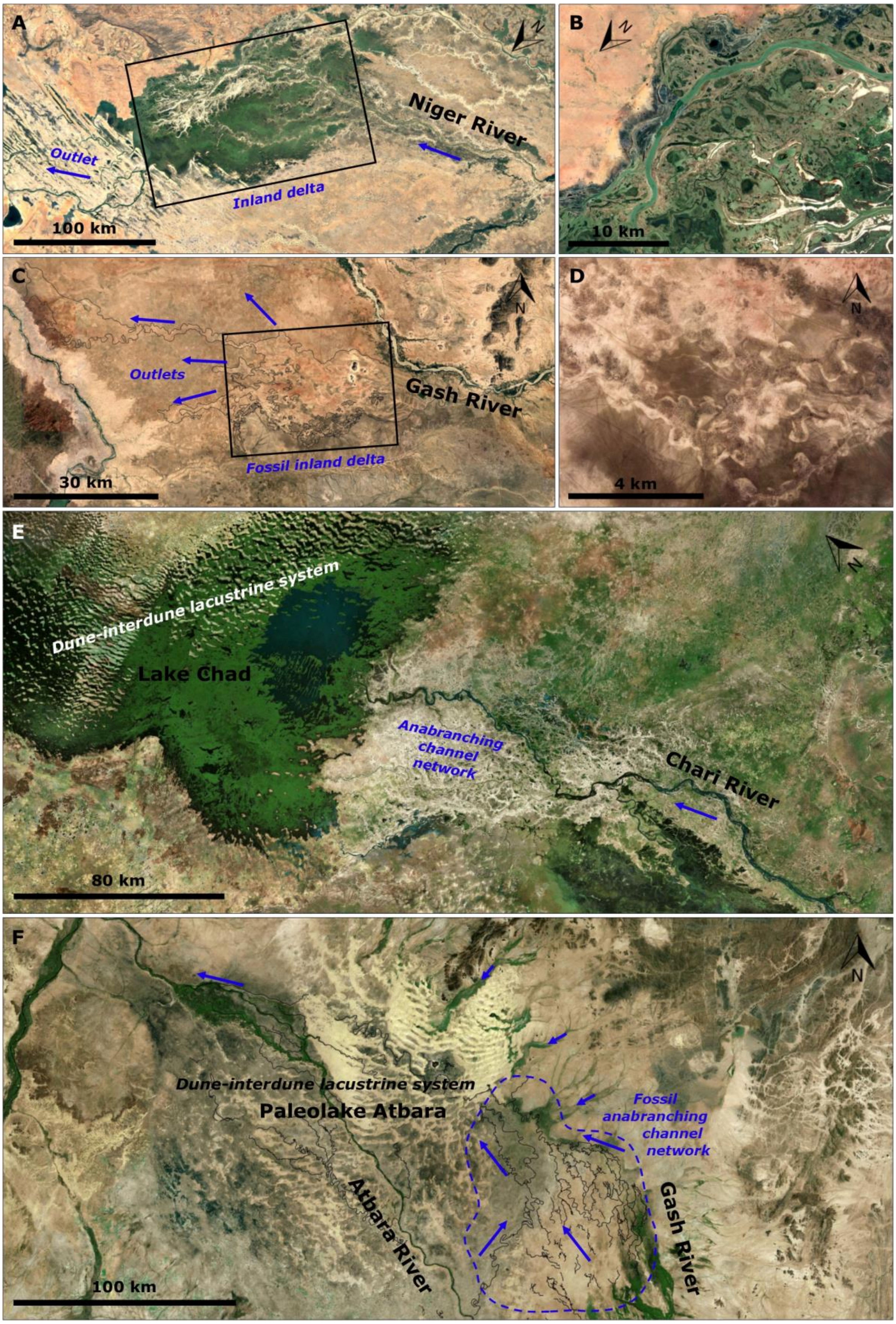


Plate 3.7. Present-day active comparisons for fossil fluviolacustrine features of the Southern Atbai. (A) The Niger River's active inland delta, with (B) a detail of anabranching channels and standing ponds in stark contrast with the desertic surroundings. (C) The Gash River's fossil inland delta (ten times smaller than the Niger's), with (D) a detail of dried up anabranching channels and former ponds. (E) Lake Chad's extant settings. The Chari River is the lake's main tributary, flanked by countless anabranching channels feeding the extensive but shallow dune-interdune system. (F) Paleolake Atbara's settings. A shallow dune-interdune system used to be fed by a large paleochannel of the Atbara River, flanked by countless tributaries generated by the splitting up of the Gash River in a former setting.

Plate 3.8. Examples of late-stage erosion and residual surfaces (A) Birdseye view of the valley of Mahal Teglinos. Severe gullying of the unconsolidated pediment is visible throughout the frame, exposing the Early Holocene to present days deposits as well as the underlying bedrock. Black arrows indicate the Middle-Holocene organic soil, red arrows indicate aeolian/colluvial deposits with archaeological remains. (B) Detail of a 4m-deep eroded section in Mahal Teglinos (same-coloured arrows as (A)). The top-right box shows the hamada ground rich of archaeological remains investigated by the team working on top of the deposit. (C) Changing a flat tyre while crossing the insidious hamada halfway between Jebel Maman and the paved road.

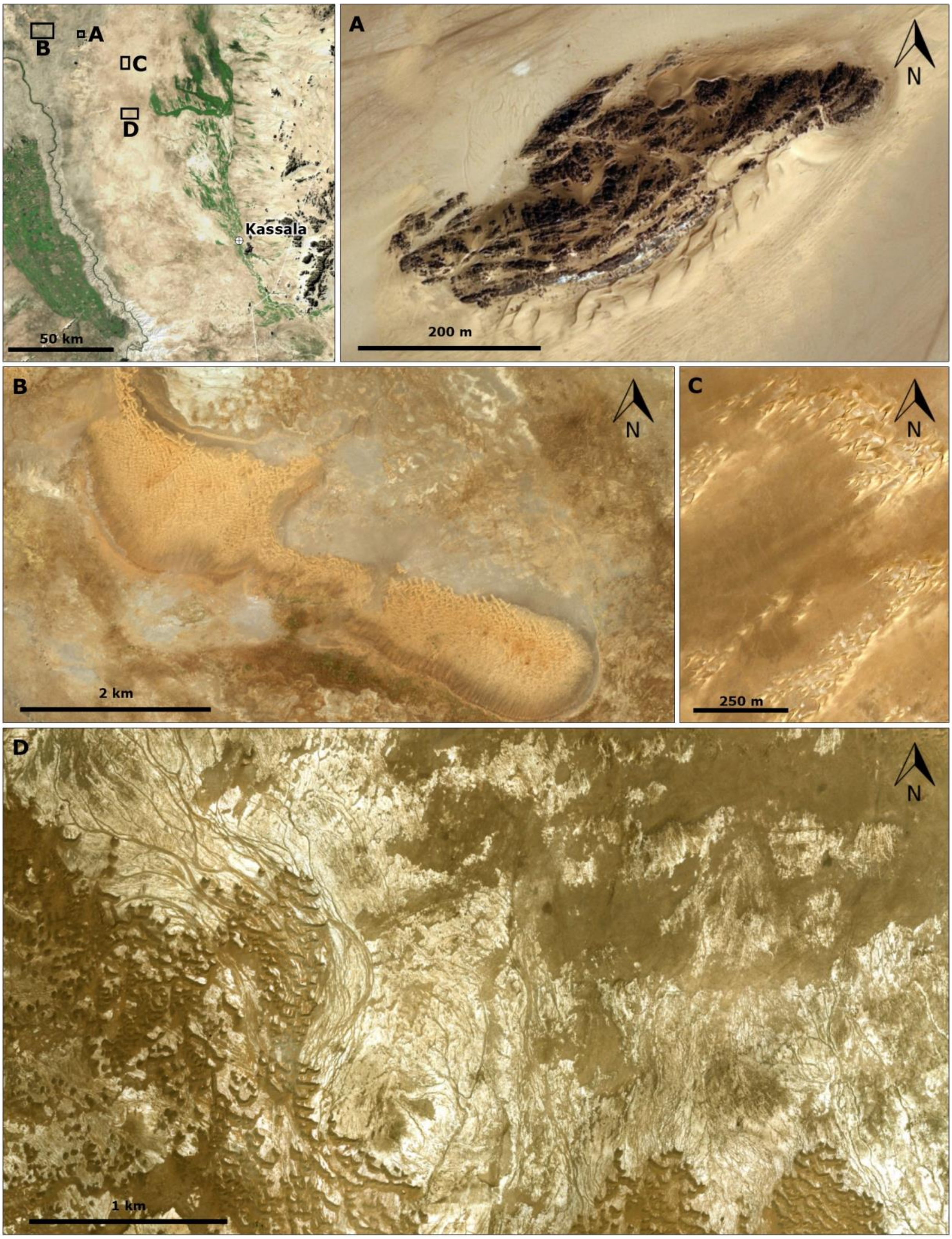


Plate 3.9. Satellite views of aeolian landforms. (A) Small inselberg covered in aeolian sand, along the main paleochannel of the Atbara. (B) Coalescing sand sheets and dunes covering the Atbara paleolake's shallow water deposits. (C) Field of barchans in the northern plain between the Atbara's main paleochannel and the outskirts of the Gash's fan. (D) Fine splay sediments re-mobilized into low energy coalescing barchans.

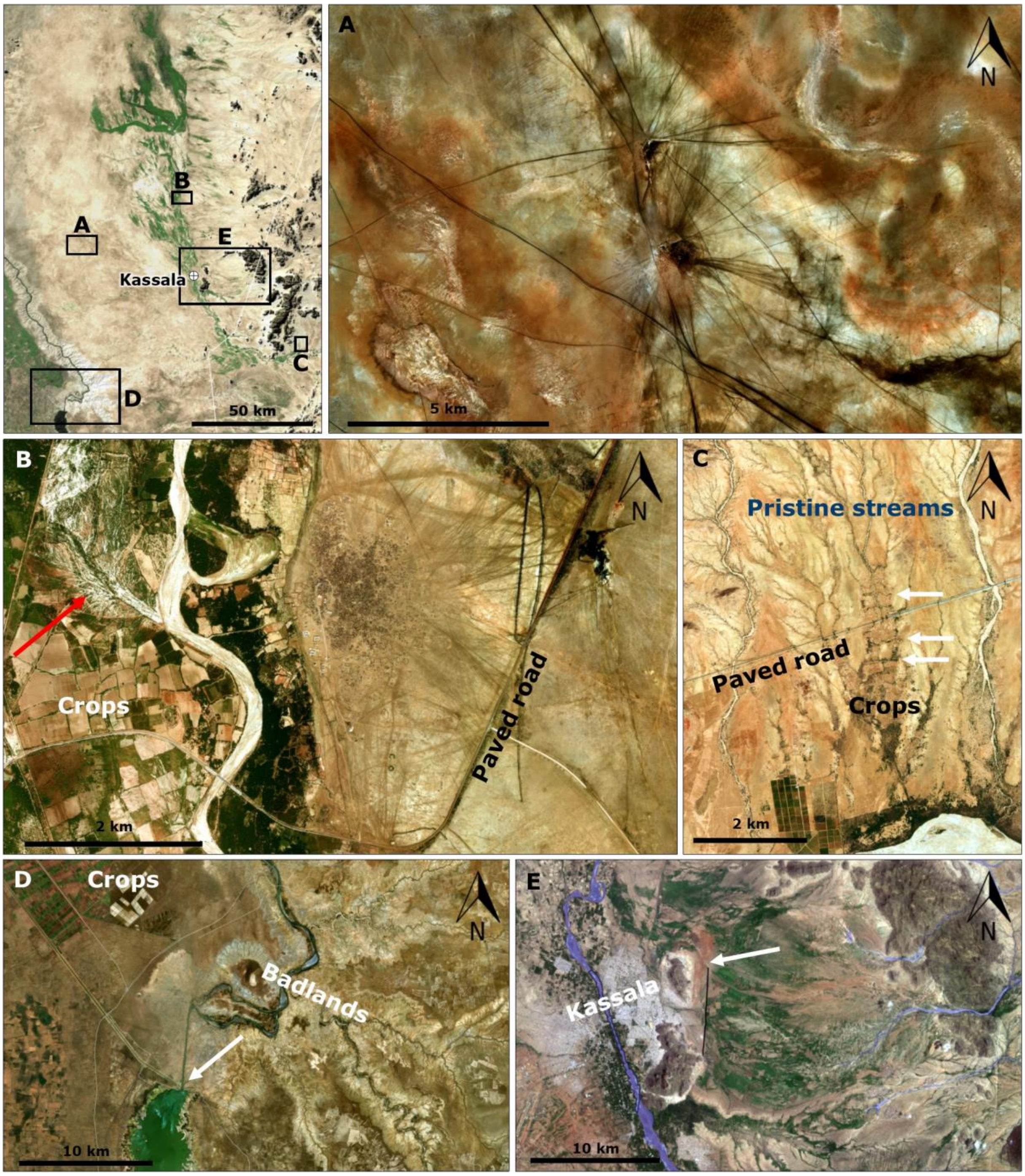


Plate 3.10. Satellite views of zoogeomorphological and anthropogenic landforms. (A) Radial animal and vehicle trackways leading to hafirs (artificial ponds) and across the open plain. (B) Trackways leaving a paved road to reach a village on the eastern bank of the Gash River. Crops and a big crevasse are visible to the left of the river (red arrow). (C) Small streams are split into sheet flows using obstacles such as paved roads and earthen barriers (white arrows) to obtain self-irrigating cultivable patches. (D) The Khashm el Girba dam on the Atbara River (indicated by the arrow). The main irrigation canal departs to the left of the structure. The regimented low flow probably caused a deepening of the badland's tributary canals incision. (E) The trench dam (white arrow) and the masonry riverbanks (red arrow), protecting the city of Kassala respectively from the floods of the eastern wadis and the Gash river.

Chapter 4 - Vestiges: locations of interest for the reconstruction of past climates and landscapes

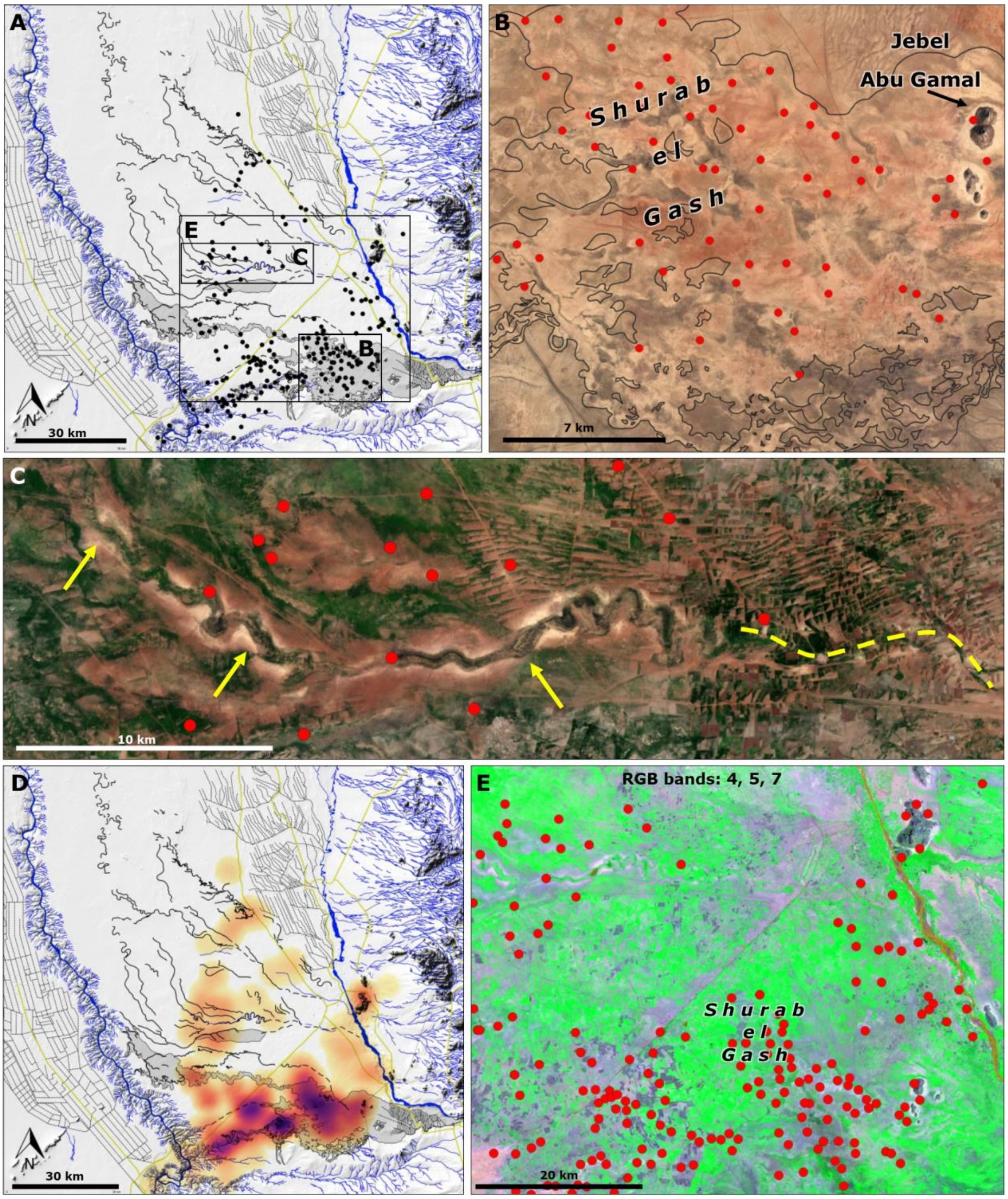


Plate 4.1.1. Archaeological sites and relict riverscapes of the Southern Atbai. (A) Archaeological sites (black dots) superimposed to a hillshade rendition of the region. Active hydrography is highlighted in blue, relict hydrography is drawn in black (thick lines) and grey (areas). Thin black dashed lines indicate modern irrigation canals. Yellow lines indicate paved roads. (B) Archaeological sites (red dots) in the area of Shurab el Gash. The area highlighted by the thin black lines corresponds to water-lain sediments deposited by the former anastomosing relict riverscape. (C) Archaeological sites (red dots) in the area of the large relict channel belonging to the second former riverscape (yellow arrows). The dashed yellow line indicates a trait of relict channel almost completely erased by agricultural activities, recognizable as a patchwork of discrete blooming parcels. (D) Cumulative Kernel Density Estimation of all known archaeological sites of the Southern Atbai. Purple hued areas indicate higher site density. (E) False colour rendition of the lower half of the Southern Atbai. Landsat multispectral images in 4, 5, 7 band combination highlights blooming vegetation in bright green, while less vegetated areas are greyer in colour. Known archaeological sites are predominantly found in areas where agricultural exploitation is less intense.

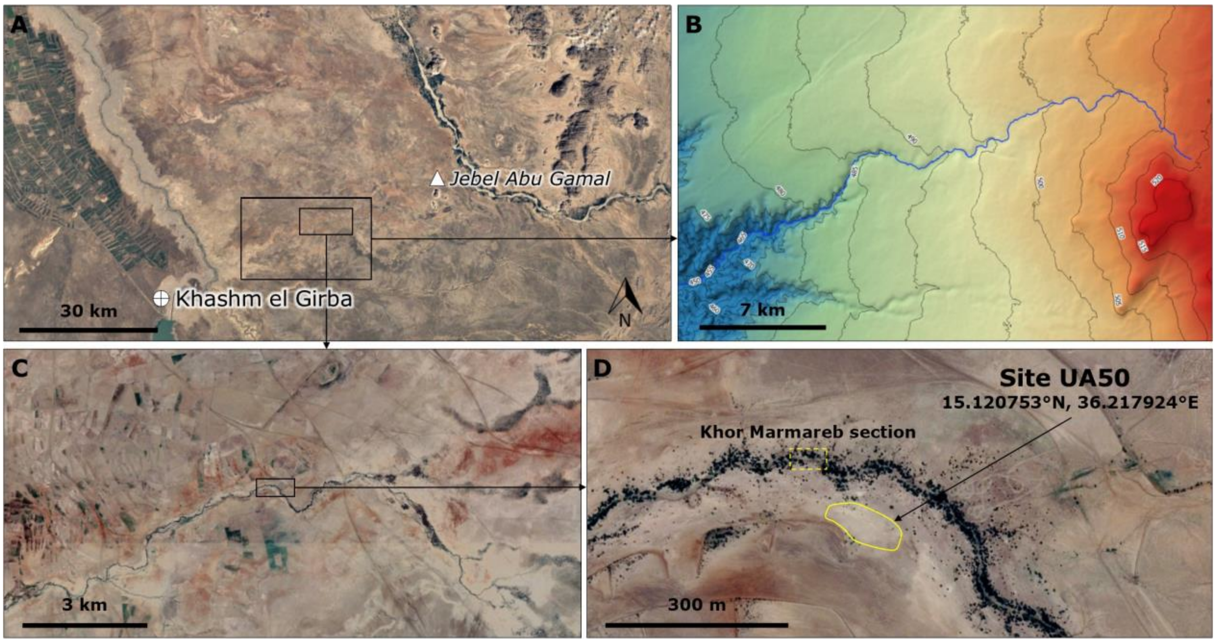


Plate 4.1.2. Overview of Site UA50 in its regional position and context. (A) Regional satellite image of the Southern Atbai, comprised between the Atbara river (left) and the Gash river (right). (B) Digital Elevation Model of the direct surroundings of Khor Marmareb (blue line), running from east to west. The colour ramp is from 470 (blue) to 520 (red) m at sea level. Contour lines interval is at 5 m. (C-D) Zooming progression to site UA50. The rust-coloured patches are plinthic ancestral soil emerging from the eroded and/or ploughed surface.

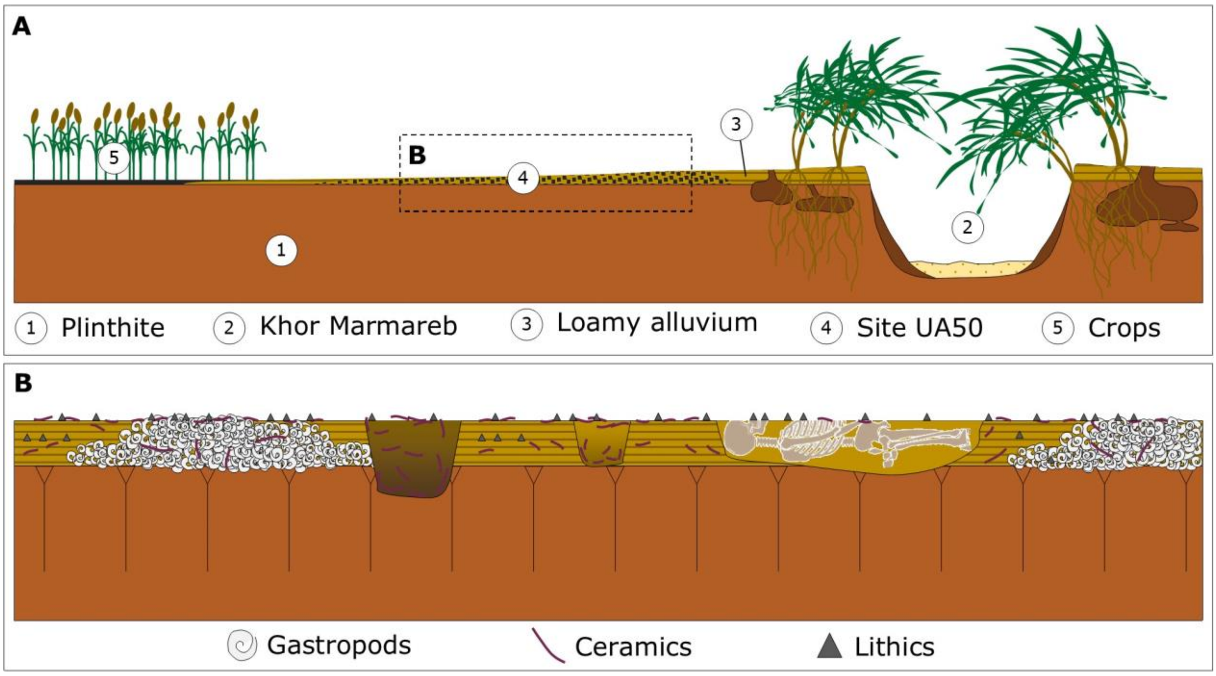


Plate 4.1.3. Schematic representation of Site UA50 and its immediate surroundings. (A) The archaeological site sets within a deflated surface formed from loamy alluvium deposited over cemented plinthite by the ephemeral floods laid by the water stream Khor Marmareb, who's banks are colonized by riparian vegetation and riddled with burrows. To the immediate outskirts of the site, sorghum crops are found. (B) Simplified representation of the site's stratigraphy. Large Mesolithic shell middens sit directly upon the plinthic paleosurface, and are in turn covered by loamy alluvium. The alluvium is cut by later pits and burials, which are revealed at current surface level, together with the summit of the shell middens, due to aeolian deflation. A residual surface composed of plentiful scatters of lithics, ceramics and faunal remain is formed.

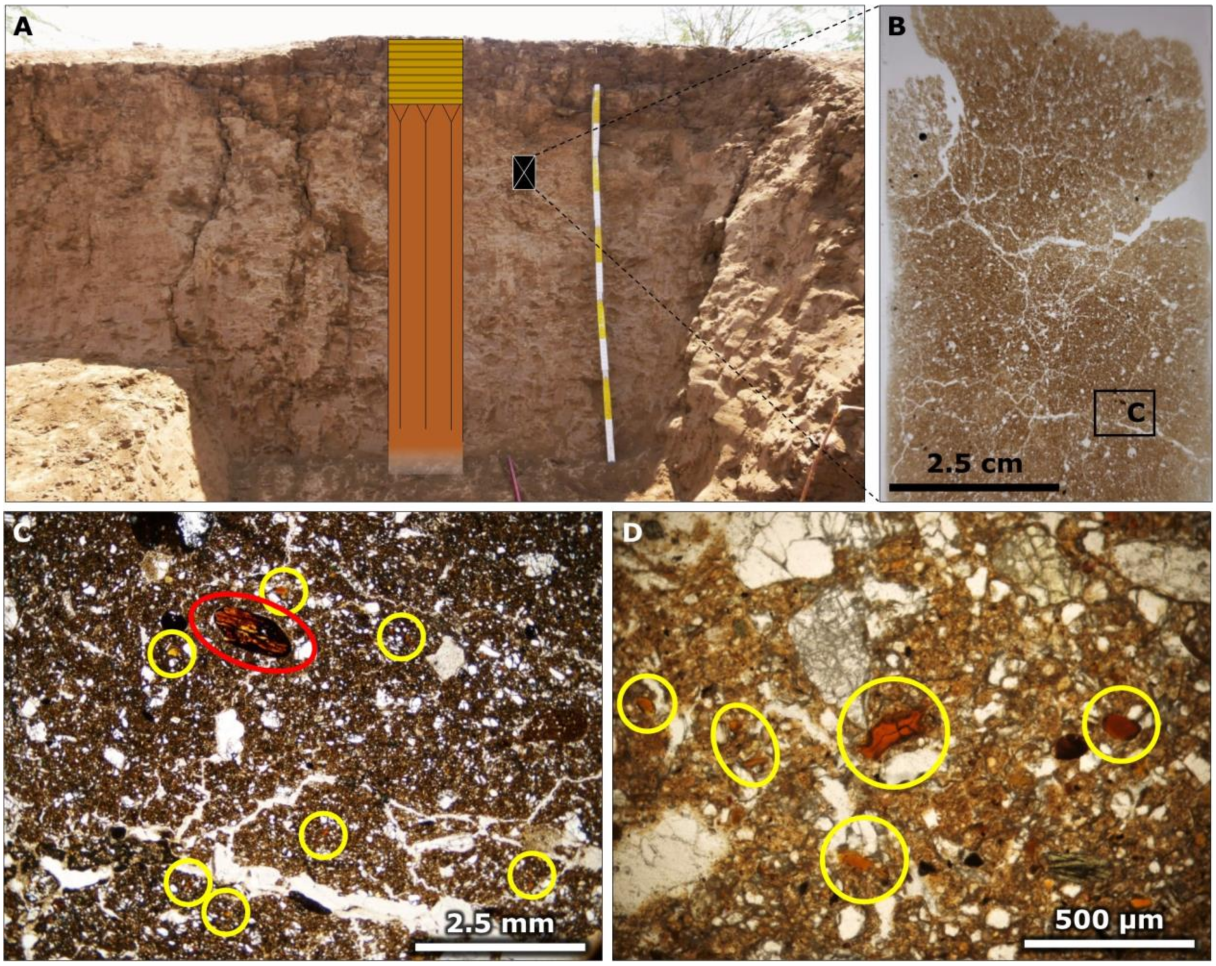


Plate 4.1.4. Thin section micrographs of the plinthite. (A) Excavated longitudinal section of the left bank of Khor Marmareb, with a simplified representation of the stratigraphy (symbols same as Plate 4.1.2). The black box indicates the location of the lifted undisturbed soil sample. (B) Scan of the thin section. Polyhedral aggregation is recognizable without magnification. (C) PPL (Plane Polarized Light) micrograph showing the porphyric distribution of mostly quarts clasts within the reddish-brown silty clay groundmass. Yellow circles indicate small rolled oxidized papules. Red circle indicates a heavily rounded bone fragment. (C) PPL micrograph in collimated light showing oxidized papules (yellow circles) and a goethite fragment (centre of the picture) at a higher magnification. Again, clasts are included within the groundmass with a porphyric distribution.

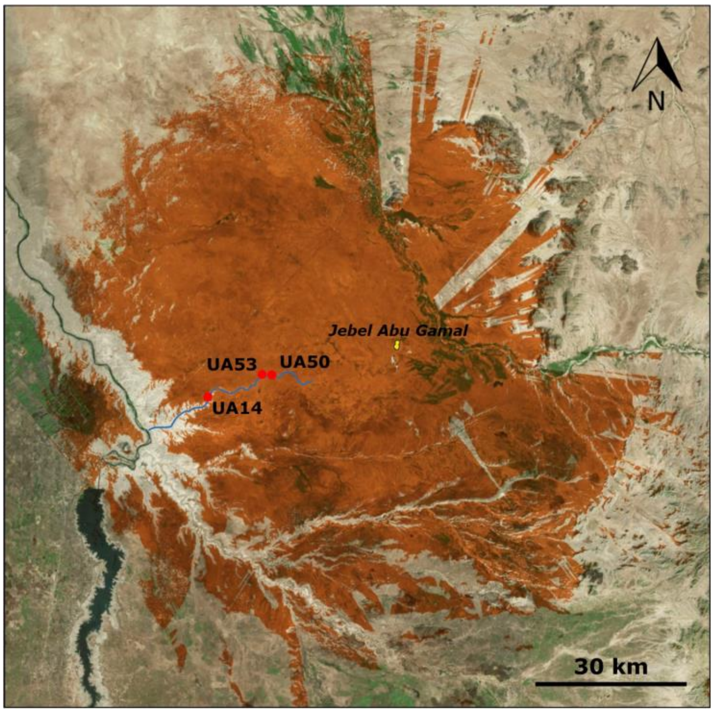


Plate 4.1.5. Viewshed of Jebel Abu Gamal. The orange hued area represents all positions from where a hypothetical observer of average body stature can see Jebel Abu Gamal (Abu Gamal Mountain). Site UA50, UA53 and UA14, situated along Khor Marmareb, are shown. Image elaborated with QGIS using *visibility:viewshed* algorithm over TanDEM X – 90 Digital Elevation Model.

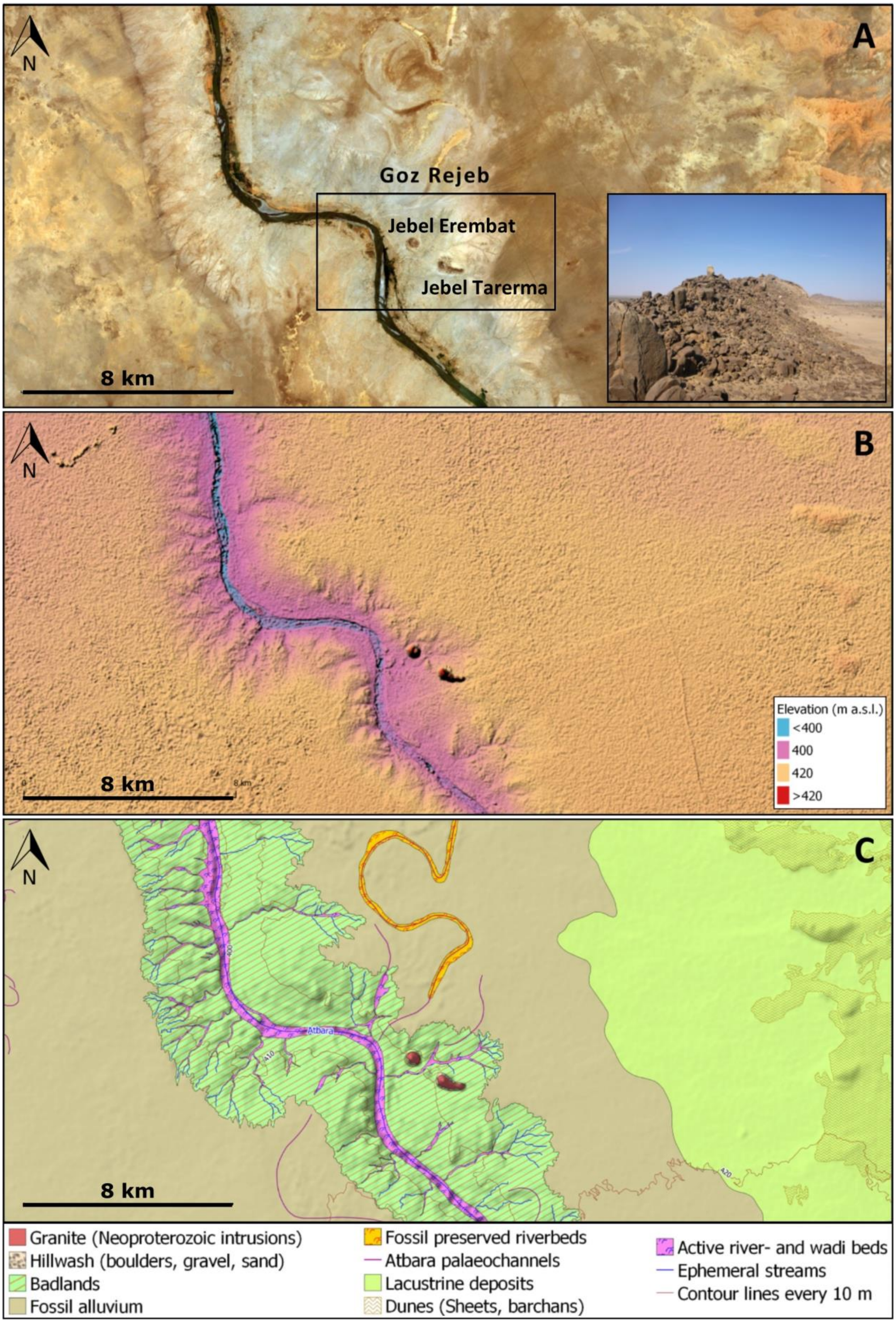


Plate 4.1.6. Characterization of the area of Goz Regeb. (A) Satellite image of Goz Regeb and its surroundings. In the box, a picture of the summit of Jebel Tarerma. (B) DEM (ALOS World 3D) of the area. The Atbara River's canyon and badlands are easily readable in blue and purple respectively; the inselbergs emerge in red. (C) Geomorphological characterization of the area (extract of *Appendix A*).

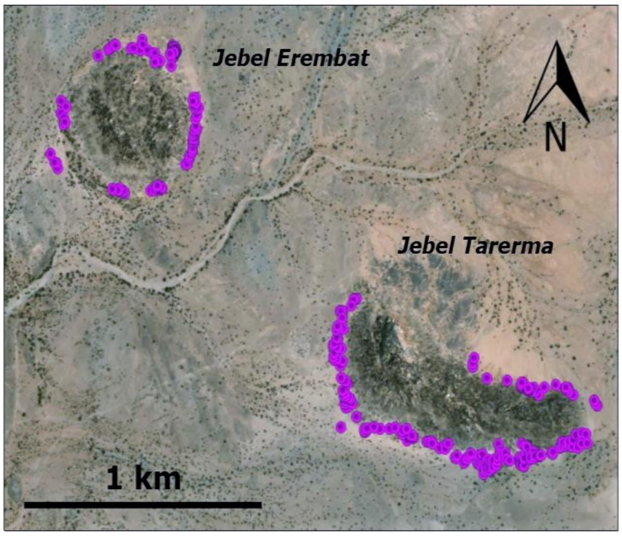
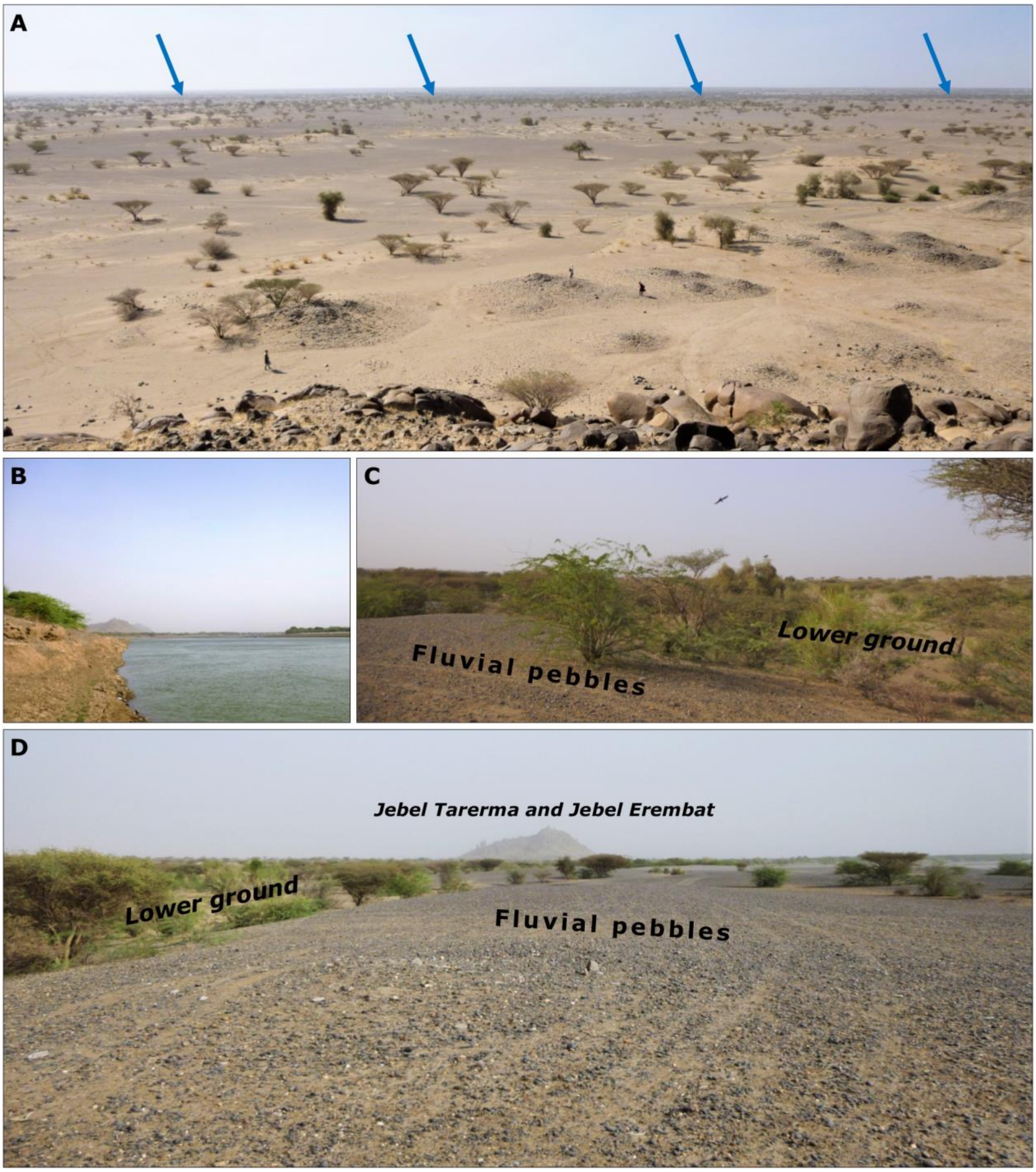


Plate 4.1.7. Mapped tumuli at Jebel Tarerma and Jebel Erembat. The mapping was carried out with QGIS using freely accessible high resolution satellite images. At the available resolution, it was possible to identify ~340 individual tumuli (purple dots).

(Below) Plate 4.1.8. The surroundings of Jebel Tarerma and Jebel Erambat, by the Atbara river. (A) East-facing view from atop Jebel Tarerma. In the foreground, by the foothill, archaeologists are surveying the monumental clusters of tumuli that surround the outcrop. In the background, the eroded Late Quaternary riverine deposits leading to the present-day entrenched Atbara river (blue arrows in the distance). (B) The Atbara river 2 km downstream of Jebel Tarerma and Jebel Erembat (visible in the background). (C, D) The pseudo-reliefs created by differential erosion of relict terraces composed of loam-engulfed imbricated pebbles.



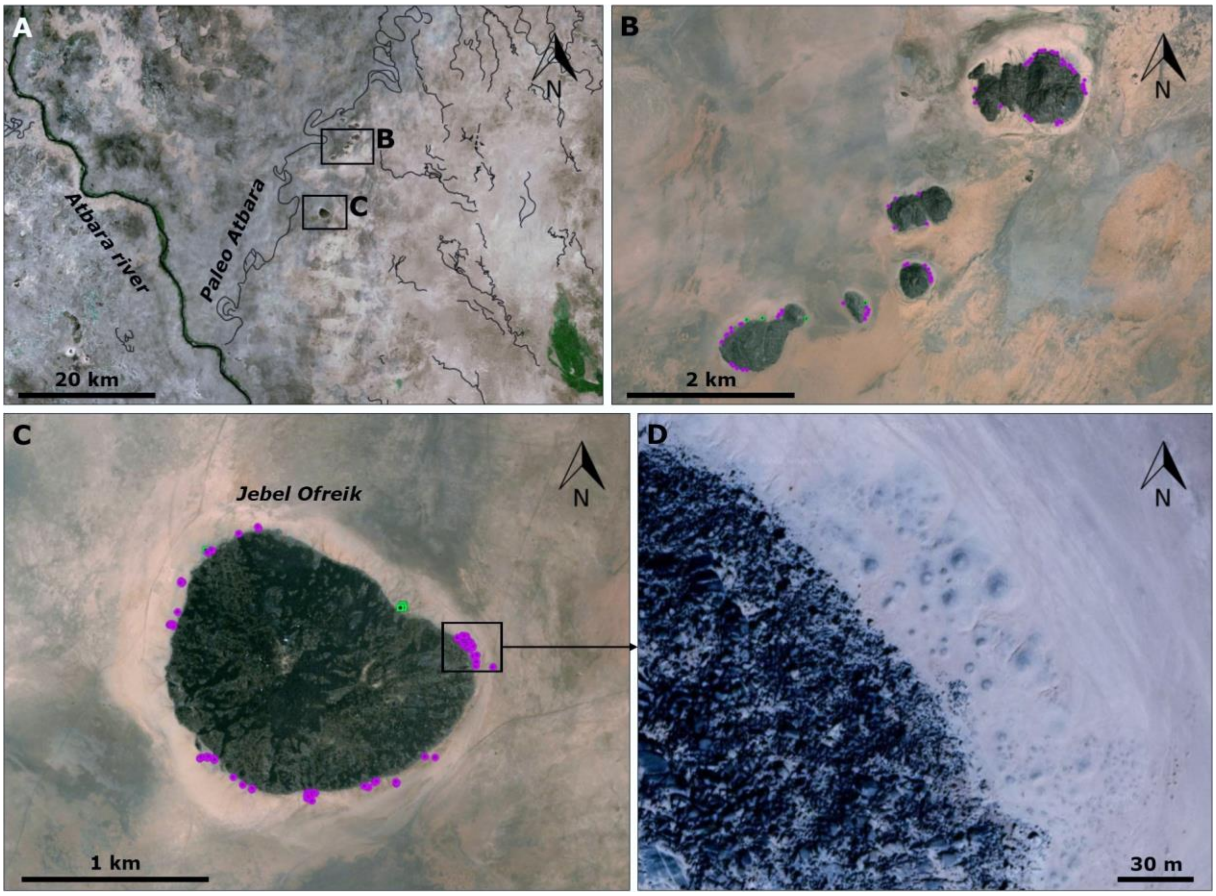


Plate 4.1.9. Archaeology and landscapes at Jebel Ofreik and its surroundings. (A) Regional-scale view of the settings of Jebel Ofreik. The present-day Atbara river flows NW, the large paleochannel (black line) used to flow NE to meet an intricate network of thinner tributaries from the paleo Gash terminal plain. In the upper left corner of the picture, the southern end of the Atbara's dune-interdune paleo-lacustrine system is visible. (B) Northern cluster of rocky outcrops whose foothills are encircled by diachronic raised funerary monuments. Purple dots indicate tumuli, green dots indicate ancient Islamic large tombs called *qubbas*. (C) Jebel Ofreik itself. (D) Close-up of a large cluster of tumuli at the eastern foothill of Jebel Ofreik. At the bottom right of the picture, dust engulfed tombs belonging to a subrecent Islamic cemetery are visible close to the older tumuli.

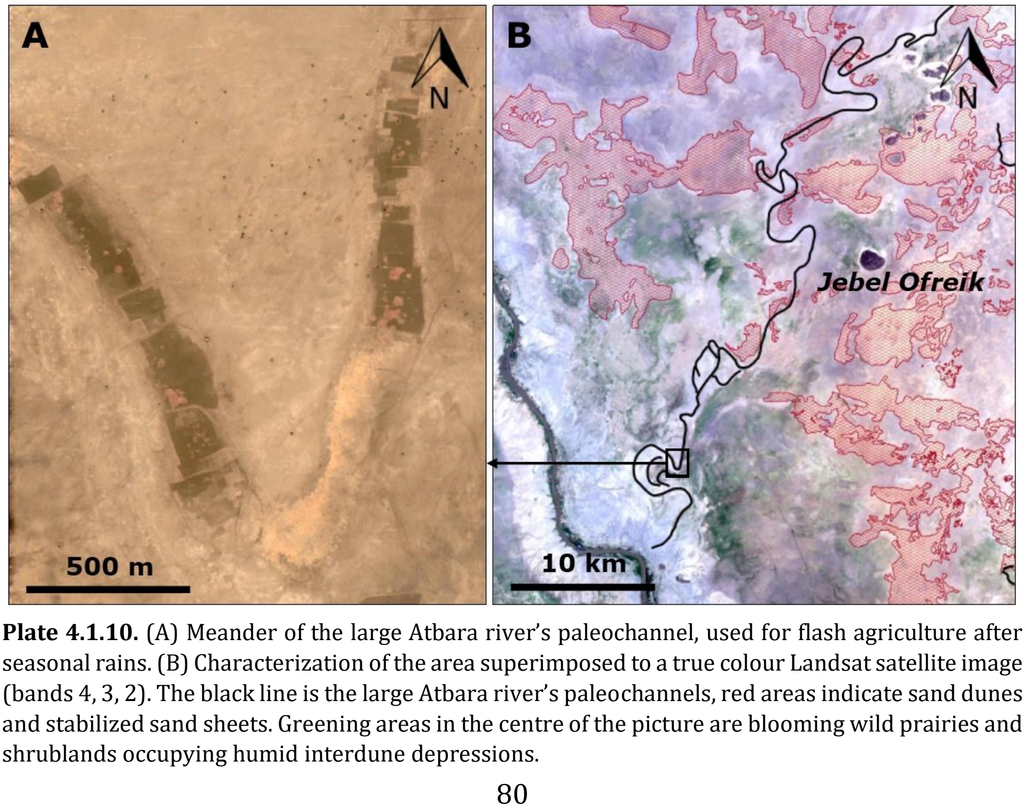


Plate 4.1.10. (A) Meander of the large Atbara river's paleochannel, used for flash agriculture after seasonal rains. (B) Characterization of the area superimposed to a true colour Landsat satellite image (bands 4, 3, 2). The black line is the large Atbara river's paleochannels, red areas indicate sand dunes and stabilized sand sheets. Greening areas in the centre of the picture are blooming wild prairies and shrublands occupying humid interdune depressions.

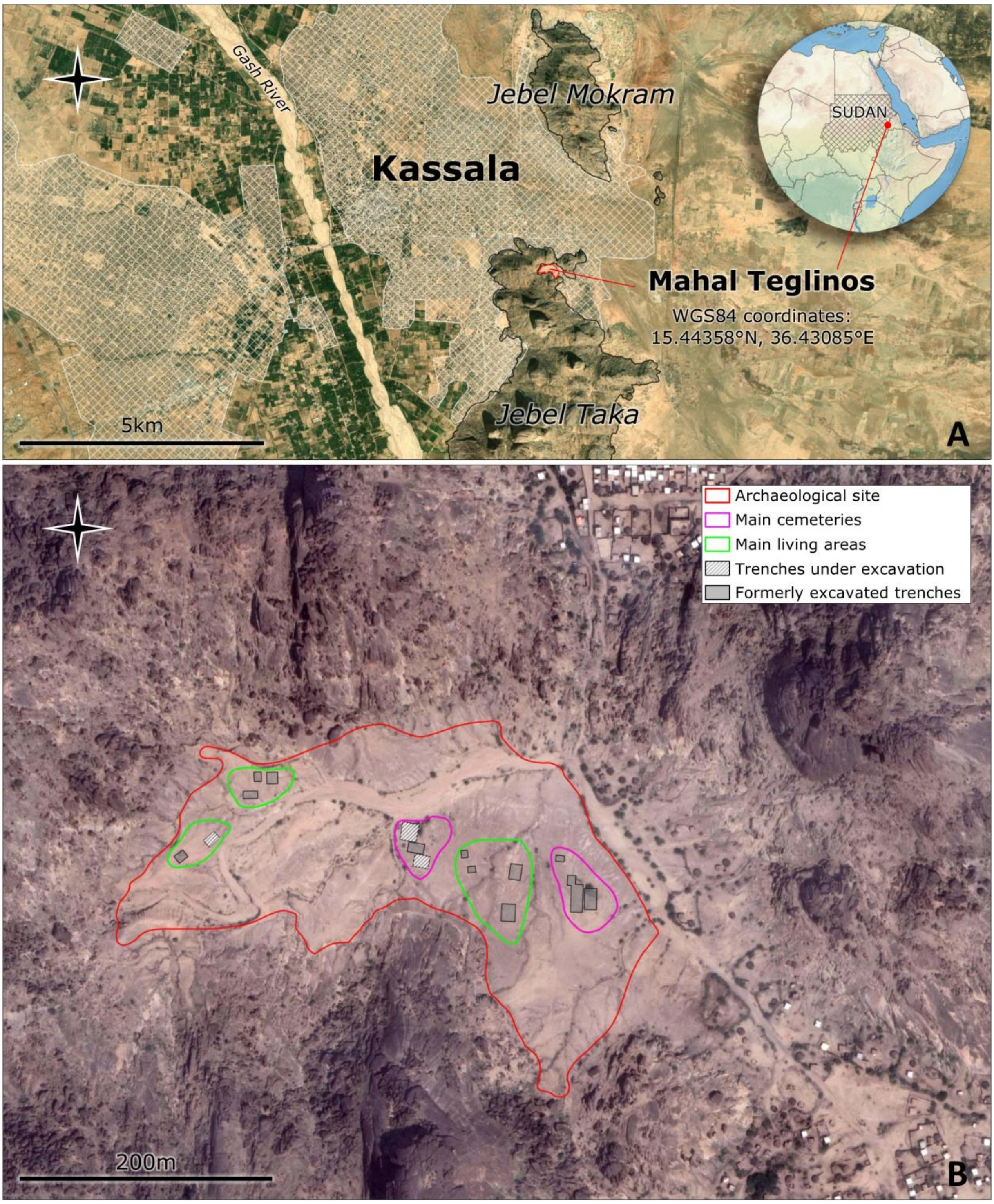


Plate 4.2.1. Overview of the site of Mahal Teglinos and its surroundings. A) Satellite view of the city of Kassala (⍰500.000 inhabitants), which is crossed by the Gash River and wraps around the Jebel Taka encircling the valley and its archaeological site (the extension of the urbanized area is indicated by the white mesh). B) Closer orthogonal view (Google Earth™) of Mahal Teglinos indicating the position of archaeological investigations and recent human-related features (cemeteries and settlements). Trench locations according to Manzo (2019). Green lines encircle the main settlements; purple lines encircle the main cemeteries; white-coloured trenches: under excavation (2019 season); grey-coloured trenches: formerly excavated (1980's, 2010-2017).

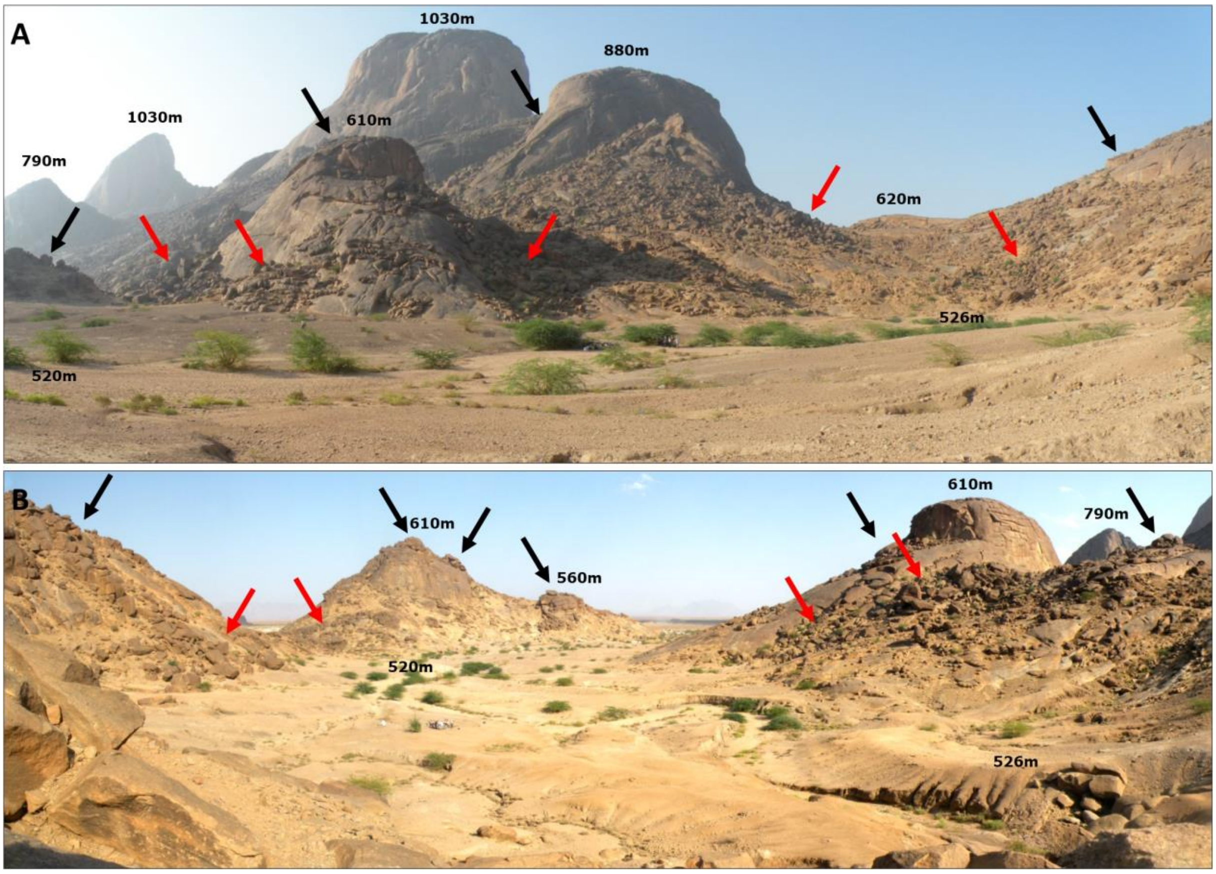


Plate 4.2.2. Geological features and ancestral processes of Mahal Teglinos. A) South-facing view of the site. In the background, the enormous granite bornhardts of the Jebel Taka tower over the surrounding alluvial plain with a prominence exceeding 500m and near-vertical slopes. B) East-facing birdseye view of the site. Lower domes surround the valley creating a secluded basin. In both panels, black arrows indicate tors, nubbins and fissure detachments in formation, while red arrows indicate the foothill chaos of boulders resulting from advanced weathering of blocks detaching from the steep etchplains. Reported altitudes, extracted from ALOS World 3D - 30m (AW3D30)'s Digital Elevation Model (DEM) (JAXA, 2015), are at sea level.

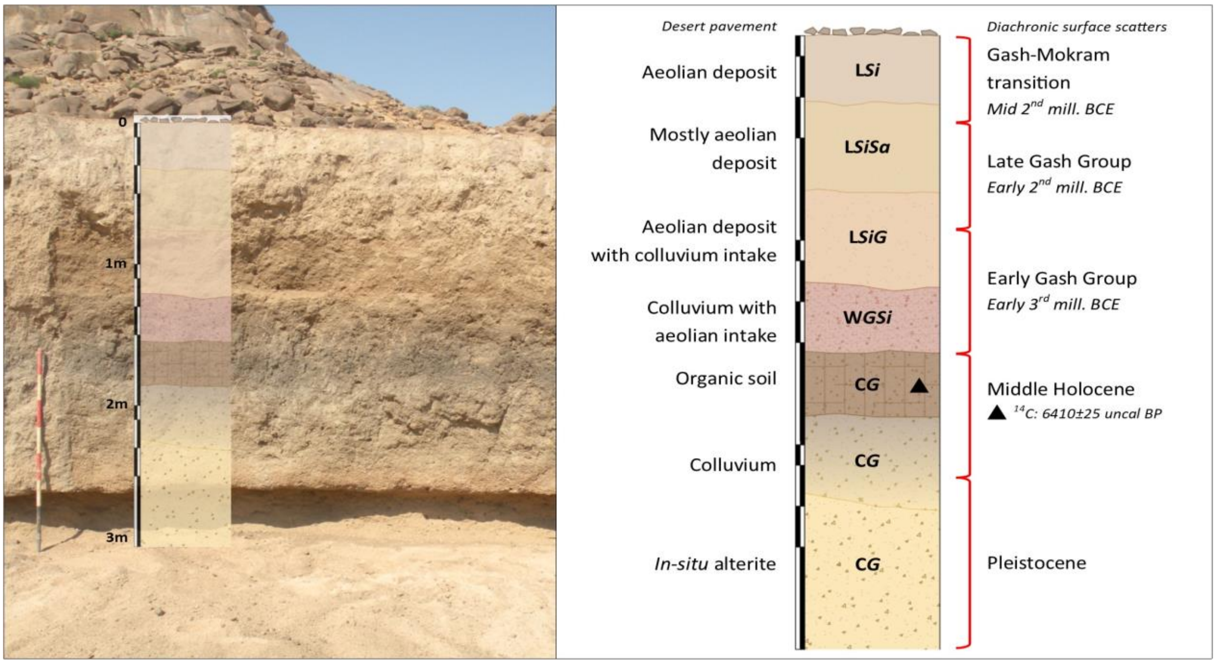


Plate 4.2.3. Pedostratigraphy and chronology of the valley's pediment. Bold and bold italic letters superimposed to the section's drawing indicate the sediment's texture: L-Loose, W-Weakly, compacted, C-Compacted, G-Gravel, Sa-Sand, Si-Silt. The left-hand column offers an interpretation of the depositional processes underlying the formation of each layer. The right-hand column offers a chronology based on radiocarbon dating and archaeological pottery found in correspondence of the exposed section, within trench K1-VI (Manzo 2017; 2020).

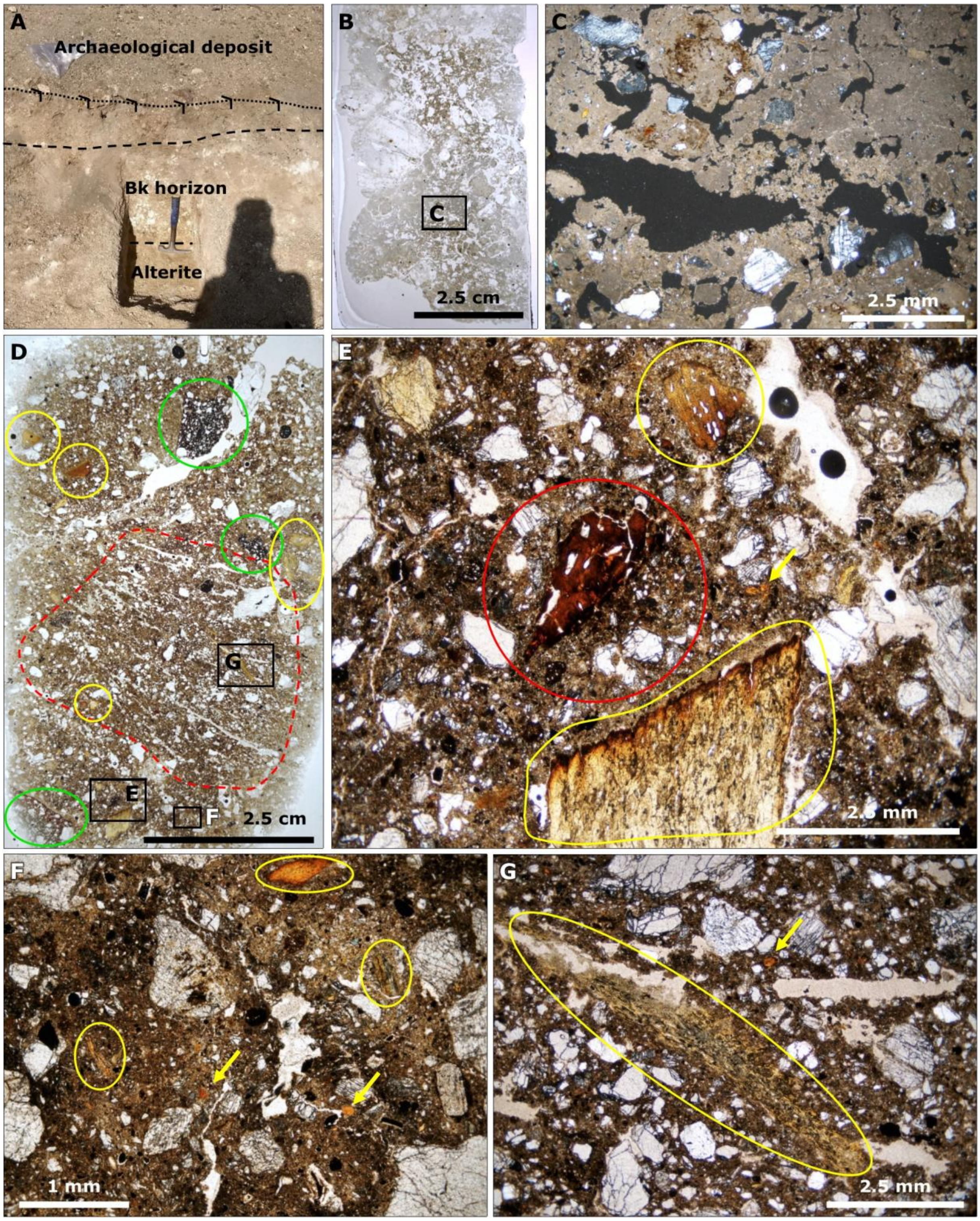


Plate 4.2.4. Micrographs of the Bk horizon and archaeological deposit. (A) The Bk horizon as it appears in Mahal Teglinos, covering the alterite and being covered by the archaeological deposit. (B) Scan image of the thin section from the Bk horizon. (C) XPL (Cross Polarized Light) micrograph of the Bk horizon. Angular feldspar and quartz clasts are engulfed within a vughy micritic lime groundmass. (D-G) Selected thin section (K1VI B2 SU168) and PPL (Plane Polarized Light) micrographs from the archaeological deposit. The red dashed line in (D) indicates trampling-induced stratification, characterized by parallel thin aggregates separated by elongated voids. The green circles indicate ceramic fragments. The red circle in (E) indicates human faecal matter. In all pictures, yellow circles indicate bone fragments and yellow arrows indicate phosphatic nodules, produced by intensive human an animal occupation by degradation of primary organic substances. In all pictures, black speckles and patches are charcoal fragments and soot. Dark-pale chromatic variability of the silty groundmass is induced by humus pans and general enrichment-depletion of decomposed organic matter.

Plate 4.2.5. Examples of severe erosion of the talus and pediment's outskirts. (A) Desert pavement composed of weathered gravel, stones and large amounts of lithic and ceramic artefacts. This covers the pristine upper strata of the pediment almost entirely. (B) Residual large blocks at the bottom of a wide gorge cut between the bottom of the active talus and the pristine Holocene deposit. (C-D) Talus and scree at the northwestern edge of the valley. Flash floods cut into the steep chaotic deposit forming ravines and mobilizing heavy debris consistently.

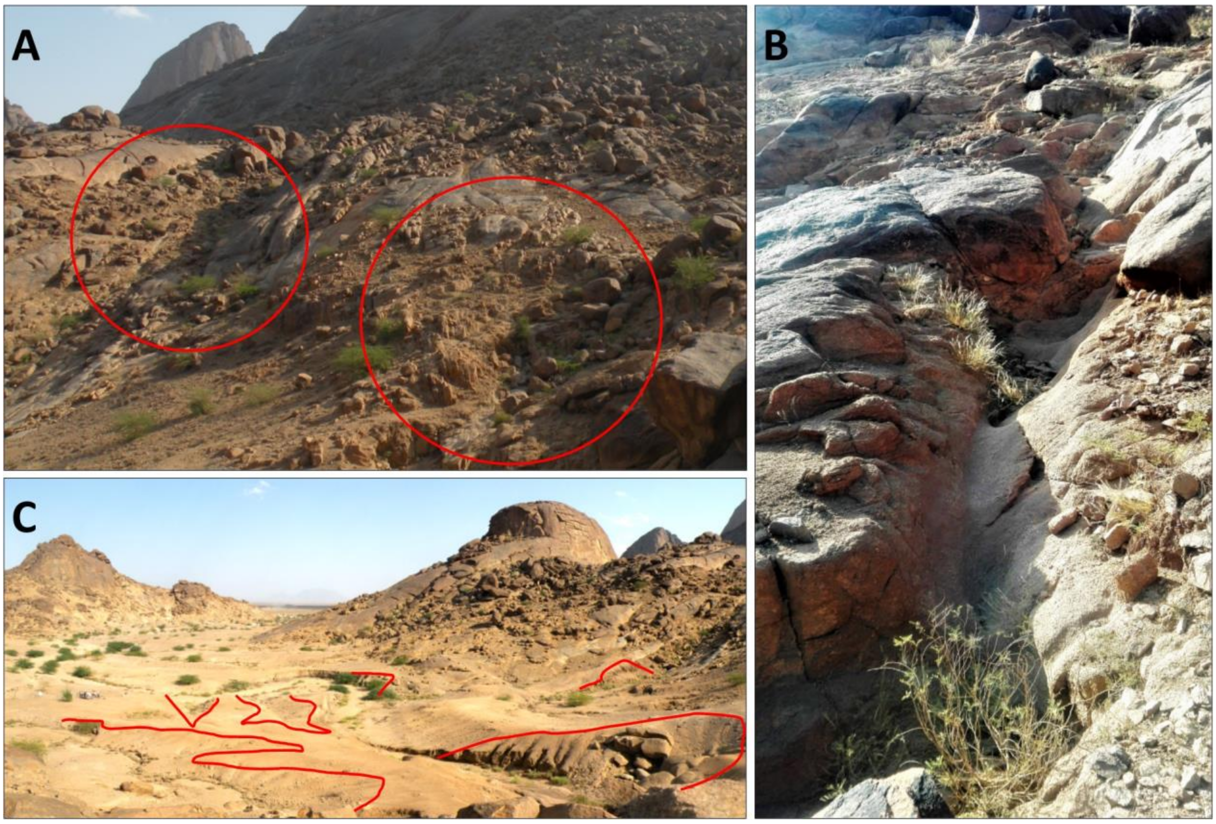


Plate 4.2.6. Examples of water erosion on the bedrock and on the loose pediment deposit. (A-B) Stripping and carving of the steep-sloping granite hillsides. Red circles indicate spots of extreme weathering, where newly formed coarse debris are produced consistently with every rainfall event (C) Birdseye view of V-shaped retreating badlands developing on the loose pediment (red-highlighted areas).

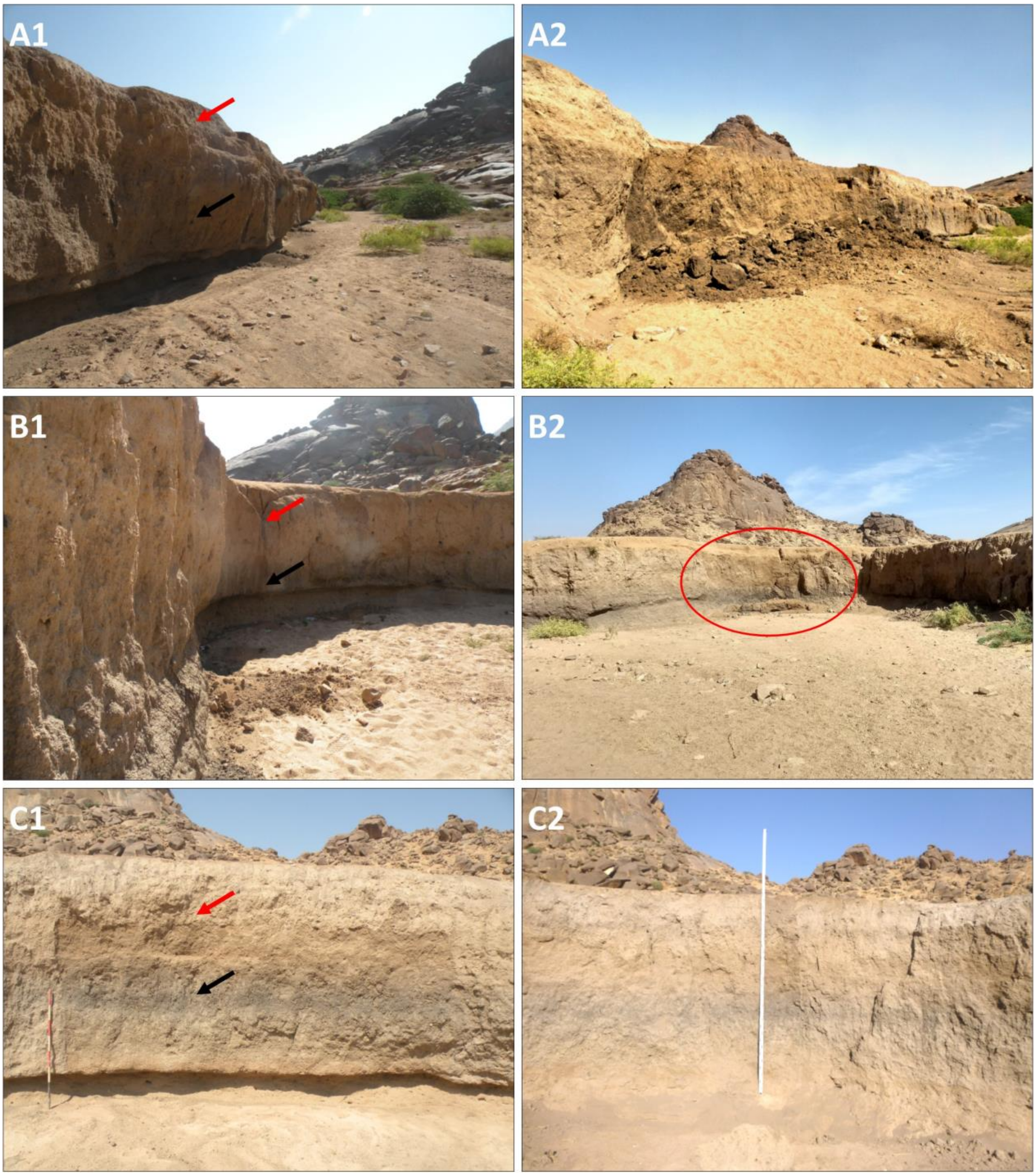


Plate 4.2.7. "Before and after" pictures of collapsed cliffs along the largest gully of Mahal Teglinos. All cliffs exceed a height of 3 m. In all pictures, the grey-hued mid-Holocene organic soil (black arrows) and the pale brown archaeological deposit (red arrows) are easily recognizable. (A1-A2) December 2017, two days apart. The collapsed volume is estimated to be roughly 20m^3 (0.5 metres overhang x 4 metres height x 10 metres lateral extension). (B1-B2) December 2017 vs. December 2019. The burials of the present-day Islamic cemetery are found a few metres back from the drop. (C1-C2) December 2017 vs. January 2019. The collapsed volume is estimated to be roughly 10 m^3 (0.3 metres overhang x 3 metres height x 11 metres lateral extension).

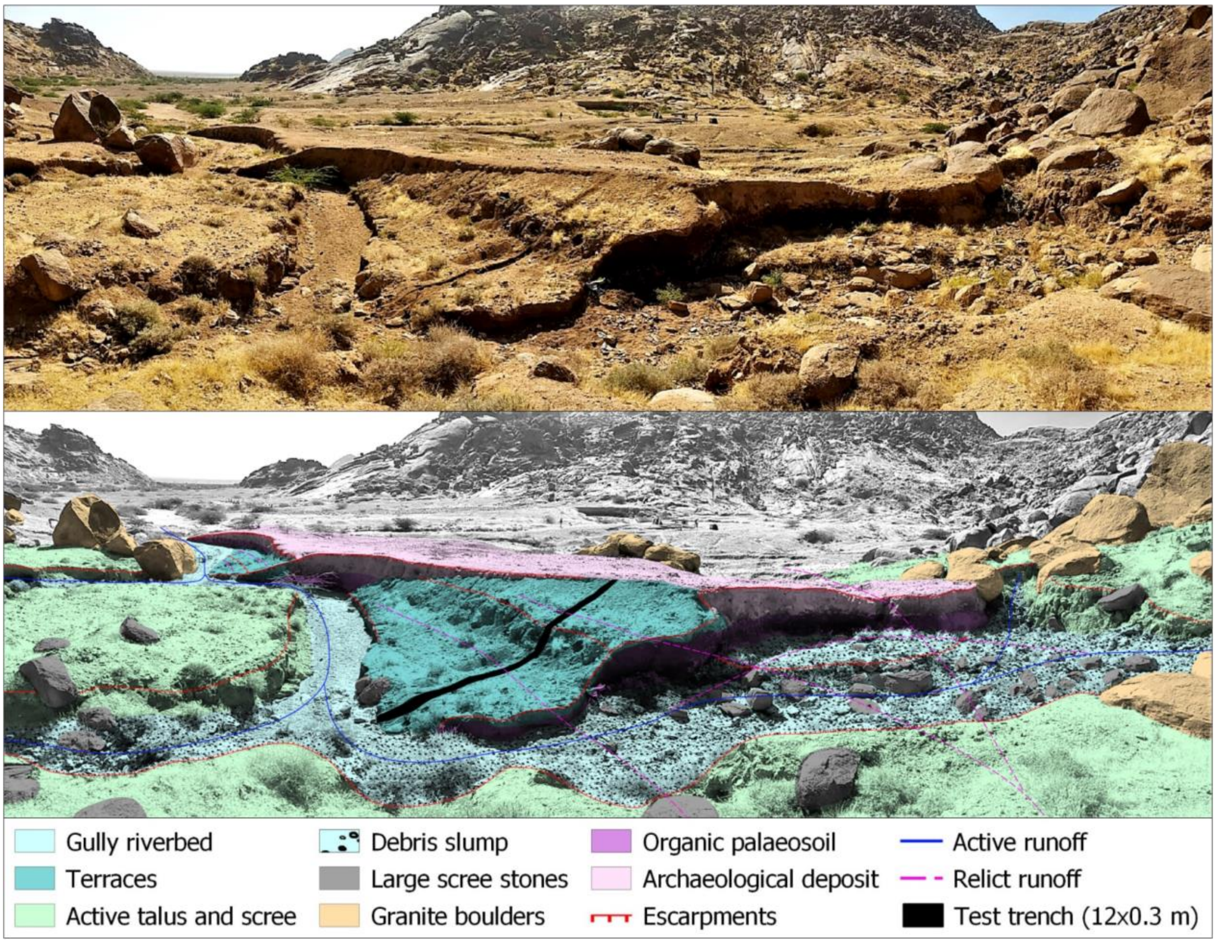


Plate 4.2.8. Southeast-facing birdseye view and geomorphological interpretation of the cut-and-fill system at the north-western interface between the pristine stratigraphy and the active talus. Large volumes of coarse debris are transported downhill, damaging the pristine stratigraphy. The test trench is discussed in Plate 4.2.8.

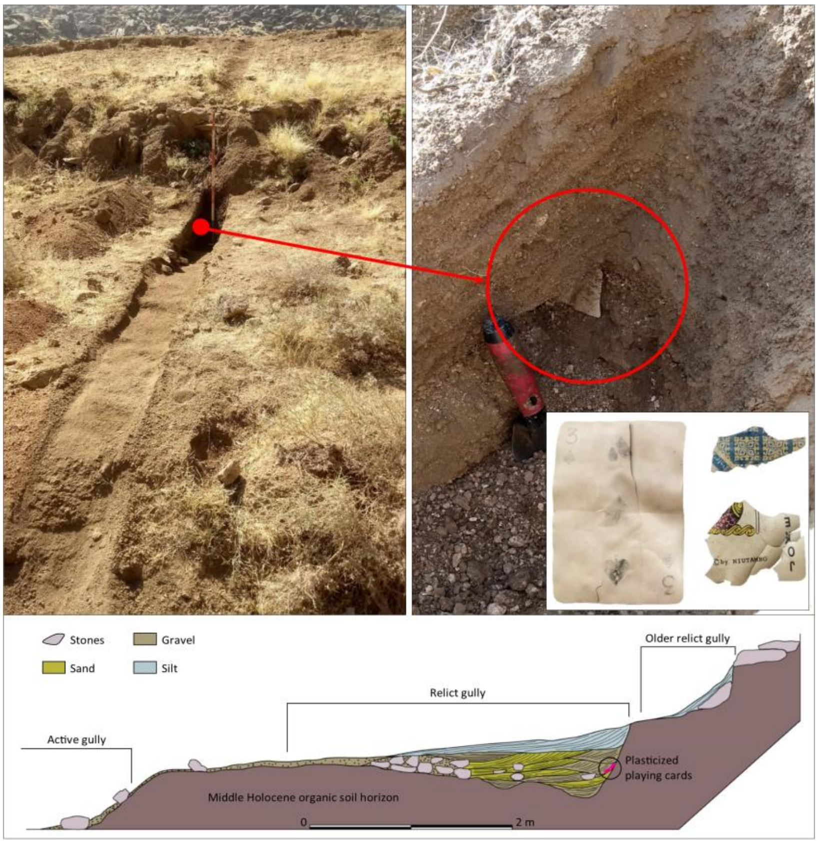


Plate 4.2.9. Detail of the plasticized playing cards embedded in the relict gully's natural backfill. The excavated strip corresponds to the test trench of Plate 4.2.7. Note how the playing card lies flat against the side of the incision, parallel to the waterflow.

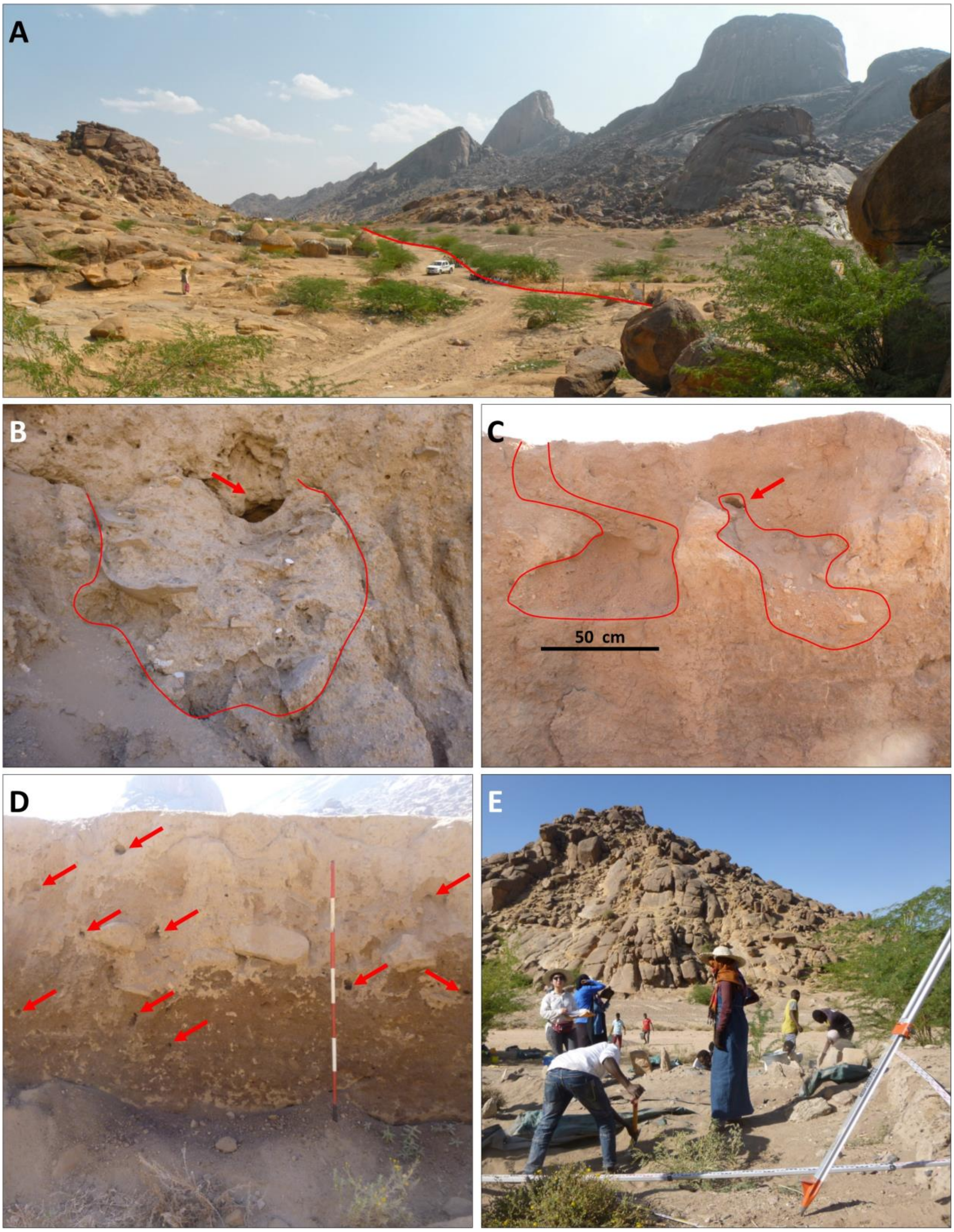


Plate 4.2.10. Examples of disruption caused by human agency and biological disturbance. (A) Panoramic south-facing view of the larger valley entrance. The red line indicates the fenced area with the building ban. Round huts can be seen to the left, while the protected archaeological site is to the right. (B-C) Large collapsed burrows created by rodents, backfilled with slumps of sediment, debris and archaeological material. They were revealed by cliff collapses that they contributed to cause. (D) Several small arthropod burrows (red arrows). (E) Archaeological excavation of a Gash Group cemetery. Several burials suffered extensive rooting damage caused by the large acacia bushes.

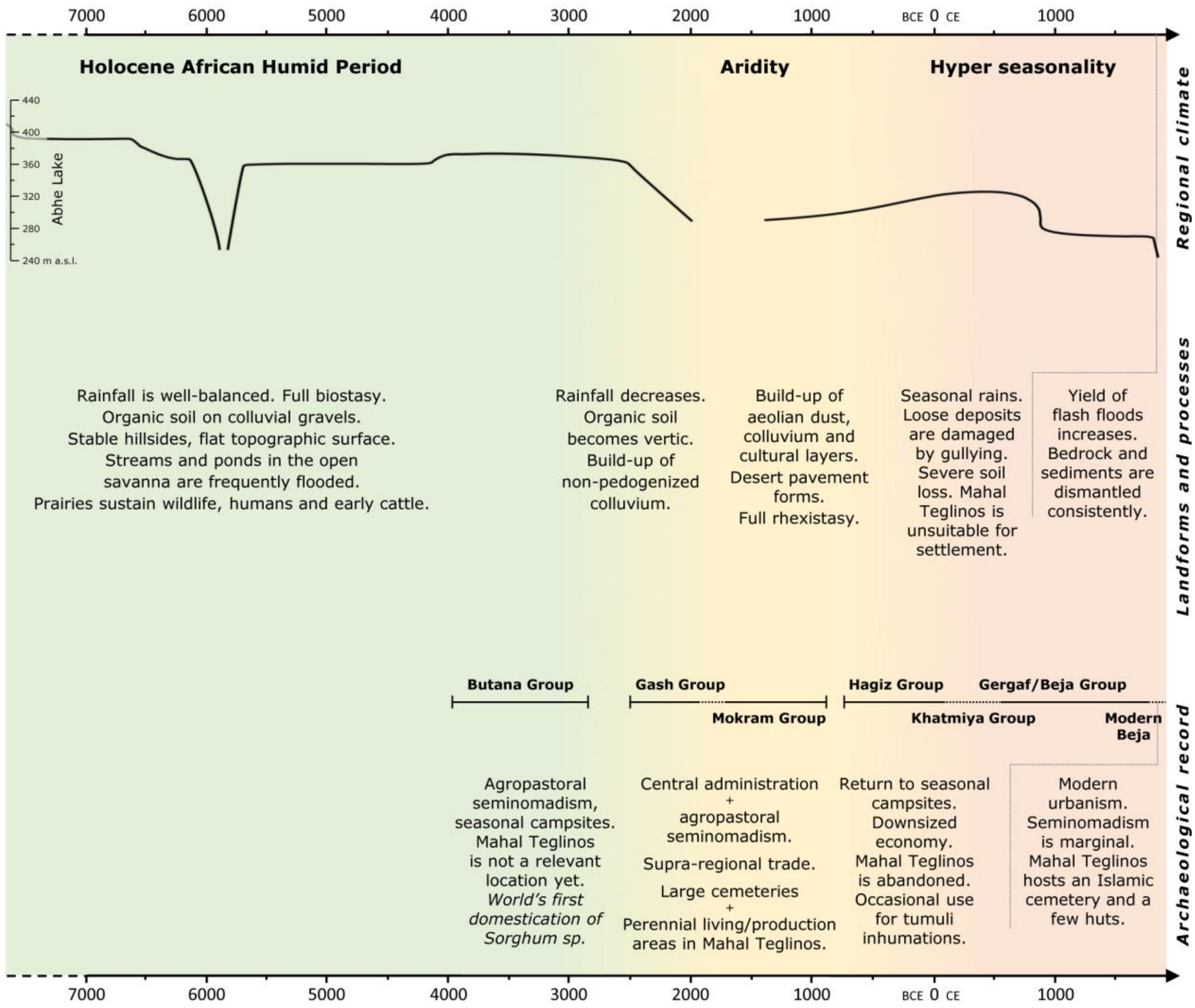


Plate 4.2.11. Timeline of the evolution of Mahal Teglinos in relation with the regional climate and archaeology. The colour-themed chronology of the main climatic settings is after Shanahan (2015). Lake Abhe's shoreline fluctuations curve (Mologni et al., 2021), was added as a recent reference for Holocene climate changes in the Horn of Africa. Mahal Teglinos archaeological record's descriptions are after Manzo (2017).

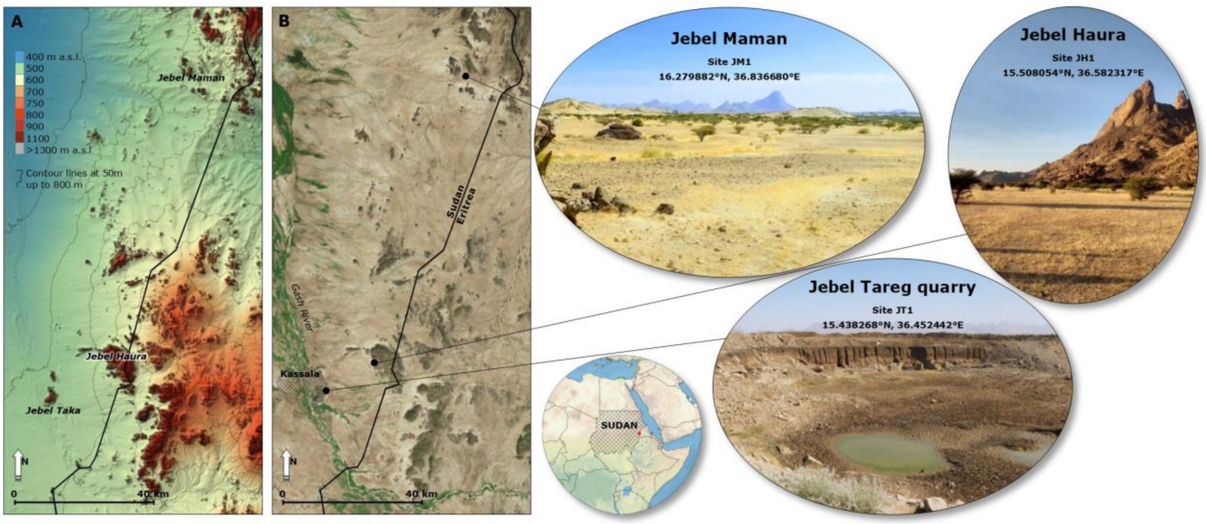


Plate 4.3.1. Overview of the study region and each investigated site. A) Digital Elevation Model (DEM) of the area, highlighting the regional topography characterized by steep rocky inselbergs emerging from a vast pediplain and alluvial plain. B) Satellite overview of the area, highlighting the locations of investigated sites JM1, JH1 and JT1 (round panels).

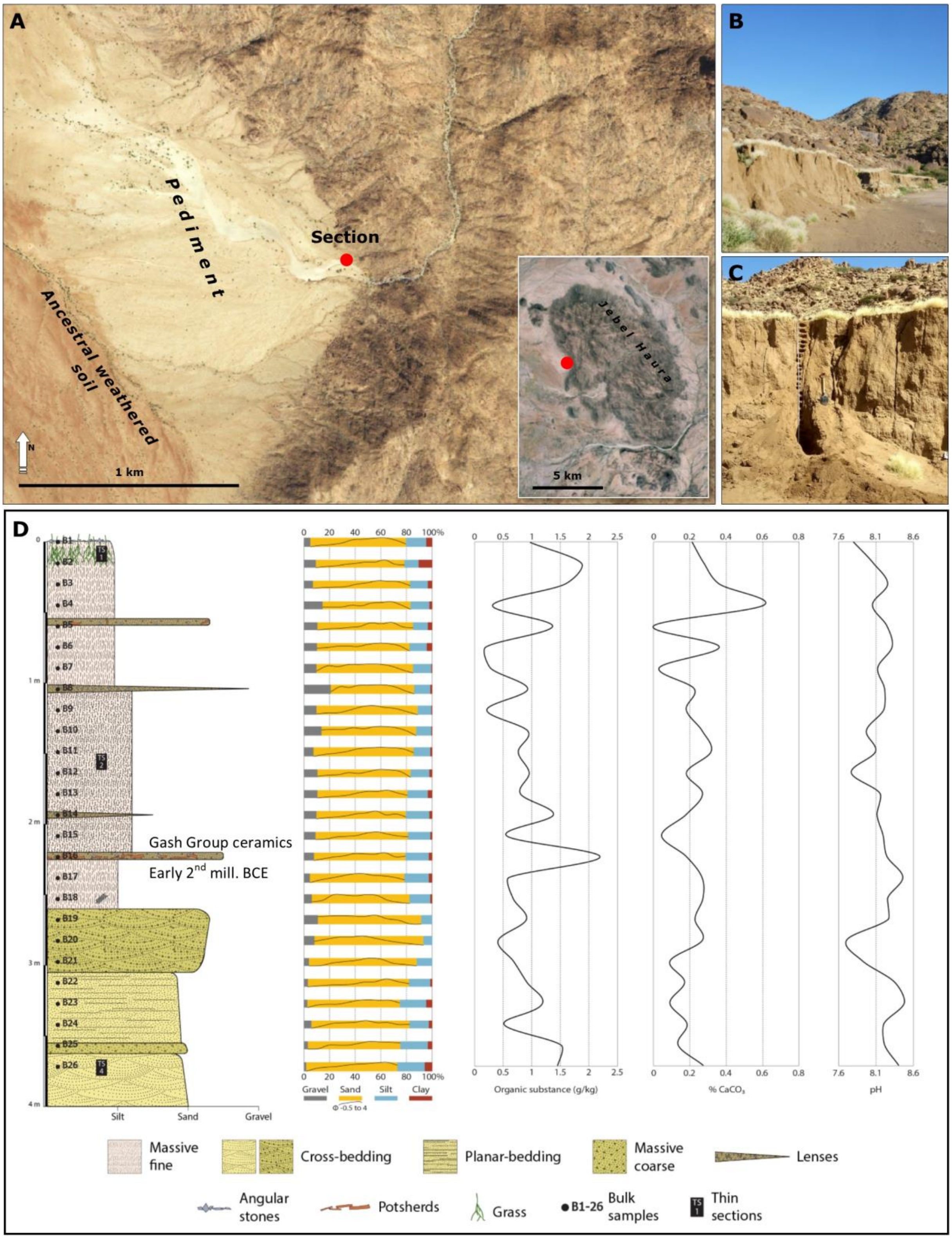


Plate 4.3.2. Jebel Haura – Site JH1. (A) Satellite view (GoogleEarth©) of the area. The unconsolidated sandy silty pediment thins out westwards, covering the ancestral laterites. (B) East-facing panoramic view of the gully-exposed section selected for the analyses. The rocky hills in the background are part of the granodioritic bornhardt assemblage of Jebel Haura. The headwaters of the eroding gully are gathered within the valleys found between the bornhardts. (C) The examined portion of the section (15.508054°N, 36.582317°E), measuring 4 m. Shovel left for scale. (D) Results of the pedosedimentary analyses carried out on the bulk samples gathered from the section. From left to right: stratigraphic log with samples and main archaeological features, cumulative grain size distribution, organic substance content, CaCO3 content, pH.

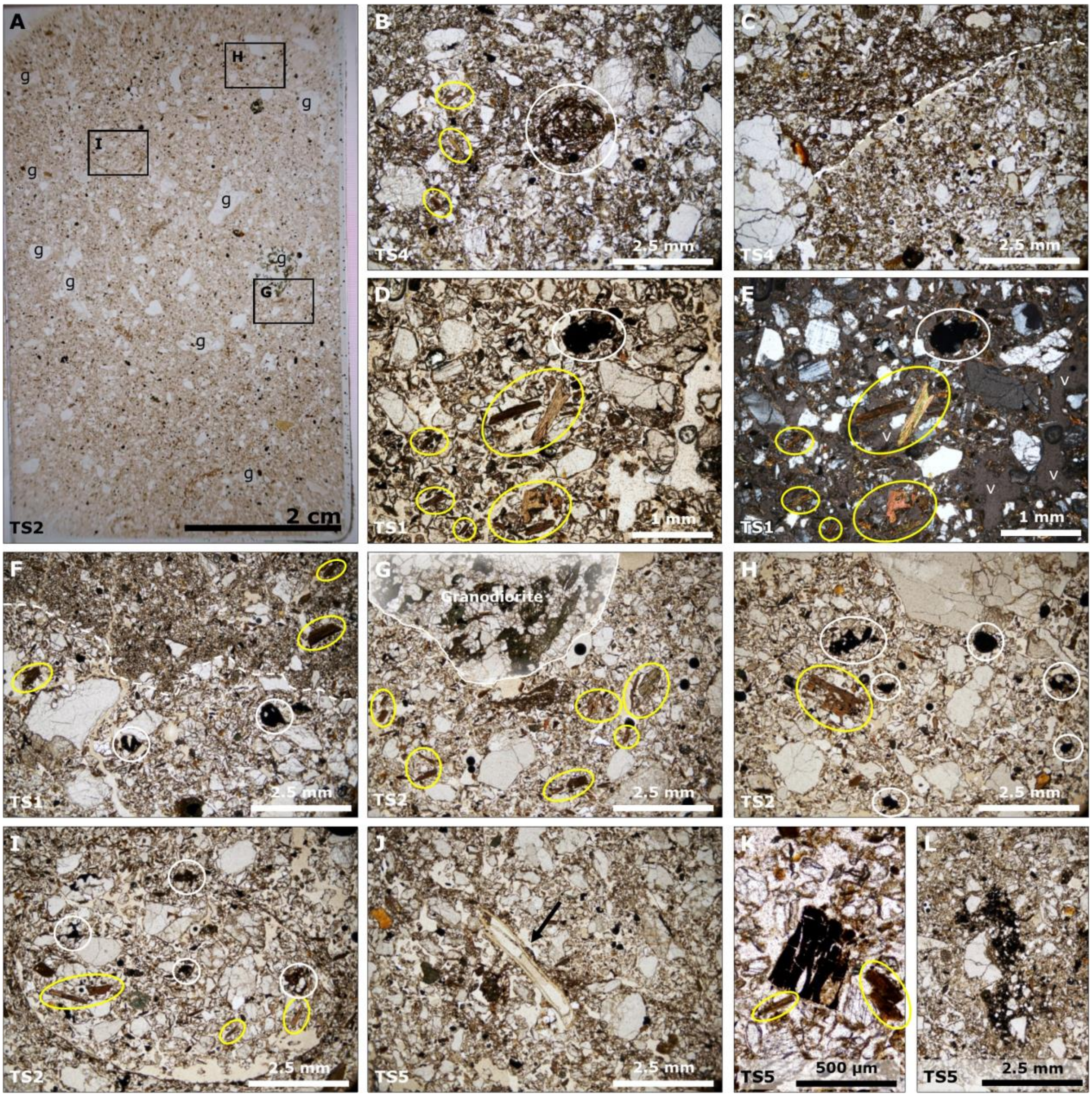


Plate 4.3.3. Selected thin section micrographs from Site JH1. (A) Scan of sample JH19TS2, representative of the general appearance of the other samples as well. The boxes refer to panels G, H and I. A few gravel-sized granitoid clasts are indicated with (g). (B-C) PPL micrographs of sample TS4. Gravel-sized quartz, granitoid clasts and rolled pedorelicts (white circle) are visible within the background mass of faintly layered aeolian quartz fine sand coated with fibrous groundmass, sporadically compressed and enriched with dark humic matter (top half in (C)). Yellow circles indicate biotite flakes (D-E) PPL and XPL micrographs of TS1. Gravel- and loess-sized quartz clasts, coated with fibrous groundmass, are visible throughout, and large structural voids (v, dull grey areas in XPL) are visible between grains and aggregates. Swelling biotite flakes (yellow circles) and magnetite fragments (white circles) are also commonly found. (F) Layered zonation between fine-humic (above dashed line) and coarse-sterile (below dashed line) sediment in TS1, with biotite (yellow circles) and magnetite (white circles) visible together among dominant quartz clasts. (G-H) PPL micrographs of TS2 showing very large granodioritic and granite clasts at the top left and top right corners respectively, included within aeolian quartz fine sand coated with fibrous groundmass. Swelling biotite flakes (yellow circles) and magnetite fragments (white circles) are also visible. (I) PPL micrographs of a large bioturbative channel in TS2, backfilled with mineral grains from the collapsed roof. Biotite flakes (yellow circles) and magnetite fragments (white circles) are visible. (J-L) PPL micrographs of TS5, showing organic inclusions such as a bone fragment (black arrow in (J)), a small charcoal fleck (K) (biotite in yellow circles), and a localized soot patch (L).

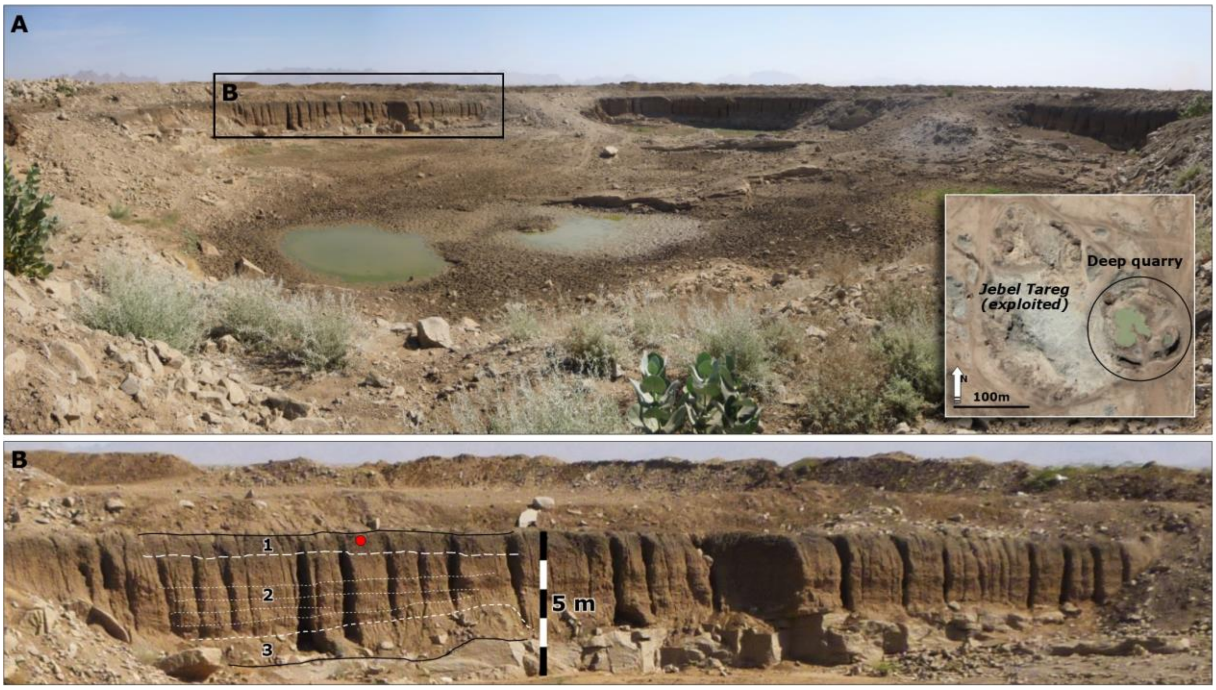


Plate 4.3.4. Jebel Tareg quarry – Site JT1. (A) East-facing overview of the quarry. Behind the observer lies the completely dismantled gneissic/granodioritic outcrop called Jebel Tareg. (B) Characterization of a portion of the exposed Quaternary pedostratigraphy. 1 indicates the Vertic Kastanozem-type soil, sampled for radiocarbon dating and micromorphological analyses (red dot 15.438659°N, 36.452548°E); 2 indicates the weathered ancestral alluvial deposit; 3 indicates gneissic saprolite (C horizon) sitting on the pristine crystalline basement. Atop the stratigraphy, unsorted disposal debris seals the sequence.

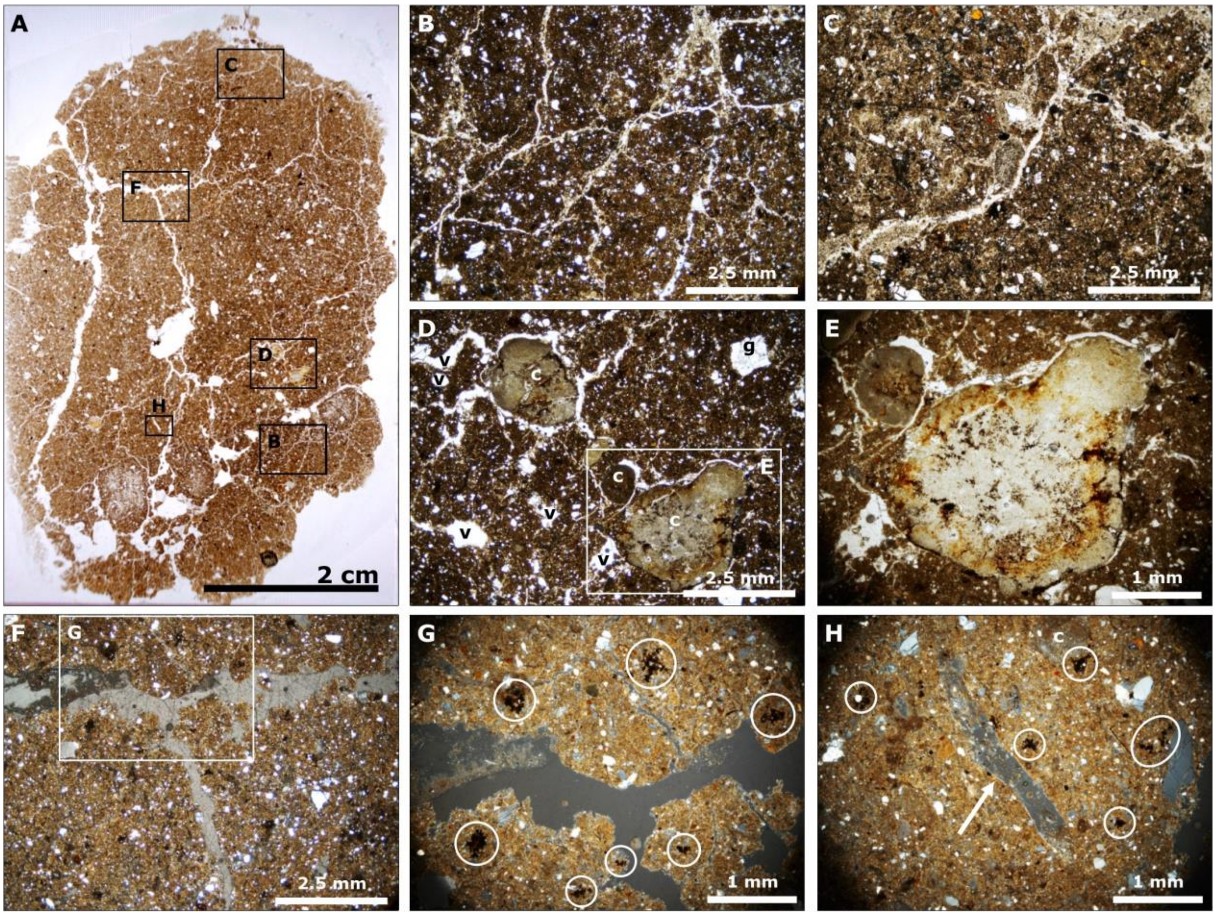


Plate 4.3.5. Selected thin section micrographs from Site JT1. . (A) Scan of the soil thin section, highlighting the dark brown general colour coupled with well-expressed planar voids separating the mass in plinths and polyhedrons. (B-C) PPL micrographs highlighting the open porphyric C/F-related distribution and the presence of several thin incipient planar voids and vesicles and a general vertic structure. (follows next page)

(continues from previous page) Small angular quartz clasts (bright white speckles) are dispersed within a fine silty clay brown matrix. (D-E) Well-rounded CaCO3 clasts (c) show hypo-coating oxidation and growth of ferruginous nodules within their mass, suggesting they were already present within the deposit at the beginning of the pedogenesis. A small granite angular clast (g) is also visible in (D). Voids are indicated with (v). (F-G) XPL micrographs highlighting, again, the open porphyric C/F-related distribution and the presence of undisturbed dendritic and mamillated ferruginous nodules growing within the groundmass (white circles). The bright speckles in (F) are predominantly subangular to subrounded quartz grains, with lesser feldspar grains and occasional granitoid and mafic accessories. (H) Another example of dendritic and mamillated ferruginous nodules (white circles) growing within bioturbated (white arrow) groundmass, surrounded by small quartz grains arranged in open porphyric distribution within the matrix (XPL).

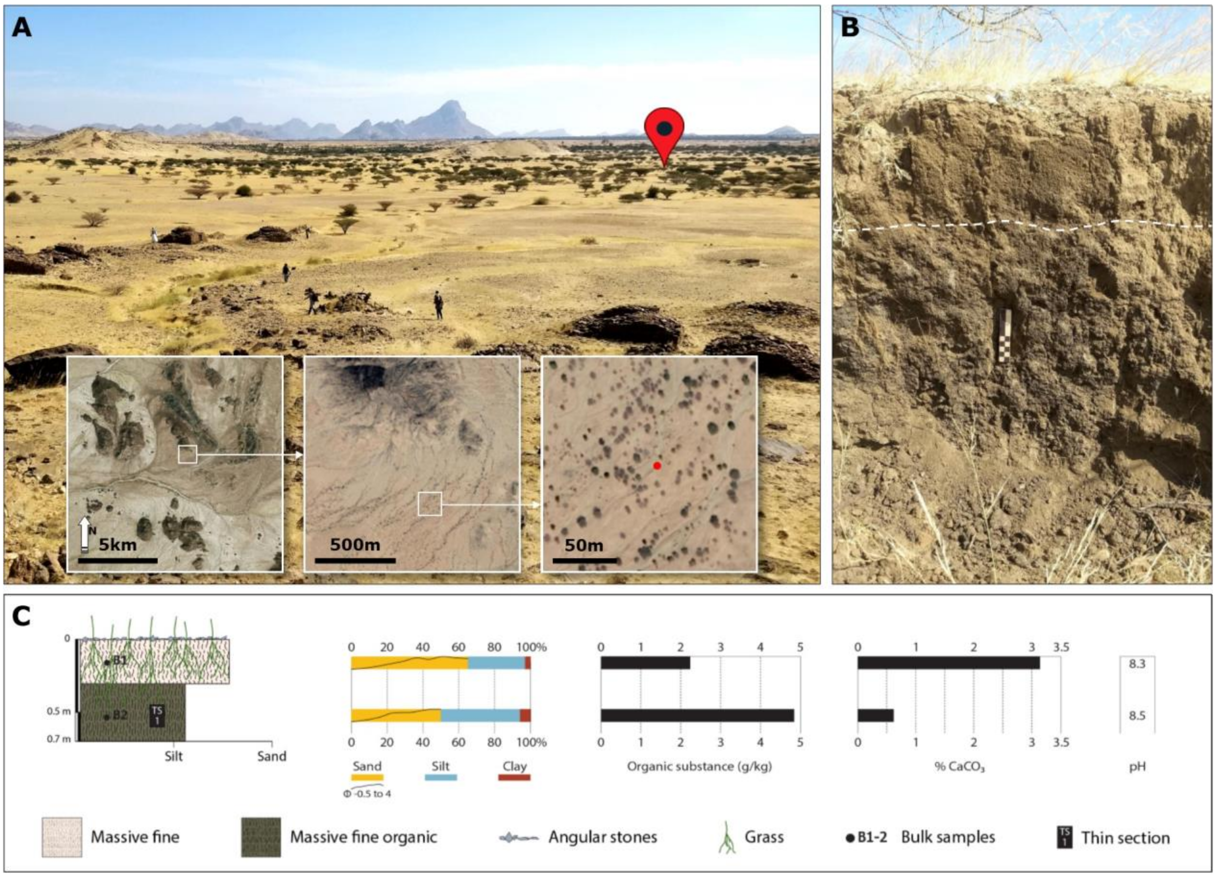


Plate 4.3.6. Jebel Maman Site JM1. (A) General settings of the site (16.279882°N, 36.836680°E), indicated by the red pinpoints in the south-facing panoramic photo and the smaller panel. The picture was taken in early December, when the ephemeral summer prairie has already dried up and only xerophytes and acacias survive on lower ground. In the foreground, the square stone structures are Medieval Islamic tombs called qubbas (Costanzo et al., 2021b). (B) Picture of the chosen section, cut by one on the countless small rills and gullies furrowing the inselberg's pediment. The dashed line separates the two main layers: pale brown sandy silt, sealing a dark grey organic horizon developed on silty sand. (C) Results of the pedosedimentary analyses carried out on the bulk samples gathered from the section. From left to right: stratigraphic log with samples, cumulative grain size distribution (gravel values for B1 and B2 are 0.53 and 0.27% respectively, not discernible from the cumulative histogram), organic substance content, CaCO3 content, pH.

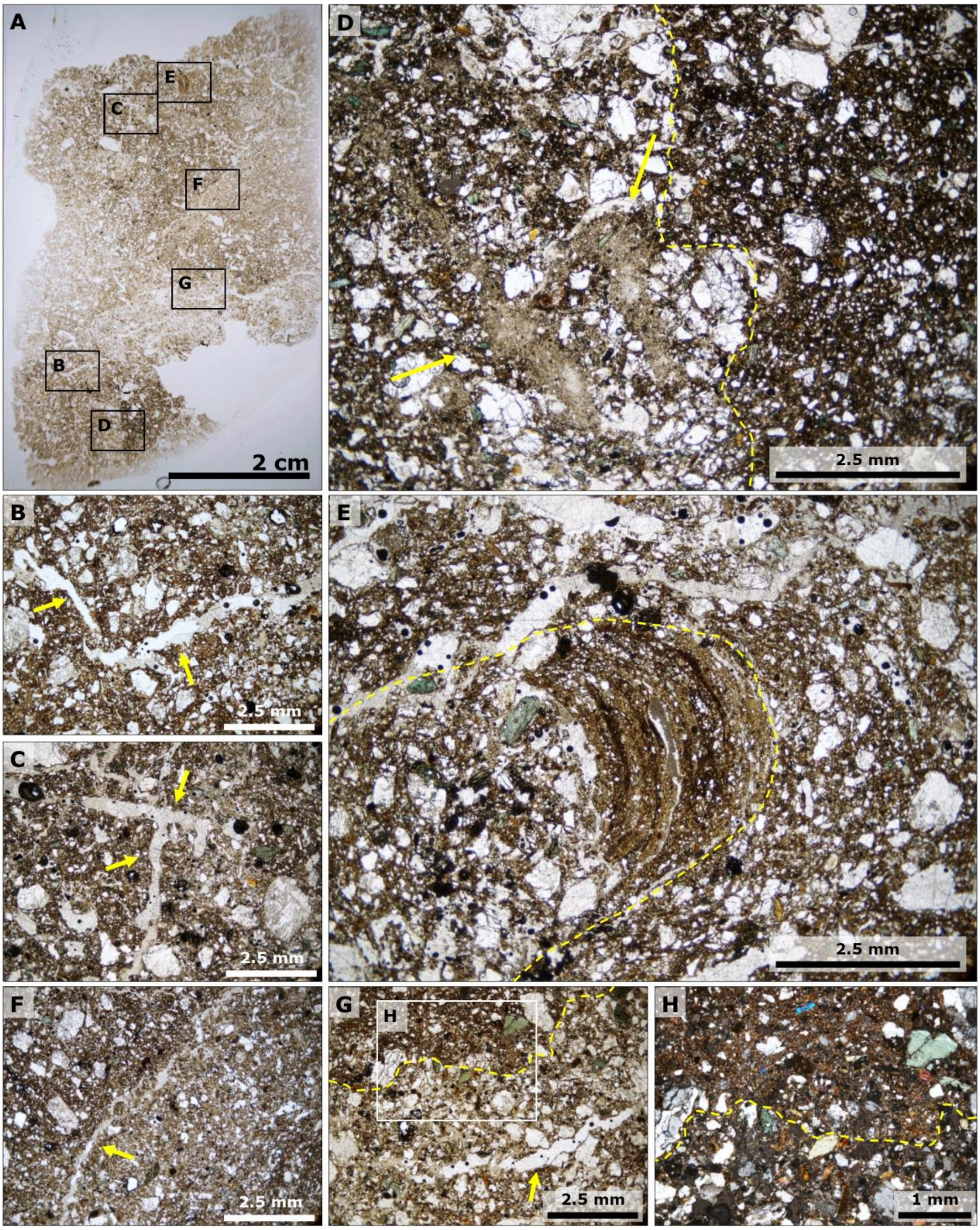


Plate 4.3.7. Selected thin section micrographs from Site JM1. (A) Scan of the soil thin section highlighting the general appearance of the soil mass, composed of paler and darker patches intimately and chaotically mixed. The boxes refer to the following panels. (B-C) Plane Polarized Light (PPL) and Cross Polarized Light (XPL) micrographs showing the general aspect of the sediment in dark patches, with subangular quartz sand dispersed into a fibrous spongy matrix disrupted by bioturbation (yellow arrows). (D) Pale and dark patches welded together (along the dashed line). The pale patch contains an amorphous CaCO3 concretion (yellow arrows). The dark patch has a different textural composition than the pale one, with lesser and finer grained clasts dispersed within the matrix (PPL). (E) Detail of a large passage (bioturbation) feature (dashed line) (PPL). (F) Unwelded pale and dark patches, separated by a thin structural planar void. This time, the pale patch is finer grained than the darker one (PPL). (G-H) Welded pale and dark patches. This time the textural composition in similar. The yellow arrow indicates an incipient planar void originating from an unwelded pale/dark spot a few millimetres to the right (see panel A)(PPL and XPL).

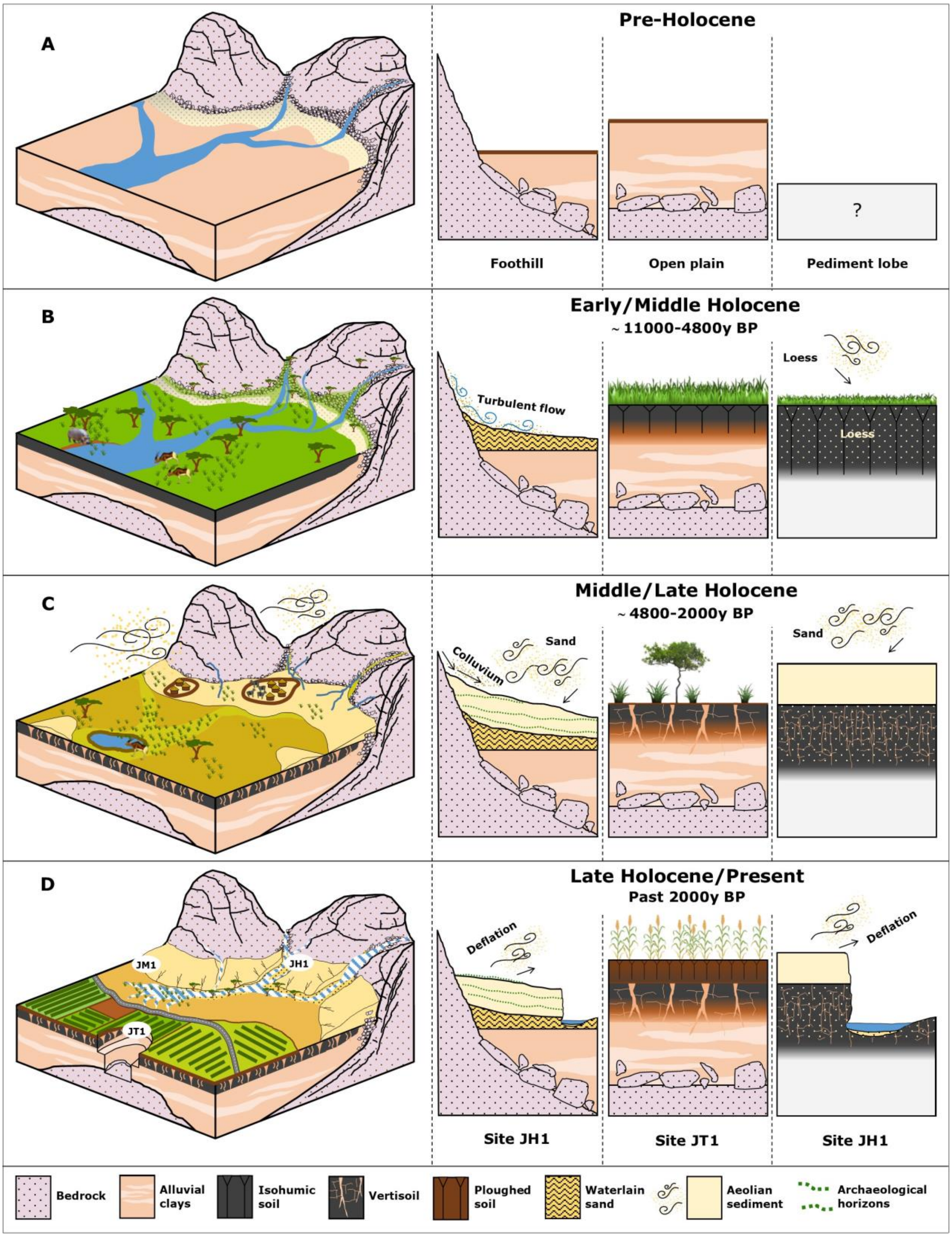


Plate 4.3.8. Theoretical model reconstructing morphogenetic processes and environments of the Kassala region, with site-specific pedostratigraphic sequences. (A) Pre-Holocene fluvial processes create the ancestral alluvial plain. No climatic and biotic data for this phase. (B) Warm-humid climate of the Early/Middle Holocene promote the formation of a prairie/woodland environment and the stabilization of foothills and open plain soil covers, with water-reliant faunal assemblages (Geraads, 1983; Manzo, 2017). (C) Drying climate of the Middle/Late Holocene causes the vertisolization of the open plain's topsoil and the colluvial/aeolian accretion of the foothill pediments, engulfing coeval archaeological horizons. (D) Strong seasonal intermittent rains and intensive land exploitation disrupt the loose foothill deposits and mask the pristine landscape, causing the fragmentation of the archaeo-environmental record.

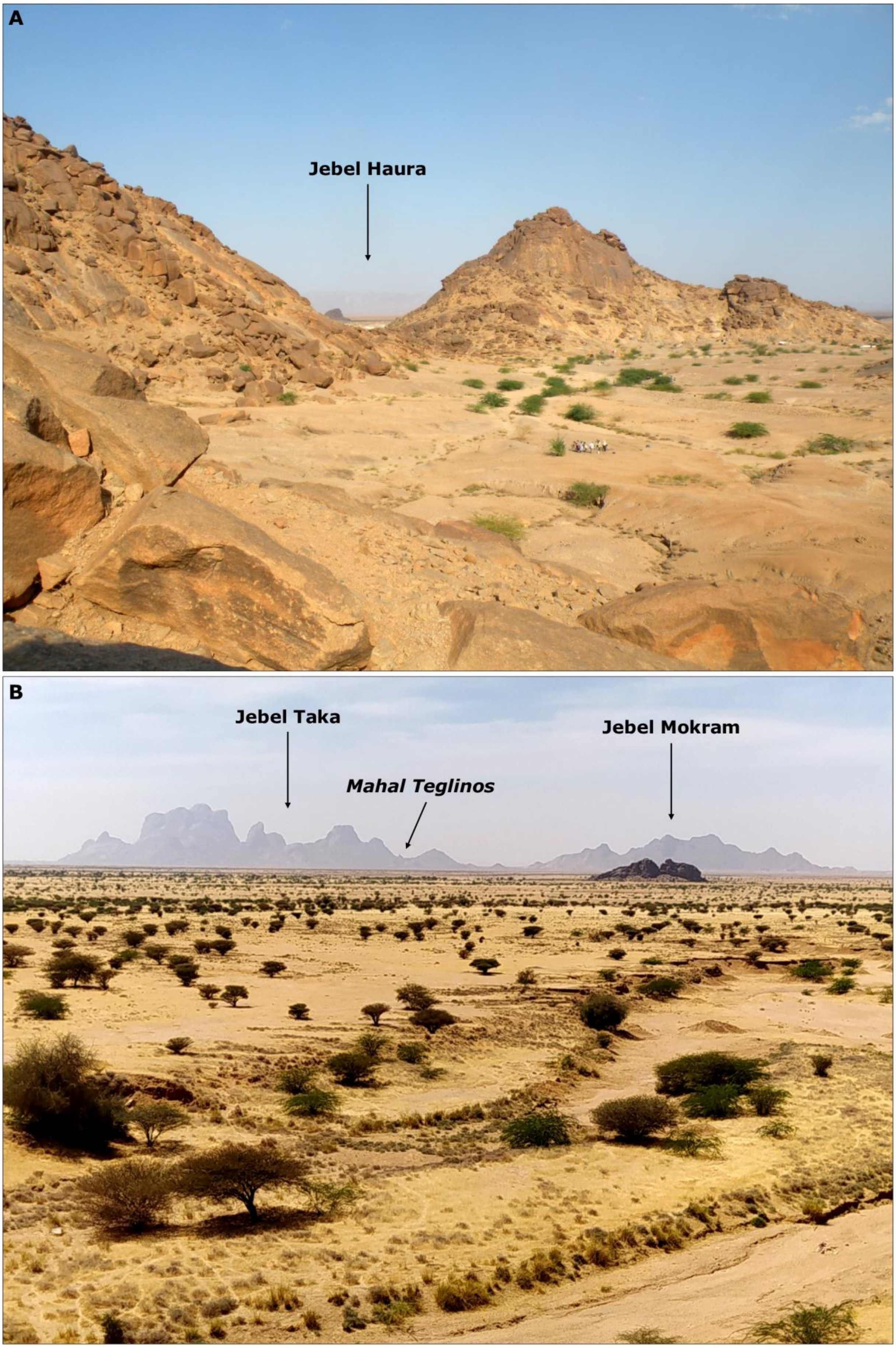
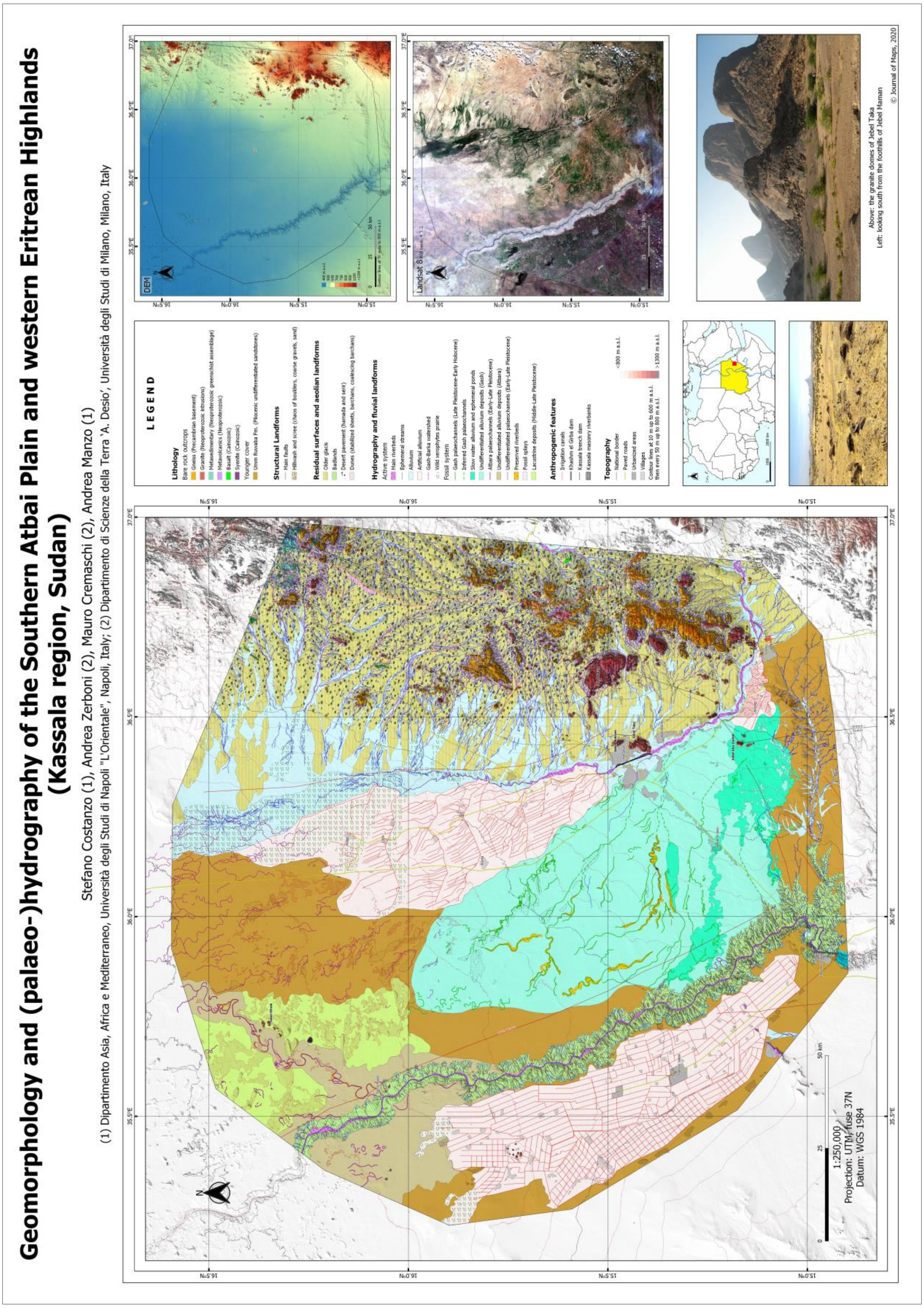


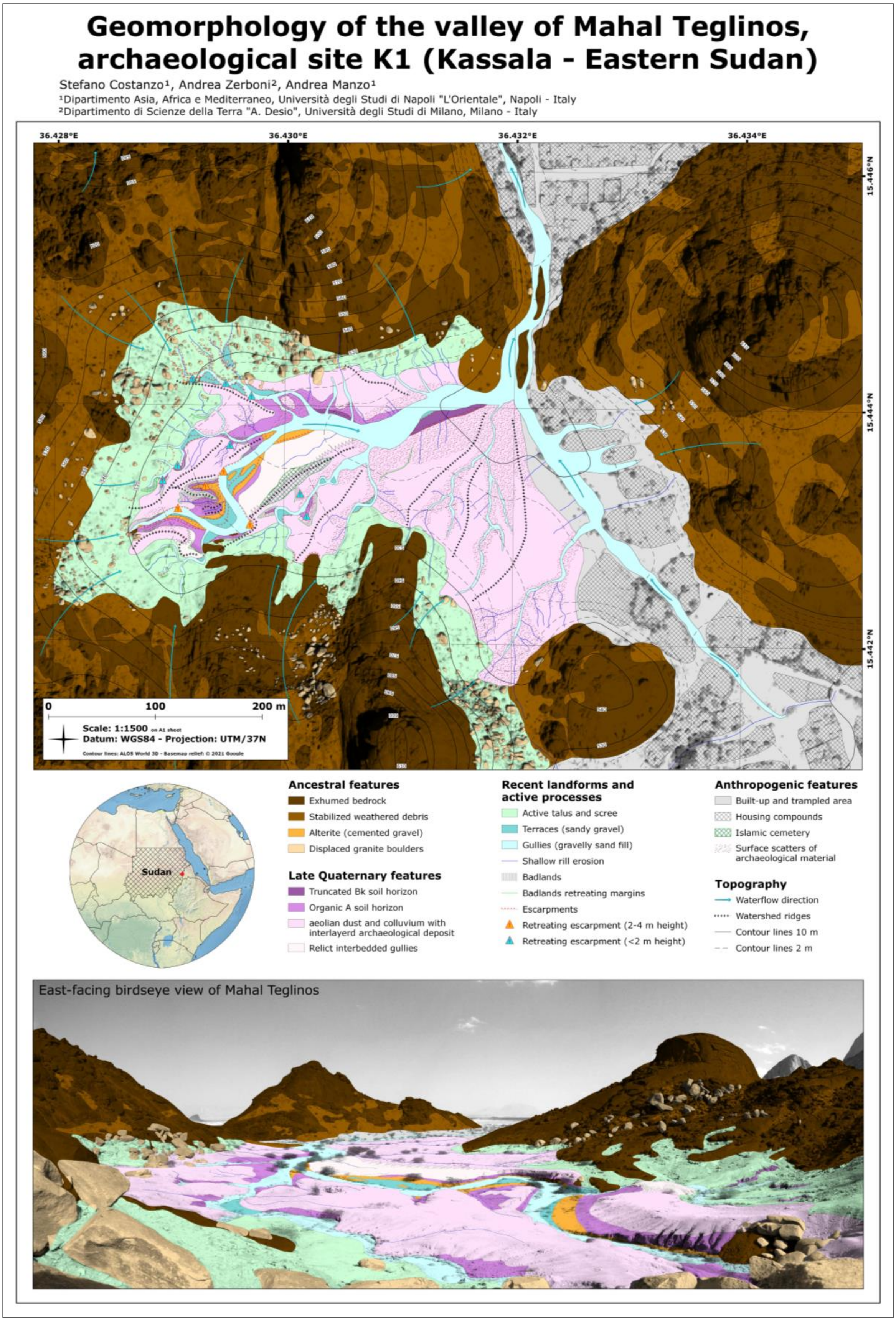
Plate 4.3.9. Mutual visibility between Mahal Teglinos and Jebel Haura (Site JH1). (A) Picture taken from Mahal Teglinos, looking east. In the background, Jebel Haura is visible, slightly masked by dusty winds. (B) Picture taken from Site JH1, looking west. Mahal Teglinos is readily recognizable, nested between the peculiar domes of the Jebel Taka.

Appendix A – Geomorphological and (palaeo-)hydrological map of the Southern Atbai and western Eritrean Highlands



For the full resolution A0 layout, please see the original publication: Costanzo, S., Zerboni, A., Cremaschi, M., & Manzo, A. (2021) Geomorphology and (palaeo-)hydrography of the Southern Atbai plain and the western Eritrean Highlands (Eastern Sudan/Western Eritrea). *Journal of Maps*, 17:2, 51-62.

Appendix B – Geomorphological map of Mahal Teglinos



For the full resolution A1 layout, please see the original publication: Costanzo, S., Zerboni, A., & Manzo, A. (2022). Active surface processes at Mahal Teglinos (Kassala, Eastern Sudan): archaeological implications for an endangered protohistoric site in Sahelian Africa. *Journal of Archaeological Science: Reports*, 43(6456):103452.

Appendix C – Thin section micromorphology descriptions

	Sample, depth	Coarse components		Groundmass	Voids	C/F related distribution, B-fabric	Aggregation, Microstructure	Pedofeatures and sedimentary features
		Mineral	Organogenic and anthropogenic					
Site UA 50	**TS3** **40 cm**	Chaotic heterometric assemblage of subangular to subrounded quartz grains ranging from 50 to 2000 µm, with lesser amounts of other same sized/shaped igneous minerals. Very few well-rounded small $CaCO_3$ clasts.	Very rare small (500-1000 µm) well-rounded unburnt bone fragments. Residual root tissue within channels.	Dull orangy-brown clay organized in moderately to highly separated plinths.	Common large subangular non accomodating interped planar voids, with common incipient thin intraped planar voids interconnecting common channels, chambers, vesicles and vughs.	Variable close to open porphyric Absent	Well-developed Complex subangular blocky structure with spongy plinths.	Common small (200 µm) radial fibrous goethite nodules. Few small (500-1000 µm) rounded/rolled pedorelicts. Illuvial clay-$CaCO_3$ paste infilling within larger chambers and packing voids. Thin perimetral clay coating of all clasts. Rare very porous discontinuous worm dropping within chambers.
Site JT 1	**JT19** **TS1** **30 cm**	Chaotic assemblage of predominant small (100 µm) quartz equilateral, subangular to subrounded grains, with rare presence of same-sized granite-derived accessories. Presence of larger (1-5 mm) granitoid clasts. Presence of relatively large (0.5-2 mm) CaCO3 well-rounded weathered clasts.	Very small phosphatised bone fragments.	Dark brown silty clay organised in moderately separated plinths.	Common long planar voids with angular and subangular mostly accommodating margins. Common thinner intra-ped planar voids. Occasional bioturbative channels and small chambers. Occasional non-accomodating structural voids.	Open porphyric Absent.	Well developed. Angular blocky.	Widespread in-situ Fe/Mn dendritic nodules. Zoned Fe hypo-coating of the CaCO3 clasts. General widespread humus enrichment. Occasional debris infilling of the planar voids.
Site JM 1	**JM19** **TS1** **50 cm**	Chaotic heterometric assemblage of clasts ranging from 20 to 2000 µm. The finer fraction is dominated by subangular to subrounded quartz grains, the coarser fraction comprises granite/gneiss/schist-derived grains with associated primary minerals.	Common very small (100 µm) phosphate nodules. Rare very small splinters of non-siliceous plant tissue.	Pale brownish grey clay with lighter-coloured patches arranged as intrusions within the darker mass. Peds are slightly developed into small plinths.	Very common channels and small vesicles (200-500 µm), arranged chaotically throughout the sample. Few thin conjugated (subvertical-subhorizontal) planar voids with subrounded accommodating margins.	Variable close to double spaced porphyric. Weakly random striated.	Poorly developed, brittle. Vesicular/spongy.	All clasts show a thin perimetral clay coating. Occasional amorphous CaCO3 concretions within larger structural packing voids. Occasional small (100 µm) dendritic Fe/Mn nodules. General humus enrichment with fibrous traces of the parent organic matter (still not discernible). Presence of a large bioturbative channel lamination. The groundmass has a general fibrous appearance with large randomly oriented convolutions.

Site	Sample, depth	Coarse components		Groundmass	Voids	C/F related distribution, B-fabric	Aggregation, Microstructure	Pedofeatures and sedimentary features
		Mineral	Organogenic and anthropogenic					
Mahal Teglinos (Site K1)	**K1 VI B2 SU168** **20 cm**	Chaotic heterometric assemblage of angular to subrounded quartz grains ranging from 50 to 1000 µm.	Very common unburnt bone fragments (0.5-4 mm). Very common ceramic fragments. Common charcoal flecks. Human faecal matter (3 mm).	Light brown silty clay.	Common subhorizontal elongated packing voids (trampling). Few channels and chambers.	Variable close to open porphyric. Very weak crystallitic.	Poorly developed, dusty. Absent.	Faint subhorizontal lamination of the groundmass. Diffuse organic enrichment in the form of dark particles, humus pans and phosphatisation. Loose crumbly worm faecal infilling of channels. Few small rolled Fe nodules. Occasional micritization of voids.
	K1 VI D1 SU86 **35 cm**	Chaotic heterometric assemblage of angular to subrounded quartz grains ranging from 50 to 1000 µm, with occasional larger (1 cm) granitoid angular grains and well-rounded CaCO3 altered clasts (3 mm).	Common small charcoal flecks. 1 large (0.5 cm) ostrich shell fragment.	Light brown silty clay.	Very common thin incipient angular accommodating planar voids. Occasional small channels and packing voids.	Variable close to open porphyric. Very weak crystallitic.	Poorly developed, dusty. Absent.	Diffuse organic enrichment in the form of dark particles, humus pans and phosphatisation. Loose crumbly worm faecal infilling of channels. Few small rolled Fe nodules.
	K1 VI B3 SU43 **45 cm**	Chaotic heterometric assemblage of angular to subrounded quartz grains ranging from 50 to 1000 µm, with occasional larger (1 cm) granitoid angular grains and well-rounded CaCO3 altered clasts (3 mm).	Common small charcoal flecks, common small (1 mm) and large (5mm) bone fragments, common small ceramic fragments. Human faecal matter (0.5 mm)	Light brown silty clay.	Very common small vughs and packing voids. Few randomly oriented channels.	Variable close to open porphyric. Very weak crystallitic.	Poorly developed, dusty. Absent.	Faint subhorizontal layering of the groundmass. Diffuse organic enrichment in the form of dark particles, humus pans and phosphatisation. Loose crumbly worm faecal infilling of channels. Few small rolled Fe nodules. Occasional micritization of voids.
	K1 Calcrete **40 cm**	Granitoid coarse gravel (up to 4 cm) chaotically dispersed into very fine CaCO3 silty micrite.	Absent	Lime micrite.	Very common thin incipient planar voids, vughs, vesicles and packing voids.	Various. Crystallitic	Well-developed to crumbly. Spongy microstructure.	Occasional dendritic Fe/Mn nodules. Occasional ferruginous hydromorphic halos within the micrite mass.

	Sample, depth	Coarse components		Groundmass	Voids	C/F related distribution, B-fabric	Aggregation, Microstructure	Pedofeatures and sedimentary features
		Mineral	Organogenic and anthropogenic					
Site JH 1	**JH19 TS1** **10 cm**	Chaotic heterometric assemblage of clasts ranging from 20 to 1000 µm. The finer fraction is dominated by subangular to subrounded quartz grains, the coarser fraction comprises granodiorite-derived grains and significant amounts of partially swollen biotite flakes and magnetite fragments.	Absent.	Almost absent, represented only by a thin fibrous clay coating of all clasts.	Very few planar voids separating brittle prisms. Dominant intergrain packing voids.	Chitonic. Absent.	Very poorly developed. Pellicular grain microstructure.	Thin fibrous clay perimetral coating of all grains. Partial swelling of the biotite flakes. Weak weathering of the larger grains with secondary clay formation. Occasional capping of larger clasts.
	JH19 TS2 **160 cm**	Chaotic heterometric assemblage of clasts ranging from 20 to 1000 µm. The finer fraction is dominated by subangular to subrounded quartz grains, the coarser fraction comprises granodiorite-derived grains and significant amounts of partially swollen biotite flakes and magnetite fragments.	1 unburnt (2 mm) bone fragment.	Almost absent, represented only by a thin fibrous clay coating of all clasts.	Very few planar voids separating brittle prisms. Dominant intergrain packing voids. Few bioturbative channels of which a very large one (∅ 1 cm) collapsed and backfilled with overlying clasts.	Chitonic. Absent.	Very poorly developed. Pellicular grain microstructure.	Thin fibrous clay perimetral coating of all grains. Partial swelling of the biotite flakes. Weak weathering of the larger grains with secondary clay formation. Very few rolled small (1 mm) pedorelicts. Few localized weakly laminated infillings of local depressions (fine silt/groundmass).
	JH19 TS4 **370 cm**	Chaotic heterometric assemblage of clasts ranging from 20 to 3000 µm. The finer fraction is dominated by subangular to subrounded quartz grains, the coarser fraction comprises granodiorite-derived grains and abundant small partially swollen biotite flakes and small magnetite fragments.	Absent.	Light brown fibrous clay, mostly in the form of clast coating but locally found as a matrix.	Diffuse packing voids. Few bioturbative channels and slightly larger chambers (up to 2 mm).	Chitonic, locally close porphyric Absent	Very poorly developed. Complex pellicular grain to spongy microstructure.	Few rolled small (1 mm) pedorelicts. Weakly laminated structure in the bottom half. Partial swelling or complete weathering of the biotite flakes. Weak weathering of the larger grains with secondary clay formation.
	JH19 TS5 **350 cm**	Chaotic heterometric assemblage of clasts ranging from 20 to 3000 µm. The finer fraction is dominated by subangular to subrounded quartz and feldspar grains, the coarser fraction comprises granodiorite-derived grains and abundant small partially swollen biotite flakes and small magnetite fragments.	Rare small bone fragments (2 mm) and charcoal flecks (500 µm).	Light brown fibrous clay, mostly in the form of clast coating but locally found as a matrix mixed with small amounts of clay.	Diffuse packing voids. Common vughs (200-1000 µm). Few bioturbative channels, of which a large one (∅ 8 mm) backfilled with loose heterometric clasts.	Chitonic, locally close porphyric Absent	Very poorly developed. Complex pellicular grain to spongy microstructure.	Few rolled small (1 mm) pedorelicts. Partial swelling of the biotite flakes. Weak weathering of the larger grains with secondary clay formation. Local concentrations of ash-enrichedgroundmass.

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A geoarchaeological perspective

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