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SCIENCE

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Geomorphology and (palaeo-)hydrography of the Southern Atbai plain and western Eritrean Highlands (Eastern Sudan/Western Eritrea)

Stefano Costanzo [a], Andrea Zerboni [b], Mauro Cremaschi [b] and Andrea Manzo[a]

[a]Dipartimento Asia, Africa e Mediterraneo, Università degli Studi di Napoli 'L'Orientale', Napoli, Italy; [b]Dipartimento di Scienze della Terra 'A. Desio', Università degli Studi di Milano, Milano, Italy

ABSTRACT

We present the geomorphology of the Southern Atbai Plain (Eastern Sudan) and the western edge of the Eritrean Highlands (Western Eritrea), in the eastern Sahel. The mountainous area consists of Paleo-Proterozoic gneiss and Neo-Proterozoic igneous rocks and meta-volcanic assemblages shaped as inselbergs and whaleback landforms by weathering. Bare-rock hills emerge from a gentle glacis that oversees the Southern Atbai alluvial plain, located between the Atbara and Gash Rivers. The plain features the SSE-NNW-oriented endorheic terminal fan of the Gash River and is crossed by intricate Early to Late Pleistocene paleochannels, whose evolution was controlled by the interplay between Quaternary regional tectonics and arid to humid climatic and environmental oscillations. The map is intended to interpret the evolution of local landscape, thus representing a tool for reconstructing the spatial and temporal distribution of Late Quaternary archaeological features and their functional relationships with the fossil fluvial system and the western foothills.

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1. Introduction and background

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, whose formation was primarily controlled by natural causes (Roberts, 2019). Factors triggering the geomorphological and ecological evolution of the Sahel include: (i) lithological and structural properties of the regional bedrock, (ii) contrasting climatic settings, alternating since the Quaternary pluvial and (hyper)arid environmental conditions. Since the Holocene, several human interventions aimed to satisfy an ever-growing demand for land for cultivation and pastureland (deforestation, overgrazing, diversion of watercourses, excavation of artificial canals, alteration of the topography) resulted in the disruption of natural ecosystems and progressive desertification of the land (ArchaeoGLOBE, 2019; Huang et al., 2020; Wright, 2017).

The Sahel of eastern Sudan, for instance, is a region crossed by large rivers – the Atbara and Gash Rivers – that have been scarcely investigated from the geomorphological point of view. Notwithstanding this, the region with its rivers 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 is sparsely inhabited, but huge human modifications altered the pristine hydrographic network with the main aim of increasing the extension of cultivable patches. Therein, a detailed geomorphological survey allowed (i) illustrating the main features of the landscape and reconstructing their evolution, (ii) inferring the palaeoclimatic factors that drove at least part of the morphogenetic processes, and (iii) providing geomorphological tools to help the archaeological interpretation of land-use changes.

2. Geography, geology and climate

The Southern Atbai (Central-Eastern Sudan, Kassala State) is the region outlined by the Atbara and the Gash Rivers. The plain is gently sloping down from SSE (560 m asl) to NNW (420 m asl), with a variability from 0.5% to 0.1%. The region is covered with Quaternary fluvial deposits, comprising glaring evidence of multiple generations of palaeochannels, and the

CONTACT Stefano Costanzo ste.costanzo92@gmail.com

remains of a Middle/Late Pleistocene shallow lacustrine deposit – the Atbara Palaeolake (Abbate et al., 2010), lying beneath a discrete assemblage of dunes. Today, the Atbara is a perennial, low-sinuosity meandering river with an incised riverbed some 10–30 m lower than the surrounding area. The Gash (known in Eritrea as Mareb) is a seasonal river that originates south of Asmara, flows along a narrow steep-sided valley, becomes an SSE-NNW-oriented braided system in the open Sudanese plain, and finally dissipates into a vast endorheic terminal fan of relevant agronomic interest (Barbour, 1961) (Figure 1). To the east of the Gash River, a deflated glacis cut by E-W aligned tributary channels (in Arabic: khors) gently slopes up to the edges of the Eritrean Highlands, whose S-N orientation creates the watershed between the Gash and the Barka catchments. South of the Atbai Plain, a slightly more rugged area today not reached by the Gash floods extends for a few tens of kilometres up to the Setit River's basin.

In the western part of the study area downstream of the Khashm el Girba Dam, the bedrock underlying the Cainozoic and Quaternary fluvial deposits is poorly exposed. It consists of Precambrian basement rocks capped by Cretaceous Nubian Sandstone and Cainozoic basalts (Abbate et al., 2010; Whiteman, 1971). Bedrock outcrops are more common in the eastern part of the region, where they form alternation of Palaeo-Proterozoic gneiss hills, probably uplifted from the basement during the formation of the Arabian-Nubian Shield, and Neo-Proterozoic igneous formations (granite and granodiorite; GRAS, 2004) in the form of inselbergs. Meta-volcanic and meta-sedimentary gold-bearing assemblages are also present (Elsamani et al., 2001; GRAS, 2004) (Figures 1 and 2).

Local climate shifts from hot semi-arid (BSh) to hot desert (BWh) (Kottek et al., 2006) from SSE to NNW. The city of Kassala, for instance, receives an average precipitation of 250 mm/year (Hermance, 2014), whilst the Gash River benefits from the high amount of precipitations of its inner Ethio-Eritrean Highlands catchment (tropical savanna; Kottek et al., 2006). Moreover, it was observed that the foothills east of the Gash can generally convoy and store enough rainfall to supply surface water for several months, both in the form of natural ponds and artificial reservoirs called *hafirs*.

3. Human occupation

Evidence of Early to Middle Pleistocene hominid presence was recorded along the deposits of the Atbara River (Abbate et al., 2010; El-Amin, 1987; Nassr, 2014). However, no deep investigation has ever been carried out elsewhere in the alluvial plain, and it is therefore impossible to infer its abundance. In contrast, many early explorers (Crowfoot, 1911; 1928) and recent research teams (Clark, 1976; Fattovich et al.,1988; Manzo, 2017; Marks & Sadr, 1988; Phillipson, 1977; Sadr, 1988; Shiner, 1971) have investigated Holocene archaeological evidence nearby the Gash River. Such investigations show a continuous occupation of the region 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 evidence actually spans from the Pre-Saroba Phase (6th–5th mill. BCE) to the Gergaf Group (mid-2nd mill. CE) (Manzo, 2017). Archaeological sites are located along the palaeochannels of the Gash River, although their temporal relationship with them is still debated (Manzo, 2019, pp. 270–271). Sites consist of deflated spreads of micro/macro-lithics, potsherds, ephemeral semi-nomadic structures, shell middens, and simple or small mound burials, with stratigraphies that rarely exceed a few centimetres due to intense deflation. Fewer known sites are located at the foothills of the inselbergs east of the alluvial plain; among these, the largest and most important one (∼10 ha), is Mahal Teglinos (or K1) (Manzo, 2017, and references cited therein). Systematic surveys east of the Gash River and to the far NE of the study area (see Main Map) are underway (Manzo, 2019).

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), within the Butana Group. The recovery of allochthonous artefacts from the Gash Group strata in Mahal Teglinos suggests that the region has also been crucial as a commercial crossway between the Nile Valley, the Horn of Africa and Arabian Peninsula since the 3rd mill. BCE (Manzo, 2017 and references cited therein). 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.

4. Methods

The Main Map's confines are arbitrary and do not represent natural/political boundaries, but a large buffer around the geographic and archaeological features mentioned within paragraphs 2 and 3. The mapping process relied on satellite images and open access Digital Elevation Models (DEM) analysed within

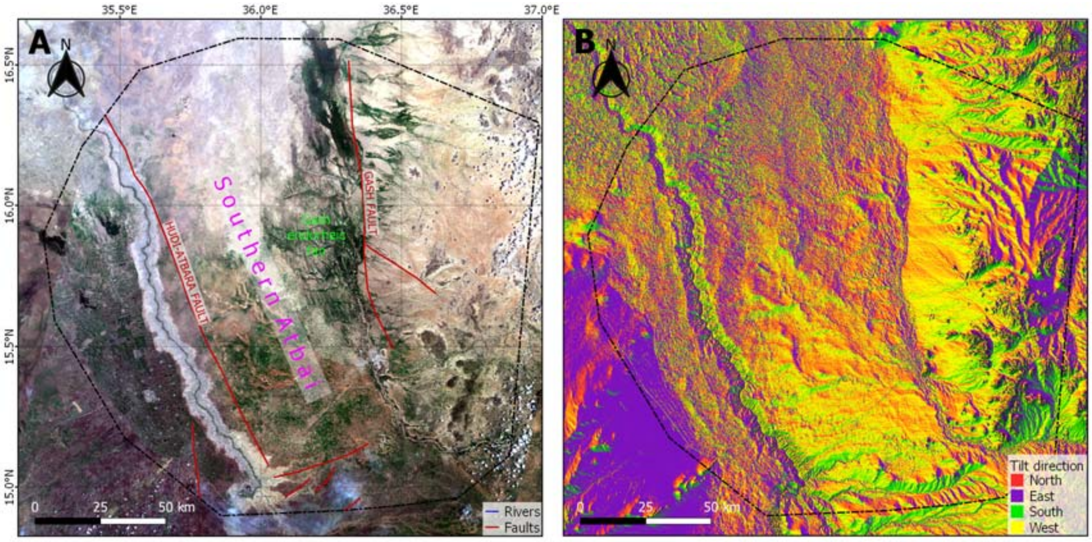

Figure 1. (A) Satellite image (LANDSAT8-OLI-TIRS, RGB bands 4, 3, 2) of the study area. (B) The Aspect model shows the invertion from a NW- to a SE-facing tilt of the plain (reddish yellow to greenish purple), likely caused by tectonic uplift along the Hudi-Atbara fault and responsible for the Late Quaternary diversion of the Gash river towards its current endorheic terminal fan.

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 (https://earthexplorer.usgs.gov/) were reprojected to UTM Zone 37N reference system. Late summer images with a <5% cloud coverage were chosen because the blooming vegetation highlights several landforms such as active and fossil channels, splays and patches of land altered by agricultural exploitation. The bands were combined in false colours to focus on the vegetation and the distribution of 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 TDM90 DEM with 3 arcsec horizontal resolution (~90 m at the equator) released by the German Aerospace Center (https://download.geoservice.dlr.de/TDM90/) was reprojected to UTM Zone 37N and used for extracting contour lines and a hillshade representation. An elevation-dependent colour scale was applied to the DEM and superimposed over the hillshade (Main Map), in order to easily observe landforms at all scales. An Aspect model (Figure 1) was created to aid the visualization of subtle variations of the compass exposure of flat areas tilted by Late Quaternary sub-regional tectonics. This is effective in interpreting the trajectory of elusive and poorly preserved palaeochannels as in the case of the migration of the Gash River. The 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 (GRAS, 2004) was used to interpret lithologies. A contoured buffer around the study area guarantees a visual clue of the surrounding geography, with regards to the continuation of the Eritrean mountains.

Field control was carried out through observation of sample units whenever possible. Vast part of the area of interest is in fact unapproachable due to the rough alternation of *serir* and *hamada* grounds, tight shrubland and crops divided by steep mud wedges, lacking any raised landmark anywhere west of the Gash River. The approach of geomorphological mapping through remote sensing observations and field control is reliable in arid lands and adheres to a well-established procedure (Azzoni et al., 2017; Perego et al., 2011; Zerboni et al., 2015; Zerboni et al., 2020).

5. General geomorphological setting

The region represented in the Main Map covers 28,500 km^2 and consists of two main physiographic units: the edge of the Eritrean Highlands to the east of the Gash River, made of an alternation of gneiss outcrops and granitic inselbergs scattered within a gravelly rugged glacis, and the alluvial plain of the Southern Atbai to the west. The latter includes the Atbara River, the active endorheic terminal fan of the Gash River and an intricate system of diachronic fossil channels that unfolds throughout the whole area comprised between the two active rivers. The Gash River separates the two main physiographic units of the Main Map, flowing into an SSE-NNW aligned shallow tectonic depression that was generated by a Late Quaternary relative displacement of two parallel faults, the Atbara-Hudi Fault and the Gash Fault (Main Map) (Abbate et al., 2010). Although very different in their appearance, the two physiographic units are considered and represented together in the Main Map because they are both significant in interpreting the subsistence

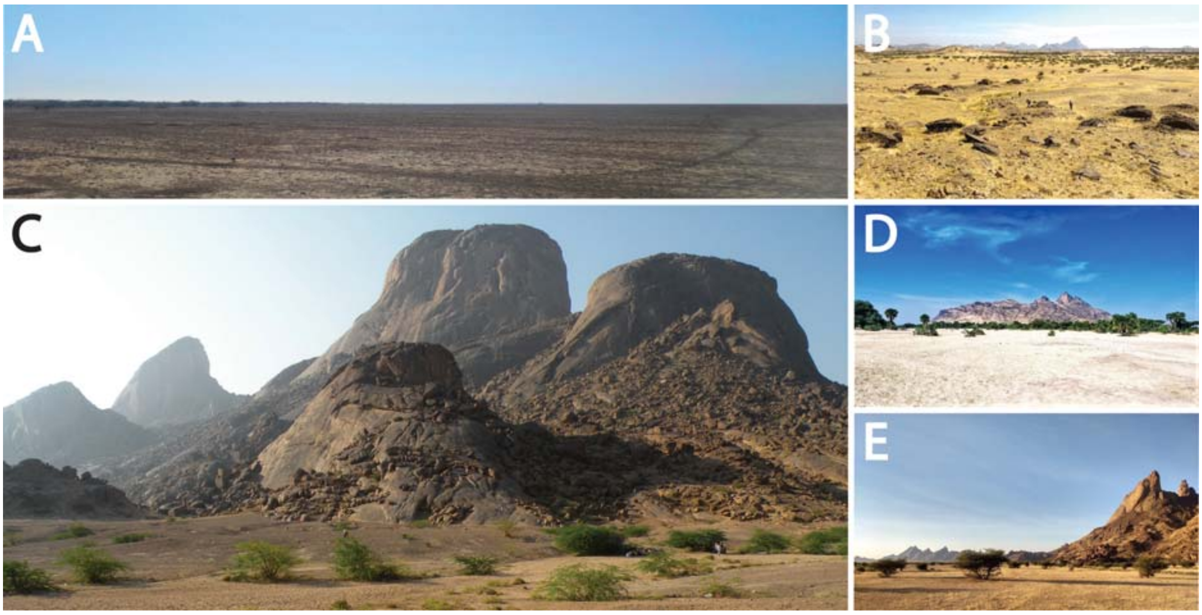

Figure 2. Some panoramic views of the study region. (A) The Southern Atbai Plain as it appears near Khor Marmadeb. (B) Inselbergs emerging from the shrubland and hamada-covered glacis, facing south from Jebel Maman. (C) The imposing granite domes of the Jebel Taka south of the archaeological site of Mahal Teglinos. (D) The meta-sedimentary outcrop of Jebel Maman seen from a dry wadi-bed. (E) The sharp granite domes of Jebel Haura.

strategies of semi-nomadic archaeological and present days human communities.

The mountainous region is an S-N aligned alternation of gneiss outcrops, meta-sedimentary gold-bearing formations and granodioritic inselbergs (Figure 2). The latter often are composites of multiple single domes and are also found sparsely scattered far from the mountain range well within the floodplain, as it is the case of the Jebel Taka, Jebel Abu Gamal, and the small domes near Goz Al Rejeb and along the Atbara's main palaeochannel (see Main Map). All geological formations are fragmented by fault systems 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 hillslopes' morphology also triggered severe erosion and soil loss within the foothill unconsolidated deposits as a result of runoff. The eastern bank of the Gash River, which represents the edge of the Southern Atbai Plain, is connected to the hills by a gentle slope. The latter is a glacis composed of coalescent deposit of colluvial sediments eroded from the hills by seasonal streams and redeposited downstream.

The Southern Atbai Plain is a vast flat area (Figure 2) completely covered by undifferentiated coarse to fine fluvial sediments, up to a few tens of metres thick (Abbate et al., 2010). Although generally unconsolidated, most of the near-surface deposits have undergone pedogenesis under former wet climatic conditions, which resulted in reddening of the soil profile and strong compaction. The plain is cut by a few khors only active for two months per year.

The easternmost section of the Main Map includes a small portion of the Barka River's catchment, which locally is very similar to the Gash River.

6. Main geomorphological features

6.1. Structural landforms

The current shape and alignment of the rock outcrops east of the Gash River, and their fragmentation caused by parallel strike-slip faults, 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). Likely, the uplift of granodioritic plutons occurred later because they appear to have dragged upwards parts of the gneiss outcrops. Solution weathering that occurred under warm and wet climatic conditions, acted preferentially along faults and fault-related fractures, sheeting joints and thermally-induced fissures (Figure 3) (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) (Figure 3). Exhumed inselbergs are surrounded by a chaos of detached blocks. They are either found at the bottom of the slope or scattered throughout the slopes, depending on the smoothness and gradient of the etchplain (Figure 3). Single granitoid blocks show varying degrees of alteration. Those

Figure 3. (A,B,F) Granite weathering – fissuring, patina coating, exfoliation – along small inselbergs at Goz al Rejeb. (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 al Rejeb.

at higher altitudes often preserve their original polyhedral shape and are coated with a dull orange to dark brown patina. 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. Nubbins and tors are also very common (Figure 3), occurring mostly atop whaleback outcrops.

6.2. Fluvial landforms

In the study region, we identified an active fluvial network and a fossil one (Main Map). The active one 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 network east of the Gash. The inactive fluvial system comprises many palaeochannels.

6.2.1. Active fluvial systems

The Atbara River 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 floodplain deposits and surrounded by a tributary system of ephemeral streams extending for up to 4 km on each side

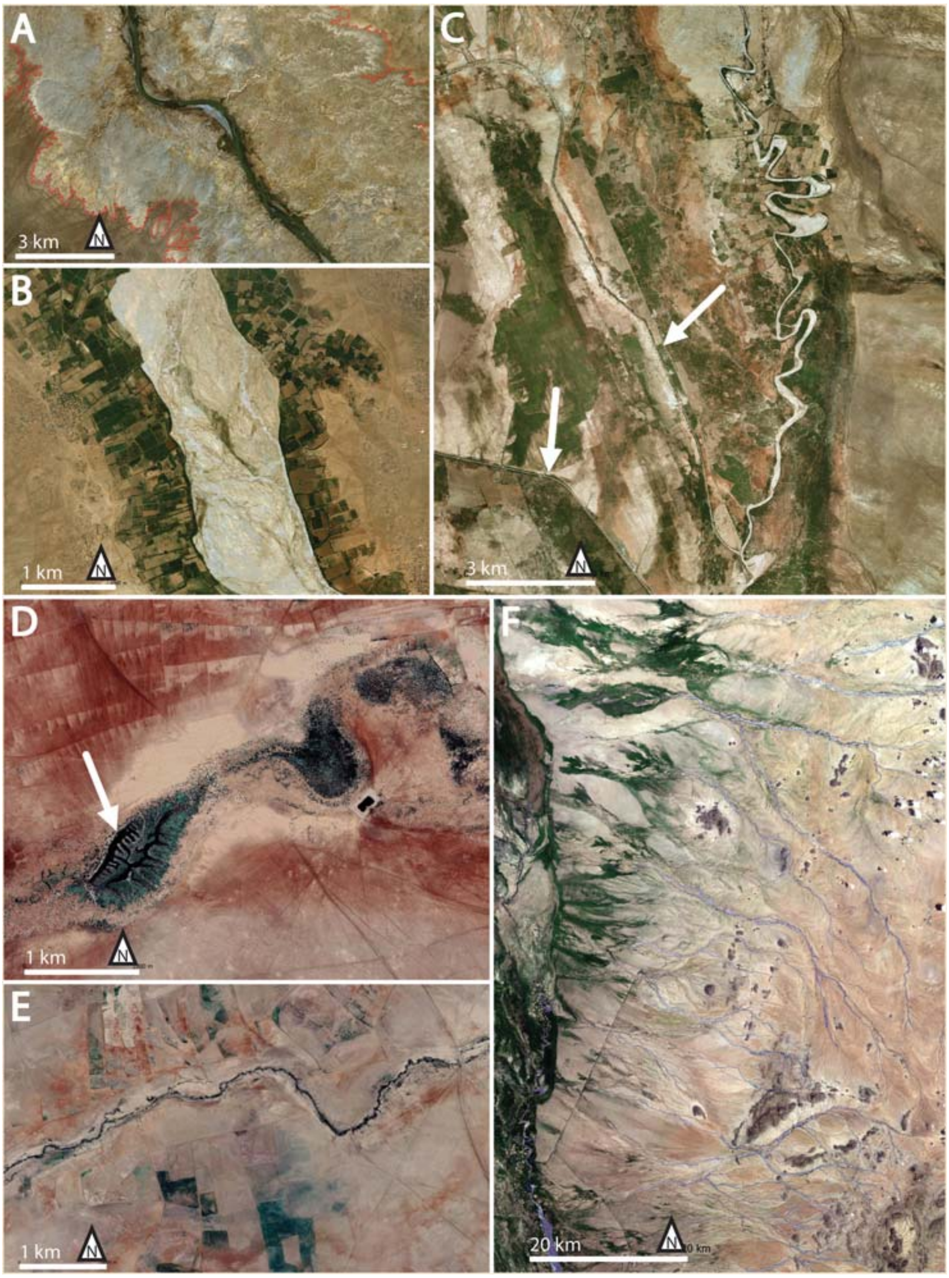

Figure 4. Satellite views. (A) The Atbara River and its surrounding badlands. (B,C) The Gash River at its widest braided stretch 12 km SE of Kassala and at its meandering stretch 45 km north of Kassala. The arrows in (C) indicate spate irrigation canals. (D) The arrows indicate oxbow-like pools in a well-preserved Gash's palaeochannel. (E) The thin Khor Marmadeb in the plain between the Atbara and Gash Rivers. (F) The dense tributary network to the east of the Gash's endorheic fan.

(mean width past the dam is 70 m, decreasing to 30 m in the northern stretches) (Figure 4).

The Gash River is a seasonal major highland wadi that becomes braided to weakly meandering in its lowlands portion (Figure 4). Its activity thus depends on the upstream water supply. Its lowlands riverbed, up to 1200 m wide with an average of 600 m, is shallow and prone to flooding (Alredaisy, 2011). It ends in a 100 km long, 30 km wide endorheic alluvial fan 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 (Barbour, 1961; Ghebreamlak et al., 2018). Over time this has led to the unregimented deposition of fine alluvium and the formation of splays across its whole extension.

The khor system that extends between the two rivers sets within topographic lows and softer ground left by the abandoned Gash's palaeochannels. The water flows E-W into the Atbara, or moves discontinuously until dissipation, or sets statically along larger abandoned meanders, forming oxbow lake-like stagnant depressions (Figure 4).

The network originating from the Eritrean hills, contrarily, is very dense and tripartite(Figure 4): (i) precipitation is gathered by the bare rock outcrops following radial patterns and converges downslope into large dendritic systems; (ii) these merge into E-W

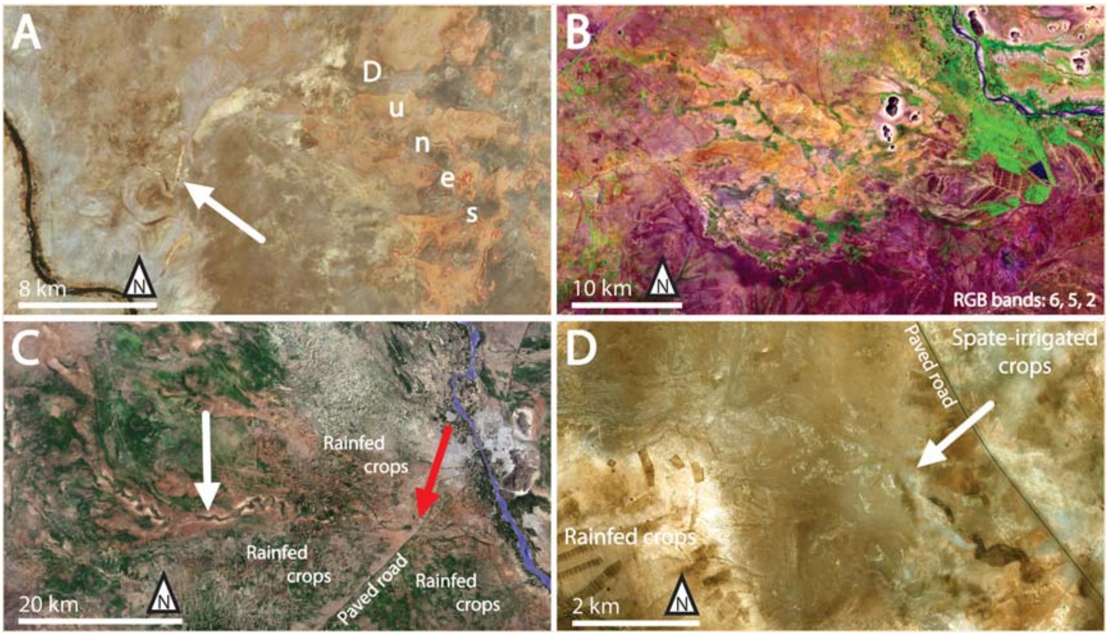

Figure 5. Satellite views. (A) The Atbara River past Goz al Rejeb. The arrow and the thin purple dashed line indicate its main Early/Middle Pleistocene palaeochannel. (B) Landsat8 false colour composition of the Gash's relict anastomosing system (yellow hued). (C) The large Gash's palaeochannel (white arrow) originating from the second relict apex. Agriculture and infrastructures badly affected the preservation of the first half of the feature (red arrow). (D) The small meandering palaeochannels (white arrow and thin dashed green lines) originating from the third relict apex, 40 km NW of Kassala.

Figure 6. (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. Grey 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 (see Main Map).

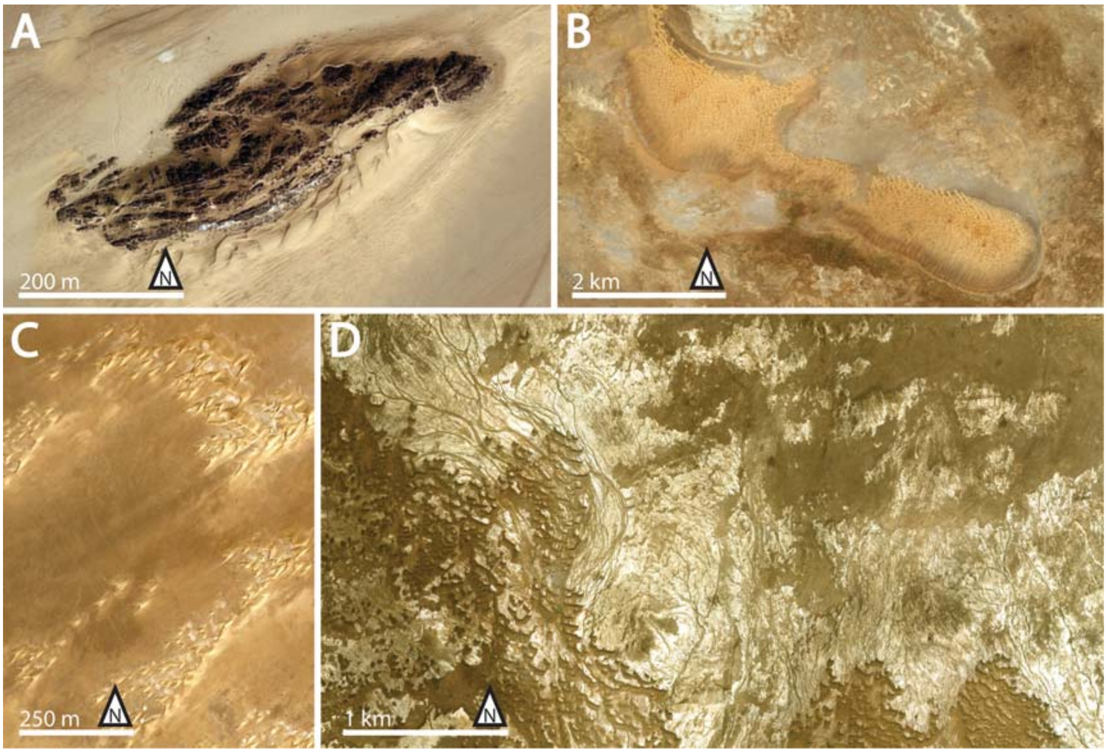

Figure 7. (A) Small inselberg covered in aeolian sand, along the main palaeochannel of the Atbara. (B) Coalescing sand sheets and dunes covering the Atbara palaeolake's shallow water deposits. (C) Field of barchans in the northern plain between the Atbara's main palaeochannel and the outskirts of the Gash's fan. (D) Fine splay sediments re-mobilized into low energy coalescing barchans.

flowing medium-sized single channels (mean width is 150 m) with gravel-dominated bedloads; (iii) the channels flow towards the lower plains splitting into splays and sheet flows on increasingly flatter ground reaching the Gash River (Figure 4). This system is responsible for consistently mobilizing new weathering products and Quaternary deposits east of the Gash River, feeding its 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.

6.2.2. Fossil fluvial systems

An old system of palaeochannels is visible to the north and north-west of the Gash alluvial plain. It includes a large SW-NE flowing Atbara palaeochannel diverging from the modern riverbed north of Goz Al Rejeb (Figure 5) and numerous S-N flowing minor streams. They constitute a Early/Middle Pleistocene fluvial landscape, characterized by a highly dynamic braided and deltaic system that used to feed the Atbara Palaeolake (Abbate et al., 2010).

A more recent system of palaeochannels, related to the Late Pleistocene to Holocene evolution of the Gash River (Manzo, 2017 and authors cited therein) is located between the Atbara and the Gash Rivers, forming a succession of coalescent fans with an SW-NE progression (Main Map). The first relict apex is located at the abrupt northward turn of the modern river; from this point a ~550 km^2 slow water system of individually small channels seemingly anastomosing originates (Figure 5). This system diverges into four small 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 modern Gash in size and morphology, originate from it (Figure 5). They appear to have been endorheic as a result of a slight uplift caused by the Hudi-Atbara Fault, which produced a SE-facing tilt of the entire northern half of the Southern Atbai Plain (Figure 1 (B)), but diagnostic traces may have been erased by agricultural practices. The third relict apex is located in correspondence with Kassala, but evidence is obscured by the urban expansion. The only recognizable palaeochannel originating from it (~15–60 m wide, high-sinuosity) is partially erased by infrastructures or covered with modern alluvium laid by the spate irrigation system (Figure 5).

6.3. Residual surfaces

The flat, gentle glacis east of the Gash River represents an archive of subsequent phases of accretion, weathering and erosion of deposits. The pediplain shows, in fact, a rather consistent stratigraphy over its whole extension. There, the Precambrian

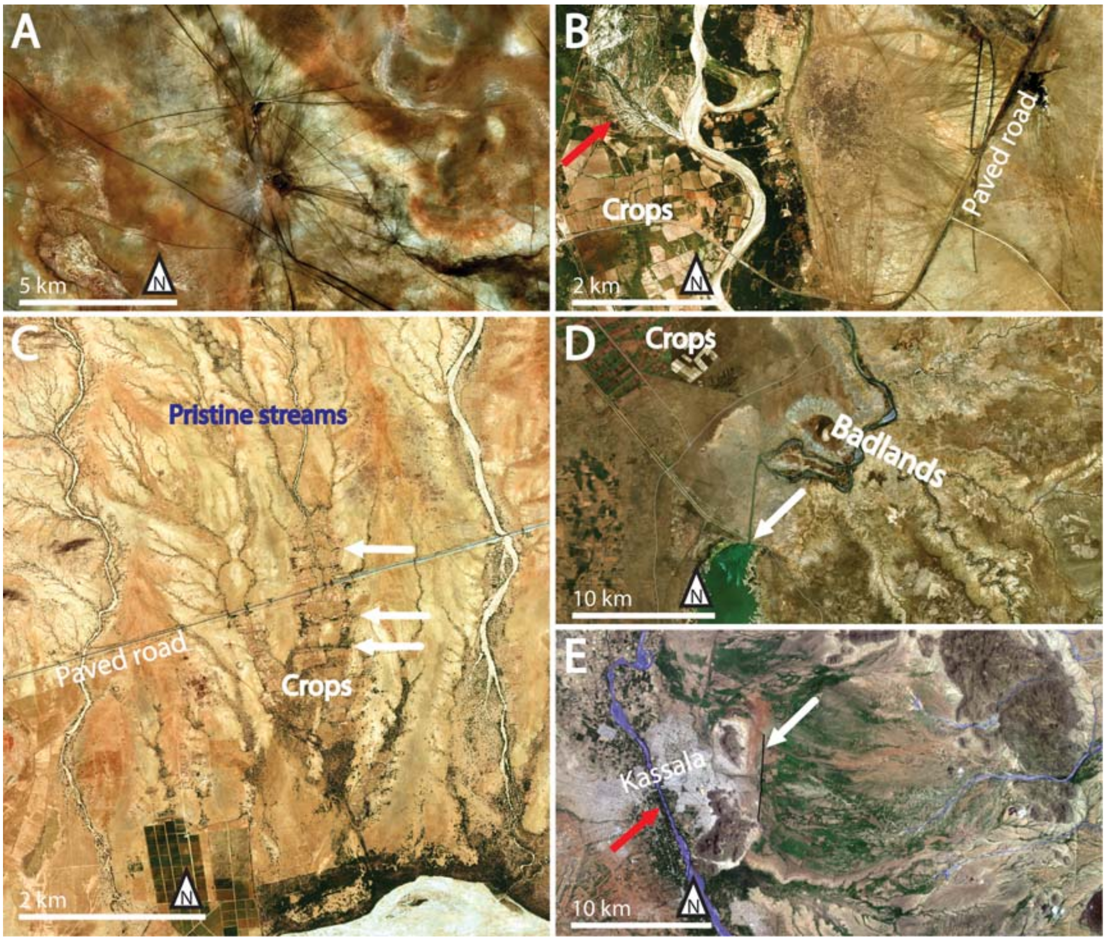

Figure 8. (A) Radial animal and vehicle trackways leading to hafirs (artificial ponds) and across the open plain. (B) Trackways leaving a paved road to reach a village on the eastern bank of the Gash River. Crops and a big crevasse are visible to the left of the river (red arrow). (C) Small streams are 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.

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) are found ubiquitously. Their formation was promoted by water availability greater than today. The current topographic surface is sealed by a residual layer of coarse gravel and small stones forming a proper desert pavement, a terminal surface landform that is commonly found throughout arid lands (Knight & Zerboni, 2018) (Figure 6). Angular stones of the *hamada* are more common approaching the hills, whereas, some patches of *serir* (rounded pebbles) are found atop of small raised terraces of the Atbara River some 130 km downstream of Khashm el Girba. The Mahal Teglinos (K1) archaeological site is a privileged location to observe aggradation, pedogenesis and erosion because recent rill erosion also exposed an Early–Middle Holocene organic paleosol (Costanzo et al., 2020; Cremaschi, 1992) and patches of calcrete and alterite underlying the whole 6 metres strong succession. Therein, depositional/erosional cycles created a wide patch of desert pavement rich in archaeological materials overlying 2 m of loose archaeological/aeolian/colluvial deposit (Figure 6).

6.4. Aeolian landforms

Windblown sand sheets and single and fields of coalescent barchans can be observed at the very northern and northwestern edges of the Southern Atbai plain (Figure 7). They cover the Early/Middle Pleistocene fluvial/lacustrine system and the Atbara Palaeolake and are sometimes stabilized by patches of shrubs and xerophytes.

Aeolian deposits are also found as localized sand sheets leaning against hillslopes, where the inselbergs provide sheltered spurs or secluded valleys, like in the case of Mahal Teglinos, where the aeolian sheet deposit reached a thickness of almost 2 m, or the case of the small reliefs along the course of the Atbara's palaeochannel (NW of the Main Map) (Figure 7).

6.5. Zoogeomorphological and anthropogenic landforms

Thousands of animal trails can be observed throughout the Southern Atbai, except for its arid northwestern fringe. Dramatic concentrations of animal trails are distributed along watercourses and in the vicinity of villages and *hafirs* (Figure 8). 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.

Agricultural activities and practices for water harvesting deeply modified the landscape at the regional scale, as in the case of the Khashm el Girba dam (Figure 8). A further example are the spate irrigation systems north of Kassala and west of Teseney (Eritrea) (Figures 1 and 4(F)), and the creation of polygonally partitioned patches of rainfed crops and diversion of minor streams into sheet flows using branches and mud wedges (Figure 8). The yearly maintenance of the crops' subdivision structures - steep earthen wedges and canals – involves the reworking of surface deposits, thus increasing surface erosion and the loss of soil and archaeological stratigraphy.

7. Conclusion

In the Southern Atbai Plain and the western edge of the Eritrean Highlands, geomorphological processes started with tectonic uplift as main driving factor in shaping the area. Yet, the extant landscape started forming in the Quaternary due to deep rock weathering, fluvial/colluvial phenomena and aeolian dynamics triggered by humid/arid climatic shifts acting around minor regional tectonic adjustments. Our investigation allowed mapping relict fluvial systems, showing a major contribution of fluvial processes to shaping the landscape, which therefore formed during Quaternary pluvial periods. The prominent role and constraints of the geomorphological settings of the region on the archaeological communities were 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 Main Map provides a base for planning archaeological surveys in unexplored areas and for the creation of GIS-based archaeological and landscape evolution models.

Software

QGIS 3.4 (QGIS Development Team, 2019) was used for the management of the mapping project in all phases. Satellite images and political maps were obtained with QuickMapServices plugin (NextGIS, 2019) for QGIS.

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Disclosure statement

No potential conflict of interest was reported by the author (s).

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ORCID

Stefano Costanzo http://orcid.org/0000-0002-0269-075X
Andrea Zerboni http://orcid.org/0000-0002-6844-8528
Mauro Cremaschi http://orcid.org/0000-0003-2934-3210

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