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GEOLOGY OF THE *HOMO*-BEARING PLEISTOCENE DANDIERO BASIN (BUIA REGION, ERITREAN DANAKIL DEPRESSION)

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Abstract. This paper deals with the geological context of the northernmost site in the East Africa Rift system which has yielded *Homo erectus*-like remains. They are dated ca. 1 Ma and have been found in the deltaic deposits of the Alat Formation belonging to the Dandiero Group. This newly defined group crops out extensively in an elongated belt from the Gulf of Zula to the north to the Garsat area to the south. In the Buia-Dandiero area it ranges in age from the Early to the Middle Pleistocene, and incorporates six formations, from bottom up: the fluvial Bukra Sand and Gravel, the deltaic and lacustrine Alat Formation, fluvial Wara Sand and Gravel, the lacustrine Goreya Formation, the fluvio-deltaic Aro Sand and alluvial Addai Fanglomerate. This succession is bounded by two major unconformities, which separate it from the Neoproterozoic basement and from the overlaying Boulder Beds fanglomerate, and has been designated the Maebele Synthem. The latter is the result of two lacustrine transgressions and regressions evidenced by two depositional sequences. The unconformities bounding the Maebele Synthem are related to the tectonic history of the basin fill and its substrate. The development of the two sequences was, instead, mainly controlled by lake level fluctuations and, hence, by climatic variations connected with the weakening and strengthening of the monsoons in the northwestern Indian Ocean. The environment where the Buia *Homo* lived was a savannah with some scattered water pools. This environment probably extended farther north along the western coastal plain of the Red Sea, and was as a preferential pathway for the dispersal of the hominids from East Africa toward Eurasia.

Riassunto. Si descrive il contesto geologico del sito di ritrovamento di *Homo erectus*-like più settentrionale nel sistema del Rift estafricano. I resti fossili, datati a ca. un milione di anni, sono stati rinvenuti nei depositi deltizi della Alat Formation appartenente al Dandiero Group, di nuova istituzione. Quest'ultimo affiora estesamente in una fascia allungata dal Golfo di Zula a nord fino all'area di Garsat a sud. Nell'area Dandiero-Buia il Dandiero Group comprende sei unità litostratigrafiche, dal basso verso l'alto: ciottolami e sabbie fluviali (Bukra), limi lacustri e sabbie deltizie (Alat), sabbie e ciottolami fluviali (Wara), limi e argille lacustri (Goreya), sabbie fluvio-deltizie (Aro) e ciottolami di conoide alluvionale (Addai) che hanno un'età compresa fra il Pleistocene Inferiore ed il Pleistocene Medio. Questa successione, limitata alla base e al tetto da due superfici di erosione che la separano inferiormente dal basamento Neoproterozoico e superiormente dai Boulder Beds, costituisce il Maebele Synthem. Quest'ultimo è il risultato di due trasgressioni e regressioni lacustri messe in evidenza da due distinte sequenze deposizionali. Le discordanze alla base e al tetto del sintema sono attribuibili alla storia tettonica del bacino, mentre le due sequenze trasgressivo-regressive sono legate alle fluttuazioni del livello del lago e innescate, pertanto, da variazioni climatiche. Esse sono in massima parte il risultato di incrementi o attenuazioni del regime monsonico instauratesi durante il Pleistocene inferiore e medio nell'Oceano Indiano nord occidentale. L'ambiente in cui viveva l'uomo di Buia era una savana caratterizzata da specchi d'acqua più o meno estesi. Questo ambiente, favorevole alla vita dell'uomo, si estendeva probabilmente verso nord lungo la piana costiera occidentale del Mar Rosso e offriva una via preferenziale alla migrazione degli ominidi dall'Africa orientale verso l'Eurasia.

Introduction

Rift basins store thick sedimentary successions composed of material eroded from the uplifting shoulders. The thick sedimentary successions contain a good record of short-term environmental variations induced by several factors, such as local and global-scale climatic fluctuations, particularly recurrent during the late Cenozoic, tectonic instability, and volcanic activity, commonly connected with rift development. In addition, volcanic activity provides tephra marker beds that can be traced basin-wide and across different basins and

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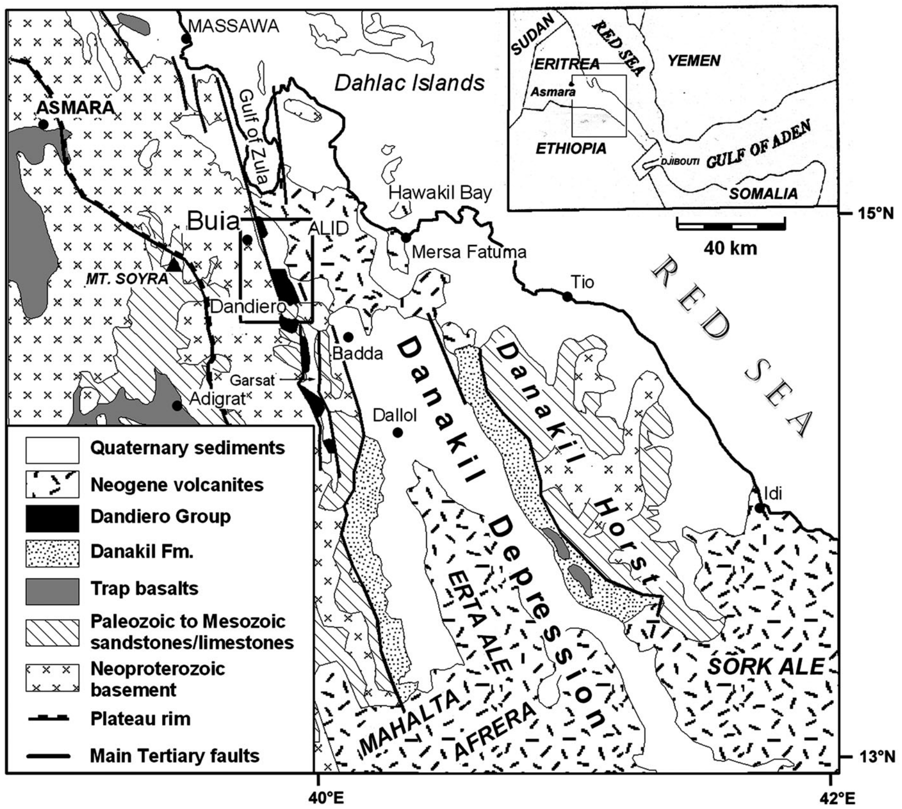


Fig. 1 - Simplified geological map of the Danakil depression. Location of Fig. 2 is given by small box.

are useful for stratigraphic correlations and radiometric dating.

Detailed biostratigraphy can be established from the rift sedimentary successions because faunal and floral remains are rapidly buried and thus preserved. Fossilization is also aided by lavas- and tephra-derived mineralized aqueous solutions that cement or replace organic remains (Hay 1986).

During the late Cenozoic, climate, landscape features and availability of water established favourable conditions for luxuriant life, including human, in the East Africa rift basins. This fossil evidence is now exposed because of the rapid erosion of the area due to continuing tectonic instability and climatic variations. This is particularly apparent in the northern sectors of the East Africa rifts where the basin sequences are continuously dismantled and dissected due to extremely arid periods sporadically interrupted by catastrophic floods. The results are always new, bare outcrops.

The objectives of our research are to investigate rifts in the Danakil depression of Eritrea not previously studied in detail, and establish the main processes of sedimentation and biological evolution (Fig. 1). The possibility that this could be a promising region to search for new Homo fossils was suggested also by depositional and tectonic settings similar to those of the contiguous Middle Awash region (Ethiopia), well known for its rich fossil sites.

The Danakil depression in the East African Rift System

The Danakil depression is located at the northern apex of the Afar region, a quasi-triangular shaped area at the intersection of the Red Sea, Gulf of Aden and East African rifts (Fig. 1). It extends NNW-SSE for about 300 km, and widens out from the gulf of Zula to the north to approximately 13° Lat. North to the south (alignment of the Quaternary Mahalta Range-Afrera and Sork Ale volcanic centres). To the west and northeast, the depression is bounded by two continental crustal blocks: the Eritrean-Ethiopian plateau and the Danakil block, respectively. Although fully continental, the elevation of the central part of the depression is largely below sea level.

The origin and evolution of the Danakil depression are tied to that of the Afar region. Several authors consider a Neogene anticlowise rotation of the Danakil block, including its southern prolongation in the Ali Sabieh high, to have been responsible for the origin of the Afar region (Laughton 1965; Burek 1970; Sichler 1980; Souriot & Brun 1992). The Danakil block (microplate) is kept fixed to the African (Nubian) plate to the north with a hinge close to the Gulf of Zula, but moves progressively away from the African plate along the Eritrean-Ethiopian plateau margin. To the south, it remained connected with the Arabian plate and experienced a right strike-slip motion relative to the Somali plateau.

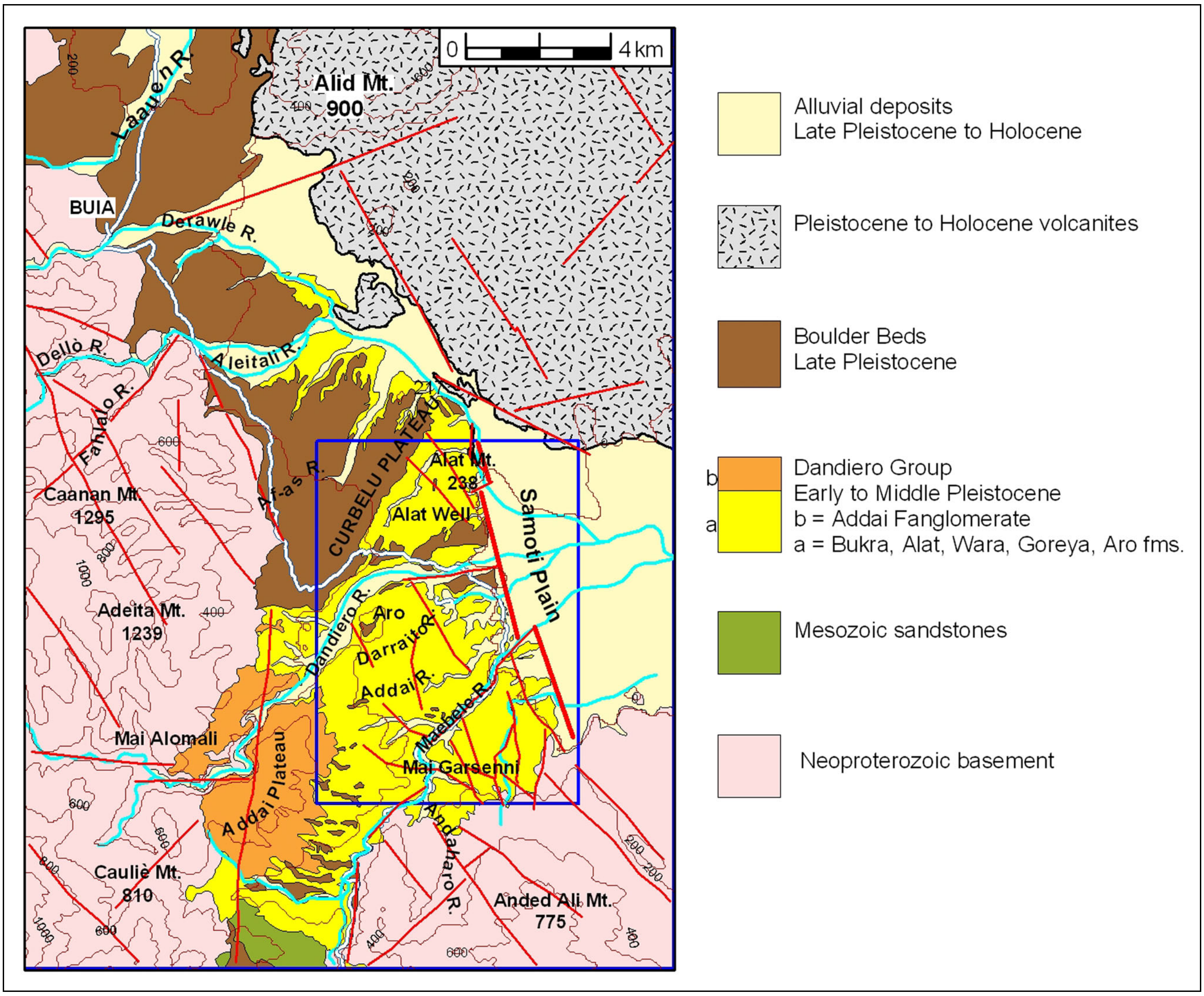


Fig. 2 - Geological map of the Buia region from Buia to Anded Ali Mt. Location of Fig. 3 is given by small box.

Other authors have tried to refine the possible geological evolution of this region. According to Chorowicz et al. (1999) and Collet et al. (2000) the rotation of the Danakil block was preceded during the Oligocene-Miocene by a left-lateral motion of the same block relative to Africa. Eagles et al. (2002) assume independent movement of the Danakil block relative to Africa, Arabia and Somalia, considering kinematic indicators of plate motion and alignments of faults and volcanoes.

Despite the different ideas on the origin of the Danakil depression, most authors agree on its individualisation since the middle Miocene above thinned and diffusely sheared continental crust partly characterized by a Precambrian basement, 1,000 to 1,500 m thick Paleozoic to Mesozoic sedimentary deposits, and few hundred metres of Oligocene trap basalts. This Precambrian to Oligocene succession straddles a wide area from the Eritrean – Ethiopian plateau to Yemen, with the partial exception of the Southern Red Sea.

The depositional basin of the Danakil depression is V-shaped, with the apex in the Gulf of Zula, and open to the south toward the central Afar region. Its sediments onlap on the Eritrea-Ethiopian plateau escarpment and on the Danakil horst and cover unconformably all the previously mentioned units down to the basement. The Danakil Formation (Brinckmann & Kürsten 1970; also called Danakil Series by Bannert et al. 1970, and Red Series by Barberi et al. 1970) marks the depression boundaries on both sides. In its type sections close to Dallol, it is composed of violet-red to bright red conglomerates and sands with mudstones, sometimes gypsiferous, and rare fresh-water gastropod-bearing limestones. Alluvial fans, high-energy streams with some swampy to lacustrine ponds were main features of the Danakil Formation sedimentary environments. Frequent basalt flows are found intercalated. Basalts at the base and toward the top of the formation give radiometric K/Ar ages of 24 Ma and 5 Ma, respectively. Due to intense faulting the thickness of the Da-

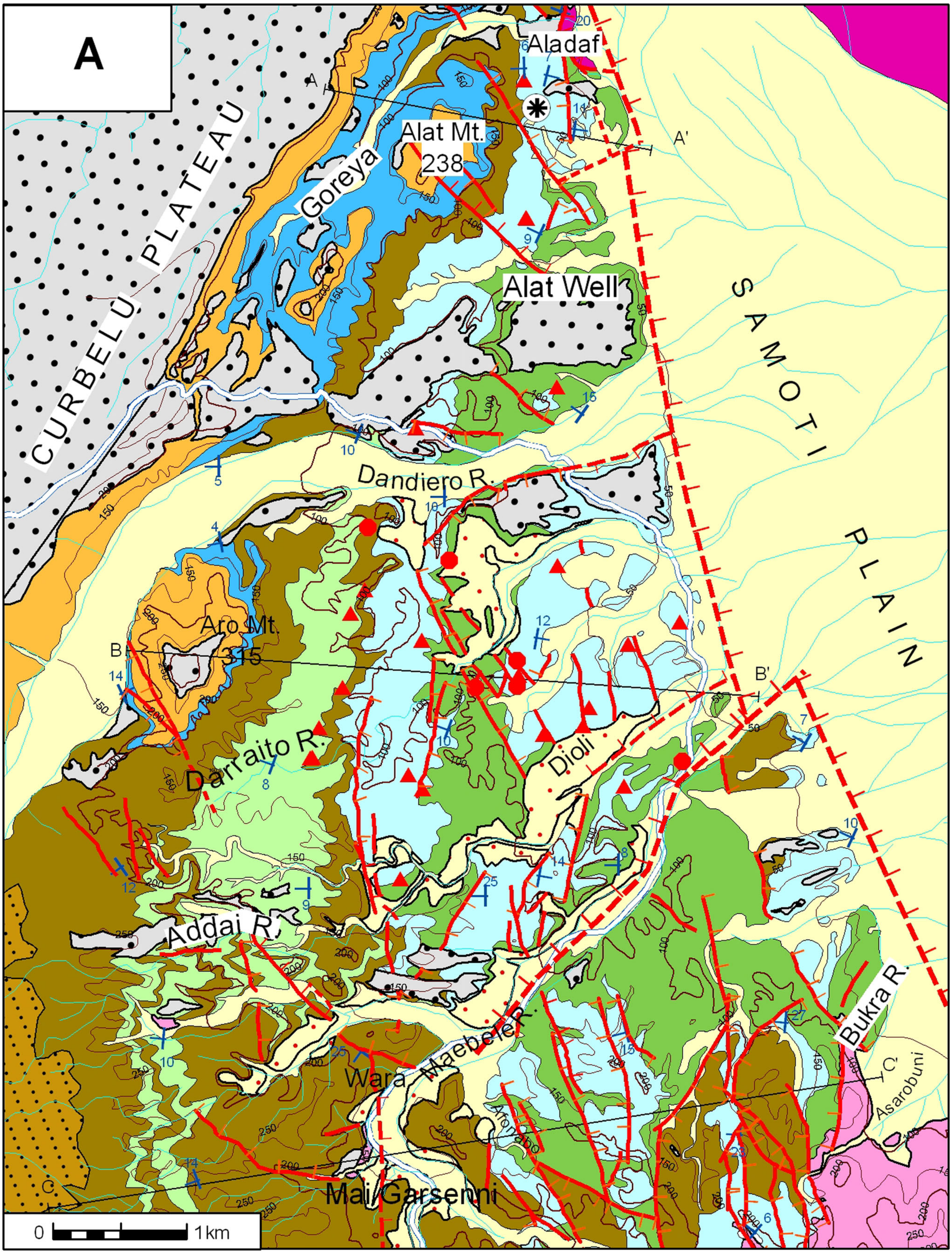
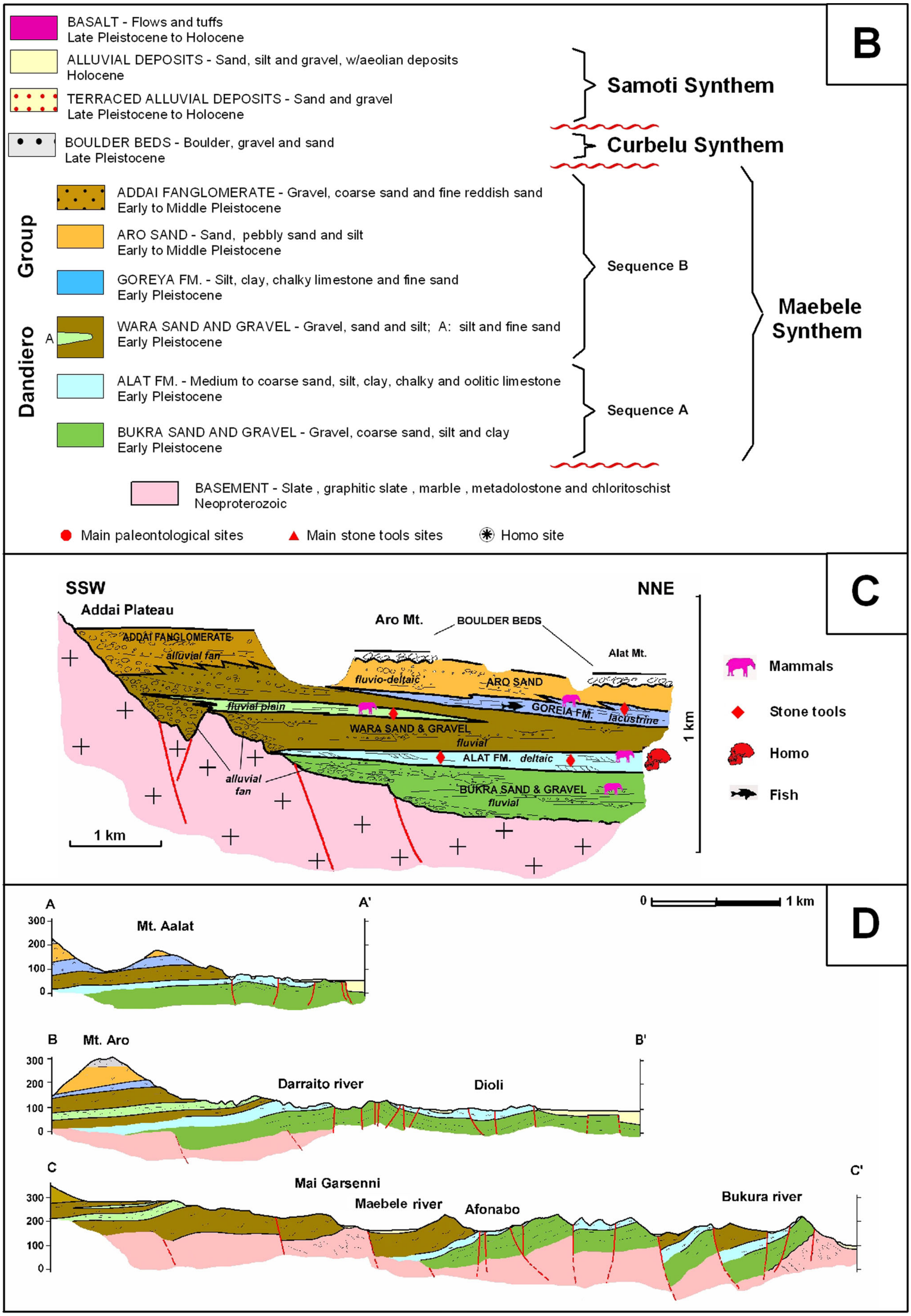


Fig. 3 - A: geological map of the Dandiero-Maebele area; B: legend of geological map; C: diagram showing stratigraphy, environmental interpretation of the Dandiero Basin fill and stratigraphical position of the main paleontological-archeological sites; D: geological cross sections Contours in meters.


B
BASALT - Flows and tuffs
Late Pleistocene to Holocene
ALLUVIAL DEPOSITS - Sand, silt and gravel, w/aeolian deposits
Holocene
TERRACED ALLUVIAL DEPOSITS - Sand and gravel
Late Pleistocene to Holocene
BOULDER BEDS - Boulder, gravel and sand
Late Pleistocene
Samoti Synthem
Curbelu Synthem
Dandiero Group
ADDAI FANGLOMERATE - Gravel, coarse sand and fine reddish sand
Early to Middle Pleistocene
ARO SAND - Sand, pebbly sand and silt
Early to Middle Pleistocene
GOREYA FM. - Silt, clay, chalky limestone and fine sand
Early Pleistocene
A
WARA SAND AND GRAVEL - Gravel, sand and silt; A: silt and fine sand
Early Pleistocene
ALAT FM. - Medium to coarse sand, silt, clay, chalky and oolitic limestone
Early Pleistocene
BUKRA SAND AND GRAVEL - Gravel, coarse sand, silt and clay
Early Pleistocene
Sequence B
Sequence A
Maebele Synthem
BASEMENT - Slate , graphitic slate , marble , metadolostone and chloritoschist
Neoproterozoic
Main paleontological sites
Main stone tools sites
Homo site
C
SSW
NNE
Addai Plateau
Aro Mt.
BOULDER BEDS
Alat Mt.
ADDAI FANGLOMERATE
alluvial fan
fluvio-deltaic
ARO SAND
fluvial plain
GOREIA FM.
lacustrine
WARA SAND & GRAVEL
fluvial
ALAT FM. deltaic
alluvial fan
BUKRA SAND & GRAVEL
fluvial
1 km
1 km
Mammals
Stone tools
Homo
Fish
D
A
A'
0
1 km
300
200
100
0
Mt. Aalat
B
Mt. Aro
B'
Darraito river
Dioli
C
C'
Mai Garsenni
Maebele river
Afonabo
Bukura river

nakil Formation cannot be ascertained with confidence. A maximum value of 1,000 m is commonly assumed.

The whitish Enkafala Formation (Beyth 1971, cited in Garland 1980), also called Zariga Formation, unconformably overlies the Danakil Formation and marks a marine ingression in the northern Danakil depression. It mainly consists of laminated gypsum and marls with some oolitic and reefal limestone and is only a few tens of metres thick. Its marine fossils have been dated by U-Th method between 200,000 and 24,000 years (Lalou et al. 1970; Brinckmann & Kürsten 1970; Bonatti et al. 1971). These dates provide evidence for a seaway connection between the northern Danakil depression and the Red Sea, possibly during interglacial highstands of sea level.

The Enkafala Formation changes transitionally into the marine Salt Formation toward the centre of the basin. This latter formation, composed of bedded halite, gypsum, potash salts and clays (Holwerda & Hutchinson 1968), occupies a wide band along the axis of the depression. It is easily distinguishable because the salts reprecipitate at the surface and generate an impressive, wide bright-white salt plain.

The Salt Formation has been drilled for potash through 975 m without reaching its base. Geophysical data reveal that the thickness of the evaporite is at least ca. 2.2 Km (Behle et al. 1975). The depocentre of this fast subsiding evaporite basin was asymmetrically located relative to the axis of the Danakil depression, since it is very close to the foot of the Ethiopian escarpment.

The upper levels of the Salt Formation gave a K/Ar age of ca. 80,000 years (Garland 1980), but the age of the lower levels is unknown. Considering its remarkable thickness, it is likely that its lower part is at least Pliocene in age. This means that there was a connection to the Southern Red Sea since ca. 5 Ma. This connection was blocked at the end of the Pleistocene by newly formed volcanic structures that are commonly related to the Alid volcanic province between Arafaile and Buia. South of the area of study, the Pleistocene axial volcanism is recorded in the Erta Ale range, where there are still active volcanoes (Barberi et al. 1972).

Unconformable on all the other formations and mainly outcropping in the lowest part of the depression, there are lacustrine sediments sometimes associated with small present-day saline lakes, such as Lake Afrera.

The northern Danakil depression and the Dandiero Basin

In the northern Danakil depression we focused our studies on the Dandiero basin (Figs. 2, 3). This basin is located 110 Km south of Massawa and 35 km south of the southern termination of the gulf of Zula (Fig. 1). It contains one of the northernmost, best-exposed Pleistocene sedimentary successions of the Danakil depression. It is NS elongated, covers an area of ca.100 sq Km, and it has altitudes ranging from 350 to 0 m. We designate this as the type area for a new Dandiero Group. In our opinion, rocks outcropping well to the south, beyond the Dandiero region belong to this group as well (Garsat, Fig. 1).

In the type region between the Dandiero and the Maebele rivers, Neoproterozoic basement rocks form the shoulders of the Dandiero basin to the west (Adeita Mt.) and to the south (Anded Ali Mt.), whereas to the east the basin is bounded by the recent sand fields of the Samoti plain, and to the north by the slopes of the Alid volcanic range and the alluvial plain and terraces of the Derawle River near Buia (Fig. 2).

This study covers more than two thirds of the basin between Buia and Maebele (Fig. 2), and research is still ongoing farther to the north and south. The Dandiero is the main river of this area. It drains the highest regions of the Eritrean plateau close to the Amba Soira (2,988 m). Together with the Maebele stream that runs through the southern portion of the basin, it disappears eastward beneath the Samoti plain sands. The landscape of the basin is arid, with some scattered oases with water wells (such as the Alat wells).

The still well preserved Addai alluvial fan controlled the sedimentary development of the Dandiero basin. Its stream channels radiate across the Addai plateau and can be followed for 4-5 Km. The fanhead is presently located where the Dandiero River leaves the basement rocks of the escarpment and enters into the lowland. This has been the entry point for most of the sediments that are presently found in the Dandiero basin and that were collected and transported by the paleo-Dandiero River during its crossing the escarpment.

Abundant sediment was available to the fan because of its location in a re-entrance of the escarpment and the presence of faults along the river course (Garland 1980). The present Dandiero River is deeply entrenched at the fanhead and its course has shifted to the northern margin of the Addai fan (Fig. 2).

The Dandiero basin occupies a nodal position between the gulf of Zula/Samoti plain/Badda corridor and the Garsat graben (Figs. 1, 2). The latter is a ~10 Km wide, NS trending graben that can be traced for 70 Km east of Adigrat (northern Ethiopia) along the western side of the Danakil depression from which is separated by a continuous ridge of basement rocks. These marginal graben are quite common along the border of the Eritrean-Ethiopian plateau (Borkenna, Asebo graben; Mohr 1967, Chorowicz et al. 1999).

The Zula/Samoti /Badda corridor (Figs. 1, 2) must be taken into account in the paleogeographic and paleoenvironmental reconstruction of the Dandiero basin, since it is commonly regarded as the seaway connection

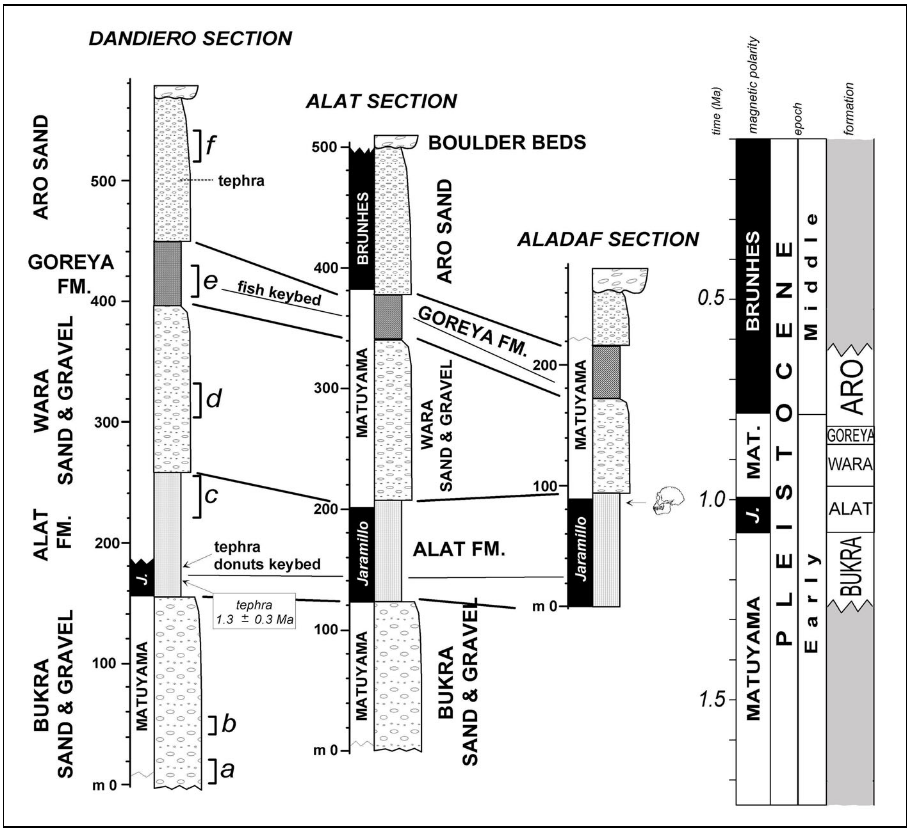


Fig. 4 - Correlation chart of measured stratigraphic sections and magnetostratigraphy. Letters (*a* to *f*) on the right of the Dandiero section indicate the stratigraphical position of the sedimentological logs in Fig. 6.

between the Red Sea and the Danakil depression during the Pleistocene and, probably, the Pliocene. However, the Pleistocene Dandiero basin, which occupies part of this corridor, contains no marine deposits and abuts against the Alid volcanic range leaving little space, if any, to accommodate a sea passageway. Further information comes from the Alid volcanic center itself (Dainelli & Marinelli 1912; Marinelli et al. 1980), a dome structure which exhibits at its core Precambrian basement rocks and an arched sedimentary sequence (Duffield et al. 1997). Within this sequence we could not find the marine molluscs of Pleistocene age that Duffield et al. (1997) reported. Conversely, the siltstones and fine sandstones occurring in the succession are similar to the Dandiero terrestrial deposits and, accordingly, contain fresh-water gastropods. It is also possible that the pillow basalts, cited by Duffield et al. (1997) and regarded as submarine, could rather be sublacustrine.

In conclusion, the evidence that the Zula/Samoti / Badda corridor acted as a seaway is controversial, and needs further confirmation. The lowland south of Mersa Fatma from the Hawakil Bay to Dallol could be considered an alternative corridor between the Red Sea and the Danakil depression, the central part of which largely lay below sea level (Dallol -100 m, Lake Asale -120 m). Along this belt the sea is prevented from entering the Danakil depression by a 50 m high sill only. The hypothesis that the Red Sea could invade Dankalia during the Pleistocene through this pathway was put forward long time ago (Munziger 1869), but has generally been disregarded, even if, since the thirties of the last century, there have been industrial projects to channel water from the Red Sea to the Danakil depression through this corridor.

Stratigraphy of the Pleistocene-Holocene successions and their substratum

The stratigraphy of the Dandiero basin has been studied in detail to be able to correctly establish the location, age and environments of the fossil remains, including *Homo* and associated lithic industries. For this purpose, various field campaigns, extensive sampling and analyses, Landsat images and aerial photos interpretation and GPS data processing all grouped through GIS techniques were carried out. The wealth of information obtained has also been used for the compilation of the map in Fig. 3. This map covers part of the Dandiero basin between Alat Mt. to the north and Mai Garsenni to the south (Fig. 3), and introduces substantially new stratigraphic elements. One is related to the previously defined Danakil Formation. Following Garland's (1980) map we had previously referred the sediments of the Dandiero basin to this formation (Sagri et al. 1998, Abbate et al. 1998). However, although they are all clastic continental successions in a similar struc-

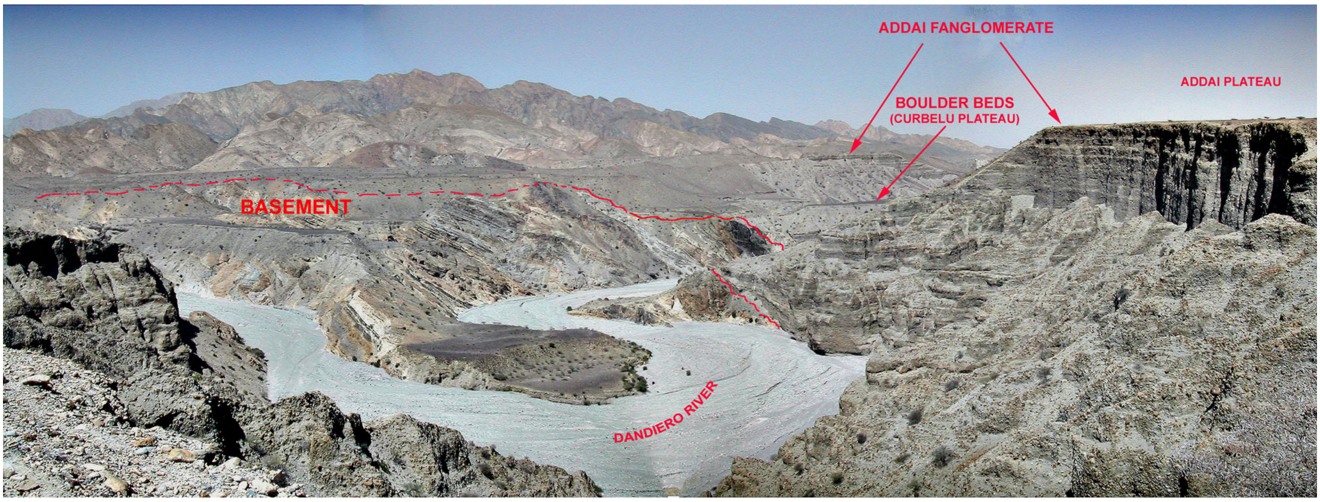


Fig. 5 - Onlap of the Addai Fanglomerate of the Dandiero Group on the Neoproterozoic basement exposed on the slopes of an entrenched meander of the Dandiero river. Terraced alluvial deposits and Boulder Beds are present too. The Addai plateau is 250 m high above the Dandiero River.

tural context, the lack of an areal continuity, the reddish color that is typical of the Danakil Formation but missing in the Dandiero basin sediments, the different time spans covered by the two successions convinced us to keeping them distinct and to designate a new Dandiero Group.

On the basis of preliminary reconnaissance, we assume that the Dandiero Group basin at the foot of the Eritrean-Ethiopian plateau occupied an area wider than that of the Dandiero region. It is likely that it extended from the gulf of Zula to the north to the Garsat graben to the south (Fig. 1).

In the type area, the Dandiero Group is ca.1,000 m thick, and incorporates fluvial, transitional (deltaic), lacustrine and alluvial fan sediments, which cover a time span from Early to Middle Pleistocene. The Dandiero Group comprises six new formations: from bottom up, Bukra Sand and Gravel, Alat Formation, Wara Sand and Gravel, Goreya Formation, Aro Sand, and Addai Fanglomerate (Fig. 3, 4). The Dandiero Group unconformably overlies a Neoproterozoic basement (Fig. 5) and is in turn unconformably overlain by the Boulder Beds, a gravel unit extensively present here as in many other rift basins of East Africa.

The major unconformities recorded in the Dandiero sedimentary succession allow its partition in terms of unconformity-bounded stratigraphic units (UBSU, *sensu* Salvador, 1994). Three synthems are proposed: Maebele Synthem, Curbelu Synthem and Samoti Synthem (Fig. 3B). Within the Maebele Synthem, which includes the six new formations of the Dandiero Group, we describe an A sequence and a B sequence. The Boulder Beds constitute the Curbelu Synthem, whereas the Samoti Synthem comprises the alluvial deposits also including the aeolian sands.

The Precambrian substratum of the Dandiero basin

Neoproterozoic units constitute the western and southern shoulders of the Pleistocene basin as well as its substratum (Fig. 5). They offer very good exposures of this sector of the East African Orogen between East and West Gondwana (Stern 1994). They form a prominent physiographic unit and were exploited as source areas of raw material for human artifacts. They also constitute the provenance areas for Pleistocene sediments.

The local Neoproterozoic units have been cursorily investigated, and work is still in progress. Although they are kept undifferentiated in the map of Fig. 2 and Fig. 3, preliminary field studies have revealed that in the northern portion near Buia they include kyanite bearing units, mainly quartz-vein related, and amphibolite schists with traces of garnets. Immediately south, along the same structure (Caulie Mt.), they are replaced by greenschist facies metasediments including slates, graphitic slates and phyllites, laminated limestones and dolostones, black and grayish/creamy marbles. It is likely that this basement shoulder exposes a high-grade and a low-grade metamorphic complex, as suggested in a sketch map by Beyth et al. (2003) (Ghedem Domain vs. Tsaliet/Tambien groups).

Moreover, it has been ascertained that the outcrops along the Dandiero assigned to Palaeozoic and Mesozoic sedimentary units in the Garland (1980) map are actually Neoproterozoic metasediments.

The basement of the southern shoulder of the basin (Anded Ali Mt.) is mainly composed of chlorite schists with dispersed polymictic metaconglomerates.

Two erosional windows of basement rocks with chlorite schists and graphitic and sericite schists have been found within the Pleistocene basin at Mai Garsenni and at Baruli in the upper Wara valley. It is interesting to note that "baruli" in the local Saho language means "scar", perhaps because of the rugged topography of the basement rocks. Both these basement highs witness the irregular topography of the basin floor.

A small patch of Mesozoic sandstone bounds the basin in its southwestern margin. It rests unconformably on the Neoproterozoic.

The Dandiero Group

Stratigraphic characteristics, lithofacies, boundaries, depositional environment, fossils and age of the six formations which comprise the Dandiero Group (corresponding to the Maebele Synthem) will be discussed in this chapter starting from the lower unit (Fig. 4).

For detailed data on paleomagnetism, faunal assemblages, stone tools and radiometric datings the reader may refer to the related papers in this issue (Albianelli & Napoleone 2004; Bigazzi et al. 2004; Martínez-Navarro et al. 2004; Martini et al. 2004).

The Bukra Sand and Gravel

This unit is named after the Bukra River, a minor stream in the SE map area, where it is best exposed. Other excellent sections occur along the Ghersaloita, Maebele and Dandiero rivers (Fig. 3A).

Distribution and thickness – Complete sections are restricted to the southernmost outcrops between the Bukra and Maebele rivers where the unit is represented by some 150 m thick gravels and coarse sands that pinch out on the basement close to Asarobuni (SE corner of the map of Fig. 3A). Farther north, the stratigraphic base does not crop out and the exposed thickness is 300 m.

Boundary relationships – This unit lies unconformably on the Precambrian basement and smooths the morphological irregularities of the basin floor due to faulting. The basal contact has been observed in the lower watershed of Bukra and Ghersaloita (Fig. 3A), where the basement is deeply oxidized, in places kaolinitized and covered by a few meters of colluvial breccias. At the top the unit passes gradually in few meters

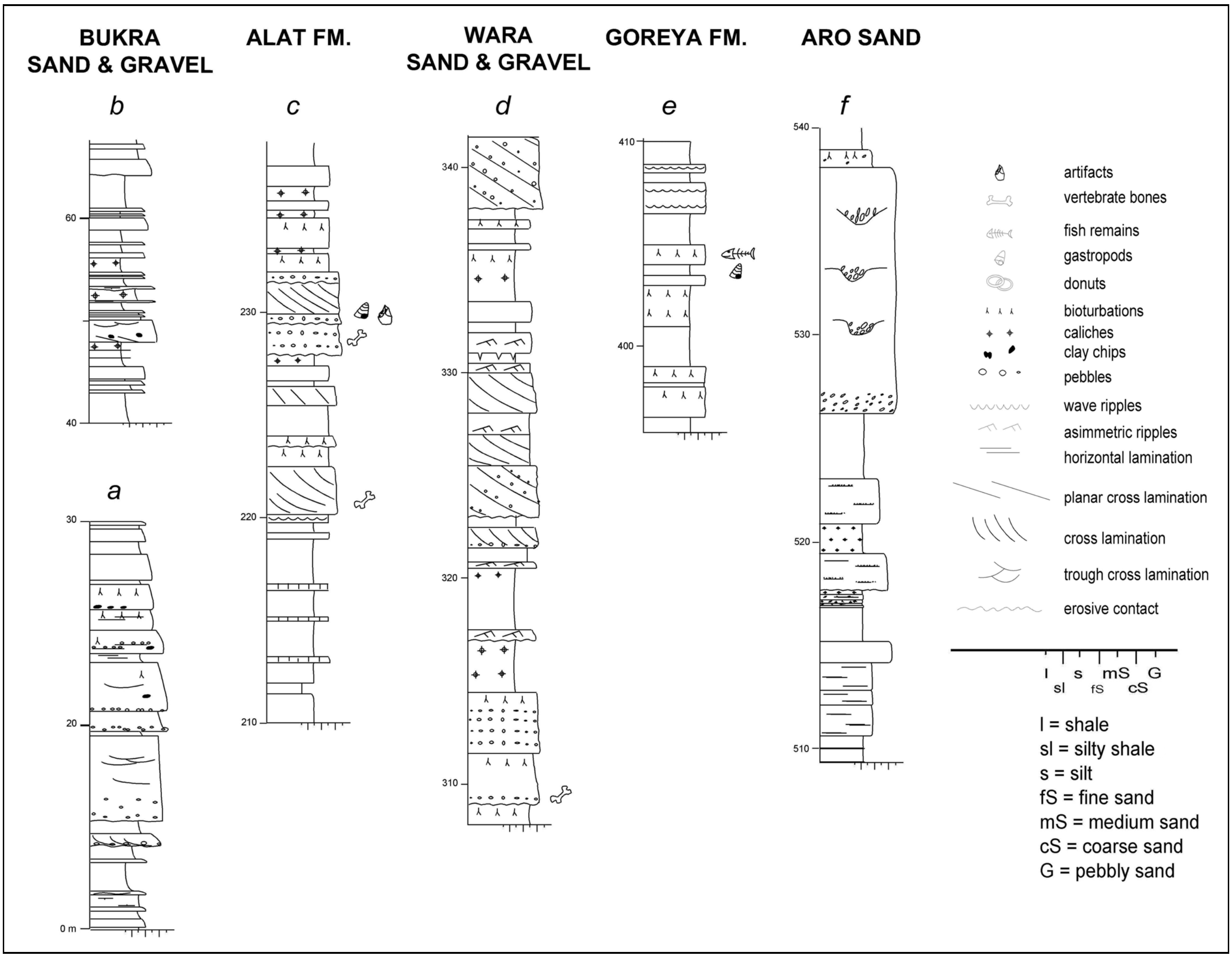


Fig. 6 - Selected sedimentological logs of the Dandiero Group formations. For their stratigraphic position see Fig. 4.

Fig. 7 - Bukra Sand and Gravel, middle portion, B2 lithofacies. Amalgamated beds of coarse and pebbly sand with basal lenticular pebbly horizons exposed on a 50 m high cliff. Ghersaloita valley.

Fig. 8 - Bukra Sand and Gravel, upper portion. Channellized sandy body included in-fine grained sediments (B3 lithofacies). The outcrop in the foreground is approximately 30 m thick. Alat well.

to the Alat Formation. At this transition silts and silty clays prevail.

Lithofacies – The basal and middle portion of the formation consists of tabular thick beds (up to 10 m thick) of gravels and pebbly sands with lenticular intercalations of silts and clays (Fig. 6 log a, Fig. 7). Erosional basal surfaces are frequent, but true channellized bodies are rare. The upper portion of the unit is characterized by lenticular sandy bodies in fine-grained sediments (Fig. 6 log b, Fig. 8).

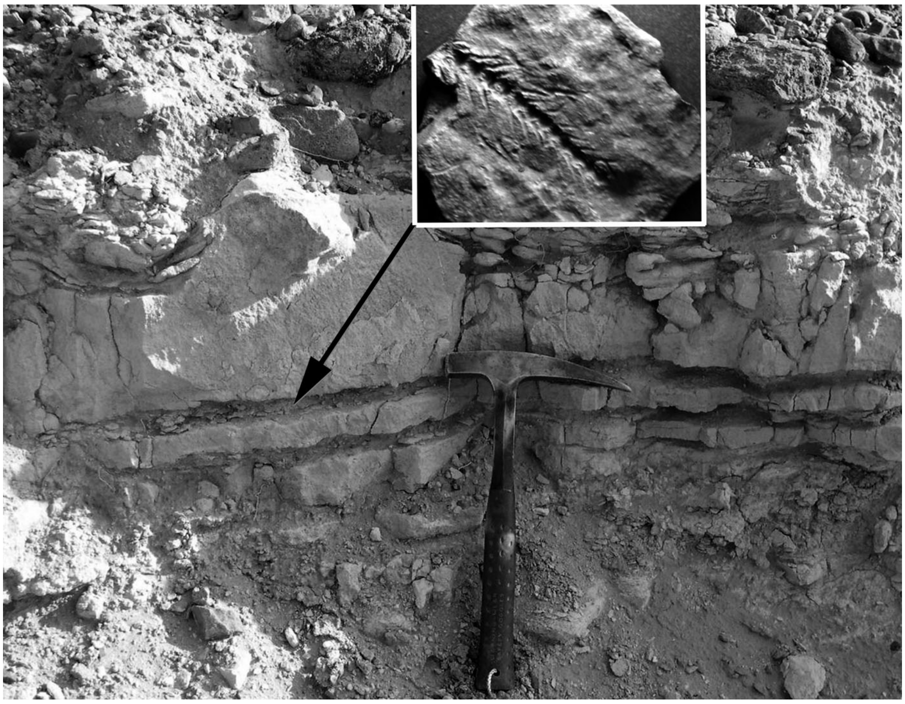
Four main lithofacies have been recognized. They are the following:

B1 – Poorly sorted polygenic gravels. The pebbles are moderately or well rounded, up to 30 cm in diameter, imbricated, with abundant matrix of coarse sand. They make up beds up to 3 m thick, which are massive, graded to cross-bedded. They are present alone or in amalgamated bed-sets. Pebble lithologies are those of the basement rocks outcropping along the western and southern basin shoulders. In the southern outcrops (Mai Garsenni/Anded Ali Mt., Fig. 2) chloritoschists pebbles are a typical component of the gravels.

B2 – This lithofacies, which is predominant in the Bukra Sand and Gravel, consists of coarse and pebbly sands. Sands occur in beds up to ten meters thick, commonly with a thin, laterally discontinuous, basal pebbly level. They are poorly sorted, massive, horizontally to through-cross laminated.

B3 – Channellized sandy bodies usually less than 10 m thick and 50 m or more wide, included in fine-grained sediments. They are multistory channels filled with medium to fine-grained sand with small pebbles

Fig. 9 - Alat Formation. Thin bedded chalky limestones containing fresh-water fishes (A2 lithofacies). Alat well.



disseminated within the sand as well as concentrated at the base of the channels. Planar and trough cross-laminations characterize these sandy bodies.

B4 – Fine sands, silts and clays occur as lenticular, relatively thin bodies interbedded into coarse-grained lithofacies B1, B2 or in thick horizons of channellized sands of facies B3. These fine sediments are massive to thin bedded, generally bioturbated, horizontally laminated and asymmetric ripples occur locally. Red, poor developed paleosols are present with rooted horizons and caliches. Thin calcareous beds with freshwater gastropods are present locally.

Fossils, artifacts and age – Vertebrate fossils are rare, mainly concentrated in the sandy levels of facies B2 and B3. Rare stone tools have been found. Gastropods, frequently represented by *Melanoides tuberculata*, are present in the thin, calcareous beds of the B4 facies.

All sampled layers record a reversed magnetozone that has been correlated with the Matuyama Chron (see Albianelli & Napoleone 2004 (Fig. 4). Since the directly overlying magnetozone in the Alat Formation has been assigned to the Jaramillo Chron, the Bukra Sand and Gravel are older than 1,07 Ma and dated as Early Pleistocene.

Environmental interpretation – The lower and middle portion of the Bukra Sand and Gravel may be referred to alluvial fans (B1) and braided rivers (B1, B2). The upper portion, mainly characterized by B3 and B4 lithofacies, documents an alluvial plain filled mostly by overbank deposits and crossed by isolated straight to low sinuosity channels.

Paleocurrents in the coarse-grained deposits indicate clastic transport toward north and northeast.

The Alat Formation

A spectacular exposure of the unit can be seen at the Alat wells and on the slopes of Alat Mt. close to the location where the Buia *Homo* remains have been found (Abbate et al. 1998; Macchiarelli et al. 2004). Many other well-exposed sections are present in the entire area of the Dandiero basin.

Distribution and thickness – In spite of its relatively small thickness, the Alat Formation outcrops extensively (Fig. 3A). It can be traced across the Dandiero basin from the Alat area, where it reaches its greatest thickness of around 100 m, to Bukra and Afonabo regions (Fig. 3A, southern areas), where is few tens of meters thick.

Boundary relationships – The Alat Formation rests conformably on the Bukra Sand and Gravel. The transition is lithologically gradual and takes place in a few meters. In contrast, the uppercontact is sharp, erosional and capped by sandy beds of the Wara Sand and Gravel. This abrupt transition marks the boundary between the A and B depositional sequences of the Maebele Synthem (Fig. 3).

Lithofacies – The lower part of the unit (10-15 m) is represented by very fine sediments consisting of silts, clays, thin calcareous beds and ash layers. Higher up in

Fig. 10 - Alat Formation, base, donuts keybed. a: tilted and faulted outcrops of the keybed near Aladaf; b: view of the upper surface of the keybed; c, d: close views of the basal surface of the keybed with different cast arrangements ("olympic" and tangential intersections); e: close view of the base of the key bed showing the donuts similar to overturned volcanic cone; f: vertical deformational structures at the interface between the donuts key bed and the underlying beds.

the sequence, sandy bodies are interbedded within fine sediments (Fig. 6 log c). Six lithofacies have been recognized.

A1 – Pale to dark-grey, thin laminated to massive clays and silts in levels up to 15 m thick. Locally they contain dark organic matter and thin layers with abundant gastropod shells. Bioturbation is common and caliche nodules also occur. One thin bed of gypso-arenites and veins of satin spar gypsum are present. Silty beds contain wave ripples.

Fig. 11 - Well developed clinostratification capped by topsets in a sandy body of the Alat Formation connected with the progradation of a Gilbert-type delta (A4 lithofacies). Aladaf hill.

A2 – Thin bedded (few mm up to 10 cm thick), laminated to poorly laminated chalky limestones containing well-preserved fresh-water fishes (Fig. 9) and abundant gastropod shells.

A3 – Distinctly-recognizable composite key horizons consisting of 2 to 3 calcareous beds, which are 5 to 20 cm thick, intensely bioturbated and alternating with thin silts and clays (Fig. 10 a, e, f). These calcareous beds exhibit peculiar ring-like structures that are preserved as concave circular depressions on the surface of the bedding plane (Fig. 10 b). These impressions are casts of an oolite-rich sandthat can be massive or faintly laminated, and subordinately contain *Cypria* ostracods and fish spines. Their mineral composition is mainly calcitic or dolomitic with secondary barite and phyllosilicates.

On overturned beds these casts look like "donuts" and this term is used to designate this basin-wide key horizon. Sometimes the donuts overlap (Fig. 10 c, d). We estimate average density of 50 donuts per 100 sq meters to greater occurrence as in the outcrop of Fig. 10 f.

To our knowledge they cannot be equated to any ring-like structures described in the literature and their ambiguous features make it problematic to relate them either to just biological or physical processes. The donuts of the Alat Formations will be the subject of a paper in progress.

Preliminary hypotheses on their origin take into account their similarities with nests dug by some fish species in the mud flats along the margins of the East Africa rift valley lakes (Feibel 1987). In the same environment flamingos build nests as small circular mounds.

Donuts may also be compared to casts of corms and bulbs of plants living in flat marshes or swamps. Corm rootlets may be matched with some finger-like casts that are found associated to the donuts.

Affinities with ring structures produced by impacts or gas seepages (Aiello et al. 2001) are less convincing.

A4 – Tabular sandy bodies, 2-3 m thick displaying well-developed clinostratification dipping 15-25 degrees and becoming asymptotic at the base with the lower bed surfaces (Fig. 11). The sands are medium to coarse-grained, and occur in single, isolated layers embedded in fine lithofacies. Locally, the clinostratification is truncated by erosional surfaces covered by trough-cross laminated sands 50-100 cm thick.

A5 – Massive, graded and trough laminated, coarse-grained to pebbly sands in beds 50-200 cm thick, stacked one upon the other and forming thickening and coarsening upwards cycles 5 to 10 meters thick. Locally, the upper thicker bed of the cycles rests on a erosional surface marked by thin and lenticular pebble lags.

A6 – Tephra bedsets occur locally at a short stratigraphic distance above and below the donuts key bed (Dandiero section, Fig. 4). The lower bedset is 80-120 cm thick (Fig. 12), the upper one is 20-50 cm thick. They are characterized by pinkish color, grain size gradation, planar or convolute (flame) lamination and load casts, and are mainly composed of glass shards with flow frame, subordinate biotite and quartz and rare lithic metamorphic fragments.

Fossils, artifacts and age – The Alat Formation has yielded human remains (one cranium, three pelvic fragments, two incisors; Abbate et al. 1998; Macchiarelli et al. 2004) reliably dated through combined magnetostratigraphic, faunal and radiometric age constraints at the Matuyama/Jaramillo boundary (0,99 Ma) (Fig. 4). They

Fig. 12 - Tephra bedset showing convolute (flame) and planar laminations (A6 lithofacies). Dandiero section, immediately under the donuts key bed. Samples from this outcrop gave a fission-track age of 1.3 ± (0.3 Ma.

belong to a *Homo* "*erectus*-like" female individual (Abbate et al. 1998; Macchiarelli et al. 2004). For their stratigraphic and sedimentological placement within the Alat Formation see later.

Levels yelding abundant fossil bones of hippos, elephants, bovids, crocodiles associated with Acheulian hand-axes and cleavers occur in this formation (Fig. 13). (Ferretti et al. 2003, Martínez-Navarro et al. 2004). Different taxa within the mammal assemblage are biochronologically significant for age calibration are the Early Pleistocene. Other fossil remains consist of freshwater fishes and molluscs (*Melanoides tuberculata*).

One continuous normal magnetozone, correlated with the Jaramillo Chron, and an overlying reversed magnetozone, correlated with the Matuyama have been identified in the Alat Formation (Fig. 4). The lower boundary of the normal magnetozone coincides with the transition to the Bukra Sand and Gravel.

The time span during the Early Pleistocene that can be assigned to the Alat Formation is at least that of the Jaramillo Chron, that is from 1.07 to 0.99 Ma. However, since the last few meters of the formation include the transition to the Matuyama Chron, we can tentatively place its upper age limit around 0.95 Ma.

Radiometric dating of the tephra was attempted on biotite and glass with conventional $^{39}Ar/^{40}Ar$ stepwise heating (Abbate et al. 1998). Most of the tephra groundmass consists of juvenile glass, so it was expected that the influence of xenocrysts would be negligible. Both glass and biotites yield, instead, step ages older than 100 Ma, which evidence significant contamination by Proterozoic minerals, and magmatic excess Ar cannot be ruled out as an additional complication. Single-grain analyses are presently under way.

Bigazzi et al. (2004) have applied fission track dating method to glass shards from the same tephra and have obtained an age of 1.3 ± 0.3 Ma, consistent with the paleontological and paleomagnetic age assignments.

Environmental interpretation – The basal portion of the Alat Formation represents lacustrine deposits on which a complex deltaic system prograded. Delta characteristics changed in time according to variable local morphological gradient and clastic supply. When the lake waters were deep and/or the competence of the feeder channels was low, a typical foresets Gilbert-type delta was built. When the competence of the feeder channels increased and/or shallow water level conditions existed, coarse sandy lobes formed at the mouth of the distributary channels.

Clinostratification and cross lamination indicate a north-northeast progradation of the deltaic system.

Further information on the environment comes from samples collected for stable isotope analyses from the lacustrine/palustrine calcareous beds (lithofacies A2) along four sections (Aladaf, Dandeiro, *Homo* Site, Dioli/Cabura) (Tab. 1 a, b). The analyses were carried out both on authigenic carbonates and gastropod shells.

The $\delta^{18}O$ values range from -4.8‰ to -9.2‰ for the calcareous beds and from 1.6‰ to -10.6‰ for the *Melanoides tuberculata* shells. These are unexpectedly low values for rift lowlands (Abell 1985; Hailemichael et al. 2002; Leng et al. 1999), and can be accounted for by a very limited evapotranspiration and a substantial watertable recharge from plateau-derived rainfall.

Along the sampled sequence Repeated fluctuations between the highest and lowest $\delta^{18}O$ values can be observed in a range of 2-3‰. The amplitude of these changes are large enough to indicate significant climatic variations.

The $\delta^{13}C$ values range from -2.1‰ to -4.8‰ for the calcareous beds and from -3.2‰ to -5.4‰ for the gastropod shells. The absence of the covariance of $\delta^{18}O$ and $\delta^{13}C$ is compatible with an open water lake or ephemeral ponds with low residence time.

To detect sedimentation rate of gastropod-bearing horizons we have carried out isotope analyses on ten

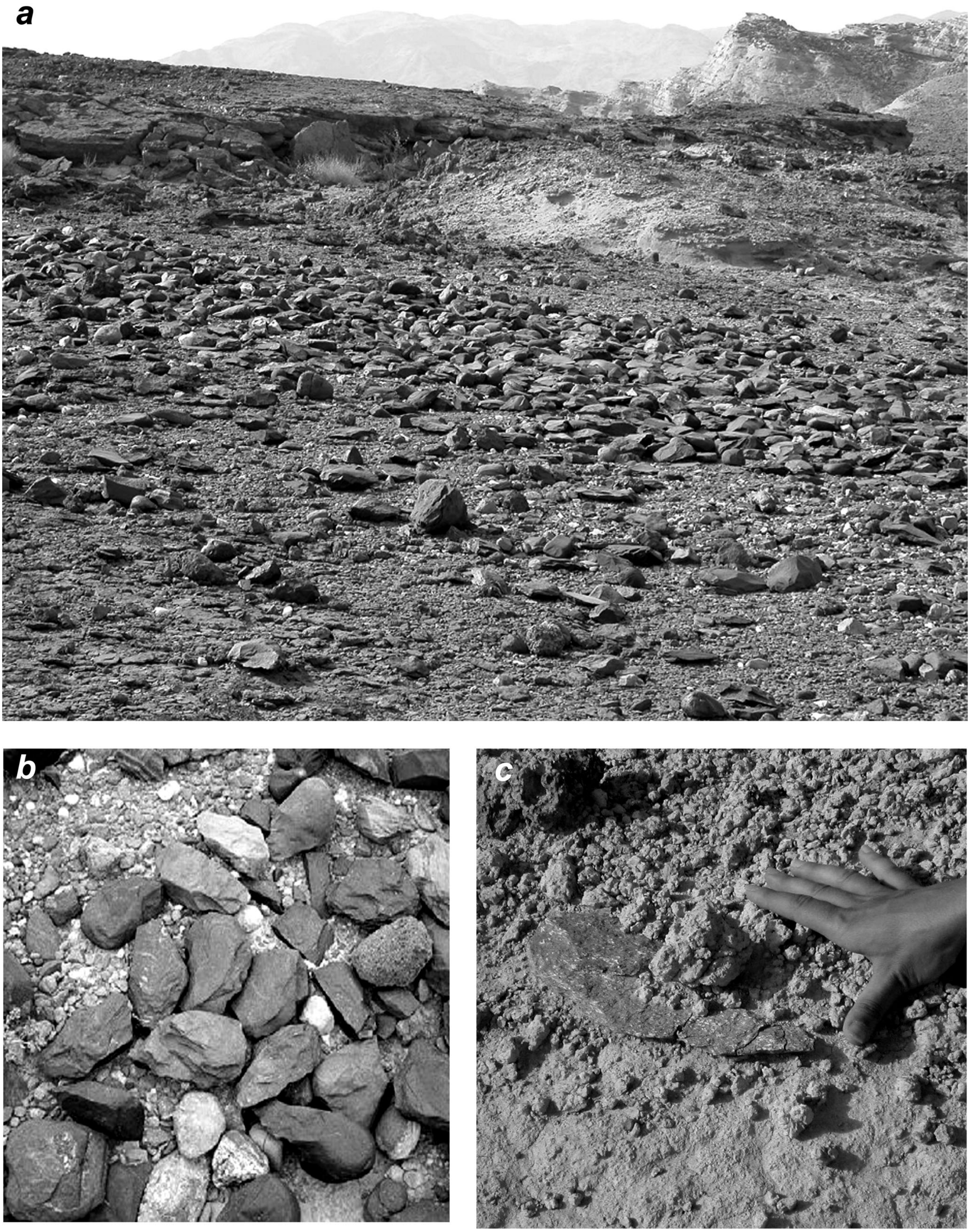


Fig. 13 - Acheulean artefacts from the Alat Formation, Dioli area (asterisk location on Fig. 3A). a: Secondary concentration of artifacts due to selective erosion of a silty beds in the Alat Formation above a sandy body with foresets; b: Close view of the same site; c: Artefact embedded in a silty clay at the top of a level characterized by abundant caliche nodules.

Authigenic lacustrine carbonates		**a**
Aladaf Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M062A	-6.9	-7.3
M062B	-3.7	-9.2
M062C	-2.8	-7.4
M062D	-3.3	-7.2
M065B	-4.2	-7.8
M066	-4.1	-6.9
M067A	-5.0	-4.8
M070A	-6.4	-7.8
M070B	-6.4	-8.4
Dandiero Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M043C	-3.2	-7.9
M056	-2.1	-6.9

***Melanoides tuberculata* shells**		**b**
Aladaf Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M067B	-3.4	-5.8
M068B	-5.4	-4.9
M069A	-4.8	-0.3
M069B	-4.5	0.7
M071	-4.1	-10.6
M072A	-3.3	-10.1
Dandiero Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M036C	-4.3	-5.5
M042A	-5	0.2
M042B	-4	1.6
Homo Site		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M0I1A	-4.2	-10.2
M0I1B	-3.7	-10.3
Cabura-Dioli Area		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M134A	-3.7	-9.4
M134B	-3.7	-9.9

Authigenic lacustrine carbonates		**c**
Aladaf Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M085A	-4.8	-6.9
M085B	-5.2	-7.7
M085C	-2.8	-7.7
M086	-4.5	-7.0
M089	-5.8	-6.9
Dandiero Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M108A	-3.3	-7.3
M108B	-0.7	-6.8
M110	-2.2	-7.5
M111C	-4.0	-7.4
M113	-2.1	-7.4
M113A	-0.1	-9.5
M151A	-4.8	-6.1
M151B	-4.8	-6.4
***Melanoides tuberculata* shells**		
Aladaf Section		
Samples	**$\delta^{13}C$**	**$\delta^{18}O$**
M088B	-4.2	1.3

Table 1 - Carbon and oxygen isotope analyses on carbonates and Gastropod shells of the Alat (a, b) and Goreya (c) formations.

different specimens of *Melanoides tuberculata* per each layer. The data show a great homogeneity of values with a standard deviation ranging from 0.3 to 1.0. As the intra-layer variability of $\delta^{18}O$ and $\delta^{18}C$ values is much lower than the one which characterizes the sampled sequence, and the estimated life-span of a *Melanoides tuberculata* being around three years, we can assume a relatively quick sedimentation rate for the gastropod-bearing levels.

The Wara Sand and Gravel

Complete exposures of this unit are present along the valley of the Maebele River and along the left bank of the Dandiero River.

Distribution and thickness – This formation is the most widely outcropping unit of the Dandiero Group. It reaches a thickness of more than 250 m in the southernmost outcrops and becomes thinner to the north.

Boundary relationships – The base of the unit is marked by thick, pebbly to coarse-grained sandy bodies which rest on the Alat Formation and on the basement. The upper contact is abrupt with the overlying Goreya Formation that is characterized by a rapid increase of fine sediments.

Lithofacies – The formation is composed of gravels and coarse-grained sands in the lower portion (Fig. 6 log d). Upward and in the downstream direction, towards north and north-east, the lithofacies become sandier (Fig. 6 log d).

Four main lithofacies are present in this unit.

W1 – Stacked and amalgamated, tabular, massive gravel beds, 1 to 4 m thick. The cobble to pebble gravels range from clast- to matrix-supported (with abundant sandy matrix) and display normal to reverse grading. Clasts are generally imbricated. Lenticular oxidized sands locally mark the top of the beds. Pebble lithologies are similar to those of the gravels in the Bukra Sand and Gravel.

W2 – Pebbly to coarse-grained sands with erosional base, in tabular beds up to 5 m thick (Fig. 14). They are massive, graded, planar and/or trough cross laminated. Small pebbles occur within the sandstones as well as at the base of the beds. They mark crude horizontal lamination. Locally, the top of the beds shows mud cracks, root traces and caliche nodules. The latter are present as clasts at the base of some beds.

W3 – Fine to medium sands in beds up to 50 cm. They are graded and horizontally laminated. Bioturbation, root traces and caliche nodules are frequent. Asymmetrical and symmetrical ripples as well as intense reddish oxidation are common features.

W4 – Pale grey silts, clay and fine sands in packages up to 5 m thick, interbedded with coarser lithofacies. These deposits are generally intensely bioturbated, with abundant root traces and caliche nodules.

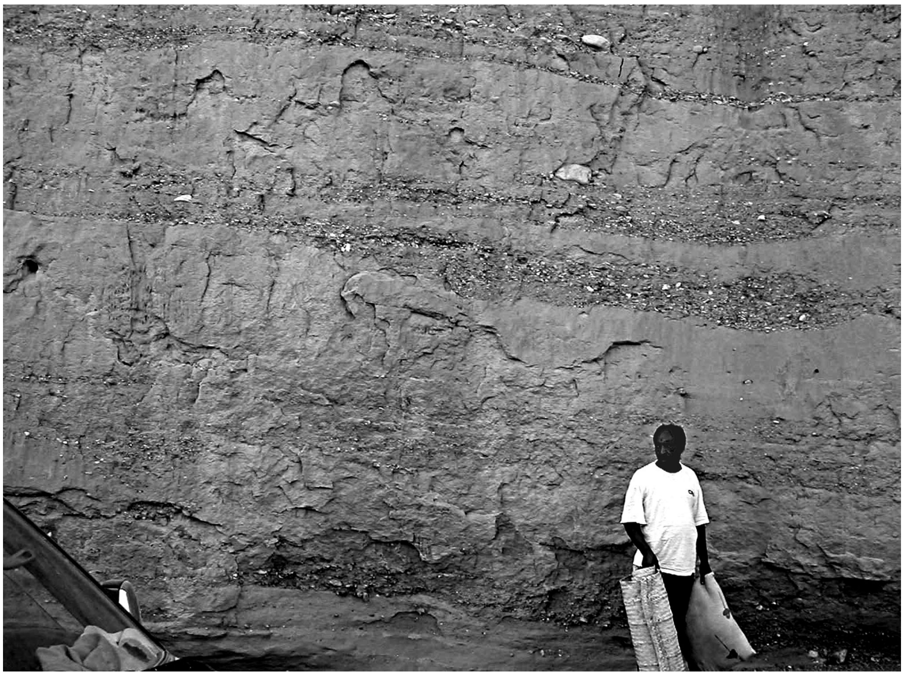


Fig. 14 - Wara Sand and Gravel, W2 lithofacies. Massive sand with erosive base marked by lenticular levels of pebbles. Wara valley.

Fig. 15 - The 40 m-thick level of fine sediments laid down in ephemeral ponds of an alluvial plain (Wara A on map of Fig 3) interbedded in the Wara Sand and Gravel, Darraito area.

Subordinate horizontal rhythmites are characterized by the alternation of thin laminae of grey and reddish fine sands and silts. Very thin calcareous beds with gastropod shells occur locally within these fine-grained lithofacies.

In the Darraito area (Fig. 3A) this lithofacies forms a laterally continuous level up to 40 m thick (Fig. 15) in the middle portion of the unit (Wara A on Fig. 3).

Fossils, artifacts and age – Mammal bones occur mainly at the base of the coarse sandy beds (W2 lithofacies). Acheulean artifacts are concentrated at the transition between the lower coarse-grained deposits and the Darraito level of fine -grained lithofacies (Wara A on Fig. 3).

The Wara Sand and Gravel correlate to the reversed magnetozone of the Matuyama Chron without reaching the overlying normal Brunhes (Fig. 4). A maximum time span for these Early Pleistocene deposits could be from 0.98 Ma (top of the Alat Formation) to 0.78 Ma (beginning of the Brunhes). However, since the polarity change Matuyama/Brunhes has been identified well above the top of the Wara unit, the estimated upper age limit of the Wara Sand and Gravel based on assumed

Fig. 16 - Goreya Formation: fine-grained deposits with alternating thin limestone beds. Goreya valley.

sedimentation rates and magnetostratigraphy could be around 0.87 Ma.

Environmental interpretation – The overall features of this unit indicate a coarse-grained, bedload-dominated fluvial system with extensive water bodies in the alluvial plain subject to frequent desiccation (playas). The common occurrence of tabular thick beds with crude horizontal lamination suggests recurrent flash floods.

Pebble imbrication and cross bedding indicate paleocurrent directions towards north and northeast.

The Goreya Formation

The type section crops out in the upper watershed of the Goreya River. Well-exposed sections occur also along the left bank of the Dandiero River.

Distribution and thickness – The unit crops out continuously in a southwest to northeast elongated belt in the western margin of the basin. It is around 50 m thick and becomes gradually thinner toward the Aro Mt. where it wedges out and is lateral transitional to the Aro Sand.

Boundary relationships – The upper transition to the Aro Sand is marked by a gradational increase of coarse-grained sediments.

Lithofacies – This unit consists mainly of fine-grained deposits in which three lithofacies can be recognized (Fig. 6 log e, Fig. 16).

G1 – It is the most common lithofacies and is represented by pale grey silts and clays, massive or thinly laminated, locally containing organic matter, in levels up to 5 m thick. They are locally intensely bioturbated and have some rooted horizons, particularly at the base and at the top of the unit.

G2 – Finely laminated, whitish limestones in centimetre to decimetre thick beds. They occur isolated or in packages, interbedded in the G1 lithofacies. Abundant fish remains and gastropod shells characterize this lithofacies, which represents a key bed in the middle portion of the Aro Sand.

G3 – Medium to fine-grained sandy beds, 0.5-1 m thick, graded, massive to parallel laminated occur mainly at the base and the top of the unit. Locally they are assembled in packages leading to thickening, fining upwards or symmetric cycles. Wave ripples are common sedimentary structures in the finer sands.

Fossils, artifacts and age – Fossil remains consist of fishes and shells of fresh-water molluscs (*Melanoides tuberculata*) as well as of reworked fragments of mammal bones that are found in the sandy lithofacies. Artifacts occur in the finer-grained sediments.

A reversed magnetozone (Matuyama) extending from the top of the Wara unit, tentatively dated 0.87 Ma, to the Matuyama/Brunhes transition (0.78 Ma) has been identified in the entire Goreya Formation (Fig. 4).

Environmental interpretation – The widespread occurrence of fine-grained lithofacies and the fossil contents indicate a fresh-water lacustrine to palustrine environment. The sandy beds, which are found mainly in the lower and upper portion of the formation, suggest episodical fluvial discharges in the lacustrine water bodies

Stable isotope analyses carried out on authigenic carbonates and gastropod shells (*Melanoides tubercula-*

ta) sampled in the Aladaf and Dandeiro river sections provide information on the hydrologic conditions of the lake (Tab. 1c).

In both sections the $\delta^{18}O$ values range from -6.1‰ to -9.5‰ for the authigenic carbonates. As noted before, these values are unexpectedly low for rift lowlands (see discussion in Alat Formation). As observed in the Alat Formation, also in this formation there are large amplitude fluctuations of the $\delta^{18}O$ values in a range of 1.9-3.4‰, that can be related to strong climatic changes.

The $\delta^{13}C$ ranges from -0.1‰ to -5.8‰ for the authigenic carbonates. In this formation the data show a low covariance of $\delta^{18}O$ and $\delta^{13}C$, which is compatible with a permanent, but temporarily restricted lake.

The Aro Sand

Incomplete but well exposed sections outcrop on the slopes of the Aro Mt. and along the left bank of Dandiero. The upper portion of the unit is truncated by Boulder Beds and, consequently, there are not complete successions.

Distribution and thickness – The Aro Sand crops out in the northwestern margin of the detailed geological map. It comprises around 120 m of medium and coarse sands with intervening fine sands and silts.

Boundary relationships – The Aro Sand passes downwards to the Goreya Formation and is unconformably overlain by the Boulder Beds. The stratigraphic reconstruction of the Dandiero Group (Fig. 3C) calls for a possible lateral and upward transition of the Aro Formation to the Wara Sand and Gravel and to the Addai Fanglomerate in the southern portion of the mapped area.

Lithofacies – Three main lithofacies can be distinguished (Fig. 6 log f).

Ar1 – Fine sands, silts and clays in packages up to 10 m thick with interbedded coarse-grained lithofacies. Silts and clays are grey, massive and intensely bioturbated. Frequently they show pedogenetic features such as reddish oxidized horizons, pseudogley and caliche nodules. Locally varve-type lamination characterizes the silty sediments. Very thin silty and marly beds contain abundant fresh-water gastropods and rare fish remains. In the sandy beds symmetrical and asymmetrical ripples are common.

Ar2 – Fine to coarse-grained sands with small pebbles concentrated at the base of the thicker beds (Fig. 17). The beds vary in thickness from 0.5 to 3 m and are arranged into thickening-upward cycles. Sands are massive, graded or cross and horizontally laminated. Locally, the beds are intensely bioturbated.

Ar3 – Very thick (up to 10 m) sets of amalgamated beds occur at the top of this unit (Fig. 6 log f). They consist of coarse to medium-grained sands. Imbricated pebbles are locally present in pockets at the base of the erosional beds. Horizontal plane lamination is the dominant sedimentary structure. Plane laminated beds are locally capped by cross-laminated fine sandstones. The tops of the beds generally show red pedogenic alteration and rooted horizons.

In addition to the lithofacies described above, a 25 cm thick tephra layer occurs locally at approximately 50 m above the base of the unit in the Dandero section (Fig. 4). Its features are similar to those described for the lithofacies A6 of the Alat Formation.

Fossils, artifacts and age – Freshwater gastropods of the same species as that found in the other units are

Fig. 17 - Aro Sand: massive and horizontally laminated coarse sand; small pebbles concentrations at the base of thicker beds. Goreya valley.

present in the fine-grained sediments together with rare fish remains. Fragments of mammalian bones were recovered associated with the pebbly levels, but they are very rare.

A normal magnetozone, referable to the Brunhes Chron, has been identified within the basal sediments of the Aro Sand (Fig. 4). The lower age limit is older than 0.78 Ma and, consequently, the base of the unit is of latest Early Pleistocene age. The Aro Sand extends upward to the Middle Pleistocene.

Environmental interpretation – The gradual basal transition to the Goreya Formation and the occurrence in the lower and middle portion of the unit of upward-thickening cycles suggest a lacustrine deltaic environment mainly characterized by the progradation of coarse-grained lobes with topsets of distributary channel sediments. Upward, the depositional environment changes into bed-load dominated fluvial systems.

The paleocurrent directions suggest a progradation of the fluvio-deltaic system in the lake from south and southwest.

The Addai Fanglomerate

This unit is named after the Addai Plateau, which hosts good exposures of the southeasternmost, gravel-rich outcrops of the Dandiero Group. The type section is located along the Dandiero River in correspondence of the meander near the Addai Plateau (Fig. 5). The Addai Fanglomerate is well exposed also in the upper watersheds of the Maebele River and its tributaries.

Distribution and thickness – The fan-shape of the outcrops and the paleocurrents suggest that the feeding point of this unit was near the meander of the Dandiero where the Addai Fanglomerate reaches a thickness of approximately 250 m. Down current, towards east and northeast, it is more than 300 m thick.

Boundary relationships – At the apex of the fan, this unit rests unconformably on the metamorphic rocks of the basement. As depicted in Fig. 3c, coarse-clastic lithofacies, similar to those of the Addai Fanglomerates, are present at the onlap of the Bukra and Wara units on the basement.

Lithofacies – This unit is dominated by pebbly beds and coarse sand lithofacies and, subordinately, by lenticular reddish sands and silts (Fig. 18).

Ad1 – Gravels in tabular or lenticular beds, 1-3 m thick, with erosional base. The cobble to pebble gravels are clast-supported with abundant sandy matrix. Pebbles are poorly sorted, moderately to well rounded and locally imbricated. Beds are massive to crudely horizontally laminated with normal to reverse grading. Pebble lithologies are similar to those of the basement rocks outcropping along the western basin shoulders. Chloritoschists pebbles seem to be missing.

Ad2 – Coarse, subordinately medium-grained sands with pebbles disseminated within the sands as well as concentrated at the base of the beds. They are massive, tabular or lenticular, 0.2 to 1.5 m thick. The sands are pedogenized with rare rooted horizons and reddish oxidations.

Fossils and age – No fossil remains have been recovered from this unit. Due to its thickness and the fresh appearance of the outcrops it is possible that its age could range from Early to Middle Pleistocene.

Environmental interpretation – The fan-shape of the outcrops and the lithofacies indicate a coarse-

Fig. 18 - Addai Fanglomerate: thick beds of polymodal gravel with lenticular interbeds of massive reddish sand. The succession is 35 m thick. Addai Plateau.

grained alluvial fan prograding into the basin during the terminal phases of the basin filling.

The Boulder Beds

The Dandiero Group is unconformably overlain by the Boulder Beds, an alluvial fanglomerate unit, with best exposures along the southeastern escarpment of the Curbelu plateau.

Distribution and thickness – This unit crops out extensively on the Curbelu plateau where it reaches its greatest thickness of ca. 50 m. Other typical outcrops crown the top of the Alat and Aro mountains. In addition, the Boulder Beds constitute at least three orders of terraced deposits.

Boundary relationships – The Boulder Beds rest unconformably above the basement and all the units of the Dandiero Group. They cap all the faults and fractures that affect the basin fill.

Lithofacies – The Boulder Beds are poorly stratified, massive clast-supported gravels with rounded boulders and cobbles in a reddish sandy matrix (Fig. 19). The clasts on the uppermost depositional surface exhibit a dark varnish cover on their exposed surface. Outsize clasts up to 100 cm in diameter are generally concentrated in the upper portion of the single beds. Some beds of coarse massive sands also occur.

Pebble lithologies are those of the basement rocks outcropping along the western and southern basin shoulders. Some quartzose sandstone pebbles most likely derive from the Mesozoic arenaceous units locally outcropping along the western escarpment.

Volcanic breccias and basaltic lava flows are interbedded in the Boulder Beds north of the Curbelu plateau beyond the area covered by the map of Fig. 3A.

Fossils, artifacts and age – No fossil remains have been discovered in this unit. Obsidian artifacts and quartz flakes are abundant on the upper surface of this unit. Based on stratigraphic relations we assume a Late Pleistocene age.

Environmental interpretation – The Boulder Beds were deposited in coalesced alluvial fans and/or fluvial systems through catastrophic floods discharging clasts derived from escarpment bordering the Dandiero basin and undergoing active faulting.

The Alluvial Deposits

The floors of major fluvial valleys are covered by coarse alluvial deposits (Fig. 3). They consist of pebbles and boulders with lentils of coarse -grained sands, and constitute also terraces a few meters above the modern fluvial channels. In the Samoti plain the alluvial deposits, probably connected to coalescing alluvial fans (bajadas), are sandier. They are partly reworked by the wind and build small dunes and aeolian sand sheets.

These deposits are included in the Samoti Synthem and their age is Late Pleistocene to Holocene.

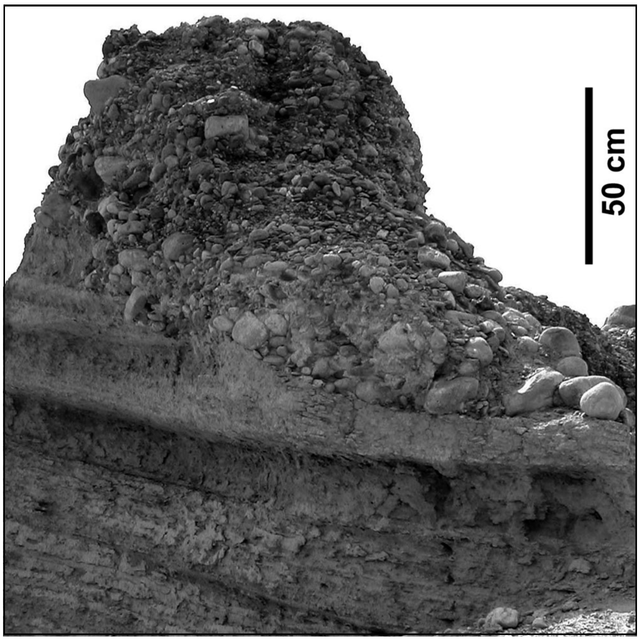


Fig. 19 - Erosional contact between the Boulder Beds and the Aro Sand. Boulder Beds are massive, polymodal and clast-supported. Aro hill.

Basalts

Late Pleistocene to Holocene basalt lavas crop out in the northwestern corner of the study area, and are partially covered by alluvial and aeolian deposits.

Detailed stratigraphy of the *Homo* site

The *Homo* remains were discovered on the slope of a small hill 300 m east of the Alat Mt. Five detailed sedimentological logs have been measured on that outcrop (Figs. 20, 21). The fossils have been found within the lacustrine delta sediments in the upper portion of the Alat Formation. In particular, the cranium and two pelvic fragments come from the top of a layer of silty clays 1.4 m thick at the base of a sandy channel. One incisor was discovered within the channel deposits, while a second incisor comes from a thin lenticular sandy bed 1.5 m below the cranium-bearing layer. A third pelvic fragment has been recently recovered on surface, at the base of the outcrop that yielded the other human bones.

The silty clays are light gray, massive or horizontally laminated. Caliche nodules occur at the top, and vertical burrows filled by sand are present too. Two

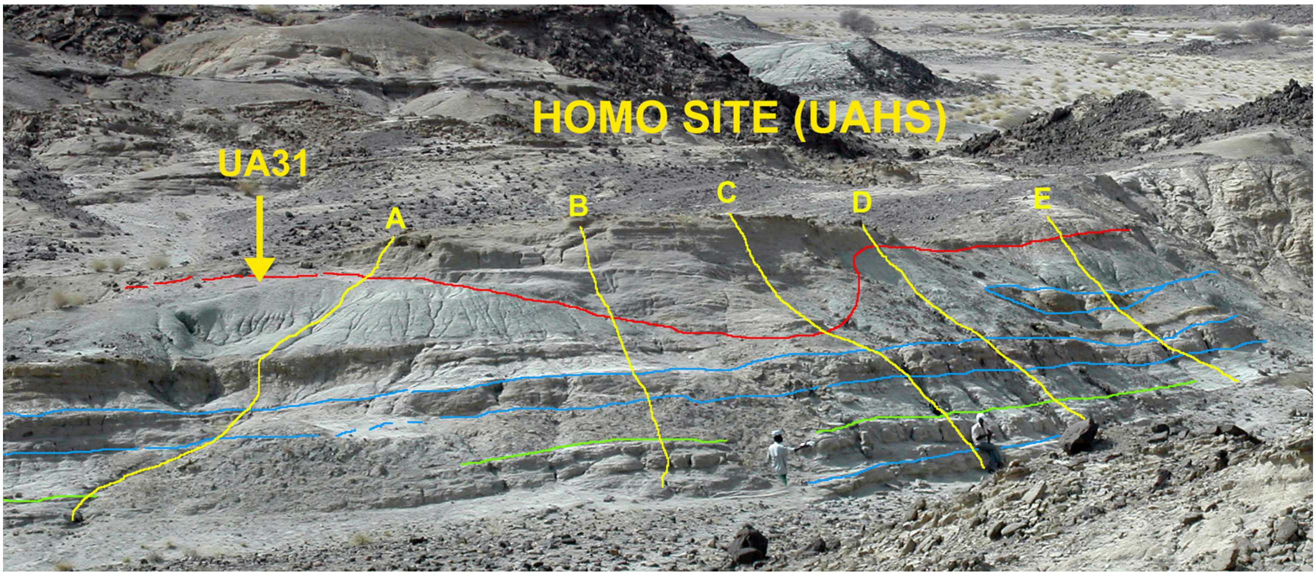


Fig. 20 - Panoramic view of the Homo Site (UAHS) with the discovery location of the UA31 skull. A, B, C, D, E are the traces of the logs in Fig. 21. The upper line marks the base of the erosive channel, the other lines mark correlated beds and the *Melanoides* keybed.

samples for palynological analyses resulted barren of fossils. The silty clays were laid down in the emerged muddy portion of a deltaic plain.

The channel cutting the silty clays is exposed for a width of 10 m but was originally wider, because the western bank is presently missing due to modern erosion (Fig. 20). The channel fill is multi-story and consists of stacked, massive, horizontally or trough laminated, 0.5-1.5 m thick sandy beds. It is characterized by lag deposits with pebbles and reworked caliche nodules. The top of the channel fill is marked by a thin layer with caliche nodules and well-developed mud-cracks. The beds at the top show asymmetrical ripples, root traces and caliche nodules. The channel is elongated in a northeast direction, and is 3 m deep and cut in fine, intensely bioturbated sediments that also host the lateral termination of another channelized, 1 m thick sandy body. The fine-grained horizon rests on a 3 m thick alternation of sandy beds, up to 0.5 m thick, and fine sediments. The sands are massive or trough cross-laminated with abundant caliche nodules. The lowermost sandy beds contains at the top abundant gastropods shells (*Melanoides*). The outcrop closes downward with two tabular sandy beds, 1 m thick, displaying very well-developed, northeast dipping foresets.

The stratigraphic and sedimentological data allow us to infer that the Buia *Homo* was living on an emerged muddy delta plain crossed by distributary channels evolving into more erosional fluvial channels during minor lake-level falls. These level variations foreran the complete lake regression and the successive development of a true alluvial plain, well represented by the Wara Sand and Gravel.

Paleocurrents and clastic sources

Many of the units we have previously described have a high percentage of coarse clastics. The composition of these clasts is referable to the lithologies of the basement and its Mesozoic sedimentary cover. They consist of phyllite, gneiss, black marble, quartzite, quartz porphyry, quartz veins, metadolostone, quartzose sandstone, and basalt.

Paleocurrent data and lithofacies distribution indicate for the Maebele Synthem a major feeding point placed in correspondence of the Addai plateau (Fig. 2). Probably minor sources can be recognized in the basement ridge that bounds southwards the Dandiero basin (Fig. 2).

As to the Boulder Beds of the Curbelu plateau, their clastic supply derived from multiple feeding points along the scarp of the rising plateau margin (Fig. 2) with the development of coalescent alluvial fans (bajadas). In contrast, the terraced Boulder Beds were laid down in wide valleys of a fluvial system more or less similar to the modern river network.

Sequence stratigraphy and basin evolution

The Dandiero basin fill was controlled by climatic and tectonic events that ruled the sedimentation in the Danakil depression during the Late Cenozoic. These events have generated depositional sequences enhanced by the rapid response of the fluvial-lacustrine system to the climate changes. These sequences can be framed in unconformity-bounded stratigraphic units at the rank

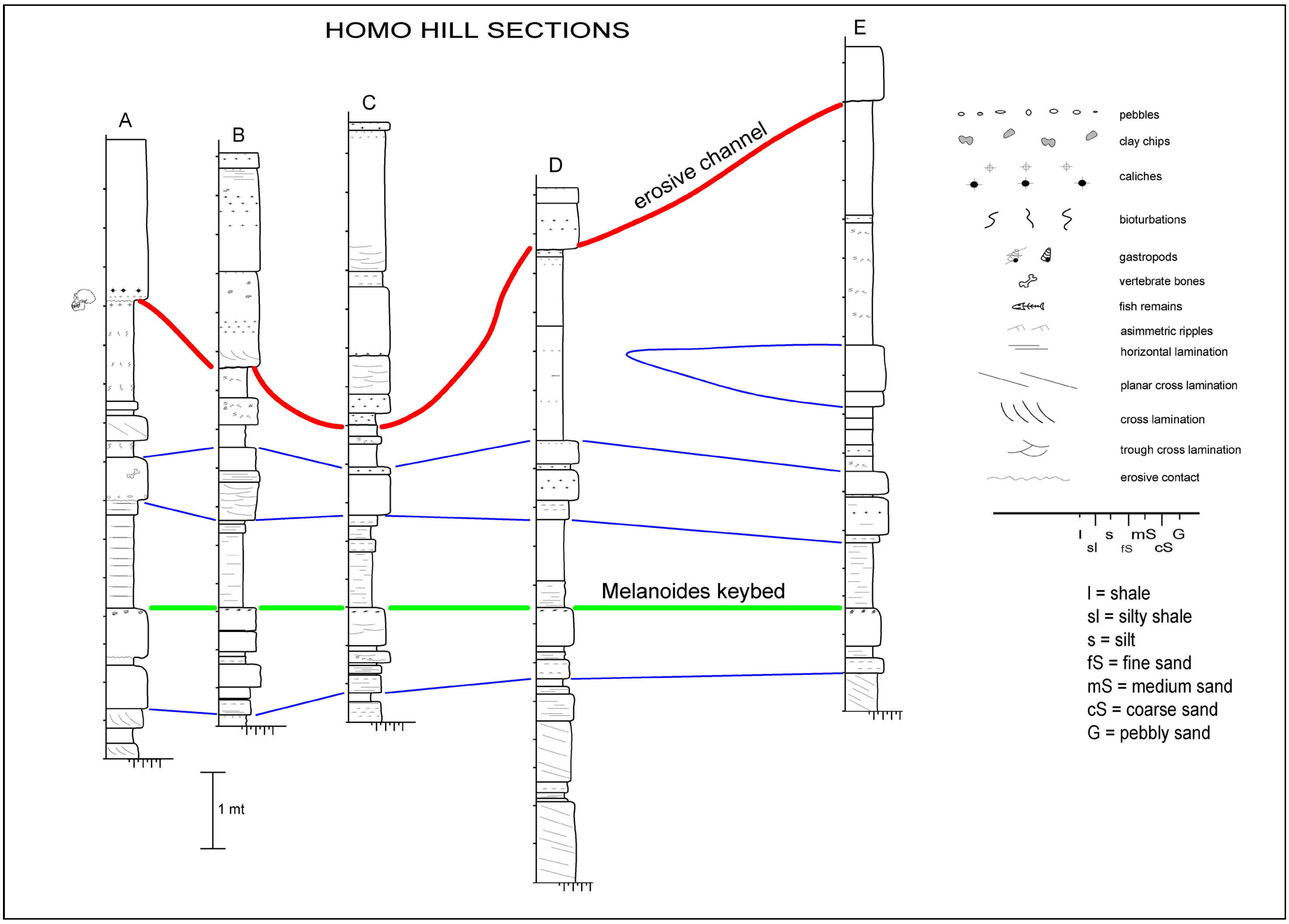


Fig. 21 - Sedimentological logs of the *Homo* Site (UAHS) outcrops.

of synthems. From the bottom, we recognize the Maebele Synthem, Curbelu Synthem and Samoti Synthem.

The Maebele Synthem is defined at its base and at its top by significant discontinuities marked by deeply erosional surfaces (Fig. 22). The lower contact is an angular unconformity between a steeply dipping basement and a mildly dipping Maebele Synthem (Fig. 5). The upper contact is still an angular unconformity, but the difference in dip between the Maebele Synthem and the overlying Curbelu Synthem is less pronounced (Fig. 22). The Curbelu Synthem, named after the Curbelu plateau, corresponds to the Boulder Beds and is closed at its top by a flat surface of no- or little deposition. The Samoti Synthem, named after the Samoti plain, includes the modern terraces and fluvial and alluvial deposits. It rests unconformably on the Maebele Synthem, but, at least in the study area, not on the Curbelu Synthem.

Within the Maebele Synthem we recognized two sequences (A and B) separated by a discontinuity. (Figs. 22, 23)

The sequence A is represented by the Bukra Sand and Gravel and the overlying Alat Formation.The basal Bukra Sand and Gravel strata are alluvial fan/braided fluvial deposits with intervening lenticular alluvial-plain fine sediments. They onlap on the basement and can be interpreted as lowstand sediments. The Bukra unit evolves upward into lenticular to tabular, coarse sandy and pebbly bodies embedded in fine flood-plain sediments (Fig. 8). They represent the transgressive system of the A sequence. The rapid upward transition to the fine-grained lacustrine deposits at the base of the Alat Formation marks the maximum flooding surface. The latter is represented by bioturbated clays and thin calcareous beds with abundant molluscs and fish remains. This bed-set is clearly recognizable in the field due to the presence of the donuts key bed (lithofacies A3 of the Alat Formation) and locally of tephra layers (Fig. 23). The maximum flooding is followed by the highstand sedimentation, evidenced by the complex lacustrine delta system of the Alat Formation at the end of the A sequence of the Maebele Synthem.

The sudden superposition of the coarse-grained sand beds referable to fluvial environment (W1 lithofacies of the Wara Sand and Gravel) above the Alat Formation signals the beginning of the B sequence (Fig. 23). The lack of evident deep incised valleys at the contact and the substantial continuity of the sedimentation from Alat to Wara suggest that the falling of the base

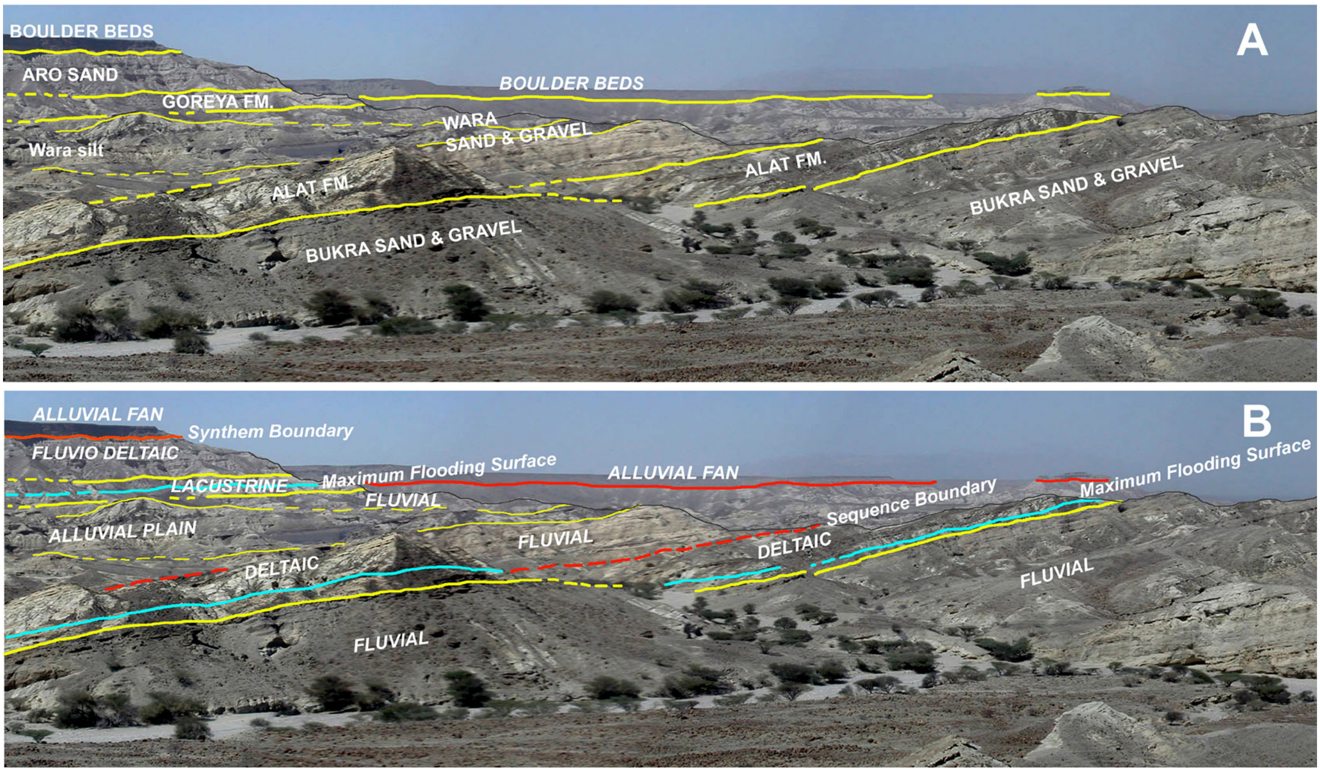


Fig. 22 - Lithostratigraphy, sequence stratigraphy and paleoenvironment interpretation of the Dandiero basin fill. Panoramic view on a 400 m thick succession from the Addai valley toward northwest. a. The lithostratigraphic units of the Dandiero Group unconformably overlain by the Boulder Beds of the Aro hill (on the left corner), Curbelu Plateau (centre) and Alat hill (right, on the background); b. Upper boundary of the Maebele Synthem: red continuous line; A/B sequence boundary: dashed red line; maximum flooding surfaces: pale blue lines. Yellow lines define the stratigraphical extension of different environments.

level of the basin was not so dramatic as to produce a marked regional unconformity.

The Wara sedimentation evolves upward in tabular, coarse sandy and pebbly bodies embedded in fine - grained flood-plain sediments that announce an incipient transgression. The rapid transition to the lacustrine sedimentation of the Goreya Formation, in its lower part characterized by fine bioturbated limestones with abundant fish remains, attest to the reaching of the maximum flooding stage (Fig. 23).

Farther above, the highstand is recorded by the sandy deltaic lobes in the upper portion of the Goreya Formation and by the basal sandy bodies of the Aro Sand, whereas the fluvial Aro Sand and the alluvial Addai Fanglomerate mark the regression that closes the deposition of the upper part of the Maebele Synthem. Afterwards, a regional deformational event involving the Dandiero basin interrupted the sedimentation and caused the tilting of the basin fill. Successive active erosion smoothed the topographic relief and prepared the basal surface for the alluvial fanglomerates (Boulder Beds).

In summary, the deposition of the Maebele Synthem commenced during the Early Pleistocene above an erosional basal surface cut in the Neoproterozoic basement. The basin subsided and created the accommodation space for the lower fluvial Bukura Sand and Gravel until the base level of the basin (lake level) raised (maximum flooding) and a lacustrine deltaic system developed (Alat Formation). Stable isotope analyses indicate a permanent open lake partially fed by underground water coming from the adjacent plateau escarpment. Successively, the lake level fell and conditions soon changed to coarse-grained fluvial sediments and fine-grained alluvial plain deposits (Wara Sand and Gravel). A second lake level rise allowed a wide lacustrine environment (Goreya Formation) transgressing from north and east. On the ground of the stable isotope analyses the lake was permanent and temporarily closed.

Later on during the late Early and Middle Pleistocene, the sedimentation evolved into the deltaic and fluvial deposits of Aro Sand. The latter and the overlying Addai Fanglomerate represent the terminal products of a forced regression caused by the uplift of the basin shoulders that closed the Dandiero Basin succession.

The Dandiero basin structural setting

The main structure of the study area is a large, NS trending, gentle anticline that involves all the units of

Fig. 23 - Selected sedimentological logs of the Dandiero, Alat and Aladaf stratigraphic sections in corrispondence of A/B sequence boundary and maximum flooding surfaces.

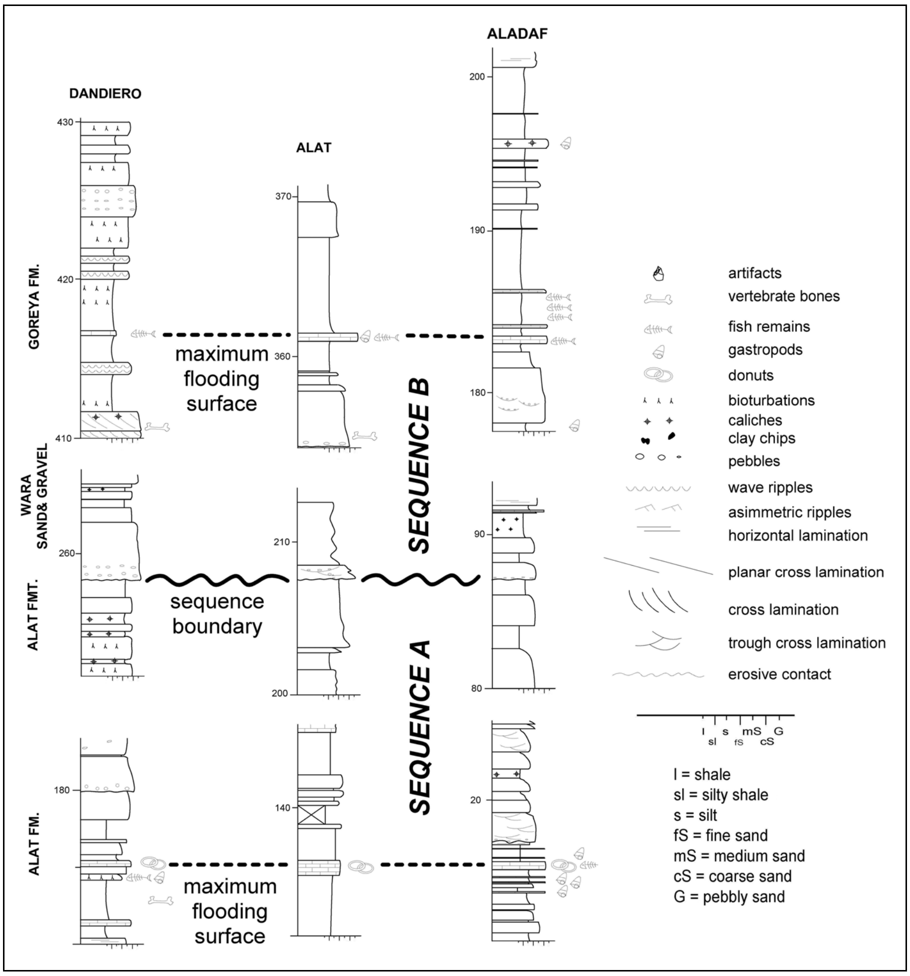
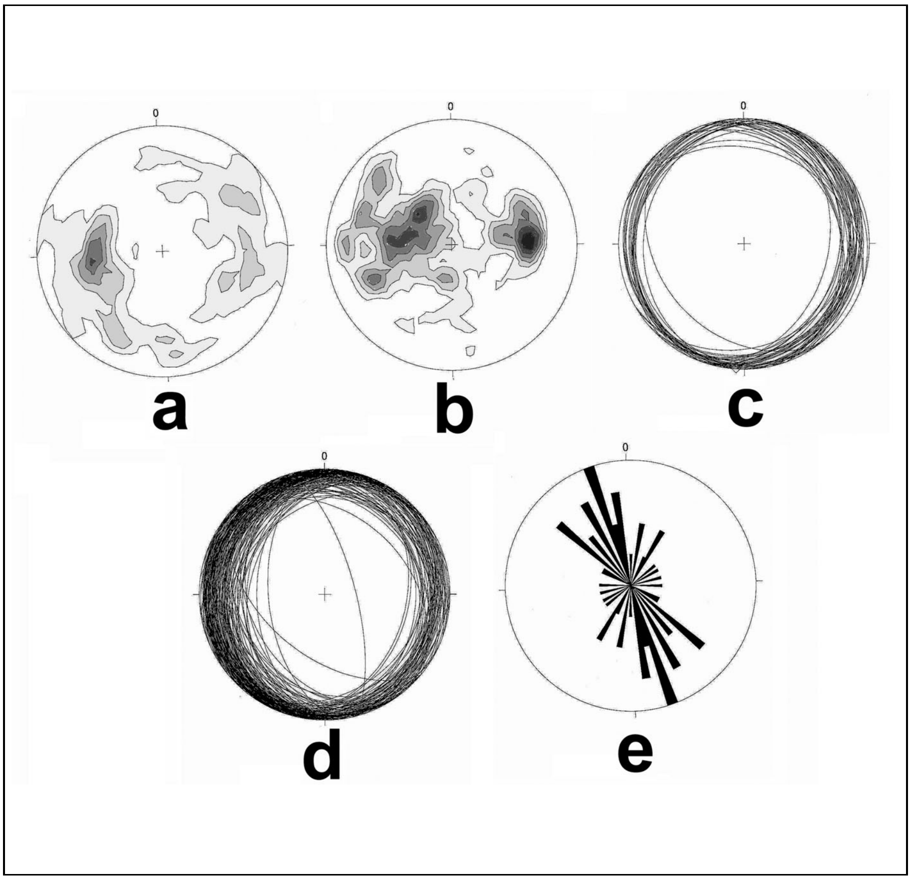


Fig. 24 - Mesostructural analyses in the Dandiero area: a. Lower hemisphere, equal area plots of 295 normal faults (includes adjoining metamorphic units). % of total X 1.0% area (max. density at 5.25). The E or W dips of the faults are distinct; b.Llower hemisphere, equal area plots of 90 slickenlines on normal faults in a. The dominant orientation is 090/42, but though diffuse, W plunging slickenlines are also common. c: great circles of 59 bedding surfaces from around the *Homo* site. They define an upright fold (184/01); d. Great circles of 256 bedding surfaces from the Dandiero basin. The E or W dips are distinct; e. Rose diagram of 29 dolerite dykes from areas adjoining the Neoproterozoic metamorphic rocks and the Pleistocene sediments. Largest petal: 13% of all values. Note that the dominant orientation is NNW-SSE.



the Dandiero Group and that can be followed along the axis for more than 10 Km (Fig. 3). Its hinge is marked by the outcrops of the Bukra Sand and Gravel that extend from Aladaf to the north to Mai Garsenni to the south. At the hinge and on the eastern limb, normal faulting dismembers and complicates the anticlinal structure. Outcrops of the Bukra Sand and Gravel and the Alat Formation are there repeatedly and variously tilted.

At the boundary with the Samoti plain, a NNW normal fault of regional significance downthrows the eastern limb of the anticline. The hanging wall is covered by recent sediments of the Danakil depression. The courses of both the Dandiero and the Maebele rivers as well as of some minor streams (such as Dioli) follow the traces of NE-SW trending normal faults transversal to the main bounding fault.

The intense Pleistocene tectonic activity witnessed by the large structures is confirmed at the mesoscale by many spectacular faults that affect the sedimentary rocks of the Dandiero basin and their metamorphic substratum. Some 300 Pleistocene faults are plotted in the stereographic projections of Fig. 24a. They are of the extensional type, dipping mainly to the W or to the E, and excellently preserved striations unambiguously suggest the normal, dip-slip nature of the faults (Fig. 24b). E and W dipping faults are considered to be synthetic-antithetic pairs related to a major east-dipping fault. Nearly all the faults are listric and a large number of the faults also show along-strike dip variation. It is likely that the slight E or W tilt of the Pleistocene sediments (Fig. 24c) may be to some extent ascribed to the effect of the listric faults.

Folds are rather rare in the sediments of the study area. Few open folds could be seen either at the outcrop or at the macroscopic scale. Lower-hemisphere, equal area plots of bedding surfaces from the Homo-bearing site show a NS trending upright fold (Fig. 24d).

The common occurrence of slump folds in the sediments suggests that some of the macroscopic folds may be related to syn- to post-depositional sedimentary processes, rather than active tectonic deformation.

Dolerite dykes cut the metamorphic rocks along the margins of the Dandeiro basin, but do not cross the Pleistocene sedimentary units. In the Bukra area the basal Pleistocene sands and gravels seal a dyke and its host basement rock. The age of the dykes is probably Oligo-Miocene and their strike is dominantly NNW-SSE distinctly coinciding with a Red Sea structural trend (Fig. 24e). They are, thus, considered to have been emplaced during the first faulting events that produced the Danakil depression.

Comparisons with other coeval *Homo*-bearing sites in the Afar region

In the Afar triangle south of the Danakil depression, a wide exposure of Late Cenozoic sedimentary strata extend from the foot of the Eritrean/Ethiopian and Somali plateaus towards the central Afar region. These sediments, which are all within the catchment of the Awash River, have been previously grouped by Kalb et al. (1982) in a newly defined Awash Group. The time spanned by this group is the last ten million years.

Subsequent detailed geological studies (White et al. 1993; de Heinzelin et al. 1999; Renne et al. 1999) at paleoanthropological localities, such as the Middle Awash valley and, downstream, in the Hadar region, provided better-constrained areal and temporal controls for the stratigraphic frame of these sediments. These new investigations have evidenced that active tectonics together with voluminous volcanism produced separate basins each with its own depositional history. This conclusion may also be easily applied to the Late Cenozoic sediments of the Danakil depression.

Moreover, using the new stratigraphic data (Asfaw et al. 2002), a close comparison can be made between the Dandiero Group and the Early Pleistocene Dakanihylo ("Daka") Member of the Bouri Formation in the Middle Awash valley, Ethiopia. Although 400 Km apart, they exhibit notable similarities. The sandy Daka Member has yielded one-million-year-old *Homo erectus* calvaria, phenetically similar to the Buia cranium, and abundant Acheulean stone tools. Moreover, its extensive vertebrate fauna is dominated by bovids and includes aquatic species. It suggests an open grassland habitat interspersed with water pools.

A similar habitat, despite local barriers among different basins, was probably shared during the Early/Middle Pleistocene by the entire territory at the foot of the Eritrean-Ethiopian escarpment from the Gulf of Zula to the entrance of the Main Ethiopian Rift Valley. The landscape was marked by wide alluvial fans and alluvial plains, deltaic systems with distributary channels, open spaces with small and shallow lakes, and swamps.

Conclusions

The newly defined Dandiero Group represents the basin fill of a system of marginal grabens bordering the Eritrean/Ethiopian plateau for some 200 Km from the Gulf of Zula to the Garsat area. In the Buia-Dandiero area this group incorporates six formations composed by alluvial, fluvio-deltaic and lacustrine deposits ranging in age from the Early to the Middle Pleistocene. This succession is bounded by two major unconformities of regional extent, which separate it from the Neoproterozoic basement and from the overlying Boulder Beds. The whole package, which is slightly deformed, constitutes the Maebele Synthem. This synthem is the result of two progradational and retrogradational fluvial and deltaic systems into lacustrine water bodies. Each of these regressive/transgressive cycles can be recognized as a depositional sequence within the Maebele Synthem, and in each sequence may be traced a clearly-expressed maximum flooding surface.

Due to its very close proximity to an uplifting plateau escarpment the Dandiero Group with its more than 700 m of sediments records a greater thickness than those of other Homo-bearing successions in the Afar region. The accommodation space for this thick succession was warranted by the strong subsidence that is a common characteristic of the marginal graben and their adjacent areas toward the axial belt of the Danakil depression (Badda, Dallol).

A rough estimate derived from a cumulate thickness of the Dandiero Group gives an accumulation rate of ca.1m/ka. This estimate is confirmed when we take into consideration well-dated shorter intervals, such as the sediment pile included between the beginning of the Jaramillo Chron to the Matuyama/Brunhes transition.

Changes in the depositional evolution reflect rift-system activities and the rapid climatic variations occurring during the Pleistocene. The lower and upper unconformity boundaries of the Maebele Synthem are related to the regional tectonic history, whereas the development of the two sequences in the basin fill was mainly controlled by base-level fluctuations and, hence, by climatic variations. More precisely, the two rises of the lake level (at 1.07-0.99 Ma and 0.87-0.80 Ma, respectively) can be referred to the strengthening of the monsoons that occurred in northwestern Indian Ocean between 1 Ma and 0.5 Ma (Clemens et al. 1996). This strengthening was probably connected to wet glacial episodes (Dupont et al. 2001), and this hypothesis is also supported by low content of aeolian dust in marine sediment cores of the north-western Indian Ocean during the same period (de Menocal 1995). The monsoonal effect on the climatic conditions of the Buia basin was enhanced by the vicinity of the Red Sea and by the impending orographic barrier represented by the Eritrean plateau and its escarpment.

In addition to the A and B sequences, lower rank cycles and sequences are also present in the Dandiero succession as witnessed by the fine sediments of the Wara A. They could be connected to minor oscillations of the lake level, triggered by less pronounced climatic changes, or by autocyclic mechanisms.

Early to Middle Pleistocene climatic variations and morphological evolution did not hamper human settlement in the Dandiero territory. Artifacts are chronologically and areally widespread in the basin fill with predominant occurrences in the fine-grained deposits, such as Alat, Goreya and Wara A units. This could be due to better living conditions in low-energy hospitable environments near stagnant water bodies (lakes and swamps), which could represent watering places and become muddy traps for large animals, such as rhinos and elephants. A further reason, not necessarily alternative, for this abundance of ambient-sensitive tools and bones could be the greater preservation potential of silts and clays. However, the high-energy riverbeds were visited to collect cobbles of basement lithologies more suitable to the tool factory.

The vertebrate fauna assemblages are predominantly composed by taxa with strong water dependence associated with much less represented taxa typical of more open landscapes (Martínez-Navarro et al. 2004; Delfino et al. 2004) (Fig. 25), along the whole Dandiero succession. Weak or strong monsoon conditions have not substantially changed this environment neither into

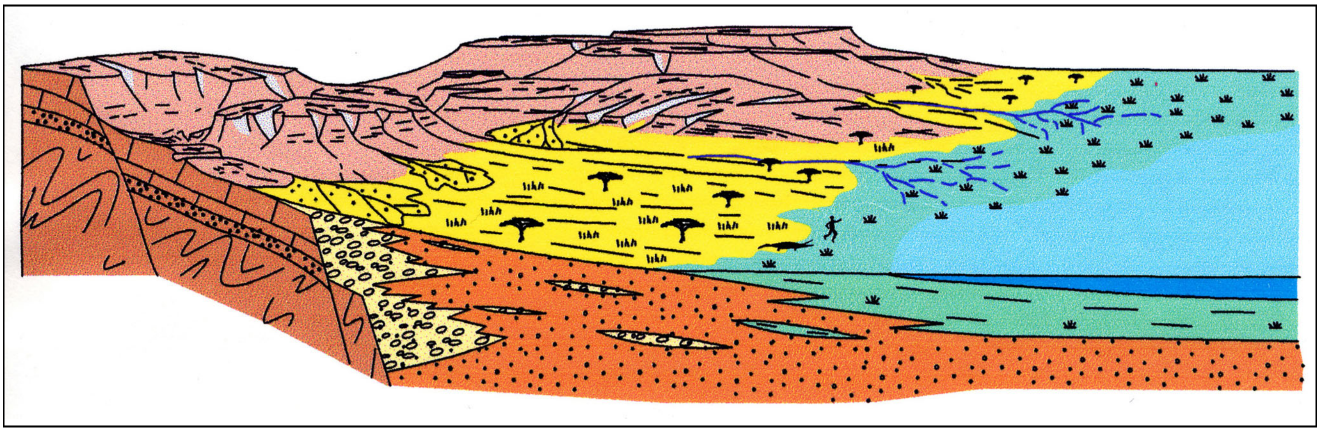


Fig. 25 - Cartoon depicting the Early Pleistocene landscape of the Dandiero Basin close to the Eritrean escarpment during one of the lacustrine transgressions.

an arid land nor into a humid forested area. Such savannah conditions are shared by many *Homo*-bearing sites along the East Africa rift valley and that of Buia is the northernmost site to date.

The geological context suggests that these environmental conditions favourable to human life were probably present farther north along the western coastal areas of the Red Sea. If they were permanent or recurrent during the whole Pleistocene, they could have facilitated continuous or sporadic dispersal of hominids from their East Africa homeland toward Eurasia.

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