The Dandiero Basin is located on the northern part of the 300 km-long Danakil depression. The geologic succession filling the Dandiero Basin is up to 1000 m thick and consists of three synthems, in ascending order: the Early-to-Middle Pleistocene Maebele Synthem of fluviolacustrine origin; the Late Pleistocene Curbelu Synthem of alluvial deposits and the Late Pleistocene to Holocene Samoti Synthem alluvio-eolian sand. This study and Main Map (1:5000 scale) focuses on the Maebele Synthem exposed in a 3.8 km² area near Mt. Alat. Regionally, the Maebele Synthem consists of six lithostratigraphic units, in ascending order: (1) the Bukra Sand and Gravel, (2) the Alat Formation, (3) the Wara Sand and Gravel, (4) the Goreya Formation, and (5) Aro Sand, (6) Addai Fanglomerate. The Bukra Sand and Gravel is about 150–200 m thick and made up mainly of fluvial sand. The Alat Formation is 70–100 m thick and consists of alternating fluvial, lacustrine and deltaic deposits. Fluvial deposits consist of sand-filled channels that occur as amalgamated or isolated bodies within floodplain mud. Lacustrine sediments consist of mud, whereas deltaic deposits are represented by sandy shallow-water and Gilbert-type deltas. The Wara Sand and Gravel is about 150–200 m thick and made up mainly of fluvial sand. The Alat Formation is 70–100 m thick and consists of alternating fluvial, lacustrine and deltaic deposits. Fluvial deposits consist of sand-filled channels that occur as amalgamated or isolated bodies within floodplain mud. Lacustrine sediments consist of mud, whereas deltaic deposits are represented by sandy shallow-water and Gilbert-type deltas. The Goreya Formation (50 m thick) consists of lacustrine, deltaic and fluvial deposits. The fluvial deposits consist of sand-filled channels the lacustrine sediments consist of mud with subordinate limestone, and the deltaic deposits are represented by sandy shallow-water deltas. The Aro Sand consists of fluvial sand up to 120 m thick. The Addai Fanglomerate (250–300 m thick) consists of coarse-grained alluvial fan.

Keywords: Danakil Depression Eritrea; facies analysis; Pleistocene; Buya; Homo

1. Introduction

The Pleistocene- Dandiero Basin is located in the northern part of the Danakil depression of Eritrea, about 40 km southeast of the Gulf of Zula (upper case on Figure 1). The basin is filled with 900–1000 m of Pleistocene alluvial to lacustrine deposits that were first mapped and described by Abbate et al. (2004). Moreover, it is well-known for the occurrence of Early Pleistocene (1 Ma) Homo remains (Abbate et al., 1998; Bondioli et al., 2006; Macchiarelli et al., 2004), and the overall basin sedimentary succession is characterized by the occurrence of distinct stratigraphic horizons rich in fossil vertebrates (Delfino et al., 2004; Martinez-
Navarro et al., 2004; Martínez-Navarro, Rook, Papini, & Libsekal, 2010) and Palaeolithic stone tools (Martini et al., 2004). The latter authors concentrated their research on 40 km² of unexplored territory (Figure 1) and outlined the first geological map and stratigraphic scheme of the area. The present work focuses on Early-to-Middle Pleistocene deposits exposed in the northernmost part of the Dandiero Basin (Figure 1(A)), around the site where fossil Homo remains were found 1995–2004 (Abbate et al., 1998; Bondioli et al., 2006). The results of high-resolution field mapping surveys are presented at 1:5000 scale, as is the architecture of the deposits exposed in this key-area of the basin. More importantly, this Main Map, delineates the spatial distribution of the main sedimentary facies associations and associated depositional environments as related to the fossil-bearing horizons, and represents also a critical tool for forthcoming paleoanthropological surveys of the Homo remains area.

2. Geological setting

The Danakil depression is a 300 km-long, NNW-SSE-oriented depression filled with Plio-Pleistocene marine evaporitic to continental deposits having its northern termination in the Gulf of Zula (Figure 1). The Dandiero Basin is elongated NS, covers an area of about 100 km² (Figure 1(A)) and is filled with 900–1000 m thick alluvial to lacustrine Pleistocene deposits (Abbate et al., 2004). The western and southern basin shoulders are made of Neoproterozoic basement

Figure 1. Geographic location and schematic geological map of the Danakil depression. (A) Generalized geological map of the Dandiero Basin (after Abbate et al., 2004). Polygon indicates the mapped area.
rocks, whereas to the north it is bounded by the slopes of the Alid volcano, and to the east by the fluvio-eolian sand field of the Samoti plain.

The sediments filling the Dandiero Basin consists of three unconformity-bounded units (Abbate et al., 2004): Maebele Synthem, Curbelu Synthem and Samoti Synthem (Figure 1(A)).

The Maebele Synthem was deposited during the Early to Middle Pleistocene (Albianelli & Napoleone, 2004; Bigazzi, Balestrieri, Norelli, Oddone, & Tewolde, 2004) and consists of six lithostratigraphic units (Abbate et al., 2004) from bottom up: fluvial Bukra Sand and Gravel (150–200 m thick), fluvo-deltaic Alat Formation, (70–100 m thick), fluvial Wara Sand and Gravel (250 m thick), lacustrine Goreya Formation (50 m thick), fluvo-deltaic Aro Sand (120 m thick) and alluvial fan Addai Fanglomerate (250–300 m thick).

The Curbelu Synthem is made of 50 m thick alluvial fan gravels deposited during the Late Pleistocene, whereas the Samoti Synthem consists of fluvial gravel that grade laterally into eolian sand accumulated during Late Pleistocene-Holocene (Abbate et al., 2004).

3. Methods

The present study consists of high-resolution mapping carried out in a 3.8 km² area between UTM coordinates: upper right 37P 601197E 1633183N – lower left 37P 599150E 1630844N, focused on the Maebele Synthem deposits. Mapping was performed using Google Earth Digital Globe images, at 1:2000 scale and then compiled and presented at 1:5000 scale. Field mapping was carried out on the basis on sedimentary facies analysis principles, that facilitated a speedy and efficient approach to understand depositional processes and environmental dynamics in relation to the paleontological and archaeological contexts (Benvenuti et al., 2006; Ghinassi et al., 2009a; Viseras et al., 2006), and facies associations were mapped as sedimentary units. Facies are here considered to be the building blocks of a sedimentary succession, providing information on the depositional processes. Mapped facies associations are therefore assemblages of genetically and spatially linked facies, and represent defined sedimentary environments. Since topographic maps at 1:2000 and 1:5000 scales do not exist for the area, Google Earth images were used as topographic base map during fieldwork for the compilation of the geological Main Map.

4. Stratigraphy of the Mapped area

The studied succession in the mapped area is 285 m thick and consists of the upper part of the Bukra Sand and Gravel, the Alat Formation, the Wara Sand and Gravel, the Goreya Formation, and most of the Aro Sand all within the Maebele Synthem (Figure 2). The Addai fanglomerate is not exposed in the study area. In order to make the map more readable, only the Maebele Synthem deposits are displayed in color, whereas the Curbelu Synthem, modern alluvial and colluvial covers are not represented on the map. Mapped units have been labeled with composite names. The first two letters point to the lithostratigraphic formation according to Abbate et al. (2004) nomenclature: BU (Bukra Sand and Gravel), AA (Alat Formation), WA (Wara Sand and Gravel), GO (Goreya Formation) and AR (Aro Sand). The second two letters indicate the depositional environment: FL (fluvial), DL (deltaic) and LK (lacustrine). Finally, the number indicates the stratigraphic position within the single lithostratigraphic unit (e.g., AA.DL4 signifies the fourth deltaic unit from the base of the Alat Formation (Figure 2).

**Bukra Sand and Gravel, (BU)** – only upper 40 m exposed. Consists of fluvial deposits of amalgamated, channel-like sand bodies (*sensu* Bridge, 2003) up to 5 m thick (BU.FL Figure 3(A)). The thickness of these sand bodies decreases upward, and at the top of unit, the sandy deposits appear almost tabular. In the Alat oasis area, a 15 m thick tabular-bedded interval of muddy deposits occurs below the fluvial sand. These muddy deposits are massive, grading
upward into well-bedded medium sand. The paucity of exposure prevents detailed sedimentological analyses; however, a deltaic origin for these deposits cannot be excluded.

**Alat Formation, (AA)** – up to 80 m thick and contains an articulated stratigraphy (Ghinassi, Papini, Yosieph, & Rook, 2009b) (Figures 3–5). The lowermost unit (AA.LK1; Figure 3(A) and (B)) is lacustrine in origin and up to 3–4 m thick. The base is marked by a 3–5 cm thick calcareous layer containing *Melanoides* sp. moulds. This consists of massive mud grading upward into wave-worked, calcarenitic layers, which bear peculiar fossil traces (‘donuts’; Abbate et al., 2012; Figure 3(B—E)) and represent a key layer in the mapped area (DN). The basal part of unit AA.LK1, includes a sandy, coarsening-upward deltaic wedge (AA.DL1; Figure 3(A)). This unit is up to 2 m thick and decreases in thickness toward the North. Channel-fill fluvial sand with erosive bases, locally up to 8–10 m thick (AA.FL1a; Figure 3(A) and (B)) overlie lacustrine

Figure 2. Schematic stratigraphic column of the Dandiero Basin-fill succession in the Alat area. See text for explanation of abbreviations used.
deposits. In the northern part of the study area, unit AA.FL1a is conformably overlain by two shallow-water-type deltas (Postma, 1990; AA.DL2 and AA.DL3), 3–5 and 15–17 m thick respectively. These units show a fining- and coarsening to fining-upward depositional trend each, and are separated by a 1–1.5 m thick lacustrine calcareous mud (AA.LK2; Figure 4(A))

Figure 3. Lower part of the study succession. (A) Bukra Sand and Gravel fluvial deposits grading upward to the fluvio-lacustrine Alat Formation. (B) Fluvial (AA.FL1) and lacustrine (AA.LK1) deposits in the lower part of the Alat Formation. Encircled hammer for scale is laying on the top surface of the donuts key bed. (C) Tabular-bedded lacustrine deposits of unit AA.LK1. The donut key bed is in the uppermost part of the outcrop. (D) Donut trace in the basal surface of the donut key bed. (E) Plan view of the donut key bed. Encircled hammer for scale.

Figure 4. The Alat Formation. (A) Panoramic view of the Alat Formation. (B) Abrupt superposition of muddy lacustrine deposits (AA.LK3) on sandy deltaic facies (AA.DL3). (C) Close view of B showing development of shell-rich deposits at the base of lacustrine unit AA.LK3. (D) Upper part of the Alat Formation showing stacking of deltaic (AA.DL4 and AA.DL5) and fluvial deposits (AA.FL2a and AA.FL2b)
and (B)). In the southern part of the study area, the deltaic and lacustrine deposits of units AA.DL2, AA.LK2 and AA.LK3 gradually pass into their fluvial feeder deposits (AA.FL1b and AA.FL1c; Figure 2), which are up to 20 m thick and consist of amalgamated sandy channels.

This fluvio-deltaic complex is conformably overlain by 8–10 m thick, laminated to massive lacustrine mud (AA.LK3) that grades upward into sandy, Gilbert-type delta (Postma, 1990) deposits (AA.DL4; Figure 4(A–D)). The deltaic sediments are as much as 15 m thick and document sediment transport toward the North. In the northern part of the study area, the Gilbert-type delta deposit is unconformably overlain by 1–3 m thick shallow-water deltaic sands (AA.DL5; Figure 5(A-B), (D)), that document minor, high-frequency, lacustrine oscillations. These sands grade upward in their fluvial feeder deposits (AA-FL2a), which are up to 5 m thick and consist of channel-like sand bodies (0.5–1 m wide and 10–15 m wide) cut in pedogenized alluvial plain mud (Figure 5(C)). AA.DL5 deposits thin southward, where AA.FL2a deposits increase in thickness. Unit AA.FL2a is covered by a sequences of fluvial AA.FL2b deposits (Figure 5(D)), as much as 15 m thick; these deposits consist of a basal, channelized sand (7 m thick) grading upward into a muddy, calcrete-rich horizon (8 m thick), that is clearly identifiable in the study area.

Figure 5. Middle part of the study succession. (A) Panoramic view of the upper Alat and lower Goreya formations separated by the Wara Sand and Gravels. (B) Uppermost part of the Alat Formation showing the shallow-water deltaic deposits of unit AA.DL5 and the fluvial sand of unit AA.FL2b separated by the alluvial plain mud with scattered channels of unit AA.FL2a. (C) Fluvial deposits of Wara Sand and Gravel (WA.FL). (D) Panoramic view of the paleoanthropological site which provided Homo remains in 1995.
Wara Sand and Gravel, (WA) – 80–90 m thick, composed of alluvial plain deposits (Bridge, 2003; unit WA.FL), consisting of channelized sand and pedogenized, overbank sandy mud (Figures 5(A) and 6(D)). WA.FL deposits are characterized by a progressive increase in the size of channelized units, which are up to 2–3 m thick close to the base of the unit and about 8 m toward the top.

Goreya Formation, (GO) – approximately 60 m thick; consists of lacustrine, deltaic and fluvial deposits. The lowermost unit (GO.LK1) conformably overlies Wara sand and gravel, is lacustrine (Talbot & Allen, 1996) in origin and up to 7 m thick (Figure 5(A)). It is made of a basal, 20–30 cm thick calcareous layer, containing Melanoides sp. moulds, which passes upward into a massive to laminated mud with sandy layers in the upper part. These deposits are erosively overlain by a 6–9 m thick-channelized fluvial unit (GO.FL1), which consists of amalgamated sandy bodies up to 10 m thick (Figures 5(A) and 6(A)). GO.FL1 deposits were ascribed (Ghinassi, Billi, Libsekal, Papini, & Rook, in press) to a meandering fluvial system (Ghinassi, 2011) draining toward North. GO.FL1 fluvial sands are conformably overlain by lacustrine sediments (GO.LK2), consisting of a basal calcareous interval (up to 80–90 cm thick) that grades upward into marly to muddy laminated deposits (up to 5 m thick; Figure 5(A)). Lacustrine mud grades upward into GO.DL1, shallow-water, deltaic sands, which are up to 17 m thick and consist of two stacked coarsening-upward intervals spanning from fine to coarse sand (Figure 6(A–B)). Deltaic deposits are erosively overlain by fluvial deposits (GO.FL2), which consists of two main intervals (Figure 6(A–B)). The lower interval (up to 5–7 m thick) is made of amalgamated, channelized coarse sand, whereas the upper one (about 15 m thick) consists of channelized medium sand alternating with pedogenized alluvial mud. GO.FL2 sand is conformably covered by GO.DL2 shallow-water deltaic sand, which bears at its base a 2–4 cm thick shell-rich, calcareous layer (Figure 6(C)).

Figure 6. Upper part of the study succession. (A) Fluvio-lacustrine units forming the upper part of the Goreya Formation. (B) Abrupt superposition of fluvial GO.FL2 sand over GO.DL1 deposits in the middle part of the Goreya Formation. (C) Uppermost part of the Goreya Formation and transition to Aro Sand. (D) Panoramic view of the middle and upper part of the stratigraphic succession filling the Dandiero Basin. Note the Boulder beds of the Curbelu Synthem at the top of the succession.
**Aro Sand, (AR)** – 50–60 m thick; consist of fluvial deposits (AR.FL). The AR.FL unit erodingly overlies the Goreya Formation, and consists of channelized sand bodies (up to 7 m thick) alternating with pedogenized overbank mud, predominant in the uppermost part of the unit (Figure 6(C) and (D)).

5. **Structural setting**

The studied succession accumulated in a tectonic depression representing the northern part of the Dandiero Basin. Such a depression formed on the western border escarpment of the Danakil Depression (Figure 1) and is associated with the development of four main families of normal faults. The two main fault systems are generally NE–SW and NW-SE oriented, and appear to be synthetic-antithetic pairs related to a major east-dipping fault of the rift escarpment, whereas the minor systems are N-S and E-W oriented. The fault planes dip between 50 and 20 degrees and show well-preserved striations, which point to normal, dip-slip movement. Only two fault systems show an overall significant displacement higher than 20 m. The first one, located on the eastern side of the study area, shows a NE-SW trend and dips down the east block for about 100 m. The second fault system, NW-SE trending, is located slightly south of Mt. Alat, shows a displacement of about 25 m and dips down the northern block.

6. **Age and fossil-bearing deposits**

The Maebele Synthem accumulated during the Early-to-Middle Pleistocene time span, based on palaeomagnetism, mammal biochronology and radiometric dating (Albianelli & Napoleone, 2004; Bigazzi et al., 2004; Ferretti, Ficcarelli, Libsekal, Tecle, & Rook, 2003; Martínez-Navarro et al., 2004). Within the Maebele, the Alat formation accumulated during the Jaramillo Subchron (Albianelli & Napoleone, 2004) and the Matuyama–Bhrunes boundary occurs in the lower part of the Aro sand. The studied succession contains abundant macrofossil remains, occurring in both deltaic and fluvial deposits, either as scattered or, most important for this study in distinct horizons. Gastropod shells (mainly *Melanoides tuberculata*) and fish remains (mainly *Clariidae indet.*) are common in calcareous lacustrine deposits (e.g., GO.LK1 in Figure 2) or in deltaic sediments (e.g., AA.DL2). Although mammal bones can occur through the entire preserved succession (Ferretti et al., 2003), two main horizons have been identified and correlated within the mapped area. The first vertebrate-bearing horizon is represented by AA.DL5 and AA.FL2a deposits, which also contained *Homo* remains (Abbate et al., 1998; Rook et al., 2010). The second horizon is represented by the lowermost part of unit AA.FL2b. The latter is the richest in vertebrate remains and stone tools seen throughout the entire succession (Abbate et al., 2004; Ghinassi et al., 2009b).

7. **Conclusions**

Our geological mapping of the northern Dandiero Basin was derived from an integrated approach combining field mapping and facies analysis methods [Main Map](#). This work resulted in a subdivision of the previously defined lithostratigraphy as used by Abbate et al. 2004 into several units, which are assumed to represent different depositional environments and facies associations).

In particular, the Bukra Sand and Gravel, Wara Sand and Gravel and Aro Sand appeared to be entirely fluvial in origin and represented mainly by amalgamated sandy channels locally alternating with pedogenized overbank mud. In contrast, the Alat and Goreya formations consist of alternating fluvio-deltaic and lacustrine deposits. The Alat Formation contains in a key bed of calcarenitic in its basal part that can be easily correlated across the study area. The upper part
of the Alat Formation contains the largest preserved remains of vertebrates, and two main horizons have been identified therein. The Goreya Formation bears a further key horizon, which consists of lacustrine calcareous mud.

Software
Hand-drawn originals were scanned, registered and redrawn in Adobe Illustrator 10. The same software was used to construct the geological cross sections.

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